Mitigation of roof uplift through vortex suppression techniques

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MITIGATION OF ROOF UPLIFT THROUGH VORTEX SUPPRESSION TECHNIQUES

A thesis submitted in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
in
CIVIL ENGINEERING
by
Collette Marguerite Blessing

2007
To: Dean Vish Prasad  
College of Engineering and Computing

This thesis, written by Collette Marguerite Blessing, and entitled Mitigation of Roof Uplift through Vortex Suppression Techniques, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this thesis and recommend that it be approved.

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Ton-Lo Wang

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Caesar Abi Shdid

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Arindam Gan Chowdhury, Major Professor

Date of Defense: July 17, 2007

The thesis of Collette Marguerite Blessing is approved.

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Dean Vish Prasad  
College of Engineering and Computing

__________________________
Dean George Walker  
University Graduate School

Florida International University, 2007
DEDICATION

I dedicate this thesis to my parents whose constant love and support has been my inspiration in completing this work.
ACKNOWLEDGMENTS

I wish to thank my Major Professor, Dr. Arindam Gan Chowdhury, for providing me with the knowledge and support necessary to complete this thesis work. I would also like to express my gratitude to my committee members, Dr. Ton-Lo Wang and Dr. Caesar Abi Shdid, for their guidance during this process. I would like to thank Dr. Forrest Masters for giving me the opportunity to begin my graduate studies at Florida International University (FIU). A special thanks to Dr. Jason Lin of WeatherPredict for providing his expertise and time in the area of my research. I am greatly appreciative of Dr. Stephen Leatherman and Carolyn Robertson for giving me the opportunity to be involved in a truly unique research project. Last, I would like to thank the “team” at the International Hurricane Research Center, Jimmy, Roy, Ivan, Bo, Walter, Phil, Natalie, Donya and Kathy-Ann, for all of their support and good advice over the past 3 years.

Finally, I would like to thank my family for all of their love and constant encouragement throughout this entire process. All my love goes to Fabian, my fiancé, whose love and humor has always reminded me that there is a light at the end of the tunnel.
The objective of this study was to assess the effectiveness of modified roof edge geometry in the reduction of high suction pressures at roof corner and edge regions through full-scale testing approach. Utilizing the RenaissanceRe 6-fan Wall of Wind (WOW) testing apparatus, a test structure instrumented with pressure transducers was equipped with six different modified roof edge geometries and subjected to hurricane force winds. A series of seven tests, six for the different roof geometries and one to determine the standard pressure distribution without any modifications, were conducted and pressure data from all seven tests were compared. Results indicated that the use of such mitigation devices resulted in an average reduction in uplift by about 50%, with the largest reduction observed from the Flat Roof AeroEdge Guard (FRAG1, patent pending) which yielded 74% decrease in the worst suction in the corner region. Testing was also performed to identify the wind speeds at which the conical vortices became strong enough to start scouring different types of roof gravel. These results offer new hope for further development in the area of hurricane damage mitigation.
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<td>Atmospheric Boundary Layer</td>
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<td>ASCE 7</td>
<td>American Society of Civil Engineers</td>
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<td>BLWT</td>
<td>Boundary Layer Wind Tunnel</td>
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<td>BLWT II</td>
<td>Boundary Layer Wind Tunnel II</td>
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<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>DAQ</td>
<td>Data Acquisition</td>
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<td>FRAC1</td>
<td>Flat Roof AeroEdge™ Cap</td>
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<tr>
<td>IBHS</td>
<td>Institute for Business and Home Safety</td>
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<tr>
<td>ID</td>
<td>Inside Diameter</td>
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<td>NSF</td>
<td>National Science Foundation</td>
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<td>NTC</td>
<td>Net Tropical Cyclone</td>
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<td>OD</td>
<td>Outside Diameter</td>
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<tr>
<td>RMS</td>
<td>Risk Management Solutions</td>
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<td>RPM</td>
<td>Revolutions per Minute</td>
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<tr>
<td>SFG</td>
<td>Sweep Function Generator</td>
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<tr>
<td>TTU</td>
<td>Texas Tech University</td>
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<td>UWO</td>
<td>University of Western Ontario</td>
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<td>WOW</td>
<td>Wall of Wind</td>
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<td>WERFL</td>
<td>Wind Engineering Research Field Laboratory</td>
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1. Introduction and Objective

Since the mid-1990s the North Atlantic Basin (defined as 0-30 degrees latitude) has experienced a substantial increase in tropical cyclone activity fueled primarily by warmer-than-usual sea surface temperatures and decreased wind shear. Goldenberg et al. (2001) concluded that the years 1995-2000 saw the highest mean number of major hurricanes and mean Net Tropical Cyclone (NTC) activity of any 6 consecutive years in the entire 1944-2000 database. The 2004 hurricane season also proved record-breaking with four storms affecting the same state, namely Florida, in one season; the last time four storms impacted one state was in 1886 when Texas endured four direct hits.

Proportional with increased frequency in hurricane land-fall is the increase in damage incurred and thus economic loss and loss of life. 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, the 2005 season set a new record with losses totaling over $100 billion (Lott and Ross, 2006). Annual loss of life also increased dramatically, rising from 196 individuals perished in the years 1986-1995 to an astonishing 1,450 between 2004 and 2005. The increase in annual losses is only projected to get worse; Risk Management Solutions (RMS) predicts a 40% increase in insured losses in Florida alone due to the above-normal tropical cyclone activity and associated damage (www.rms.com).

With approximately half of the United States population currently living within 50 miles of the coastline, the development of advanced structural mitigation techniques to protect communities against such devastating damage is an absolute necessity. The wind engineering community currently employs a variety of different test methods to evaluate
wind effects on structures and develop design strategies accordingly. Thus far the focus for such research has been on wind tunnels, especially boundary layer wind tunnels (Figure 1a). Boundary layer wind tunnels test scaled structures at scaled wind speeds and assume that such simulation can replicate atmospheric wind flow characteristics around bluff structures, such as buildings with sharp edges and corners, despite notable differences in Reynolds number. As suggested by Simiu and Miyata (2006), this hypothesis is only partially true; studies comparing full-scale and wind tunnel data have concluded that in many instances load characteristics in the wind tunnel are much lower than those occurring in the full-scale environment. Although wind tunnels have proved extremely useful in the understanding of how structures interact with the environment, their inability to reproduce full-scale turbulence characteristics often leads to an underestimation of loads.

Full-scale component testing is the primary method for evaluating performance of individual building components under full-scale conditions (Figure 1b). This test method is useful in understanding how individual components will react to wind-like loadings generated by actuators. The primary limitation of this method is that components are not treated as integral members of the structural system and cannot be expected to react as though they are parts of an entire building that is being impacted by a hurricane.

Another full-scale testing initiative involves simulating wind loads with pressure boxes located on the exterior of a test structure (Figure 1c). The $7 million “Three Little Pigs” project currently under way at the University of Western Ontario (UWO) aims to identify precisely how buildings are destroyed by wind during hurricanes so that they can be better built in the future. Though having a great research potential, this project is not
aiming to simulate an actual wind field with the turbulence effects that may be observed in a realistic bluff-body aerodynamics problem.

Field studies for wind engineering also contribute to the understanding of bluff-body aerodynamics. Texas Tech University (TTU) currently operates the largest field study program in which a building instrumented with pressure transducers and meteorological instrumentation collects data during actual wind storm events such as thunderstorms occurring before a frontal passage (Figure 1d). Because the building is not exposed to severe windstorms such as hurricanes there is still a lack of data concerning structural response to hurricane force winds.

Figure 1. Wind Tunnel and Full-Scale Test Initiatives, (a)Wind tunnel testing, (b)Full-scale component testing, (c) Full-Scale Building Testing using Pressure Bags (UWO), (d) Field Studies of Loads On Buildings (TTU)
Though all of these tests methods have contributed greatly to the understanding of wind effects on structures, there is a need for a full-scale test facility which will allow for “holistic” testing of structures under realistic hurricane conditions. The objective of this project is to conduct such full-scale testing using the RenaissanceRe 6-fan Wall of Wind (WOW) to simulate hurricane force winds for the purpose of evaluating roof mitigation techniques. The WOW is not intended to replace other test methods but to complement current testing systems.

The primary cause of roof failure during hurricanes is roof uplift due to severe negative pressures at roof edge and corner regions induced by vortex generation. Vortex generation refers to a process in which flow separation occurs as the wind flow meets a bluff body, such as a low-rise structure, and is forced to separate from the object (Figure 2). This separation stimulates the formation of a turbulent shear layer above the object where vortices build. These vortices then interact with the roof structure evoking strong negative pressure at edge and corner regions. As pointed out in the Institute for Business and Home Safety (IBHS) “Preliminary Damage Observation: Hurricanes Charley, Frances, Ivan and Jeanne” (2004) 70-80% of all peeling of shingles and sheathing was initiated at the edge or corner regions by strong negative pressures associated with vortex generation.

Studies previously conducted using wind tunnels have shown that the application of modified roof edge shapes to a building can reduce, and in some cases even eliminate, the suction induced by vortex generation. This research proposes to evaluate in the full-scale the performance of four different prototype designs of modified edge shapes and two standard edge shapes under hurricane-force winds and determine which design is
most effective in reducing/eliminating negative pressure in the roof and corner regions (Figure 3). The ultimate goal of this project is to utilize the results of the above experiments to provide residents in hurricane-prone regions with alternative, cost-effective methods to better protect their homes.

Figure 2. Uplift for Conventional Roof Edge

Figure 3. Uplift for Aerodynamic Edge Shape
2. Background

2.1 Full-Scale Testing

Research pertaining to the high suction pressures associated with roof corner regions has been extremely active due to their tremendous scales and associated damage during severe wind events (Wu et al. 2000). Full-scale testing initiatives, such as the Wind Engineering Research Field Laboratory (WERFL) at Texas Tech University (TTU), have provided invaluable data describing the roof pressure distributions associated with these high wind events and flow visualizations of conical (delta-wing) vortices which influence these pressure distributions.

Certain advantages are associated with full-scale aerodynamic testing that are not reflected when experimenting with other wind/structure test methods. In the case of bluff-body aerodynamics, the complexities of flow separation, separation length, vortex generation and reattachment phenomena are unable to be reproduced in a wind tunnel environment where dimensionless quantities that determine turbulence characteristics, such as Reynolds and Jensen numbers, can never be matched.

Roof Pressure Distribution

The WERFL at TTU full-scale test facility has been instrumental in conducting research in the area of wind effects on structures, specifically in helping to determine the roof pressure distributions. The facility was established in the late 1980s as a long-term project sponsored by the National Science Foundation (NSF) (Kishor et al. 1992). Since its inception, the project has provided valuable data about how winds in the atmospheric boundary layer impact structures and also served to verify results obtained from wind
tunnel testing. The experimental building is a pre-fabricated flat-roof structure with dimensions of 30 ft x 45 ft x 13 ft. The structure is located on the TTU campus in flat, open terrain.

Kishor et al. (1992) performed some of the first field experiments at TTU, measuring pressures on a flat roof caused by non-boundary layer flows such as thunderstorms, wind gusts and downburst. The test building facility, situated on a rotating platform, allowed the researchers to control the angle at which the building experienced the wind flow and was equipped with instrumentation to measure both wind speed and differential pressure. Pressure data was collected using nine transducers located at the roof corner and two on the windward wall. The 15-minute duration pressure time histories confirmed what wind tunnels had previously established: strong suction pressures occurred at the roof corner region during extreme wind events with the worst suction pressures resulting from cornering winds having a 225° angle of attack. This study also found that mean pressure coefficients \( (C_p\,_{\text{mean}}) \) varied little between different taps while minimum pressure coefficients \( (C_p\,_{\text{min}}) \) displayed significant scatter. Values of \( C_p\,_{\text{min}} \) along the roof corner ranged from -6 to -12 (Kishor et al. 1992). Wu (2000) performed similar experiments and observed comparable results, however negative pressures in his experiment peaked as high as -26.

In an effort to validate other full-scale test results as well as observe the effect of high suctions on structural damage, Hongchao (2006) used the propellers of a Hercules C-130 aircraft to generate wind flow for experimentation at TTU. Hongchao tested a manufactured home and a modular home, recording pressure data on the roofs of each structure under the influence of winds from the C-130. As expected, Hongchao observed
strong roof corner suctions that agreed with previous wind tunnel and full-scale tests. For wind speeds above 50 mph, damage to roofs was also observed as shingles often began peeling from the roof at ridges and eaves.

*Flow Visualization*

Part of understanding the pressure distribution on roofs during severe wind events is understanding the flow mechanisms behind suction pressures of such magnitude (Banks et al. 1999). Banks et al. (1999) proved that a correlation between location of the vortex core and the worst suction pressures indeed existed. In a two part study which included both full-scale and wind tunnel testing, the WERFL at TTU was used to simultaneously collect pressure data while capturing the location of the vortex through use of video and colored yarn segments tied to nodes of a metal grid. As expected, the full-scale visual testing determined that the worst suction pressures occurred beneath the location of the vortex core and moved further from the apex (corner) of the roof as the vortex moved.

A full-scale study by Wu (2000) expanded on the previous study and generated further conclusions regarding the relationship between incident wind, conical vortices, and high suction pressures. Similar to Banks et al. (1999), Wu (2000) observed that the worst suction pressures occurred beneath the position of the vortex core, however, Wu also determined that it is the horizontal wind angle which most significantly influences the structure and position of the conical vortex. On the other hand, the vertical wind angle of attack was found to directly affect the peak pressures occurring at the corner regions. This study also established that the formation of conical vortices was most
favorable when the incident wind had a horizontal angle of attack between 15° and 75° and that suction pressures peaked at the roof corner and reduced significantly near the vortex reattachment point.

\textit{Full-scale Testing vs. Wind Tunnel Testing}

A combination of wind tunnel and full-scale testing has led to a relatively comprehensive understanding of wind-induced roof pressures, though discrepancies in data do exist. An experiment performed by Lin et al. (1995) using a wind tunnel facility served to compare and verify results obtained in a full-scale study at TTU. The study was performed using the Boundary Layer Wind Tunnel II (BLWT II) at UWO. Three models of differing heights (7.8 cm, 15.6 cm and 23.4 cm) were tested in the wind tunnel along with two 1:50 scale models of the TTU experimental building, one with the actual roof pitch of 1:60 and the others with a flat roof. All models were subjected to a laminar flow and a boundary layer flow modeled after the full-scale flow observed at the TTU test site.

A comparison of results between the model and full-scale tests indicated good agreement between pressure coefficients in the interior taps but significant variation in those recorded at corner taps. As Lin (1995) suggests, these differences may be attributed to mismatches in tap diameter, edge geometry, Reynolds number (affecting turbulence characteristics) and the presence of natural variations in wind not present in the wind tunnel. In general, pressure coefficients measured in the wind tunnel underestimated the most severe full-scale peak and rms $C_p$ near the corner.
Previous studies which served to compare wind tunnel and full-scale data have demonstrated the same discrepancies. This issue becomes problematic as wind design codes are based on wind tunnel test results. If pressure coefficients are indeed lower in the wind tunnel, then design codes reflecting these values may result in building provisions that do not adequately protect against severe windstorms.

2.2 Vortex Suppression Initiatives

In an effort to reduce the catastrophic effects of hurricane force winds on residential and commercial roof structures several studies have set out to observe the effects of surroundings and alternative roof geometries on vortex generation. This innovative field of study is appropriately entitled “vortex suppression” as methods are currently being sought to disrupt and deflect the conical vortices from the roof structure to drastically reduce the effects of the extreme vortex-induced roof suctions. It is widely believed that simple modifications in the shape of the roof edge may drastically reduce the vortex generation as well as associated damage (Surry and Lin, 1995). The following sections discuss both full-scale and wind tunnel studies conducted in an effort to eliminate this problem.

Parapets as Means of Vortex Suppression

For decades, parapets have been examined in the wind tunnel as a means of vortex suppression simply because of their presence as a standard architectural feature. One of the first studies to specifically consider the role of these building components in vortex suppression was carried out by Baskaran and Stathopoulos (1988) at the Boundary
Layer Wind Tunnel (BLWT) of the Building Aerodynamics Laboratory at Concordia University in Montreal, Canada. A 1:400 scale model representing a simple square building was equipped with pressure sensors concentrated in the corner regions and subjected to boundary layer flow. Several different parapet heights and thicknesses were tested in parametric parapet configurations as well as single-side parapet configurations. Researchers determined that parapets could have both positive and negative effects on suction pressure coefficients. The presence of parametric parapets at least 1 m in height proved effective in reducing pressure coefficients in the corner regions of buildings both 12 m and 96 m in height, however, the reduction was far more significant in the tall building variation ($\geq 96$ m). This study also showed that the presence of parapets shorter than the 1 m critical height actually caused an increase in corner peak suctions. In general, the parametric parapet had a tendency to reduce corner pressure coefficients more significantly than a parapet present on only one side of the roof.

Parapet thickness was also found to reduce peak corner pressures in certain configurations. The standard parapet thickness used in this study was 0.3 m, however, the researchers found that increasing the parapet thickness for the single-side parapet configuration demonstrated a decrease in the suction at the corner regions whereas only small reductions were observed in the parametric case.

One portion of an experiment conducted by Lin and Surry (1993) tested a traditional partial parapet and a single sawtooth partial parapet as a means of mitigating vortex generation at the roof corner. The experiment, carried out at the Boundary Layer Wind Tunnel I (BLWTI) at UWO, determined that the sawtooth partial parapet was more effective in reducing suction at the corners resulting in an average 50% reduction in peak
and rms pressures. Additionally, the rectangular partial parapet could have potentially increased the suction at the corners by allowing the formation of additional vortices (Lin and Surry, 1993).

A follow-up study conducted by Surry and Lin (1995) observed dual and triple sawtooth parapets and a porous parapet as methods to mitigate high suction pressures. The multiple sawtooth parapets, though initially expected to yield better results than the single sawtooth variation, showed no improvement from the single sawtooth one tested in the previous study, reducing the corner pressure by only about 30%-40%. Also, although the sawtooth parapets did yield a reduction in suction, Surry and Lin (1995) detected that the vortices were still attached to the roof. The porous parapet configuration yielded a decline in the magnitude of pressure coefficients by about 70% making it the most successful configuration for effectively eliminating vortex generation.

More recently, Kopp, et al. (2005) have conducted further studies at the UWO BLWTII assessing the effects of parapets on roof pressure coefficients as well as testing alternative parapet geometries as a means of reducing suction pressures at roof corner regions. The first experiment in the series focused on the effects of varying types of parapets on roof pressures as well as the adequacy of the ASCE 7 wind loading provisions for designing parapets.

As determined by Baskaran and Stathopoulos (1988) and Surry and Lin (1995), Kopp et al. also found that parametric parapets which met a certain height requirement (greater than 1.8 m for the latter case and greater than 1 m for each of the former cases) effectively reduced the magnitude of the worst suctions found in the roof corner regions. This reduction was attributed to the parapets’ ability to displace the vortices so that they
were no longer attached to the roof surface resulting in a relatively uniform pressure distribution. Testing of shorter parapets also yielded results similar to those attained in previous experiments such that the presence of parapets less 0.9 m tall actually increased the worst suctions experienced in the corner regions to values greater than the no-parapet case. In addition, parapets present on a single wall caused an increase in suction due to the formation of additional vortices at the edge of the parapet which acted to strengthen the suction at the corresponding corner.

ASCE 7-05 (American Society of Civil Engineers) currently prescribes several provisions regarding the presence of parapets on a structure. One such provision, which allows for corner zones to be treated as edge zones when a parapet of at least 0.9 m height is present, does account for the potential reduction in $C_p$ however, the required height directly conflicts with results from the study conducted by Kopp et al. which indicated that a parapet of 0.9 m would actually increase suction pressures for certain building heights. In order to mitigate this discrepancy, Kopp et al. (2005) suggested that the current parapet height requirement be adjusted to a value of $h/(H+h) > 0.23$ which reflects the relationship between parapet height and eaves height which plays an important role in determining reduction of negative pressure. In addition, Kopp et al. (2005) pointed out that the ASCE 7-05 values for pressure coefficients in the interior zones without parapets present proved non-conservative compared with values measured in the field. As mentioned previously, the presence of low parapets only served to increase these interior pressures and it was suggested that that ASCE 7-05 provisions reflect the potential increase in value.
Additional testing in this study considered eight modified roof edge configurations as methods for mitigating vortex generation at the roof edge and corner regions. The eight different configurations included a no parapet case, solid parapet with height \( h = 0.9 \) m and 0.3 m thick, 50% solid screen parametric parapet with \( h = 0.9 \) m, slotted parapet, solid parapet with no corner, solid parapet with 50% screen corner, solid parapet with raised corner and parametric spoiler. Each configuration was subjected to winds consistent with open country terrain from a 325° wind angle which is the direction associated with the worst suction pressures.

Analysis of the mean pressure coefficient distributions yielded interesting results as the 8 configurations were clearly divided into two well defined distributions. The first group, consisting of the parapets with slotted corners, porous corners, raised corners and no corners, showed distributions similar to that of the solid parametric parapet with \( h = 0.9 \) m, which had higher \( C_p \text{ mean} \) values associated with it. The second group, consisting of the no-parapet case, spoiler and porous parapet, and also having definitively similar distributions, was associated with much lower \( C_p \text{ mean} \) values. The rms distributions followed the same pattern.

Based on these distributions it was determined that the five configurations associated with higher \( C_p \text{ mean} \) values, the solid parametric parapet of 0.9 m height performing the worst out of the group, would not be very effective in reducing the corner vortex. Within that group, the three configurations without corners had smaller surface pressures than the solid parametric parapet, however, the rms distributions still indicated the presence of vortices in the corner region. Moreover, the surface pressure values for these three cases were still more negative than those values observed when no parapet
was present. Kopp et al. concluded that in the event that a parapet was necessary, any of the cases without corners would slightly alleviate structural loads, however, these values would still be higher than if there were no parapet.

For the three remaining parapet configurations, the porous parapet, spoiler and no parapet, the mean distributions indicated a reduction in the corner vortices and thus a reduction in local loading. The porous parapet and spoiler resulted in reductions even lower than the no parapet case; however, neither configuration destroyed the corner vortex completely. Results from this study clearly support the fact that reductions in the corner vortex and thus suction pressures are highly dependent on parapet geometry and there is a need for research to suppress vortex formation through alternative strategies.

Few full-scale studies have been conducted to evaluate the effects of parapets on roof corner suction pressures. One full-scale test which did successfully determine this relationship was done by Stathopoulos et al. (1998) at the Loyola Campus of Concordia University (Montreal, Canada). Just as in wind tunnel testing, pressure coefficients collected on a small building with and without parapets indicated that the presence of parapets that met a certain minimum height requirement did result in a reduction of uplift at the roof corner. The parapets acted in deflecting the vortices away from the roof surface, thus, the higher the parapet the greater the decrease in suction pressures. Conversely, parapets of relatively low height actually increased suction pressures at the corners by causing a secondary flow separation at the top of the parapet.
**Modified Roof Edge Shapes and Surrounding Terrain**

Beyond examining parapets, recent studies have focused on developing modified roof edge shapes to be attached to the roof during preparations for high-wind events. Drawing on conclusions from flow visualization testing, Wu (2000) developed a modified roof edge shape called a Conical Vortex Disrupter (Figure 4) in an attempt to mitigate the extreme negative pressures caused by conical vortices. The device, installed at the roof corner at WERFL test building, effectively reduced suction pressures by 90% of the mean value and 80% of the peak value. Area averaged loads were also reduced by 50% for tributary areas smaller than 8.2 ft².

![Figure 4. Conical Vortex Deflector (Courtesy of Wu, 2000)](image)

Melbourne and Cheung (1988) performed a first-of-its-kind study regarding vortex suppression at the Boundary Layer Wind Tunnel at Monash University in Australia. The purpose of the research was to determine if a vented edge would reduce the high negative pressures at the leading edge of a cantilevered grandstand roof that was
to be built in Australia. The 1:100 scale model of the cantilevered roof was fitted with pressure taps and subjected to a typical wind flow over suburban terrain roughness of $z_0 = 0.02$ m. The experimental procedure involved subjecting the roof to said flow pattern and measuring the mean, standard deviation and peak response of the vertical displacement of the leading edge for several different vented roof configurations. The displacement values, $z$, were then converted into equivalent pressure coefficients. Melbourne and Cheung (1988) noted that the maximum response occurred near the center of the roof. The study concluded that minor slots made in the cantilever roof (width of 5% of cantilever length) yielded discernable reductions of approximately 25% in the response and thus the pressure coefficients. The ideal placement of these slots to achieve maximum reduction was found to be 0.04 m from the edge of the roof.

In the second portion of an experiment conducted by Lin and Surry (1993) which first examined the effectiveness of parapets in reducing suction, several roof corner geometric modifications were evaluated as means of mitigating vortex generation at the roof corner. The experiment, carried out at the BLWTI at UWO, tested the effectiveness of a rounded roof edge and cylinders on the roof on reducing the high suctions typical of the roof corner region. Pressure measurements were recorded along 3 lines where conical vortices would occur on a 1:50 scale model of the TTU experimental building.

The rounded roof edge displayed the most significant reductions in corner pressures reducing the peak, mean and rms pressure coefficients by more than 60%. The dual cylinder configuration exhibited reductions in negative pressure of up to 60%, 50% and 55% for the peak, mean and rms pressures respectively when placed at a distance less than or equal to $s/H = 0.2$ from the corner while the single cylinder variation displayed a
reduction in the rms pressure coefficient by about 20% but did little to reduce the mean and peak values. In this particular experiment, the fraction s/H represented the non-dimensionalized x-coordinate where s equaled the x-coordinate and H equaled the height of the test structure. This format was used for comparison purposes so that the location of pressure coefficients on test structures of different dimensions could be compared.

A follow-up study by Surry and Lin (1995), which also first examined the effects of parapets on roof suction, examined the effects of surroundings and several additional roof corner geometric modifications on roof pressures of low-rise buildings. Surry and Lin (1995) concluded that one of the primary factors affecting vortex intensity was surrounding terrain. In order to verify this theory, wind tunnel testing was conducted in which three different surrounding configurations were generated and tested with a 1:50 model of the TTU experimental building.

The TTU scale model building duplicated the same 1:60 slope as occurred in the actual building and was equipped with 176 pressure taps concentrated primarily in the edge region. As in the previous experiment of Lin and Surry (1993), the flow used in the wind tunnel was modeled after the boundary layer flow conditions observed at the TTU experimental building during full-scale testing.

All three surrounding configurations for this study were designed to replicate a commercial/industrial development of two rows of adjacent buildings facing parallel to roadways. A control test was performed with an isolated building before surroundings were brought in to form a basis for comparison. Results of this study indicated that the presence of surroundings changed the spatial distribution of pressure coefficients on the roof as well as significantly reduced the value in the corner regions for all three cases.
The presence of buildings tended to disrupt the corner vortices and their formation reducing the mean, peak and rms $C_p$. For cornering winds specifically, $C_p$ values were reduced even more considerably when the winds approached from the direction of the densest configuration of structures. Though the reduction of vortices due to the presence of surroundings was decidedly based on specific configurations of buildings, the presence of any configuration of surroundings generally lead to a reduction in magnitude of pressure coefficients by about 50-65%.

In addition to the parapet configurations tested in this study mentioned previously, 3 modified roof geometries including semi-cylindrical projections on two windward walls, rooftop solid radial splitters and rooftop porous radial splitters, were also considered as possible configurations for mitigating roof suction. The same oncoming turbulent flow was used in this study as in the previous portion of the experiment and results were compared to the isolated case.

Surry and Lin (1995) observed that the semi-cylindrical projections applied in the roof corner region reduced the mean, fluctuating and rms pressure coefficients by about 60%. Furthermore, the incidence of the semi-cylindrical projection appeared to have eliminated the corner vortices completely resulting in a more uniform pressure distribution with the exception of a localized area of suction at the very edge of the roof.

The rooftop porous and radial splitters resulted in a reduction of $C_p$ over the roof by about 60%, the former resulting in a slightly higher reduction possibly due to the ability of the screen to “dissipate flow energy,” as suggested by the author. Surry and Lin (1995) suspected three main factors for this occurrence: the porous screen interrupted
vortex formation; the porous screen absorbed energy of the flow, and the small vortices that did form on top of the parapet avoided the top of the actual roof structure.

2.3 The Need for Full-Scale Hurricane Simulation

Though full-scale test facilities do exist (TTU, Loyola), they are few in number and have limitations when it comes to simulating hurricane force winds. The TTU facility, while extremely useful in collecting wind loads on buildings, is limited to environmental conditions inherent to that area which do not include tropical cyclones. As a result the facility may not be able to observe “worst case” conditions because the magnitude of the winds under which measurements take place is far from those associated with tropical cyclones. In a wind tunnel environment, components are tested at a fraction of their true size and at a fraction of the actual wind speed they would be exposed to, thus violating Reynolds number similarity. In wind tunnels, only external geometry is modeled, so the interactions of the wind with individual building components are not captured.

Full-scale hurricane simulations and testing will circumvent the above mentioned disadvantages and will allow for realistic experiments under programmable, controllable and repeatable hurricane environments.
3. Methodology

3.1 The Wall of Wind Test Facility

Testing for this project took place at Florida International University using the RenaissanceRe 6-fan WOW full-scale testing facility. The RenaissanceRe 6-fan WOW is an expansion on the previous prototype WOW (Figure 5) which consisted of a 2-fan array of Chevy 496 fuel-injected engines driving airboat propeller shafts. The 2-fan WOW measures 16 ft tall and 8 ft wide, making it useful for individual component testing but limited in the fact that a test structure could not be fully engulfed in the flow due to size constraints.

Figure 5. Prototype WOW System
The 6-fan WOW system came to fruition after the limitations of the prototype were realized (Figure 6). The larger WOW system consists of a 2x3 array of Chevy 502 big block carburetor engines turning Airboat Drive Units CH3 2:1 propeller drives. Measuring 16 ft tall by 24 ft wide, it is far more suitable for holistic full-scale testing than the prototype unit. The system is equipped with counter-rotating propellers (Figure 7), four large propellers closest to the engine and three smaller ones directly behind the others. The propellers limited the maximum revolutions per minute (rpm) of the engine to 4400. The four large propellers helped to increase the air flow through the system while the three smaller propellers accelerated the flow. For this study, the back four propellers were set at a constant pitch of 15° while the three smaller propellers were set at 10°. This configuration of pitches allowed for the maximum amount of air flow through the system at the highest possible rpm. The counter-rotating function of the propellers helped to eliminate the swirl from the flow.

Figure 6. 6-fan RenaissanceRe WOW
Each engine was mounted in a steel frame measuring 96 in by 96 in. The frame was equipped with wedges in each corner to direct flow into the propellers (Figure 8). Each engine frame was then connected to an octagonal shaped diffuser which helped to minimize "dead zones" in the flow. "Dead zones" occur as a result of flow separation and often cause back flow which yields negative velocities in the wind field. The diffuser section was an integral part of ensuring an uninterrupted flow during testing.

Figure 7. Counter-Rotating Props on 6-Fan WOW

Figure 8. Wedges in WOW Engines
The 6-fan WOW was capable of generating maximum wind speeds of 129 mph, representing a mid-grade Category 3 hurricane on the Saffir-Simpson hurricane intensity scale. The maximum rpm of each engine was approximately 4400 and 5500 with and without the propellers respectively. The scope of this project did not include turbulence effects in the wind field as the WOW is not currently equipped with a turbulence generator system. This concept will be discussed in the chapter describing future work with the WOW.

**WOW Test Structure**

All testing for this experiment was done using a plywood test structure measuring 10 ft x 10 ft x 10 ft (Figure 9). The test structure, equipped with standard window and door fixtures, rested on a square concrete pad and was secured to the ground using a system of guy wires. The test structure was placed at a 45° angle 9 ft from the edge of the WOW diffuser section and 16 ft from the back propellers for all testing (Figure 10). This distance allowed the flow to develop while keeping the structure close enough to the source of the flow so that it still experienced high velocity winds.

![Figure 9. WOW Test Structure](image)
The structure was designed to withstand the maximum 125 mph winds generated by the WOW. For this experiment, the structure housed 16 pressure transducers, standard 1/4" nominal diameter peat rock gravel and a variety of different aerodynamic edge shapes. The top of the structure was coated with "Peel-N-Seal," a lightweight resilient, rubber-like product used primarily to patch holes in roofs following the passing of a hurricane. The "Peel-N-Seal" product acted as a weather-proofing device for the test structure to ensure that instrumentation did not get damaged from inclement weather or debris.

3.2 System Controls

WOW Controls

The six engines of the WOW were simultaneously controlled using LabVIEW algorithms developed by PrimeTest Automation. A manual ignition wired through the software provided a mechanism to turn the engines on after which the rpm of individual engines was directly controlled using the LabVIEW software. Each engine was equipped
with a Hightech HSR 5995 servo attached to the throttle, the physical mechanism that controls the rpm on the engine. A calibration curve correlated the position of the throttle to the servo position which was then in turn controlled by the researcher through the LabVIEW software. The position of the servo vs. rpm differed slightly from engine to engine so each engine had to be calibrated separately. This mechanism allowed the user the choice of running all engines at the same rpm or running select engines at different rpm. With the LabVIEW waveform editor, different rpm profiles were created and loaded into the program so that engines automatically adjusted rpm based on the function in the waveform. The waveform editor provided a more accurate mechanism for engines to quickly change speed, producing non-stationary gusts that are experienced in an actual tropical cyclone event.

The LabVIEW software helped to enhance the safety of the system by monitoring the performance of the six engines. A total of 48 thermocouples (eight for each engine) monitored the temperature of the cylinders in the engines. Senders attached to the engines and wired to the software monitored water temperature, oil temperature, oil pressure, voltage and rpm for each engine. Each of these elements had a range of values where operation of the engines was considered safe; the LabVIEW software monitored these values to make sure that threshold values were not reached.

In the case that any value would surpass the threshold values, an alarm on the channel caused the screen on the LabVIEW software reporting that particular parameter to turn red and engines were automatically restored to their idle rpm ranging between 750 and 1000 rpm depending on the engine. This function provided two advantages to the user: first, by programming the system to return the engines immediately and
simultaneously to idle rpm, engines were spared further damage that might have been incurred had a threshold value been reached and the operator was unaware; second, by turning the afflicting parameter red on the screen, the operator was made aware of which system parameter could potentially harm the engine and the problem could be properly addressed. The LabVIEW software program allowed the user the freedom to run different wind speed profiles while monitoring the safety of the engines to ensure efficient running of the system.

**Data Acquisition**

The data acquisition (DAQ) system for the WOW was also developed by PrimeTest Automation using the LabView software (Figure 11). All pressure transducers and wind monitors were wired to the LabVIEW DAQ for data collection. The DAQ operated at a standard sampling rate of 200 Hz and data could either be collected continuously by manually triggering data record, or for a specified period of time. Each time a test was run, data was automatically time-stamped and saved as a tab delimited file. The time stamp allowed each test to be labeled uniquely for easy future referencing and the tab delimited format in which files were saved allowed for easy import into Microsoft Excel. Also, Microsoft Excel had a maximum of 65,000 rows of data which could be stored in one file whereas tab delimited files were under no such limit, making them an ideal method of storage for files with such a high sampling rate.

Calibration of instruments was also run through the DAQ. For pressure transducers, the DAQ was switched into a “calibration mode” where it was able to read raw voltages from the instruments. A hand-held Omega PCL-200C calibration kit
generated known pressures and a calibration curve was established correlating the known pressures to the raw voltages read by the DAQ. This calibration curve was then added to the DAQ in spreadsheet format so that during testing, the DAQ would automatically convert voltages to pressures so that pressures were displayed on the screen and also stored.

![Figure 11. WOW DAQ System](image)

The wind monitors were calibrated in a similar fashion as the pressure transducers. An anemometer drive unit generated a known rpm which was then related back to frequency changes read by the DAQ to create a calibration curve for the wind monitors. A further conversion of rpm to wind speed also took place so that the end result was a wind speed reading in miles per hour (mph). For calibration of the wind direction, a known excitation voltage was applied to the potentiometer and a calibration curve relating the known voltage to a wind direction was created. Calibration
spreadsheets created in the DAQ were continuously read during data acquisition allowing the DAQ system to provide real-time plots of pressure and wind speed time histories during testing as well as continuously update the three-second average and instantaneous peak differential pressures and wind speeds.

3.3 Experimental Set-up

The following section provides a detailed description of the instrumentation used in this project as well as preliminary testing that was conducted in order to provide reference values for the primary experiments.

*Instrumentation*

*Wind Monitors*

This experiment required the use of four RM Young model 05103V wind monitors to measure the wind profile created by the WOW (Figure 12). Wind monitors were made of UV stabilized plastic with stainless steel and anodized aluminum fittings, making the instrument ideal for full-scale testing due to its durability. Each wind monitor recorded wind speed and direction with ranges between 0-224 mph and 0-360° respectively. The wind speed sensor consisted of a durable four-blade helicoid propeller which produced an AC sine wave voltage signal between 0-5 volts (V). As mentioned previously, the frequency of the sine wave was directly proportional to wind speed. The wind direction sensor was a lightweight vane with a low aspect ratio which made it an accurate reporting device for highly fluctuating winds. A potentiometer housed in a sealed chamber produced an output voltage directly proportional to the vane angle.
Pressure Transducers

Sixteen Setra model 265 very low differential pressure transducers were used for this project to measure the suction pressures on the roof induced by a hurricane-like wind flow (Figure 13). Each transducer had two ports, a reference pressure port and a port exposed to the roof of the test structure which measured the fluctuating pressures on the roof. The result was a differential pressure which reported into the DAQ as a voltage ranging from 0-5 V and was then calibrated and converted into psf (pounds per square foot). The transducers had a pressure range of ±1.8 psi or roughly ±260 psf (pounds per square foot) and reported at a frequency of 10 Hz and an accuracy of ±1 %.

The pressure transducers were connected to the reference pressure and dynamic pressure ports using a system of tubing. The reference pressure measurement was taken in a pressure pit located approximately 50 ft north-east of the corner of the test structure (Figure 14). A 3 in PVC pipe extended from the pressure pit into the test structure and
was then reduced to a ¼” in PVC pressure manifold (Figure 15, Figure 16). The pressure manifold distributed the reference pressure to 16 different PVC ball valves. Each PVC ball valve was connected to a 12 in piece of ¼ in ID (inside diameter) polyurethane tubing. The polyurethane tubing was connected to a piece of 240 in silicon tubing approximately 1/16 in ID via a plastic reduction fitting. This 1/16 in ID tubing was then attached to another piece of 1/4 in ID polyurethane tubing reduced to 3/16 in ID tubing which was attached to the actual reference pressure port (Figure 17). The additional reduction of the ¼ in ID tubing to the 3/16 in ID tubing was done because the port on the transducers had a 3/16 in diameter opening and accurate measurements required a secure fit of the tubing to the transducer. The 3/16 in ID tubing was not used initially because the small size of the tubing could have created more resonance if run the entire length of the connection. The small silicon tubing connected between the larger polyurethane tubing served to filter out any noise cause by the resonance of the tubing and is therefore referred to as restrictor tubing.

Figure 13. Setra model 265 Very Low Differential Pressure Transducer
Figure 14. Schematic of WOW Pressure Pit Location

Figure 15. Three in PVC Pipe Extended from Reference Pressure Line
The tubing system for the dynamic pressure port was much simpler. Here, the \( \frac{1}{4} \) in ID polyurethane tubing was connected to a \( \frac{1}{4} \) in OD (outside diameter) copper pressure tap which extended from the roof. The tubing then extended down where it was spliced into 2 different lines using a plastic \( \frac{1}{4} \) in barbed "T" connection. One line of tubing ran straight down from the splice and was connected to another ball valve which served as a draining function should any water collect in the tubing. The other tube formed a U-shape and was then connected to the dynamic pressure port on the transducer (Figure 18). As with the reference pressure port, a small reduction of the \( \frac{1}{4} \) in ID tubing to the 3/16 in ID tubing was placed directly before the pressure port to account for its smaller size. The total length of tubing that ran from the roof tap to the pressure port was restricted to a maximum of 12 in as longer tubing could have resulted in distorted measurements. The U-shape also served as a guard against water damage; in the event that water entered the system from the roof and flowed down to the ball valve and
through the U-shape, it would never actually reach the pressure transducer because as it would have gotten trapped at the bottom of the U.

Figure 17. Pressure Transducer with Restrictor Tubing

Figure 18. U-Shape Roof Port Connection for Prevention of Water Damage

The extensive tubing system needed for the pressure transducers required two types of calibrations, a standard and dynamic calibration, to be performed to ensure a certain level of accuracy in the measurement. The standard calibration, mentioned previously in the *Data Acquisition* section, served two main purposes; first, it acted as a simple method to check that the pressure being fed into the pressure port was the same as
that being reported through the DAQ, second, it helped to verify the factory calibration of the instrument which occurred at the time of assembly. Because initial calibrations indicated slight variation from the factory setting, a separate calibration was performed on each transducer using the Omega PCL-200 hand held calibration kit before each experiment to ensure proper function of the instrumentation (Figure 19). The on-site calibration curve was used for each transducer to ensure the highest level of accuracy in the measurements. Figure 20 shows the calibration curves for transducers 1-4 which are very similar to the factory calibration curve.

![Figure 19. Omega PCL-200 Calibration Kit](image)

The second type of calibration was a dynamic calibration. The dynamic calibration was performed on both the reference pressure port and roof pressure port (dynamic port). The purpose of the dynamic calibration was to evaluate the affects of the tubing lengths on the frequency response of the measurements. Previous testing has demonstrated that extended tubing lengths often result in amplitude and phase shifts thus distorting the measurement.
The dynamic calibration of the pressure transducers was achieved using a BK Precision Sweep Function Generator (SFG) and a standard audio amplifier and audio speaker. The SFG was attached to the audio amplifier which was then attached to the speaker. Two ¼ in holes were drilled into the speaker and a pressure transducer was attached to each of the two holes. The first pressure transducers was attached directly to one of the openings in the speaker via a small, ¼ in piece of tubing approximately 2 in long. The second transducer was attached to the remaining opening by a combination of tubing beginning with a 2 in piece of ¼ in ID polyurethane tubing extending from the speaker. The ¼ in ID polyurethane tubing was then attached to 1/16 in ID silicone tubing using a plastic reducer fitting which was then increased a final time to a 2 in piece of 3/16 in ID polyurethane tubing that connected directly to the reference pressure port of the transducer (Figure 21). The SFG then generated a random function signal that was
amplified by the audio amplifier and then applied to the pressure transducers via the speaker. The time histories resulting from the SFG signal were recorded by the DAQ.

![Figure 21. Set-up for Dynamic Calibration of Pressure Transducers](image)

Several different combinations of silicone and polyurethane tubing were tested, each time altering the length of the silicone tubing. The purpose of altering the length of the silicone tubing, or restrictor tubing, was to determine which length of tubing would appropriately remove all noise from the measurement. It was essential to remove noise from the reference pressure to assure that all differential pressure measurements referenced a uniform measurement. If this was not the case, measurements would have varied greatly due to a fluctuating reference pressure measurement. First, the two transducers were tested directly attached to the speaker which resulted in two very similar fluctuating time histories. Next, 18 in, 24 in, 48 in, 72 in, and 120 in pieces of tubing were tested. With each increasing length, the amount of noise in the time history of the
transducer attached to the speaker through tubing compared to the transducer attached directly to the speaker decreased. The last piece of tubing tested, a 240 in piece, was the most effective in dampening out noise and therefore was used for this experiment (Figure 22). By applying restrictor tubing to filter out high frequency noise, a transfer function did not have to be applied to the data to account for resonance in the tubing, thus no post-processing of data was necessary.

The dynamic calibration for the roof pressure port was much simpler and served only to verify that the 12 in tubing used did not cause significant phase and amplitude shift in the data. To achieve this calibration the same set-up of pressure transducers and speaker was used, however, one of the transducers was attached to the speaker with only a 12 in length of polyurethane tubing and no restrictor tubing. The SFG was used to generate sine waves over multiple frequencies and pressure time histories for the transducers were observed for each frequency. The two transducers measured very similar pressure time histories over all frequencies, and therefore no transfer function was needed for the roof pressure side of the transducers (Figure 23). The calibration performed for these experiments indicated that the tubing configurations specified above were appropriate for both the reference and roof pressures.

Reference Velocity Measurements

Before testing of the modified edge shapes was conducted, velocity measurements were taken to establish both the free-stream velocity profile produced by the WOW and a curve relating wind speed and engine rpm. In order to get the true free-stream velocity, all velocity profile measurements were taken without the presence of the test structure as
the structure would have affected the wind field. These free-stream measurements provided information about the specific velocity values that would be present at the test structure eave height which was the focal point of the pressure testing and scour testing. By already knowing the velocity profile prior to testing, all pressure measurements could be directly related back to a wind speed without having to take simultaneous pressure and wind speed measurements.

(a)

(b)
Figure 22. The Effect of Different Tubing Lengths on Pressure Time Histories, (a) Pressure Time Histories with no Restrictor Tubing, (b) Pressure Time Histories with No Tubing and with 72 in Restrictor Tubing, (c) Pressure Time Histories with No Tubing and 120 in Restrictor Tubing, (d) Pressure Time Histories with No Tubing and with 240 in Restrictor Tubing
Figure 23. Roof Port Tubing Lengths, (a) Pressure Time Histories with No Tubing, (b) Pressure Time Histories with no Tubing and with 12 in ¼ in ID Polyurethane Tubing
The Free-Stream Velocity Profile

The first step in achieving the free-stream velocity profile measurements was to construct a moveable frame where wind monitors could be secured to take measurements. A frame was built using Unistrut, a system of galvanized steel beams, and connected together using grade A steel bolts (Figure 24). The steel frame measured 24 ft wide by 16 ft high and had a depth of 9 ft. Four wind monitors were secured to the frame in a square configuration with 8 ft sides (Figure 25), a configuration chosen so that the velocities of four fans could be measured simultaneously at the same reference point. This concept was very important to establish how the fans affected each other.

Figure 24. Unistrut Velocity Measuring Frame in Front of WOW
The Unistrut frame housing the wind monitors was able to move in three planes of motion via a system of sliding trolleys, pulleys and winches (Figure 26). Two electrically controlled winches controlled the side-to-side and up-and-down movement while movement toward and away from the diffuser was done by rolling trolleys. The winches made it possible to control the movement of the frame accurately from a safe distance from the WOW during testing. The external frame control system allowed for more exact placement of measurements, more efficient running of the engines and increased safety of the researchers.

After the frame was created to take velocity measurements and positioned a distance of 9 ft from the edge of the diffuser, the maximum velocity produced by the WOW running at 3000 rpm was determined. This wind speed was obtained through a series of trial and error tests where wind monitors were moved to several different locations to determine the position and value of the maximum wind speed. The
instantaneous peak wind speed achieved when all 6 engines ran at 3000 rpm was 71 mph, representing a very strong tropical storm on the Saffir-Simpson hurricane intensity scale. At the time of this testing, the WOW was limited to running at a maximum 3000 rpm due to a carburetor problem which did not allow enough fuel to flow through the engine. As a result, after running the engines for a period of several minutes at a higher rpm, the engines would overheat and the pistons would melt. This problem was resolved with the help of new carburetors and larger fuel lines. After both scour and pressure testing were concluded, a second round of scour tests were conducted at the adjusted maximum of 4400 rpm. Additional velocity measurements were also taken and determined that the maximum wind speed at 4400 rpm was 129 mph, representing a strong Category 3 storm on the Saffir-Simpson scale.

Figure 26. Close-up Winch used to Move Unistrut Frame Up and Down and Side-to-Side

Once the maximum velocity at eave height was determined, the free-stream reference velocity profile along the span of the eave was measured. First, the frame was moved using the system described above, a distance of 6 ft from the edge of the diffuser
section. Velocity measurements, with a one-minute averaging time, spanning a 15 ft length at the eave height of the building were taken with all six fans running at 3000 rpm and again later at 4400 rpm. Another set of velocity measurements were taken at 9 ft from the diffuser section which represented the distance from the corner of the building to the diffuser section.

The determination of the maximum wind speed led way to a second round of measurements relating fan rpm to wind speed, necessary for gravel scour testing. Again, the Unistrut wind monitor frame was used, however, for the purpose of these measurements, the frame was fixed at the position where the eave height of the structure would sit as this was the area most crucial for the gravel scour testing and pressure testing.

All engines were first brought to their respective idle rpm for a brief warm-up period. The rpm of each engine was slowly increased, via the servo control, a small percentage while the wind monitors recorded velocities. Each time a velocity was recorded, the configuration of engines with their respective rpm was noted. After wind speed measurements were complete, curves were created for each individual engine reflecting the relationship between rpm and wind speed. These curves were used for gravel scour testing to determine the wind speed where gravel began scouring as wind speed measurements were not taken during actual testing.

*Control Pressure Measurements*

After initial velocity profiles were taken, the test structure was placed in front of the WOW and instrumented with pressure transducers so that control pressure
measurements could be taken for the pressure testing. Using the curve relating rpm and wind speed, six-minute pressure time histories were recorded while all engines of the WOW ran at 3000 rpm. As mentioned previously, this rpm corresponded to a maximum wind speed of 71 mph. Measurements were taken with the test structure positioned at a 45° angle with respect to the WOW without any type of edge shape attached. These pressure values were later used to determine reductions in uplift on the roof with the presence of the modified edge shapes.
4. Experiments

This study consisted of two different tests which aimed to help better understand the development of vortices through visual testing and better protect against damage caused by vortex generation through product testing. This chapter will outline the specific test procedures for both tests.

Experimental Test Shapes

A total of four modified edge shapes and two standard edge shapes were tested between the gravel scour testing and the pressure testing. The modified edge shapes were designed and patented by Jason Lin Ph.D., Vice President of WeatherPredict Consulting Inc. under the AeroEdge™ trademark. AeroEdge™ represents a family of patented aerodynamic devices to be installed on roof and wall edges to suppress force-generating edge vortices. Products are non-intrusive exterior devices representing a simple and inexpensive way to equip new construction as well as retrofit existing construction. The four modified shapes used were the Flat-Roof AeroEdge™ Cap (patented), the Flat Roof AeroEdge™ Guard (patent pending), the Gable Edge Cap Vortex Suppressor (patented) and the Gable Edge Screen Vortex Suppressor (patent pending)(Figure 27).

The gable edge shapes were slightly modified in their application to the flat roof to account for the different slope of the roof and both shapes were similar in design to their flat roof counterparts with the exception of their height which was generally much shorter. The testing of the gable edge shapes mainly contributed to determining a relationship between edge shape height and the degree to which suction was reduced as
previous tests have suggested that shorter edge shapes are not as effective in mitigating roof suction.

Surry and Lin (1995) described several aerodynamic mechanisms through which roof suction could be reduced through modified edge shapes. These aerodynamic mechanisms are reflected in the design of the AeroEdge™ products and include the following:

Figure 27. Modified Edge Shape Designs, (a) Flat Roof AeroEdge Cap, (b) Flat Roof AeroEdge Guard, (c) Gable Roof Edge Cap Vortex Suppressor, (d) Gable Edge Screen Vortex Suppressor
(1) Eliminating sharp edges that create vortices

(2) Disrupting the vortices formation

(3) Disturbing the vortices

(4) Displacing the formed vortices

The remaining two edge shapes tested, which are prescribed in current construction practices, were the Econosnap standard edge fascia and the Drain-Thru Gravel Stop (Figure 28). Because these shapes are an industry standard, pressure data representative of what an actual flat roof structure would feel during a storm was collected. All of the above products were manufactured by the Hickman Company, located in Asheville, NC.

![Figure 28. Standard Edge Shape Designs, (a) Econosnap Standard Fascia, (b) Drain-Thru Gravel Stop](image)

**Experiment 1 – Gravel Scour Testing**

The first experiment done for this study was the gravel scour testing. This test focused on understanding the visual concept of vortex generation while also examining the affects of vortex suppression methods on the physical structure of the vortex. Four
different edge shapes were tested including the standard Econosnap Fascia, the Drain-Thru Gravel Stop, the Flat Roof AeroEdge Cap, and the Flat Roof AeroEdge Guard. A professional photographer positioned on a platform above the WOW captured footage of all testing. The platform was located a safe distance from the WOW and allowed for a clear view of the roof top at a down-looking angle of 30°.

For the first test configuration in this series, the test structure, equipped with the standard Econosnap Fascia on the windward side and the Gable Edge Screen Vortex Suppressor on the leeward side, was placed in front of the WOW at a 45° angle with respect to the WOW (Figure 29). The Gable Edge Screen Vortex Suppressor was present on the leeward side of the structure for all testing, and in this case, was used as a mechanism to keep large amounts of gravel from spilling off the roof. The roof was then covered with a 2 in thick layer of ¼ in nominal diameter river gravel. All six engines of the WOW were brought to idle speed and then rpm was gradually increased until the gravel on the roof began to scour. Once the gravel scour commenced, the engines were brought back down to idle.

![Figure 29. Test Structure Equipped with Econosnap Standard Fascia](image)
Gravel scour was observed at 2750 rpm for this configuration which corresponded to a 60 mph maximum wind speed. A waveform was then created to reflect this transition point. The waveform first brought the engines up to the critical 2750 rpm where they were held for two minutes. The rpm was then increased to 2800 rpm for two minutes, 2900 rpm for another two minutes then 3000 rpm for a final three minutes making the test duration a total of nine minutes (Figure 30). A series of digital photos were taken after this test and each subsequent test was completed to document the shape and size of the scour.

![Waveform for Gravel Scour Testing](image)

Figure 30. Waveform Function for Standard Edge Shapes, Econosnap Fascia and Drain-Thru Gravel Stop for Gravel Scour Testing

For the second test configuration, the standard Econosnap Fascia was replaced by the Standard Gravel Stop on the windward side of the structure (Figure 31). A 2 in thick layer of ¼ in nominal diameter river gravel was replaced on the roof. All six engines
were turned on and brought up to idle rpm. The engine rpm was again brought gradually upward until visible movement of gravel was noted. Similar to the previous test, visible movement of gravel was observed at 2750 rpm or 60 mph. The same waveform run in the first configuration was run again for a nine minute duration during which time video footage captured the evolution of the gravel scour.

For the third configuration, the Drain-thru Gravel Stop was replaced by the Flat-Roof AeroEdge Guard (FRAG1) (Figure 32). The roof surface was refilled with a 2 in layer of ¼ in thick nominal diameter river gravel. The WOW was then run using the same procedure as the previous test where the engines were brought to idle and then increased until scouring was observed. Because of the altered configuration of the test structure, only slight gravel scour was observed at the maximum 3000 rpm. To account for this difference in rpm, a new waveform was created starting the engines at idle rpm and ramping engines to 3000 rpm for seven minutes. Video footage was recorded simultaneously as the waveform was run.

Figure 31. Test Structure Equipped with Drain-Thru Gravel Stop
For the fourth and final test configuration, the FRAG1 was replaced by the Flat Roof AeroEdge Cap (FRAC1) on the windward side of the structure (Figure 33). A run of the engines from idle to maximum rpm again indicated only slight gravel scour at 3000 rpm. The same waveform run for FRAG1 testing was run again while video was recorded.
Experiment 2 – Pressure Testing to Evaluate Vortex Suppression

The next set of tests served to establish the influence of vortex mitigation techniques in reducing suction pressures under the influence of the wind speeds produced by the WOW. For these tests, the same test structure was used and was situated in front of the WOW at a 45° angle. Simultaneous pressure measurements were taken throughout this experiment. Sixteen pressure taps were installed on the roof in a triangular configuration with the majority of taps concentrated in the Zone 3 roof zone as defined by ASCE 7-05 (Figure 34). According to ASCE 7-05, the Zone 3 area represents the section of the roof that will experience the worst suction pressures and therefore has the most strict design criteria. The area is calculated based on the critical distance “a” which is the smaller value of 10% of the least horizontal distance of the structure or 0.4h (where h=height of the structure); this value cannot, however, be less than 4% of the least horizontal dimension or 3ft. Based upon the dimensions of the structure to be modeled, the critical distance “a” is calculated to be 3 ft resulting in an effective Zone 3 wind area of 9 ft². It was crucial to have the taps concentrated in this area in order to properly record the fluctuating pressures in that section of the roof.

Seven different edge configurations, including a control test, were tested to determine their effects on reducing suction caused by conical vortices. The different configurations are described below.

**Configuration 1**: Test Structure with no edge shape attached (control test).

**Configuration 2**: Standard Econosnap Fascia on the windward side of the structure and Gable Edge Screen VortexSuppressor on the leeward side.
Configuration 3: Standard Drain-Thru Gravel Stop on the windward side of the structure and Gable Edge Screen Vortex Suppressor on the leeward side.

Configuration 4: Flat Roof AeroEdge Guard on the windward side of the structure and Gable Edge Screen Vortex Suppressor on the leeward side.

Configuration 5: Gable Edge Vortex Cap Suppressor extended 2.375 in above the roof surface on the windward side of the structure and Gable Edge Screen Vortex Suppressor on the leeward side.

Configuration 6: Gable Edge Vortex Cap Suppressor extended .5 in above the roof structure on the windward side of the structure and Gable Edge Screen Vortex Suppressor on the leeward side.

Configuration 7: Gable Edge Screen Vortex Suppressor on both the windward and leeward sides of the structure.

A standard test procedure was employed for each of the seven tests. First, the edge shape being tested was installed on the roof using 1¼ in galvanized ring shank nails, the standard fastener used to install edge fascia in current building practices. Next, a wave form was created which brought the engines from idle rpm to 3000 rpm for six minutes and then back down to idle (Figure 35). This waveform was chosen to fulfill two main objectives of this study. First, it was essential to collect full-scale pressure data under worst-case tropical cyclone conditions. By running the engines at 3000 rpm, it was possible to recreate tropical storm conditions in the full-scale environment and collect corresponding pressure data. Second, because gravel scour testing was also tested at 3000 rpm, a comparison could be made regarding the area where gravel scour occurred.
and the corresponding pressures. This waveform was run for each different edge configuration.

Figure 34. Pressure Tap Locations with Coordinate (0,0) referencing the roof corner and the horizontal and vertical axis representing the x and y axis respectively.

Table 1. X and Y Coordinates of Pressure Tap Location

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>P2</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>P3</td>
<td>12</td>
<td>2.375</td>
</tr>
<tr>
<td>P4</td>
<td>12</td>
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<td>12</td>
<td>5.4375</td>
</tr>
<tr>
<td>P6</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>P7</td>
<td>24</td>
<td>6.125</td>
</tr>
<tr>
<td>P8</td>
<td>32</td>
<td>6</td>
</tr>
<tr>
<td>P9</td>
<td>32</td>
<td>8</td>
</tr>
<tr>
<td>P10</td>
<td>32</td>
<td>14.375</td>
</tr>
<tr>
<td>P11</td>
<td>32</td>
<td>24</td>
</tr>
<tr>
<td>P12</td>
<td>48</td>
<td>6.75</td>
</tr>
<tr>
<td>P13</td>
<td>60</td>
<td>6</td>
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<td>P14</td>
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<td>P15</td>
<td>60</td>
<td>27</td>
</tr>
<tr>
<td>P16</td>
<td>60</td>
<td>45</td>
</tr>
</tbody>
</table>
Pressure data was collected simultaneously while the waveform was run. All transducers sampled data at 100 Hz for six minutes. The seven resulting time histories were then transferred from the DAQ for data analysis.

**Experiment 3 – Gravel Scour Testing at 4400 rpm**

After initial gravel scour testing and pressure testing were completed, a second round of gravel scour testing was performed at the maximum 4400 rpm. For the second round of tests only the standard Econosnap Fascia and FRAG1 edge shapes were tested as the other two edge shapes resulted in similar gravel scour patterns. The shapes were installed in the same manor as in the previous gravel scour testing and the tests structure was again positioned at a 45° with respect to the WOW. A waveform was created which brought the WOW from idle rpm to 4400 rpm in 30 seconds for a duration of one minute.
This waveform was run three times so that the test structure was subjected to 4400 rpm or 129 mph maximum wind speeds for three minutes, though not consecutively (Figure 36).

Figure 36. Waveform for Second Round of Gravel Scour Testing

**Data Analysis**

Data analysis for the gravel scour tests involved qualitative and quantitative analysis of digital photos to observe how modified edge shapes affected the visual structure of the vortex. This evaluation made it possible to determine whether or not a particular edge shape was effective in vortex suppression. All images were compared back to the standard roof which consisted of a gravel roof equipped with the Econosnap Fascia.

Three different criteria were used to evaluate images and determine whether or not a particular modified edge shape could potentially reduce suction pressures. The first
criterion involved comparing the wind speeds at which gravel scour was first observed. If a modified edge shape increased the wind speed where gravel scour began it was considered potentially effective in reducing suction caused by cornering winds.

Next, the magnitude of gravel scour was considered. Previous studies have shown that modified edge shapes both reduce the suction at the windward corners and cause a more uniform pressure distribution so that the entire roof is under the same reduced amount of force. This reduction would appear visually if the size of the area affected by gravel scour was reduced with the presence of a modified edge shape. To achieve this comparison, dimensions of gravel scour area were taken after each test so that a comparison could be made to the standard roof and the shape could be evaluated for effectiveness. If gravel scour area at the roof corner was decreased and the roof displayed a uniform gravel scour over the majority of the remaining roof section, the shape was considered potentially effective in vortex suppression.

The final criterion to be considered was the location where gravel scour was initiated on the roof. Modified edge shapes have often had the effect of deflecting turbulent flow vertically above the structure and horizontally away from the corner regions. Deflecting the flow horizontally is considered advantageous as it both reduces suctions caused by the vortices and causes any additional suction to occur away from the essential connections which secure the roof to the structure. If the presence of an edge shape was able to influence the location of the initiation of gravel scour, it was considered likely that that same edge shape would result in decreased suction pressures.

After a visual analysis of gravel scour was concluded, pressure time histories were analyzed to determine the quantitative reduction in suction pressures caused by
modified edge shapes. In order to analyze this data, differential pressure values obtained during pressure testing were first converted to pressure coefficients. Pressure coefficients are dimensionless quantities defined as the differential pressure divided by the dynamic pressure (Eq. 1). Pressure measurements were non-dimensionalized for comparison purposes. By performing this conversion, pressure coefficients from this study could be compared to quantities recorded in previous studies without having to consider similarities in wind speed.

\[ C_p = \frac{\Delta p}{\frac{1}{2} \rho V^2} \]  

(Eq. 1)

where \( C_p \) is the pressure coefficient, \( \rho \) is the density of air, and \( V \) is velocity.

The velocity values used to non-dimensionalize were obtained from measurements taken during initial velocity measurements at the eave height. A curve of the mean velocity profile was created and the coordinates representing the location of the pressure taps were transposed to the plane of the velocity measurements (Figure 37). By representing the pressure tap locations on the plane of measurement, wind speeds specific to each tap could be used to calculate the dynamic pressure making pressure coefficients more accurate.

The data analysis of the pressure time histories had 3 main objectives:

1. Compare time histories and determine whether or not a reduction in Zone 3 suction pressures occurred due to the aerodynamic edge shapes
2. Compare peak pressure from both control and aerodynamic edge shape testing to values suggested by ASCE 7-05 to determine whether or not more conservative values should be implemented.

3. Establish co-relation of pressure values between different points of the roof to determine if aerodynamic edge shapes were effective in breaking the coherency of the shed vortices.

Figure 37. Wind Velocity Profile from WOW at 3000 rpm

The first objective was accomplished by recreating the pressure time histories using the pressure coefficients instead of the differential pressure values. Pressure coefficients were then used to calculate $C_{p \text{ min}}, C_{p \text{ max}}, C_{p \text{ mean}},$ and $C_{p \text{ rms}}$ for each tap and
each different test. These values were compared to the values recorded for the control test and the percentage difference was calculated in order to evaluate the reduction in roof corner suction.

The $C_{p\,min}$ values obtained for the control test were then compared to ASCE 7-05 Zone 3 design coefficients to determine whether or not current code values are adequately conservative. This was done to verify that design values obtained from wind tunnel testing and modeling accurately describe what is actually occurring in the atmosphere. If design values are too conservative than structures can be over-designed resulting in unnecessary use of supplies and money. On the other hand, a structure not designed to code could suffer catastrophic damage in the event of a sever storm.

The $C_{p\,min}$ values obtained from pressure testing of modified edge shapes were also compared to current design values to determine if the addition of a modified edge shape would reduce suction enough that the Zone 3 region could actually be designed under Zone 2 values. This comparison would establish whether or not the presence of aerodynamic edge shapes would constitute the design of Zone 3 by Zone 2 values. As mentioned previously, a current provision in the code makes this exception for the presence of parapets that meet a certain height requirement.

Three-dimensional plots were created showing pressure data for each individual test to establish a co-relation of pressure values between different points on the roof. The control test with no modified edge shape was again used as a basis for comparison as the co-relation between points in this case would represent the common case for current structures. As concluded in previous studies and verified in this full-scale study, the case with no modified edge shape demonstrated extremely high suction on the corner and
along the edge of structure which reduced drastically with distance from the edge. Three-dimensional plots from pressure testing with modified edge shapes were therefore not only examined for reduction but different pressure patterns altogether. One hypothesis of this study was that the modified edge shapes may drastically reduce suction at the corner while having little effect on the slight suction seen towards the middle of the roof. This case would result in a more uniform pressure distribution and contour plots were evaluated for changes in co-relation such as this. Three-dimensional plots were also scanned for an appreciable increase in positive pressure anywhere on the roof which would essentially have the opposite effect of suction but still cause significant damage.
5. Results and Discussion

Gravel scour and pressure testing were conducted to evaluate the influence of modified edge shapes on the structure of conical vortices and roof corner suction pressures, respectively. Four different edge configurations were tested for gravel scour and seven for pressure testing. Results indicated that certain edge shapes did have an impact on both the structure of the conical vortices and the pressures experienced at the roof corner region.

Gravel Scour Testing Results

Gravel scour testing resulted in a noticeable difference between the scour occurring with the Econosnap Fascia and Drain-Thru Gravel Stop and that occurring with FRAG1 and FRAC1 AeroEdge™ edge shapes. The Econosnap Fascia lead way to a significant area of gravel scour initiated at the roof corner (Figure 38). At its furthest point, the scour extended a distance of 42 in from the corner of the roof and spanned 19 in across at its widest point. A ray superimposed on the digital photos extending from the corner towards the middle of the roof at a 45° angle with respect to the roof edge acted as a center line in order to compare whether or not scour patterns were symmetrical. In this case, the centerline made it apparent that the pattern of scour was highly asymmetrical with significantly more scour occurring to right of the reference line, or the west side of the structure. From this observation it was concluded that the flow was slightly turbulent. The turbulent nature of the flow could be attributed to environmental cross winds, asymmetrical obstructions at the test site, or natural turbulence caused by the framing of the WOW. Though it is noteworthy to observe that turbulence does exist in the flow, this
study is primarily focused on the area affected by gravel scour and not necessarily the shape therefore it is not important to specifically classify these turbulence characteristics.

The Drain-Thru Gravel stop also resulted in a significant amount of scour (Figure 39). Like the Econosnap Fascia, the scour initiated close to the corner of the roof, however, a small area of gravel right at the corner remained intact. The scour resulting from the Drain-Thru Gravel Stop was much more symmetrical than the previous pattern, forming a heart-shaped pattern nearly evenly distributed on either side of the superimposed centerline. The scour extended 39 in from the roof corner to the center of the roof along the centerline. The "peaks" on either side of the heart extended 42 in from the roof corner towards the center of the roof and at its widest point the heart shape...
measured 30 in. The scour pattern also illustrated the fact that the vortices formed at about a $15^\circ$ angle form the southeast and southwest edges of the structure. This is consistent with previous studies which have showed that conical vortices form on both edges adjacent to the leading corner at angles anywhere from $10-15^\circ$.

![Figure 39. Gravel Scour Associated with Drain-Thru Gravel Stop](image)

Both the FRAG1 and FRAC1 modified edge shapes appeared to have suppressed the suction associated with the conical vortices as no gravel scour was evident after the test took place (Figure 40, Figure 41). Digital photos and video taken during actual testing supported this assumption. Digital photos taken after running the waveform showed no obvious signs of scour and measurements taken after testing verified that the depth of the gravel remained the same at the corner both before and after the roof was subjected to tropical storm force winds. Video footage reviewed after the testing showed
random gravel movement sporadically throughout the waveform; however, no significant scour was observed. Results from these tests supplied visual support that the presence of modified edge shapes does affect the structure of the vortices. This change in vortex structure could be attributed to the vortex being deflected above the surface by the modified edge shape so it no longer interacted with the roof or the vortex being completely destroyed by the edge shape so that the flow pattern no longer existed. Pressure measurements would verify whether or not the lack of gravel scour resulted in a decrease in uplift.

Gravel scour testing at 4400 rpm revealed similar results to testing conducted at 3000 rpm. With the presence of the standard Econosnap Fascia, approximately $\frac{3}{4}$ of the roof surface experienced gravel scour in the same heart shape pattern seen at 3000 rpm (Figure 42). The FRAG1 edge shape again performed well by completely eliminating scour on the roof (Figure 43). Measurements recorded during pressure testing helped to determine how the change in the scour pattern corresponded to a change in roof pressure.

Figure 40. Gravel Scour Associated with FRAG1 AeroEdge™ Shape at 3000 rpm
Figure 41. Gravel Scour Associated with FRAC1 AeroEdge™ Shape at 3000 rpm

Figure 42. Gravel Scour Associated with Econosnap Fascia at 4400 rpm
Pressure Testing Results

Pressure testing results both verified the validity of the WOW in full-scale testing and revealed that the presence of certain modified edge shapes reduced the suction at the roof corner. Pressure data recorded during the control testing where no edge shape was attached to the roof was compared to similar data recorded from pressure taps 50001, 53001, 50044 and 53044, located at the four corners of the WERFL at TTU at wind angles of 45°, 135°, 225°, and 315°. A comparison between the data showed similarities in the magnitude of the $C_p_{\text{min}}$ recorded at the four taps at TTU and values recorded at the taps closest to the corner during WOW testing. For example, WOW tap #3 recorded a $C_p_{\text{min}}$ of -18.23 while the four TTU corner taps recorded $C_p_{\text{min}}$ values around -20. The slight difference in values could be attributed to differences in environmental conditions,
etc., however, the fact that data is so close given two completely different test methods is very promising for the future of the WOW. This conclusion is extremely important to the prospect of the WOW as it shows that the flow produced by the WOW is very similar to the atmospheric flow and thus it is a valid and accurate way to perform full-scale testing on both building components and entire structures.

Pressure testing of modified edge shapes demonstrated that certain edge shape configurations had a significant impact on not only the suction pressure at the roof corner but also on the pressure distribution on the roof. The first test performed which was the control test with no edge shape, yielded typical results with high suctions present at the corners and edges which reduced with distance from the edge of the structure. The most negative pressure that occurred was recorded at pressure tap #3, located 12 in from the roof corner in the x-direction and 2.375 in from the roof edge in the y-direction. This tap was especially vulnerable to feeling extreme suction because it was located closer to the edge of the structure in the y-direction than any of the other taps. The resulting $C_p \text{ min}$ was -18.23 which was not only consistent with TTU data but also with wind tunnel studies conducted by Surry and Lin (1995) which yielded a $C_p \text{ min}$ of almost -18 at a corner tap for boundary layer flow equivalent to the environmental flow at TTU. All of the taps along edge of the test structure yielded $C_p \text{ min}$ values from -6 to -17.

The Econosnap standard fascia resulted in a similar pressure distribution with a minimum $C_p \text{ min}$ value of -14.42 at tap #7. The fact that the $C_p \text{ min}$ value occurred at tap #7 as opposed to tap #3 in the no edge shape case indicated that the pressure distribution was slightly altered due to the presence of edge shape. The Econosnap fascia had the effect of slightly reducing the extreme suction in the taps at the very corner but as a result,
remaining taps recorded lower negative peak pressures. The Drain-Thru Gravel Stop, which was tested directly after the Econosnap Fascia, in most cases resulted in a slight increase of $C_p\min$ effectively resulting in more negative pressure coefficients.

The FRAG1 standard edge shape yielded the best results in terms of reducing the overall suction on roof as it reduced the suction experienced by 14 out of the 16 taps. The most extreme peak suction recorded at tap #3 was reduced by 74% and the $C_p\text{mean}$ at the same tap was reduced by 71%. Overall, the $C_p\min$ was reduced anywhere from 15-74% depending on the location of the tap. The $C_p\text{mean}$ values were reduced anywhere from 25-70%, again depending on the tap location. The resulting pressure distribution was much uniform due the presence of this edge shape which can be seen in the 3D-plots (see Appendix A). The $C_p\min$ over all taps during this test was -7.35 with the presence of the FRAG1 which was significantly high compared to the minimum values present in the additional time histories with the remaining shapes. The range of peak $C_p\min$ was between -2.15 and -7.35 which demonstrated that the pressure distribution became much more uniform with the presence of this edge shape indicating that the coherency of the vortices was disrupted. It is though that the FRAG1 edge shape acted in destroying the rotational flow of the vortices altogether thus making it extremely successful in reducing uplift.

The Gable Edge Vortex Cap Suppressor extending 2.375 in above the roof of the test structure consistently reduced roof uplift by 10-45% on all taps except for #15. Though the reductions with this shape were not as considerable as in the previous shapes, the shape proved consistent in that it helped to alleviate the structure of suction pressure throughout the entire surface of the roof and not just in taps located close to the edge.
The variation of the shape extending only .5 in from the roof of the test structure performed very similar to its taller variation by reducing suction at all taps except for #15 which was located close to the center of the roof. Reductions of 7-56% were observed for the remaining taps which reflected even more significant reductions than the taller version. Changes in $C_p$ mean were far less consistent as some taps reflected an increase in $C_p$ mean while some reflected a decrease in $C_p$ mean. In either case, the changes were relatively insignificant. Though this shape did result in a slight reduction in uplift, it is not suggested that it be applied to a flat roof for the purpose of uplift mitigation; what can be concluded from these results is that a taller shape is needed to appreciably and consistently reduce uplift on a flat roof.

The final shape tested, the Gable Edge Screen Vortex Suppressor, both increased and decreased pressures depending on the location of the taps. While previous shapes also caused increases in suction at certain taps, the increases were quite small comparatively. In this case, the presence of the Gable Edge Screen Vortex Suppressor actually caused an increase in suction of 107% at tap #8 located along the edge of the roof and resulted in a minimum $C_p$ of approximately -13 which was very similar to the Econosnap Fascia case. These results are consistent with previous studies which have shown that shorter parapets have a tendency to increase suction on the roof at certain locations. The one positive aspect of this shape was that it did slightly reduce the range of pressures felt by the roof so the pressure distribution over the roof was somewhat more uniform. Figure 44 illustrates how each tap was affected by each shape.
Figure 44. Response of Individual Pressure Taps to each Edge Shape Configuration
**ASCE 7-05 Comparison**

In order to compare WOW pressure data with ASCE 7-05 design values, design wind pressures for components and cladding (C&C) were first calculated for the test structure. Calculations are shown below.

For components and cladding:

\[
q = 0.00256 \times K_z \times K_{zt} \times K_d \times I \times V^2 \quad \text{(Eq. 1)}
\]

Where \(K_z\)=exposure factor; \(K_{zt}\)=topographic factor; \(K_d\)=directionality factor; \(I\)=importance factor; \(V\)=basic design wind speed.

\[
p_s = q[(GC_p) - (GC_{pi})]
\]

Where \(GC_p\)=external pressure coefficient; \(GC_{pi}\)=internal pressure coefficient.

In this case, the test structure was considered to be a partially-opened (according to ASCE 7-05 specifications) residential structure in flat terrain making the importance factor, \(I\), and the terrain factor, \(K_{zt}\), both equal to one. The directionality factor, \(K_d\), equaled 0.85 which is the constant used with ASCE 7-05 load combinations. Finally, the basic wind speed value, \(V\), used to calculate the design pressure was assumed to be 146 mph, the 3-sec gust design wind speed for Miami-Dade County in South Florida. Using these values, “q” was calculated and plugged into the formula to obtain \(P_s\). For our
application the internal pressure, GC_{pi}, equaled to zero for the partially enclosed case and GC_p, the external pressure, varied depending on the zone for which pressure was calculated. In this particular case, GC_{pi} was considered to be zero because the internal pressure of the test structure was not considered; therefore, in order for the values in the study to be comparable to ASCE 7-05 design values, this adjustment was made. Design pressure values for the C&C can be found in Table 2.

Table 2. Design Pressures (psf) for the Component and Cladding

<table>
<thead>
<tr>
<th>Design Zone</th>
<th>Zone 1, 2 &amp; 3</th>
<th>Interior Zone 1</th>
<th>End Zone 2</th>
<th>End Zone 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>11.8</td>
<td>-39.4</td>
<td>-70.9</td>
<td>-110.2</td>
</tr>
</tbody>
</table>

In order to compare these values with data measured during WOW testing, the pressure coefficients for the case with no edge shape attached had to be converted back to psf using the 146 mph 3-sec gust as the velocity value for the conversion. Because the original pressure coefficients were based on a 6-min mean wind speed, the 146 mph 3-sec gust was converted to a 6-min mean wind speed value of 107.96 mph. C_{p \text{ min}} values recorded for each tap in the no-edge-shape case were converted back to psf and the results of this conversion can be seen in Table 3.
### Table 3. Equivalent pressure Values from WOW No Edge Shape Pressure Testing

<table>
<thead>
<tr>
<th>Tap Number</th>
<th>$C_{p \text{min}}$</th>
<th>Design Pressure (psf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>-7.002</td>
<td>-201.904</td>
</tr>
<tr>
<td>P2</td>
<td>-5.696</td>
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<td>P3</td>
<td>-18.231</td>
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<tr>
<td>P4</td>
<td>-12.553</td>
<td>-361.964</td>
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<td>P13</td>
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<tr>
<td>P14</td>
<td>-3.905</td>
<td>-112.590</td>
</tr>
<tr>
<td>P15</td>
<td>-2.617</td>
<td>-75.471</td>
</tr>
<tr>
<td>P16</td>
<td>-1.784</td>
<td>-51.452</td>
</tr>
</tbody>
</table>

For taps 1-11 located in End Zone 3, the pressures recorded during WOW testing in most cases far exceeded the design values specified by ASCE 7-05. Only 1 tap out of the 11 located in this region experienced pressures in the range of the design values. The largest difference in design values occurred at tap #3 which recorded a minimum pressure value of -525.6805 psf, almost five times the -110.2 psf value suggested in the code. Taps 12-15 also saw much lower negative pressures than the End Zone 2 design pressures suggested. Tap 16, the only tap located in interior Zone 1, recorded a minimum pressure of -51.452 psf which was still more negative than the -39.4 psf design value indicating that even regions classified as interior zones are potentially under-designed. These results are consistent with recent full-scale vs. wind tunnel studies which have suggested that pressures recorded in the full-scale are usually at least double those recorded in the wind tunnel under similar conditions. This comparison suggests that the ASCE 7-05 values should be reviewed as they may not be conservative enough, specifically in...
designing homes in the High-Velocity Hurricane Wind Zone. With the help of full-scale testing, more conservative pressure design values could be implemented in future versions of ASCE 7. Also, because of the success of the aerodynamic edge shapes in reducing roof suction, these retrofits could easily be considered as acceptable modifications for applying less negative design pressures for Edge Zone 3 design and construction.
6. **Conclusions and Future Work**

Gravel scour testing and pressure testing were conducted and determined that the presence of modified edge shapes alter the physical structure of conical vortices as well as reduce the extreme suctions associated with cornering winds. The largest reduction was seen with the FRAG1 aerodynamic edge shape which resulted in a 74% reduction in peak pressures at the roof corner and a 71% reduction in mean pressure values. Because these products were so successful in testing, it is the hope of the author that they will become available for public use as a valuable and cost-effective method for reducing roof damage caused by hurricane-force winds.

Expansions could be made on the current experiments for future testing in this field. The first thing that should be considered is adding a turbulence simulation system within the WOW that better reproduces conditions in the Atmospheric Boundary Layer (ABL). This could be achieved by using a system of rudders located directly in front of the propellers that are controlled and can be moved within a certain range to create turbulence. A computational fluid dynamics (CFD) analysis would have to be performed to determine the size of the rudders and the range of motion necessary to create such turbulence conditions. The addition of this type of system would lend even more credibility to research involving WOW testing.

The current set-up of engine frames consists of two rows of three fans each sitting flush against one another. Though it has been determined that the system produces the expected maximum wind speed values, it is possible that by fanning the engines and adding a honeycomb design made of PVC tubing, wind speeds would increase. This is because fanning the system would open up space between the fans and increase the air
draw of the system. The PVC honeycomb would act almost as a wind tunnel by propelling air flow into the system through a system of pipes. Both the increase in airflow and the speed at which air enters the system are thought to influence the maximum wind speeds produced by the WOW. Adding a contraction to the WOW is also being considered as a means of increasing maximum wind speeds.

Beyond alternating the configuration of the WOW, another possible expansion to the system would be the addition of fans to allow the WOW to be used for testing of two-story structures. This would require the addition of three fans to the top of the system and three stacked vertically to the side. This would increase the effective area of the WOW so that larger structures could be accommodated.

Another modification to the current system that could potentially make it more efficient would be changing the current engines to hydraulic systems. A hydraulic system would use less fuel and potentially create higher wind speeds. While decreasing the amount of fuel used would certainly cut costs, the power required to run such a large hydraulic system could exceed the cost of gas previously used though it would certainly be more convenient.

Currently, a pre-fabricated steel structure is under construction and will be the new facility housing the RenaissanceRe 6-fan WOW. Enclosing the WOW will offer several advantages over the current field set-up. First, because all testing with the WOW up to this point had taken place outside, atmospheric winds are often a concern. This phenomenon has not been considered for this study because during testing winds were generally light and variable and not thought to have had a significant impact on the measurements. With the indoor facility, testing can be performed with a certain level of
increased confidence that wind speed measurements are not being compromised by atmospheric cross-winds or increased by wind flowing in the same direction of the WOW. The indoor facility will also offer a certain level of protection against natural weather patterns, such as rain, that often interfere with testing as well as damage electrical equipment.

Current testing has verified the validity of the WOW as an acceptable means of full-scale testing and future developments will secure its place as a world class full-scale testing facility.
REFERENCES


Appendix A. Three-Dimensional Plots of Pressure Coefficients for Each Edge Shape

Figure 45. Cp Distribution for No Edge Shape Case
Figure 46. Cp Distribution for Econosnap Fascia Case
Figure 47. Cp Distribution for Drain-Thru Gravel Stop Case
Figure 48. Cp Distribution for FRAG1 Edge Shape Case
Figure 49. Cp Distribution for Gable Edge Screen Vortex Suppressor Case
Figure 50. Cp Distribution for Gable Roof Edge Cap Vortex Suppressor .5 in Case
Figure 51. Cp Distribution for Gable Roof Cap Vortex Suppressor 2.375 in Case
### Appendix B. Comparison of Edge Shape Results

Table 4. (a) Comparison of Edge Shape Results

<table>
<thead>
<tr>
<th>Pressure Taps</th>
<th>No Edge Shape</th>
<th>Econosnap Fascia</th>
<th>Drain-Thru Gravel Stop</th>
<th>FRAG1</th>
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Table 4. (b) Comparison of Edge Shape Results (continued)

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<th>Pressure Taps</th>
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<th>Gable Edge Vortex Cap (2.375&quot;)</th>
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Figure 5.2: Comparison of $C_p_{min}$ for all Edge Shapes
Figure 53. Comparison of $C_p$ mean for all Edge Shapes
Figure 54. Comparison of $C_p^{\text{rms}}$ for all Edge Shapes