



A Resource for the State of Florida

**HURRICANE LOSS REDUCTION
FOR
HOUSING IN FLORIDA:**

Section 6

Comparing Full-Scale and Wind Tunnel Results

A Research Project Funded by
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SUMMARY

This report summarizes results of Clemson University's continuing field research on wind effects on buildings during the land falling hurricanes of 2005. The project goal is to analyze field data of wind pressures and wind tunnel studies on model houses and compare pressure coefficients. The report presents results of full-scale pressure measurements made during tropical cyclones in the 2005 Hurricane season, experimental wind tunnel test results from scale model buildings and a pressure visualization prototype end-user software. Partial results are details are presented through the World-Wide Web.

The report was prepared by David O. Prevatt, Ph.D., Assistant Professor and Director of the Wind Load Test Facility at Clemson University. The author wishes to acknowledge the contributions of Clemson University graduate and undergraduate students who participated in this research and assisted with the final preparation of the report. In particular, recognition is paid to two graduate students, Mr. Russell R. Carter who led field investigation exercises and to Mr. Peter L. Datin who carried out full-scale and wind tunnel analyses of pressure data. The author is grateful for the contributions and consultation with Dr. Stanley T. Birchfield, Assistant Professor of Electrical and Computer Engineering at Clemson University and his students for leading the research effort to develop the pressure visualization software.

KEYWORDS: Aerodynamics, boundary layer, buildings, wind engineering, full-scale, wind tunnels, suburban terrain, residential.

1. PROJECT SCOPE

The primary goal of this project is analysis of field data of wind pressures and wind tunnel studies on models of houses located in a typical Florida neighborhood. The pressure measurements were recorded during the passage of four hurricanes during the 2004 Hurricane season. The report presents results on the following sub-tasks described below:

Subtask 1 – Data Analysis of Field Data on neighborhood houses

Five instrumented prototype homes were hit by tropical cyclone-strength winds during 2005, yielding pressure and wind speed data for further analysis. The field data included near-ground level hurricane-strength wind speeds and directions, and pressure measurements from sensors located in critical corner roof areas of houses situated in residential neighborhoods. We performed the following scope:

1. Conduct field investigations at the houses to record location of surrounding buildings, and large obstructions relative to the prototype house.
2. Analyze pressure sensor data and available wind speed data to derive pressure coefficient time-histories for the houses affected by the hurricanes.

Subtask 2 – Wind Tunnel Model Studies

ASCE 7 wind design pressure coefficients are based on research conducted in boundary layer wind tunnels. There is limited full-scale data available to validate wind load results. Wind tunnel studies on models of the prototype houses need to be compared to full-scale results with wind tunnel studies.

Conduct wind tunnel studies to develop a pressure coefficient database to serve as a baseline for future studies that include the wind load variation in open and suburban terrain.

1. Construct 1:50 scale geometrically-similar models of the prototype houses, measure pressures at equivalent locations to full-scale, and determine the pressure coefficients at pressure taps for the incident wind direction of the storm.
2. Compare wind tunnel test results for incident wind with prototype pressure data derived from the houses in the storm direction.

Subtask 3 – Wind Pressure Visualization

To aid in the review and analysis of this data, wind tunnel studies require analysis of very large volumes of data, since a high sampling rate is needed (greater than 400 samples per second) and models need a dense tap array of several hundred pressure taps. Developing prototype end-user visualization software would be vital to achieve this goal. The proposed software should be capable of 3D-display of pressure distributions, and provide flexibility to allow the user view model at any rotation, translation, or scale.

1. Develop a file format to relate the wind pressure statistical data with the 3D building geometry structure and coordinates of the pressure sensors.
2. Write software to parse the statistical data, and to display results in 3D.

2. BACKGROUND

Hurricanes remain one of the most costly natural hazards within the United States. The average annual loss due to windstorm damage in the East and Gulf Coast states is about \$5 billion. Recent hurricane damage in 2005 from Hurricanes Katrina, Rita and Wilma highlight the vulnerability of residential buildings in coastal areas. Damage from high winds disproportionately affects low-rise residential buildings located along vulnerable coastal areas of the Carolinas, Florida and Gulf States. The provision of reliable scientific information that relates damaging wind speeds with failure loads of building components is needed to evaluate the effectiveness of retrofit and existing structural design of houses and to validate current methodologies for boundary layer wind tunnel tests.

The analysis of time-histories of wind speeds and wind-induced pressures on buildings are critical for post-storm engineering analyses of building damage. However, existing anemometers at regional airports typically do not provide the high-quality data on wind characteristics and in many cases, these anemometers typically are switched off or prior to the storm or lose power during the event. In addition, typically the flat, airport terrain

around the anemometers are not representative of the rougher suburban environments in which most homes are located.

To address this shortfall, the Florida Coastal Monitoring Program, started in 1998, has conducted field measurements of hurricane wind velocities and wind-induced pressures on residential buildings. This related study carries out model scale experiments in Clemson's boundary layer wind tunnel and provides a comparison between full-scale and model scale wind pressures.

Until recently there has been very limited data available on the full-scale pressure distribution for low-rise buildings exposed to hurricane-force winds. The majority of previous full-scale and wind tunnel studies (Levitan and Mehta 1992) focused primarily on commercial construction that built in less complex terrain and with simpler building shapes than the typical residential neighborhood. In addition, the few wind tunnel studies on houses used relatively simple house shapes (Holmes 1982) that did not incorporate intersecting roofs and architectural features commonly seen in residential neighborhoods today.

Even fewer full-scale wind tunnel results are available for houses located in suburban exposures. As a result, building codes currently provide neither wind pressure coefficients nor sufficient guidance for estimating wind loads for typical residential construction with complex shapes and architectural features. Residential structures typically have suffered more damage than commercial structures, owing to the prescriptive nature of building codes for non-engineered structures and limited wind design guides. There is an urgent need to understand the wind load generated on low-

rise buildings and to improve building code provisions to address the design requirements for these unique geometries.

2.1 Sources of Full-Scale Data – The FCMP Project

In 1998, university research collaboration by Clemson University and Florida International University initiated a program called the Florida Coastal Monitoring Program (FCMP) to conduct research aimed for a better understanding of wind loads that typical houses in suburban areas experience during hurricanes. The FCMP is a research collaboration between Clemson University, University of Florida, Florida International University, and the Institute for Business and Home Safety, which has mobilized research teams before a hurricane makes landfall to place instrumentation on houses in the path of the storm. This instrumentation was developed at Clemson University and consists of two main components, 10-m (33-ft) tall wind towers, pressure-sensors, and data acquisition and communication equipment to measure wind-induced pressures on the roofs of buildings (Masters et al 2003). The FCMP program has successfully deployed the wind towers and instrumentation in several storms since 1998 (Table 1).

Table 1. List of Storms with Wind Towers Deployments

Year	Storm
1998	Georges
1999	Dennis
	Floyd
	Irene
2000	Gordon
2001	Gabrielle
	Michelle
2002	Isidore
	Lili
2003	Isabel
2004	Charley
	Frances
	Ivan
	Jeanne
2005	Dennis
	Katrina

	Rita
	Wilma

The following sections briefly explain the main FCMP instrumentation components:

- **Wind Anemometer Towers** – Portable towers designed to resist 200 mph winds support instruments to measure wind speed at 5 m and 10 m heights, temperature and barometric pressure changes during a hurricane (see Figure 1). Summary wind speed data is collected from each tower and stored on a computer before being transmitted in near real-time to the World Wide Web, <http://users.ce.ufl.edu/~fcmp/>. Currently six self-powered wind towers are available for deployment.



Figure 1. Tower Deployed for Data Collection.

- **Pressure Sensors on Residential Buildings** – Pre-selected and pre-wired residential structures located in suburban neighborhoods are fitted with pressure sensors prior to a hurricane landfall. Battery operated computers collect the time histories of wind induced pressures from up to 28 absolute pressure transducers installed on the roofs of the buildings. An additional pressure transducer, located either in the attic or in the yard, away from the structure, identified as the reference pressure transducer, is used to monitor changes in atmospheric pressure. This reference pressure gage is necessary to convert pressures measured at roof sensors to the non-dimensional pressure coefficients.

2.2 The 2005 Hurricane Season Deployments

2005 was the most active hurricane season on record, with 28 named storms, with four of those making landfall in the United States. Hurricane Dennis (Figure 2) was the first storm to make landfall, affecting both the Louisiana and Florida coasts. The season was most memorable for Hurricane Katrina (Figure 3), which became the most costly hurricane disaster to hit the US, resulting in over 1800 deaths and over \$100 billion in damage. Hurricane Rita (Figure 4) caused several hours of traffic gridlock as residents of Galveston County, Texas, attempted to evacuate the coast. Hurricane Wilma (Figure 5) made landfall in Florida's Gulf Coast and caused damage that included the failures of glass curtain-wall structures in Miami, FL.

The FCMP program deployed wind towers in all four events and collected 817 hours of wind speed and directional data (Table 2). Additionally, the five instrumented houses in the FCMP that were hit by hurricane-force winds yielded approximately 204 hours of wind-pressure data (Table 3). Three houses were subjected to hurricane force winds

during Hurricane Dennis (peak 3-second gusts of 54 m/s (121 mph)), two in Destin, FL, and one in Navarre, FL (Figure 2). Hurricane Wilma (peak 3-second gusts of 49 m/s (109 mph)) struck the other two houses, one located in Naples, FL, and the other in Marco Island, FL (Figure 5).

Table 2. 2005 FCMP Wind Tower Deployments.

Tower Data			
Storm	Tower	Number of Files	Hours of Data
Dennis	T0	22	5.5
	T2	138	34.5
	T3	101	25.25
Katrina	T0	92	23
	T1	104	26
	T2	56	14
	T3	77	19.25
Rita	T5	29	7.25
	T0	102	25.5
	T1	53	13.25
	T3	74	18.5
Wilma	T5	105	26.25
	T0	75	18.75
	T1	57	14.25
	T2	62	15.5
	T3	16	4

Table 3. Data Summary from Instrumented Houses Collected in 2005.

House Data							
Storm	House No.	Number of Files	Hours of Data	Wind Speed	Wind Direction	Reference Pressure	# of Pressure Taps
Dennis	FL-23	173	43.25	No	Yes	Yes	23
	FL-24	130	32.5	Yes	Yes	No	26
	FL-26	149	37.25	Yes	Yes	Yes	20
Wilma	FL-18	189	47.25	Yes	Yes	Yes	26
	FL-19	176	44	Yes	Yes	Yes	25
Totals		817	204.25				

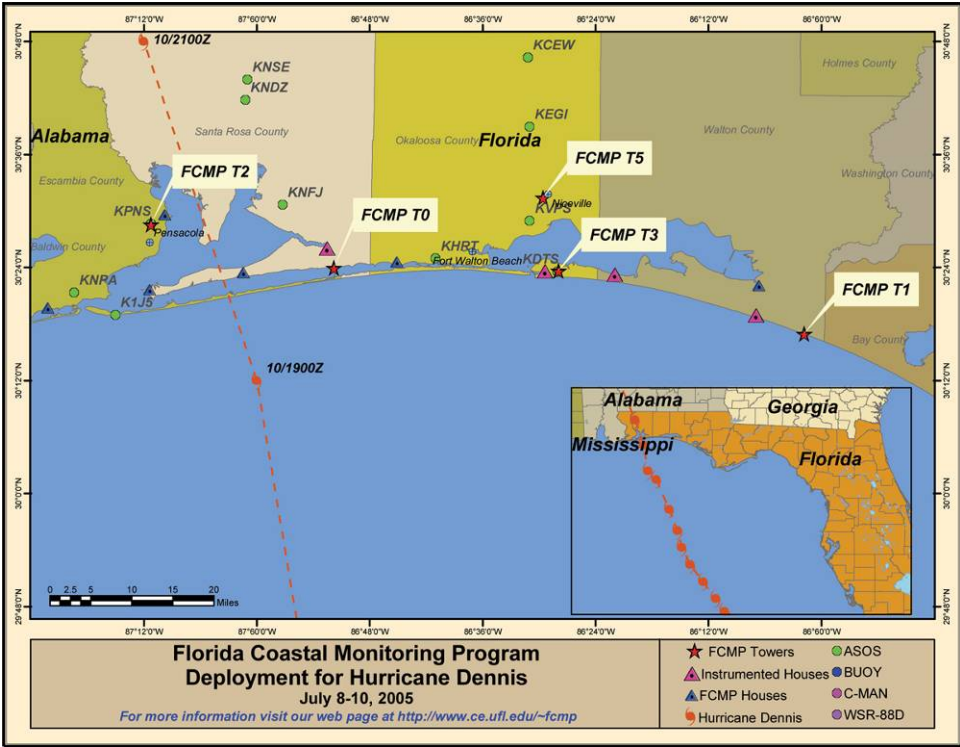


Figure 2. Track of Hurricane Dennis and FCMP Towers and House Locations.

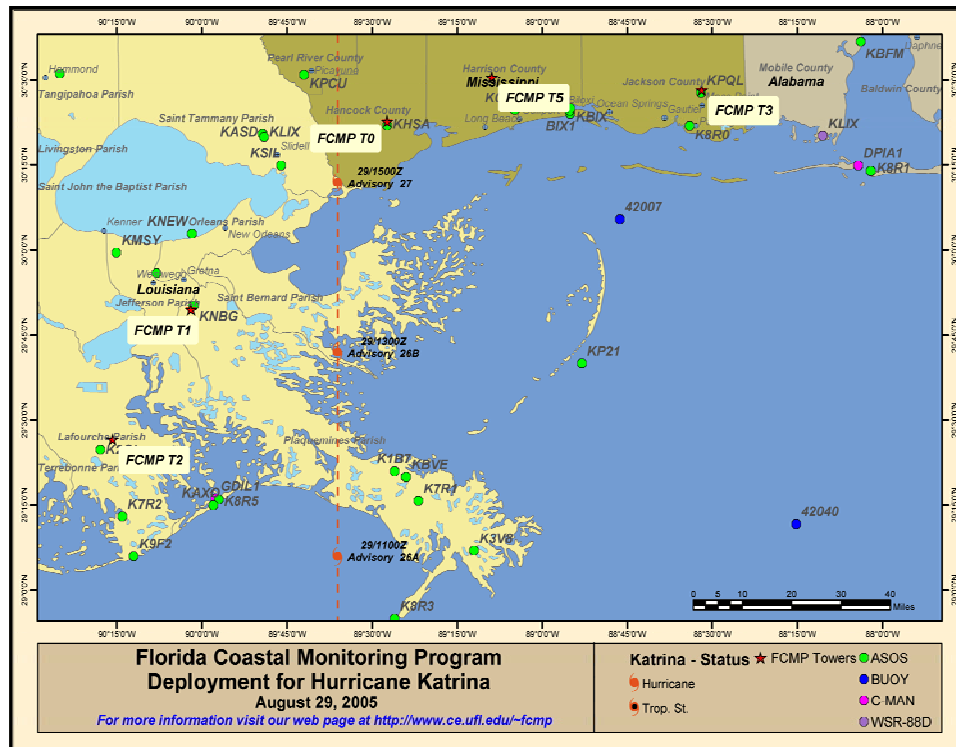


Figure 3. Track of Hurricane Katrina and FCMP Towers and House Locations.

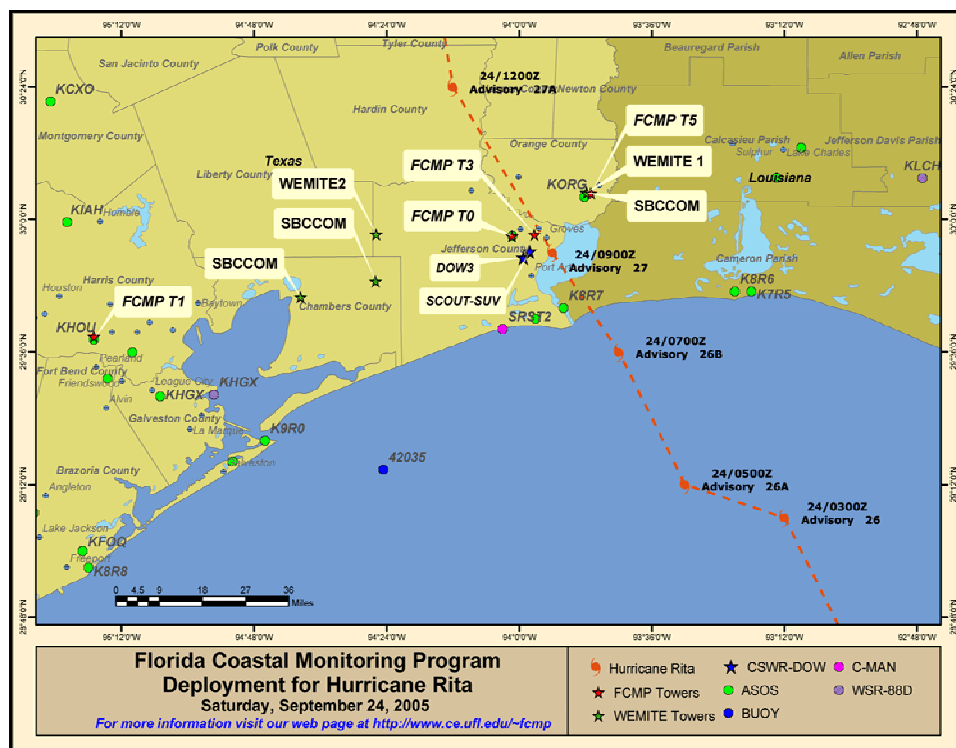


Figure 4. Track of Hurricane Rita and FCMP Towers and House Locations.

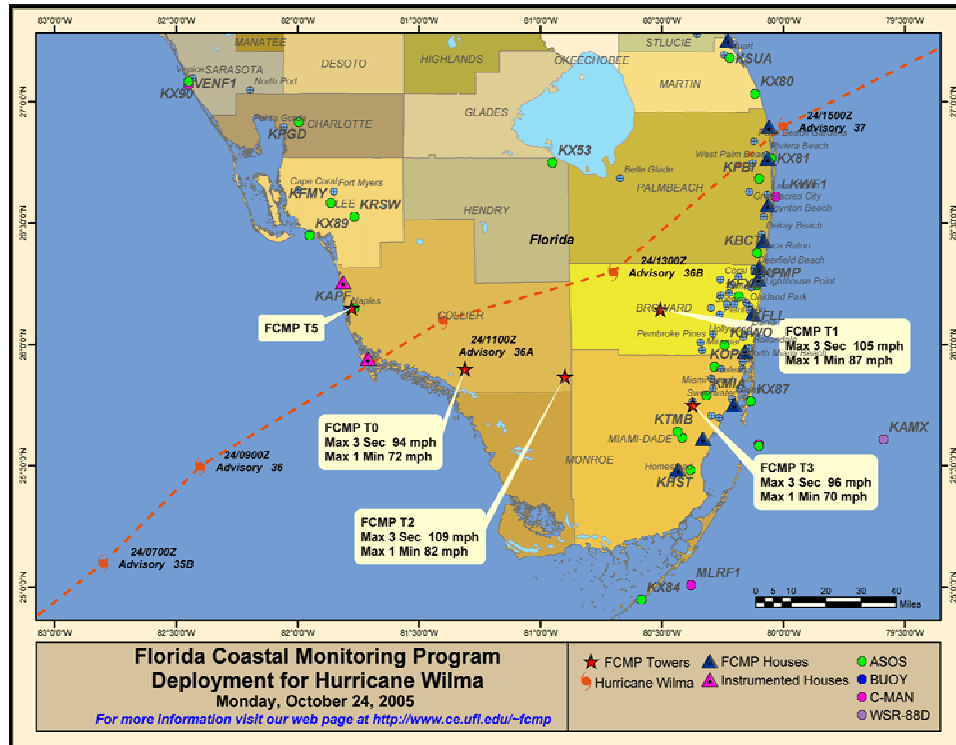


Figure 5. Track of Hurricane Wilma and FCMP Towers and House Locations.

3. FULL-SCALE DATA COLLECTION AND ANALYSIS

3.1 Field Surveys of Prototype Houses

In January and February 2006, a team of Clemson University civil engineering students, led by Russell Carter and including Peter Datin, Stephen Furr and Kenneth Hill, conducted field surveys of the five houses that were hit by strong winds in the 2005 hurricane season (see Table 4). The team documented the dimensions of the prototype houses and of its immediate neighboring buildings and verified locations of the pressure sensors on the roofs of these buildings. The team used digital photographs of the terrain and surroundings in eight cardinal directions around the house (shown in Figure 6).



North



Northeast



East



Southeast



South



Southwest



West



Northwest

Figure 6. Cardinal Directions for FL-18.

Table 4. FCMP House Identifications and Locations.

House Identification Number	City, State	Hurricane	Latitude	Longitude	Date of Field Survey
FL-18	Marco Island, FL	Wilma	25° 56' 30.4"	81° 42' 53.1"	1/21/06
FL-19	Naples, FL	Wilma	26° 15' 23.4"	81° 49' 1.0"	1/21/06
FL-23	Destin, FL	Dennis	30° 23' 15.2"	86° 22' 4.7"	2/3/06
FL-24	Destin, FL	Dennis	30° 23' 35.9"	86° 29' 29.2"	2/3/06
FL-26	Navarre, FL	Dennis	30° 26' 2.4"	86° 52' 39.4"	2/4/06

Field documentation of neighborhoods is needed in order to create scale models of the prototype building's immediate surroundings in the wind tunnel. Accurate measurements of pressure tap locations are also needed to ensure agreement between the prototype and scale-model structures. Brief descriptions of the prototype houses follows below:

3.1.1 Prototype House FL-18

The FL-18 House is a single-story, L-shaped house on Marco Island, Florida (Figure 7). The roof shape consists of inter-connected Dutch-hips and a gable end roof over the garage. The house has extensive lawns with low hedges along the property boundaries (Figure 8). There are a few ornamental trees that are approximately 30 ft or less in height. The surrounding houses are approximately similar in size to the prototype house.

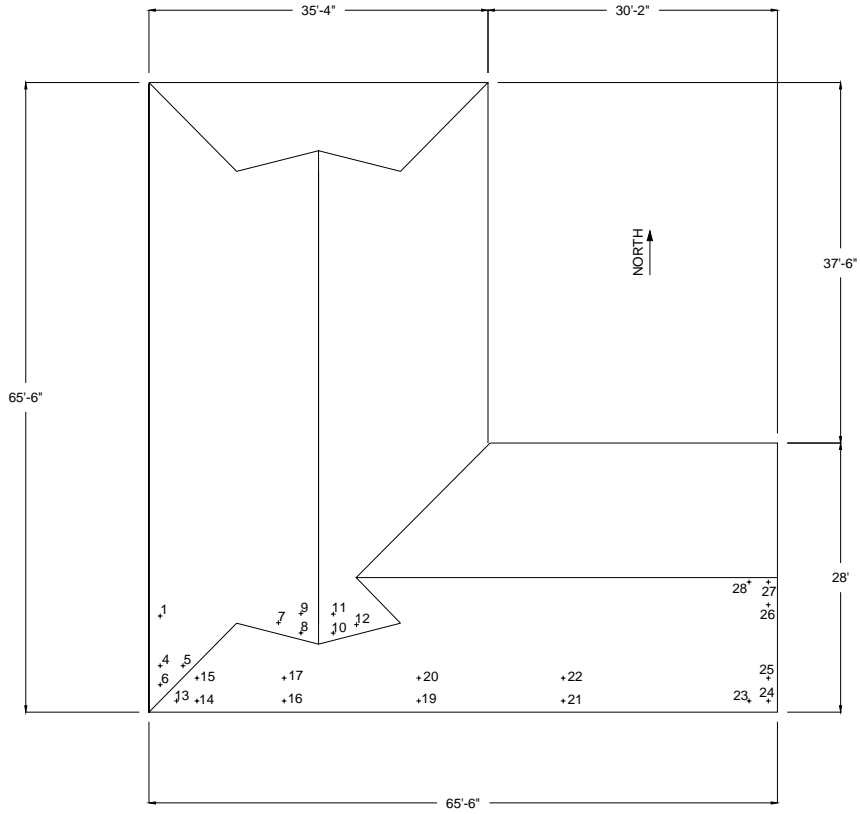


Figure 7. Roof Plan of Prototype FL-18 Showing Tap Locations.



Figure 8. Front View of Prototype FL-18.

3.1.2 Prototype House FL-19

The FL-19 House is a single-story rectangular house measuring approximately 49 ft by 39 ft in plan and approximately 15 ft 7 in tall at the roof ridge (Figure 9). The roof structure is a Dutch-hip shape with low-sloped roofs over the porch at the rear of the home (Figure 10 and 11).

Some of the neighboring lots are densely covered with vegetation and trees, while other lots are sparsely covered. Maximum tree height ranges between 30 and 40 ft.

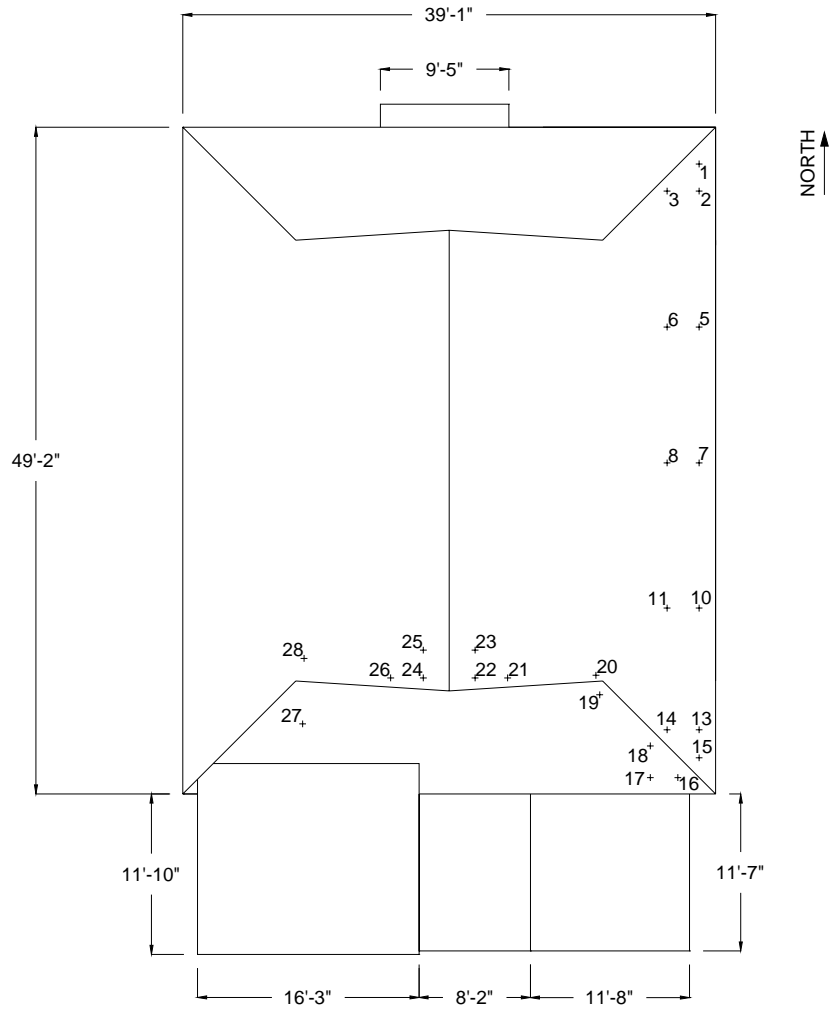


Figure 9. Roof Plan of Prototype FL-19 Showing Tap Locations.



Figure 10. Front View of Prototype FL-19.



Figure 11. View of Prototype FL-19 Attached Porch at Rear of House.

3.1.3 Prototype House FL-23

The FL-23 House is a single-story house located in Destin, FL, situated in a suburban neighborhood with wide lawns and ornamental plants. The building measures approximately 56 ft by 50 ft in plan and 16 ft 7 in. to the ridge (Figure 12). The roof structure consists of inter-connected gable roof areas (Figure 13). The tree heights in the area range from approximately 16 to 24 ft. The neighboring houses are of similar geometry and height.

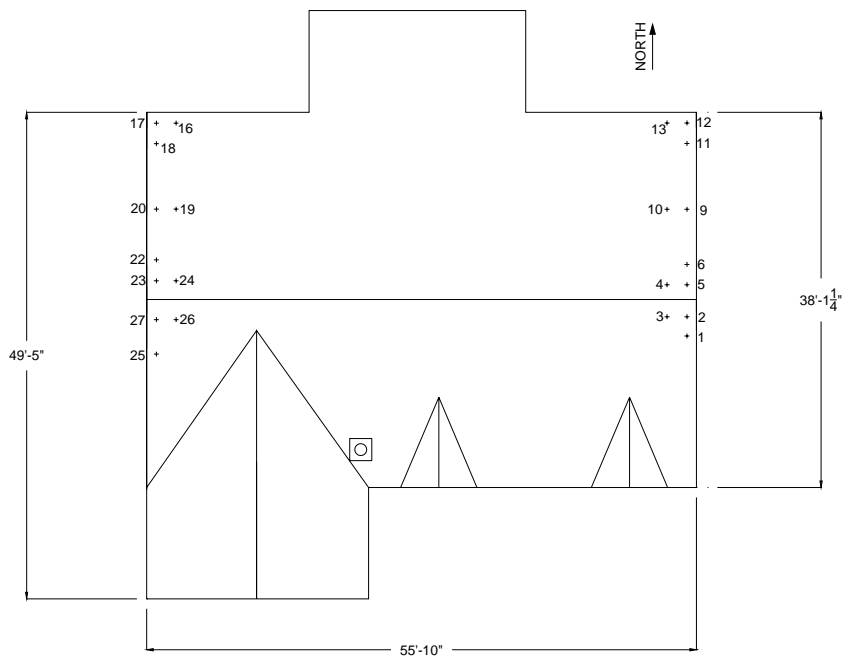


Figure 12. Roof Plan of Prototype FL-23 Showing Tap Locations.



Figure 13. Front View of Prototype FL-23.

3.1.4 Prototype House FL-24

The FL-24 House is a single-story house located on flat site in Destin, Florida. The building measures approximately 72 ft by 45 ft in plan and is 13 ft 3 in tall at the roof ridge (Figure 14). The roof structure consists of relatively low-sloped inter-connected gable roof areas, and the center section is approximately 6 in. taller than either side (Figure 15).

There is a mix of ornamental, deciduous, and pine trees within the neighborhood, ranging in height from 1 to 1.5 times the ridge height of FL-24. The neighboring structures vary in geometry but are of similar height. 6 ft tall wood fences surround most of the backyards in the neighborhood.

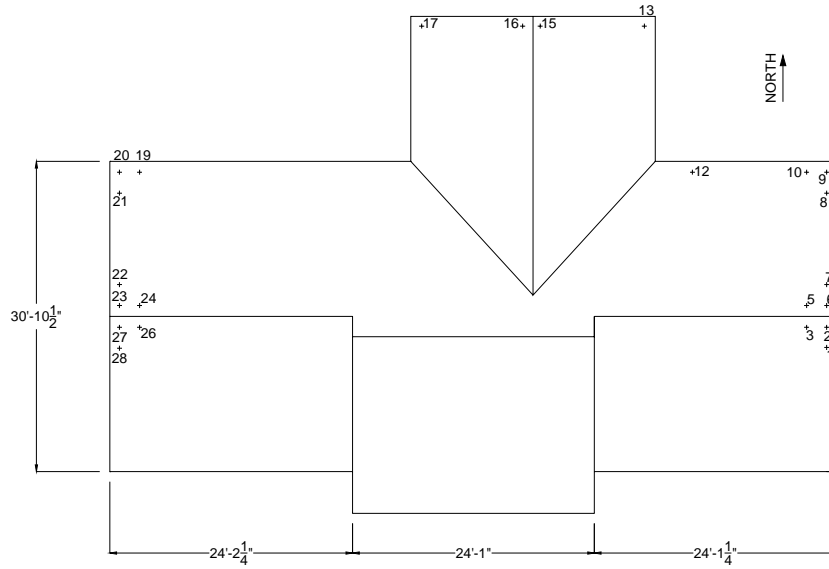


Figure 14. Roof Plan of Prototype FL-24 Showing Tap Locations.



Figure 15. Partial Front View of Prototype FL-24.

3.1.5 Prototype House FL-26

The FL-26 House is a single-story ranch house located on flat site in Navarre, Florida. The building measures approximately 56 ft by 54 ft in plan and is about 16 ft tall at the roof ridge (Figure 16). The roof structure consists of a gable-roofed section that intersects with a hip roof section over the principal living area of the structure (Figure 17).

There are a few trees surrounding the building in its immediate vicinity and along the east side a pine forest dominates the terrain. A 6 ft high privacy fence divided the adjoining properties. The investigators found that the roof of this building was replaced since Hurricane Dennis, since the pressure sensor brackets are no longer in place.

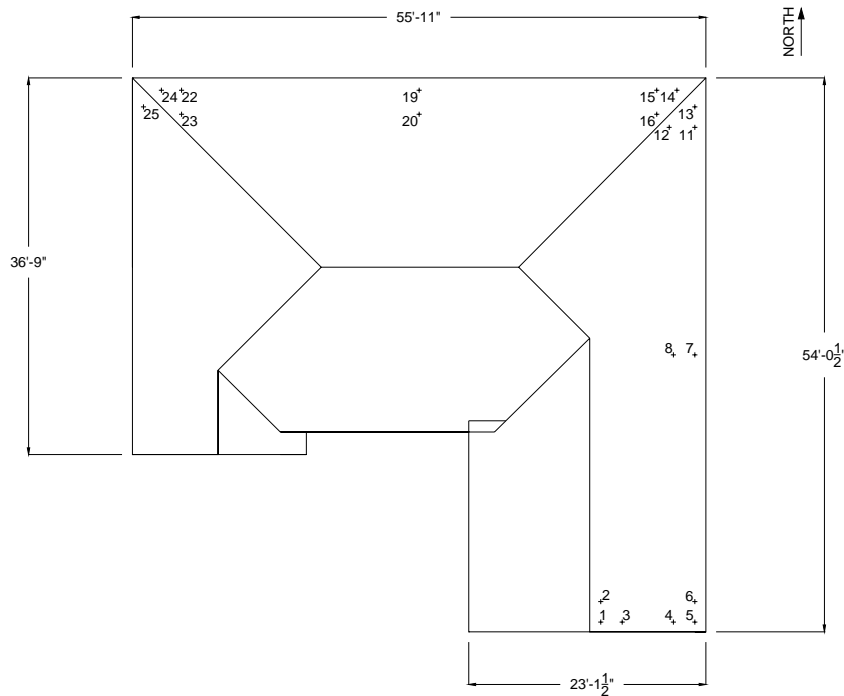


Figure 16. Roof Plan of Prototype FL-26 Showing Tap Locations.



Figure 17. Front View of Prototype FL-26.

3.2 Full-Scale Analysis of Pressure coefficients

3.2.1 Data Collection

Prior to the landfalls of the storms, we installed approximately 25 to 28 absolute pressure sensors (Michot 1999) on the roofs of the prototype houses locating sensors at corners, near eaves and ridges. We installed a wind anemometer (3-cup and vane) to monitor the wind velocity and direction at the edge of the roof at ridge height of the roof. Note that each house had been pre-wired and had unobtrusive metal cleats installed on the roofs in order to facilitate rapid installation of sensors and data collection equipment. We setup sturdy house boxes containing a data acquisition computer and battery power to collect and store pressures and wind speed data during the passage of the hurricane. The computer interface is written in C++ programming language and data is collected at 100 samples per second and stored in 15 min long files for the duration of the storm. A

typical data record for one house would contain 150 to 200 files covering 30 to 40 hours. The wind speed data from the 3-cup anemometer is reported directly in mph and is a 3-second gust wind speed.



Figure 20. Aerial View of Tower T0 Location During Hurricane Katrina.

3.3 Near Real-time Updates

Once a portable tower is located and starts collecting data it uplinks to the FCMP database via cell phone every 15 minutes. The summary tower data collected and processed by the laptop Tower XP data acquisition system is uploaded. The data summary includes the wind speeds for different averaging times, longitudinal and lateral

turbulence intensity, temperature, relative humidity, and barometric pressure. The two most predominantly used numbers are the 3 sec gust speed and the 60 sec mean wind speed from the 10 m anemometers.

3.4 Validated Wind Speed Summary

After each hurricane, the data record updates include validated plots of the wind speed recorded by each tower (Figure 21 to 24). The data joins results from individual 15 minute data files into a single graph showing wind speed and direction for the entire time the tower was operational before during and after the peak winds of the hurricane. The data plot is set to the coordinated universal time (UTC) and plotted for various averaging times.

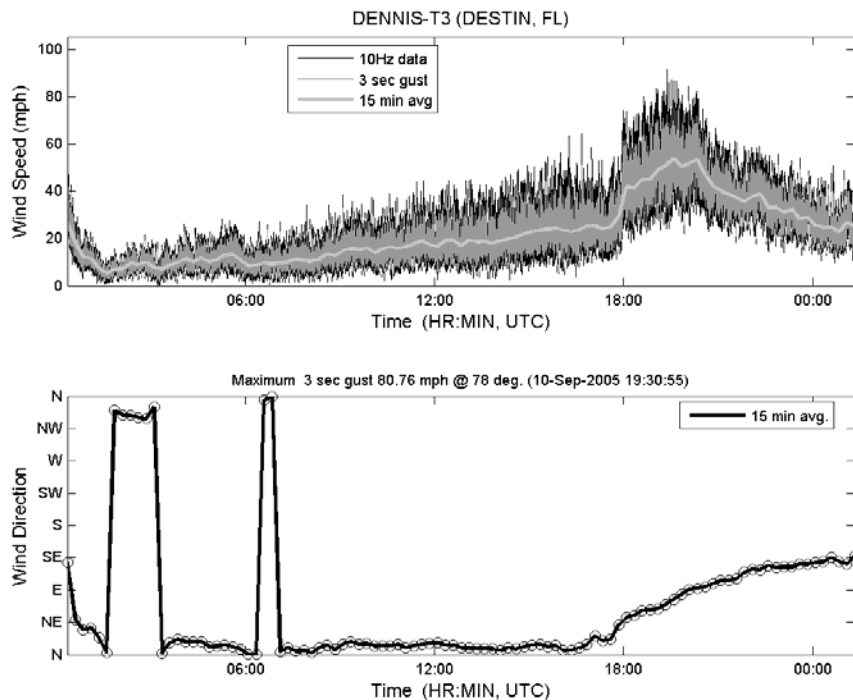


Figure 21. Plot of Wind Speed and Direction Collected by T3 - Hurricane Dennis.

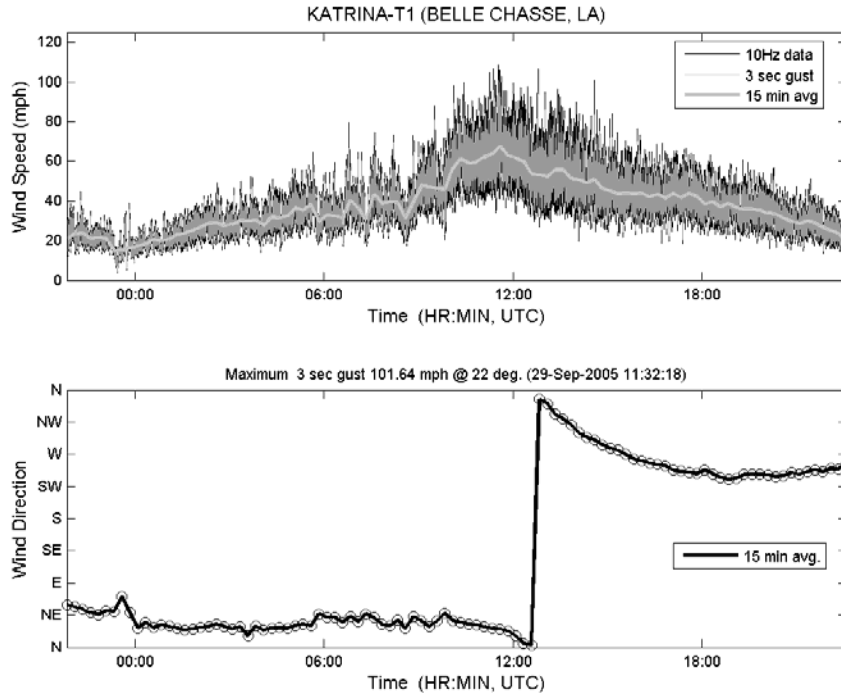


Figure 22. Plot of Wind Speed and Direction Collected by T1 - Hurricane Katrina.

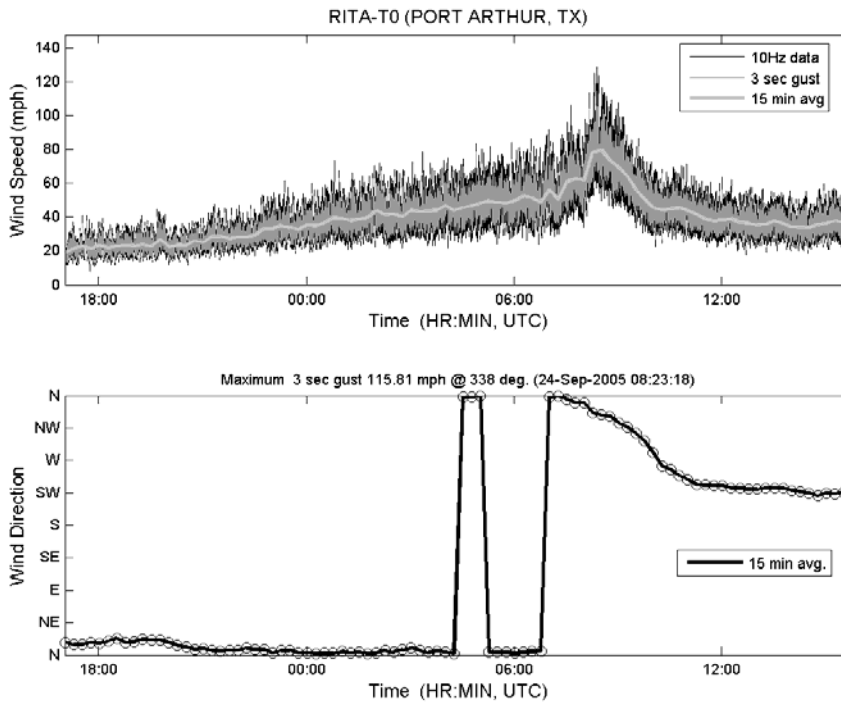


Figure 23. Plot of Wind Speed and Direction Collected by T0 - Hurricane Rita.

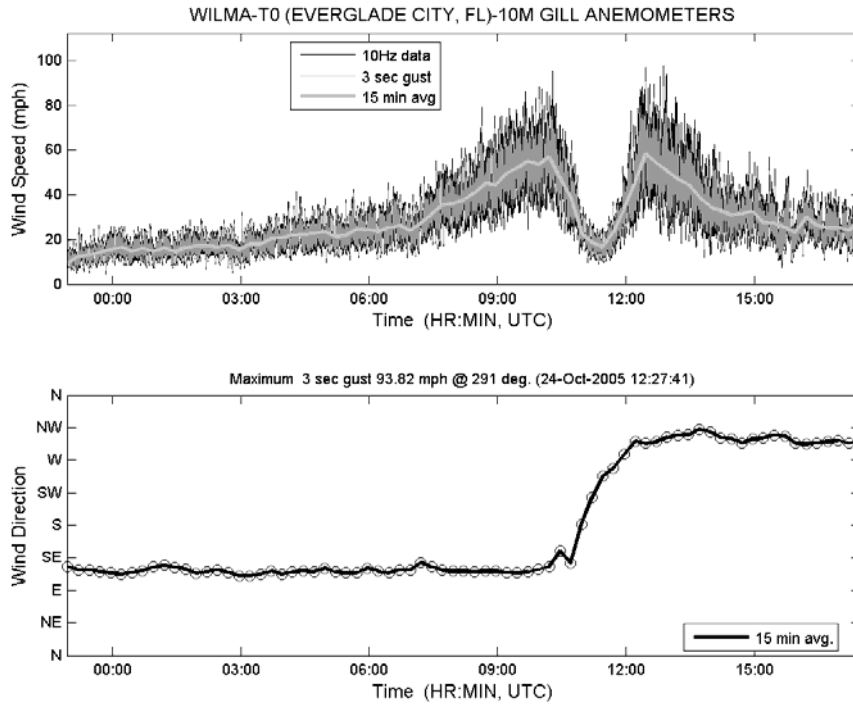


Figure 24. Plot of Wind Speed and Direction Collected by T0 - Hurricane Wilma.

3.5 Data Analysis

For every pressure sensor output reading, we used a pressure calibration chart to convert raw voltage to engineering units (i.e. pound per square foot (psf)). We used the pressure values obtained at a reference sensor located a short distance away from the house to establish changes in ambient barometric pressure. We subtracted this barometric pressure reading from each roof top sensor value and made temperature corrections to obtain the wind-induced pressures on the roof, as developed in (Dearhart 2003).

3.6 Wind Speed Data and Pressure Coefficients

Applied Research Associates (ARA), Raleigh, NC provided the simulated wind speed and directional information used in this analysis. We selected this data because it is based on a wide collection of independent data sources and has its methodology has shown to provide reasonable results. A comparison of the ARA’s simulated wind speed and the measured wind speed for each of the houses is provided in Table 5. The ARA model simulated wind speeds in open terrain at 10 m height and we adjusted these values, using theoretical conversion (Simiu, 1996), to reflect the 3 sec gust speed to suburban terrain and ridge height of the house roof. In our analysis, we used the wind speed estimates developed by Applied Research Associates (ARA 2006) provided in Figures 25 through 29.

Table 5. Comparison of ARA Model Wind Speeds to Full-scale Wind Speeds.

House	ARA Model Data			Full Scale Data		
	Peak 3 Sec. Gust Wind Speed (mph) ¹	Corrected Peak 3 Sec. Gust Wind Speed (mph) ²	Wind Direction (degrees)	Peak 3 Sec. Gust Speed (mph) ³	Peak 15 Min. Wind Speed (mph) ³	Wind Direction (degrees)
FL-18	110	70	319	N/A	N/A	N/A
FL-19	104	64	355	N/A	N/A	N/A
FL-23	77	48	133	N/A	N/A	N/A
FL-24	85	51	109	58	45	N/A
FL-26	117	72	141	44	36	N/A
1. Simulated in open terrain at 10 meter height. 2. Corrected for suburban terrain at mean roof height. 3. Peak wind speeds were measured at roof height and in suburban terrain.						

We adjusted the roof pressure measurements for atmospheric pressure and temperature changes during the storm. We used temperature measurements from the

meteorological towers located near to the prototype houses for temperature corrections. Using the roof pressure and wind speed we calculated the external pressure coefficients at the sensor locations on the roof using the formula given below:

$$C_p = \frac{P}{0.00256 V^2} \quad \text{Eqn. 1}$$

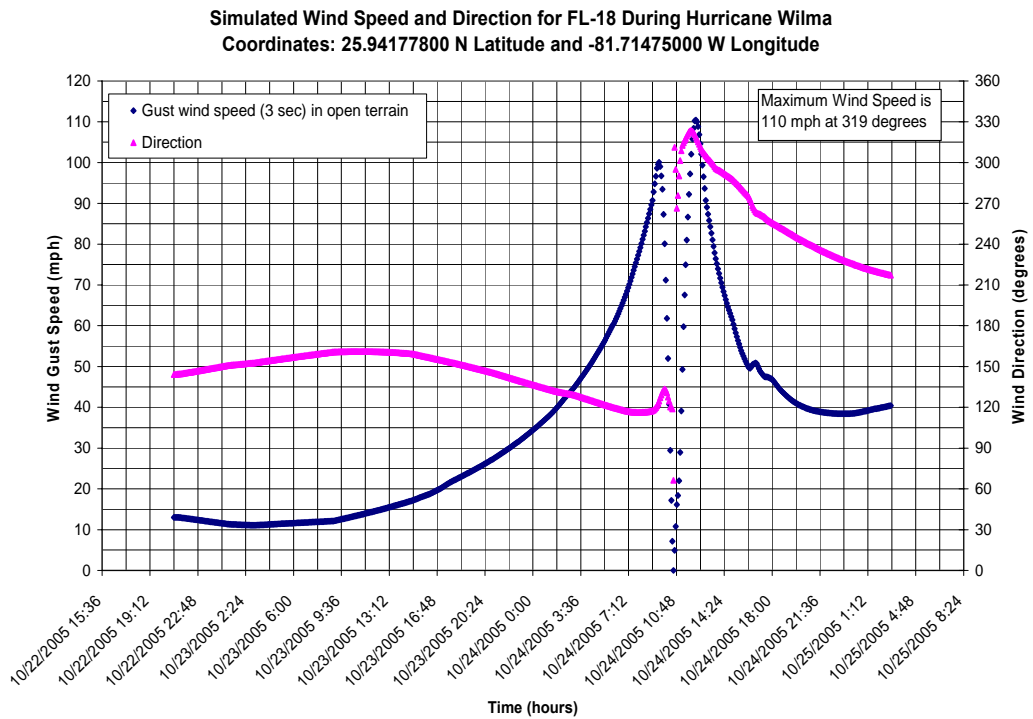


Figure 25. ARA’s modeled wind speed and direction at the FL-18 site.

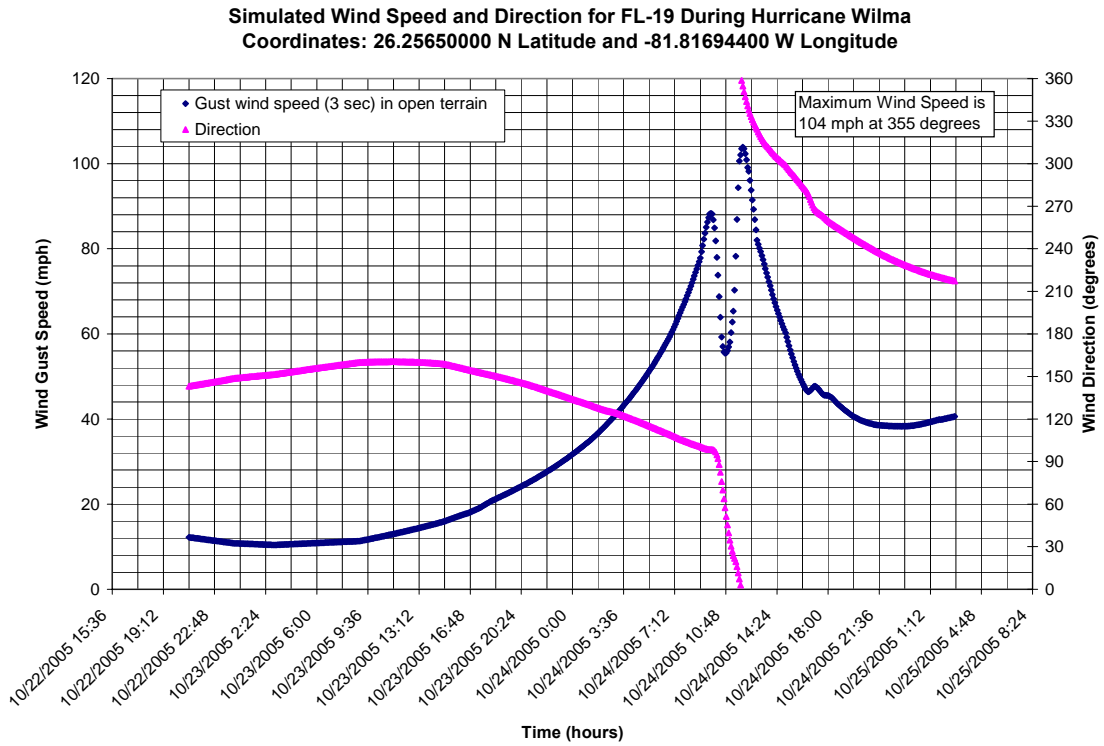


Figure 26. ARA's modeled wind speed and direction at the FL-19 site.

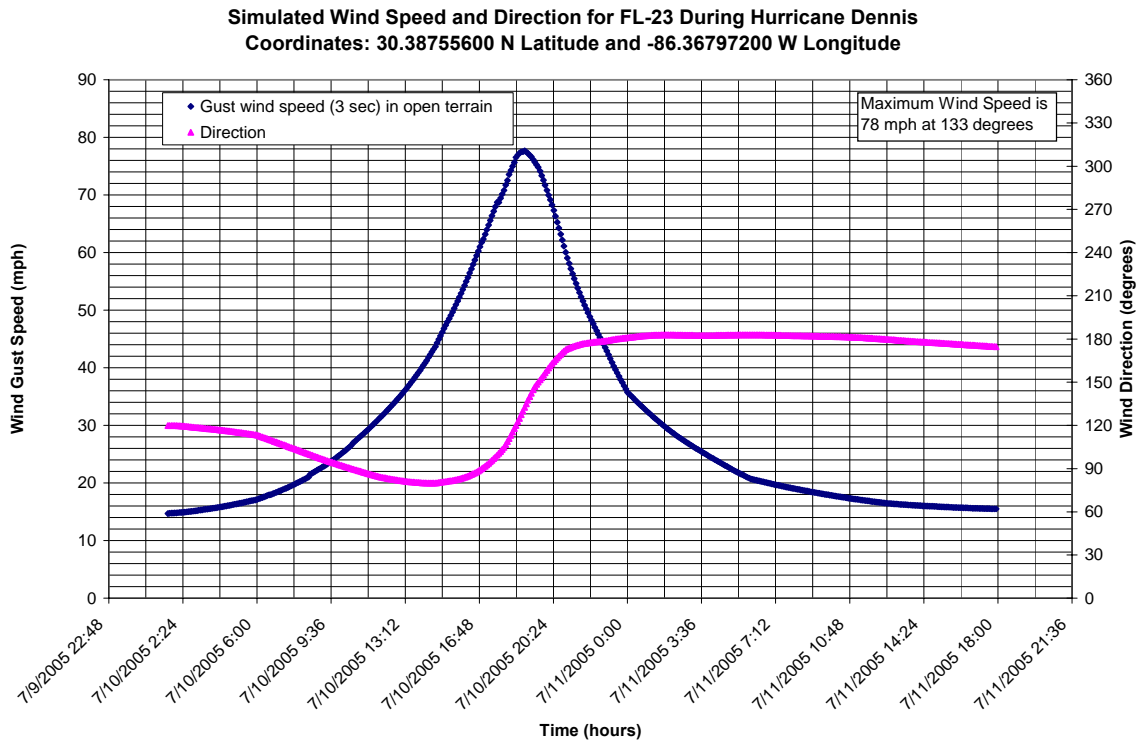


Figure 27. ARA's modeled wind speed and direction at the FL-23 site.

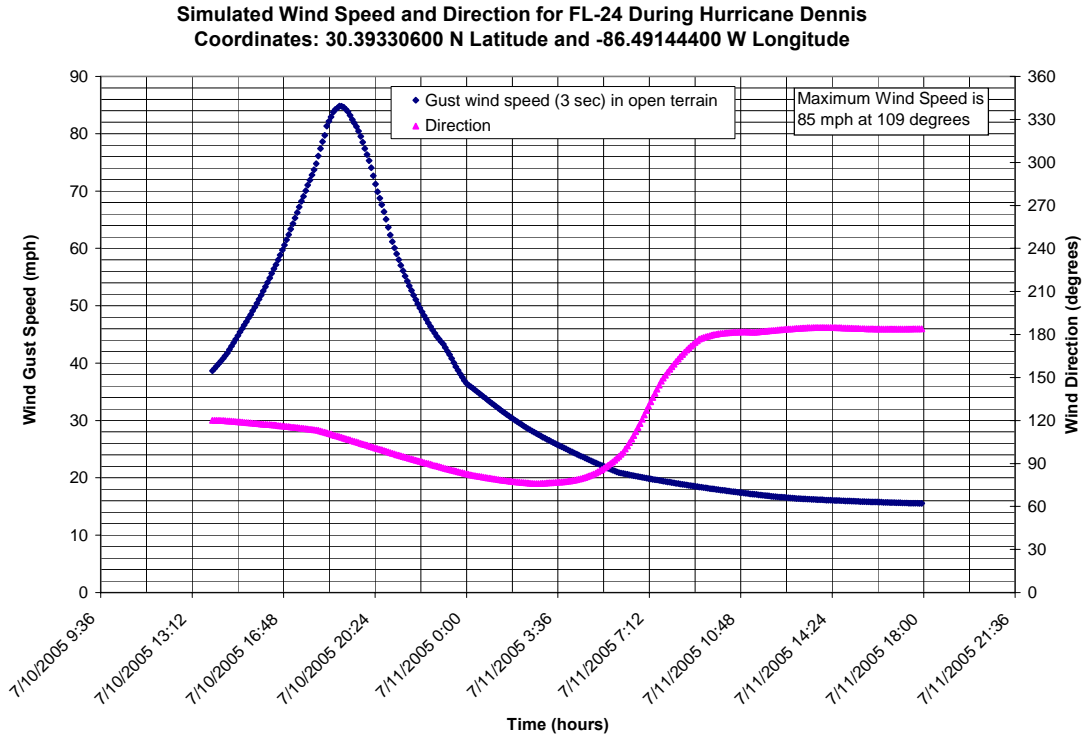


Figure 28. ARA's modeled wind speed and direction at the FL-24 site.

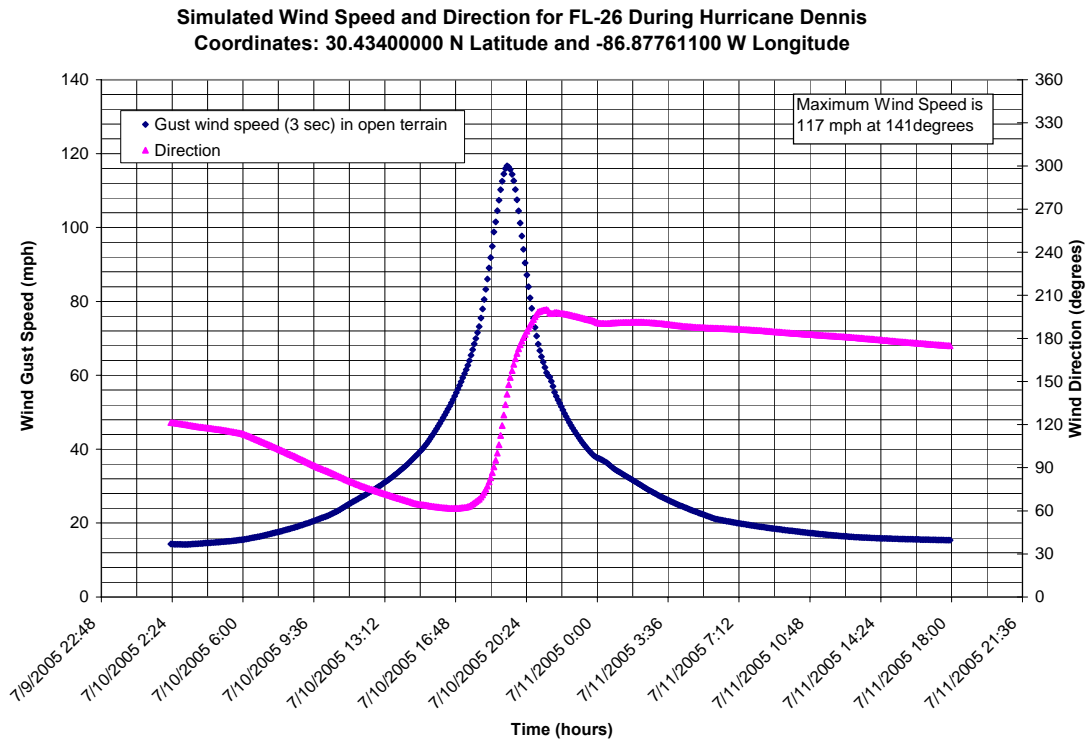


Figure 29. ARA's modeled wind speed and direction at the FL-26 site.

3.7 Pressure Results FL-18 Prototype House

The FL-18 House experienced a peak 3-second gust wind speeds of 31 m/s (70 mph) during Hurricane Wilma, from a direction of 355 degrees.

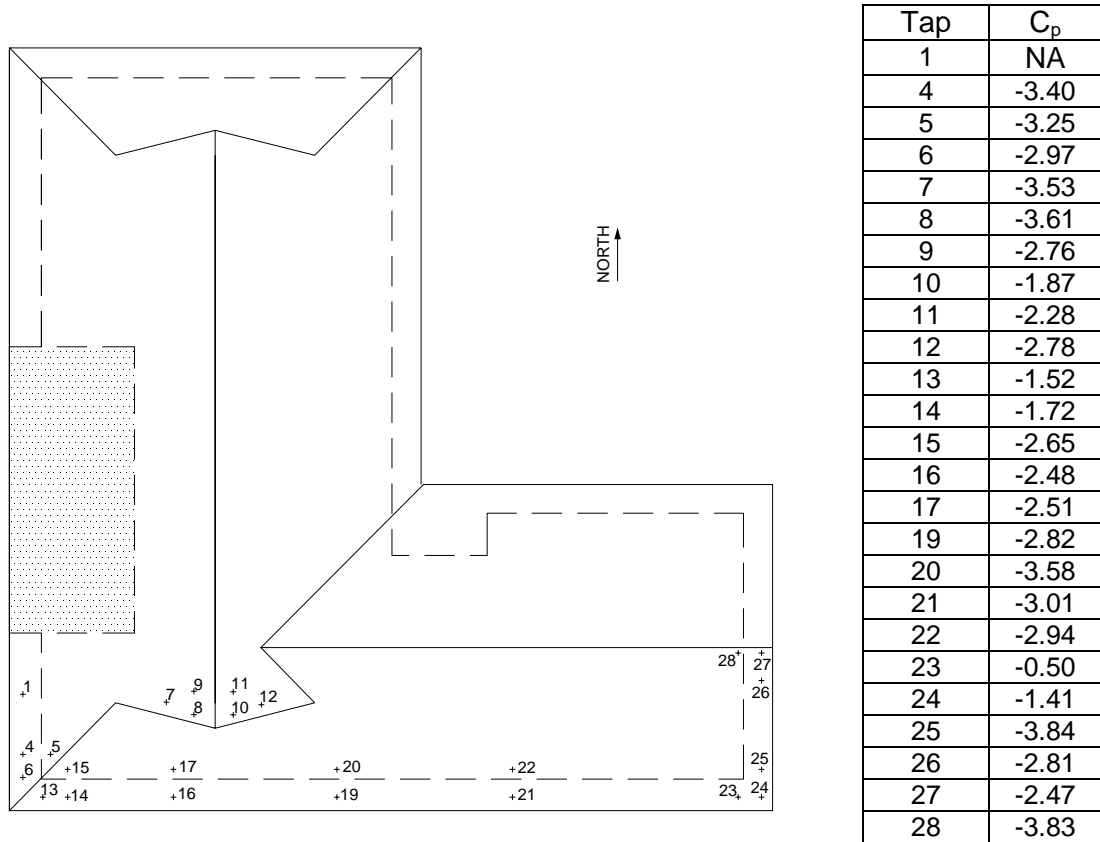
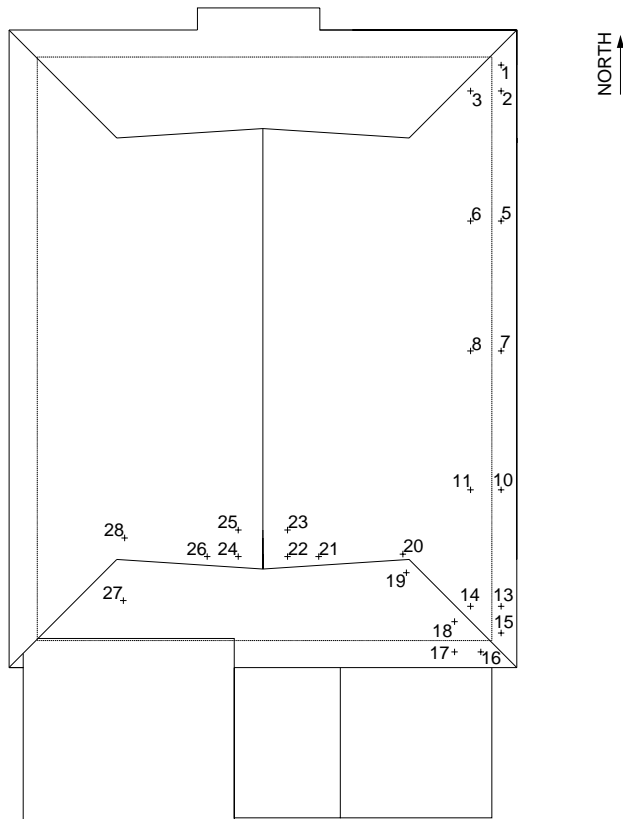


Figure 30. Schematic of FL-18 with preliminary peak minimum pressure results.



Tap	C_p
1	NA
4	-3.40
5	-3.25
6	-2.97
7	-3.53
8	-3.61
9	-2.76
10	-1.87
11	-2.28
12	-2.78
13	-1.52
14	-1.72
15	-2.65
16	-2.48
17	-2.51
19	-2.82
20	-3.58
21	-3.01
22	-2.94
23	-0.50
24	-1.41
25	-3.84
26	-2.81
27	-2.47
28	-3.83

Figure 31. Schematic of FL-19 with preliminary peak minimum pressure results.

4. WIND TUNNEL TESTING

4.1 Wind Tunnel Testing

We conducted wind tunnel studies on models of the prototype structures in the atmospheric boundary layer wind tunnel at the Wind Load Test Facility (WLTF) of Clemson University. This open flow boundary layer wind tunnel has a working section that measures 3 m (10 ft) wide and 2 m (6.7 ft) high and overall length of 30 m (100 ft). We simulated upwind terrain at 1:50 geometric scale and modeled the velocity and turbulence intensity profiles to model suburban exposure. Details of the tunnel set up (Figure 25) and instrumentation are provided by Chen (Chen 2000).

We established the velocity and turbulence intensity profiles by using a combination of spires measuring 241.3 mm (9.5 in) wide at the top and 406.4 mm (16 in) wide at the base), a 25.4 mm x 203.2 mm (1 in x 8 in) trip board at the based of the spires, and 76.2 mm (3 in) cube roughness elements randomly installed along the wind tunnel floor to simulate suburban terrain roughness.

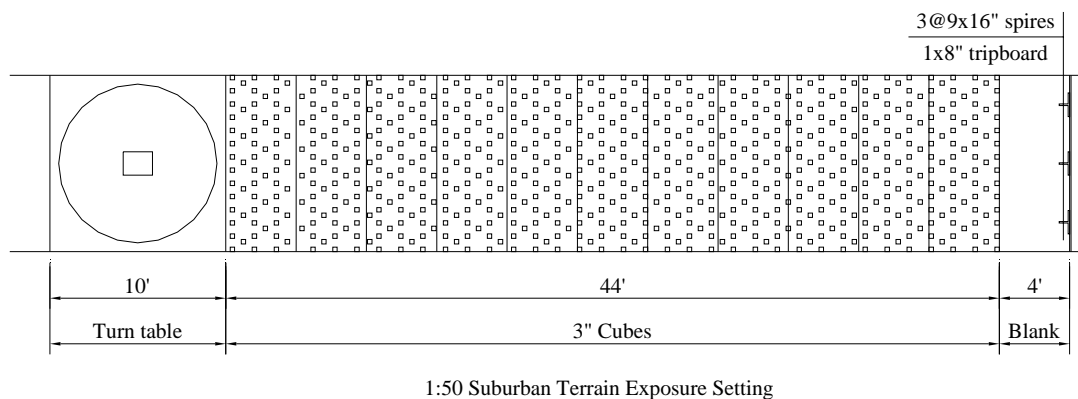


Figure 32. Wind tunnel terrain arrangement for 1:50 suburban exposure.

We obtained the simulated mean wind velocity and turbulence intensity profiles shown in Figure 26. We compared the measurements with the log-law which showed good agreement with a velocity profile roughness element $z_0=0.4$ m.

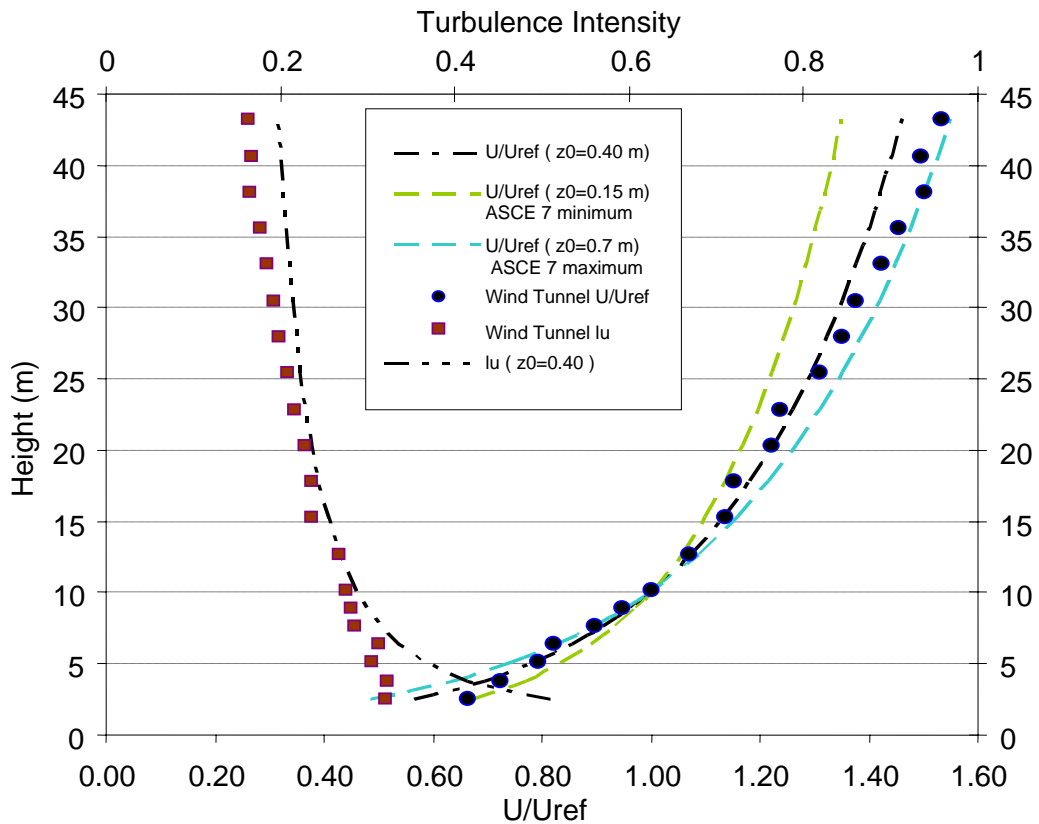


Figure 33. Wind Velocity and Turbulence Intensity Profile for 1:50 Suburban Terrain.

4.2 Models

We constructed the pressure tap models of the prototype houses using 5.6 mm (0.22 in) thick acrylic sheet and 1.6 mm (0.063 in) diameter stainless steel pressure taps installed at the locations of the full-scale pressure sensors. We modeled the surrounding houses

out of blue extruded 50.8 mm (2 in) and 76.2 mm (3 in) polystyrene sheets that were then glued together with silicone sealant.

4.3 Data Collection

The wind tunnel data collection system uses a Scanivalve Corporation USB based data acquisition system, consisting of Scanivalve ZOC33/64PX miniature pressure scanners. Each pressure tap on the model is attached to the pressure scanner using 1.6 mm (0.063 in) I.D. vinyl tubing. The pressure scanners are connected to a 16-bit RAD A/D3200 analog-to-digital converter that converts the analog pressure data to digital format for input to the computer. The A/D3200 is mounted into a RADBASE 3200 that includes the USB system to relay the digital data to a control/storage computer. The data acquisition system is software controlled linked to the storage computer through a Telnet protocol over the wind tunnel's Ethernet/Fiber Optic internet system.

We took 120 seconds of data sampled at 300 Hz for each wind direction measured. We varied the wind direction in 10-degree intervals for 360°. We analyzed the wind tunnel pressure data collected for each of the 36 wind directions on 1:50 scale models in flat suburban terrain conditions. Summary statistics are provided in Figures 27 and 28 below (Note: top value is peak minima / bottom value is peak maxima pressure coefficients.)

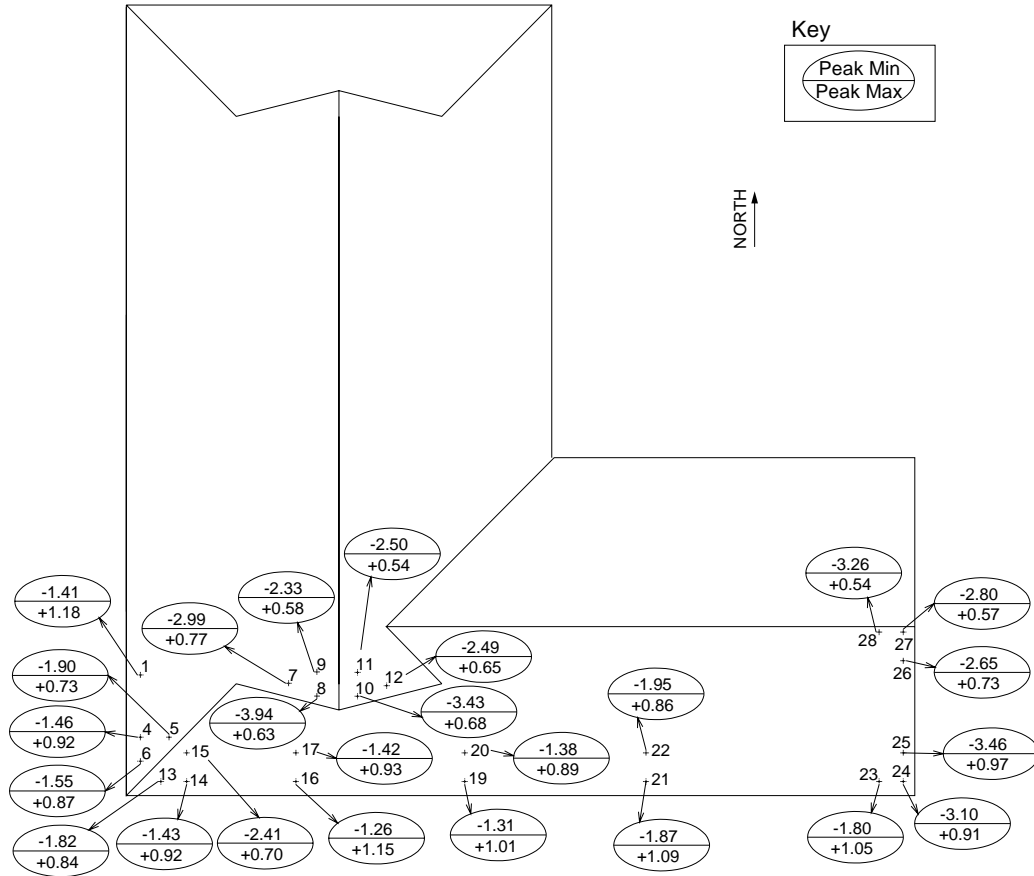


Figure 34. Peak Minima and Maxima External Pressure Coefficients for FL-18.

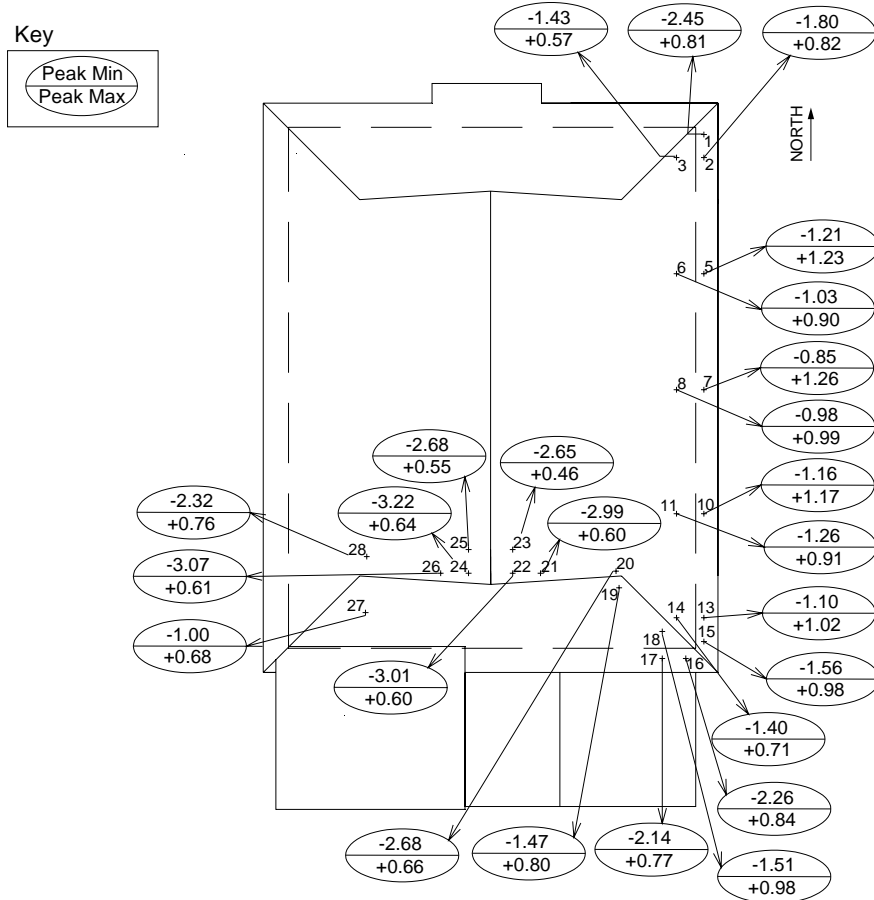


Figure 35. Peak Minima and Maxima External Pressure Coefficients for FL-19.

4.4 Comparison of Full-Scale and Model-Scale Pressure Data

The peak external measured minimum (negative) pressure coefficients from the full-scale data are compared to that of the model-scale tests for corresponding angle of attack in Tables 6 and 7 below. The external pressure coefficients from FL-18 and FL-19 presented are preliminary values and further analysis and validation are continuing. The lack of reliable wind speed data from non-functional anemometers at the houses did not provide independent validation of ARA’s simulated wind speed used for the determination of pressure coefficients.

Table 6. Preliminary Uncorrected External Pressure Coefficients for FL-18 for 320°.

Tap	Full - Scale Analysis			Wind Tunnel Test		
	C _p Minimum	C _p Maximum	Δ C _p	C _p Minimum	C _p Maximum	Δ C _p
1	N/A	N/A	N/A	-0.94	0.70	1.64
4	-3.40	1.68	5.08	-1.06	0.65	1.71
5	-3.25	0.45	3.69	-0.76	0.33	1.09
6	-2.97	0.77	3.74	-1.01	0.57	1.58
7	-3.53	0.15	3.68	-0.67	0.30	0.98
8	-3.61	0.03	3.63	-0.80	0.30	1.10
9	-2.76	0.53	3.29	-0.58	0.31	0.89
10	-1.87	1.78	3.65	-1.63	0.10	1.72
11	-2.28	-0.32	1.96	-1.52	0.08	1.61
12	-2.78	1.00	3.77	-1.22	0.13	1.35
13	-1.52	2.24	3.76	-1.32	0.17	1.49
14	-1.72	2.03	3.75	-1.14	0.32	1.46
15	-2.65	0.91	3.56	-1.47	0.07	1.54
16	-2.48	1.44	3.91	-0.83	0.28	1.11
17	-2.51	1.18	3.69	-1.07	0.26	1.34
19	-2.82	0.74	3.56	-0.90	0.31	1.21
20	-3.58	0.23	3.81	-0.82	0.25	1.07
21	-3.01	0.74	3.75	-0.82	0.35	1.18
22	-2.94	0.67	3.61	-1.00	0.33	1.33
23	-0.50	3.35	3.85	-0.81	0.24	1.05
24	-1.41	2.13	3.54	-0.88	0.30	1.19
25	-3.84	0.07	3.91	-0.91	0.21	1.12
26	-2.81	1.15	3.95	-1.23	0.32	1.55
27	-2.47	1.38	3.85	-1.36	0.14	1.50
28	-3.83	0.20	4.03	-1.30	0.12	1.42

Table 7. Preliminary Uncorrected External Pressure Coefficients for FL-19 for 355°.

	Full – Scale Analysis			Wind Tunnel Test		
Tap	C _p Minimum	C _p Maximum	Δ C _p	C _p Minimum	C _p Maximum	Δ C _p
1	-0.96	0.91	1.88	-1.65	0.30	1.95
2	-1.70	0.74	2.44	-1.76	0.33	2.09
3	-1.20	3.79	4.99	-1.23	0.24	1.47
5	-0.21	1.76	1.96	-1.02	0.24	1.26
6	-1.23	0.83	2.06	-1.03	0.25	1.27
7	-1.38	0.95	2.32	-0.85	0.20	1.05
8	-0.04	2.23	2.27	-0.63	0.24	0.87
9	-0.88	1.45	2.34	-0.63	0.16	0.79
10	-3.24	1.16	4.40	-0.54	0.16	0.69
11	-0.57	1.28	1.85	-0.53	0.15	0.67
13	-1.39	1.04	2.43	-0.63	0.10	0.73
14	-1.35	1.67	3.02	-0.66	0.11	0.77
15	-1.57	1.37	2.94	-0.70	0.09	0.79
16	-1.87	0.34	2.21	-0.58	0.08	0.66
17	-1.07	1.21	2.28	-0.73	0.07	0.80
18	-2.37	0.10	2.48	-0.73	0.07	0.79
19	-0.82	1.78	2.60	-0.50	0.07	0.58
20	-0.97	1.58	2.55	-0.67	0.08	0.76
21	-2.37	0.23	2.60	-0.71	0.07	0.79
22	-1.39	3.48	4.87	-0.81	0.09	0.90
23	-2.05	1.16	3.21	-0.76	0.08	0.85
24	-1.79	1.52	3.31	-0.73	0.11	0.84
25	-0.79	2.30	3.09	-0.61	0.09	0.70
26	-2.91	1.00	3.91	-0.79	0.10	0.89
27	-0.94	2.09	3.03	-0.63	0.14	0.77
28	-3.48	1.36	4.84	-1.65	0.30	1.95

5. WIND PRESSURE VISUALIZATION SOFTWARE

Prototype wind pressure visualization software has been written to display 3D pressure distributions overlaid on a building. With this software, an end user can analyze and interact with wind pressure data by immediately viewing the data from different locations, and by observing the impact of various statistical analyses of the data. A basic flowchart of the program is shown in the figure below.

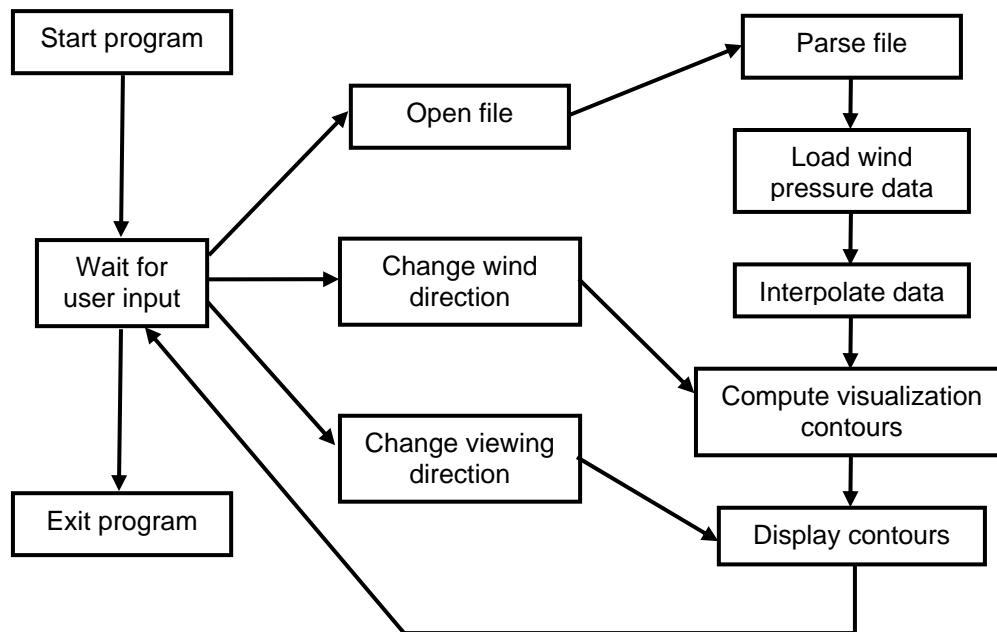


Figure 36. Program Flowchart for the SeeBreeze Visualization Software.

5.1 Background

Previous researchers have attempted to visualize wind pressures on buildings (Banks et al. 2000). This has been a common problem in wind tunnel testing for some time.

Studies on flat roofs have shown that the largest mean and peak suction values are observed for taps beneath the conical 'delta-wing type' corner vortices that occur for oblique winds. It has been assumed that similar results occur on sloped roofs, but to date no studies have confirmed the phenomenon. Since most buildings of a non-

residential nature do not have this problem, studies have not been conducted on sloped roofs.

The effect of aerodynamic buffeting around two- and three-dimensional bluff bodies in tandem was investigated by (Havel 2001), for moderate Reynolds number, turbulent flows. Havel combined flow visualizations, surface pressure and velocity measurements, changes in aerodynamic loading and macroscale flow features to study the phenomena. The civil engineer is concerned mostly with the surface pressures generated.

Prior research has investigated other means to visualize the flow. (Lopes 1997) developed a graphical use interface, FlowVis, as a visualization tool for graphical post-processing of data defined in a 2D or 3D raster grid. Written in the C programming language, this software provides a quick and efficient way to display analysis results obtained either from numerical models or experimental setup.

More recent work has sought to process the visual information in a form that is more usable (Machacek and Rosgen 2001). The authors developed a measurement system using a stereo arrangement of two CCD cameras to visualize, classify (based on topological features) and quantify complex flows in large scale wind tunnel experiments. The authors proposed using topological features of the flow, e.g. stream lines, separation and reattachment regions, stagnation points and vortex lines are extracted directly and preferably visualized in real-time in a virtual wind tunnel environment.

The system is based on a three dimensional particle tracking method (3D-PTV) using a stereo arrangement of two CCD cameras. A frame rate of 120 frames per second allows measurements at high flow velocities. For the 3D-PTV method an approach is taken

where the tracer particles are recorded such that consecutive frames form continuous path lines. The 3-dimensional positions and shapes of the particle path lines are reconstructed by means of the epipolar constraint and the stereo camera model. The particle path segments which contain both velocity and topological information are then analysed to extract the relevant information. Neutrally buoyant helium bubbles are used as tracer particles. Matching the density of the ambient air, the bubbles are ideal flow tracers in this respect.

Finally the closest project to what was discussed for the wind tunnel was by (Usselton 1998) who developed software to apply visualization techniques to aeronautics data collected during wind tunnel experiments. Interaction between the software developers and the wind engineers has been crucial in making the software useful to these particular users. The interaction has also been important in building the scientists' confidence in the use of interactive, computer-mediated analysis tools.

The motivation for this work stems from the available database of wind tunnel studies and the need to determine new uses. Full scale data from the FCMP houses will provide real-world pressure variations. With the help of the wind tunnel the researchers will be able to determine the maximum loaded areas on houses. The purpose of this study is to identify the common features in a house that contribute to extreme pressure values. The objective of this software is to utilize wind tunnel pressure data to generate contour plots on residential buildings. The program will allow for rapid comparison of the variability of wind pressures with wind direction and variation among different building shapes and with different terrain conditions.

5.2 Structure of the Program

The wind tunnel data results is collected from the experimental output and stored in very large data files (typically about 30 GB per test), containing information on the building geometry, tap locations, and wind pressure data (min, max, and mean) for all the taps and sampling instants. The location of the pressure taps on the building surfaces are stored in x, y co-ordinates related to each planar surface. The pressure coefficient information is stored in this file for each wind direction, and there are several files used for a complete experiment, to cover all wind directions tested.

An interpolation algorithm was needed to convert the individual pressure tap readings into contours displayed on a 2-dimensional plane. Several methodologies were attempted to see which would work, including nearest neighbor and linear interpolation . The v4 algorithm included in the Matlab code has been used in the past by Clemson's WLTF wind engineering researchers with reasonable results. However, after trial and error the SeeBreeze development team selected a weighted averaging algorithm as the initial methodology, because it was simpler to implement and provides reasonable results.

The interpolation algorithm computes the color of the pixel at location (x,y) on a surface as follows:

- For each tap i on the surface,
 - Compute the distance d_i from the pixel location to the tap (in our implementation d_i is computed on the full-scale model in inches)
 - Compute the inverse exponential $\pi_i = \exp(-d_i)$
- Compute the normalization constant by summing the values of all taps: $z = \sum_i \pi_i$

- Compute the interpolated pressure value using a weighted average of the taps:

$$p(x, y) = \sum_i \pi_i p_i / z$$

- Use table lookup to determine the color associated with $p(x, y)$, given the current color map

The visualization software, called SeeBreeze, for parsing the file and displaying the data was written primarily in the Spring 2006 semester by students in a combined senior-level / graduate-level Software Engineering course in the Electrical and Computer Engineering Department at Clemson. Two of the students from the class continued to work on the project during the summer to refine and extend the capabilities of the software.

The code was written in Visual C++ with MFC for controlling the basic window functionality and OpenGL for rendering the data in 3D. Writing the code in C++ has enabled us to achieve display speeds far greater than are possible with higher-level languages such as Matlab.

The software uses a novel file format that we have developed specifically for this project that is divided into four sections. First, the coordinates of the vertices of the wireframe building are stored. Secondly, the sequence of vertices that define the various surfaces of the building are recorded. Thirdly, the file contains the format of the filenames containing the sensor coordinates and actual wind data, along with the actual wind directions contained in those files. Finally, auxiliary data such as the offset of the coordinate systems of the sensors and building surfaces is stored. Being composed of ASCII text, this file is easily edited by the user by hand.

In this prototype version the SeeBreeze software can be used to display statistical data (mean, peak minimum, peak maximum and standard deviations) of the pressure coefficients on a geometrically complex roof structure. Future versions of the software will include the ability to display time-history data that illustrates the spatial and temporal variations of wind pressures, as well as pressure-coefficients data from wall and other building surfaces.

5.3 Results

A screenshot of the wind pressure overlaid on a residential building (the FIU 1 house) is shown in the figure below. By clicking and dragging the mouse, the user can translate and rotate around the building, as well as zoom in and out. The arrows on the menu bar allow the user to change the wind direction, which is shown both by the black arrow to the right of the house, as well as the value along the right side of the status bar at the bottom of the window. In addition to the mean of the data over time, which is displayed in this example, the user may also choose to display the minimum or maximum instead.

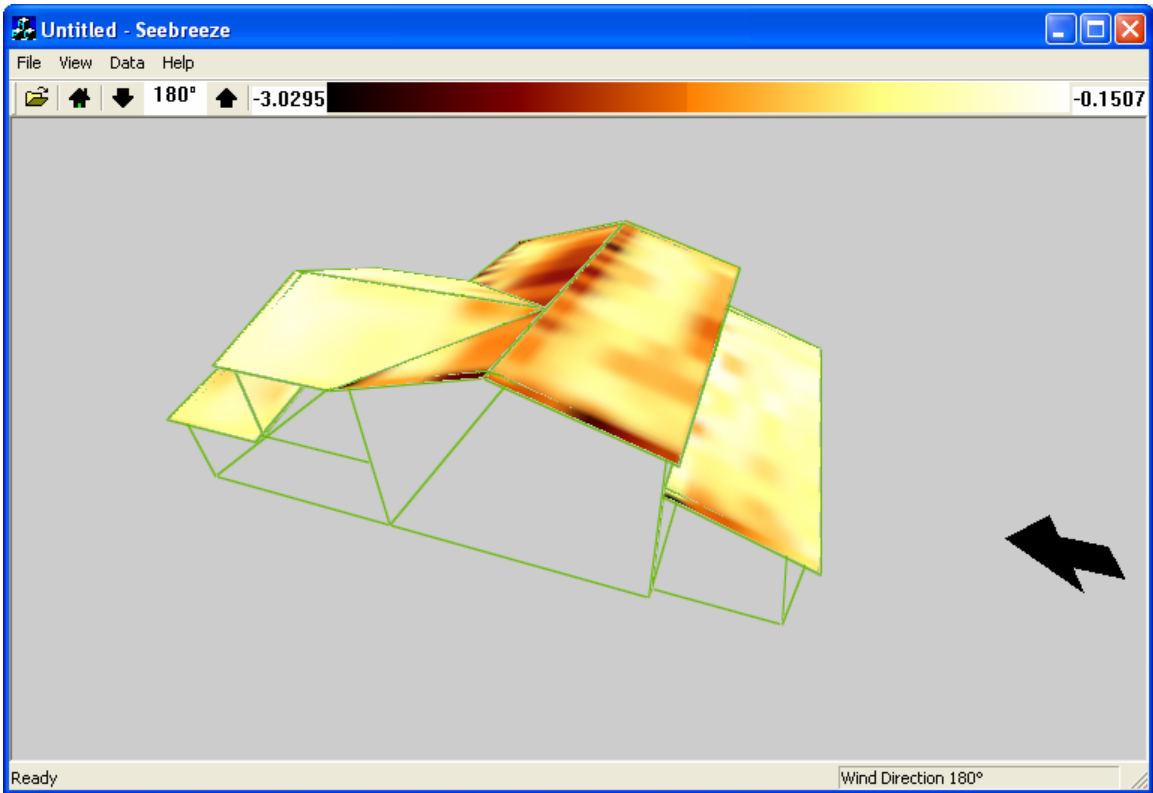


Figure 37. Screenshot of the SeeBreeze Program

Views of this house from several different directions are shown below. Such views are obtained in real time as the mouse is dragged, thus providing instantaneous visualizations of the data from arbitrary viewpoints. The same is true for changing the wind direction. Future versions of the software are expected to allow the user to change the time instant as well.

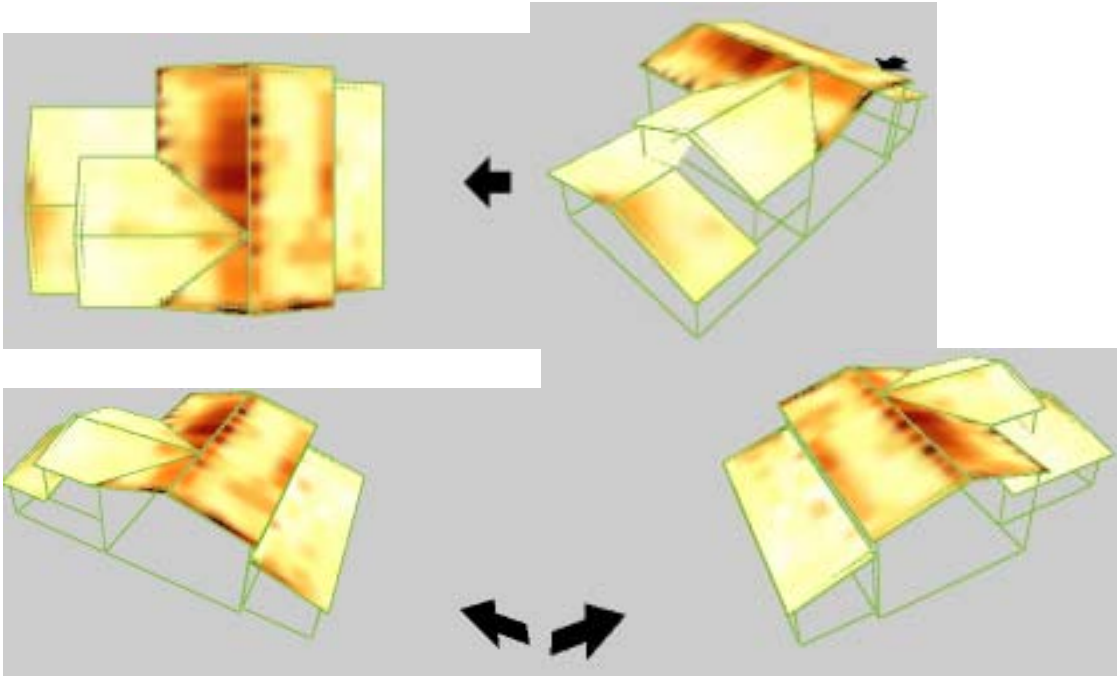


Figure 38. Rotated Views of the House Model Showing Pressure Contours.

5.4 Web Page

Further information is provided on the program and the course instruction at <http://www.davidoprevatt.com/student-projects/seebreeze/> and the course information is provided at <http://www.ces.clemson.edu/~stb/ece417> . Real-time updates of the progress of the field deployment during the hurricane landfall can be tracked at the Florida Coastal Monitoring Program (FCMP) website at <http://users.ce.ufl.edu/~fcmp/>. Through the FCMP website people can monitor the deployments of the towers and locations of full-scale prototype buildings in relation to the hurricane path.

6. CONCLUSIONS

The data collection possible during the 2005 hurricane season and the novel development of pressure visualization software program has advanced available knowledge on the wind-structure interactions for residential structures. Several iterations are yet required to validate these preliminary results and provide final comparative data between the wind tunnel and full-scale experiments.

7. REFERENCES

- Banks, D., Meroney, R. N., Sarkar, P. P., Zhao, Z., and Wu, W. (2000). "Flow visualization of conical vortices on flat roofs with simultaneous surface pressure measurement." *Journal of Wind Engineering and Industrial Aerodynamics*, 84(1), 65-85.
- Chen, M.; (2000) "Characterization of Wind Pressure Fluctuations On a Gable Roof House," Ph.D. Dissertation, Department of Civil Engineering, Clemson University, SC.
- Dearhart, E.; (2003) "Comparison of Field and Model Wind Pressures On Residential Buildings in Tropical Storm Winds," MS Thesis, Department of Civil Engineering, Clemson University, SC.
- Havel, B., Hangan, H., and Martinuzzi, R. (2001). "Buffeting for 2D and 3D sharp-edged bluff bodies." *Journal of Wind Engineering and Industrial Aerodynamics*, 89(14), 1369-1381.
- Holmes, J. D. "Comparison of Model and Full-Scale Tests of the Aylesbury House," *Wind Tunnel Modeling for Civil Engineering Applications*, Proceedings of *International Workshop on Wind Tunnel Modeling Criteria and Techniques in Civil Engineering Applications*, Gaithersburg, MD, 1982, pp. 605-618.
- Levitan, Marc. L, and Kishor C. Mehta "Texas Tech field experiments for wind loads part 1: building and pressure measuring system," *Journal of Wind Engineering and Industrial Aerodynamics*, 41-44 (1992), pp. 1565-1575.
- Lopes, A. M. G. (1997). "FlowVis - a CAD based solution for the graphical post-processing of scalar and vectorial data." *Environmental Modelling & Software*, 12(2), 161-168.
- Machacek, M., and Rosgen, T. (2001). "Development of a quantitative flow visualization tool for applications in industrial wind tunnels." *Proceedings of the 19th International Congress on Instrumentation in Aerospace Simulation Facilities (ICIASF)*, Cleveland, Ohio, 125-134.
- Masters, F, Gurley, K and Reinhold, T (2003). "Ground level wind characteristics of Isidore and Dennis", 11th International Conference on Wind Engineering, Lubbock, Texas, June 2-5, 2003.
- Michot, B. J., "Full-Scale Wind Pressure Measurement Utilizing Unobtrusive Absolute Pressure Transducer Technology," Master of Science Thesis, Clemson University, Department of Civil Engineering, 1999.
- Simiu, E. and R. Scanlan (1996) "Wind effects on structures (3 ed.), New York (US): John Wiley & Sons.
- Uselton, S. P. (1998). "ExVis and Wind Tunnel Experiment Data." *IEEE Computer Graphics and Applications*, 18(4), 75-77.