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Wind Load Determination Using Field Data and Wind Tunnel Studies on Residential Buildings

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Abstract

The Caribbean islands from Grenada through Cuba continued to suffer wind damage during the 2004 and 2005 hurricanes seasons. Engineering research is urgently needed to minimize the damaging effects of these winds on residential buildings. The House Instrumentation System of the Florida Coastal Monitoring Program successfully recorded high-resolution wind pressure on a single family house from within Tropical Storm Isidore (2002) and Hurricane Ivan (2004). This paper briefly reviews the process of full-scale tests and presents the wind pressure data collected in two extreme wind events. The corresponding wind tunnel model studies were conducted in the Boundary Layer Wind Tunnel at Clemson University, and these results were compared with field measurement data to validate the current wind tunnel testing techniques. The comparison of full-scale and wind tunnel tests showed that the wind tunnel simulation results generally agree with the hurricane wind loads observed in two extreme wind events, through the peak negative pressure coefficients were insufficient to be reproduced at several test locations.

Keywords

Full-Scale; Hurricane; Wind Load; Wind Tunnel Tests; Low-rise Residential Buildings

1. Introduction

As also occurs in Caribbean islands today, housing and infrastructure in many Atlantic and Gulf Coast states of the United States are at risk of damaging winds and storm surge from hurricanes. Recent hurricane activity has demonstrated the urgent need to improve the hurricane-resistance of constructed facilities, particularly for residential buildings which continue to bear a disproportionately high portion of economic losses. The economic losses due to hurricanes can be minimized only by improving the structural performance of buildings and this requires that we also improve our understanding of the impact of hurricane wind loads on houses. To this end, previous researchers have conducted several full-scale experiments to determine wind loads on low-rise buildings (Eaton and Mayne., 1975; Richardson., 1990; Levitan and K.C. Mehta, 1992), yielding knowledge that has furthered our understanding of wind/structure interaction, and also led to improved wind tunnel simulation methods. Historically, the wind load design codes were developed by utilizing the data set collected in wind tunnel tests of generic model buildings, using scaled wind velocity profiles that were validated by the previous full-scale studies (Stathopoulos., 1979; Ho et al., 2005). However, the previous full-scale and wind tunnel studies focused on extra-tropical storms rather than on hurricane wind climates, and there is now evidence to suggest that hurricanes exhibit wind field characteristics that differ from those of extra-tropical storms (Choi., 1978; Master., 2004).

The evidence suggests that current wind tunnel simulations may not adequately represent hurricane wind structure and therefore lead to erroneous load predictions. However, limited full-scale studies have been conducted to quantify hurricane wind loads on low-rise buildings. It therefore remain a high priority to obtain full-scale measurements of both hurricane wind fields and resultant wind loads to 1) refine the current understanding of the interaction between severe winds and structures and 2) to validate or evolve current wind tunnel simulation techniques and the interpretation of results.

A field measurement program funded by the State of Florida has resulted in 32 homes scattered along the coast of Florida that have been retrofitted and are instrumented with pressure sensors when a hurricane threatens the area. These instrumented buildings are private homes where the homeowners have agreed to participate in the instrumentation project in exchange for assistance in retrofitting their homes to improve the resistance of their houses to hurricane winds and wind effects. This project, the Florida Coastal Monitoring Program (FCMP) was initiated in 1998 by Clemson University initiated with funding from the Florida Department of Community Affairs, South Carolina Sea Grant Consortium, the Institute of Business and Home Safety, the National Institute for Standards and Technology and Florida Sea Grant. The consortium of research partners now includes Clemson University, the University of Florida, the Florida International University, Florida Institute of Technology, and the Institute for Business and Home Safety. The thrust of the FCMP research is to collect in-field hurricane wind field and pressure data on the roofs of residential structures. Pressure sensors and anemometers are installed on single family homes in the path of a land falling storm, and custom built portable weather towers collect wind field data near the coast. In 2004, 16 homes were instrumented and all experienced at least tropical storm force winds. In addition, the FCMP deployed 10-m meteorological towers near to the houses to collect detailed wind characteristics during the passage of the storm. The subject of this paper is an instrumented home (referred to as FL-27) located in the Florida panhandle that collected wind speed and roof uplift pressure data during Tropical Storm Isidore (2002), and Hurricane Ivan (2004). This paper will present the methodology used to measure and analyze extreme wind loads on the FL-27 House, and use these full-scale datasets to validate the wind tunnel methods used to reproduce hurricane wind loads.

2. Florida Coastal Monitoring Program (FCMP) – Field Measurement of Wind Loads

In order to quantify the hurricane wind field and wind loads on full-scale low-rise buildings, the FCMP has developed two independent systems. These are respectively referred to as the Mobile Tower System and the House Instrumentation System. The objectives of FCMP are as follows:

- To measure hurricane wind velocities and turbulence during landfalling storms
- To determine the wind-induced pressures on critical roof areas of residential buildings
- To compare full-scale results with wind tunnel studies on scale model buildings, and
- To evaluate the effectiveness of inexpensive retrofit measures.

The Mobile Tower System, described in several FCMP published papers (Master., 2004; Gurley et al., 2005; Aponte., 2004), is designed to collect wind velocity data at 5 and 10 meter heights as well as barometric pressure, temperature, and relative humidity. The House Instrumentation System uses anemometers and pressure transducers to collect wind field information at the house roof height and hurricane wind loads on the critical roof areas.

Figure 1: Photos of Wiring System and Roof Brackets for Instrumented House (Reinhold, 2006)

The field measurement system uses absolute pressure transducers with a modified sensitivity and offset to allowed detailed measurements of pressure time histories with a resolution of 0.005 kPa. Since absolute pressure transducers are used, it is necessary to back out the atmospheric pressure changes and a weak sensitivity to temperature variations.

2.1 Description of Experimental Building and Site

Data from one of the houses, designated FL-27 was used to compare pressure coefficients from field measurements and the wind tunnel. FL-27, located in Gulf Breeze, FL, weathered two storms, Tropical Storm Isidore in 2002 and Hurricane Ivan in 2004. The house is surrounded by similarly sized residences, and the entire community is nearly surrounded by forest to the east, west and south. The location of House FL-27 is categorized as spare suburban terrain according to ASCE 7-02 provision (ASCE 7, 2002). FL-27 is single-story residence having a sloping roof of intersecting hips and gabled shapes. The roof slope is approximately 20 degrees. Twenty-four pressure sensors were mounted on the roof, near eaves, ridges and corners as shown in Figure 3. Two pressure sensors were installed in the attic of the house to monitor internal pressure to monitor ambient atmospheric pressure.

2.2 Determination of Wind Speed and Wind Direction at Mean Roof Height of FL-27 House

Two 3-cup anemometers were mounted on the house roof to collect wind speeds and wind directions with the House Instrumentation System sampling these channels at 1/3 Hz. Additional information on the wind flow around FL-27 was obtained from the mobile towers that were located in nearby open exposure areas (parking lots, airports etc.) near to the house.

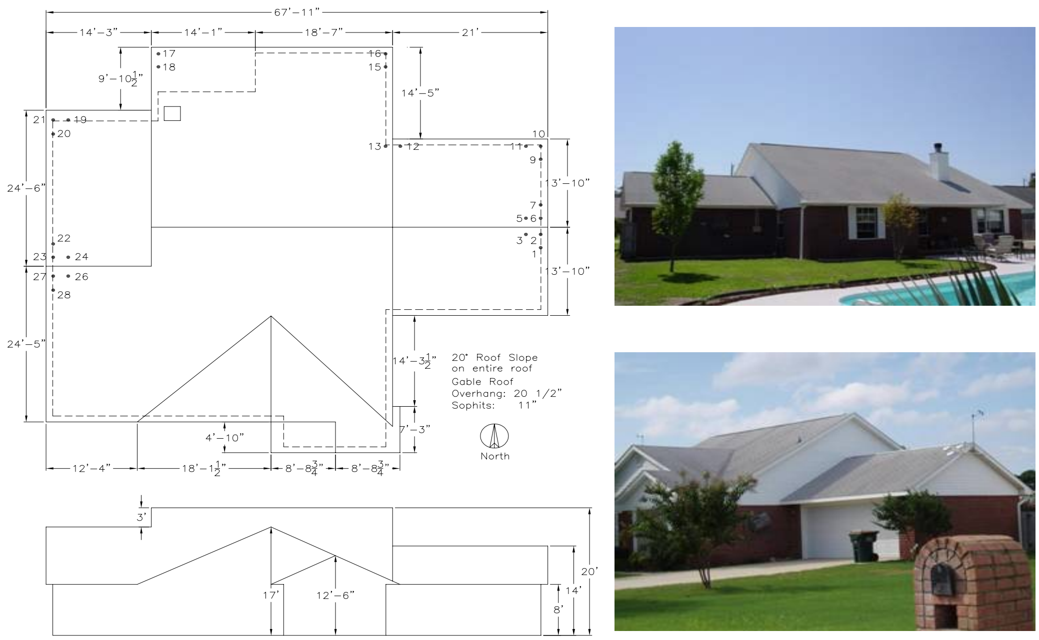


Figure 2: Drawings of FL-27 and Photograph Showing Installed Pressure Sensors on Roof

Because anemometers are located about 4.5ft above the roof ridge (21.5ft above the ground), their records were unavoidably disturbed by both the experimental house itself and the surrounding structures. However, the incident wind flow information around House FL-27 recorded by the House Instrumentation System can be verified by comparing with the corresponding mobile tower records. Table 1 summarizes these mean wind speeds and wind directions collected by the Mobile Tower System and House Instrumentation System during Tropical Storm Isidore and Hurricane Ivan.

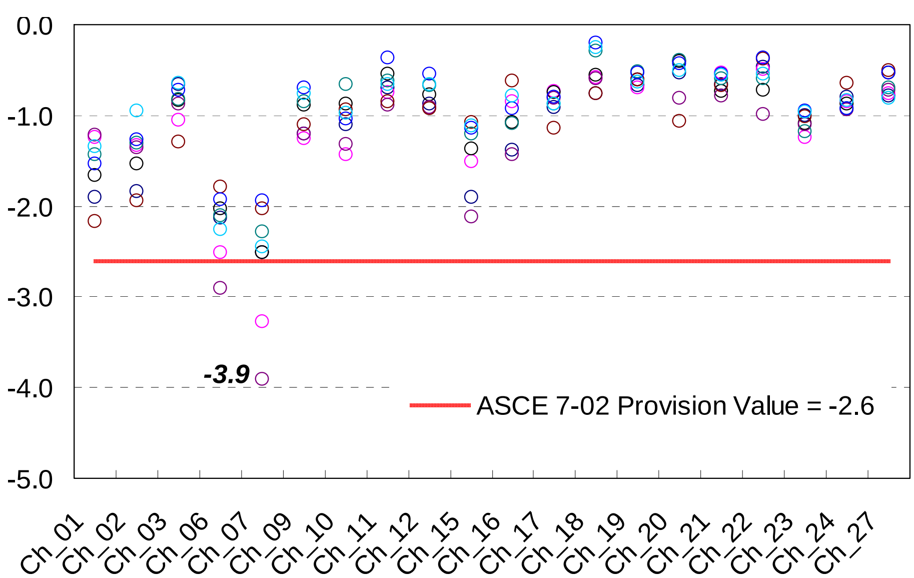


Figure 3(a): The peak negative pressure coefficients observed on FL-27 House roof in Tropical Storm Isidore

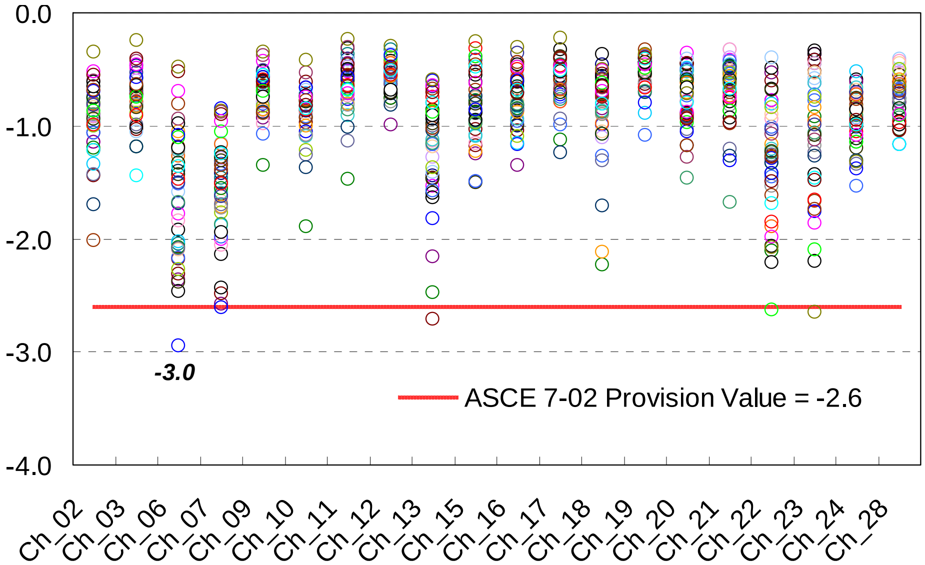


Figure 3(b): The peak negative pressure coefficients observed on FL-27 House roof in Hurricane Ivan

Table 1: Maximum wind speeds measured at FL-27 and Nearest Wind Tower

	Tropical Storm Isidore		**Hurricane Ivan**	
	House (FL-27)	**Wind Tower**	**House (FL-27)**	**Wind Tower**
Max. 15 min. wind speed (m/s)	7.8	18.9	15.5	30.8
Wind direction at 15 min. speed	125°	125°	110°	125°
Equiv. 3-sec gust wind speed (m/s)	16.6	16.9	33.0	34.8

The House Instrumentation System successfully collected 165 sequential 15-minute segments of data records from Tropical Storm Isidore and 211 data records for Hurricane Ivan from FL-27. Each data record contains the pressure sensor reading, wind speed and direction data. The mean, peak negative, peak positive and standard deviation of pressure coefficients recorded during each quarter hour period were calculated. Figure 3 shows the peak negative pressure coefficients observed during the data records having the highest mean wind speeds during the storms. Each vertical group represents the pressure coefficient calculated to a single 15-minute full-scale record.

3. Wind Tunnel Simulation of Hurricane Wind Load

The full-scale tests for House FL-27 in Tropical Storm Isidore and Hurricane Ivan provided for the first time, field data of hurricane wind loads that can be used to validate the current wind tunnel simulation procedures. A 1:50 scale model plexi-glass building was fabricated and pressure taps installed in the roof. Twenty-four pressure taps were installed to correspond to the locations of the full-scale pressure sensors, and four hundred and seventy-two additional taps were also installed (Figure 4). Styrofoam models (also correctly scaled were constructed and placed to simulate the effect of the existing neighboring buildings.

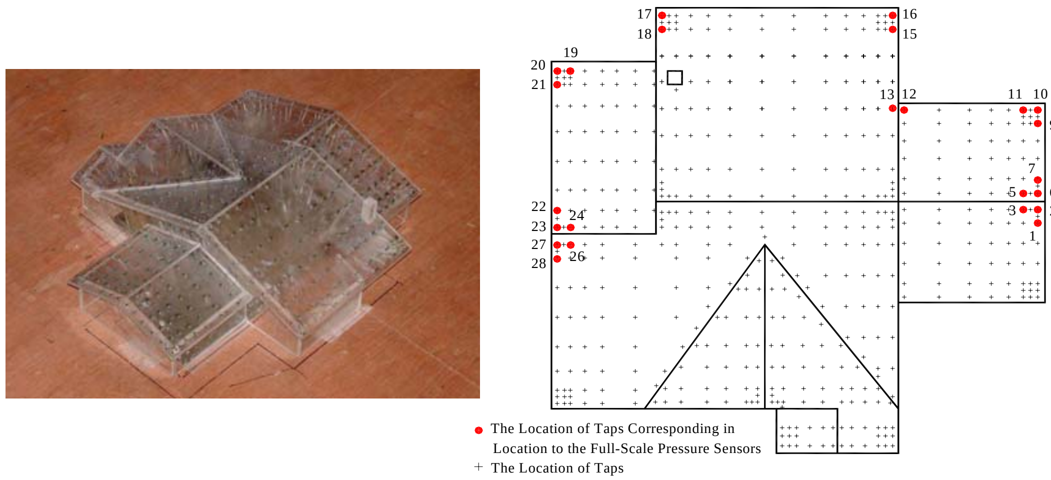


Figure 4: House FL-27 model used for wind tunnel simulation

3.1 Wind Tunnel Set-up and Boundary Layer Simulation

FL-27 house model studies were conducted in the Boundary Layer Wind Tunnel at Clemson University. A 1:50 suburban terrain exposure was developed in the wind tunnel by combining spires, trip boards and roughness elements along 48ft of the upstream fetch. The wind velocity profile in the wind tunnel matched the log-law natural atmospheric boundary layer. Figure 5 shows that the mean wind speed profile matches well with the log-law relationship for the standard sparse dense suburban terrain (roughness length z_0 =0.3 m) that reflects well the environment of House FL-27. The wind speed and turbulence intensity profile fits well with the log-law relationship at mean roof height.

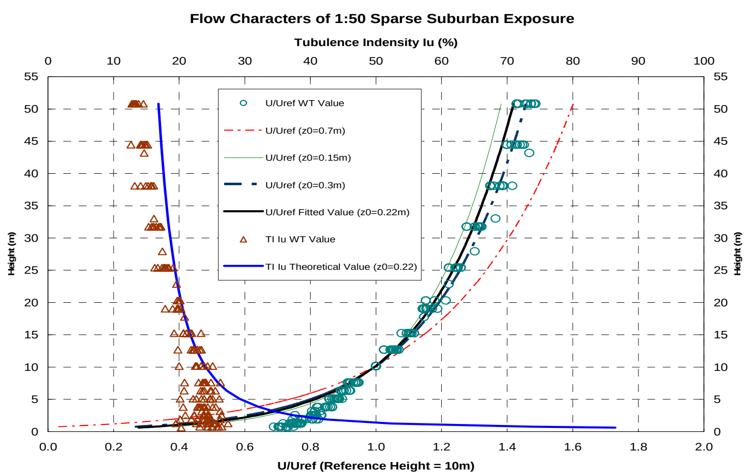


Figure 5: Mean Speed and Turbulence Intensity Profile for 1:50 Suburban Terrain

3.2 Analysis of Wind Tunnel Studies

The incident wind directions at FL-27 for maximum wind speeds in Tropical Storm Isidore and Hurricane Ivan were 110˚ and 125˚, respectively. Wind tunnel pressure coefficients were obtained for winds at 10˚ degree intervals. For comparison purposes, the wind tunnel incident wind direction were set to correspond to the full-scale directions and 16 trial runs were taken and a plot of results in shown in Figure 6. A contour plot of the results is shown in Figure 7 below.

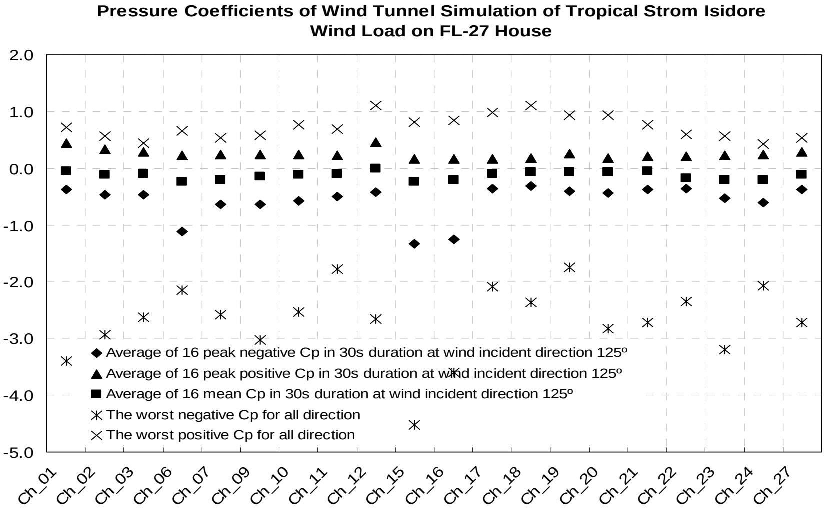


Figure 6(a): Pressure coefficients of wind tunnel simulation of Tropical Storm Isidore

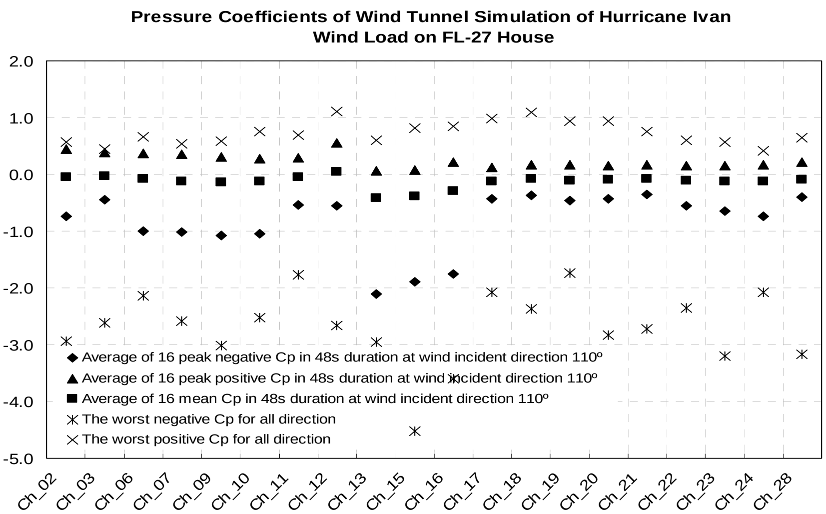
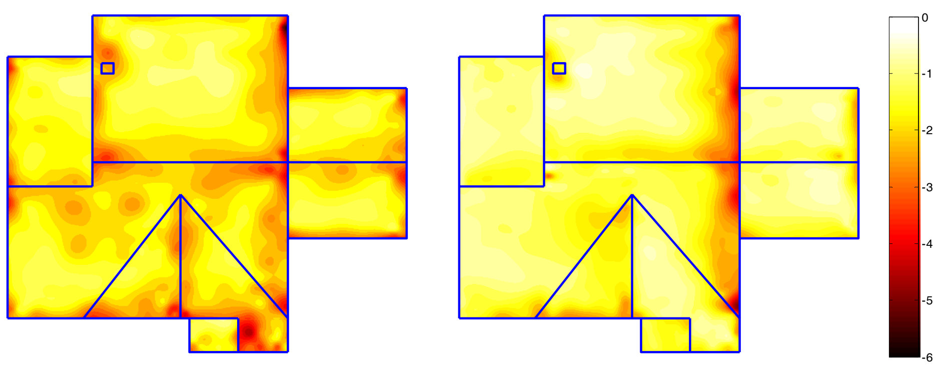


Figure 6(b): Pressure coefficients of wind tunnel simulation of Hurricane Ivan



(a) All directions = 0° -360° (b) Wind incident direction

Figure 7: The worst negative pressure coefficients on House FL-27 model roof

4. Comparison of Field Measurement and Wind Tunnel Simulation Results

Figure 8 compares full-scale and model studies of the mean, peak minimum, peak maximum and standard deviation of pressure coefficients of wind directions measured during Tropical Storm Isidore and Hurricane Ivan, thusly showing overall agreement between full-scale and wind tunnel test results. Fig.13 shows the linear regression analyses of the man peak minimum, peak maximum and standard deviation of pressure coefficients obtained from full-scale and wind tunnel data. This analysis was performed to determine if the wind tunnel boundary layer and model studies adequately simulated extreme wind loads on the experimental building. The linear regression analyses of standard deviation of pressure coefficients show that the wind tunnel results close match the corresponding full-scale results. A small shift of the standard deviation of pressure coefficients was approximately 0.03 between the model and full-scale values recorded during Tropical Storm Isidore. This small shift suggests that the model study was able to faithfully reproduce fluctuations in pressures coefficients. The fair correlation coefficient and the small scatter between full-scale and model test results also suggest that the standard deviation of pressure coefficients closely correspond between House FL-27 and its smaller representative model.

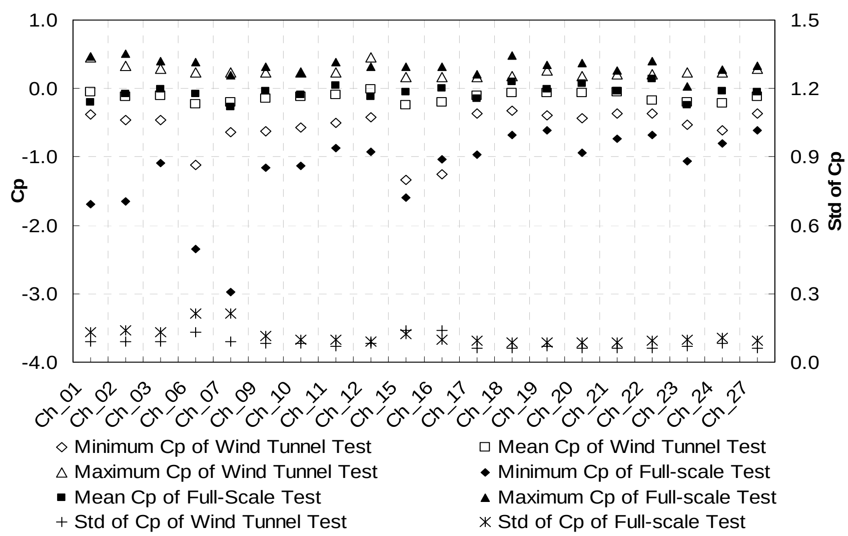


Figure 8(a): Comparison of Cp values of full-scale tests (Tropical Storm Isidore) Vs. wind tunnel tests

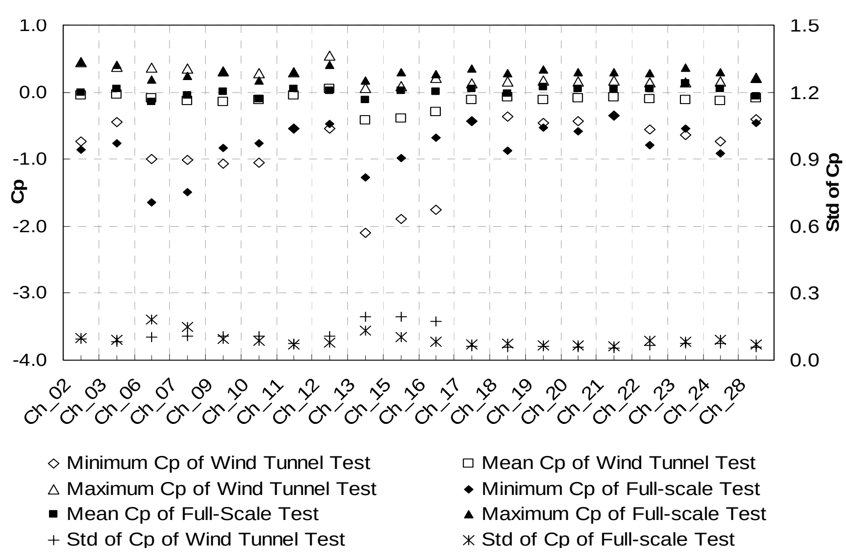


Figure 8(b): Comparison of Cp values of full-scale tests (Hurricane Ivan) Vs. wind tunnel tests

The linear regression analysis of the mean, peak minimum and maximum pressure coefficients presented in Figure 9 show some shifts between the model of House FL-27 and full-scale test results. The great shift is approximately 0.6Cp that occurs when comparing the peak minimum pressure coefficients between model and actual test data recorded during Tropical Storm Isidore. A shift of 0.6 Cp in the full-scale values represents a change of about 2.3psf of wind pressure for the wind speeds observed during this storm. Original estimates of uncertainties associated with corrections for reference pressures, temperature variations, and calibration errors were approximately +/- 2.0psf. However, the shifts between model and full-scale results still can be considered due to system errors in the full-scale House Instrumentation System.

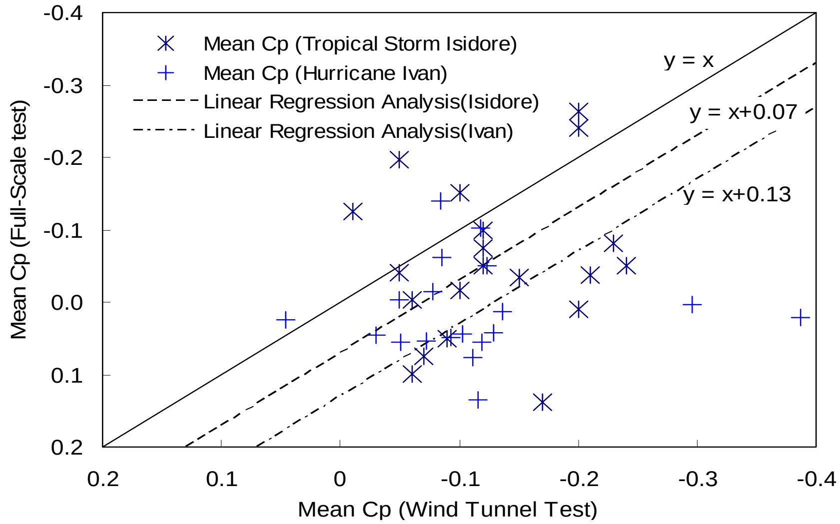


Figure 9(a): Linear regression analysis of mean Cp of full-scale and model studies

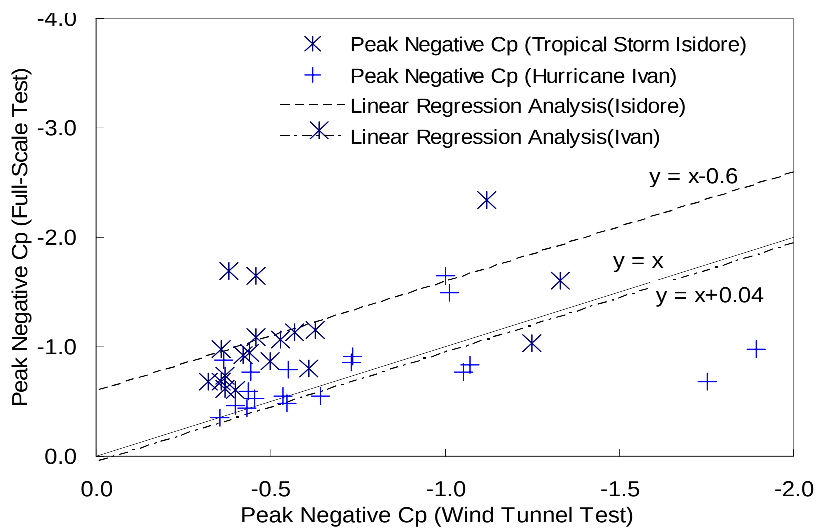


Figure 9(b): Linear regression analysis of peak negative Cp of full-scale and model studies

5. Conclusion

Full-scale wind tests of House FL-27 during Tropical Strom Isidore (2002) and Hurricane Ivan (2004) has provided a wealth of high resolution data on how extreme wind loads interact with a low-rise residential structure in a suburban setting. The data from these full-scale test results offer the ability to validate current wind tunnel simulation method and ASCE prescriptive wind loads, and recommend improvements where necessary to achieve improved performance of residential structures subjected to hurricane winds. Wind tunnel studies of the subject house were conducted at the Clemson Wind Load Test Facility, and results compared with the full-scale data.

The results indicate strong agreement between wind tunnel and full-scale data when comparing means and standard deviations of Cp values. However, the wind tunnel results demonstrated an almost uniformly unconservative departure from full-scale in the case of peak minimum and maximum Cp values. The full-scale results gathered from Tropical Strom Isidore and Hurricane Ivan indicates that peak pressure coefficients can exceed the current prescriptive wind loads for components and cladding in ASCE 7-02. However, these findings are only preliminary, and a follow up study will consider several additional full-scale datasets from other structures and hurricane events, as well as a thorough analysis of the influence of uncertainty in the collection and analysis of full-scale roof uplift pressure data.

The Florida Coastal Monitoring Program collected substantial amounts of hurricane wind field and wind load data during the 2004 and 2005 hurricane season. The results of this effort are beginning to offer new insight into the interaction between extreme winds and man-made structures. Ultimately the outcomes of the research are intended to offer supporting evidence to those working to upgrade the prescriptive measures for construction of more wind resistant and still affordable housing.

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