Aerodynamic Mitigation of Roof Suction Using Solar Panels

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AERODYNAMIC MITIGATION OF ROOF SUCTION
USING SOLAR PANELS

A Thesis
Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
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by
Laura M. Iverson
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ABSTRACT

This thesis aims to evaluate the feasibility of solar panels to be used as aerodynamic mitigation devices to reduce roof suction caused by high-speed winds on flat-roof, low-rise buildings. Roof suction is caused by negative pressures resulting in uplift on the roof, due to the wind passing over the sharp edges of the roof. Suction is a common cause of failure for these types of flat-roof, low-rise buildings during extreme wind events such as hurricanes, as the uplift force can cause the roof to separate from the building. A variety of mitigation devices have been proposed in the literature to mitigate this failure mode, which are expanded upon in the literature review. Solar panels would be a convenient medium to use as a mitigation device as the demand for green energy grows. The solar panels can be arranged around the roof’s edges which would eliminate the sharp corners that cause separation and suction on the roof.

The ability of the panels to decrease the suction on the roof was tested in two ways. The first was a flow visualization study, where sand was used to show the flow patterns on the roof, with the removal of sand being a visual indication of suction. The second method required that pressure taps be added to the building, so that the pressure with and without solar panels could be recorded. Both of these tests demonstrated that the addition of the panels was beneficial to decreasing the suction on the roof. The panels reduced peak suction, as well as decreasing the range of pressures the roof was subjected to, resulting in a more even distribution of the pressure. The pressure measurements were used to calculate the pressure coefficients on the roof, which were compared to the ASCE Standard. The ASCE Standard was found to be less conservative than the pressure coefficients, with the wind tunnel tests having more extreme values.

An ANSYS Fluent model of the bare-roof building was also created for comparison with the open jet wind tunnel tests, and was run through ANSYS’s Large Eddy Simulation (LES). This
produced a qualitatively similar pressure coefficient distribution to the wind tunnel test, but it cannot be compared directly since the LES contour is a snapshot of the roof pressure coefficients rather than a computed result from the time history, like the open jet wind tunnel results. However, ANSYS produced a time history of the lift coefficients, so that was plotted and compared with a graph of the lift coefficient from the wind tunnel test. The resulting graphs were similar, as was the mean value for the lift coefficient.
CHAPTER 1: INTRODUCTION

Hurricanes cause a large amount of loss, both in respect to life and property. The annual average economic losses due to hurricanes increased from $1.3 billion in the years 1949-1989 to $10.1 billion from 1990-1995; with the occurrence of Hurricanes Katrina and Rita, and the 2005 season set a new record with losses totaling over $100 billion (Lott 2006). Herbert et al. also found in 1996 that the annual average economic loss was increasing. His research determined that the annual average from 1940-1949 was $450 million, from 1950-1959 was $1,090 million, from 1960-1969 was $2,040 million, from 1970-1979 was $1,650 million, from 1980-1989 was $1,913 million, and from 1990-1995 was $5,833 million (Hebert 1996). This is a large drain on the economy of hurricane-prone regions, and, though advanced forecasting, warnings, and better emergency response services can reduce the loss of life, the economic impact of the destruction of the built environment can have lasting implications for these regions. Comprehensive research is needed to increase the resiliency and sustainability of buildings under extreme windstorms such as hurricanes.

The extreme wind speeds of hurricanes are at one range of the windstorm spectrum, grouped near tornadoes and very heavy thunderstorms. At the other end are modest windstorms, which cause very little damage to the built environment. However, all winds have the potential to cause destruction in low rise-buildings due to the mild to severe range or loads that can be sustained for some time under a windstorm. These loads can hurt the structure, and endanger its inhabitants. One of the main failure types resulting from this force is suction, which is especially prevalent in hurricane-prone areas.

Suction is a very common cause of damage from wind in low-rise buildings, because when wind interacts with the building, flow-induced forces are created. As the flow passes over the sharp
corners of a building, separation occurs. This flow separation causes vortices to form on the roof, creating local suction, possibly initiating roof failures at the corners. The suction force can vary depending on the angle of the wind and the overall shape of the roof. Negative pressures are typically experienced at the corners of the windward edges. As a further complication, wind flow is dynamic, so the ‘windward’ face of the building can change from moment to moment, creating uplift forces in multiple locations of the roof, though typically the highest pressures are near corners and edges of the roof (Dixon).

There have been several studies conducted on different configurations of aerodynamic mitigation devices on bare, flat roofs in order to decrease the pressure differential. However, the potential of solar panels as aerodynamic mitigation devices has not been considered as a possibility. All structures must have a capacity to resist certain loads, such as wind, in order to be safe for use. Determining the wind impact is crucial to many structures, as this impact can be very unpredictable and destructive. This is important in the design of buildings, especially residential and office buildings where people live and work. Failure of these structures often results in lives lost, as well as significant property damage. Due to the high cost of failure, it is especially important to find ways to mitigate these issues.

This study examines whether solar panels, already widely used, could be used in place of traditional aerodynamic mitigation devices. As the human population grows, demand for fuel will continue to grow, leading humanity to seek new sources of energy. Solar energy is one of the most commonly available types of renewable energy in many parts of the world. The use of solar panels to generate energy is becoming more commonplace. Solar energy is considered a type of energy called ‘green energy’, as it does not produce carbon dioxide emissions, otherwise known as greenhouse gases. These emissions can be especially troublesome in large cities where they create
smog and air quality issues. The cleanliness of sunlight as an energy source is an important factor, in addition to its excellent return on investment. The initial investment in solar panels can be relatively high; however, the energy savings created by the investment can justify the capital cost. Solar panels become even more economically feasible if they can serve multiple purposes, such as aerodynamic mitigation devices as proposed in this study. They may become even more accepted as an alternative to traditional fuel sources, such as fossil fuels.
CHAPTER 2: LITERATURE REVIEW

2.1 Why Use Aerodynamic Mitigation?

Aerodynamic mitigation of roofs is essential to reducing the economic impact of hurricanes, as the roof is typically the most vulnerable place for wind damage. Therefore, ideas must be developed to reduce this force in order to minimize the impact of the storm on the roof and surrounding areas. One option to minimize wind loads is to alter the roof shape with aerodynamic mitigation features. These features can reduce drag and lift coefficients on the roof, which in turn reduce the hurricane-induced loads. This prevents the hurricane loads from damaging the roof and causing it to become wind-borne debris. Many different aerodynamic roof mitigation strategies are suggested in literature (Banks and Merony 2001; Bitsuamlak 2013; Cochran 1997).

As wind forces on bluff bodies is primarily a result of their shape, the addition of elements to change the shape of the bluff body, called shape modification, can be used to reduce aerodynamic loads on the structure. This approach has been used to reduce wind loads on tall buildings, bridges, and the roofs of low-rise buildings. The roof edge can be modified to reduce the total uplift on the roof, or total suction.

2.2 Effects of Suction on Low-Rise Buildings

In the area of low-rise buildings, many efforts have been made to understand and reduce the suction and uplift on the roofs of these buildings. Many of these previous projects used scale building models, outfitted with pressure taps, in a wind tunnel to simulate full-scale, real world data. Banks et al. (2000) performed an experiment in order to better understand the flow characteristics that produce the negative pressure coefficients for suction by studying low-rise buildings in wind tunnels. The greatest suction occurred directly below the moving vortex core, shown in Figure 1 below. The magnitude of the suction beneath the core was seen to vary inversely
with the vortex size for smooth flow, but there was no relation between the vortex size and suction for turbulent flow (D. Banks 2000).

![Vortex Diagram](image)

**Figure 1: Conical 'Delta-Wing' Corner Vortices (D. Banks 2000)**

Banks and Meroney in 2001 studied how conical vortices produce rooftop surface pressures, including the relationship between suction and the upstream flow. The flow velocity component normal to the roof edge determines the speed of the vortex spin, regardless of the wind direction angle. This result indicates that the pressure above the vortex is always controlled by the speed of the gusts that pass over the roof corner (Banks and Merony 2001). In a 2008 study by Prasad et al. (Prasad 2009), low rise building models were tested with flat, gabled, and hip roof configurations. This study determined that the uplift on the roof was significantly influenced by the roof shape. The 45° hip and gable roofs performed the best under the 7 m/s turbulent test wind. The gabled roof reduced the peak suction by 91% when compared with a flat roof.

### 2.3 Aerodynamic Mitigation in Literature

Some of the first studies of roof corner geometric modifications and their effect on roof pressures were done by Surry and Lin in the mid-1990’s. In their conference paper “ Suppressing Extreme Suction on Low Buildings by Modifying the Roof Corner Geometry” they compared the measurements from a 1:50 scale model in a wind tunnel to full-scale experimental results. The study determined that the suction generated on the roof was due to vortices generated near the
corner by the adjacent straight, sharp edges, like delta wing vortices that generate lift on airplanes. High suction as present near the edge and corner in the along wind direction, along rays of 10° and 22°. Several mitigation strategies were suggested and explored in the paper which is detailed below.

The first was partial parapets of width 0.12H and height 0.06H, which reduced the suction close to the corner by 24%-40% for the negative peak coefficient of pressure, 10% for the mean coefficient of pressure, and 20%-30% for the rms coefficient of pressure. Clearly, this type of parapet is best for reducing the fluctuating loads, rather than the overall pressures. Saw tooth parapets were also determined to be better than traditional rectangular parapets, as the rectangular ones may have in fact induced additional vortices. The second method considered was the addition of rooftop cylinders near the corner, which reduced the suctions near the corner by up to 60% for the negative peak coefficient of pressure, 50% for the mean coefficient of pressure, and 55% for the rms coefficient of pressure. A single cylinder had the greatest effect on the rms coefficient of pressure, while a dual cylinder layout had a greater effect on the peak and mean coefficients of pressure. However, the primary drawback to this technique was that the cylinder’s success decreased with increased distance from their position. The third examined mitigation technique was rounding the edges of the roof by attaching round edge plates with a radius of 0.1H to the wall. This had the best results, as it reduced the peak, mean, and rms coefficients of pressure by over 60% (Surry 1993).

Lin and Surry published another paper in 1995 that explored the effects of surroundings on the generated suction from wind loads. They examined seven configurations of roof modifications to the geometry and how they influenced the suction on the roofs studied. The first set of geometry modifications aimed to eliminate the straight sharp edges that create vortices: rounded edges, semi-
cylindrical projections, and curved plates. The second set of geometry modifications aimed to disrupt the vortices formation: partial parapets and porous parapets. The third set of geometry modifications aimed to disturb the vortices: rooftop porous fences, rooftop cylinders, and solid or porous rooftop splitters. The fourth set of geometry modifications aimed to displace vortices that were already formed, using full parapets. These modifications are shown in Figure 2 below. They found that the presence of nearby buildings greatly reduced suction on the roof. At the corner, the mean pressure coefficient was reduced by 50-65%, and the rms and peak pressure coefficients were reduced up to 50% compared to a stand-alone building. Since most low buildings are situated in suburban or urban areas, this could impact design greatly.

All of the seven considered roof geometric modifications greatly reduced the high roof suction at the windward corner and edges compared to the unmitigated roof that was the control test. The porous parapets had the greatest effects as they led to a suction reduction of up to 70% near the corner and also resulted in a very flat pressure distribution pattern over the entire roof. The semi cylindrical projects did nearly as well as the round roof edges, reducing suction by more than 60%. The rooftop splitter configurations resulted in reductions of about 60% for high suction magnitude, with the porous splitters being a little more effective than solid ones. The saw tooth parapets reduced the suction near the corner by up to 40%, however, there was also a surprise from this data set. It was expected that the multi-saw tooth configuration would have better results than the single-saw tooth parapet. Contrary to this assumption, the dual and triple saw tooth configurations did not have a better result than the single-saw tooth configuration (Lin 1995).
Figure 2: Geometric Configurations (Lin 1995)
Chowdhury et al. (2007) tested six different roof geometries using the Wall of Wind. The largest reduction achieved was 74% in localized pressures by using the aerodynamic mitigation device Flat Roof Aero Edge Guard (Chowdhury 2007). Mahmood et al. (2008) tested various buildings types at the Texas Tech University using a 1:100 scale in different wind flow conditions. This experiment determined that rounding the roofs greatly decreased suction by up to 80% for the localized pressures (Mahmood 2008). Pindado et al. (2006) determined that cantilever parapets reduced suction, as the air stream between the parapet and the building reduced the conical vortices (Pindado 2009). Kopp et al. in 2005 did a more extensive study on the results of parapets in reducing conical vortices formation. The study focused on parapet height as a determining factor on flat roofs to decrease corner uplift. It concluded that parapets did reduce suction loads because they raise the position of the corner vortex so it no longer lies on the roof, but it is highly dependent on the height of the parapet. The greatest benefit came from a parapet that was 0.9 m all around the roof, with an extra 0.9 m at the corner. It was also determined that a parapet with a slotted corner would still be effective, but not as much as the solid parapet (Kopp G.A. 2005).

In an effort to suppress conical vortices, screens (D. Banks 2000), aerodynamic edges and devices (Banks and Merony 2001; Prasad 2009), and roof-edge parapets have been tested (Suaris 2010). Although all of these attempts to suppress the conical vortices worked to an extent, the research did not address the stability and strength of the devices themselves under extreme winds. The devices can fail due to extreme wind loads or airborne debris and leave the roof again vulnerable to uplift loadings. In addition to this problem, these devices are typically located at corners, since that is the key location for reducing vortex pressure. However, the middle of large roofs is also susceptible to large negative pressures, and this requires a different mitigation technique than those described above. A solution must be found that can reduce the wind load on
the roof at its corners, but also reduces the load on the mitigation device itself so that it will not fail. It must also take into account the negative pressures that can develop in the middle of large roofs.

### 2.4 Solar Panels in Literature

Much work has already been done with respect to wind loading on solar panels. Stathopoulous et al. conducted a wind tunnel test for standalone solar panel surfaces and panels attached to flat roofs. They computed the pressure and force coefficients from the pressure tap data, and tested different configurations to find the critical wind condition for suction. The panels near the roof edges experienced the greatest net force load. The study yielded pressure coefficients for solar panel design in several scenarios (Stathopoulous 2014). Specifically, with regards to tilted solar panels on flat roofs, David Banks discussed the uplift wind loads on tilted flat solar panels. His results showed no significant increase in loads for panels aligned with the building axes. However, the wind loads around the corners of the building were higher, due to the conical vortices that form around the corners of wide, rectangular, low-rise, flat-roofed buildings. The increase in wind load on these corner panels was related to the direction of the panel tilt relative to the vortex swirl, the position of the panel relative to the reattachment point of the vortex, and how close the panel was to the wind-ward corner where the vortices form (D. Banks 2013).

The impact of other parts of the building can also impact the wind load on a solar panel or solar panel array. Browne et al. (2013) investigated the effect of parapets on solar arrays. The authors examined the changes in wind flow that occur when an obstruction, like a parapet, is placed in the stream. The authors concluded that increasing parapet height increased the peak wind loads acting on the solar array, due to the corner vortices formed by the wind flow. However, the
increases were dependent on location of the array on the roof, the location of the panels in the array, and the array geometry (Browne 2013).

2.5 Wind Speed Profiles in Literature

This study will make use of a previously developed wind speed profile, based on the paper by Aly and Bresowar, published in 2016. The Computational Fluid Domain (CFD) profile used in this paper was compared to experimentally measured profiles for an open terrain exposure, as shown below. The CFD wind profile was compiled from a C++ code and input into ANSYS Fluent as the inlet velocity profile. Both a comparison of the mean velocity profile and the turbulence intensity profile are shown Figure 3 below. The profile is very accurate when compared with the experimental data until it reaches a substantial height, in this case 2.5 times the reference height, is reached. The reference height is typically the top of the building, so the profile being accurate up to more than double the building height is more than sufficient for the purpose of this study (Aly 2016).

Figure 3: CFD Wind Speed Profiles in Comparison with Experimentally Measured Profiles for an Open Terrain Exposure: (a) Mean Wind Velocity Profile and (b) Turbulence Intensity Profile
CHAPTER 3: OBJECTIVES AND METHODOLOGY

3.1 Objectives

The main objective of this research is to determine if solar panels can be used as aerodynamic mitigation devices on low-rise, flat-roof buildings. This objective will be achieved by building scaled models to test in an open jet wind tunnel, as well as creating a virtual model of the bare roof case to compare with the wind tunnel results. Two types of building models will be created, one with a bare flat roof, and one with solar panel aerodynamic mitigation around the edges. The computer models will be drawn using AutoCAD Civil 3D, while the scale models are created using Plexiglas at a scale of 1:27 in the lab.

The scaled, wind tunnel models will be tested in two ways. First, sand will be placed on the top of the model, the wind tunnel will be turned on, and video footage will be recorded of the reaction on the top of the model to the wind loading. Solar panel ‘models’ made of Plexiglas will then be added to the building, and the experiment with sand and wind will be repeated. The results will be compared by observing the recorded video footage as well as the amount of sand remaining on the roof in each case. Second, pressure taps will be added to the building, and connected to sensors. These sensors will measure the pressure distribution over the building for a bare roof case, with no solar panel models attached to it. Then the test will be run again, this time with the Plexiglas solar panel models attached to the roof of the building. Each of the pressure tests will be run at three different wind direction angles. These results will be used to compute the pressure coefficients on the roof, which will be plotted in a contour plot. This will be compared to the pressure distribution obtained through the ANSYS Fluent for the bare roof case.
3.2 Wind Tunnel Visualization Testing

First, a model was created out of Plexiglas at a scale of 1:27 to the actual size, using two different thicknesses of Plexiglas were used. Two of the sides as well as the top were made from \( \frac{2}{16} \) inch Plexiglas, while the remaining two sides were made of \( \frac{3}{16} \) inch Plexiglas to add rigidity to the model. All of the sides were carefully measured and cut with the thickness of the Plexiglas in mind to ensure that the overlapping edges were taken into account. Once the flat-roofed building model was complete, the solar panel models were cut and fit onto the building model to ensure accuracy. The dimensions used for the model of the solar panels were obtained from Canadian Solar (CanadianSolar).

The flat-roofed building model was covered with sand to visualize the flow pattern that would emerge from wind on the building. The open jet wind tunnel in Room 1401 in Patrick Taylor Hall was used to simulate the wind flow. The model being acted upon by the wind was videotaped, and several stills from this video will be shown in the results section. Following this first test, the solar panel models were then added to the model roof and the wind loading and videotaping were repeated. After this test, it was observed that some air may be encroaching between the model Plexiglas solar panels and the Plexiglas of the roof, so these edges were sealed with 3M tape and the videotaping and wind loading were repeated for a case of full sealing of the solar panels to the edge of the roof.

3.3 Pressure Tap Configurations and Pressure Testing

Pressure taps in the building surface were used to gauge the pressure on the surface for three different wind direction angles. The 0-degree measurement was taken with the longer edge of the building in the along wind direction, the 45-degree measurements were taken with the building at a 45-degree angle as in the visualization test, and the 90-degree measurements were
taken with the shortest side of the building in the along wind direction. A tap layout was generated in AutoCAD Civil 3D, shown below in Figure 4, to optimize the placement of the taps for the pressure measurement during the test. A number of 128 pressure measurement points was chosen, as the circular pneumatic connectors used in data collection can hold 64 tubes each. A grid of the layout was drawn onto the Plexiglas model for accuracy, and then small holes were drilled at each of the specified locations. A small tube was inserted into each of the holes that was numbered so that the pressure measurement could be taken at these locations. The tubes were numbered at both ends to ensure accuracy in the data collection. Each of the tubes was cut flush with the Plexiglas surface so that they would not hinder the wind flow over the building as the data was collected. The opposite end was attached to a circular pneumatic connector to gather the pressure data from the tubes.

Figure 4: Pressure Tap Layout (mm)
The circular pneumatic connector is shown below, with the pressure tube connection on the right hand side, while the instrument on the left hand side is connected to the data acquisition box. The plate in the middle isolates each of the signals to ensure accuracy.

![Circular Pneumatic Connector](image)

**Figure 5: Circular Pneumatic Connector**

The data acquisition box was attached to the computer to collect the readings from each of the pressure taps on the surface of the building. A Cobra probe, to measure velocity, was set up in front of the building model. The probe was located 2h in front of the model, where h was 6 inches, the height of the building model. The probe tip was located at the same height as the building, and was angled so that the velocity inlet pointed directly into the oncoming flow from the open jet. This measurement device is shown below in Figure 6, and it was also attached to a data acquisition system to enable data collection from the sensor. Once all of the sensors were set in place, the data collection could begin.

First, both collection systems were initiated. The pressure sensor hardware limited the data collection to 625 frames per second (fps), and the time limit for the pressure collection was set by specifying the total number of frames required. The pressure was normalized to zero during a time of no airflow in the open jet for reference. The velocity readings from the cobra probe, pictured below in Figure 6, were also zeroed, to give a more accurate reading.
Figure 6: Cobra Probe for Velocity Measurement

For both the pressure and velocity readings, a test of five seconds was taken in still air for data normalization after tests completion. As per the Law of Similitude, the following equation must be satisfied:

\[
\left[ \frac{U}{ft} \right]_m = \left[ \frac{U}{FL} \right]_p \quad \text{(Equation 1)}
\]

As the scale model is 1:27 of full size, a model test time of 5 minutes was determined to be adequate to satisfy the Law of Similitude. The open jet tunnel was turned on, and pressure and velocity readings were taken with the aforementioned intervals. The data was captured from the data acquisition box for the pressure taps using ScanTel software on a computer in the lab. The scan groups were listed and the channels set in the software so that the data could be collected and later associated with each pressure tap. The data was collected using a binary system, which was then converted in the more typical format of actual pressures. A five-minute test was run for each of the following scenarios for the building pressures, as shown in Table 1 and Table 2 on the following pages.

The data was collected from each of these setups, and the pressure was converted from binary files to long format files so that they could be easily read by Matlab in Comma Separated
Value format (.csv). The velocity readouts from the cobra probe were also converted to an Active Page (.ap) file so that they also could be read in Matlab and correlated with the pressure data. The files were then read in Matlab. First, the average of the still air test was used to normalize the data to prevent errors due to imperfect readings or laboratory equipment. The average for each direction (along wind, across wind, and vertical) was subtracted from the data set to normalize it. Then $Q$ was calculated using Equation 2 below from a journal article by Richard and Hoxey in 2012, shown below (Richards 2012).

$$q = \frac{\rho}{2} (V^2) = \frac{\rho}{2} (u^2 + v^2 + w^2) \quad \text{(Equation 2)}$$

Where $\rho$ is the air density, $V$ is the instantaneous wind speed, and $u$, $v$, and $w$ are the instantaneous velocity components at the reference position. In this case, the reference position was located at the height of the building, two building heights in front of the building for minimal wind flow interference and most accurate readings.
Table 1: Model Arrangements without Solar Panels

<table>
<thead>
<tr>
<th>Model Position</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 degrees</td>
<td><img src="image1.png" alt="Picture" /></td>
</tr>
<tr>
<td>45 degrees</td>
<td><img src="image2.png" alt="Picture" /></td>
</tr>
<tr>
<td>90 degrees</td>
<td><img src="image3.png" alt="Picture" /></td>
</tr>
</tbody>
</table>
Table 2: Model Arrangements with Solar Panels

<table>
<thead>
<tr>
<th>Model Position</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 degrees</td>
<td><img src="image1.png" alt="Picture" /></td>
</tr>
<tr>
<td>45 degrees</td>
<td><img src="image2.png" alt="Picture" /></td>
</tr>
<tr>
<td>90 degrees</td>
<td><img src="image3.png" alt="Picture" /></td>
</tr>
</tbody>
</table>
The mean pressure coefficient was calculated using Equation 3 below, also from the Richard and Hoxey paper (Richards 2012).

\[ \bar{C}_p(\bar{\theta}) = \frac{\bar{p}}{\bar{q}} \]  
(Equation 3)

The pressure coefficient is assumed to be only a function of the mean wind direction (\(\bar{\theta}\)). The maximum and minimum pressure coefficients are defined in Equations 4 and 5 below (Richards 2012).

\[ \bar{C}_{p^*}(\bar{\theta}) = \frac{\bar{p}}{\bar{q}} \]  
(Equation 4)

\[ \bar{C}_{p^\circ}(\bar{\theta}) = \frac{\bar{p}}{\bar{q}} \]  
(Equation 5)

Where \(\bar{q}\) is the maximum observed dynamic pressure, \(\bar{p}\) is the maximum pressure observed during an observation period, and \(\bar{p}\) is the minimum pressure observed. It should be noted that on roof taps the mean pressure is rarely positive, so in some cases the maximum pressure is actually a weak suction. For the analysis of the data with this experiment, each pressure coefficient was used to create contour plots of the roof surface. The calculations of the mean, maximum, and minimum pressure coefficients used the upper and lower quartiles for pressure and the dynamic pressure to ensure accuracy.

A quartile is each of three values of the random variable that divides a population into four groups. For example, in the lower quartile, twenty-five percent of the data falls below the value, while seventy-five percent falls above it. For the upper quartile value, the numbers are reversed such that seventy-five percent of the data falls below the value, while twenty five percent falls above it. While the peaks, both minimum and maximum, can fluctuate considerably with each experiment, the quartiles are much more stable. The quartile values were calculated using a Matlab function written by Joseph A. Main, using a modified version of a function previously written by Fahim Sadek, based on the procedure discussed in Sadek et al. (Sadek 2002). The mean pressure
reading was divided by the mean dynamic pressure to get the mean pressure coefficient for each tap. The upper pressure quartile was divided by the upper dynamic pressure quartile, to get a maximum pressure coefficient value for each tap. The lower pressure quartile was divided by the upper dynamic pressure quartile, to get a minimum pressure coefficient value for each tap. These values were then plotted against a grid of the pressure taps, which was measured from the model itself in millimeters to ensure accuracy.

### 3.4 Pressure Coefficient Comparison with ASCE 7-10 Standard

The first step for comparison of the pressure coefficients obtained through the open jet wind tunnel testing to the ASCE 7-10 Standard was to calculate the coefficients given by the procedure in the code. This was accomplished by following the procedure in Chapter 30.4, titled Part 1: Low Rise Buildings. This section is applicable on low rise buildings, which is defined in part 26.2 of the code as a building with a mean roof height less than or equal to 60 feet, and a building whose mean roof height does not exceed the least horizontal dimension. Section 30.4 is used to determine the design wind pressures on the building under consideration. The external pressure coefficient is the comparable quantity for this thesis, so that is what will be calculated. Also present in the design wind pressure equation are the internal pressure coefficient and the velocity pressure at the mean roof height. Each component should be designed for the maximum positive and negative pressures (ASCE/SEI 2013).
The value of ‘a’ was then determined using the guidance provided by the code. First, ‘a’ was calculated for the full sized model. The first value to be determined is the least of 1) 10% of the least horizontal dimension or 2) 40% of the height. For the full size model, these values are 1) 0.91 m and 2) 1.6m. However, the lesser value of 0.91 cannot be less than either 4% of the least horizontal dimension (0.364 m) or three feet. The required value for the full sized model is then 0.9144 m (3 feet). The area and then external pressure coefficient of each zone was then calculated by plotting the areas on Figure 30.4-2A of the code. The required value of ‘a’ for the open jet wind tunnel model is 35 mm. Both the areas and the pressure coefficients for the full scale model are shown below in Table 3.

Table 3: Calculation of External Pressure Coefficients from ASCE 7-10 Code

<table>
<thead>
<tr>
<th>Zone</th>
<th>Effective Wind Area (m²)</th>
<th>External Pressure Coefficient, GCₚ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>86.32</td>
<td>-0.9</td>
</tr>
<tr>
<td>Zone 2</td>
<td>35.01</td>
<td>-1.1</td>
</tr>
<tr>
<td>Zone 3</td>
<td>3.34</td>
<td>-1.8</td>
</tr>
</tbody>
</table>
The pressure coefficients calculated from the open jet wind tunnel tests are not directly comparable to the ASCE guidelines. The wind speed from the open jet wind tunnel tests is equivalent to the mean hourly wind speed. The ASCE Standard uses the 3-second gust speed to determine the pressure coefficients and it also uses a reference height of 10m, so a conversion factor is needed since the building full scale reference height is the roof height, or 4 meters. The process for determining the conversion factor needed or the reference height change is shown in Equation 6 and Equation 7:

\[ U = U_{10} \times \left( \frac{Z}{Z_0} \right)^\alpha \]  
\text{(Equation 6)}

\[ \frac{U}{U_{10}} = \left( \frac{4}{10} \right)^{0.15} = 0.8716 \]  
\text{(Equation 7)}

Where \( U \) is the reference velocity at 4 meters, and \( U_{10} \) is the reference velocity at 10 meters. \( Z/Z_0 \) is the height over the new reference height, and \( \alpha \) is 0.15 for open terrain. The conversion required for the 3-second gust to hourly conversion was determined using the Durst Curve, and the conversion factor required to change from an hourly mean wind speed to a 3 second gust is 1.52. Therefore, the three-second gust wind speed at a reference height of 10 meters is the mean hourly wind speed at 4 meters times the Durst Curve correction factor times the inverse of the conversion factor from Equation 7.

\[ U_{3-s, 10m} = U_{\text{hourly,4m}} \times 1.52 / 0.8716 = U_{\text{hourly,4m}} \times 1.744 \]  
\text{(Equation 8)}

The conversion factor, 1.744, shall be called CF in future equations for simplicity. Since the pressure coefficient is a function of \( U \), the conversion factor must be adjusted to fit the \( C_p \) function, if the factor is to be multiplied by \( C_p \) directly. The \( C_p \) function is shown below in Equation 9.

\[ C_p = \frac{p-p_0}{\frac{1}{2} \rho U^2} \]  
\text{(Equation 9)}
The modified wind speed equation is shown below in Equation 10, along with the same equation, but with the conversion factor pulled out to make the computations simpler to change between the hourly wind speed at 4 meters and the 3-second gust speed at 10 meters.

\[ C_p = \frac{p-p_0}{\frac{1}{2}\rho(U^*CF)^2} = \frac{p-p_0}{\frac{1}{2}\rho U^2CF^2} = \frac{p-p_0}{\frac{1}{2}\rho U^2} \cdot \frac{1}{CF^2} = \frac{p-p_0}{\frac{1}{2}\rho U^2} \cdot 0.3288 \]  

(Equation 10)

The conversion factor of 0.3288 was applied to all wind tunnel tests for comparison with the ASCE Standard only. All other pressure coefficient results were calculated using Equation 9 alone.

3.5 Virtual Model Creation

The flat roof building model has a width of 13.7 m, a depth of 9.1 m, and a height of 4 m. For ANSYS Fluent, the building needs to be inside of a computational domain. The computational fluid domain outside of the building will have dimensions with respect to the height (H) of the building mentioned previously. This domain will have a length of 35H, a width of 16H, and a height of 10H, as shown below in Figure 8.

![Figure 8: Computational Domain around Building](image)
Once the model was completed in AutoCAD, the three dimension model was exported into stereolithographic (.stl) format. Then the model was imported into ICEM CFD, used through LSU’s Virtual Lab. The various surfaces on the model were defined. For the computational domain, the surfaces were classified as an inlet, outlet, roof, ground, side 1, and side 2. The space between the building and the interior of the computational domain is defined as the fluid. Then, all of the surfaces are meshed to accurately capture the wind data during simulation in ANSYS Fluent. The mesh is then exported from ICEM CFD and imported into ANSYS Fluent. Using the LSU supercomputer, Mike2, the models are run through ANSYS Fluent to determine the pressure coefficient distribution on the roof with and without the solar panel additions. The virtual model was tested only for a wind direction of 45°, as this angle typically creates the most suction, as verified in the open jet wind tunnel testing. The corner placed in the along wind direction will receive the most uplift, and the vortices will develop along the two sides, as shown in the literature (Banks and Merony 2001; Banks, et al. 2000).

### 3.6 Large Eddy Simulation in ANSYS Fluent

After these mesh file was created, it was imported into ANSYS Fluent 16.0 as a mesh (.msh) file, where it was rotated and translated until it was in the correct position in the X, Y, Z space. The positive Y direction needs to be pointing up, and the smallest value in the Y domain must be positive for the flow parameters to be input correctly. Parameters for the flow were input using a C++ code that mimics the actual flow of the wind near the ground (Y=0) and then increases as the distance from the ground increases. The Large Eddy Simulation Model was chosen for the Viscous Model. A wide range of eddy sizes can characterize turbulent flow. However, the largest eddies are comparable in size to the characteristic length of the mean flow, while smaller eddies are responsible for dissipating turbulent kinetic energy. With the Large Eddy Simulation of
ANSYS Fluent, large eddies are computed directly, while smaller eddies are modeled. Large eddies primarily transport momentum, mass, and energy, while small eddies do not affect these and other scalar terms significantly. Large eddies derive energy from the mean flow, and transfer energy to smaller eddies. The smallest eddies convert turbulent energy into internal energy using viscous dissipation. Small eddies are also less dependent on the geometry and more consistent than large eddies, making large eddies more problem dependent. Large eddies are much more influenced by the geometry of the model and the boundary conditions of the flow, so a simulation run with respect to large eddies will be more specific, and less universal than one with small eddies. When comparing geometries, a solution which is too universal can be less exact and not as useful to specific research concerns. Resolving only the large eddies also allows for a coarser mesh to be used, along with larger time-steps, reducing the computational cost of the simulation, though the simulation must be run for a sufficiently long flow time to achieve convergence on key statistics of the flow being modeled.

The Large Eddy Simulation in ANSYS Fluent solves spatially averaged time-dependent Navier-Stokes equations to filter out eddies who scales are smaller than the grid spacing used. Navier-Stokes equations describe the motion of viscous fluid substances. They are derived from an application of Newton’s second law that the rate of change of momentum of a body is directly proportional to the force applied, and this change in momentum occurs in the direction of the applied force. This law is applied to fluid motion, along with the assumption that the stress in a fluid is the sum of a diffusing viscous term and a pressure term. The resulting equations then govern the dynamics of the large eddies that are simulated. For incompressible flows, the Navier-Stokes Equation is defined in Equation 6.

\[
\frac{\delta u_i}{\delta t} + \frac{\delta(u_i u_j)}{\delta x_j} = \frac{1}{\rho} \frac{\delta p}{\delta x_i} + \nabla \cdot \left( \nu \frac{\delta u_i}{\delta x_j} \right)
\]  
(Equation 11)
The filter can be described using Equation 7 below. This filter is a function of the grid size. If an eddy is smaller than the grid size, it is removed and modeled by a subgrid scale model, while larger eddies are solved numerically used the filtered Navier-Stokes equation.

\[
\mathbf{u}(x, t) = \mathbf{u}(x, t) + \mathbf{u}'(x, t) \quad \text{(Equation 12)}
\]

The resulting equations then govern the dynamics of the large eddies that are simulated. For incompressible flows, the theory can be summarized by the following equations. Once the Navier-Stokes equations are filtered, the following equation is obtained:

\[
\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial u_i}{\partial x_j} \right) - \tau_{ij} \quad \text{(Equation 13)}
\]

where \( \tau_{ij} \), the subgrid scale turbulent stress, is defined below in Equation 9.

\[
\tau_{ij} = \rho (\mathbf{u}_i \mathbf{u}_j - \mathbf{u} \mathbf{u}) \quad \text{(Equation 14)}
\]

The transient state was chosen for the time solver option, rather than steady and a pressure based solver was used. Boundary conditions were set for each of the zones created by the mesh. These conditions are shown below in Table 3 below.

Table 4: Boundary Conditions of ANSYS Fluent Model

<table>
<thead>
<tr>
<th>Zone</th>
<th>Boundary Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>Wall</td>
</tr>
<tr>
<td>Ground</td>
<td>Wall</td>
</tr>
<tr>
<td>Inlet</td>
<td>Velocity – Inlet</td>
</tr>
<tr>
<td>Outlet</td>
<td>Outflow</td>
</tr>
<tr>
<td>Side 1</td>
<td>Symmetry</td>
</tr>
<tr>
<td>Side 2</td>
<td>Symmetry</td>
</tr>
<tr>
<td>Top</td>
<td>Symmetry</td>
</tr>
</tbody>
</table>

The wall boundary condition is used to bound either fluid and solid regions. In viscous flows, the wall condition enforces a no-slip boundary condition. The velocity inlet condition is used to define the velocity and scalar properties of the flow at inlet boundaries. The outflow condition is used to model flow exits when the details of the velocity and pressure are not known before the flow.
problem is solved. This condition is best used when the exit flow is close to a fully developed condition, as in this case. Symmetry boundary condition are used when the physical geometry of interest, and the expected pattern of the flow/thermal solution, have mirror symmetry.

The reference values for the problem solution were also defined in ANSYS Fluent. The velocity reference value was determined from the C++ file used for the flow generation. The reference velocity is the velocity at the top of the building height, 19.5 meters per second. The reference area was calculated to be the windward surface. Because the building is at a 45-degree angle, this did require some calculation. A length of 16 meters was found to be the width of the windward area, and the building height multiplied by the width to obtain the windward area. The 16 meter measurement is shown below on the model in Figure 9.

![Figure 9: Reference Value Calculation](image)

Monitors were set to plot and write the drag and lift coefficients for the building, and velocity monitors were placed at the inlet at the building height to use as the inlet velocity, similar to how the cobra probe measures the velocity in a wind tunnel. A time step of 0.001 was used in order to reach convergence, based on the mesh size. The maximum iterations per time step was set at 20 to
prevent unnecessarily long computations. Once all of the parameters are specified, the model will be initiated and then iterations will be run until the values for the drag and lift coefficients converge for the mesh. Once these values are obtained, the results will be viewed, and the pressure distribution on the building will be analyzed, especially the contour plots of the roof.

The primary interest for the Large Eddy Simulation Model is the comparison of the contour plot of the pressure coefficients for the roof, compared to the wind tunnel study. However, the drag and lift coefficients for the bare roof building were also recorded with ANSYS Fluent through the time history, and are plotted in the results and discussion section. Drag and lift coefficients are both obtained by integrating pressure over building surfaces or mitigation device surfaces, with each pressure using the tributary area of the pressure reading. The drag coefficient is defined below in Equation 10:

\[ C_d = \frac{F_d}{0.5\rho U^2 H W} \]  \hspace{1cm} (Equation 15)

where \( F_d \) is the drag force, \( \rho \) is the air density, \( U \) is the reference wind speed at the building height (H), and \( W \) is the width of the building. Similarly, Equation 11 defines the lift coefficient below:

\[ C_l = \frac{F_l}{0.5\rho U^2 H W} \]  \hspace{1cm} (Equation 16)

where \( F_l \) is the lift force.
CHAPTER 4: RESULTS AND DISCUSSION

4.1 Wind Tunnel Visualization

As previously mentioned, the building model, constructed of Plexiglas, was covered with sand and placed in a generated wind. Below in Figure 10, the initial picture of the building is shown, covered with sand, the undisturbed preliminary case.

Figure 10: Flat-Roof Building Model before Wind Loading

As the wind loading was applied, the conical vortices formed become apparent on the surface of the building. Figure 11 shows these conical vortices which formed on the windward corner along both building sides.

Figure 11: Flat-Roof Building Model with Conical Vortices
Figure 12 shows the building after one minute and nine seconds of air flow using the wind generator in 1401 Patrick Taylor Hall at Louisiana State University. Most of the sand that was on the building has been removed from the wind force.

Figure 12: Flat-Roof Building Model after One Minute of Wind Loading

After this process was performed for the flat-roof building with no solar panel mitigation, the solar panels were added to the model and the experiment was repeated. Below, Figure 13 shows the initial state of the building covered with sand, the undisturbed preliminary case.

Figure 13: Flat-Roof Building Model with Solar Panels before Wind Loading
After one minute under the wind load, the sand had moved, but not in the previously shown conical vortex pattern. The sand was evacuated under the solar panel models themselves. This pattern is shown in Figure 14, with the evacuated sand areas circled in red.

![Figure 14: Flat-Roof Building Model with Solar Panels with Sand Evacuation](image)

It was hypothesized that wind could have come up through the slight separation between the solar panel models and the building model, causing sand to move away from the edges on the windward side. However, that did not explain the other two areas that were missing sand, as they were on the leeward edges of the building.

It is possible that vortices caused by the obstruction in wind flow generated turbulence on the leeward side of the building, which forced air up into the gap between the solar panel models and the building model. To test this theory, another round of wind testing was performed, but this time with the edge between the solar panel models and the building model sealed with tape. Below is the starting picture for that test, Figure 15.
Figure 15: Flat-Roof Building Model with Solar Panels and Sealed Edges before Wind Loading

The Figure 15 above can easily be compared with the figure below, which is after a wind loading event of the same time interval as that which caused the sand evacuations in the above case, as shown in Figure 16. There is no apparent distinction between the two cases, so the solar panel models did protect the building model from experiencing the conical vortices seen in the first test with no solar panel mitigation. The seal around the edges of the solar panels connecting them to the roof also clearly shows a notable improvement compared to the second test case, with unsealed solar panels as the wind load still affected the roof, as seen from the sand evacuation.

Figure 16: Flat-Roof Building Model with Solar Panels and Sealed Edges after Wind Loading
4.2 Pressure Testing in Open Jet Wind Tunnel

The pressure coefficient was derived from the pressure data obtained from the 128 pressure taps located on the model. The following tables and figures show the pressure coefficient distribution without the solar panels aerodynamically mitigating the roof suction, and figures which show the pressure distribution with solar panels on the edges of the roof, at the 45-degree angle previously discussed. The mean local pressure coefficient distribution, the maximum local pressure coefficient distribution, and the minimum local pressure coefficient distribution for each of the wind tunnel direction angles is shown in the following sections.

4.2.1 Mean Local Pressure Coefficients

The mean pressure coefficients on the surface of the roof for each pressure tap were calculated using Equation 3 above. Once these values were calculated, the maximum and minimum of the local mean pressure coefficient values were identified, and are shown on Table 4 below. Positive pressures exert a downward force on the roof, while negative pressure induce suction and exert an upward force on the roof. This study is primarily focused on negative pressure, as it can lead to roof uplift and detachment. Table 5 below shows the maximum and minimum mean pressure coefficient values on the roof during the wind tunnel tests with respect to the three wind direction angles, as well as with and without the solar panel models.

Table 5: Peak Values of Mean Pressure Coefficients With and Without Solar Panels

<table>
<thead>
<tr>
<th>Wind Direction Angle</th>
<th>Maximum Values</th>
<th>Minimum Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Pressure Coefficient Without Solar Panels</td>
<td>Mean Pressure Coefficient With Solar Panels</td>
</tr>
<tr>
<td>0-Degree</td>
<td>-0.1866</td>
<td>-0.3824</td>
</tr>
<tr>
<td>45-Degree</td>
<td>-0.1958</td>
<td>0.4578</td>
</tr>
<tr>
<td>90-Degree</td>
<td>-0.1430</td>
<td>0.1295</td>
</tr>
</tbody>
</table>
For the maximum local values, with both the 45 degree and 90 degree cases, the maximum value of the mean pressure coefficient changed from negative to positive with the addition of the solar panels. As mentioned above, mitigating negative pressure is the focus of this study, so this is a positive result for the test. The 0-degree case did not show a reduction in negative pressure, but rather a slight increase. This is a negative outcome, but the increase in negative pressure for that one direction is less substantial and therefore less significant than the decrease in negative pressure from the other two wind direction angles. Overall, the addition of the solar panel models had a positive effect on reducing the maximum mean pressure coefficient on the roof.

For the minimum local values, all cases show a reduction in negative pressure with the addition of the solar panel models on the roof. The angle with the largest benefit was the 45-degree wind direction angle case. The minimum mean pressure coefficient went from -3.4597 in the bare roof case to a -0.8212 in the case with the solar panels. The least affected wind direction angle was 90-degrees, where the longer side of the building was perpendicular to the wind flow. The negative pressure reduction was not as dramatic of a result as the 45-degree angle case or the 0-degree angle case because the wind pressure was distributed along a larger area due to the increased length of that side. The 90-degree case had the least negative pressure to begin with, so it is logical that the reduction would not be as dramatic as a case which had a larger amount of suction to be reduced from the beginning.

4.2.2 Maximum Local Pressure Coefficients

The maximum local pressure coefficients on the surface of the roof for each pressure tap were calculated using Equation 4 above. Once these values were calculated, the maximum and minimum of the maximum local pressure coefficient values were identified, and are shown on Table 5 below. Positive pressures exert a downward force on the roof, while negative pressure
induce suction and exert an upward force on the roof. This study is primarily focused on negative pressure, as it can lead to roof uplift and detachment. Table 6 below shows the maximum values of the maximum pressure coefficients on the roof during the wind tunnel tests with respect to the three wind direction angles, as well as with and without the solar panel models.

Table 6: Peak Values of Maximum Pressure Coefficients With and Without Solar Panels

<table>
<thead>
<tr>
<th>Wind Direction Angle</th>
<th>Maximum Values</th>
<th>Minimum Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-Degree</td>
<td>0.3004</td>
<td>0.2547</td>
</tr>
<tr>
<td>45-Degree</td>
<td>0.3785</td>
<td>0.8468</td>
</tr>
<tr>
<td>90-Degree</td>
<td>0.2383</td>
<td>0.6129</td>
</tr>
</tbody>
</table>

For the maximum values of the local maximum pressure coefficient, in all cases no negative pressure was observed. Therefore, mitigation did not substantially affect this measure, as there was no negative pressure to mitigate. The addition of the panels did increase the positive pressure in the 45 degree and 90 degree cases, but lowered the positive pressure in the 0-degree case. With respect to the minimum values, both the 0-degree case and the 45-degree case saw a reduction in the negative pressure. Interestingly, the 90-degree case saw a change from positive pressure to negative pressure with the addition of the solar panel models. This switch to negative pressure is odd, but the 90-degree case was also the only case to begin with a positive bare roof value. So rather than reducing the already existing negative pressure, as in the other cases, the solar panels seem to have caused a slight area of negative pressure with that wind direction angle. The most substantial reduction in negative pressure occurred in the 0-degree wind direction, where the pressure coefficient went from -0.0607 to -0.0236.
4.2.3 Minimum Local Pressure Coefficients

The minimum pressure coefficients on the surface of the roof for each pressure tap were calculated using Equation 5 above. Once these values were calculated, the maximum and minimum of the mean pressure coefficient values were identified, and are shown on Table 7 below. Positive pressures exert a downward force on the roof, while negative pressure induce suction and exert an upward force on the roof. This study is primarily focused on negative pressure, as it can lead to roof uplift and detachment. Table 7 below shows the maximum and minimum mean pressure coefficient values on the roof during the wind tunnel tests with respect to the three wind direction angles, as well as with and without the solar panel models.

Table 7: Peak Values of Minimum Pressure Coefficients With and Without Solar Panels

<table>
<thead>
<tr>
<th>Wind Direction Angle</th>
<th>Maximum Values</th>
<th>Minimum Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-Degree</td>
<td>-0.1866</td>
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</tr>
<tr>
<td>45-Degree</td>
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<td>0.4578</td>
</tr>
<tr>
<td>90-Degree</td>
<td>-0.1430</td>
<td>0.1295</td>
</tr>
</tbody>
</table>

In all cases, the maximum local uplift was reduced by the addition of the solar panels on the roof. The angle with the largest benefit was the 45-degree case, where the wind attack angle was perpendicular to a corner of the roof. The minimum pressure coefficient went from -2.3222 in the bare roof case to a -0.6177 in the case with the solar panels. The least affected angle was 90-degrees, where the larger side of the building was perpendicular to the wind flow. This was not as dramatic of a result as the 45-degree angle case or the 0-degree angle case because the wind pressure was distributed along a larger area due to the increased length of that side. The 90-degree case had the least suction to begin with, so it is logical that the reduction would not be as dramatic as a case which had a larger amount of suction to be reduced from the beginning.
4.2.4 Contour Plots with a 0 Degree Wind Direction Angle

The pressure coefficient was derived from the pressure data obtained from the 128 pressure taps located on the model. The mean pressure coefficient was calculated using Equation 3, the maximum pressure coefficient was calculated using Equation 4, and the minimum pressure coefficient was calculated using Equation 5. On the following pages are figures which show each of these pressure coefficients in a contour plot over the roof surface, for both the bare roof and aerodynamically mitigated cases. The wind direction is shown in these figures as a red arrow on the contour plot.
Figure 17: Mean Pressure Coefficient Contour Plot of Roof at 0 Degree Wind Direction Angle
Figure 18: Mean Pressure Coefficient Contour Plot of Roof with Solar Panels at 0 Degree Wind Direction Angle
Figure 19: Maximum Pressure Coefficient Contour Plot of Roof at 0 Degree Wind Direction Angle
Figure 20: Maximum Pressure Coefficient Contour Plot of Roof with Solar Panels at 0 Degree Wind Direction Angle
Figure 21: Minimum Pressure Coefficient Contour Plot of Roof at 0 Degree Wind Direction Angle
Figure 22: Minimum Pressure Coefficient Contour Plot of Roof with Solar Panels at 0 Degree Wind Direction Angle
4.2.5 Contour Plots with a 45 Degree Wind Direction Angle

The pressure coefficient was derived from the pressure data obtained from the 128 pressure taps located on the model. The mean pressure coefficient was calculated using Equation 3, the maximum pressure coefficient was calculated using Equation 4, and the minimum pressure coefficient was calculated using Equation 5. On the following pages are figures which show each of these pressure coefficients in a contour plot over the roof surface, for both the bare roof and aerodynamically mitigated cases. The wind direction is shown in these figures as a red arrow on the contour plot.
Contour Plot of Roof (Wind Direction Angle - 45 Degrees)
Mean Pressure Coefficient

Figure 23: Mean Pressure Coefficient Contour Plot of Roof at 45 Degree Wind Direction Angle
Figure 24: Mean Pressure Coefficient Contour Plot of Roof with Solar Panels at 45 Degree Wind Direction Angle
Figure 25: Maximum Pressure Coefficient Contour Plot of Roof at 45 Degree Wind Direction Angle
Figure 26: Maximum Pressure Coefficient Contour Plot of Roof with Solar Panels at 45 Degree Wind Direction Angle
Figure 27: Minimum Pressure Coefficient Contour Plot of Roof at 45 Degree Wind Direction Angle
Figure 28: Minimum Pressure Coefficient Contour Plot of Roof with Solar Panels at 45 Degree Wind Direction Angle
4.2.6 Contour Plots with a 90 Degree Wind Direction Angle

The pressure coefficient was derived from the pressure data obtained from the 128 pressure taps located on the model. The mean pressure coefficient was calculated using Equation 3, the maximum pressure coefficient was calculated using Equation 4, and the minimum pressure coefficient was calculated using Equation 5. On the following pages are figures which show each of these pressure coefficients in a contour plot over the roof surface, for both the bare roof and aerodynamically mitigated cases. The wind direction is shown in these figures as a red arrow on the contour plot.
Figure 29: Mean Pressure Coefficient Contour Plot of Roof at 90 Degree Wind Direction Angle
Figure 30: Mean Pressure Coefficient Contour Plot of Roof with Solar Panels at 90 Degree Wind Direction Angle
Figure 31: Maximum Pressure Coefficient Contour Plot of Roof at 90 Degree Wind Direction Angle
Figure 32: Maximum Pressure Coefficient Contour Plot of Roof with Solar Panels at 90 Degree Wind Direction Angle
Figure 33: Minimum Pressure Coefficient Contour Plot of Roof at 90 Degree Wind Direction Angle
Figure 34: Minimum Pressure Coefficient Contour Plot of Roof with Solar Panels at 90 Degree Wind Direction Angle
4.2.7 Comparison of Pressure Coefficients with ASCE 7-10 Standard

After the ASCE Standard Pressure Coefficients for wind design pressures were computed in Section 3.4, they were compared with the pressure coefficients generated from the open jet wind tunnel, after using a conversion factor, also described in Section 3.4. The comparison is shown in Table 8 below. The minimum pressure coefficient for each zone is displayed, regardless of wind direction angle. All wind direction angles were compared, and the minimum pressure coefficient was chosen for each zone, as the code specifies that each component must be designed for the maximum positive and negative pressures (ASCE/SEI 2013).

Table 8: Comparison of Pressure Coefficients from ASCE Standard and Open Jet Wind Tunnel

<table>
<thead>
<tr>
<th>Zone</th>
<th>ASCE Standard</th>
<th>$C_p$ 95%</th>
<th>$C_p$ - estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.9</td>
<td>-1.1453</td>
<td>-1.7946</td>
</tr>
<tr>
<td>2</td>
<td>-1.1</td>
<td>-1.3981</td>
<td>-1.8110</td>
</tr>
<tr>
<td>3</td>
<td>-1.8</td>
<td>-1.6378</td>
<td>-2.0853</td>
</tr>
</tbody>
</table>

The $C_p$ 95% value was calculated using the quartile method developed Joseph A. Main, using a modified version of a function previously written by Fahim Sadek, based on the procedure discussed in Sadek et al. (Sadek 2002). The upper quartile was divided by the mean value of ‘u’, the along wind speed, to determine the maximum pressure coefficient to compare with the ASCE Standard. The lower quartile of the pressure readings was divided by the mean value of ‘u’, the along wind speed, to determine the minimum pressure coefficient to compare with the ASCE Standard. The varies slightly from the method used elsewhere in this thesis (the contour plots use the pressure coefficient formula developed by Hoxley), but this method is more consistent with the ASCE Standard values, making the comparison more accurate. The 95% descriptor is the confidence interval of the quartile calculation. The $C_p$ estimated values were found by using the absolute maximum and minimum from the pressure results for the pressure coefficient calculations. Table 8 shows that these values are less conservative than those calculated using the quartile method, because the maximum and minimum are more variable than the upper and lower.
quartile values. However, the quartile values are more consistent across data sets, and are therefore more reliable. Both the $C_p$ 95% and the $C_p$ Estimated pressure coefficient values are more conservative than the ASCE code.

A comparison of these same values compared with similar values for the wind tunnel model with solar panels is below in Table 9. The same methods were used to calculate and choose the displayed pressure coefficients as in Table 8.

Table 9: Comparison of Pressure Coefficients With and Without Solar Panels

<table>
<thead>
<tr>
<th>Zone</th>
<th>No Panels</th>
<th>With Panels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_p$ 95%</td>
<td>$C_p$ - estimated</td>
</tr>
<tr>
<td>1</td>
<td>-1.1453</td>
<td>-1.7946</td>
</tr>
<tr>
<td>2</td>
<td>-1.3981</td>
<td>-1.8110</td>
</tr>
<tr>
<td>3</td>
<td>-1.6378</td>
<td>-2.0853</td>
</tr>
</tbody>
</table>

4.3 Large Eddy Simulation Model Comparison

Once the wind tunnel simulation was complete in ANSYS Fluent, the lift and drag coefficients were graphed with time. This figure is shown below in Figure 35, and the mean drag and lift coefficients were also computed using Matlab. The mean lift coefficient was 0.8231, and the mean drag coefficient was 0.5059, both calculated as in Equations 10 and 11. However, while they were both calculated using the same equation, a conversion factor needed to be used so that they could be compared accurately. The experimental results were computed using the roof area, while the ANSYS Fluent LES results were computing using a reference area of 64 m$^2$. To rectify this difference, the lift coefficient from the experimental results was multiplied by the roof area, to cancel the ‘area’ variable in the lift coefficient equation, see Equation 11 for reference. Then, the experimental lift coefficient was divided by the reference area used in the ANSYS Fluent LES model, 64 m$^2$. For comparison,
Figure 36 shows the lift coefficient graphed with time for the bare roof wind tunnel case, at the 45 degree wind direction angle. The mean value for the lift coefficient in this case was 0.7115.

The velocity components that were recorded by the monitors in ANSYS Fluent (along wind, across wind, and vertical) are graphed along with time below, in Figure 37. The following figure, Figure 38, shows the value q, defined in Equation 2, above, graphed with time. A contour plot of the mean pressure coefficient of the roof from the ANSYS Fluent Model is shown below in Figure 39. The contour distribution plotted in ANSYS of the roof pressure coefficient is qualitatively similar to the plots generated from the wind tunnel tests. The two tests cannot be directly compared, as the LES contour is a snapshot of the pressure coefficients on the roof, rather than a minimum, maximum, or mean value.
Figure 35: Drag and Lift Coefficients from LES
Figure 36: Lift Coefficients for Open Jet at 45 Degree Wind Direction Angle
Figure 37: LES Model Wind Velocity Components for Bare Roof Case
Figure 38: Q vs. Time for LES Bare Roof Case
Figure 39: ANSYS Fluent Roof Pressure Coefficient Contour
CHAPTER 5: SUMMARY AND CONCLUSION

Through both the flow visualization experiment with sand in the open jet wind tunnel, as well as the pressure tap results, having solar panels, or something with the same shape, clearly reduces negative pressure on the roof. This suction mitigation could be key in reducing the amount of damage caused due to the flow separation caused by synoptic winds. The flow visualization test clearly showed that substantially less sand was displaced from the roof, even when the solar panels were not completely sealed to the roof. The panels provided enough of a disruption to the hard corner of the roof edge that the conical vortices were not created. When the panel models were properly sealed to the roof, almost no sand was displaced at all, showing that much less suction occurred.

From the pressure taps in the next wind tunnel experiment, it can be concluded that the addition of the solar panel models decreased the peak local suction on the roof. In the 0-degree case, the maximum local suction as reduced by approximately 61%, the 45-degree case saw an impressive maximum local suction reduction of 86%, and the 90-degree case had its peak local suction reduced by 27%. It was also apparent from the data that the panel models reduced the range of local pressures on the roof, which improves the roof performance by having a more even pressure distribution across the surface. For the 0-degree case, the range shrunk from 1.433 to 0.3757, and for the 45-degree case the range shrunk from 2.1225 to 0.4401. However, for the 90-degree case, the range actually grew slightly from 0.4405 to 0.5412. The anomaly of the 90-degree case in this instance is not surprising, as that setup had the lowest suction to begin with, so it was difficult to mitigate it with the solar panel models. The addition of solar panels models decreased the peak local suction in all cases, and reduced the range of pressures seen by the roof in two of the three cases.
When the local pressure coefficients were converted to a form comparable to the ASCE Standard using a conversion factor, it was found that that ASCE Standard was less conservative than either the of the calculated pressure coefficients. The pressure coefficient conversion was accomplished in two different ways, one using the upper and lower quartiles of the pressure values obtained from the roof, and the other using more localized maximum and minimum pressures.

For the ANSYS Fluent model, more testing needs to be done. The pressure coefficient distribution on the roof was qualitatively very similar to that of the wind tunnel tested model. However, the two tests cannot be directly compared, as the LES contour is a snapshot of the pressure coefficients on the roof, rather than a minimum, maximum, or mean value. A steady-state Reynolds Stress Model test may need to be run to get area-averaged pressure coefficients for comparison to the wind tunnel results. It would also be interesting to test the model with the solar panel models in ANSYS Fluent, and see if the results obtained are comparable to that of the wind tunnel study.
REFERENCES


VITA

Laura Michelle Iverson, a native of Covington, Louisiana, received her bachelor’s degree in Civil Engineering at Louisiana State University in Baton Rouge in 2015. Her interest in structural engineering led her to immediately begin her Masters of Science Degree in Civil Engineering, also at Louisiana State University. She concentrated her degree in Structural Engineering, while working as a civil engineer in the private sector. She will receive her master’s degree in August 2016 and will then transition into full time work as a civil/structural engineer in the private industrial sector.