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Hurricane Wind Loads on Residential Structures: Full-Scale Measurements and Analysis from 2004 and 2005

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Abstract

The Florida Coastal Monitoring Program (FCMP) is a research program in the U.S. that deploys portable instrumentation in the path of landfalling hurricanes to collect wind data. The primary objective is to quantify over-land near-surface hurricane wind velocity and uplift loads on residential structures using full-scale experiential methods. The program is sponsored by the Florida Department of Community Affairs and NOAA, and consists of contributors from the University of Florida, Clemson University, Florida International University, Florida Institute of Technology, and the Institute for Business and Home Safety. The research goal is to help reduce hurricane wind damage to residential structures by providing 'ground-truth' data about the intensity of the wind, the resultant loads on residential structures, and the performance of these structures in high winds.

The full-scale hurricane data measurements are conducted with two separate data collection systems. The FCMP deploy portable weather towers to capture the hurricane wind field behavior at 5 and 10 meters, as well as temperature, humidity, rainfall and barometric pressure. This data is disseminated in real-time to the public domain via the FCMP web site http://www.ce.ufl.edu/~fcmp. The second system uses pressure sensors to collect wind pressure data on the roofs of occupied residential structures along the Florida and Carolina coastlines. To date, 32 houses along the Florida coastline, 4 along South Carolina, and 2 along the North Carolina coastline have been outfitted to receive these sensors. The data from this house system provides full-scale, in-situ datasets for comparison with wind tunnel model studies of the subject homes, as well as the ASCE-7 wind load provisions.

During the hurricanes of 2004 and 2005 the FCMP recorded several datasets from homes that experienced sustained hurricane level winds. A total of sixteen homes were instrumented during three of the 2004 storms, and six homes were instrumented over three storms in 2005. Nine of these homes collected pressure data in sustained hurricane level winds, a first in experimental wind engineering. Details will be provided regarding the deployment of the portable towers and the instrumentation of the coastal homes. Preliminary analysis of this full-scale data will be presented along with comparison with wind tunnel models. Implications regarding the current state of knowledge of extreme wind loading will be discussed.

Keywords
Full-scale, wind loading, low-rise

1. Introduction

The FCMP was initiated in 1999 to provide the wind engineering community an improved understanding of wind loading on low-rise structures. Initial efforts started at Clemson University (CU) and the University of Florida (UF). At present team efforts also include Florida International University (FIU) and Florida Institute of Technology (FIT). Funding support has been provided by the Florida Department of Community Affairs (DCA), the National Oceanic and Atmospheric Administration (NOAA), the Federal Emergency Management Agency (FEMA), Florida Sea Grant, South Carolina Sea Grant and Institute for Business and Home Safety (IBHS).

The FCMP full-scale data collection system consists of two separate systems, known as the FCMP towers and FCMP Houses. Other related FCMP activities include post-event damage evaluation, which provided crucial data to relate winds speed to damage, and capacity testing of house components in-situ to evaluate retrofit effectiveness.

1.1 FCMP Towers

The FCMP consists of an inventory of six portable towers designed and built at Clemson University (Poss, 2000). The towers are located at the University of Florida where upgrades and maintenance is performed. In 2003 the towers were upgraded with cellular data transmission capability, relaying summaries of wind information to a public website every 15-minutes during landfall. In 2006 this real-time system is being upgraded with satellite transmission capability, using NOAA's Geostationary Operational Environmental Satellite (GOES) to provide redundant reliability. Meteorologist, engineers, researchers and the public, benefit from this research effort by accessing the data summaries via direct data transfer or remote accessing thru the FCMP web site at http://www.ce.ufl.edu/~fcmp.

The FCMP mobile towers (Figure 1) are designed to meet U.S. Department of Transportation (DOT) requirements for transport as a conventional trailer, and withstand peak gust wind speed of 90 m/s (200 mph). The FCMP tower mobility and easy assembly (approximately twenty minutes by a three man crew) allows the deployment in almost in any terrain exposures condition.

Figure 1: FCMP mobile tower in tow, and tower deployed during Charley (2004) in Plant City, FL

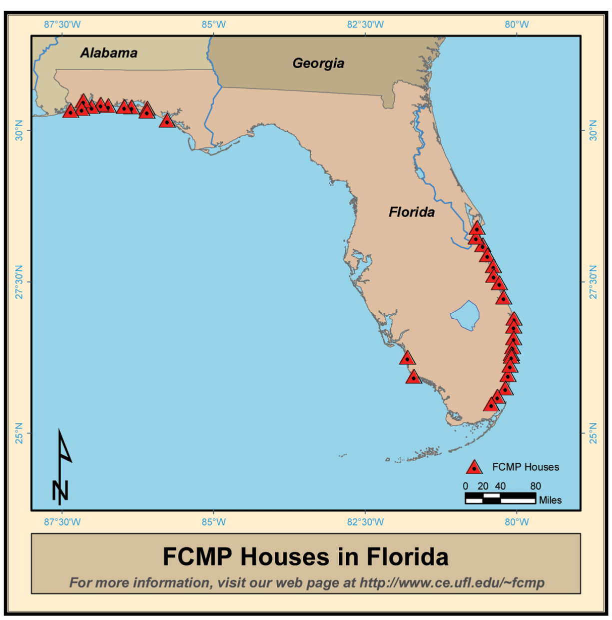
The tower sensors are located at 3, 5 and 10 m. The data acquisition system measures 3D wind speed and direction at the top two levels and collects temperature, rainfall, barometric pressure, and relative humidity data at the tower's base. Two RM Young anemometry system, a wind monitor and a custom array of three gill propeller, collect data at the 10-m level, which the World Meteorological Organization deems as the standard wind speed observation height. A second array of gill propellers collects wind data at the 5-m level to measure winds at the approximate eave height of a single-story home (Masters, 2004).

The data acquisition system consist of two separate computers systems. The first consists of a PC that collects the data at a sampling rate of 100Hz, and store it on two separate hard drives. The second system consists of a laptop computer that collects the data at sampling rate of 10Hz, and stores the data into a single hard drive. This system was incorporated in the 2003 hurricane season and it is responsible to connect to the internet via cellular modem and upload statistics summaries (Masters, 2004).

The FCMP extensive tower database contains hundreds of hours information collected during Tropical Cyclones: Georges (1998), Dennis (1999), Floyd (1999), Irene (1999), Gordon (2000), Gabrielle (2001), Michelle (2001), Isidore (2002), Lili (2002), Isabel (2003), Bonnie (2004), Charley (2004), Frances (2004), Ivan (2004), Jeanne (2004), Dennis (2005), Katrina (2005), Rita (2005) and Wilma (2005).

1.2 FCMP Houses

The FCMP full-scale house data collection research consists of measuring wind pressure data on the roof, soffit and walls of residential houses. Home owners agree to collaborate with the FCMP in exchange for retrofits to their houses to help mitigate hurricane damage (e.g. replacement of roof covering, wind resistant shingles, wind and impact rated garage doors, among others). The current FCMP house inventory contains a total of thirty-two houses in Florida, four in South Carolina and two in North Carolina. Figure 3 shows the distribution of these houses. The location of these houses had been carefully selected using the historical frequency of land-falling hurricanes in these regions. The homes are spaced at intervals of 16 to 24 km (10 – 15 mi), and most are within 1.5 km (1 mi) of the coastline. Typically the houses are one or two stories tall, have composition shingle roof covering and the surrounding areas are suburban and relative free of tree cover.



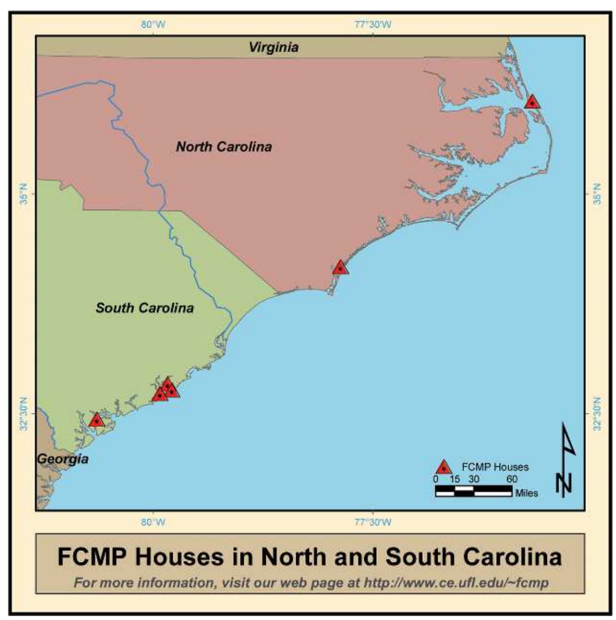


Figure 3: FCMP House locations along: Florida, South Carolina and North Carolina

The participating houses are prepared during the off season. This consists of installing brackets to attach the sensors to the roof, and exterior wiring to connect the sensors to the computer system. Figure 4 (a) shows the wires for the individual sensors, and 4 (b) shows the plastic piping containing these wires, installed under the overhang. All of the wires meet at a disconnect box shown in Figure 5 (a), to which the computer data collection system is attached (Fig. 5-b). The pressure sensors are mounted on the roof, and the computer system is installed, within days of an approaching hurricane, and retrieved immediately after the event.

The computer is contained in a 60" Steel Jobsite Box shown in Figure 5 (b). The inside is customized to accommodate a PC, CPU batteries (to provide up to 24-36 hours of power), time lapse VCR (to record images of the house during the storm) and miscellaneous tools. The box final weight is around 300 lb, heavy enough to resist high winds.


(a)


(b)

Figure 4: (a) FCMP personnel prepares cables (b) PVC piping system


(a)


(b)

Figure 5: (a) House Disconnect Box (b) House Computer Box

The data acquisition system measures data at a sampling rate of 100 Hz. The data is stored digitally into two independent hard drives every 15 minutes. The field instrumentation consists of a maximum of twenty eight Microswitch 142 PC-15 absolute pressure transducers. Reference pressure sensors are located inside the house attic, and at ground level located in the camera mounting base plate. In addition, many houses have a 3-cup-anemometers installed on a 54 inches extension from the roof eave.

The sensors are sheltered in a 12 in diameter aluminum pan (roof) or square plastic box (soffit), distributed along the roof, soffit, walls and camera mounting base plate (Figure 6). Detailed technical information is presented by Michot (Michot, 1999), some of the most relevant points are: voltage signal resolution of pressures to ±0.005 psf, there is an offset voltage unique from sensor to sensor, and the transducers are sensitive to temperature changes. Michot reported a temperature adjustment factor of 0.0144 Volts/ºF for a sensor circuit of sensitivity of 20.6 psf/Volt. All of this information is accounted for in the analysis of results.

(a)

(b)

Figure 6: (a) sensors mounted on roof (b) sensor mounted on wall

Extensive analysis of the FCMP full-scale houses data collected during hurricane Frances (2004), Ivan (2004), Jeanne (2004), Dennis (2005) and Wilma (2005) is currently underway, and some preliminary results along with wind tunnel model comparisons will be presented at this conference proceeding in another paper by Dr. Prevatt (Clemson University). This paper will include some of the assumption made in order to analyze the full-scale data. The subject is a house instrumented during Hurricane Ivan in Pensacola, FL.

2. FCMP house full-scale data collection

FCMP personnel actively monitor the National Hurricane Center (NHC) bulletins during the Atlantic Hurricane Season. When a hurricane threatens the southeast coasts of the United States, FCMP personnel prepare to deploy mobile towers and setup the instrumented FCMP houses. The house setup process requires a crew of at least four people; this task is accomplished in a time frame of three to four hours per house.

The FCMP house database contains valuable information for the wind engineering community. The 2004 effort is the first true sustained hurricane wind pressure data collected on an occupied residential structure. Previous to that the FCMP captured wind pressure data in two houses during tropical storm Isidore (2002). Additional information of the analysis and wind tunnel modeling for this event are provided by Dearhart (2003). The most current database contains wind pressure data for the following hurricanes: Frances (2004), Ivan (2004), Jeanne (2004), Dennis (2005) and Wilma (2005). Table 1 summary the FCMP house database for such events. The max wind speed indicates the highest recorded 3-second gust at that house location.

Table 1: Summary of FCMP House database 2002 - 2005

Storm	Year	FCMP House ID	City, State	Number of Records	Start Time (UTC)	End Time (UTC)	House Anemometer Heigth (m)	Local Exposure Measured Max Wind Speed (mph) @ Anemometer Height		Open Exposure Estimation* Max Wind Speed (mph) @ 10m Height Zo = 0.03	
								3-Sec	1-Min	3-Sec	1-Min
Isidore	2002	FL-27	Gulf Breeze, FL	165	9/25/2002 21:45:20	9/27/2002 15:15:09	6.553	54	28	N.A.	N.A.
		FL-25	Mary Esther, FL	159	9/26/2002 01:09:01	9/27/2002 17:08:36	N.A.	N.A.	N.A.	N.A.	N.A.
Frances	2004	FL-06	Jensen Beach, FL	142	9/5/2004 14:04:10	9/7/2004 01:39:04	7.062	91	58	106	86
		FL-04	Vero Beach, FL	101	9/4/2004 21:54:10	9/5/2005 23:08:23	N.A.	N.A.	N.A.	105	86
		FL-03	Vero Beach, FL	175	9/5/2004 14:58:23	9/7/2004 10:43:37	N.A.	N.A.	N.A.	105	86
		FL-02	Melbourne Beach, FL	271	9/3/2004 10:50:40	9/6/2004 06:44:03	N.A.	N.A.	N.A.	97	79
		FL-01	Melbourne, FL	317	9/3/2004 02:14:57	9/6/2004 09:59:54	N.A.	N.A.	N.A.	87	71
Ivan	2004	FL-30	Pensacola, FL	219	9/14/2004 23:19:28	9/17/2004 06:20:23	6.553	109	65	114	93
		FL-28	Pensacola, FL	185	9/15/2004 01:56:23	9/17/2004 00:22:13	N.A.	N.A.	N.A.	105	85
		FL-27	Gulf Breeze, FL	211	9/14/2004 20:04:33	9/17/2004 01:04:03	6.553	82	45	97	79
		FL-26	Navarre, FL	247	9/15/2004 13:22:32	9/18/2004 03:14:05	6.096	59	32	89	73
		FL-24	Destin, FL	314	9/13/2004 19:23:33	9/16/2004 18:40:54	6.096	56	31	78	63
		FL-23	Destin, FL	303	9/13/2004 19:37:39	9/16/2004 23:48:49	6.096	57	32	75	61
Jeanne	2004	FL-02	Melbourne Beach, FL	200	9/26/2004 17:25:19	9/28/2004 19:38:55	N.A.	N.A.	N.A.	101	82
		FL-01	Melbourne, FL	115	9/25/2004 03:16:57	9/26/2004 08:07:45	N.A.	N.A.	N.A.	92	75
		FL-31	Melbourne, FL	177	9/25/2004 20:34:09	9/27/2004 16:49:35	N.A.	N.A.	N.A.	87	71
		FL-32	Merritt Island, FL	161	9/25/2004 22:51:16	9/27/2004 15:14:02	N.A.	N.A.	N.A.	79	64
Dennis	2005	FL-24	Destin, FL	130	7/10/2005 11:31:13	7/11/2005 19:57:33	6.096	59	28	N.A.	N.A.
		FL-26	Navarre, FL	149	7/9/2005 16:24:52	7/11/2005 05:46:58	6.096	43	22	N.A.	N.A.
		FL-23	Destin, FL	173	7/9/2005 21:22:53	7/11/2005 16:47:38	N.A.	N.A.	N.A.	N.A.	N.A.
Wilma	2005	FL-18	Marco Island, FL	189	10/22/2005 18:31:47	10/24/2005 17:59:36	6.096	77	46	N.A.	N.A.
		FL-19	Naples, FL	176	10/22/2005 20:25:27	10/24/2005 16:35:57	N.A.	N.A.	N.A.	N.A.	N.A.

FCMP house database contains 1025.75 hrs of data for major storm deployments during 2002 - 2005
**Estimation performed by Applied Research Associates parametric hurricane wind field model (Vickery, et al, 2000)*

2.1 Data processing and analysis

The data processing requires exporting each file into ASCII format, which is then converted into MATLAB format for easy manipulation. In order to analyze the data a series of consideration need to be addressed. First, each data channel is validated by visually analyzing the time history of the raw voltage measurements to provide a list of the functioning sensors. Secondly, a reference pressure sensor is selected using either a sensor installed in the attic, the sensor located in the camera mounting base away from the house, or from a nearby mobile tower. Third, identify a nearby FCMP mobile tower or local ASOS station to access temperature time history, this is required in order to apply correction changes due to temperature effects on the pressure transducers. Fourth, identify a source of wind speed for the expected value peak 3-Sec gust. Various sources are available for this: (a) using the 3-cup anemometer mounted on the house, (b) from nearby mobile tower measurement applying the proper adjustment for exposure and height or (c) by using overland wind field model estimations.

The pressure differential needed for calculation of the pressure coefficient can be computed using one of two equations, depending on the dataset conditions: equation (1) is used for the case where the reference pressure is obtained from the attic or camera sensors, and the second equation (2) for the case where the reference pressure is obtained from a nearby tower.

$$\Delta P(t)_i = \left[\begin{array}{l} \left(V(t)_i - Vo_i + \Delta Temp \times \dfrac{0.0144}{20.6} \times \alpha_i \right) \times \alpha_i - \\ \left(V(t)_{REF} - Vo_{REF} + \Delta Temp \times \dfrac{0.0144}{20.6} \times \alpha_{REF} \right) \times \alpha_{REF} \end{array} \right] \quad (1)$$

$$\Delta P(t)_i = \left[\begin{array}{l} \left(V(t)_i - Vo_i + \Delta Temp \times \frac{0.0144}{20.6} \times \alpha_i \right) \times \alpha_i - \\ \left(P(t)_{REF} - Po_{REF} \right) \end{array} \right] \qquad (2)$$

Where, (all pressures are in psf):

- $V(t)_i$, voltage for channel *i* @ time *t* for: 15min Mean value, Max and Min moving average for durations of {10Hz, 5Hz, 2Hz, 1Hz, 1/2Hz, 1/3Hz}
- Vo_i, voltage for channel *i* @ time t_o (15min Mean) pre-storm data
- $V(t)_{REF}$, voltage for reference channel @ time *t* (15min Mean)
- Vo_{REF}, voltage for reference channel @ time t_o (15min Mean) pre-storm data
- $\Delta Temp$ [ºF], temperature change from between time t_o and *t*
- α_i [psf/Volt], sensitivity factor for channel *i*, obtained from sensor calibration test
- $P(t)_{REF}$, atmospheric pressure @ time *t*, from Tower Data (15min Mean)
- Po_{REF}, atmospheric pressure @ time t_o, from Tower Data (15 Min Mean) pre-storm data

The mean, root mean square RMS, maximum and minimum peaks pressure coefficients are then calculated using equation (3), where $\frac{1}{2}\rho$ is taken as a constant value of 0.00256 which reflects the mass density of air for the standard atmosphere i.e., temperature of 59 ºF and sea level pressure of 29.92 inches of mercury and dimensions associated with wind speed in mph.

$$Cp(t)_i = \frac{\Delta P(t)_i}{\frac{1}{2}\rho V_{3Sec}^2} \qquad (3)$$

3. Preliminary Results of FCMP house FL-27 during Hurricane Ivan (2004)

The FCMP house FL-27 is located in Gulf Breeze, FL approximately 40 mi ENE from the landfall site in Gulf Shores, AL. Aerial pictures of the house are shown in Figure 7 (Courtesy of Google Earth Pro), also the sensor layout configuration is provided in Figure 8. The FCMP collected 52 hours of data prior to and during the storm landfall. The dataset consist of 21 functioning pressure sensors, two of which were an attic and camera sensor. Local wind conditions were captured with the house anemometer located 4 ft above the ridgeline and 21.5 ft from the ground. Additional meteorological data is available from mobile tower T1 located at Pensacola Regional Airport, FL approximately 11.5 mi NW of this house. The tower data provided the temperature changes and wind direction since the house anemometer did not record the wind direction.

Figure 7: Aerial Pictures of FCMP House FL-27 in Gulf Breeze, FL

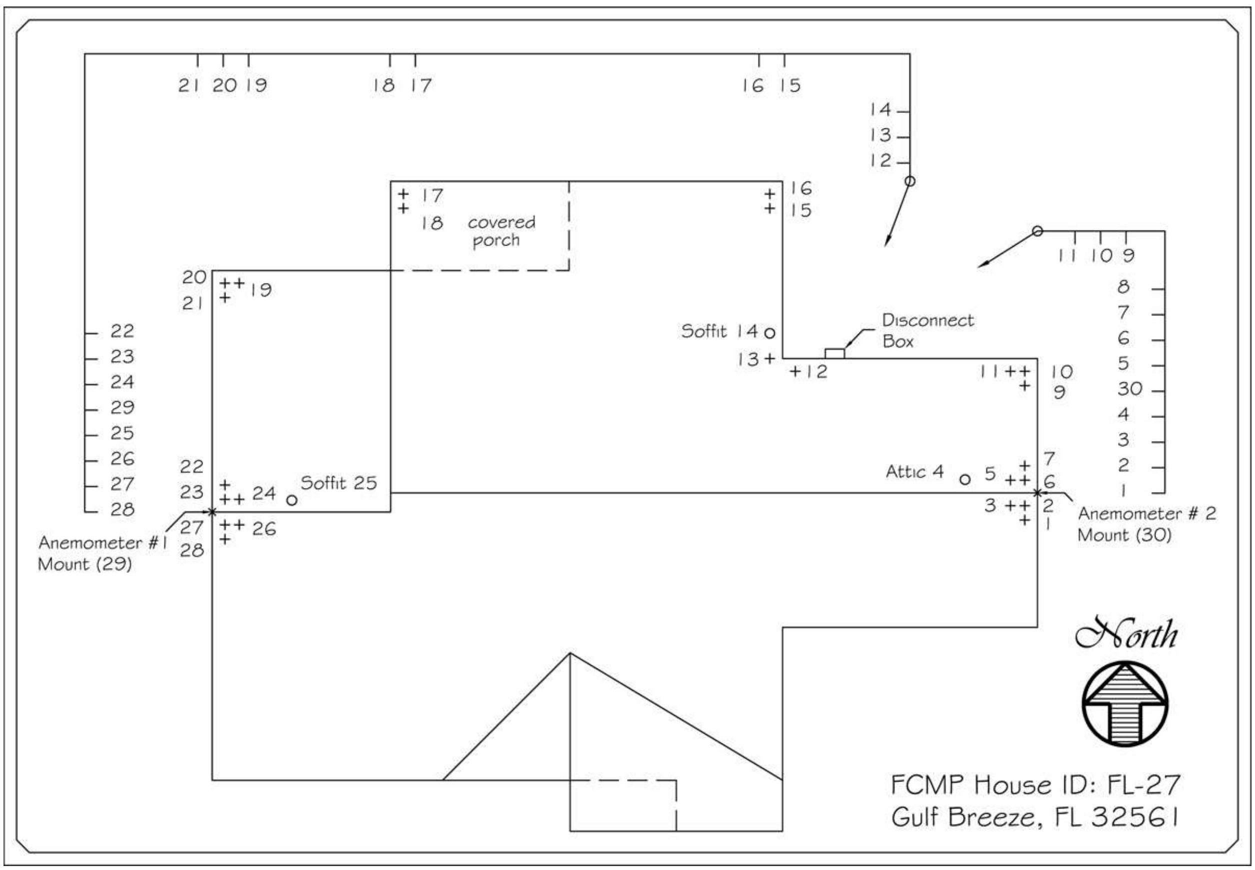
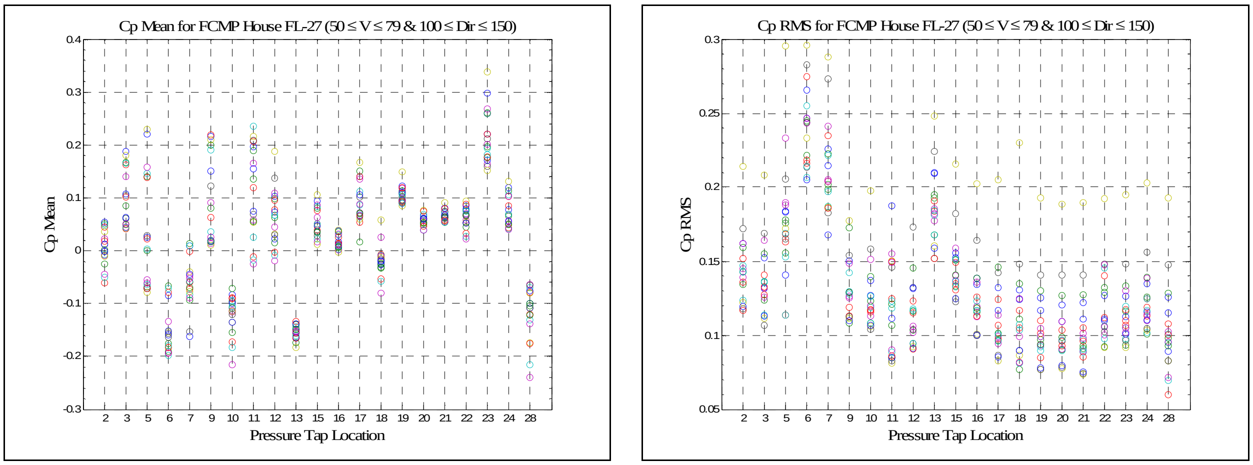


Figure 8: Sensor Layout configuration for FCMP House FL-27

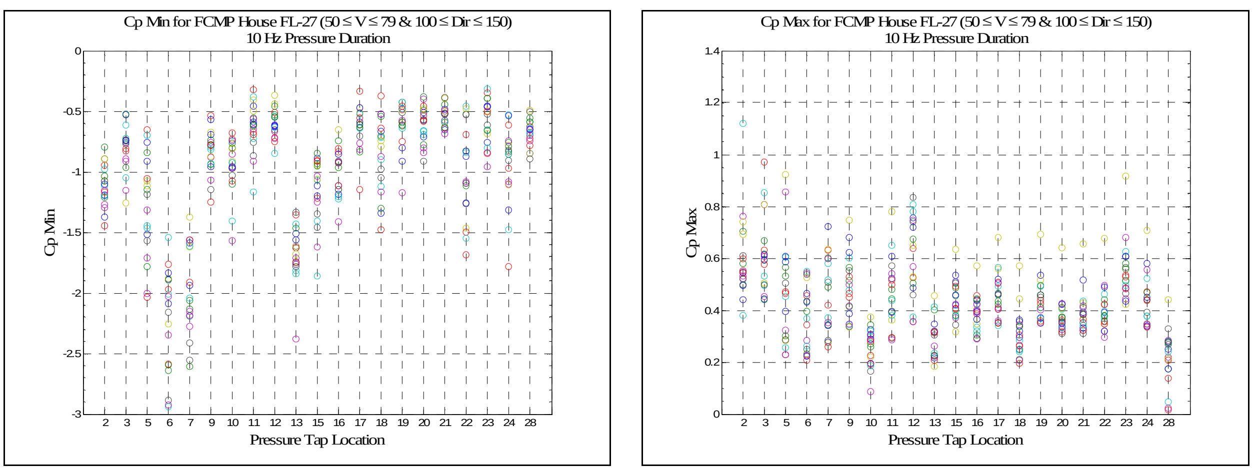
For this dataset the instantaneous pressure differential is calculated using equation (1), and the pressure coefficients are computed using equation (3), for each 15 min segment. In earlier full-scale vs. wind tunnel model comparisons by Dearhart (2003), the mean and RMS pressure coefficient are fairly easy to match, but this is not always the case when comparing the maximum and minimum peaks, taking this into consideration the maximum and minimum peaks are computed for various time duration of 10, 5, 2, 1, 1/2 and 1/3 Hz. The pressure coefficients presented in Figures 9 and 10 correspond to 3-SecGust wind speeds greater than 50 mph and wind direction swath of 50º from 100º to 150º measured from north. Figure 9 (a) and (b) shows the 15 minute mean and RMS pressure coefficients respectively. Figure 10 (a) and (b) show the minimum and maximum peak pressure coefficient respectively.

Pressure taps in locations 6 and 7 exceeded the minimum negative ASCE 7 pressure of -2.6. Any conclusions regarding full-scale vs. wind load provision loads will follow extensive additional analysis of this and the other datasets collected on multiple houses during the 2004 and 2005 hurricane seasons. Clemson University is currently conducting the parallel wind tunnel studies of each of the subject homes that measured sustained hurricane level winds.



(a) (b)

Figure 9: (a) 15 minutes mean Cp (b) 15 minutes RMS Cp



(a) (b)

Figure 10: (a) 10 Hz Peak Min Cp (b) 10 Hz Peak Max Cp

Currently on going work is being conducted by the author in order to quantify the error in the full-scale data sets down to the fact that the temperature change used to apply the correction is obtained from a nearby weather station or FCMP tower; this will incorporate some error due to the local effects that possibly will cause temperature change on both locations simultaneously. The other scenario is due to the human error for the reason that in some cases the sensor have not been properly identify an the calibration factor as been assigned as the average value obtained from the calibration test performed approximately on 200 sensor, this will need to be investigated to find a range of possible outcomes by varying the calibration factor assigned. Finally the estimation of the 3-sec wind gust might be achieve by implementing different techniques and assumptions this will providing a range of the maximum 3-sec wind gust for the each studied case. All this parameters combined offer diverse ranges of pressure coefficients for any 15 minute segment, therefore a range of uncertainty need to establish for each sensor considering all possible scenarios.

4. Conclusions and Remarks

Extensive analysis of the FCMP house database is ongoing by University of Florida and Clemson University. At UF full-scale data analysis is conducted to provide confidence levels for the pressure coefficients, the goal is to produce and disseminate full-scale pressure coefficients. Wind tunnel model studies are conducted in the Boundary Layer Wind Tunnel at Clemson, both research will complement and provide new conclusion to the wind engineering for low-rise structures.

Preliminary analysis of the FCMP full-scale vs. wind tunnel house data, are provided by Dearhart (2003), Reinhold (2005) and in these conference proceedings presented by Dr. Prevatt. Potential implication from these studies could make and impact in the wind load standards. Preliminary analysis suggests that the peak negative pressure coefficients obtained from the full-scale data frequently exceeded the ASCE 7 coefficients for the corresponding roof zones.

Acknowledgements

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