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A Damage Assessment and Wind Loading Analysis of Residential Structures Built Post-1996 in Punta Gorda in the Wake of Hurricane Charley

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A Damage Assessment and Wind Loading Analysis of Residential Structures

Built Post-1996 in Punta Gorda in the Wake of Hurricane Charley

by

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ABSTRACT

One of the communities in the path of Hurricane Charley as it came ashore August 13, 2004, was Punta Gorda, recording gusts up to 145 mph. This project utilizes aerial photos taken approximately 10 days after the storm battered the area, using a digital photography program. Focusing on the one-story residential structures (houses) of the Punta Gorda area, a damage assessment could be made of the area's homes, and how they stood up to the storm. This study focused further on homes built after major changes to the local/state building codes went into effect (starting in 1996) after the devastation left in south Florida by Hurricane Andrew in 1992. After selecting approximately 20 damaged houses, damaged from wind loading only, an analysis of these houses (or types of houses) could then be undertaken complying with the most current building/wind codes used at the time of Charley's landfall. Furthermore, by looking at the pictures, and using reports outlining the types of damage seen from the storm, the building/wind codes could then be checked for their effectiveness.

After performing a wind loading analysis on houses similar to those seen in the selected pictures, and using the wind code provisions of ASCE 7-98, calculations show a substantial increase in local wind pressure to various zones of the roof. High pressure zones of the roof included the ridges of the gable and hipped style roofs, as well as the corners and the edges.

More emphasis needs to be placed on the installation of the clay tiles (mandated by certain deed-restricted subdivisions of Punta Gorda). If the tiles are ripped off from the wind, then the roof sheathing becomes exposed to the environment, and if this becomes damaged, rain leaking down into the interior of the house would cause additional damage.

Chapter 1 Introduction

1.1 Introduction

This thesis is an offshoot of a previous project published in June of 2005, titled "Impact of Hurricane Charley on Residential and Commercial Construction" [1]. In this report, houses were examined in Punta Gorda Isles (PGI), Charlotte County, Florida, after Hurricane Charley made a direct hit on the area as it made landfall, subjecting the structures in the area to at or above design level wind speeds.

By using a software program called Electronic Field Study, provided by Pictometry International, a huge database of digital, aerial photos were made available of the PGI area approximately 8 to 10 days after Charley passed through the town. The addresses and exact location of residential structures (houses) and commercial structures (gas stations, banks, etc.) fitting the criteria for the project (built post-1996), were found from information obtained from the Charlotte County Property Appraiser's Office, as well as that found using Microsoft Streets and Trips, and local maps. With a database of 747 houses built in the PGI area after 1996, 425 were examined for damage or the lack thereof, and then classified with three different levels of damage. Their damage classification was based on the area of tile missing from the roof, which was found from the Pictometry software. Based on the severity of "area missing" of tile, the houses were classified as no damage, minor damage, and damaged.

Beginning the research for this study, and continuing where the NSF report stopped, the list of damaged houses was used as a starting point. Ignoring the data on commercial structures, the aim of this subsequent project was to:

1) Look at the different types of damage seen from the photos
2) Try to form some conclusions and recommendations about how the building/wind design codes for residential structures at the time of the storm's landfall (August 13, 2004) were suited to survive the storm
3) Suggest any improvements that might be needed.

1.2 Scope of the Project

The aims of this project were to start by looking at the damage seen to the houses from the Pictometry software, and see if any common patterns could be found in the pictures. A report was written by FEMA [2], which was a "mitigation assessment team" report for the hurricane's damage to the parts of Florida that encountered damage during the storm. This report was used to further investigate the damage suffered by the houses in the Punta Gorda area. In this report, it outlined the most common types of damage seen to homes from the storm, as well as the social and economic impacts the storm had on the area. It also documented extensively different types of damage observed on all different kinds of structures as a result of the storm's high winds (120+ mph).

Given all of this data, an assessment was made by looking at the types of damage observed in the Pictometry photos, and cross-referencing them to the FEMA report, and then looking for any flaws in the building/wind codes used for the residential structures at the time. This damage investigation was done by using a fundamental engineering structural design approach to the problem, and seeing what conclusions could be formed.

1.3 Organization of the Report

This report is organized into seven chapters. Chapter 2 gives a background on the progression and landfall of Hurricane Charley, how hurricanes form, the development of the current wind and building codes in the state of Florida. Chapter 3 discusses some basic fundamental subjects on wind loading on structures, some common roof shapes encountered in Punta Gorda, and how to use ASCE 7-98 to design for wind loads. Chapter 4 gives a discussion of how data was obtained for the research of this project. Chapter 5 then details how the analysis of the project was carried out. Finally chapters 6 and 7 give the conclusions and recommendations, respectively.

Chapter 2 Background

2.1 Hurricane Meteorology

Every year hurricanes cost areas of the southeastern United States millions, and sometimes billions of dollars in damage. Florida is especially vulnerable to hurricane development as it is a peninsula surrounded by the Atlantic Ocean to the east, the Gulf of Mexico to the west, and to the south and southeast lays the Caribbean Sea. Florida's geographical location is akin to "a finger sticking out in the wind", as was seen in the hurricane season of 2004 when Florida was hit by four hurricanes and one tropical storm. This particularly severe hurricane season was followed by an even more catastrophic hurricane season in 2005, when Hurricane Katrina tore through the coastal and adjacent inland counties of southeastern Louisiana, Mississippi, and Alabama, causing not only terrible damage but also a significant loss of life.

In order to minimize the opportunity for structural failure, and, more importantly, loss of life, every effort should be made to design a structure that can stand up to hurricane-force winds in areas where hurricanes are encountered. All types of construction design, including both commercial and residential, should, and for the most part do, take into account the high wind loads and pressures seen on buildings during hurricanes.

Before discussing the effect of hurricane-force winds on houses, a general understanding of what hurricanes are should be elaborated on in order to simplify the overall report. The official Atlantic hurricane season, defined by the National Hurricane Center (NHC) [5], lasts roughly from June 1 to November 30, with storms sometimes forming earlier or later in the year.

Most hurricanes in the Atlantic Ocean begin their lives typically as tropical waves drifting westward off the western coast of Africa north of the Equator. A tropical wave is generally known as an elongated area of low air pressure causing rain and thunderstorms. Once this concentrated area of thunderstorms passes over the warm waters of the Atlantic just north of the Equator, then the process for development into a hurricane can proceed. To feed the thunderstorms, warm, moist air from the ocean surface rises. As it meets cooler air at higher elevations, the moisture in the air condenses and falls back to the surface as rain. During the condensation of the water vapor, energy is also released in the form of latent heat, often referred to as the latent heat of condensation. This latent heat warms the cooler air at the higher elevations, causing it rise further. More warm, moist air is then drawn in from the ocean surface to fill the void left by the rising air. This cycle continues to draw the warm, moist air into the developing storm.

As the warm, moist air is drawn from all directions (under ideal development circumstances) across the ocean surface, a circulation develops (counterclockwise for the northern Hemisphere), around the low air pressure center of the storm. As the storm further develops, cool air devoid of moisture rises, and is expelled outward in all directions from the storm in the form of high cirrus clouds. As warm, moist air at the earth's surface is drawn in towards the center of circulation, winds near this area increase dramatically. The most severe winds are felt in the region near the center of the storm. The constant cycle of condensation and evaporation creates rain bands that form around the center of circulation, giving the classical spiral shape of a hurricane. When the storm's strength becomes significant, and it reaches hurricane status, an "eye" develops. This eye is the center of circulation of the storm, and due to the centripetal forces acting on the storm, this part of the cyclone is virtually cloud, wind and rain-free. In fact, while in the eye of a large hurricane, the weather can be quite calm, while severe weather rages along the border of the eye wall [3], [4].

Depending on the severity of this circulating storm, different classifications have been assigned to them by the National Hurricane Center. As the storm shows some signs of organized circulation around an area of low pressure, the storm is called a tropical depression and assigned a number. If the storm further develops with sustained wind speeds exceeding 39 mph, it becomes a tropical storm and is given a name. Finally if the storm intensifies to the point where its sustained wind speeds exceed 74 mph, it becomes a hurricane. Figure 2.1 shows a radar view of Hurricane Ivan making landfall in the Florida Panhandle (September 2004). Figure 2.2 shows the cross section of a hurricane.

At the beginning of every hurricane season, the NHC forms a list of names for the upcoming season, typically one name for each letter of the alphabet, alternating from a male name to a female name, or vice versa. Table 2.1 shows the different classifications of tropical cyclones in the Atlantic region. Hurricanes are further classified into five different levels according to the Saffir-Simpson Scale, based on their wind velocity, and corresponding potential for damage if they make landfall at those velocities. Table 2.2 shows the Saffir-Simpson scale.

Table 2.1: Different Classifications of Atlantic Cyclones

Storm Classification	Wind Speed (mph)	Description
Tropical Depression	$\leq$ 38	No eye visible; Poorly organized
Tropical Storm	39 to 73	Spiral shape begins to develop; Eye usually not visible; Assigned a name
Hurricane	$\geq$ 74	Eye becomes visible; Spiral shape evident

Table 2.2: Saffir-Simpson Hurricane Scale

Category	Sustained Winds (mph)	Damage Level
1	74 to 95	Minimal
2	96 to 110	Moderate
3	111 to 130	Extensive
4	131 to 155	Extreme
5	155 +	Catastrophic

2.2 Hurricane Charley

Hurricane Charley started as a tropical wave off the western coast of Africa in early August of 2004 and drifted westward towards the Caribbean Sea. On August 11, it reached hurricane status, with its center positioned approximately 40 miles southwest of Jamaica. It then proceeded to move more north-northwest, and then north, moving just east of the isle of youth in southwestern Cuba, crossing Cuba and the Straits of Florida, and then moving more north-northeast towards the southwestern coast of Florida. Hurricane warnings and watches were put into effect along most of the west coast of Florida as Charley crossed Cuba, indicating that hurricane conditions were likely (warning) or possible (watch) within the next 24 to 36 hours. Once Charley crossed Cuba it strengthened into a category 4 storm, with maximum sustained winds of 131 mph.

During the late afternoon of August 13, 2004, Charley made landfall on the southwest coast of Florida near Cayo Costa, just north of Captiva Island, at the mouth of Charlotte Harbor. At this time Charley's estimated maximum sustained winds were around 150 mph. Charley was a fairly small and compact storm in terms of its diameter, and as a consequence its hurricane-force winds extended within roughly 7 miles of the center of the storm. It continued to move north-northeastward at a speed of approximately 15 to 20 mph, and hit Punta Gorda, a small community at the northeastern end of Charlotte Harbor, directly. After passing through Punta Gorda, Charley continued on its north-northeastward track and moved through central Florida to Orlando, and exited the Florida peninsula just north of Daytona Beach in the early morning of August 14. It then moved back over the Atlantic for a short time and made a second landfall near the South Carolina/North Carolina border, after which it gradually dissipated and lost its tropical cyclone characteristics.

Figure 2.3 shows the track of Hurricane Charley, as plotted out by the NHC. Figure 2.4 shows a radar image of Charley making landfall over the southwest Florida coastline. Figure 2.5 shows the wind swath of Charley's hurricane force winds. Table 2.3 shows the coordinates of Charley's center as it passed through Florida.

Table 2.3: Hurricane Charley Position and Corresponding Wind Velocities

Date/Time (UTC)	Position Lat. (°N)	Position Lon. (°W)	Pressure (mb)	Wind Speed (kt)	Wind Speed (mph)	Stage
09 / 1200	11.4	59.2	1010	30	35	tropical depression
09 / 1800	11.7	61.1	1009	30	35	"
10 / 0000	12.2	63.2	1009	30	35	"
10 / 0600	12.9	65.3	1007	45	52	tropical storm
10 / 1200	13.8	67.6	1004	40	46	"
10 / 1800	14.9	69.8	1000	45	52	"
11 / 0000	15.6	71.8	999	55	64	"
11 / 0600	16.0	73.7	999	55	64	"
11 / 1200	16.3	75.4	995	60	69	"
11 / 1800	16.7	76.8	993	65	75	hurricane
12 / 0000	17.4	78.1	992	65	75	"
12 / 0600	18.2	79.3	988	75	86	"
12 / 1200	19.2	80.7	984	80	92	"
12 / 1800	20.5	81.6	980	90	105	"
13 / 0000	21.7	82.2	976	90	105	"
13 / 0600	23.0	82.6	966	105	120	"
13 / 1200	24.4	82.9	969	95	110	"
13 / 1400	24.9	82.8	965	110	125	"
13 / 1700	25.7	82.5	954	125	144	"
13 / 1800	26.1	82.4	947	125	144	"
14 / 0000	28.1	81.6	970	75	86	"
14 / 0600	30.1	80.8	993	75	86	"
14 / 1200	32.3	79.7	988	65	75	"
14 / 1800	34.5	78.1	1000	60	69	tropical storm
15 / 0000	36.9	75.9	1012	40	46	extratropical
15 / 0600	39.3	73.8	1014	35	40	"
15 / 1200	41.2	71.1	1018	30	35	"
15 / 1800						merged with front
13 / 0430	22.7	82.6	966	105	121	landfall on south coast of Cuba near Playa del Cajio
13 / 1945	26.6	82.2	941	130	150	landfall near Cayo Costa, FL, and minimum pressure
13 / 2045	26.9	82.1	942	125	144	Landfall near Punta Gorda, FL
14 / 1400	33.0	79.4	992	70	80	landfall near Cape Romain, SC
14 / 1600	33.8	78.7	997	65	75	landfall near North Myrtle Beach, SC

(Courtesy NHC [5,6])

According to a report written by Pasch, et. al [6], from the NHC, on Hurricane Charley, the maximum sustained winds estimated for the Punta Gorda area were around 144 mph. This estimate comes from ground wind measurements from anemometers taken as the storm was approaching from the southwest. They were recording maximum sustained winds of 90 mph, before the instruments failed, which is common for ground wind-measuring devices during hurricanes. Approximately 10 minutes after the instruments failed, the minimum pressure for that station was recorded. This indicates that the storm's center passed closer to that station after the wind-measuring instruments failed, giving credibility to the 144 mph wind estimates.

2.3 Punta Gorda and its Importance to this Study

Punta Gorda was chosen as the area of interest to this report in large part due to the fact that the vast numbers of aerial photos provided by Pictometry were made available for examination. Given that the pictures were taken over a period of about 8 to 10 days of the area after Charley passed through, and that it was directly hit by the storm carrying winds of around 140 mph; this seemed to be a good opportunity to make an inspection of damage of the area's houses to understand how well houses built to the current building codes survived.

The majority of the houses in this area also were built relatively recently (within the past 10 to 15 years), giving a solid database of houses that fit into the time frame of the current building codes. In addition, the average cost of a home in PGI, a subdivision (deed restricted waterfront community) of Punta Gorda making up the majority of the area containing residential houses, was around \$435,000, with an average living space area of 3500 ft^2 [1]. These numbers mean that, given the fact a higher than average cost for a house was paid, poor construction of the individual homes should be minimal from the data set, and the homes should in most cases meet or exceed building code requirements. With this being said, it was hoped that some useful information could be deduced by looking at the pictures of the damaged homes to potentially bring to light any flaws in the code. Figures 2.6 and 2.7 show a map view of Punta Gorda and its surrounding locations.

2.4 Development of the Current Florida Building/Wind Codes

After Hurricane Andrew (category 5) passed through south Florida on August 24, 1992, state lawmakers and building officials saw a significant need for reforming the way homes and other residential structures were being built. Widespread devastation was prevalent all along the storm's path in south Florida, being especially visible in the Miami-Dade County area. According to Thompson [8], the houses built in the area between 1980, and the year the storm hit, 1992, were 68 percent more likely to be uninhabitable after the storm than the homes built earlier. This was in part a result of a building boom in that time period, leading to more liberal construction methods being allowed by local building commissions, as well as a higher likelihood of poor construction by contractors in order to maximize profits and their workload. Another problem also evident for the homes built at the time was a lack of clear cut guidelines to design a house to withstand wind loadings experienced during a hurricane. The end result of the storm showed that there was a need for a more detailed, and uniform building code to be developed.

Up to that time, the Standard Building Code (SBC) governed the design of residential structures in the southeastern United States. As a result of the extensive investigation that followed the aftermath of the storm, detailed construction specifications were developed, resulting in the creation of the "Standard for Hurricane Resistant Residential Construction (SSTD 10)" [9], also referred to 'SSTD 10'. It was published in 1993, and revised in 1999 [10], and provided a prescriptive wind resistant design method, as well as construction details for one, two, and three story residential buildings, and was used for high-wind regions of the coastal sections of the U.S. where the SBC had governed residential construction, including Florida.

Starting in 2002, Florida adopted its own building code (FBC) [11], with the wind load provisions required for wind design being deferred to those required in ASCE 7-98 [12]. The FBC has subsequently been revised since the 2001 code, to the current version at the time of the writing of this paper to a 2004 code. However the construction methods for the wind design of houses has changed little. ASCE 7-98 is a standard published by the American Society of Civil Engineers, titled "Minimum Design Loads for Buildings and Other Structures". Chapter 6 of this standard outlined how to obtain wind loads for buildings of different size and shape, including typical residential structures, like houses. It has since been revised in 2002 (ASCE 7-02), and 2005 (ASCE 7-05), but chapter 6 has remained relatively unchanged.

The 2001 FBC was the latest building code built at the time that Hurricane Charley hit southwest Florida. ASCE 7-98 was the related wind load provision used with the 2001 FBC. Assuming that the latest homes in the Punta Gorda area were built to the requirements of the 2001 FBC and ASCE 7-98, these references will be used throughout this report as the codes that will be closely examined for any for any potential flaws, as stated earlier in this paper.

Figure 2.1: Hurricane Ivan Making Landfall
(Courtesy of the NHC website [5]).

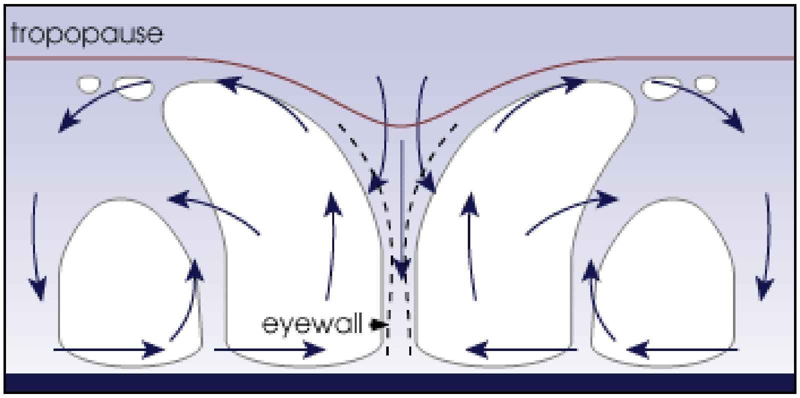


Figure 2.2: Hurricane Cross Section
(Courtesy of "Tropical Cyclones", the Wikipedia website [4])

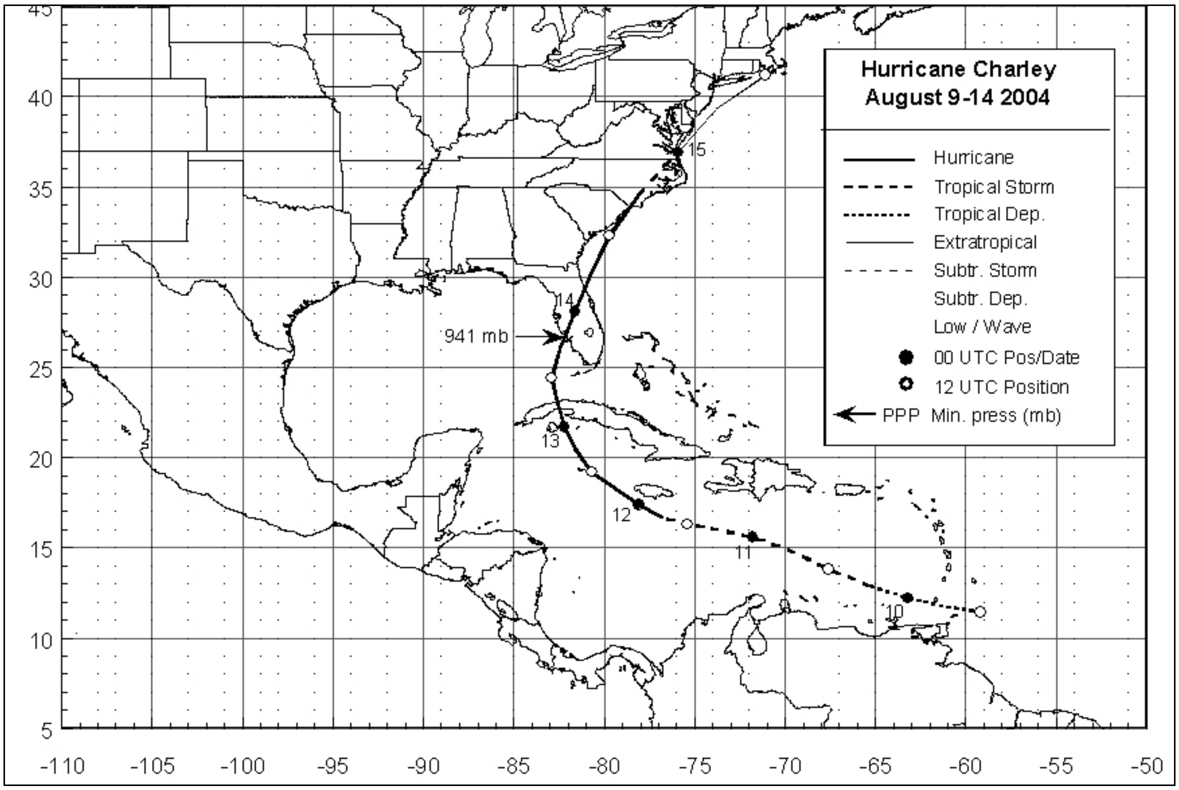


Figure 2.3: Storm Track of Hurricane Charley
(Courtesy NHC Report on Charley [6]).

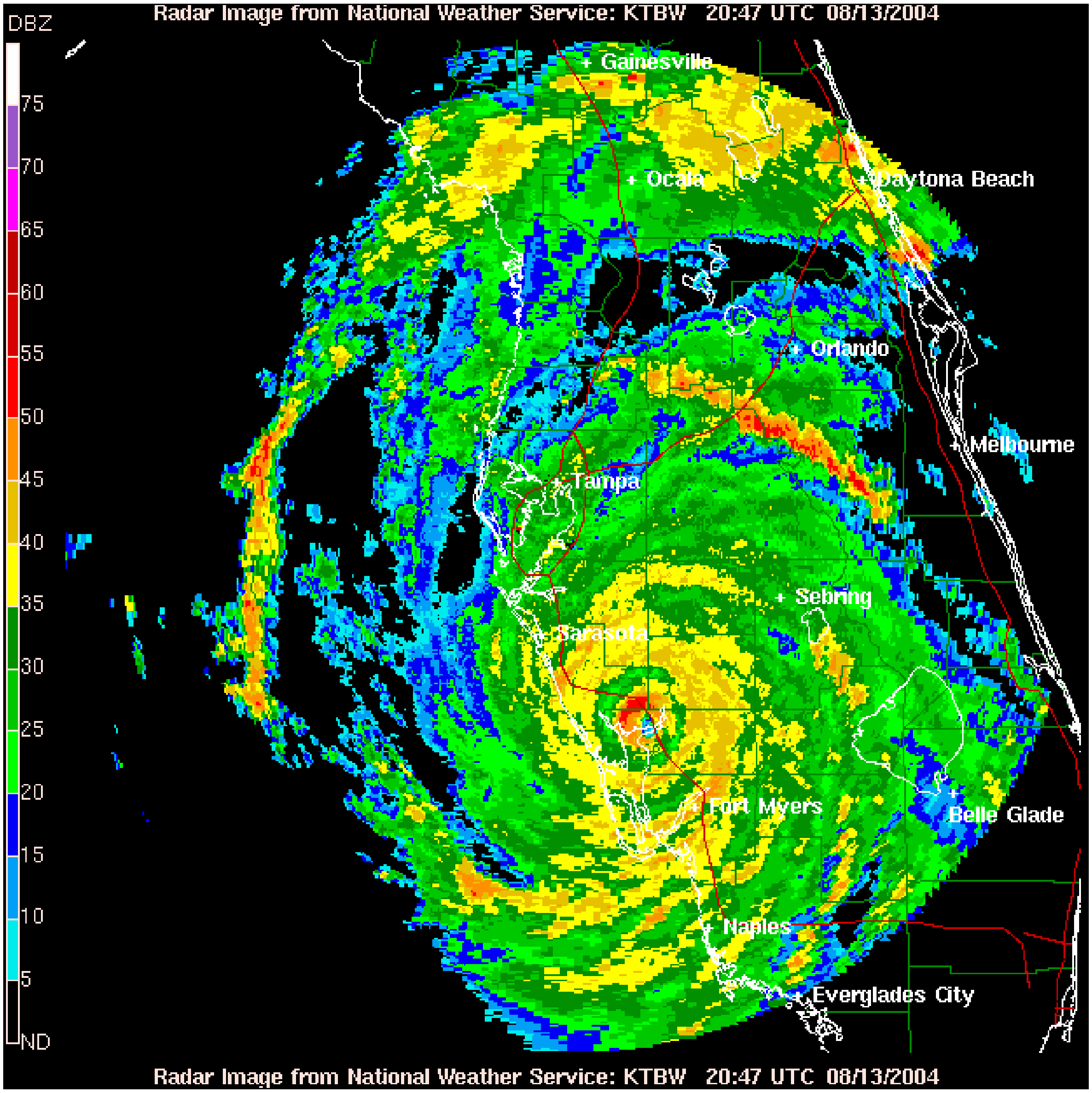


Figure 2.4: Radar Image of Charley Making Landfall
(Courtesy of "Hurricane Charley Impact Study", USGS [7])

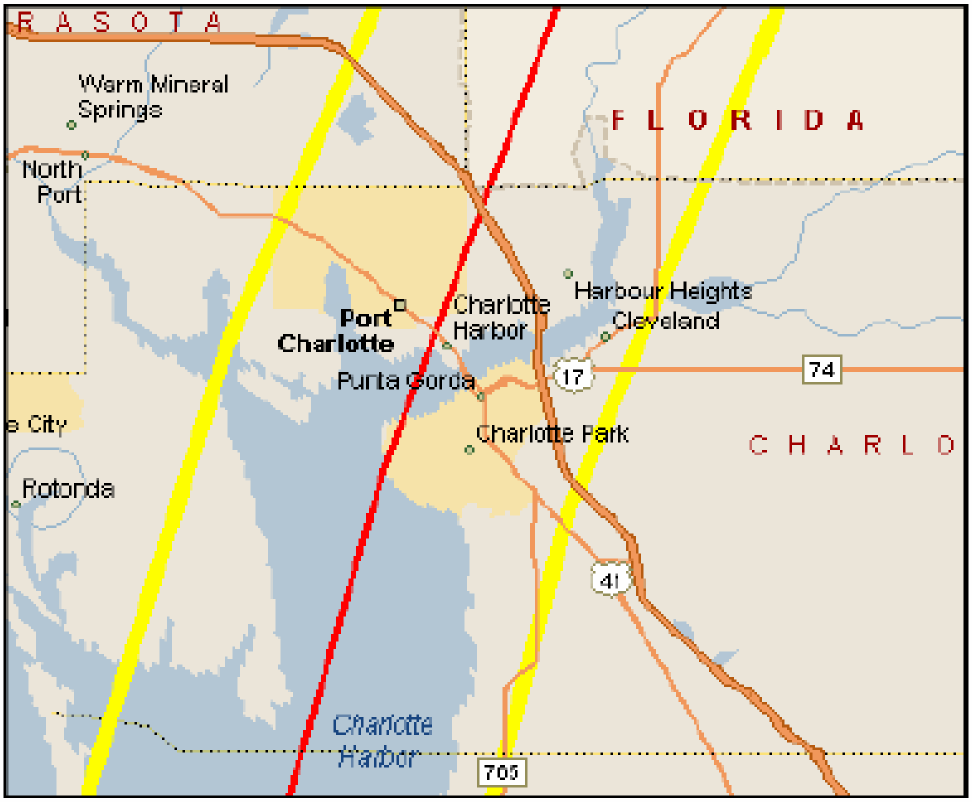


Figure 2.5: Hurricane Charley Wind Swath Through PGI

This figure shows where the center of the storm passed through the Punta Gorda area (red line), and where the hurricane-force winds were felt, approximately 7mi. from the center. (Courtesy Sen, et. al [1]).

Figure 2.6: Location of Punta Gorda Relative to Florida

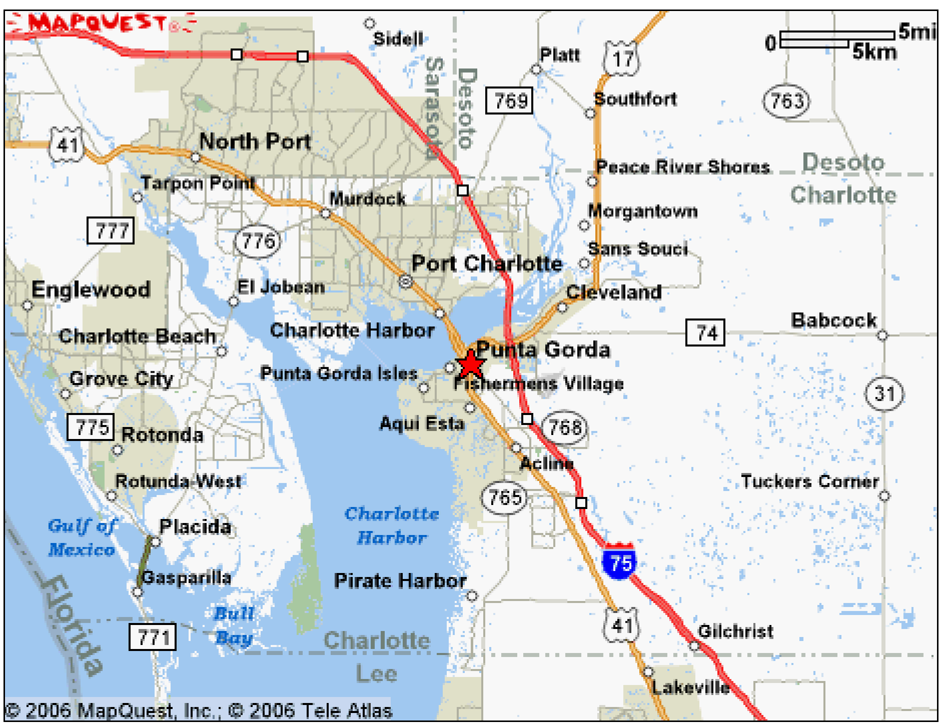


Figure 2.7: Map of Punta Gorda

Chapter 3 Finding the Design Wind Load

3.1 Introduction

This chapter will discuss how wind loads are found using the ASCE 7-98 standard. Before this can be done, however, it is important to first talk about the common roof shapes of houses encountered in Punta Gorda. After the roof shapes are defined, a basic understanding of how wind loads behave on structures, and how pressure coefficients are developed, will be discussed. With this knowledge, the topic of how to use the ASCE 7-98 standard can then be elaborated upon with better understanding.

3.2 Common Roof Shapes

In the Punta Gorda area, the majority of homes are one-story homes with either a hipped, gabled, or combination hipped/gabled roof. Gabled roofs are roofs that slope upwards from opposite walls and meet at a ridge in the center. The walls perpendicular to the gables are often called the gable end, or wall. Figure 3.1 shows a typical gabled roof house. Hipped roofs are sloped on all sides and also meet in a ridge. Figures 3.2(a) and (b) show a typical hipped roof house. The houses in Punta Gorda typically would be hipped, but some would have both hips and gables. More discussion will be placed on this variability later in the paper.

3.3 Wind Loads on Structures

Wind loading on structures has many variables such as wind velocity, wind direction relative to the structure, the height of the structure, the shape of the structure, and the size of the structure, to name some of the more important items. This subject also can get very complicated when discussing the different wind effects associated with turbulent wind flow, and how their loads are distributed to the structure. The purpose of this section is to explain the relevant topics to this study and how they are related to the ASCE 7-98.

Pressure coefficients are a necessary part of wind loading analysis. Using Bernoulli's equation, the concept can be explained. Assuming the same height along a streamline, the pressure, p, air density, ρ_a, and air velocity, U, are related below:

$$p + \frac{1}{2}\rho_a U^2 = constant \qquad \text{Eq. (3.1)}$$

This equation shows how energy is conserved from one point to another along a streamline. Relating Eq. (3.1) to flow around a structure, assume the pressure, p, and velocity, U, occurs at some location on or around the structure, while p_0 and U_0 are the pressure and velocity at a location unaffected by the structure.

$$p + \frac{1}{2}\rho_a U^2 = p_0 + \frac{1}{2}\rho_a U_0{}^2 \qquad \text{Eq. (3.2)}$$

Rearranging,

$$p - p_0 = \frac{1}{2}\rho_a \left(U_0{}^2 - U^2\right) \qquad \text{Eq. (3.3)}$$

The surface pressure on a body is usually expressed in the form of a non-dimensional pressure coefficient, as shown below:

$$C_p = \frac{p - p_0}{\frac{1}{2}\rho_a U_0^{\ 2}}$$ Eq. (3.4)

Applying Bernoulli's equation:

$$C_p = \frac{\frac{1}{2}\rho_a \left(U_0^{\ 2} - U^2\right)}{\frac{1}{2}\rho_a U_0^{\ 2}} = 1 - \left(\frac{U}{U_0}\right)^2$$ Eq. (3.5)

In general, a positive pressure will be indicated by a positive pressure coefficient, and a negative pressure, or suction, will be indicated by a negative pressure coefficient. Suction occurs when the local velocity at the surface point exceeds that of the unaltered velocity (U_0), and positive pressure occurs when U_0 is not exceeded. As wind flows around a structure/object, there is a point on the object's surface where the flow "separates" around the object. Typically at this separation point the flow velocity is zero, giving a pressure coefficient value of one. This point is often referred to as a stagnation point. Figure 3.3 is taken from Holmes [13], and illustrates the concept of fluid flow around a wing-shaped object, showing the stagnation point. At the stagnation point, all of the kinetic energy from the wind is transformed into pressure head.

Figures 3.4 and 3.5 are taken from Newberry and Eaton [14], and show the fluid flow around a flat plate, and the corresponding pressure distribution on the front face of the plate. Looking at Figure 3.5 the stagnation point on the plate is at the geometric center of the plate, and the lower pressure coefficients away from the center show that only a fraction of the kinetic energy from the flow is transformed into pressure head. By looking at pressure coefficients from this perspective one can visualize how the wind diverges from a point (pressure coefficient values that are either positive or negative fractional values), or converges to a point (pressure coefficient values that are either positive or negative values that are integers greater than 1).

As said before the size and shape of the structure in question affects how pressure will be distributed. Typically, hipped roofs behave better under high wind loading than do gabled roofs. This is most likely due to the more aerodynamic shape of the hipped roof since it is sloped on all sides. Figure 3.6 shows two houses of approximately the same footprint area, but one with a gabled roof and one with a hipped roof, and their corresponding pressure distribution. It was taken from a paper written by Meecham, et. al [15], and show the results obtained from a wind tunnel analysis for both houses (scaled down to 1:100 for the experiment). The pressure distribution is the worst case pressures from all wind directions, shown collectively on one picture of each house. Looking at the figure, the gable roofs receive higher pressures around their gable end walls, as the hipped roofs receive higher pressures along the ridges of the hips, as well as on the corners. The gabled roof, however, does receive the highest pressures, showing pressure coefficient values near the gabled end walls of -6.5.

3.4 Using ASCE 7-98

Before discussing how the design wind loads are determined using ASCE 7-98, a brief discussion of the Standard's terminology should first be presented. When discussing wind direction, a windward side of a building is the part which is facing the wind, or the upwind side. The leeward side is the side of the building facing away from the wind, or the downwind side. Typically, for the majority of houses, the windward part of the house will receive positive wind pressures, while the leeward side will receive suction. A building's structural members and attachments are often collectively referred to as the building envelope. ASCE 7-98 splits the building envelope into two categories, the Main Wind Force Resisting System (MWFRS) and the Components and Cladding (C&C). The MWFRS is defined in the ASCE 7-98 as "*An assemblage of structural elements assigned to provide support and stability for the overall structure. The system generally receives wind loading from more than surface.*" The C&C are defined as "*Elements of the building envelope that do not qualify as part of the MWFRS*."

The *SEAW Commentary on Wind Code Provisions* [16] points out how when designing the MWFRS, large design areas are most often used when designing for the wind pressure. This is because the wind pressures will be acting on larger parts of the building's main structural frame and supports, such as its walls, roof girders and beams, and all the connections. The design pressure coefficients for MWFRS are typically smaller than those for C&C. This is because the wind loads acting on the MWFRS are not localized to one small part of the structure, but rather over one side of the wall or roof. On the other hand, the C&C elements such as wall siding and roof tiles or shingles can have high localized wind pressures on certain parts of the structure relative to its size and shape. Once the wind loads are known for the MWFRS and C&C, the specific elements of the building envelope corresponding to each group can then be designed, based on their areas, spacing, etc.

The mean roof height (h) is defined by ASCE 7-98 as "*the average of the roof eave height and the height to the highest point on the roof surface*". For roofs with slopes less than 10°, the mean roof height is taken as the roof eave height.

Another important consideration in using the ASCE 7-98 is a building's exposure category. Exposure category takes into account the surrounding environment upwind of the building to be analyzed. For the purposes of this report, since Punta Gorda is in a low lying area near or on the water, only Exposures B and C were considered relevant. Exposure B is defined as "*Urban and suburban areas, wooded areas, or other terrain with numerous closely-spaced obstructions having the size of single-family dwellings or larger.*" Use of this exposure is restricted to buildings for which the previously mentioned terrain prevails in the upwind direction for a distance of at least 1500 ft., or 10 times the height of the building or structure, whichever is greater. Exposure C is defined as "*Open terrain with scattered obstructions having heights generally less than 30 ft.*" This category includes "*flat, open country, grasslands and shorelines in hurricane prone regions*". Once the exposure category is known, an exposure coefficient (K_z) is given, based on the exposure category and mean roof height, to use in the wind pressure calculations.

An importance factor (I) is a coefficient used in the wind pressure calculations. Different values are assigned to different classifications of buildings. Houses are given building classification 2, with the associated importance factor of 1.00. Buildings that house large amounts of people are given importance factors greater than 1.00 in order to make the design pressure more conservative due to the added "importance" of the structure.

The directionality factor (K_d) accounts for "*(1) the reduced probability of the maximum winds coming from any given direction; and (2) the reduced probability of the maximum pressure coefficient occurring for any given wind direction*". It is only used in when used with load combinations found in Chapter 2, such as:

$$U = 1.2D + 1.6 * K_d * W + 0.5L \qquad \text{Eq. 3.6}$$

, where U is the ultimate load, D is the dead load, K_d is the directionality factor, W is the wind load, and L is the live load. For the purposes of this report, an ultimate load analysis will not be performed on any parts of the houses being studied, therefore the directionality factor can be assumed to be 1.00.

The topographic factor (K_{zt}) is used when a building is located on a ridge or hill, and takes into account wind speed-up effects around these features. Since Punta Gorda, and south Florida in general, is relatively flat, this factor is ignored and assumed to be 1.00.

The enclosure classification, either enclosed (E), partially enclosed (P), or open (O), refer to the amount of openings a building's walls have and are used to determine the internal pressure coefficients acting on a building's interior. ASCE 7-98 defines an open building as, "*A building having each wall at least 80% open. This condition is expressed for each wall by the equation $A_o \geq 0.8A_g$ where:*

A_o = total area of openings in a wall that receives positive external pressure, in ft^2 (m^2)

A_g = the gross area of that wall in which A_o is identified, in ft^2 (m^2)"

A partially enclosed building is defined as, "*A building which complies with both of the following conditions:*

1. *the total area of openings in a wall that receives positive external pressure exceeds the sum of the areas of openings in the balance of the building envelope (walls and roof) by more than 10%, and*
2. *the total area of openings in a wall that receives positive external pressure exceeds 4 ft^2 (0.37 m^2) or 1% of the area of that wall, whichever is smaller, and the percentage of openings in the balance of the building envelope does not exceed 20%.*

These conditions are expressed by the following equations:

1. $A_o > 1.10A_{oi}$
2. $A_o > 4\ ft^2$ $(0.37\ m^2)$ *or* $> 0.01A_g$, *whichever is smaller, and* $A_{oi}/A_{gi} \leq 0.20$

   where:

   A_o, A_g *are as defined for Open Building*

   A_{oi} *= the sum of the areas of openings in the building envelope (walls and roof) not including* A_o, *in* ft^2 (m^2)

   A_{gi} *= the sum of the gross surface areas of the building envelope (walls and roof) not including* A_g, *in* ft^2 (m^2) "

Finally, an enclosed building is defined as a building that does not meet the requirements of the partially enclosed or open buildings. Once the enclosure classification is known, then an internal pressure coefficient can be chosen, depending on the enclosure classification. This coefficient is used for the wind pressure calculations.

The effective wind area is the area used to determine the external pressure coefficients (GC_p). When using it for component and cladding elements, it is defined as, "*the span length multiplied by an effective width that need not be less than one-third the span length*".

The wind load provisions of ASCE 7-98, prescribe the designer to select one of three different methods to obtain the wind loads for whatever type of building is being analyzed. Method 1 is a simplified procedure, intended on simplifying the process of calculating the wind loads. However, this method is only applicable to a few specific types of buildings. The buildings must be 30 feet or less in height, "rigid" (their fundamental frequency must be greater than 1 Hz.), and regular shaped (defined as, "a building or other structure having no unusual geometrical irregularity in spatial form"), and have a roof slope less than 10°. This method streamlines the calculation process for MWFRS and C&C design pressures of the above-mentioned types of buildings, but its solutions are rather conservative, and broad.

Method 2 is the analytical design method. The main requirement outlined in the wind provisions of the Standard require that the building is regular shaped, as described above. It provides design pressures for MWFRS and C&C for various types of building shapes. The focus of this report was on low-rise buildings ($h \leq 60$ft) with hipped and/or gabled roofs, since the houses in Punta Gorda fit these criteria.

Method 3 is the wind tunnel design method, from which pressure coefficients are found using a wind tunnel analysis. This method is recommended for buildings of irregular shape, or of a roof shape that is not similar to those found in the ASCE 7-98.

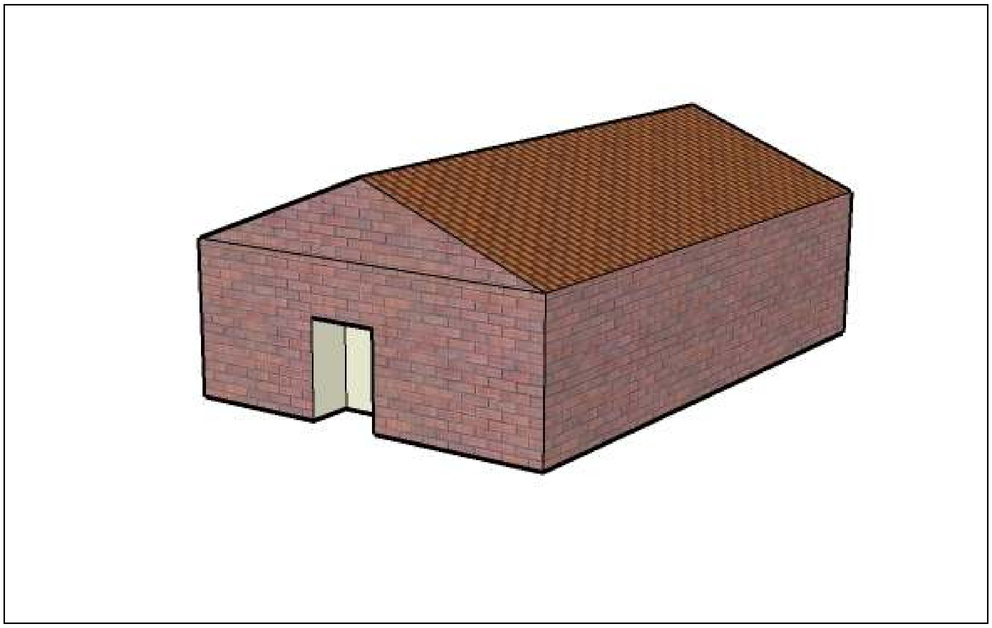
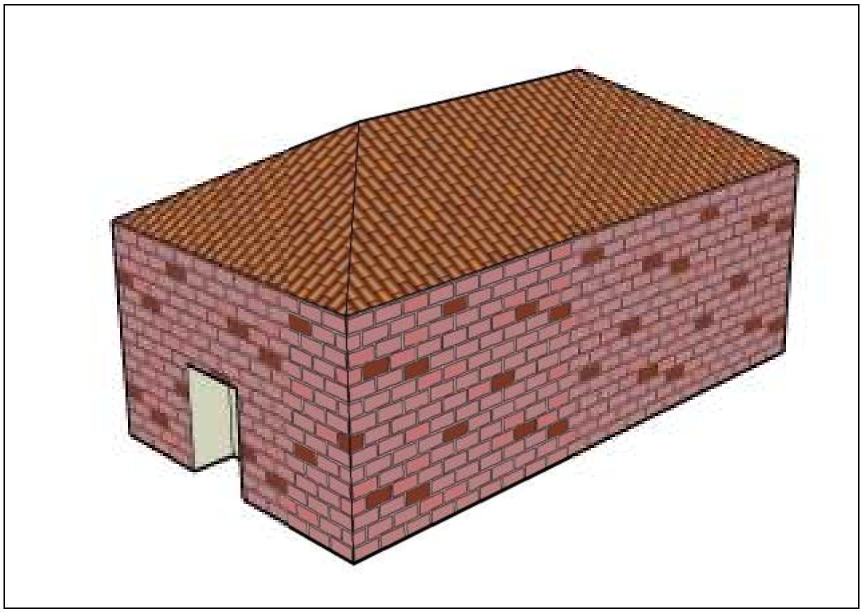
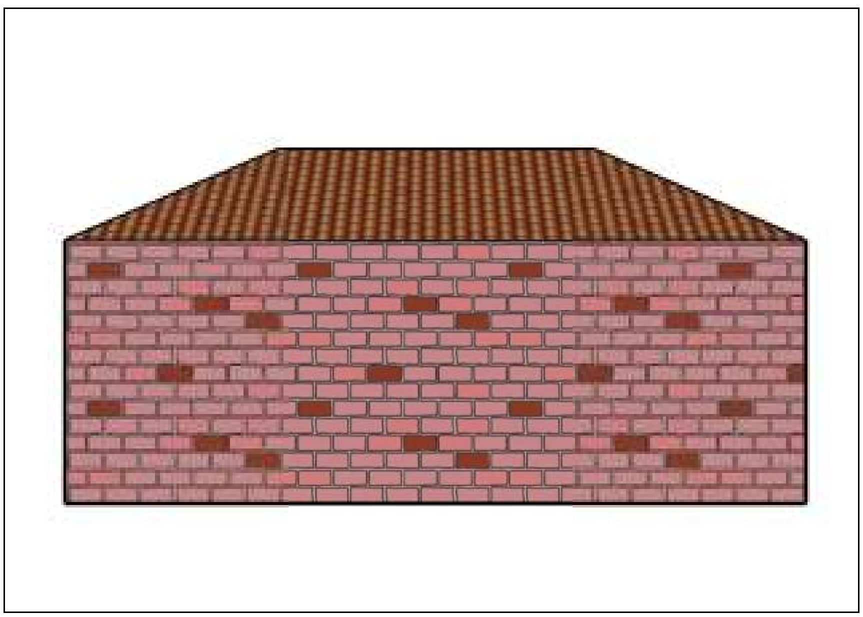


Figure 3.1: Typical Gabled Roof House



(a)



(b)

Figure 3.2: (a) Typical Hipped Roof, (b) Typical Hipped Roof—Side View

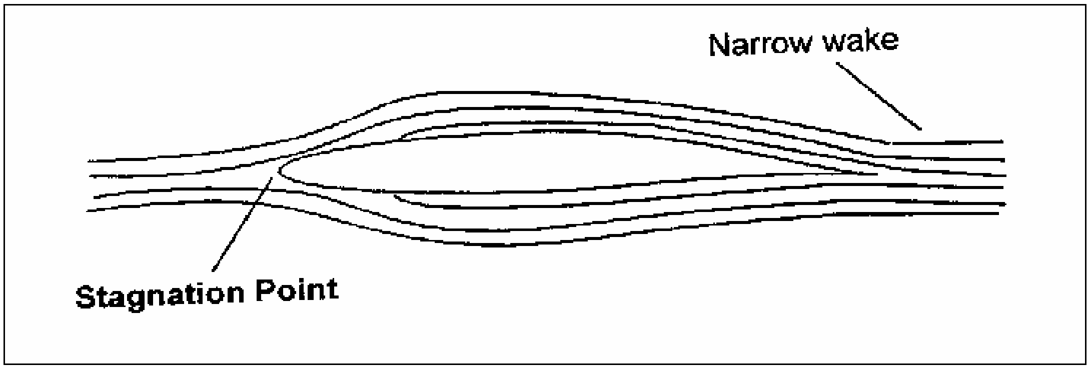


Figure 3.3: Airflow Around an Object
(Courtesy of Holmes [13]).

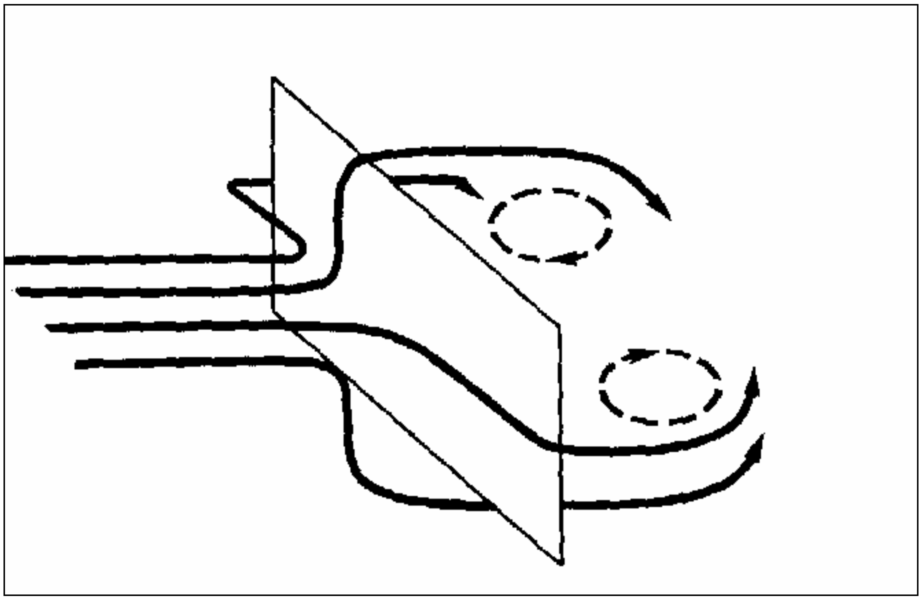


Figure 3.4: Flow Around a Flat Plate
(Courtesy of Newberry and Eaton [14]).

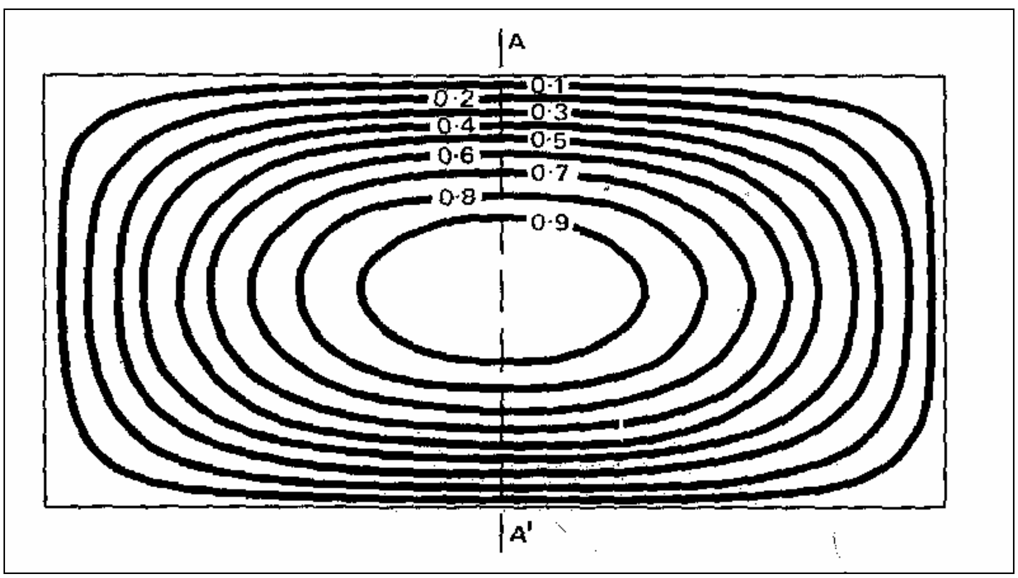


Figure 3.5: Pressure Distribution on the Front Face of the Plate
(Courtesy of Newberry and Eaton [14])

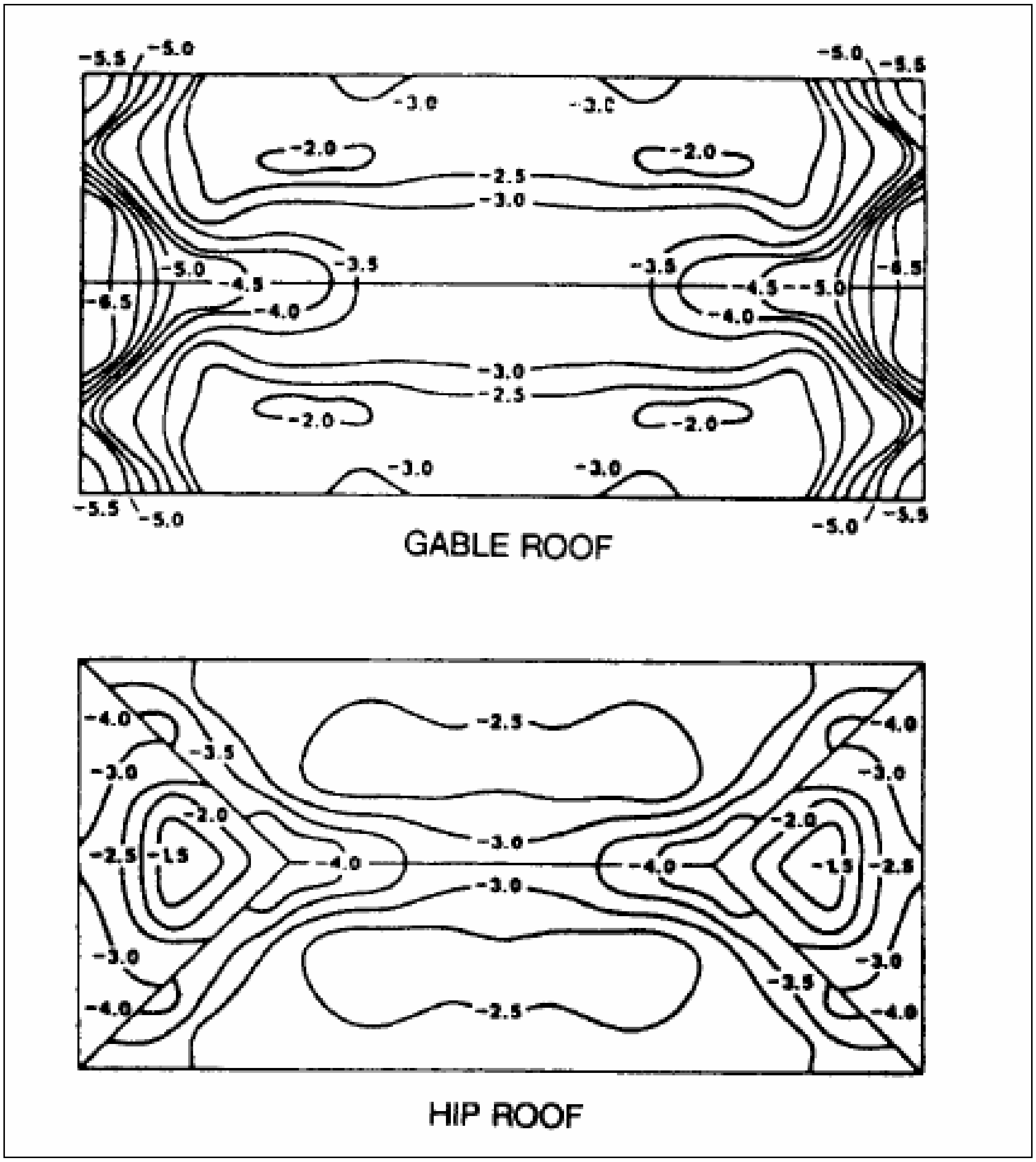


Figure 3.6: Worst Case Hipped and Gabled Roof Pressure Distribution
(Courtesy Meecham, et. al [15]).

Chapter 4 Method to Obtain Data

4.1 Introduction

This chapter discusses how the pictures of the damaged houses were selected using the Pictometry program based on the type of wind damage, year built, etc. It then discusses how data was collected for the houses selected to perform an accurate comparison between the design wind pressure and the Hurricane Charley wind pressures.

4.2 Selecting Damaged Houses Using Pictometry

The program known as Electronic Field Study 2.6, created by Pictometry International is a program that gives aerial photos of various areas from oblique angles, as opposed to the traditional aerial views which are orthogonal, and one area is taken from all four cardinal directions (north, south, east, and west). The advantage of looking at a building at an oblique angle is that the sides of the building become more visible than when looking straight down, as would be the case from an orthogonal photo. Using this program, with local latitude and longitude coordinate information, and other local geographical information, uploaded, individual building locations could be found using an address search. Not all of the houses on the Pictometry maps were in the uploaded databases, therefore for those houses their corresponding addresses were found using the Charlotte County GIS website [16], maintained by the Charlotte County Property

Appraiser's office. Once a house was selected, its image could then be captured and sent to another program as a jpeg file.

The main advantage to this program, however, was that the area around Punta Gorda, including PGI, was photographed only a little over a week after Hurricane Charley went through the area, giving a good look at the damage to the area from the hurricane. The majority of the pictures of the area were taken on August 21, 2004, only eight days after the storm made landfall in the area. A few of the pictures were taken a couple of days later on the 23rd. The fact that the pictures were taken right after a major hurricane swept through the area, became the foundation for the research of this project.

The criteria for finding damaged houses was to find a house that appeared damaged from the photograph from wind loading damage only, not damage occurring from windborne debris. Windborne debris damage is damage that occurs when objects are blown into the house due to the high hurricane winds. The type of damage that is incurred results from an impact load, and is outside the scope of this project.

Once the wind damaged house was found the house had to be built on or after 1996, when the major code changes went into effect following Hurricane Andrew. This was done first by looking over the list of "damaged" and "minor damaged" houses from the Sen, et. al report [1], as the author of this thesis had access to all of the computer files and data from that research. The "damaged" and "minor damaged" houses had already been located, and their pictures catalogued, by researchers who wrote that report. After the homes previously recorded had been investigated for wind loading damage, then the rest of the area was searched for houses fitting the criteria. Once a candidate house was found, its address was determined using local maps of the area and cross-referencing with the Charlotte County GIS website. When using the website, an address was entered into the site and an account number would come up. After selecting the account number, the property appraiser's information of the house would become visible, along with the year the house was built.

The selected houses were compiled into photos, and are shown in Appendix A. The pictures include the type of damage observed, a marker pointing which way is north, and the year the house was built. Once the houses were selected, an analysis of the structures using the ASCE 7-98 could then be attempted by finding the house dimension information, and their roof slopes. Appendix B shows ground photos of some houses in PGI taken with a digital camera.

4.3 Attempted Methods to Collect Data for the Wind Analysis

The most logical way to get the dimension data for the houses was to obtain copies of the individual plans from the Punta Gorda Building Department. After talking to various officials in the department and waiting for responses for an extended period of time, it became evident that the plans would not be available for copying, forcing the research to find another way to find the necessary data.

With the aid of Dr. Gray Mullins, a civil engineering professor at USF, another data collection method was developed. By using surveying equipment a basic house dimension could be plotted. Two theodolites were mounted on one tripod, along with an electronic distance measurement (EDM) device mounted to each theodolite. The tripod was set up in the area of the house to be plotted and a reflector was placed in close proximity to the house. The distance was then recorded from each EDM to the reflector, with each theodolite's horizontal angles being set to zero for a reference. Points along the house were then "shot to" from each theodolite to provide data points for a plot. Once the horizontal and vertical angles were recorded for each point from each theodolite, the data theoretically could then be plotted. Dr. Mullins wrote an algorithm on an Excel spreadsheet that would take the recorded data and plot it out, and also give the distances between data points. Once the data had been analyzed by the spreadsheet, then the dimension information of a house could be approximately determined. Since all of the data for a house was recorded from one location, only the part of the house visible from that location could be plotted, however the data could give an estimation of the wall length, eave height, roof height, and roof slope. Digital photos would also be taken of each house cross-referenced to each plot. Figures 4.1 and 4.2 show photos of the stereoscopic apparatus as it was used in the field.

The plan was to take the stereoscopic equipment to Punta Gorda and plot out the dimensions of the houses in the area that fit the criteria of being built on or after 1996. Once a large number houses were plotted, a statistical analysis could find the average dimension information required for an ASCE analysis. After the first trip to the area with the equipment, approximately 4 houses were plotted in 6 hours time; however when the data was analyzed, the algorithm could not plot the data correctly. It was found that the number of the data points selected for each house plotted was insufficient. On a return trip more care was taken to plot out each house, but not as many houses could be plotted in the same amount of time. The amount of time now spent plotting each house ranged from 1.5 to 3 hours. After a couple of weeks of traveling to Punta Gorda from Tampa (a roughly 100 mile trip), with the majority of houses still not plotting as hoped, this method was abandoned due to the large amounts of time spent with little results.

The algorithm did work correctly, however the amount of time required, and visual obstructions, such as trees and bushes around each home, which interrupted the segments between the data points, made this method unsuccessful.

4.4 Method of Data Collection for the Wind Analysis

After two unsuccessful attempts to obtain the dimension information for houses like those seen in the Pictometry, it was determined to ask professional engineers and contractors in the field about the house information. The first people contacted were local roofing contractors in Southwest Florida. Their contact information was found with the help of the Florida Roofing, Sheet Metal and Air Conditioning Contractors Association, Inc. (FRSA). Using their website and corresponding with their executive director, Steve Munnell, gave access to the email addresses of their members, dozens of roof contractors throughout Florida. Emails were sent out to the contractors, along with an attachment containing various questions about construction methods of roofs, and building information. Some responded, and their feedback gave a solid footing from which to continue the research. Appendix C lists these responses, along with the question attachment that was sent to them.

Further search for local professionals with knowledge of residential structure design/construction, as well as anyone with knowledge of wind loading design, led to a local engineer with sound knowledge in both areas, Jack Harrington. Mr. Harrington was licensed engineer with years of experience designing structures, including houses, for wind loading. He also knew the most common roof slopes, and approximate footprint dimensions, of most houses in southwest Florida and Punta Gorda, as he was from Port Charlotte, a community only about ten miles northeast of Punta Gorda. Mr. Harrington also allowed an Excel spreadsheet which he had written that performs C&C and MWFRS analyses on low-rise buildings using ASCE 7-98, to be used for research on this project.

After general information had been gathered about residential construction, and a tool was now available to assist the calculation process, an analysis for the houses in the selected photos could be undertaken.

Figure 4.1: Stereoscopic Equipment in the Field

Figure 4.2: Reflector Used as a Reference Point for the EDM

Chapter 5 Damage Observations and Analysis

5.1 Introduction

This chapter provides details on how an analysis was developed for the selected houses found using the Pictometry program. FEMA 488 [2], which was a report compiled by FEMA detailing the types of damage seen from Charley not only in the Punta Gorda area but throughout all parts of the state affected by the storm. It gave detailed description of the types of damage encountered to all types buildings that were subjected to the storm's high winds, and specifically discussed the structural performance of houses built with the post-Andrew building/wind codes in effect. It also gave conclusions and recommendations to potential problems in the construction and design practices as seen from assessing damage to the homes in the storm's path. This report pointed out that most homes built with the modern building/wind codes fared quite well with very few homes suffering major structural damage. However tile loss was common, specifically around the high pressure zones of hipped and gabled roofs.

By reading this report and cross-referencing their findings with the selected photos of the Punta Gorda area found using Pictometry, patterns of damage were observed in different regions of the roof that seemed common throughout the Punta Gorda area. These problem zones included the ridges and edges of hipped roofs, where roof tiles were often seen to be missing.

With all of the damage found on the selected houses, and nearly all seen in the area using Pictometry, to not have damage to its MWFRS elements, the decision was made to focus the analysis on the components and cladding of the selected houses, as all of those houses had some form of tile damage. Most of the houses encountered in Florida fit into a range of roof slopes of roughly 10° to 30°, as told by Jack Harrington. Therefore the analysis would focus on this range of roof slopes, and compare the design wind speed wind pressures of Punta Gorda (120 mph) to those estimated to go through the area when Charley hit (140 mph). The mean roof height would vary from 12 ft. to 30 ft., and the exposure category would vary for each roof height, from B to C.

5.2 The FEMA 488 Report and its Findings

The FEMA 488 Report titled, "Hurricane Charley in Florida: Observations, Recommendations, and Technical Guidance" was written in April of 2005. The report discusses every aspect of damage seen to structures impacted from Charley in the state of Florida. The types of structures discussed ranged from commercial buildings such as warehouses, gas stations, banks, or hotels, to residential structures such as one to two story houses and manufactured homes, and also critical and essential facilities such as fire and police stations and hospitals. This report focused on the information and findings related to houses.

The report began by discussing the wind effects of the storm as it went through Florida. It estimated the 3 second wind gusts in Punta Gorda to be between 125 and 140 mph for Exposure B, and between 140 and 160 mph for Exposure C structures. 3 second gusts are peak winds measured over a 3 second time period during a storm. ASCE 7-98 includes basic wind speed maps that have contour lines along different regions of the US where high-wind events are common. The map which includes Florida was adopted by the 2001 FBC, along with all of the wind loading provisions of ASCE 7-98. Figure 5.1 shows copy of the basic wind speed map for the 2001 FBC. Its wind speed requirements are identical to those found in ASCE 7-98. Looking at the coastal region of Charlotte County, where Punta Gorda is found, the design 3 second gust speed is 120 mph.

The report also points out that the Florida legislature modified the definition of Exposure C for the FBC (Chapter 553.71 of the Laws of Florida [17]). The modified exposure category is defined as, "*'Exposure category C' means, except in the high velocity hurricane zone, that area which lies within 1,500 feet of the coastal construction control line, or within 1,500 feet of the mean high tide line, whichever is less. On barrier islands, exposure category C shall be applicable in the coastal building zone set forth in s. 161.55(5).*" This modification implies that the majority of houses in Punta Gorda, specifically PGI are in this exposure category, due to the fact that there are canals winding throughout this entire area.

The report discusses how for the most part, houses built to building codes after the major changes went into effect following Hurricane Andrew fared quite well, with major structural damage such as roofs being lifted off the walls being uncommon. The components and cladding damage, however, was widespread throughout most of the hurricane's path. This included garage doors being pulled out from suction, roof tiles being blown away, as well as damage to doors and windows. Since the roofs were the area of focus from the Pictometry pictures, and roof tiles were exclusively used for houses in the Punta Gorda area, the damage observations and findings to roof tiles was used as a reference. It found that tile damage was widespread from where it made landfall near Punta Gorda up to Orlando, in the central part of the state. Many reasons were given for damage such as error from construction in applying the tiles to the roof; however some roofs that appeared to have their tiles placed correctly still had tiles missing on the hip or ridge region of the roofs. This pattern was seen many times in the Punta Gorda area, as well as them being blown off from eaves near the roof edges.

The most common methods of attaching tiles to the roof were either by using mortar, or by directly fastening them using a nail or a screw. Another less common method of attaching the tiles would be to use a foam-set adhesive. The tiles would be fastened to an underlayment, which in turn would be fastened to the roof sheathing, typically a wood ply sheet. There are four methods outlined to attach roof tiles, as prescribed by the FRSA *Concrete and Clay Tile Installation Manual* [18], and these methods are adopted by FBC as the way to install the roof tiles. Field tiles are the tiles that are spread across the bulk of the roof surface, while hip and ridge tiles are the tiles that form the lines along a hipped or gabled roof where two roof surfaces meet. Figure 5.2 shows one of the common ways to install a hip/ridge tile, as shown in the FRSA installation manual. In one of the four installation methods, the manual recommends that the hip and ridge tile is set in a continuous bed of mortar, and then fastened with a nail or screw into the ridge/hip board. Figure 5.3 shows how the ridge/hip board is aligned along the roof, with the ridge/hip tiles attached to it. The hip and ridge tiles can be seen as intersection lines along the field tiles. Figure 5.4 shows a digital photo showing a ridge line of tiles of a house in PGI.

The report discussed hip and ridge tiles blow offs as common. It said that since the hip/ridge tiles projected a few inches higher than the surrounding field tiles, there a greater possibility for higher wind velocities to be felt in this region due to turbulence.

5.3 Damage Observations of the Selected Houses

Using the FEMA report as a reference, houses in the Punta Gorda area were looked over using the Pictometry software, wind damage to the houses was seen as hip and ridge damage. Appendix A shows the selected houses, along with comments in the figures pointing out the various types of wind damage. Appendix B shows some ground photos taken with a digital camera of some houses in Punta Gorda, taken while on a trip to the area. For each selected house, they are circled in blue, and their year built is shown, along with an arrow pointing in the direction of North. The types of damage seen looking at these photos correlates to the type of damage discussed in the FEMA report, with damage seen to hips and ridges, as well as to corners and edges along the eaves. The photos were evidence to focus on these regions when performing the wind analysis using ASCE 7-98.

5.4 Wind Analysis of the Damaged Houses Using ASCE 7-98

The most current building and wind codes to which the houses in Punta Gorda were built were the 2001 Florida Building Code, and the wind provisions of ASCE 7-98 (chapter 6 of the Standard). The analysis was carried out based on this principle, so that the resulting wind pressure values would reflect the most up-to-date wind load design values available to homes built at the time of Charley's arrival. Focusing on a component and cladding (C&C) analysis, and using the C&C analysis spreadsheet, the wind pressure analysis could be done. The roof slopes would fit in the range between 10° and 30° (a common range according to Mr. Harrington, and the various contractors who responded to my questions), where one of the figures from ASCE 7-98 (figure 6-5B) provides pressure coefficient for zones of hipped and gabled roofs. Figure 5.5 shows this figure that was used in the C&C analysis. In the figure hip and ridge zones are classified as zone 2 for hipped and gabled roofs. The corners along the eaves for hipped roofs are zone 3. A comparison would be shown between the design pressures of zones 2 and 3 for the design wind speed of the Punta Gorda area (120 mph), and for the maximum hurricane 3 second wind speed estimated by the FEMA Report for Exposure C (160 mph). This wind speed was chosen due to the fact that most of PGI would be classified as Exposure C. The mean roof height for the calculations would vary from 12 to 30 ft., and for each roof height there would be a calculation for Exposure B and Exposure C.

Before the results are presented, a brief discussion of how the C&C wind pressures are calculated will be explained to give a better understanding of how the spreadsheet obtained the design pressures.

The Analytical Method of ASCE 7-98 (Method 2) was used to carry out the analysis. In this method, first the design wind speed must be found. This is found from the basic wind speed discussed earlier and shown in Figure 5.1. The wind directionality factor (K_d), importance factor (I), exposure category (B or C) and corresponding exposure coefficient (K_z), topographic factor (K_{zt}), enclosure classification (E, P, or O) and corresponding internal pressure coefficient (GC_{pi}) are found next. After that the external pressure coefficients (GC_p) are then found based on the effective wind area taken off of a graph (like that shown in Figure 5.5), depending on roof height, shape, and slope. There are different external pressure coefficients corresponding to the different zones of the roof or wall being analyzed. Once the internal and external pressure coefficients are found, then the velocity pressure (q_h) can be determined. It is defined by Equation 5.1, or Equation (6-13) in ASCE 7-98:

$$q_h = 0.00256 K_z K_{zt} K_d V^2 I (lb/ft^2) \qquad \text{Eq. 5.1}$$

Once the velocity pressure has been found, then the design pressure can be found. As shown by Equation 5.2, or Equation (6-19) in ASCE 7-98:

$$p = q_h[(GC_p) - (GC_{pi})](lb/ft^2) \qquad \text{Eq. 5.2}$$

, where p is the design pressure. The above equation is only used for the C&C of buildings with mean roof heights less than or equal to 60 ft.

For the purposes of this study, the importance factor is 1.00 because a house is a class 2 building. The basic wind speed will vary between the 120 mph design speed and the 160 mph hurricane wind speed. The wind directionality factor will be 1.00 since this is only a wind analysis, and no load combinations are to be used. The exposure category will vary between B and C as stated above. The topographic factor will be 1.00, since topographic effects from wind loading will not be seen in the coastal region of Southwest Florida. The enclosure classification will assume the houses are enclosed, with minimal openings (this is done to simplify the number of calculation for the wind analysis). The corresponding internal pressure coefficients will be +0.18 for the positive pressure case, and -0.18 for the negative pressure case. When the external pressure coefficients are found there will be both positive and negative external pressure coefficients for a roof zone. Looking at Equation 5.2 above, the positive external coefficient will subtract the positive internal pressure coefficient, and vice versa. The external pressure coefficients will be found from Figure 5.5. After inputting the design wind speed, mean roof height, and exposure category, while leaving the enclosure classification, building classification, and topographic factor constant, the C&C analysis spreadsheet then calculates the velocity pressure, and determines the design pressure. The design pressure data is output for a range of effective wind areas from $10ft^2$ to $200ft^2$.

When looking at the more complex hip and gable roof shapes of the Pictometry pictures and comparing them to the simple hip and gable roof shapes of Figure 5.5, the zone placement is straightforward. Looking at the figure, zone

2 will be placed at every ridgeline, valley, and edge of a hip or gable roof. Wherever the zone 2 areas intersect, on a gable roof, that region is a zone 3, and any corners over eaves, either hip or gable, will also be zone 3. Zone 1 will be any field region not included in zones 2 or 3. The expected design pressure values should be highest for the overhang regions of zones 2 and 3, as the negative pressure external pressure coefficients for these zones in the plots at the bottom of the figure are the largest for these zones.

Looking at the zone assignments in Figure 5.5, the width of zones 2 and/or 3 is defined as "a". "a" is defined as "*10 % of the least horizontal dimension of the house or 0.4h* (where h is the mean roof height), *whichever is smaller, but not less than either 4% of least horizontal dimension (1 m.)* ". The exact placement of the zones was not needed for this analysis, as the data of interest were the design pressure values of these zones, not exactly where the pressures would be assigned.

To further explain how the spreadsheet performs the calculation to obtain the wind pressures for the component and cladding of a hipped or gabled roof with a slope and roof height described above, a worked out example will be presented:

Example Problem:

Find the component and cladding design wind pressures using the wind provisions of ASCE 7-98 for a one-story hipped roof house with a mean roof height of 25 feet, located in an inland area of Punta Gorda, Florida. Find the wind pressures for the roof tiles. Using the same procedure, find the *corresponding wind pressures for a wind speed of 140 mph. The roof slope of the house is 5:12. Assume the house is "enclosed".*

Given Information:

h = 25 ft

Step1: *Find the basic wind speed V and wind directionality factor K_d.*

Looking at Figure 6-1b of the Standard, the basic wind speed of the Punta Gorda area is found to be 120 mph. Since this is a wind loading analysis only, and no load combinations are to be used, the wind directionality factor is 1.00.

$V = 120mph\,;\ K_d = 1.00$

Step 2: *Find the importance factor, I.*

Looking at Table 1-1 of the Standard, this building is classified as a Category II building. Knowing this information, Table 6-1 gives a Category II building, in a hurricane region with *V* > 100 mph, an importance factor value of 1.00.

$I = 1.00$

Step 3: *Find the exposure category and corresponding velocity pressure coefficient K_z or K_h.*

Since only a component and cladding analysis is being calculated, only K_z will be found. As described in the problem statement, the house is located in an "inland" area, implying that the house is not lying near the coastline. The Punta Gorda area is a suburban area, with many houses around, and the terrain is relatively flat, with no escarpments. Therefore the exposure category for this house is B. Looking at Table 6-5 of the Standard, the exposure coefficient K_z is 0.70 for a house's components and claddings with *h* of 25 ft. and exposure B.

$$K_z = 0.70$$

Step 4: *Find the topographic factor, K_{zt}.*

Since the land is flat, and there are no escarpments K_{zt} will be set equal to 1.00.

$$K_{zt} = 1.00$$

Step 5: *Find the enclosure classification, and corresponding internal pressure coefficient, GC_{pi}.*

Following the same procedure used in this study, the house will be assumed to be classified as enclosed (E). Looking at Table 6-7 of the Standard, the internal pressure coefficients for an enclosed building are $\pm$ 0.18.

$$\pm GC_{pi} = \pm 0.18$$

Step 6: *Find the external pressure coefficients, GC_p.*

A roof slope of 5:12 is approximately 23°; therefore Figure 6-5B of the Standard will be used to find the external pressure coefficients. Figure 5.5 shows Figure 6-5B of the Standard. Figures 5.6 and 5.7 show the graphs from where the pressure coefficients are found, corresponding to each roof zone. Figures 5.8 and 5.9 show the corresponding roof zones, depending on whether the roof is gable or hip. Since the roof for this problem is a hipped roof, Figure 5.9 will be from where the zones will be found. The zones of the roof are found based on the length '*a*', where *a* was defined earlier. For simplification, the exact zone dimensions do not need to be defined, just a simple understanding of how they are arranged, which is shown in Figure 5.9.

The problem statement asked for the wind pressures to be found for the roof tiles. Since the component and cladding of the roof to be designed for are the roof tiles, the design area will be small. Looking at Figures 5.6 and 5.7, all of the external pressure coefficient data is constant for design areas of 10 ft^2 or less.

Therefore, a design area of 10 ft^2 will be used to find the external pressure coefficients.

To simplify the problem procedure for this example, one zone will be selected to obtain the external pressure coefficients, and then the calculation of the wind pressure can be shown. For this example, zone 1 will be chosen to obtain the external pressure coefficients. Looking at figure 5.6, the positive external pressure coefficient for zone 1, with an area of 10 ft^2, is +0.5. The negative external pressure coefficient for zone 1 is -0.9.

$$+GC_p = 0.5;\ -GC_p = -0.9$$

Step 7: *Find the velocity pressure, q_h.*

Using Equation 5.1, listed above:

$$q_h = 0.00256 K_z K_{zt} K_d V^2 I = 0.00256(0.70)(1.00)(1.00)(120)^2(1.00)\,psf = 25.8\,psf$$

Similarly, for the 140 mph wind:

$$q_h = 0.00256(0.70)(1.00)(1.00)(140)^2(1.00)\,psf = 35.1\,psf$$

Step 8: *Find the design pressure, p.*

Using Equation 5.2, listed above, the positive pressure acting on zone 1 is:

$$p = q_h[(GC_p) - (GC_{pi})] = 25.8\,psf[(0.5) - (-0.18)] = 17.5\,psf$$

The negative pressure acting on zone 1 is:

$$p = 25.8\,psf[(-0.9) - (0.18)] = -27.9\,psf$$

For the 120 mph basic wind speed, the design pressures for the roof are:

$$\boxed{p = +17.5\,psf, -27.9\,psf}$$

Similarly, for the 140 mph hurricane wind, the positive pressure is:

$$p = 35.1\,psf[(0.5) - (-0.18)] = 23.9\,psf$$

The negative pressure is:

$$p = 35.1\,psf[(-0.9) - (0.18)] = -37.9\,psf$$

For the 140 mph basic wind speed, the design pressures for the roof are:

$$\boxed{p = +23.9\,psf, -37.9\,psf}$$

This simplified example was done for one zone of the roof. For the analysis of this report, the design pressures of all zones were found for the 120 mph design wind speed, and the 160 mph hurricane wind speed. The positive pressure values signify the wind pressures “pushing” on the roof surface, while the negative pressure values are uplift or suction pressures, and signify the wind pressures “pulling” on the roof surface.

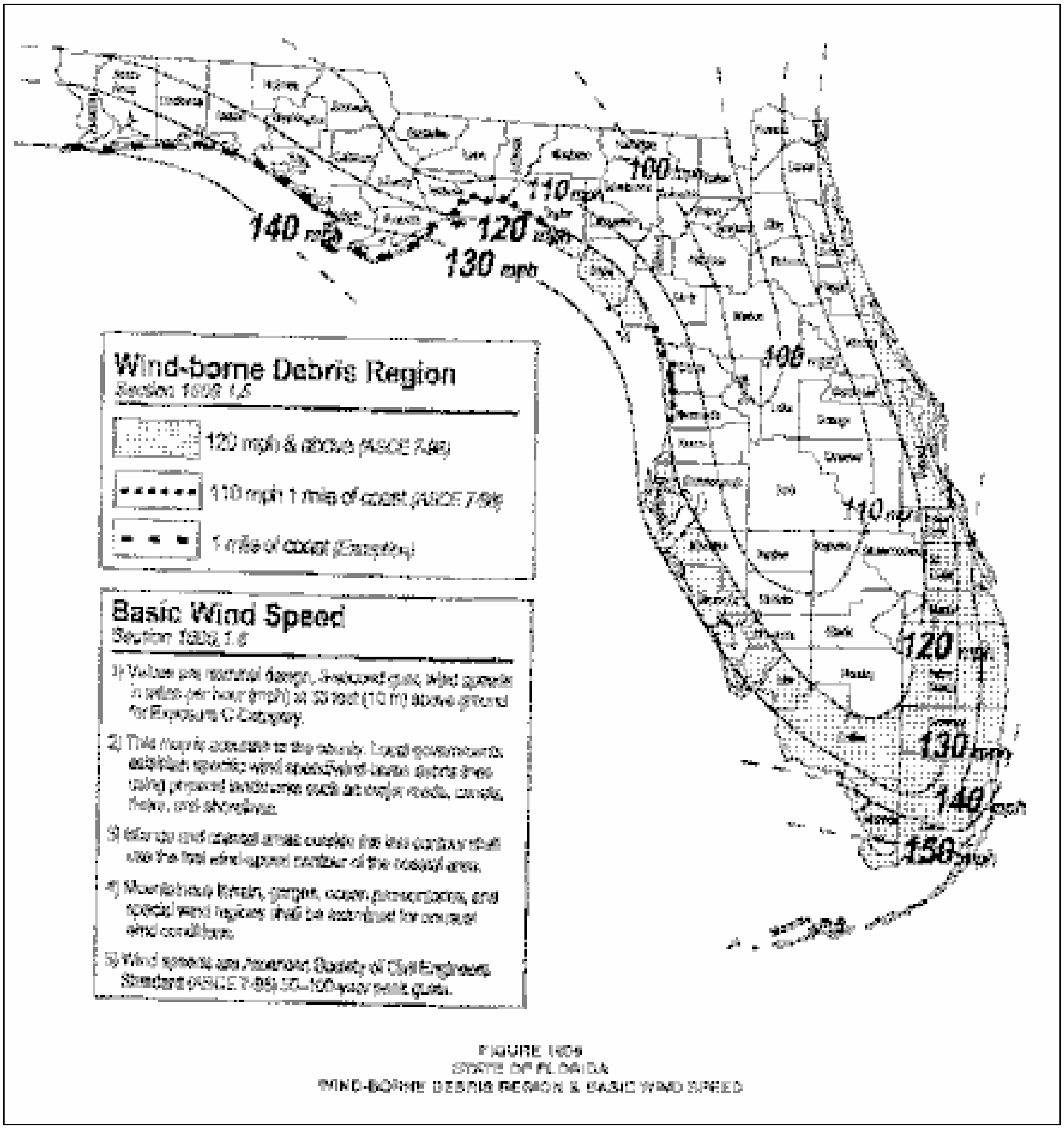


Figure 5.1: 2001 FBC Basic Wind Speed Map
(Courtesy of the 2001 FBC, Figure 1606).

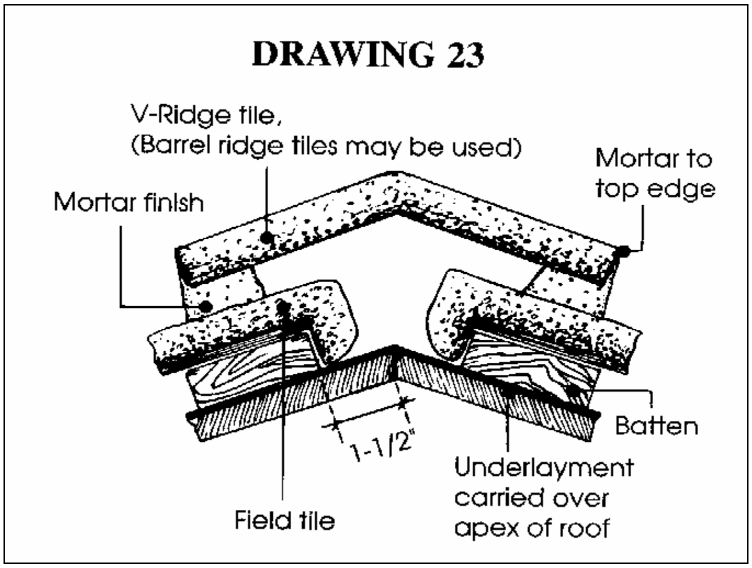


Figure 5.2: Ridge/Hip Tile Installation Instructions
(Courtesy of the FRSA roof tile installation manual [18]).

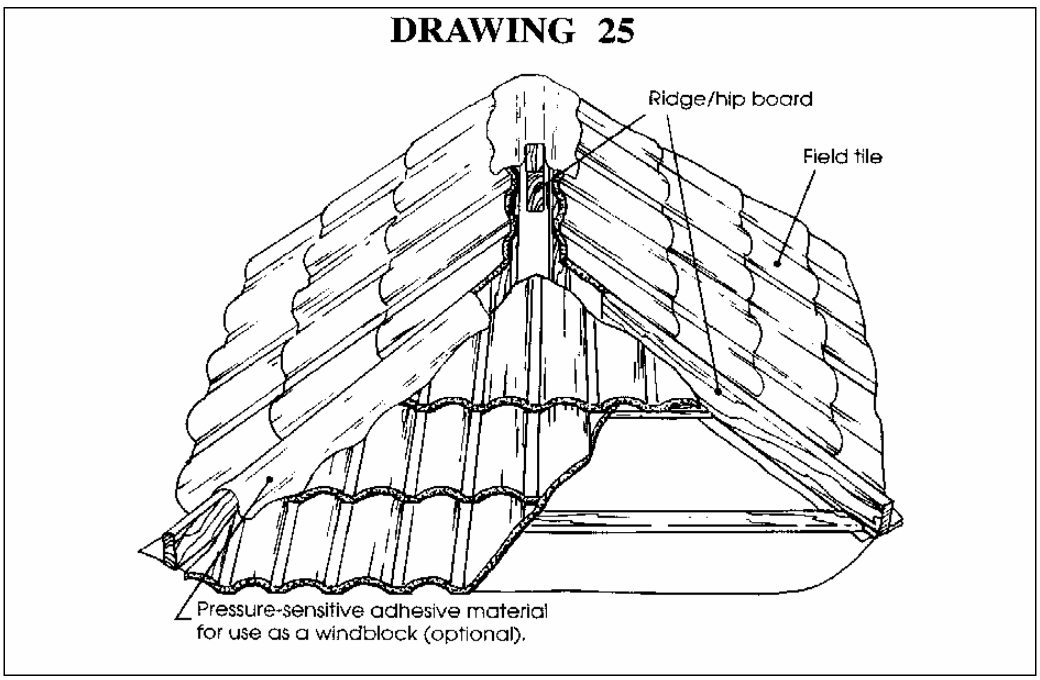
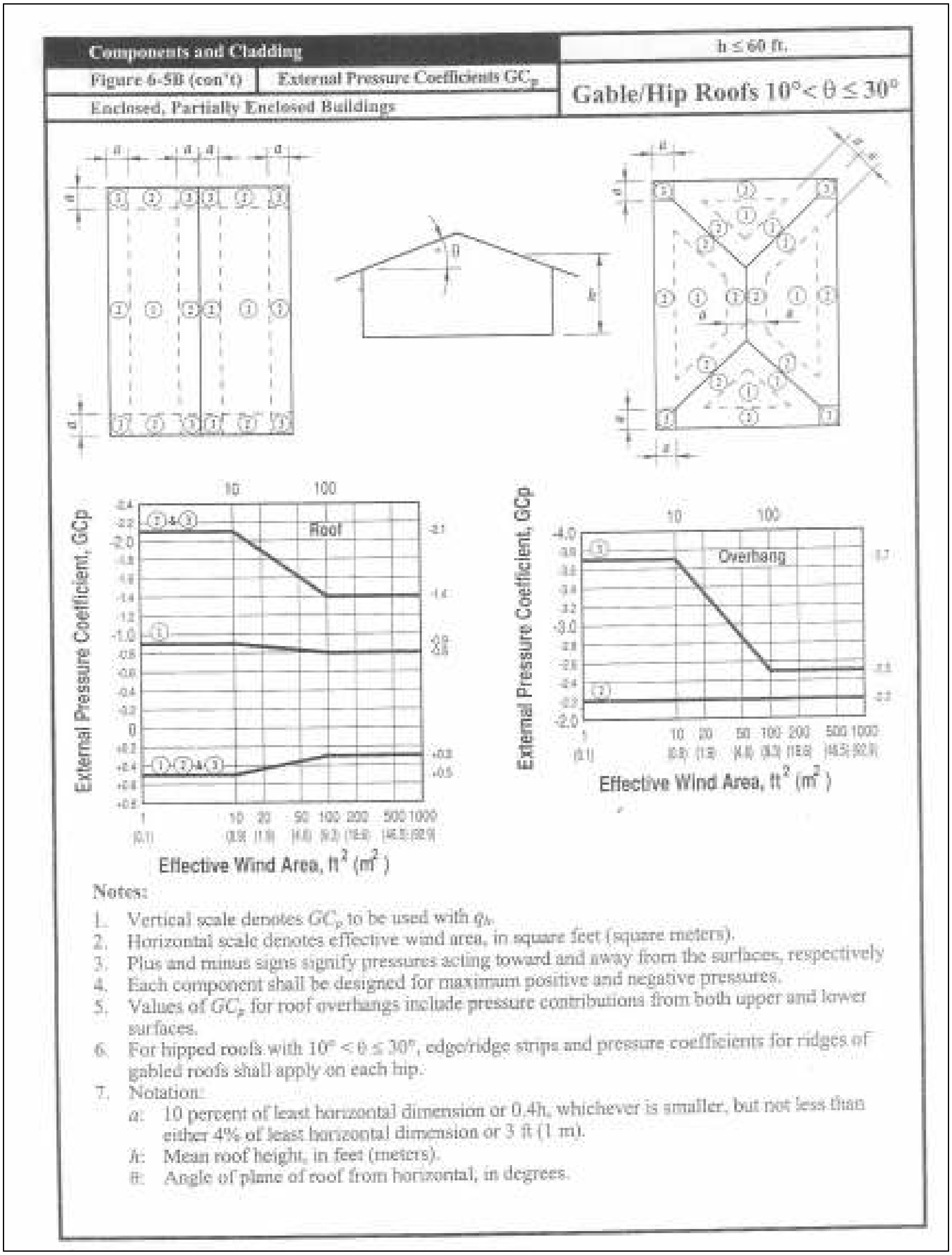


Figure 5.3: View of the Ridge/Hip Board
(Courtesy of the FRSA roof tile installation manual [18])


Figure 5.4: View of Ridges on a House in PGI



Notes:

1. Vertical scale denotes GC_p to be used with q_h.
2. Horizontal scale denotes effective wind area, in square feet (square meters).
3. Plus and minus signs signify pressures acting toward and away from the surfaces, respectively.
4. Each component shall be designed for maximum positive and negative pressures.
5. Values of GC_p for roof overhangs include pressure contributions from both upper and lower surfaces.
6. For hipped roofs with 10° < θ ≤ 30°, edge/ridge strips and pressure coefficients for ridges of gabled roofs shall apply on each hip.
7. Notation:
   - a: 10 percent of least horizontal dimension or 0.4h, whichever is smaller, but not less than either 4% of least horizontal dimension or 3 ft (1 m).
   - h: Mean roof height, in feet (meters).
   - θ: Angle of plane of roof from horizontal, in degrees.

Figure 5.5: ASCE 7-98, Figure 6-5B
(Courtesy of ASCE 7-98 [12]).

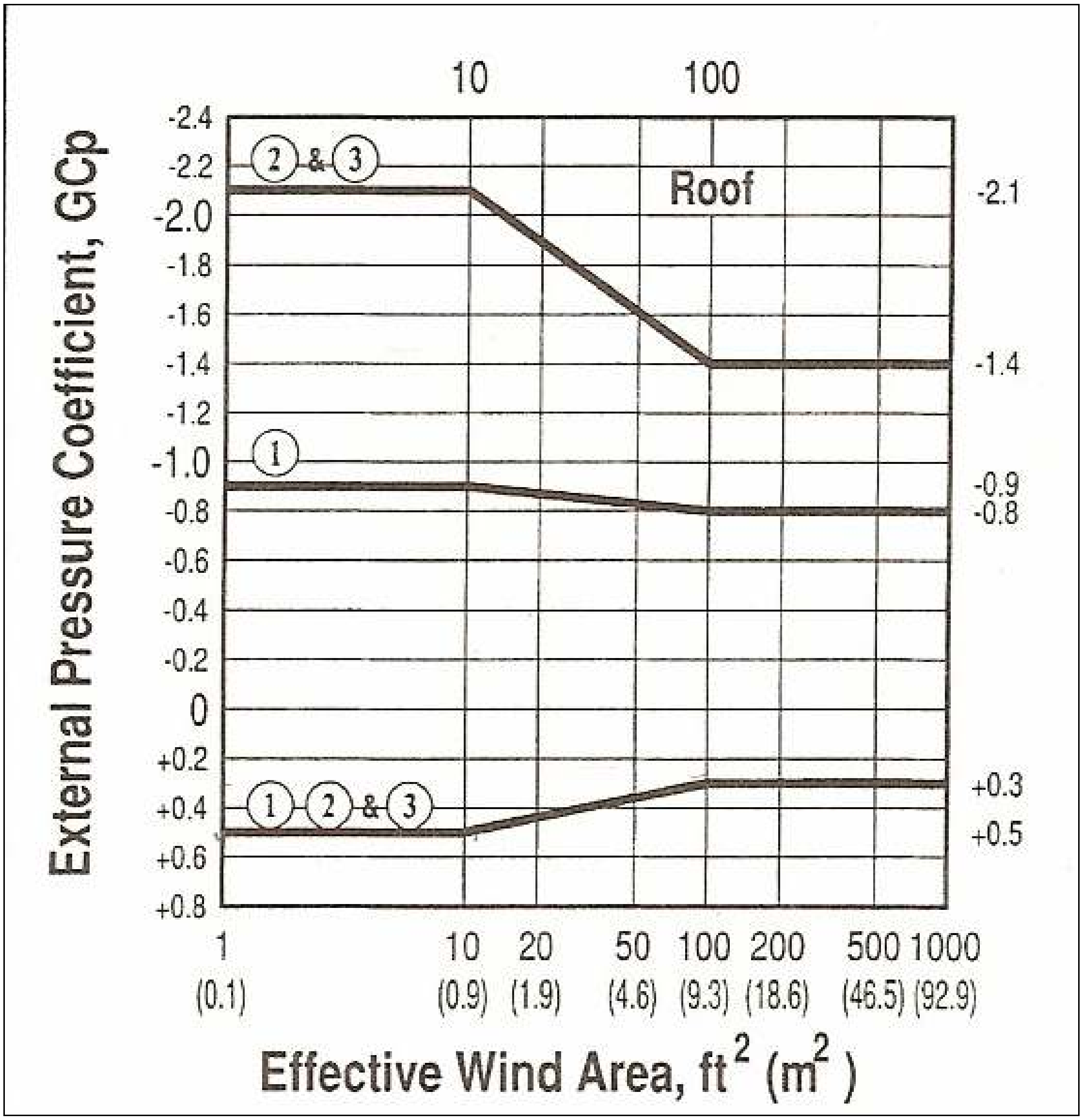


Figure 5.6: External Pressure Coefficient Data for Exterior Roof Zones
(Courtesy of ASCE 7-98 [12]).

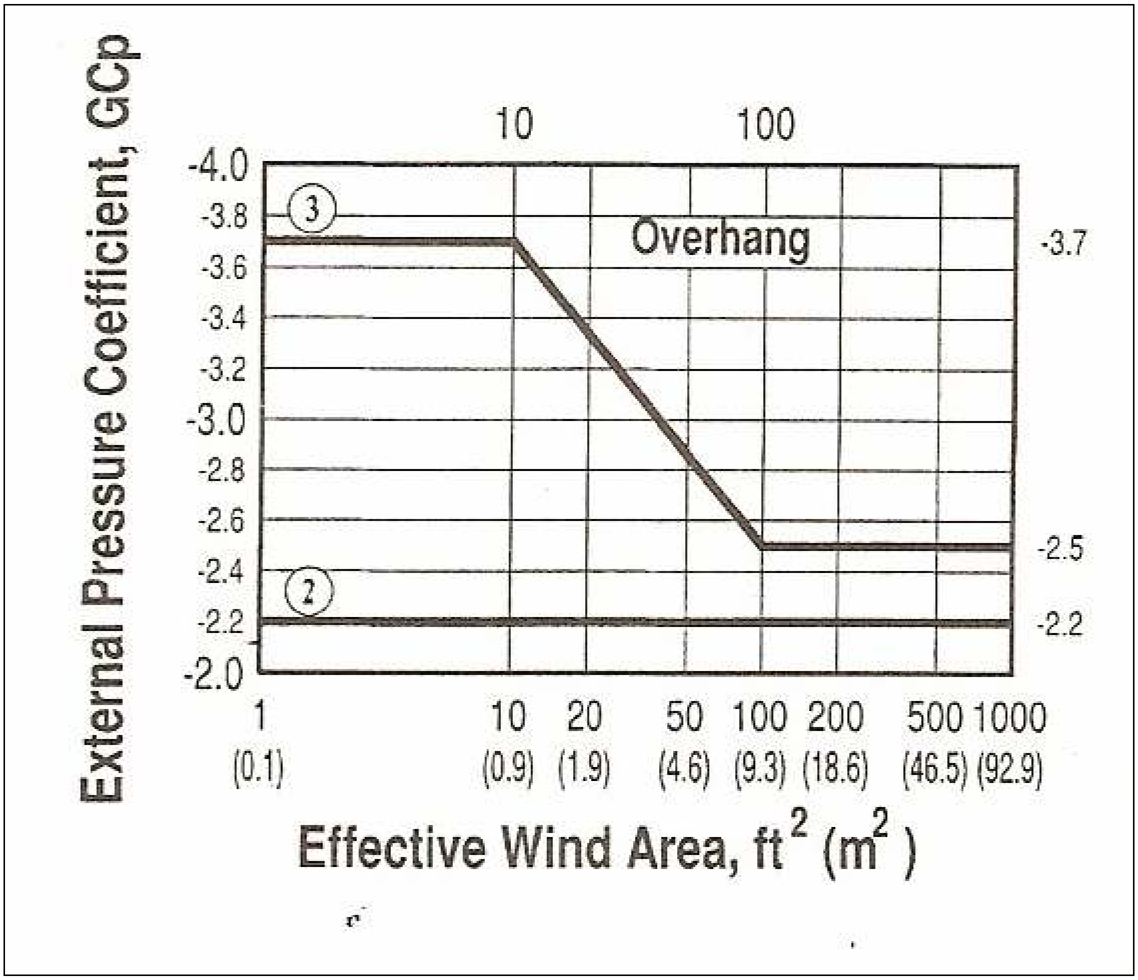


Figure 5.7: External Pressure Coefficient Data for Overhang Roof Zones (Courtesy of ASCE 7-98 [12]).

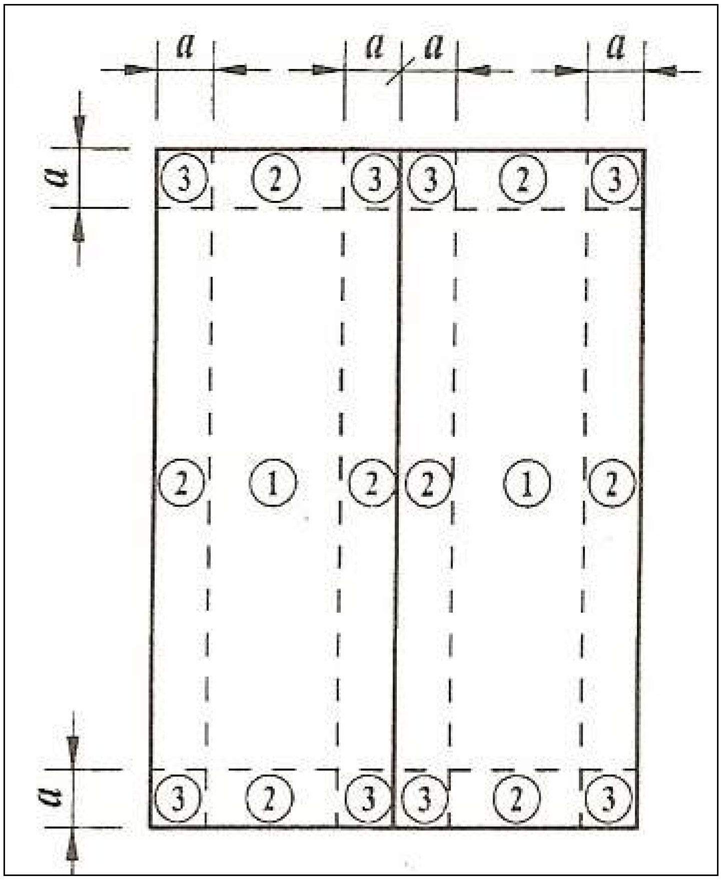


Figure 5.8: Gabled Roof Zone Assignments
(Courtesy of ASCE 7-98 [12]).

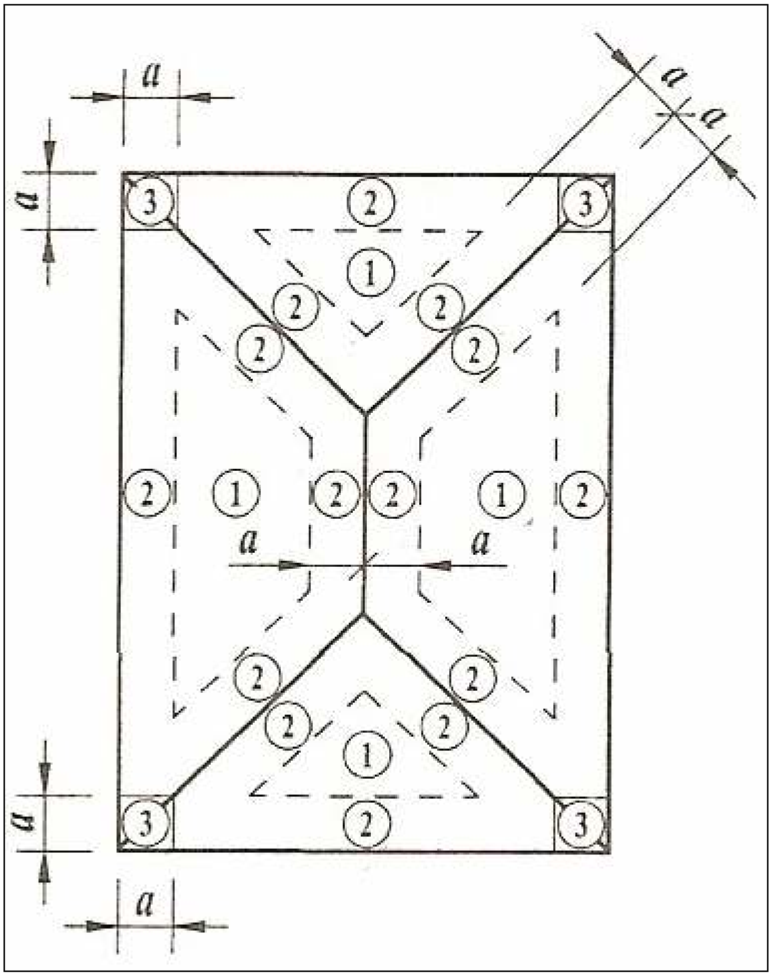


Figure 5.9: Hipped Roof Zone Assignments
(Courtesy of ASCE 7-98 [12]).

Chapter 6 Results and Discussion

6.1 Results of the Wind Analysis

The complete results of the ASCE 7-98 analysis, using the C&C analysis spreadsheet are shown in Appendix D, Tables D.1 to D.12. The tables are presented for mean roof heights of 12, 15, 20, 25, and 30 ft. For each roof height the component and cladding analysis was done for Exposure B and C, and for each exposure the design wind speed was set to 120 mph and 160 mph.

Due to the fact that none of the coefficients changed for *Exposure B*, for both the design wind speed of 120 mph and the hurricane wind speed of 160 mph, the design pressures were the same for all of the roof heights analyzed. Because of this, Tables D.1 and D.7 show the design wind pressures for all of the roof heights tested for Exposure B, for the design wind speed, and the hurricane wind speed, respectively.

Focusing on the tile damage from the Pictometry photos, a design area suitable for investigating the pressure values on roof tiles was chosen as 10 ft^2. This area was chosen because all of the external pressure coefficient data remains constant corresponding to design areas of 1 to 10 ft^2. This trend is shown in the plots to determine external pressure coefficient data, based on design area, shown in Figures 5.6 and 5.7, as taken from Figure 5.5 earlier mentioned in this report. The roof zones that correspond to Figures 5.6 and 5.7

are shown in Figures 5.8 and 5.9, also taken from Figure 5.5. Looking at Figures 5.8 and 5.9, the ridge and corner zones correspond to zones 2 and 3, which is where most of the tile damage was observed from the Pictometry pictures. Figure 5.6 shows the external pressure coefficients for the exterior roof zones, or the zones of the roof not including the overhang. Figure 5.7 shows the external pressure coefficient data for zones 2 and 3 when those zones are found on an overhang. Zone 1 is the field area of the roof. Tables 6.1 to 6.5 show the summarized results of pressure data for zones 2 and 3, both exterior roof and overhang, for a design area of 10 ft^2.

Table 6.1: Design Wind Pressures (psf) for Mean Roof Height of 12 ft (Design Area = 10 ft^2)

Mean Roof Height	12 ft.							
Design Area	10 sq. ft.							
DESIGN PRESSURE (psf)								
Exposure	B				C			
	Design Wind Speed				Design Wind Speed			
Zone	120 mph		160 mph		120 mph		160 mph	
2 (exterior roof)	18	-59	31	-105	21	-71	38	-127
2 (ext.overhang)	N/A	-57	N/A	-101	N/A	-69	N/A	-122
3 (corner roof)	18	-59	31	-105	21	-71	38	-127
3 (corner overhang)	N/A	-96	N/A	-170	N/A	-116	N/A	-206

Table 6.2: Design Wind Pressures (psf) for Mean Roof Height of 15 ft (Design Area = 10 ft^2)

Mean Roof Height	15 ft.							
Design Area	10 sq. ft.							
DESIGN PRESSURE (psf)								
Exposure	B				C			
	Design Wind Speed				Design Wind Speed			
Zone	120 mph		160 mph		120 mph		160 mph	
2 (exterior roof)	18	-59	31	-105	21	-71	38	-127
2 (ext.overhang)	N/A	-57	N/A	-101	N/A	-69	N/A	-122
3 (corner roof)	18	-59	31	-105	21	-71	38	-127
3 (corner overhang)	N/A	-96	N/A	-170	N/A	-116	N/A	-206

Table 6.3: Design Wind Pressures (psf) for Mean Roof Height of 20 ft
(Design Area = 10 ft^2)

Mean Roof Height	20 ft.							
Design Area	10 sq. ft.							
DESIGN PRESSURE (psf)								
Exposure	B				C			
	Design Wind Speed				Design Wind Speed			
Zone	120 mph		160 mph		120 mph		160 mph	
2 (exterior roof)	18	-59	31	-105	23	-76	40	-135
2 (ext.overhang)	N/A	-57	N/A	-101	N/A	-73	N/A	-130
3 (corner roof)	18	-59	31	-105	23	-76	40	-135
3 (corner overhang)	N/A	-96	N/A	-170	N/A	-123	N/A	-219

Table 6.4: Design Wind Pressures (psf) for Mean Roof Height of 25 ft
(Design Area = 10 ft^2)

Mean Roof Height	25 ft.							
Design Area	10 sq. ft.							
DESIGN PRESSURE (psf)								
Exposure	B				C			
	Design Wind Speed				Design Wind Speed			
Zone	120 mph		160 mph		120 mph		160 mph	
2 (exterior roof)	18	-59	31	-105	24	-79	42	-141
2 (ext.overhang)	N/A	-57	N/A	-101	N/A	-77	N/A	-136
3 (corner roof)	18	-59	31	-105	24	-79	42	-141
3 (corner overhang)	N/A	-96	N/A	-170	N/A	-129	N/A	-229

Table 6.5: Design Wind Pressures (psf) for Mean Roof Height of 30 ft
(Design Area = 10 ft^2)

Mean Roof Height	30 ft.							
Design Area	10 sq. ft.							
DESIGN PRESSURE (psf)								
Exposure	B				C			
	Design Wind Speed				Design Wind Speed			
Zone	120 mph		160 mph		120 mph		160 mph	
2 (exterior roof)	18	-59	31	-105	25	-83	44	-147
2 (ext.overhang)	N/A	-57	N/A	-101	N/A	-80	N/A	-142
3 (corner roof)	18	-59	31	-105	25	-83	44	-147
3 (corner overhang)	N/A	-96	N/A	-170	N/A	-134	N/A	-238

Looking at the data in Appendix D, the percent change in all design pressures of all roof zones increased by 77.8% when the wind speed was changed from

120 mph to 160, for each exposure and all roof heights. This is due to the fact that all of the pressures were obtained from the same coefficients, and the variable that changed was the wind speed. For example the design pressure for zone 2 (exterior roof), for Exposure B, mean roof height of 12 ft., changed from -59 psf for a wind speed of 120 mph to -105 psf for a wind speed of 160 mph, giving a predicted increase in suction pressure of 77.8%.

Another finding is shown in Table 6.6. As the roof height increased, the difference between the exposure coefficients for B and C increased as well. As the mean roof height increased, the exposure coefficients for Exposure C increased, while they remained constant for Exposure B. As Table 6.6 shows, the design pressures increased, for the same wind speed, by 21.2% for a mean roof height of 15 ft. when changing from Exposure B to Exposure C. The percent change between exposures increased up to the mean roof height of 30 ft., where there was a 40.2% increase from Exposure B to Exposure C.

Table 6.6: Percent Change in Design Pressures from Exposure B to Exposure C for each Roof Height

Roof Height (ft.)	Percent Change
12	21.2
15	21.2
20	28.7
25	34.9
30	40.2

Chapter 7 Conclusions and Recommendations

7.1 Conclusions

The conclusions show that by increasing the value of the design wind speed for hipped/gabled roofs with roof slopes of 10° to 30° the predicted design pressures for all zones would increase by 77.8%, with one exposure and mean roof height. Looking at the damage from the Pictometry pictures, most of the damage to those houses appear to be either at the corners of the hip roofs (zone 3 (overhang)), and at the ridges and valleys (zone 2, (both exterior roof and overhang)). Apparently a 78% increase in pressure (negative pressure is the cause of the tiles being uplifted) in these regions is more than enough for them to fail. Not all the houses that were viewed with Pictometry built post-1996 followed this trend, as some showed no damage at all, leading to an obvious conclusion that the building code performed quite well. However, the selected houses, and many other houses in the area, did have ridge and corner damage to their roofs. The reason for the observed failure in the roof tiles could be faulty construction, or possibly the pressure coefficients in these regions could be raised to larger values. The houses in the PGI area did experience wind speeds at or above their designed levels, however with the 40 mph increase in wind velocity that was used for this study, and by looking at the selected photos, the most vulnerable parts of the roof zones became visible.

Another observation made when looking through the data was that the design pressure values increased by values ranging from 21.2% to 40.2%, depending on the mean roof height, when the exposure was changed from B to C, leaving the design wind speed constant. This shows that by a designer possibly making an error in classifying a house's exposure level, failure of a roofs components and claddings could occur if they are designed to at or close to their failure capacity for the lower exposure (Exposure B).

7.2 Recommendations

In looking at the conclusions, even though the ASCE 7-98 wind load provisions performed well, the first recommendation is that more care should be taken when designing the components and claddings for the ridge and corner regions of hipped/gabled roofs. A more conservative estimate of the design pressure in these regions would give a better factor of safety, as it has been shown above that these regions are the most vulnerable to tiles being pulled off. Raising the external pressure coefficient values for the hip and ridge zones in the ASCE 7 standards, would not be too conservative, as the analysis and pictures have shown what regions are potential problem areas, when designing for components and claddings, such as roof tiles.

After performing a rather simple components and cladding analysis, the complexity of using the ASCE 7-98 wind standard became evident. The lack of clarity in many of the variables used in conducting the wind pressure calculations, could lead a designer to make the wrong decision for a design. One problem is the enclosure classification above, if someone were to classify a building as open (O), when, according to the Standard it was supposed to be partially enclosed (P), the difference in internal pressure coefficients between these two classifications would lead the designer to over-design any element of the house (either MWFRS or components and cladding). This potential mistake could be a very costly one. Another problem is the mean roof height definition; the Standard says the mean roof height is the average of the highest point on the roof and the eave height for roofs with slopes greater than 10°. The question that comes up is, "What if there are multiple hip high points for one roof span?" Going by the mean roof height definition, the mean roof height would most likely be below the hip high points. This would lead to lower exposure coefficient values, and possibly underestimating the wind loads on the house in question. In order to reduce the possibility for error in using the wind provisions of the ASCE 7-98, and subsequent ASCE 7, standards, the procedure for obtaining the coefficients and factors necessary for calculations should be simplified further.

Adding to this recommendation, more engineers need to become more proficient in understanding how to design structures, such as houses, for wind loading using wind standards like that which is used in Florida (ASCE 7-98). This problem was observed in the FEMA report, and left them to point out that no matter how simplified and condensed the wind codes become, without a basic understanding of how to design for wind, unnecessary damage will continue to occur from high wind events like hurricanes, as seen in the selected Pictometry photos.

References

[1]. Sen, R., Meloy, N., Pai, N., and Mullins, G. “Impact of Hurricane Charley on Residential and Commercial Construction”. *NSF Final Report CMS-0456569*. 2004.

[2]. “Hurricane Charley in Florida: Observations, Recommendations, and Technical Guidance”. *Federal Emergency Management Agency (FEMA) Report 488*. 2005.

[3]. “How Hurricanes Work”. The How Stuff Works Website. <http://science.howstuffworks.com/hurricane1.htm> Last Accessed on 25 January 2006.

[4]. “Tropical Cyclones”. The Wikipedia Website. <http://en.wikipedia.org/wiki/Hurricanes#Intensities_of_tropical_cyclones> Last Accessed on 25 January 2006.

[5]. The National Hurricane Center Website. <http://www.nhc.noaa.gov/index.shtml> Last Accessed on 25 January 2006.

[6]. Pasch, R., D. Brown, and E. S. Blake. Tropical Cyclone Report: Hurricane Charley. Revised 5 January 2005. National Weather Service – National Hurricane Center – Tropical Prediction Center. Accessed 26 January 2006 <www.nhc.noaaa.gov/2004charley.shtml>.

[7]. “Hurricane Charley Impact Study”. USGS Coastal and Marine Geology Program. Accessed 26 January 2006. <http://coastal.er.usgs.gov/hurricanes/charley/>

[8]. Thompson, L. E., and Thompson, C. C. C. “Hurricane Andrew Destruction on Housing”, *International Journal for Housing Science and its Application*, Vol. 18, No. 4, pp. 239-250, 1994.

[9]. Southern Building Code Congress International. Standard for Hurricane Resistant Residential Construction (SSTD 10-93), Birmingham, AL, 1993.

[10]. Southern Building Code Congress International (1999). Standard for Hurricane Resistant Residential Construction (SSTD 10-99), Birmingham, AL, 1999.

[11]. 2001 Florida Building Code, Department of Community Affairs, Tallahassee, FL <http://www.floridabuilding.org/bc/default.asp>

[12]. ASCE 7-98 Minimum Design Loads for Buildings and Other Structures, New York, NY, 1998.

[13]. Holmes, J. D. *Wind Loading of Structures*. Routledge Publishing. 2001.

[14]. Newberry, C.W., Eaton, K.J. *Wind Loading Handbook*. Published by the United Kingdom Department of the Environment. 1974.

[15]. Meecham, Davenport, and Surry. "The magnitude and distribution of wind-induced pressures on hip and gable roofs". *Journal of Wind Engineering and Industrial Aerodynamics*. Vol. 38, Issues 2 – 3, July – August 1991, pages 257 – 272.

[16]. Charlotte County Geographic Information Systems (GIS) website. <http://www.ccgis.com>. Last Accessed on 25 January 2006.

[17]. "Building Construction Standards", Chapter 553. *Laws of Florida*. 2004 Legislation.

[18]. *Concrete and Clay Tile Installation Manual*. Prepared by the Florida Roofing, Sheet Metal and Air Conditioning Contractors Association, Inc. 2003.

Appendices

Appendix A Damaged Houses Selected Using Pictometry

Included in this appendix are the selected houses, found by using the Pictometry software program. Each selected house is circled in blue, and the year that it was built is included next to it as a text box, along with a marker pointing north. The pictures were taken by Pictometry on August 21, 2004.

Appendix A (Continued)

Property #1

Figure A.1: Wind Damage Done to Ridges (Property #1)

Appendix A (Continued)

Property #2

Figure A.2: Wind Damage Done to Ridges (Property #2)

Appendix A (Continued)

Property #3

Figure A.3: Combination of Ridge and Corner Damage (Property #3)

Appendix A (Continued)

Property #4

Figure A.4: Wind Damage Done to Ridges (Property #4)

Appendix A (Continued)

Property #5

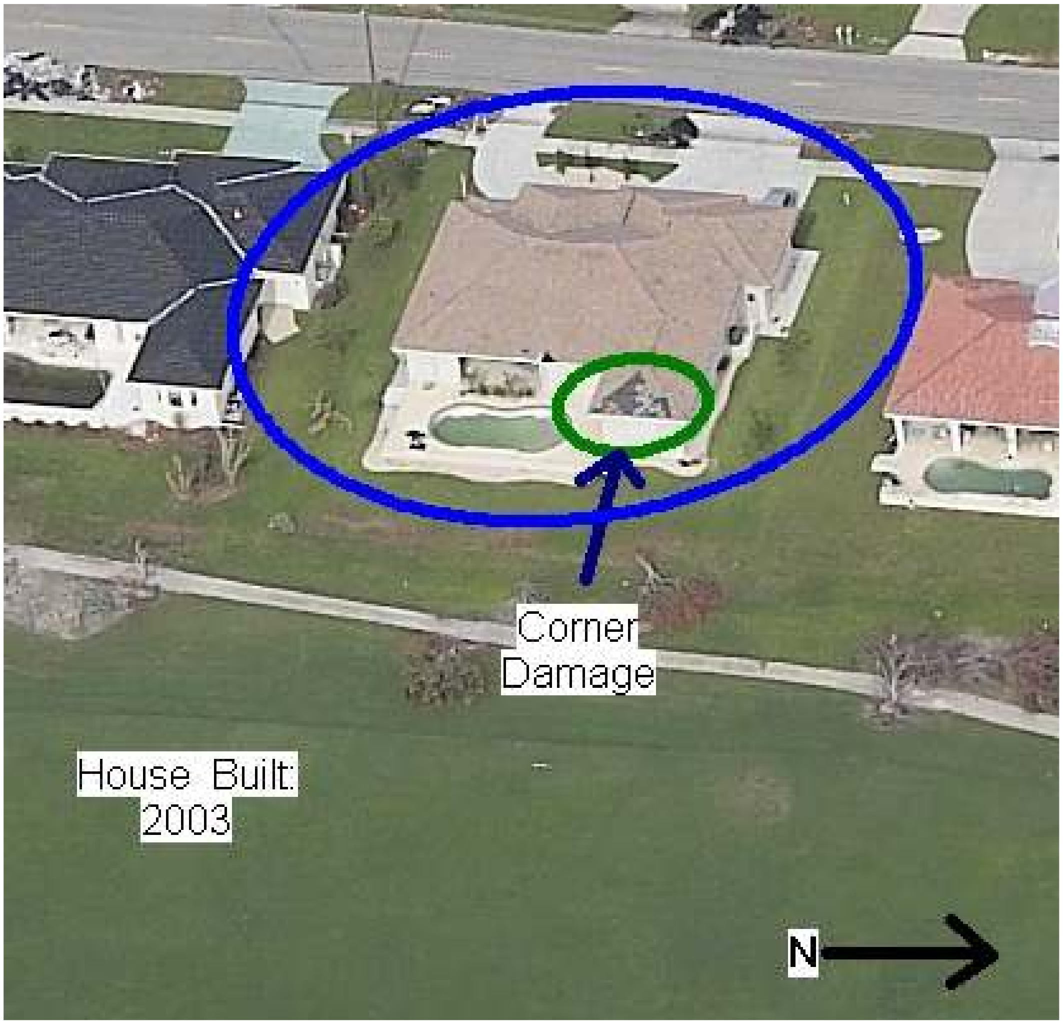


Figure A.5: Corner Damage (Property #5)

Appendix A (Continued)

Property #6

Figure A.6: Corner Damage (Property #6)

Appendix A (Continued)

Property #7

Figure A.7: Ridge and Corner Damage (Property #7)

Appendix A (Continued)

Property #8

Figure A.8: Ridge and Corner Damage (Property #8)

Appendix A (Continued)

Property #9

Figure A.9: Ridge Damage (Property #9)

Appendix A (Continued)

Property #10

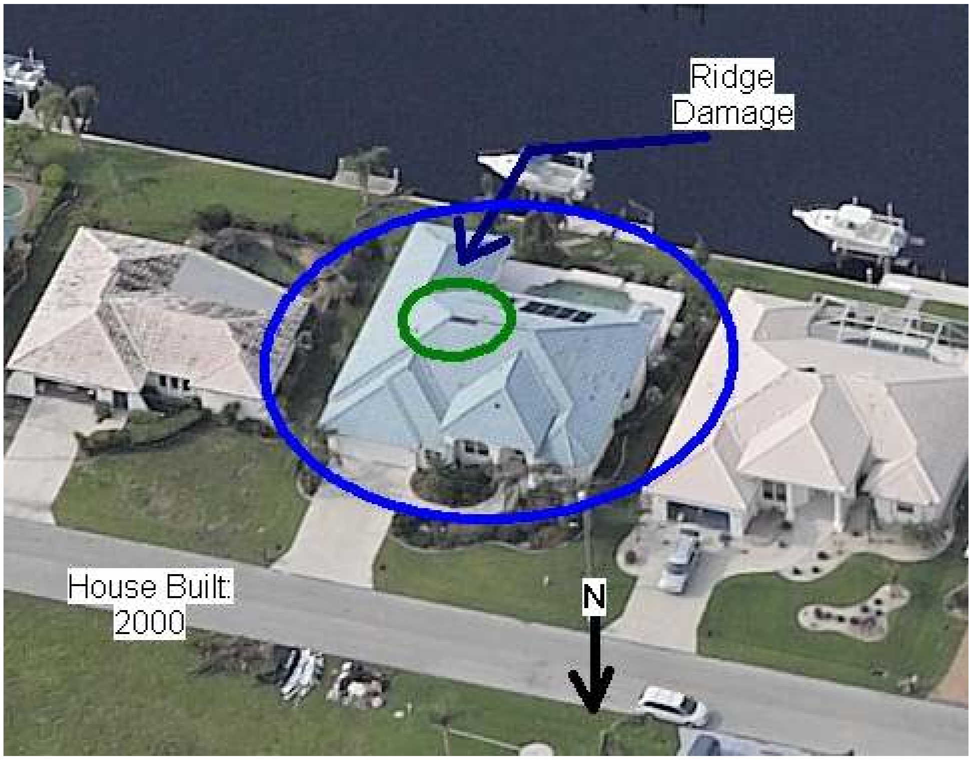


Figure A.10: Ridge Damage (Property #10)

Appendix A (Continued)

Property #11

Figure A.11: Ridge Damage (Property #11)

Appendix A (Continued)

Property #12

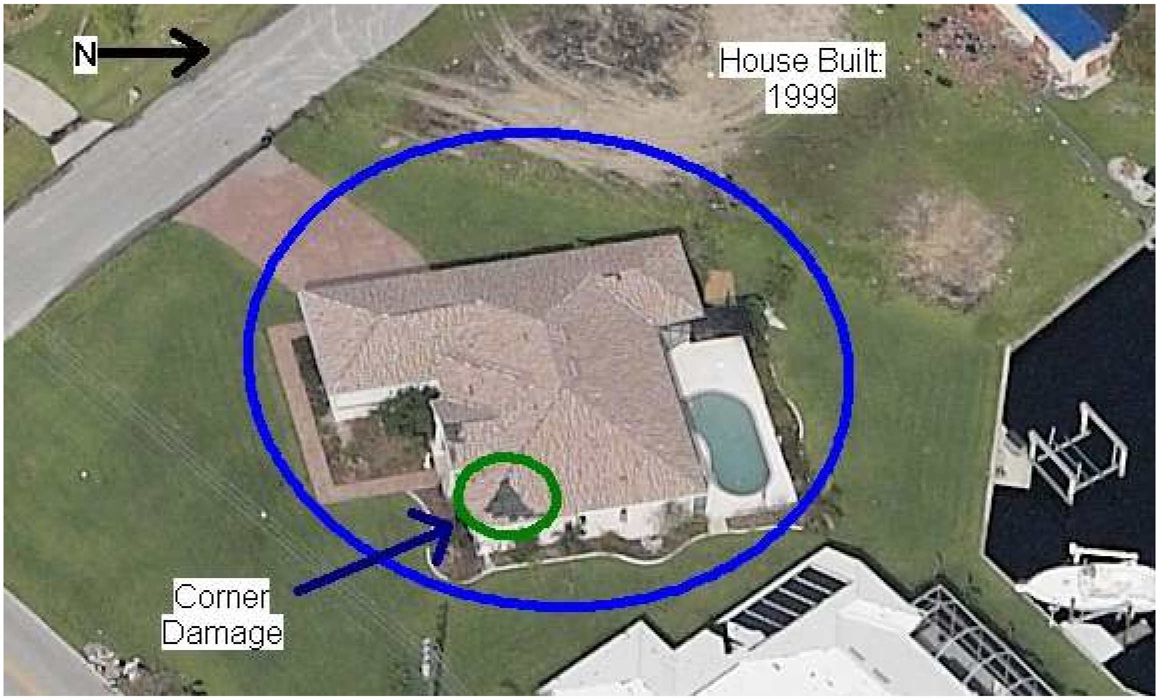


Figure A.12: Corner Damage (Property #12)

Appendix A (Continued)

Property #13

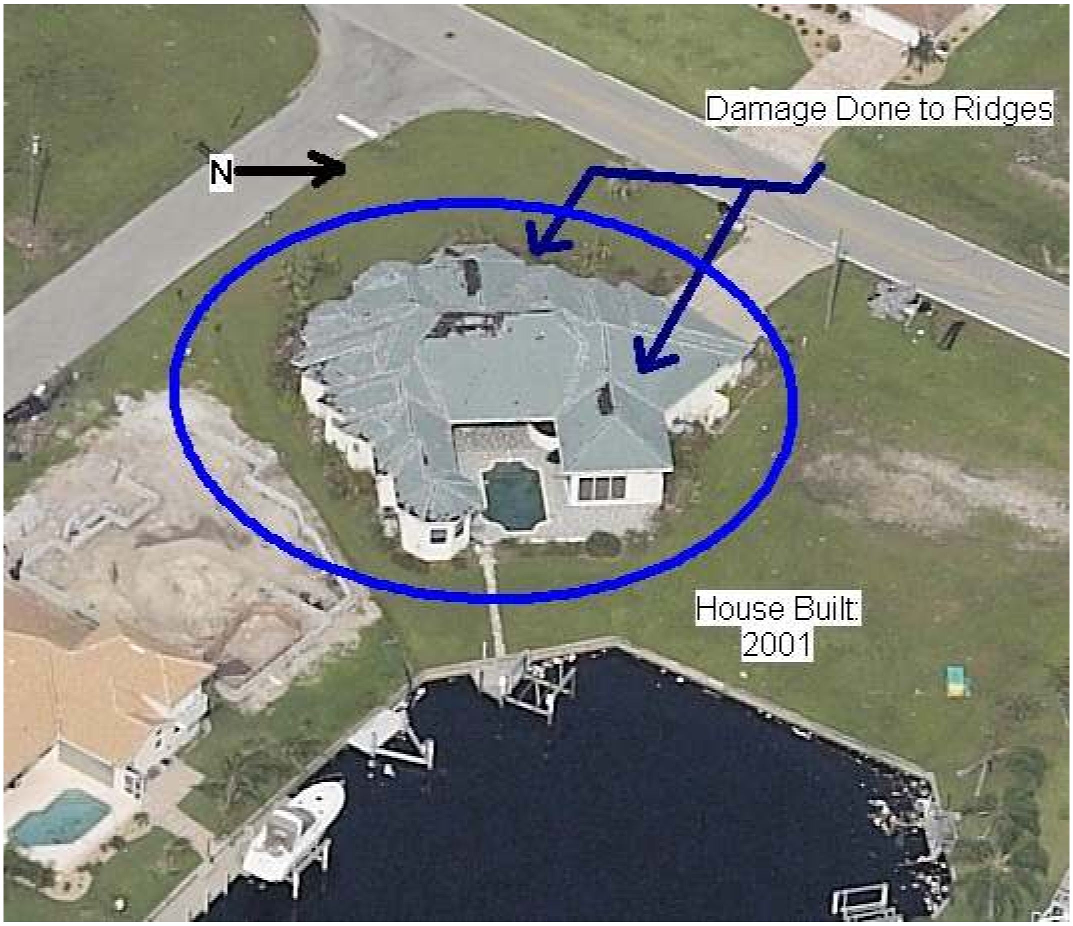


Figure A.13: Ridge Damage to a Large House (Property #13)

Appendix A (Continued)

Property #14

Figure A.14: Ridge and Corner Damage (Property #14)

Appendix A (Continued)

Property #15

Figure A.15: Ridge Damage (Property #15)

Appendix A (Continued)

Property #16

Figure A.16: Ridge Damage (Property #16)

Appendix A (Continued)

Property #17

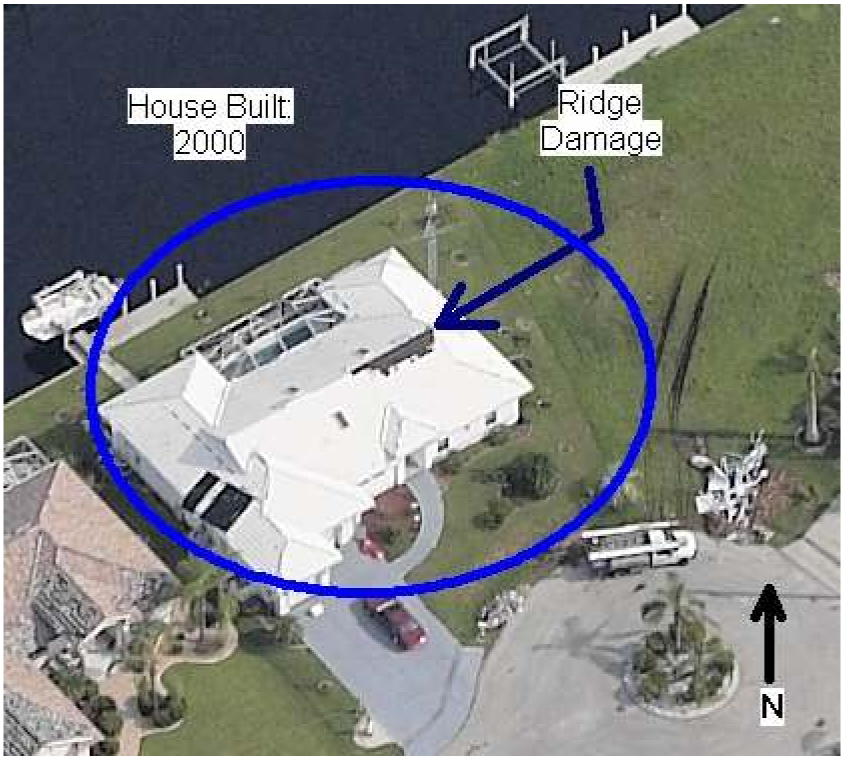


Figure A.17: Ridge Damage (Property #17)

Appendix A (Continued)

Property #18

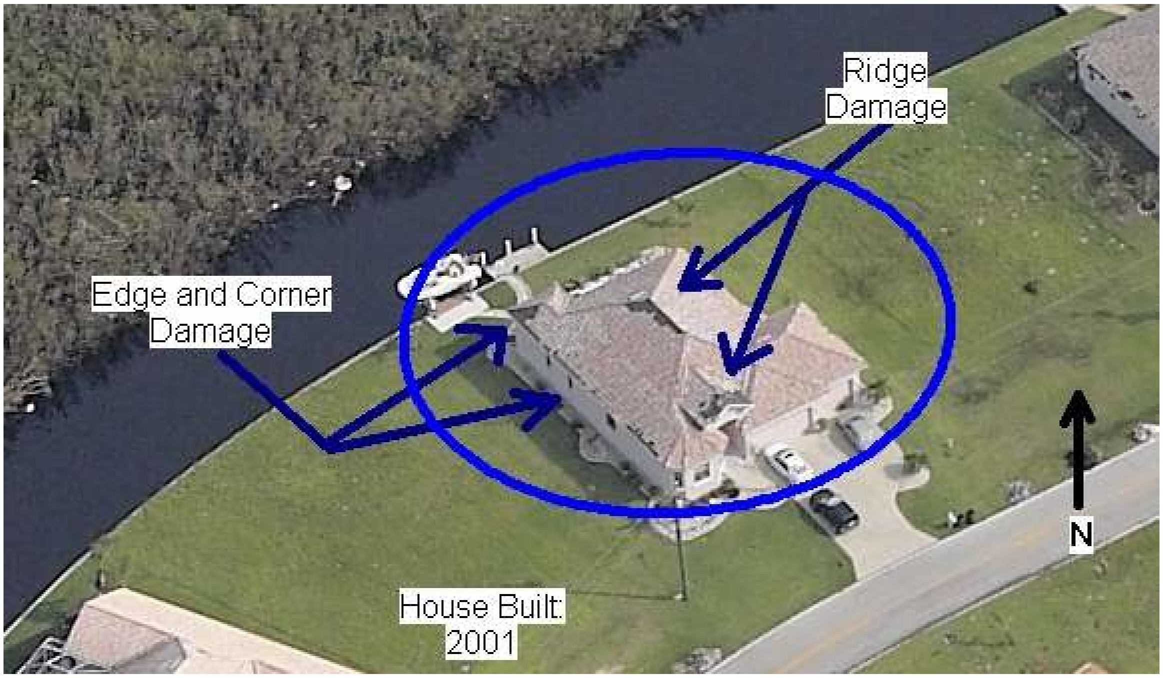


Figure A.18: Various Damage Types (Property #18)

Appendix A (Continued)

Property #19

Figure A.19: Ridge Damage (Property #19)

Appendix A (Continued)

Property #20

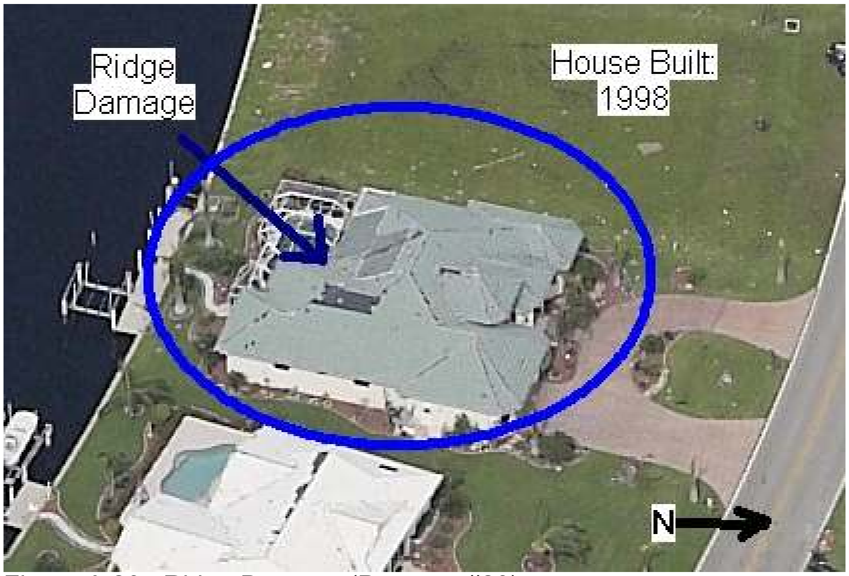


Figure A.20: Ridge Damage (Property #20)

Appendix A (Continued)

Property #21

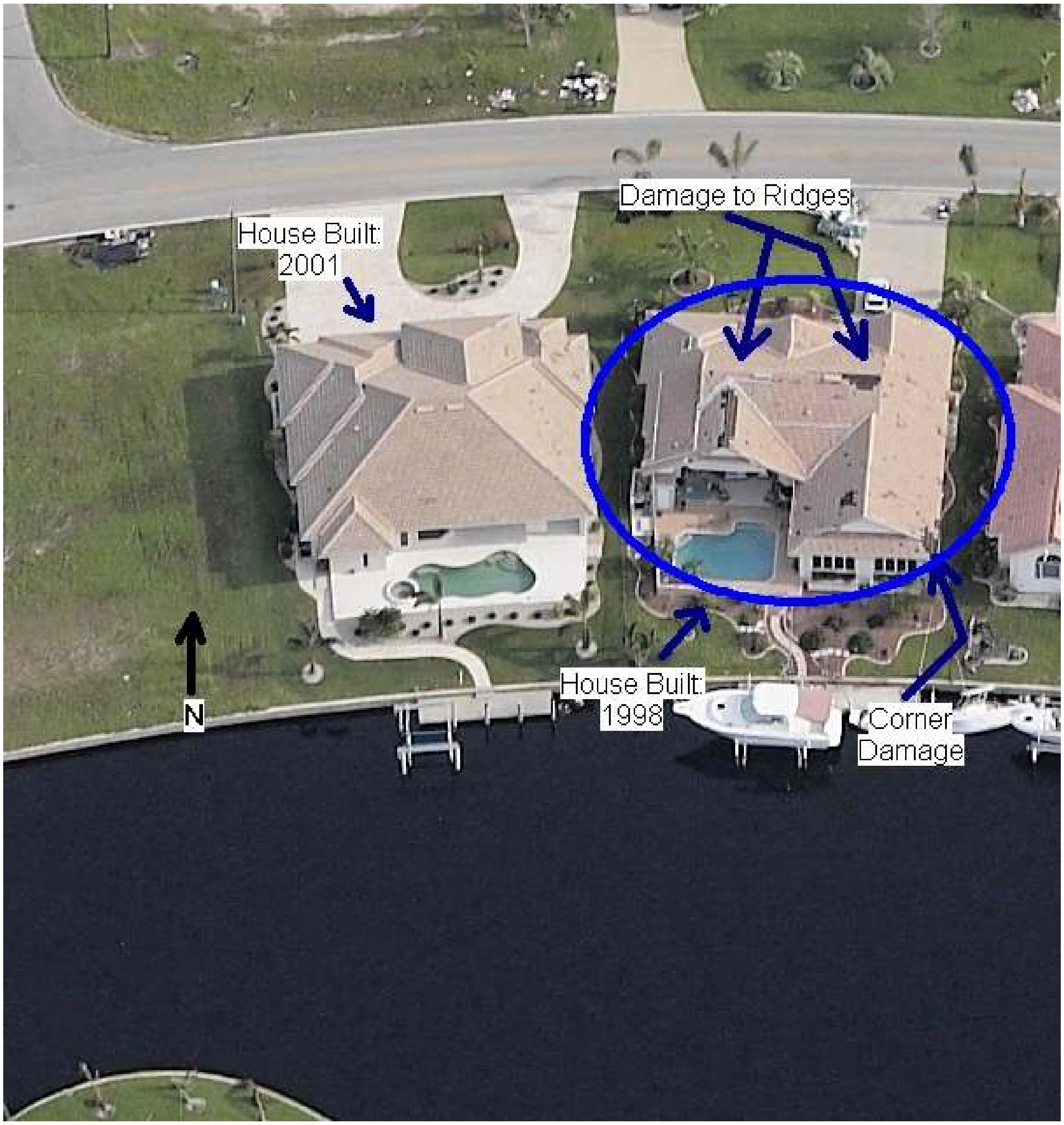


Figure A.21: Ridge and Corner Damage (Property #21)

Appendix A (Continued)

Property #22

Figure A.22: Ridge and Edge Damage (Property #22)

Appendix B Ground Pictures of Houses in PGI

This appendix shows some digital photos taken of the PGI area. The pictures show mainly a hipped roof style, but with multiple spans or multiple hips on one span. Some of the roofs may be part gable or hip. The houses are numbered, but their numbering is not related to the numbered houses shown in Appendix 1. The pictures were taken during different trips to the area, during November of 2005.

Appendix B (Continued)

House #1

Figure B.1: Hipped Roof With Multiple Hips on One Span (Front View)

Appendix B (Continued)

House #1

Figure B.2: View of the Wall of House #1

Appendix B (Continued)

House #2

Figure B.3: Multiple Span Hipped Roof House

Appendix B (Continued)

House #2

Figure B.4: Closer View of Ridges Over Front

Appendix B (Continued)

House #3

Figure B.5: Side View of a House that is Part-Gabled and Part-Hipped Roof

Appendix B (Continued)

House #4

Figure B.6: House that has Multiple Gables

Appendix B (Continued)

House #5

Figure B.7: Hipped Roof With Multiple Hips Over One Span

Appendix B (Continued)

House #5

Figure B.8: Close-Up of the Top Ridge on a Hipped Roof

Appendix B (Continued)

House #6

Figure B.9: Hipped Roof

Appendix B (Continued)

House #6

Figure B.10: Close-Up of Ridgeline and Valleys

Appendix C Response from Contractors

This appendix shows first shows the set of questions that was set to the roofing contractor members of FRSA that worked in the southern part of Florida. Following the questions document are the individual responses from the contractors who participated in the study.

Appendix C (Continued)

QUESTIONS TO CONTRACTORS/ENGINEERS ABOUT THE PGI HOUSES

Roofs and Shingles

1) When applying the roof sheathing, is there any particular design/building code to apply the sheathing?
2) What type of roof sheathing do you most often use?
3) How is roof sheathing typically applied when clay tiles are to be applied to the roof?
4) Do you use any particular design/building code to apply the shingles/tiles to the roof?
5) How do you apply a typical clay shingle (e.g. one screw to fasten, with some mortar)? Is this the standard method used by most builders/contractors?
6) How common do you use and/or encounter roofs with the foam application shingles? Is there any advantage of using this type of shingle fastening method over the standard method of application?
7) Are there any different application procedures when applying the shingles along a roof edge or a ridgeline? If so, how are they different?
8) Do you encounter installation problems of shingles around air vents, solar panels, etc.?

Appendix C (Continued)

9) What is the common spacing of roof truss bracing for hipped and gabled roofs? What would be the size of the member used for bracing (2 X 4, 4 X 4, etc.)?
10) What are some common roof slopes for hipped and gabled roofs on a typical one or two story residential house?
11) What are the lengths of typical roof overhangs encountered when dealing with hipped or gabled roofs?
12) When applying hurricane fasteners, are there any building requirements to how they should be applied? Do you use any particular design/building code to apply the fasteners?
13) What are the most common dimensions of roof panels that are encountered when dealing with hipped or gabled roofs?

General

1) What is the typical spacing of a wall's studs, on center, for a typical residential house?
2) Are hurricane-resistant windows now required to be installed when a new building is to be constructed?
3) What building code do you use or refer to most often when building a residential structure, like a one-story house?

4) Is there any aspect of the design of any parts of the building envelope of a house that you think needs to be addressed in more detail in any future publications of the current design/building codes?
5) Do you know of any engineering firms that specialize in designing residential structures, like houses?

Appendix C (Continued)

Response from Alan's Roofing:

Roofs and Shingles

1) *When applying the roof sheathing, is there any particular design/building code to apply the sheathing?* Yes nail patterns are every 4" from the gutter edge up including all gable ends for 2 consecutive feet.. After this it is every 6" a nail is to be installed into the sheeting, thus into a rafter. The down side is replacement for homeowners in the future due to extreme labor intensive replacement that may be unaffordable for the average homeowner. This concept is good for the insurance companies but in the long run may have an impact on the middle class.

2) *What type of roof sheathing do you most often use?* ½" cdx 4 ply plywood, do not use the wafer board due to once wet or condensation it deteriorates rapidly.

3) *How is roof sheathing typically applied when clay tiles are to be applied to the roof?* As stated above

4) *Do you use any particular design/building code to apply the shingles/tiles to the roof?* Manufactures specifications with our knowledge to increase performance. Remember that in the field (with installers) we know what works in the long run, the manufacturers many times change there installations due to our knowledge. This has happened to me many times over the years.

5) *How do you apply a typical clay shingle (e.g. one screw to fasten, with some mortar)? Is this the standard method used by most builders/contractors?* There are 4 methods of installation, 1 being installed by foam method, 2nd being installed by cement, 3rd being installed to the water proofing agent by screws, and the 4th by what is called system1 method, this incorporates the use of 1" x 2" batten strips screwed to the roof and then the tiles screwed to the battens.

6) *How common do you use and/or encounter roofs with the foam application shingles?* Is there any advantage of using this type of shingle fastening method over the standard method of application? No such thing to install foam with asphalt shingle installation.

7) *Are there any different application procedures when applying the*

shingles along a roof edge or a ridgeline? If so, how are they different? Roofing cement is also used along with roofing nails. Standard procedure.

8) *Do you encounter installation problems of shingles around air vents, solar panels, etc.?* not with a knowledgeable installer, also plenty of roofing cement.

9) *What is the common spacing of roof truss bracing for hipped and gabled roofs? 2 foot on center with ½" plywood clips. What would be the size of the member used for bracing (2 X 4, 4 X 4, etc.)?*

10) *What are some common roof slopes for hipped and gabled roofs on a typical one or two story residential house?* 4 and 5/12 pitch roofs are of the norm.

11) *What are the lengths of typical roof overhangs encountered when dealing with hipped or gabled roofs?* 2 to 3 feet

12) *When applying hurricane fasteners, are there any building requirements to how they should be applied? Do you use any particular design/building code to apply the fasteners?* This is where the big problem comes in to play!!! Code requires that all the holes in the strapping to be nailed, thus destroying the integrity of the wood due to - to many nails in a small area, big ,big problem!!!!

13) What are the most common dimensions of roof panels that are encountered when dealing with hipped or gabled roofs?

General

1) *What is the typical spacing of a wall's studs, on center, for a typical residential house?*

2) *Are hurricane-resistant windows now required to be installed when a new building is to be constructed?* yes

3) *What building code do you use or refer to most often when building a residential structure, like a one-story house?*

4) *Is there any aspect of the design of any parts of the building envelope of a house that you think needs to be addressed in more detail in any future publications of the current design/building codes?* Yes the Sophit

area which acts like an umbrella, this is an area not addressed enough for wind uplift. The standard construction is aluminum panels which are very flimsy and are ripped apart in a small wind thus leaving an umbrella effect to the entire underside if the roof structure!!!!!

5) *Do you know of any engineering firms that specialize in designing residential structures, like houses?* No comment at this time, good luck with the research Alan's Roofing, Est. 1978 with owner still working on job

Appendix C (Continued)

Response from Kelly Roofing:

Roofs and Shingles

1) *When applying the roof sheathing, is there any particular design/building code to apply the sheathing?*

2) *What type of roof sheathing do you most often use?* ½" CDX 4-ply

3) *How is roof sheathing typically applied when clay tiles are to be applied to the roof?* Same Way

4) *Do you use any particular design/building code to apply the shingles/tiles to the roof?* Yes: Florida Building Code

5) *How do you apply a typical clay shingle (e.g. one screw to fasten, with some mortar*)? Is this the standard method used by most builders/contractors? Clay Tiles are installed the same way all other tiles are installed.

6) *How common do you use and/or encounter roofs with the foam application Tile*? It is becoming much more popular now. *Is there any advantage of using this type of shingle fastening method over the standard method of application?* Yes, stronger hold and less broken tiles from walking on the roof.

7) *Are there any different application procedures when applying the shingles along a roof edge or a ridgeline?* Yes *If so, how are they different?* We use a ridge anchor bar that allows us to fasten with a screw the cap tiles and then we use rt-600 tile adhesive to secure the leading edge of each cap tile.

8) *Do you encounter installation problems of shingles around air vents, solar panels, etc.?* Vents no, solar most certainly yes

9) *What is the common spacing of roof truss bracing for hipped and gabled roofs? What would be the size of the member used for bracing (2 X 4, 4 X 4, etc.)*? 24" oc

10) *What are some common roof slopes for hipped and gabled roofs on a typical one or two story residential house?* 5 or 6 :12

Appendix C (Continued)

11) *What are the lengths of typical roof overhangs encountered when dealing with hipped or gabled roofs?* 24"

12) *When applying hurricane fasteners, are there any building requirements to how they should be applied? Do you use any particular design/building code to apply the fasteners?* Yes: FBC

13) *What are the most common dimensions of roof panels that are encountered when dealing with hipped or gabled roofs?*

General

6) *What is the typical spacing of a wall's studs, on center, for a typical residential house? 24"* oc

7) *Are hurricane-resistant windows now required to be installed when a new building is to be constructed?* Yes, or shutters need to be supplied to the *homeowner.*

8) *What building code do you use or refer to most often when building a residential structure, like a one-story house?* FBC

9) *Is there any aspect of the design of any parts of the building envelope of a house that you think needs to be addressed in more detail in any future publications of the current design/building codes?* YES! Flat roof anchor specifications. We saw so many of them blown off after Wilma. I have a perfect solution.

10) *Do you know of any engineering firms that specialize in designing residential structures, like houses?* NO

Appendix C (Continued)

Response from Tampa Roofing:

Roofs and Shingles

1) *When applying the roof sheathing, is there any particular design/building code to apply the sheathing?* Yes

2) *What type of roof sheathing do you most often use?* Roof sheeting is installed by others before we get there, however when I have the ability to influence the sheeting I always ask to use 5/8" plywood, although ½" osb board will meet code.

3) *How is roof sheathing typically applied when clay tiles are to be applied to the roof?* Usually the trusses have to be beefed up for tiles to handle the weight, but 5/8" will still be ok.

4) *Do you use any particular design/building code to apply the shingles/tiles to the roof?* After Oct. 1st we are operating under the international building code, or the residential code. The residential code is a little easier.

5) *How do you apply a typical clay shingle (e.g. one screw to fasten, with some mortar)?* Is this the standard method used by most builders/contractors? You can install clay tiles with mortor. However concrete does not easily bond to clay. Most people do not know how to bond the concrete to clay, and most of what you see will not last. Most of the state can install clay tiles with screws. In the high wind areas you need to either also install wires, or tile caulk. You can install tiles in a urethane foam, but my experience shows that the aged testing that was originally done is not accurate, and after five or six year the foam starts to break down. We only use stainless screws. We will also use the tile caulk in high wind areas or when the slope gets over 8/12

6) *How common do you use and/or encounter roofs with the foam application shingles?* Is there any advantage of using this type of shingle fastening method over the standard method of application? No. foam it too expensive for shingles. Nails work too well.

7) *Are there any different application procedures when applying the shingles along a roof edge or a ridgeline?* If so, how are they different? On an open rake edge you have to install a layer of roofing cement.

Appendix C (Continued)

8) *Do you encounter installation problems of shingles around air vents, solar panels, etc.?* No

9) *What is the common spacing of roof truss bracing for hipped and gabled roofs? What would be the size of the member used for bracing (2 X 4, 4 X 4, etc.)?* Most common trusses are made with 2x4. On my house I used conventional construction with 2x12

10) *What are some common roof slopes for hipped and gabled roofs on a typical one or two story residential house?* In the last 10 years, the most common roof pitch is 5/12

11) *What are the lengths of typical roof overhangs encountered when dealing with hipped or gabled roofs?* Most houses built today are 18 to 24 inches

12) *When applying hurricane fasteners, are there any building requirements to how they should be applied? Do you use any particular design/building code to apply the fasteners?* That is done by others before we get there

13) *What are the most common dimensions of roof panels that are encountered when dealing with hipped or gabled roofs?* Don'tknow

General

1) *What is the typical spacing of a wall's studs, on center, for a typical residential house?* Don't know

2) *Are hurricane-resistant windows now required to be installed when a new building is to be constructed?* I believe so.

3) *What building code do you use or refer to most often when building a residential structure, like a one-story house?* The residential Florida code

4) *Is there any aspect of the design of any parts of the building envelope of a house that you think needs to be addressed in more detail in any future publications of the current design/building codes?* Most of the roofing structure that failed was because the soffit ventilation failed. This left an opening for wind pressures to get into the attics, and allowed the sheeting to blow out. Right now there is serious consideration to eliminating roof

and soffit ventilation in high wind areas. The thought is that most a.c. ducts leak. The thought is to make the attics an a.c. plenum chamber. This whole idea will prove to be a huge mistake. If you will notice you windows sweating on most mornings, If you insulate the bottom side of your roof decking, and close off the attic space, your dew point will be somewhere either in the plywood, or at the base of the plywood at the insulation line. I am afraid that once this application is 5 to 10 years old, we will have a tremendous amount of houses that will dry rot. Imagine what would happen if a hurricane came through and the fasteners rusted out from the sweating, or worse case if the plywood just breaks down.

5) *Do you know of any engineering firms that specialize in designing residential structures, like houses?* No.

Appendix C (Continued)

Response from Steve Munell, Executive Director of FRSA:

Answers to Questions Submitted by James Newberry, USF

1. 2004 Florida Building Code (FBC), Florida Residential Code (FRC) and Existing Building Code (FEBC).

2. ½ inch or 5/8 inch plywood or OSB for most residential structures. For commercial building, wood, metal of concrete decks are used.

3. Wood deck used, fastened per the Code depending on the area of the state.

4. Asphalt/fiberglass shingles are installed according to the 2004 FBC or 2004 FRC. The reference document in the FBC for concrete and clay tile installation is the FRSA/TRI Concrete and Clay Roof Tile Installation Manual – Fourth Edition.

5. The FRSA/TRI Manual provides information on four different tile installation systems – mechanically fastened directly to deck; mechanically fastened using battens; mortar set; and adhesive set.

6. Foam adhesive is not used for the installation of asphalt shingles in Florida. It is used for the installation of concrete or clay roof tile.

7. They are installed differently. Different nailing pattern than field shingles. A starter course is used at the eave with specific nailing and adhesive requirements.

8. If the application of shingles around vents and skylights is done properly, with the use of appropriate flashing methods and materials, there should not be any problems. Most problems in these areas are the result of poor workmanship.

9. Please contact the Florida Homebuilder Assn. For answer to this question.

10. Common slopes would range from 4/12 to 8/12.

11. Please contact Florida Homebuilders Assn. on this one.

12. Florida Homebuilders Assn. can also answer this question.

Appendix C (Continued)

13. Not sure of this question. Common decking panels are 8 ft. x 10 ft.

General:

1. Florida Homebuilders Assn. Can answer this.
2. Florida Homebuilders Assn.
3. Florida Residential Code of Florida Building Code.
4. The Florida Building Commission is continuously reviewing all parts of the Codes. The new 2004 Codes are the product of these reviews. They are currently working on revisions for the 2006 version of the Code.
5. Please check with the Florida Homebuilders Assn.

Steve Munnell
FRSA

Appendix D Complete Results of the Wind Analysis

All of the data in the tables presented below are the design pressures, in pounds per square foot (psf), using the ASCE 7-98 to design for components and cladding of a hipped/gable roof with roof slopes in the range of 10° to 30°, for mean roof heights less than or equal to 60 feet. The figure used in the Standard for these calculations is Figure 6-5B (page 46).

Appendix D (Continued)

Table D.1: Design Pressures for Exp. B, with Mean Roof Heights of 12 to 30 ft. (V = 120 mph)

Design Wind Speed	120 mph							
Mean Roof Height	12 to 30 ft.							
Exposure	B							
DESIGN PRESSURE (psf)								
	Design Area							
Zone	10 sq. ft.		20 sq. ft.		35 sq. ft.		50 sq. ft.	
1 (interior roof)	18	-28	16	-27	15	-26	14	-26
2 (exterior roof)	18	-59	16	-53	15	-49	14	-46
2 (ext.overhang)	N/A	-57	N/A	-57	N/A	-57	N/A	-57
3 (corner roof)	18	-59	16	-53	15	-49	14	-46
3 (corner overhang)	N/A	-96	N/A	-86	N/A	-79	N/A	-74
DESIGN PRESSURE (psf)								
	Design Area							
Zone	80 sq. ft.		100 sq. ft.		200 sq. ft.			
1 (interior roof)	13	-26	12	-25	12	-25		
2 (exterior roof)	13	-43	12	-41	12	-41		
2 (ext.overhang)	N/A	-57	N/A	-57	N/A	-57		
3 (corner roof)	13	-43	12	-41	12	-41		
3 (corner overhang)	N/A	-68	N/A	-65	N/A	-65		

Appendix D (Continued)

Table D.2: Design Pressures for Exp. C, with a Mean Roof Height of 12 ft. (V = 120 mph)

Design Wind Speed	120	mph						
Mean Roof Height	12	ft.						
Exposure	C							
DESIGN PRESSURE (psf)								
	Design Area							
Zone	10	sq. ft.	20	sq. ft.	35	sq. ft.	50	sq. ft.
1 (interior roof)	21	-34	19	-33	18	-32	17	-32
2 (exterior roof)	21	-71	19	-65	18	-59	17	-56
2 (ext.overhang)	N/A	-69	N/A	-69	N/A	-69	N/A	-69
3 (corner roof)	21	-71	19	-65	18	-59	17	-56
3 (corner overhang)	N/A	-116	N/A	-104	N/A	-95	N/A	-90
DESIGN PRESSURE (psf)								
	Design Area							
Zone	80	sq. ft.	100	sq. ft.	200	sq. ft.		
1 (interior roof)	16	-31	15	-31	15	-31		
2 (exterior roof)	16	-52	15	-49	15	-49		
2 (ext.overhang)	N/A	-69	N/A	-69	N/A	-69		
3 (corner roof)	16	-52	15	-49	15	-49		
3 (corner overhang)	N/A	-82	N/A	-78	N/A	-78		

Appendix D (Continued)

Table D.3: Design Pressures for Exp. C, with a Mean Roof Height of 15 ft. (V = 120 mph)

Design Wind Speed	120	mph						
Mean Roof Height	15	ft.						
Exposure	C							
DESIGN PRESSURE (psf)								
	Design Area							
Zone	10	sq. ft.	20	sq. ft.	35	sq. ft.	50	sq. ft.
1 (interior roof)	21	-34	19	-33	18	-32	17	-32
2 (exterior roof)	21	-71	19	-65	18	-59	17	-56
2 (ext.overhang)	N/A	-69	N/A	-69	N/A	-69	N/A	-69
3 (corner roof)	21	-71	19	-65	18	-59	17	-56
3 (corner overhang)	N/A	-116	N/A	-104	N/A	-95	N/A	-90
DESIGN PRESSURE (psf)								
	Design Area							
Zone	80	sq. ft.	100	sq. ft.	200	sq. ft.		
1 (interior roof)	16	-31	15	-31	15	-31		
2 (exterior roof)	16	-52	15	-49	15	-49		
2 (ext.overhang)	N/A	-69	N/A	-69	N/A	-69		
3 (corner roof)	16	-52	15	-49	15	-49		
3 (corner overhang)	N/A	-82	N/A	-78	N/A	-78		

Appendix D (Continued)

Table D.4: Design Pressures for Exp. C, with a Mean Roof Height of 20 ft. (V = 120 mph)

Design Wind Speed	120	mph						
Mean Roof Height	20	ft.						
Exposure	C							
DESIGN PRESSURE (psf)								
	Design Area							
Zone	10	sq. ft.	20	sq. ft.	35	sq. ft.	50	sq. ft.
1 (interior roof)	23	-36	21	-35	19	-34	18	-34
2 (exterior roof)	23	-76	21	-69	19	-63	18	-60
2 (ext.overhang)	N/A	-73	N/A	-73	N/A	-73	N/A	-73
3 (corner roof)	23	-76	21	-69	19	-63	18	-60
3 (corner overhang)	N/A	-123	N/A	-111	N/A	-101	N/A	-95
DESIGN PRESSURE (psf)								
	Design Area							
Zone	80	sq. ft.	100	sq. ft.	200	sq. ft.		
1 (interior roof)	17	-33	16	-33	16	-33		
2 (exterior roof)	17	-55	16	-53	16	-53		
2 (ext.overhang)	N/A	-73	N/A	-73	N/A	-73		
3 (corner roof)	17	-55	16	-53	16	-53		
3 (corner overhang)	N/A	-87	N/A	-83	N/A	-83		

Appendix D (Continued)

Table D.5: Design Pressures for Exp. C, with a Mean Roof Height of 25 ft. (V = 120 mph)

Design Wind Speed	120	mph	
Mean Roof Height	25	ft.	
Exposure	C		

	Design Area							
Zone	10	sq. ft.	20	sq. ft.	35	sq. ft.	50	sq. ft.
1 (interior roof)	24	-38	22	-37	20	-36	19	-35
2 (exterior roof)	24	-79	22	-72	20	-66	19	-62
2 (ext.overhang)	N/A	-77	N/A	-77	N/A	-77	N/A	-77
3 (corner roof)	24	-79	22	-72	20	-66	19	-62
3 (corner overhang)	N/A	-129	N/A	-116	N/A	-106	N/A	-100

DESIGN PRESSURE (psf)

	Design Area					
Zone	80	sq. ft.	100	sq. ft.	200	sq. ft.
1 (interior roof)	17	-34	17	-34	17	-34
2 (exterior roof)	17	-57	17	-55	17	-55
2 (ext.overhang)	N/A	-77	N/A	-77	N/A	-77
3 (corner roof)	17	-57	17	-55	17	-55
3 (corner overhang)	N/A	-91	N/A	-87	N/A	-87

Appendix D (Continued)

Table D.6: Design Pressures for Exp. C, with a Mean Roof Height of 30 ft. (V = 120 mph)

Design Wind Speed	120	mph						
Mean Roof Height	30	ft.						
Exposure	C							
DESIGN PRESSURE (psf)								
	Design Area							
Zone	10	sq. ft.	20	sq. ft.	35	sq. ft.	50	sq. ft.
1 (interior roof)	25	-39	22	-38	21	-37	20	-37
2 (exterior roof)	25	-83	22	-75	21	-69	20	-65
2 (ext.overhang)	N/A	-80	N/A	-80	N/A	-80	N/A	-80
3 (corner roof)	25	-83	22	-75	21	-69	20	-65
3 (corner overhang)	N/A	-134	N/A	-121	N/A	-110	N/A	-104
DESIGN PRESSURE (psf)								
	Design Area							
Zone	80	sq. ft.	100	sq. ft.	200	sq. ft.		
1 (interior roof)	18	-36	17	-35	17	-35		
2 (exterior roof)	18	-60	17	-57	17	-57		
2 (ext.overhang)	N/A	-80	N/A	-80	N/A	-80		
3 (corner roof)	18	-60	17	-57	17	-57		
3 (corner overhang)	N/A	-95	N/A	-91	N/A	-91		

Appendix D (Continued)

Table D.7: Design Pressures for Exp. B, with Mean Roof Heights of 12 to 30 ft. (V = 160 mph)

Design Wind Speed	160 mph						
Mean Roof Height	12 to 30 ft.						
Exposure	B						
DESIGN PRESSURE (psf)							
	Design Area						
Zone	10 sq. ft.		20 sq. ft.		35 sq. ft.		50 sq. ft.
1 (interior roof)	31	-50	28	-48	26	-47	25	-46
2 (exterior roof)	31	-105	28	-95	26	-87	25	-82
2 (ext.overhang)	N/A	-101	N/A	-101	N/A	-101	N/A	-101
3 (corner roof)	31	-105	28	-95	26	-87	25	-82
3 (corner overhang)	N/A	-170	N/A	-153	N/A	-140	N/A	-131

DESIGN PRESSURE (psf)						
	Design Area					
Zone	80 sq. ft.		100 sq. ft.		200 sq. ft.	
1 (interior roof)	23	-45	22	-45	22	-45
2 (exterior roof)	23	-76	22	-73	22	-73
2 (ext.overhang)	N/A	-101	N/A	-101	N/A	-101
3 (corner roof)	23	-76	22	-73	22	-73
3 (corner overhang)	N/A	-120	N/A	-115	N/A	-115

Appendix D (Continued)

Table D.8: Design Pressures for Exp. C, with a Mean Roof Height of 12 ft. (V = 160 mph)

Design Wind Speed	160	mph
Mean Roof Height	12	ft.
Exposure	C	

DESIGN PRESSURE (psf)

	Design Area							
Zone	10 sq. ft.		20 sq. ft.		35 sq. ft.		50 sq. ft.	
1 (interior roof)	38	-60	34	-58	32	-57	30	-56
2 (exterior roof)	38	-127	34	-115	32	-106	30	-100
2 (ext.overhang)	N/A	-122	N/A	-122	N/A	-122	N/A	-122
3 (corner roof)	38	-127	34	-115	32	-106	30	-100
3 (corner overhang)	N/A	-206	N/A	-186	N/A	-170	N/A	-159

DESIGN PRESSURE (psf)

	Design Area					
Zone	80 sq. ft.		100 sq. ft.		200 sq. ft.	
1 (interior roof)	28	-55	27	-55	27	-55
2 (exterior roof)	28	-92	27	-88	27	-88
2 (ext.overhang)	N/A	-122	N/A	-122	N/A	-122
3 (corner roof)	28	-92	27	-88	27	-88
3 (corner overhang)	N/A	-146	N/A	-139	N/A	-139

Appendix D (Continued)

Table D.9: Design Pressures for Exp. C, with a Mean Roof Height of 15 ft. (V = 160 mph)

Design Wind Speed	160 mph							
Mean Roof Height	15 ft.							
Exposure	C							
DESIGN PRESSURE (psf)								
	Design Area							
Zone	10 sq. ft.		20 sq. ft.		35 sq. ft.		50 sq. ft.	
1 (interior roof)	38	-60	34	-58	32	-57	30	-56
2 (exterior roof)	38	-127	34	-115	32	-106	30	-100
2 (ext.overhang)	N/A	-122	N/A	-122	N/A	-122	N/A	-122
3 (corner roof)	38	-127	34	-115	32	-106	30	-100
3 (corner overhang)	N/A	-206	N/A	-186	N/A	-170	N/A	-159

DESIGN PRESSURE (psf)						
	Design Area					
Zone	80 sq. ft.		100 sq. ft.		200 sq. ft.	
1 (interior roof)	28	-55	27	-55	27	-55
2 (exterior roof)	28	-92	27	-88	27	-88
2 (ext.overhang)	N/A	-122	N/A	-122	N/A	-122
3 (corner roof)	28	-92	27	-88	27	-88
3 (corner overhang)	N/A	-146	N/A	-139	N/A	-139

Appendix D (Continued)

Table D.10: Design Pressures for Exp. C, with a Mean Roof Height of 20 ft. (V = 160 mph)

Design Wind Speed	160	mph
Mean Roof Height	20	ft.
Exposure	C	

DESIGN PRESSURE (psf)

	Design Area							
Zone	10 sq. ft.		20 sq. ft.		35 sq. ft.		50 sq. ft.	
1 (interior roof)	40	-64	37	-62	34	-61	32	-60
2 (exterior roof)	40	-135	37	-122	34	-112	32	-106
2 (ext.overhang)	N/A	-130	N/A	-130	N/A	-130	N/A	-130
3 (corner roof)	40	-135	37	-122	34	-112	32	-106
3 (corner overhang)	N/A	-219	N/A	-197	N/A	-180	N/A	-169

DESIGN PRESSURE (psf)

	Design Area					
Zone	80 sq. ft.		100 sq. ft.		200 sq. ft.	
1 (interior roof)	30	-58	28	-58	28	-58
2 (exterior roof)	30	-97	28	-93	28	-93
2 (ext.overhang)	N/A	-130	N/A	-130	N/A	-130
3 (corner roof)	30	-97	28	-93	28	-93
3 (corner overhang)	N/A	-155	N/A	-148	N/A	-148

Appendix D (Continued)

Table D.11: Design Pressures for Exp. C, with a Mean Roof Height of 25 ft. (V = 160 mph)

Design Wind Speed	160 mph							
Mean Roof Height	25 ft.							
Exposure	C							
DESIGN PRESSURE (psf)								
	Design Area							
Zone	10 sq. ft.		20 sq. ft.		35 sq. ft.		50 sq. ft.	
1 (interior roof)	42	-67	38	-65	35	-64	33	-63
2 (exterior roof)	42	-141	38	-128	35	-118	33	-111
2 (ext.overhang)	N/A	-136	N/A	-136	N/A	-136	N/A	-136
3 (corner roof)	42	-141	38	-128	35	-118	33	-111
3 (corner overhang)	N/A	-229	N/A	-207	N/A	-189	N/A	-177
DESIGN PRESSURE (psf)								
	Design Area							
Zone	80 sq. ft.		100 sq. ft.		200 sq. ft.			
1 (interior roof)	31	-61	30	-61	30	-61		
2 (exterior roof)	31	-102	30	-98	30	-98		
2 (ext.overhang)	N/A	-136	N/A	-136	N/A	-136		
3 (corner roof)	31	-102	30	-98	30	-98		
3 (corner overhang)	N/A	-162	N/A	-155	N/A	-155		

Appendix D (Continued)

Table D.12: Design Pressures for Exp. C, with a Mean Roof Height of 30 ft. (V = 160 mph)

Design Wind Speed	160	mph
Mean Roof Height	30	ft.
Exposure	C	

DESIGN PRESSURE (psf)								
	Design Area							
Zone	10	sq. ft.	20	sq. ft.	35	sq. ft.	50	sq. ft.
1 (interior roof)	44	-70	40	-68	37	-66	35	-65
2 (exterior roof)	44	-147	40	-133	37	-122	35	-115
2 (ext.overhang)	N/A	-142	N/A	-142	N/A	-142	N/A	-142
3 (corner roof)	44	-147	40	-133	37	-122	35	-115
3 (corner overhang)	N/A	-238	N/A	-215	N/A	-196	N/A	-184

DESIGN PRESSURE (psf)						
	Design Area					
Zone	80	sq. ft.	100	sq. ft.	200	sq. ft.
1 (interior roof)	32	-64	31	-63	31	-63
2 (exterior roof)	32	-106	31	-102	31	-102
2 (ext.overhang)	N/A	-142	N/A	-142	N/A	-142
3 (corner roof)	32	-106	31	-102	31	-102
3 (corner overhang)	N/A	-168	N/A	-161	N/A	-161