GREEN ROOFS AND WIND LOADING

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EXECUTIVE SUMMARY

Green roofs or vegetated roofs are a plant and soil based system as a roof cover. Green roof systems have been shown to be an environmentally friendly alternative based on various factors; such as, reduced volume of stormwater, improved water quality if used with a cistern, reduced lifecycle cost, improved air quality, ambient temperature reduction, and roof material sustainability. While it is advantageous to implement the new, more environmentally friendly green roof construction practices and products, there is a need to determine if this new technique is a safe alternative to existing roofing practice. As the green roof industry grows, research to determine the construction methods of a green roof in terms of wind protection are needed. There is a need to document the effectiveness of green roofs with high wind events by addressing the following questions: Do winds have an effect on greenroof material loss? Do greenroof materials modify green roof pressure conditions that would need a modification to current design codes? Does the level of vegetation establishment affect the material loss and pressure distribution?

The use of green roofs in the United States is a relatively new practice, used sparingly since the late 1990's, and therefore not much is known about how they will perform in extreme wind conditions experienced in different parts of the Country. This is especially true in Florida where, during the Atlantic hurricane season, the heavy winds and rains of tropical cyclones are a reality. In Florida, particularly along the coast, the strong winds of these storms cause millions of dollars in damage to buildings and infrastructure. The risk of unsecured objects becoming

projectiles presents a significant risk to property and person. Due to the fact that the media used in the construction of green roofs is light weight and granular and there can be hundreds or even thousands of individual plants, it can be impractical to mechanically fasten these components to the roof deck. Nevertheless it is known that the root system of the plants become entangled and form one continuous mat. But, the plant root interaction and installation practices are reasons green roofs need to be examined for how they respond under high wind events.

This research is conducted to measure wind and its effects with and without mitigation methods. Based on a review of the literature there are several options for measuring the effects. Visual observation of a full scale test under high wind conditions, and pressure measurements from a green roof would be beneficial in predicting failures and for providing data for the analyses of design of a green roof. For wind mitigation, the benefit of vegetation, the use of rolled erosion control products prior to vegetation establishment, and the use of a parapet wall all appear reasonable for protection.

Initial testing is conducted at Florida International University's (FIU) Hurricane Research Center utilizing the Wall of Wind (WOW). This WOW test apparatus is capable of producing wind speeds over 100 mph and with the placement of a square 10ft by 10ft by 10ft building structure in front of the wind. It is desired to observe a worst-case scenario utilizing a green roof system without a parapet installed atop of the building and without plants or any erosion control materials. It is also emphasized that short aluminum edge restraints along the perimeter of the green roof were not connected to the roof as part of the worst-case scenario. It is observed that while the green roof distorted by rolling over itself at the corners, no significant material is lost from the roof for a 1 minute and 30 second 78 mph gust of wind. It is further observed that the corner edge restraint collapsed and the drainage matt folded over the growth media, thus preventing further damage. From this wind effect, it is recommended to secure the edge restraint either mechanically or using a sufficient adhesive to prevent its failure.

The use of vegetation relative to a bare soil surface is believed to reduce wind erosion of soils on green roofs. Zhang et al (2006) concluded that soil erosion induced by winds decreased with the level of plant cover. This is due to the root structure of the plant holding the soil together and the plant mass above the growth media either providing wind breaks or laying down on the growth media protecting it from the erosive forces. To observe such phenomena, the researchers designed, developed and implemented two full scale green roofs, one on the East coast of Florida and the other on the West Coast to continuously monitor the effects of wind on green roofs. They had a grid of very low differential pressure transducers and a high speed anemometer for wind speed and direction. The monitoring provided data for pressure points on the green roof from winds of different direction and speed.

The reduction of wind erosion with the use of vegetation is observed first hand when comparing the green roof at the Florida Showcase Green Envirohome (FSGE) which has well established vegetation to the green roof at the Port Charlotte Ray's Stadium (PCRS) which has a newly planted green roof. The green roof at FSGE experienced almost no media loss under low wind conditions while the green roof at PCRS experienced significant loss under similar conditions. A geosynthetic erosion control blanket is added to the PCRS and the growth media loss significantly reduced.

As part of this research the two green roofs chosen for this project, FSGE and PCRS, are chosen based on location (being near the Florida East and West coasts respectively) and level of vegetative establishment. No significant, over 50 mph, instantaneous wind events occurred during the monitoring duration of this research, as a result ASCE code 7-05 is compared to the data collected and extrapolated for higher wind conditions to determine resulting pressure for wind speeds of 130 mph. Based on the pressure coefficients obtained during the monitoring duration, the pressure predictions for the well established vegetated roof (WEVR) at FSGE are determined to be slightly higher than those used in ASCE Code 7-05 estimated design loads. Based on this analysis, pressure changes for hurricane speed winds are predicted to have an overall average uplift pressure envelope within ASCE Code 7-05 design standards with vegetation cover enhancing sustainability under wind events.

The newly established vegetated roof (NEVR) at PCRS has measured pressure predictions that are double the estimated design loads allotted by ASCE Code 7-05. This does not necessarily imply that a NEVR increases uplift pressures on a roof but rather the model is based on available data with wind speeds less than 50 mph, does it might not have the correct parameters, and the assumptions that allow for extrapolation to high wind speeds may not as accurate as those obtained from hurricane force winds. Also, it should be noted that ASCE Code 7-05 is based on assumptions of no unusual geometry and cross winds which existed at PCRS. A green roof in Bonita Bay Florida (west coast and about 50 miles south of PCRS) was in the path of Hurricane Charley in 2004 and despite incomplete vegetative cover, there was no visible damage to the green roof.

The instrumentation of the green roofs also allows for examination of the pressure distribution across both green roofs. It is shown that the FSGE green roof, which is well established, had a uniform pressure distribution while the PCRS green roof, which is not well established, had a more erratic pressure distribution. This shows the benefit of established vegetation to reduce the pressure coefficient and therefore the resulting pressure field. It is also shown that objects near the green roof such as trees, parapets, and adjacent buildings can provide a wind break and protect the green roof from the loss of materials during strong winds. The use of a parapet wall is shown to protect the roof from high uplift forces by eliminating the zones on the roof most susceptible to these forces; those are the corners and the edge of the roof.

Computer programs currently used to analyze roof design considering uplift forces on a roof, such as ASCE Code 7-05 are reasonable to use with structures that have green roofs. Care should however be used in the selection of the parameters of the model, and more work and field data from a number of monitoring stations with high wind velocities may be needed to better define these parameters for all green roof building options.

The results of this research showed that green roofs with wind protection (erosion blankets and then mature plants in a continuous matrix, hurricane protection adhesive for edge restraints, and parapets) pose no additional risk from the loss of materials during high wind events such as hurricanes. It is shown that while a green roof may experience damage during these high wind events that minimal material leaves the roof. Also, establishment of vegetation and implementation of conventional erosion control techniques will further prevent damage and minimize media loss from the roof.

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Many students provided technical skills and time, and thus thanks are extended to those who helped with the construction and monitoring, namely Erik Stuart, Eric Smith, Oscar Robyaner, Lillie Thomas, and Bryan Rivera for helping with collecting samples, construction, and maintenance of the green roofs.

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ASCE	American Society of Civil Engineers
B	Horizontal dimension of building
C	Turbulence intensity factor
$\mathrm{C_p}$	Pressure coefficient
$\mathrm{C_{pmean}}$	Average minimum pressure coefficient
EPA	Environmental Protection Agency
FDEP	Florida Department of Environmental Protection
FEMA	Federal Emergency Management Agency
FIU	Florida International University
FSGE	Florida Showcase Green Envirohome
G	Gust Factor
GC_p	Product of gust factor and external pressure coefficient
GC_{pi}	Product of gust factor and internal pressure coefficient
H	Mean roof height of structure
HRC	Hurricane Research Center
I	Importance factor
IBHS	Institute for Business and Home Safety
	Integral length scale of turbulence
K_d	Wind directionality factor
K_z	Velocity pressure exposure coefficient

K_{zt}	Topographic factor
L	Integral length scale factor
	Intensity of turbulence
NAH	New American Home
NEVR	Newly Established Vegetated Roof
NI	National Instruments
o.d.	Outer diameter
P	ASCE design pressure (psf)
PCRS	Port Charlotte Rays Stadium
Q	Base wind pressure (psf)
Q	Background response factor
SMAL	Stormwater Management Academy Laboratory
SU	Student Union
UCF	University of Central Florida
UHIE	Urban Heat Island Effect
V	Velocity (mph)
W.C.	Water Column
WEVR	Well Established Vegetated Roof
WOW	Wall of Wind
Z	Height above ground level (ft)
z_g	Nominal height of the atmospheric boundary layer
z_{min}	Exposure constant

	Equivalent height of structure
A	3-sec gust power law exponent
Δp	Change in pressure (psf)
P	Density (slug/ft^3)
	Integral length scale power law exponent

CHAPTER ONE: INTRODUCTION

Background

Due to the growing population, people are paving over the natural elements of the world with impervious area in order to accommodate the drive of today's culture. Although this driving force helps the world industrially, it speeds the process of weakening the Earth's environment. In order to help alleviate some of the harm the planet has already encountered, researchers have been studying various ways to counteract this problem by utilizing "greenroofs" – a term as defined by the Environmental Protection Agency to identify any rooftop that benefits the environment through energy conservation, whether it is with the aid of solar panels, wind turbines, or vegetation. By utilizing these efforts, researchers have shown a greater improvement on energy conservation by almost 50% (Hardin 2006). Focusing on greenroofs for this literature, these continuing endeavors have been positive in helping the environment through stormwater quality management, as well as energy efficiency; however, the problem still lies in the structural development of these environmental rooftops in relation to severe weather conditions like hurricanes.

In Florida, the structural reliability of roofing systems have been a problem for many years since the peninsula is a bulls-eye for hurricane conditions. Due to the hurricanes that occurred within a 44 day span in 2004, the U.S. Department of Homeland Security Federal Emergency Management Agency (FEMA) disbursed $4.85 billion among victims that experienced 4 category-five hurricanes in one season, with 87.7% of the total disaster fund allotted (FEMA 2005). According to a survey conducted at the University of Florida (2005), 50% of tiled (unprotected) rooftops experienced roof and window damage as a result of the 120 mph winds while only 23.9% (unprotected) rooftops with no tile experienced the same during the hurricane events of 2004 (Brandt 2005). By taking preventative measures during a high wind event, research shows that potential roof damage can be reduced; however, it may still occur.

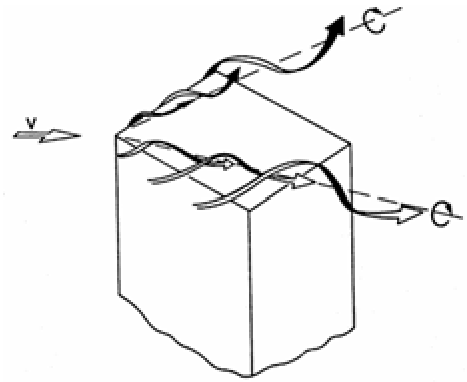


Figure 1: Vortex generation [Source: Blessing 2007]

Roof damage is induced by vortex generation, an occurrence of significant negative pressure (uplift) under harsh weather. This phenomenon is a turbulent flow in which separation of wind flow is created due to the interaction between the wind force and an obstruction, such as a low-rise structure, where it is forced to separate from the object as shown in Figure 1 (Blessing 2007). Based on the direction of wind, the failure of roofing materials are greater along the perimeter or the corner regions of the windward side of the roof. Conventional roofing materials, including asphalt shingles, wooden shingles, clay shingles, and tile shingles, are highly susceptible to damage if not properly adhered to the roof deck in addition to weathering over time. Given that current methods of roofing have these problems, substituting green materials like soil and vegetation are questionable to withstand the same damage.

Current provisions outlined by the American Society of Civil Engineers (ASCE), ASCE Code 7-05, use data from research to develop standard methods for structural design under various load combinations due to live, dead, wind, flood, rain, and seismic loads. Specifically for wind design, loads on components and cladding for the structure are determined by using one of three different methods of investigation: the simplified method, the analytical method, and the wind tunnel method (ASCE 2005). ASCE calculates pressure based on factors and coefficients used for a 3 second wind gust provided by tables, figures, and graphs in ASCE Code 7-05. The pressures identified by this analysis are considered to be the design pressures for the structure under the specified wind event and are used to aid in the design of structures for combating wind uplift. While ASCE Code 7-05 is used widely throughout the United States for structural design, it is unknown if this code is applicable in the design of buildings with greenroofs or vegetated roof tops.

Greenroof systems have been shown to be an environmentally friendly alternative based on various factors; such as, reduced lifecycle cost, improved air quality, ambient temperature reduction, stormwater management credit, sustainability and preservation of the environment. Recent research studies attempt to determine the construction methods of an ideal greenroof for environmental purposes, yet there is an absence of standards for the best design required to achieve acceptable structural performance and sustainability under wind loads. Since greenroofs are relatively new to the modern construction industry, there is a lack of adequate research based on the application of these unconventional building materials; therefore, geotechnical methods used to control wind erosion are appropriate in order to tackle the problem at hand.

Wind uplift failure occurs when the soil media layer is removed or projected from the roof due to wind; therefore, the use of soil erosion preventative techniques reduces the likelihood of failure. In order to control uplift, soil particles are reinforced by increasing soil cohesion, integrating geo-textile materials for soil stability, roughness of the soil surface, vegetation cover, and utilizing wind breaks. Generally, light weight expanded clay is employed due to its ability to support vegetative growth (as well as structural load bearing capacity with respect to the light weight of soil media). Furthermore, because clay is highly cohesive in comparison to other soils, saturation during irrigation and heavy rain events adds to the control of wind through soil cohesion. By making use of vegetation and increasing the cohesion of clay by adding water, wind speed is cut at ground level and uplift is prevented from the addition of weight by water. Additionally, wind breaks are effective in the way of cutting wind speed by 20% over an area 10 to 12 times the height of the barrier before and behind it (Roose 1996).

Research, Scope, & Objectives

For the purpose of this study, wind loads on two greenroof tops are analyzed and compared to ASCE Code 7-05. Located in Florida, one roof resides in Indiatlantic, FL (East coast) and the other roof is planted in Port Charlotte, FL (West coast). The East coast greenroof is a well established vegetated roof (WEVR) which was planted in the summer of 2007; while, the West coast greenroof is a newly established vegetated roof (NEVR) built in the beginning of

2009. Both greenroof systems are constructed using the same green building materials but differ in size, geometry, depth, and wind control techniques.

Uplift pressures are measured to determine the best wind control method, specifically comparing the effects of a newly established greenroof to a well established greenroof. Bi-directional pressure transducers are used in relation to a wind monitoring device to correlate the relationship between wind and pressure in contrast to the different design methods currently implemented. After analyzing the pressure distributions atop the surface of the soil per roof, the results are compared to ASCE Code 7-05 analytical method calculations.

There is a necessity to document the effectiveness of greenroofs under high wind conditions; thus, the following objectives are outlined by the three questions needed to be addressed:

1. Do winds have an effect on green roof material loss?
2. Do greenroof materials modify local pressure conditions that would need a modification to current design codes?
3. Does the level of vegetation establishment affect the material loss and pressure distribution?

This study presents results from the climate conditions and the monitoring sites designed and implemented for this research. Located in Florida, each greenroof is subjected to harsh conditions of humidity, hot temperatures, and large rain events. Since all data collected are based on field conditions, new variables are introduced and those affecting wind uplift cannot be completely isolated; nor can wind speed and direction be controlled.

Approach

This literature is composed of six chapters. In Chapter One, an introduction on greenroofs is presented along with the objectives and scope of this thesis. Next, green technologies are examined in Chapter Two; while, modern research cases aiding in the development of studying wind uplift on greenroofs are also presented. Then, a controlled field investigation on greenroofs with simulated wind loads is studied in Chapter Three. In Chapter Four, a full scale monitoring design and implementation, as well as, background information on the construction of each greenroof is presented. The results compiled from testing are then discussed in Chapter Five. Finally, conclusions of this research are outlined in Chapter Six along with recommendations for future monitoring techniques for the evaluation of green technologies for maximum wind uplift control.

CHAPTER TWO: GREENROOFS & CONSTRUCTION METHODS

Florida is known for two major resources: the endless supply of sunshine and late afternoon rain showers. With these types of continual sources, Florida is a premium location for greenroof application. Unfortunately, between June 1st and November 30th, hurricane season is active and, in some years, they are worse than others. For those who live in areas where hurricanes are within the norm, torrential downpours and 75 – 150 mph winds are structurally devastating. If structures are already targets for hurricane destruction, damaging other structures with flying debris are a major concern, especially with greenroofs. In order to resolve the problem, this study tests various techniques to combat hurricane winds by utilizing the green technologies presently available as well as wind erosion techniques like geo-textiles, vegetation cover, and wind breaks. Due to the lack of detailed research conducted on this matter, the proceeding background information is solely based on the studies of the various components needed to construct a greenroof in relation to the investigation of wind uplift on vegetated rooftops in the state of Florida.

Greenroofs

What is a Greenroof?

According to the Environmental Protection Agency (EPA), a greenroof consists of vegetation and soil (starting at a minimum depth of 3”) – or an artificial vegetation mat, planted over a waterproofing membrane, with the addition of other sustainable materials, such as a root barrier, drainage system, and an irrigation network shown by the general greenroof schematic illustrated in Figure 2 (http://www.epa.gov/).

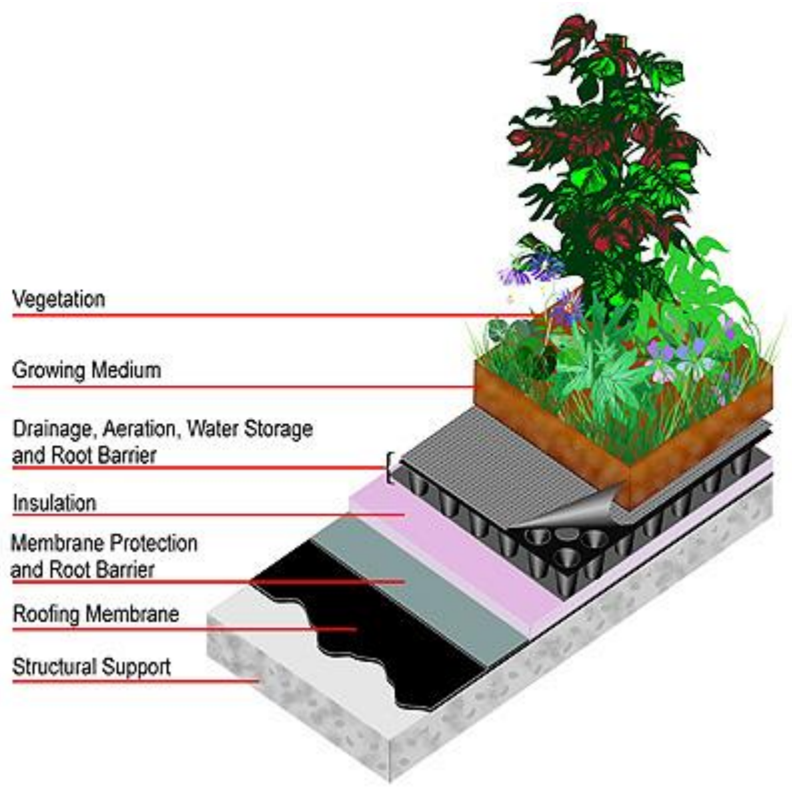


Figure 2: General greenroof cross-section [Source: http://email.asce.org/ewri/LIDInitiatives.html]

Greenroofs can be used on various structures, including industrial facilities, residences, offices, and other commercial buildings. Utilized throughout Europe for many years, these roofs are widely used for the environmental benefits produced through stormwater management and energy savings potential, while also sustaining an aesthetic appeal.

Figure 3: Intensive greenroof (left) in Chicago, Illinois and an extensive greenroof in Dearborn, Michigan [Source: http://urbanneighbourhood.com/?p=2080 and http://www.greenroofs.org/index.php/grhccommittees/290?task=view respectively]

There are essentially two types of greenroofs available for private and commercial use: intensive greenroofs and extensive greenroofs. Intensive greenroofs are actively used primarily on commercial buildings due to the structural load and complexity of the greenroof itself. Extensive greenroofs, on the other hand, are passively applied both privately and commercially due to their low installation costs as well as its minimum need for maintenance.

An example of both greenroofs is presented in Figure 3 with the intensive greenroof located in Chicago, Illinois, and the extensive greenroof located in Dearborn, Michigan. Atop Chicago's City Hall (completed in 2001), the intensive greenroof serves as a treatment to the urban heat island effect with a cost of $2.5 million with a surface area of about half an acre (www.greenroofs.com). Alternatively, the extensive greenroof covering the Ford Plant was recognized as the largest greenroof in the world by the 2004 Guinness World Record with a surface area of approximately 10.4 acres and an installation cost of about $3.6 million (www.greenroofs.org).

Table 1: Greenroof characteristics in relation to intensive and extensive roofs in accordance with the Environmental Protection Agency (EPA) [Source: http://www.epa.gov/]

GREEN ROOF CHARACTERISTICS	
INTENSIVE	**EXTENSIVE**
Minimum soil depth of 1 ft.	Requires only 1 - 5 inches of soil depth.
Accommodates large trees, shrubs, and well-maintained gardens.	Capable of including many kind of vegetative ground cover and grasses.
Adds 80 - 150 lbs/sq. ft of load to a building structure.	Adds only 12 - 50 lbs/sq. ft depending on soil characteristics and the type of substrate.
Regular access accommodated and encouraged.	Usually not designed for public accessibility.
Significant maintenance required.	Annual maintenance should be performed until plants fill in.
Include complex irrigation and drainage systems.	Irrigation and drainage systems are simple.

As outlined in Table 1, intensive greenroofs are far more involved than extensive greenroofs. Although both types of roofs are beneficial environmentally, intensive greenroofs allow for regular access; making it similar to a park environment atop the roof. As a result, an extensive greenroof is an affordable and simple alternative to the more expensive and complex intensive greenroof while still maintaining the environmental and aesthetic benefits of a vegetated roof.

Environmental Benefits

With the loss of environment through the pavements and structures needed to develop society, heat is retained within these impervious materials and problems like the urban heat island effect (UHIE) become more evident. Due to these issues, greenroofs are an ideal solution to reduce the UHIE phenomenon given the plethora of environmental benefits they ensure.

Green rooftops are sometimes referred to as eco-roofs which help manage stormwater runoff by mimicking a variety of hydrologic practices generally associated with open space. The vegetation atop the roof soaks in the rainfall in support of evapotranspiration while also preventing stormwater runoff reducing it annually by about 50% during short duration storms (www.metrocouncil.org) as shown in Figure 4.

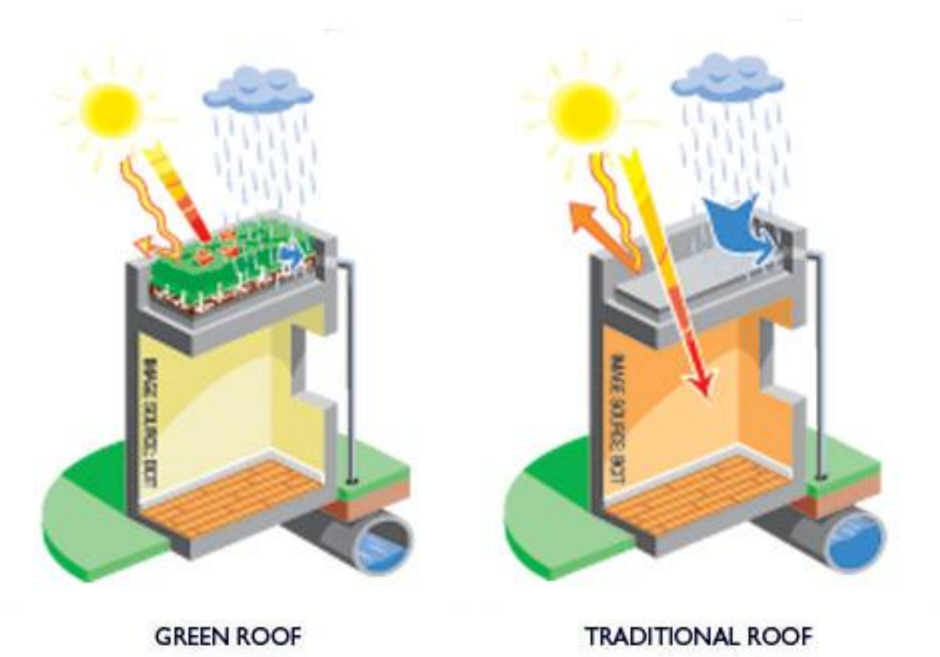


Figure 4: Natural effects on a greenroof in comparison to a traditional roof [Source: commons.bcit.ca/greenroof/images/roof_types.jpg]

Research has shown many benefits to utilizing vegetated roofs (specifically outlined by Table 2). The main benefit (in Florida), however, is the ability to keep the interior of the building covered cool in the summer which reduces the need for more air conditioning; in return, cutting the amount of energy usually consumed. Furthermore, with the large amounts of rain experienced throughout the year, greenroofs also aid in the reduction of sewage system loads by assimilating large amounts of rainwater (http://www.epa.gov/).

Table 2: Green roof benefits cited by the Environmental Protection Agency (EPA) [Source: http://www.epa.gov/]

GREEN ROOF BENEFITS
Reduce sewage system loads by assimilating large amounts of rain water
Absorb air pollution, collect airborne particulates, and store carbon.
Protect underlying roof material by eliminating exposure to the sun's ultraviolet (UV) radiation and extreme daily temperature fluctuations.
Serve as living environments that provide habitats for birds and other small animals.
Offer an attractive alternative to traditional roofs, addressing growing concerns about urban quality of life.
Reduce noise transfer from the outdoors.
Insulate a building from extreme temperatures, mainly by keeping the building interior cool in the summer.

Applications around the World

Greenroofs have been around for thousands of years. One of the oldest greenroofs can be dated back to 500 B.C. with the Hanging Gardens of Babylon illustrated by the Dutch artist Martin Heemskerck in Figure 5. Considered one of the Seven Wonders of the World, this ancient greenroof was built over arched stone beams and held together and waterproofed with layers of reeds, thick tar with soil, plants, and trees (Wanielista et al 2008). Within the past 200 years, countries around the world have adopted these methods with a more modern approach to construction.

Figure 5: A 16th-century hand-colored engraving of the "Hanging Gardens of Babylon" by Dutch artist Martin Heemskerck. [Source: http://en.wikipedia.org/wiki/File:Hanging_Gardens_of_Babylon.jpg]

With the advancements of green technologies in the twentieth century, European countries jumped at the chance to build green with Germany leading the pack. Since many studies have been conducted in Germany, the contemporary greenroof industry originated in and emerged in the 1960's, in which the best methods for greenroof construction in order to ensure maximum stormwater benefit as well as recommending maintenance routines and materials for assembly are now available. Between 1989 and 1999, over 350 million square feet of greenroofs were built on structures throughout the country of Germany (Penn State 2006). Combined with poor environmental quality, social pressures, and a political social climate, the German community supported the implementation of greenroofs which drove their current popularity throughout the country (Dunnett & Kingsbury 2004). Recently, there has been a “green craze” within the United States due to a growing unhealthy environment and documented success from the Eastern side of the world.

(a) Greenroof atop a building in Beijing, China **(b) Solaire building in New York**

(c) ACROS Fukuoka building, Japan **(d) Millenium Park, Chicago**

Figure 6: Greenroof applications around the world [Source: http://greenroofs.wordpress.com/contact-us/]

Within the past 100 years, the United States has shown a history of using greenroofs; like the 1930’s greenroof still seen today at Rockefeller Center in New York. Due to the UHIE, the city of Chicago in Illinois has taken the lead in sustainability within the U.S. with 2.5 million square feet of greenroofs in place and more planned (Paulson 2006). Chicago also hosts one of the largest greenroofs in the world with the 24 acre Millenium Park shown in Figure 6 (d). In Dearborn Michigan, the Ford Motor Company saved millions of dollars in reduced stormwater management facilities after building a 10.4 acre greenroof on its new facility (Hardin 2006).

With the successes seen in other parts of the world, Florida has been taking a step further in their environmental management plans by adding greenroofs to new construction since 2003. There are currently seven greenroofs in Florida with more underway:

- UCF Student Union and Stormwater Lab (2 locations)
- Envirohome on East Coast (5 separate ones)
- New American Home in Orlando
- Bonita Bay Maintenance House
- Tampa Bay Rays Charlotte County Stadium
- General Works in Sanford (commercial building)
- Nancy Foster Environmental Center in Key West

Studies at UCF

Since the opening of the Stormwater Management Academy at the University of Central Florida (UCF) in 2004, greenroof research has been a priority in studying the various methods of stormwater quality through the advancement of green technologies. There are four greenroofs that have been installed and three of those greenroofs have been monitored by UCF students for environmental conditions which can be seen in Figure 7: the UCF Student Union (SU), the New

American Home (NAH), the Stormwater Management Academy Laboratory (SMAL), and the Florida Showcase Green Envirohome (FSGE). For this section, research conducted on the UCF SU, the NAH, and the SMAL will be discussed in detail.

(a) An extensive greenroof atop the Student Union at UCF

(b) 1 of 5 greenroofs monitored at the Florida's Showcase Green Envirohome (FSGE) located in Indialantic, FL

(c) New American Home in Downtown Orlando, FL

(d) An extensive greenroof atop the Stormwater Lab

Figure 7: Greenroof projects researched by the University of Central Florida (UCF) [Source (a): http://www.stormwaterenvironments.com/success_stories.html (c): http://homebuilding.thefuntimesguide.com/2007/03/energyefficient_greenhomeideas.php (d): (Wanielista et al 2007a)]

The Student Union Green Roof

The first major UCF greenroof project was conducted by Mike Hardin at UCF atop the Student Union (SU). Shown in Figure 7 (a), the vegetated roof is composed of approximately 4 inches of green materials, 3 inches of growth media and 1 inch of pollution control media, with an area of about 1600 sq. ft, designed for minimum upkeep and maximum environmental benefit. The extensive greenroof was installed in March 2005 and maintained full vegetation cover in about one year (Hardin 2006). The main objective for this study was the design and benefit of a drip irrigation system with the addition of a cistern, while also measuring stormwater quality across eighteen test beds differing in soil media, irrigation rates, and vegetation. Outlined in Table 3 are the water budget parameters chosen for Hardin's study: precipitation rates (P'), irrigation rates (I'), evapotranspiration rates (ET'), supplementary water source (Z'), cistern overflow (O'), geenroof media storage (Ms'), greenroof filtrate, and cistern storage (S').

Table 3: Water Budget Parameters of Interest. [Source: (Hardin 2006)]

PARAMETERS	ANTICIPATED VALUE
P' [in/GR Area]	62.51*
I' [in/GR Area]	1 in/week or 2 in/week
ET' [in/GR Area]	0.14**
Z' [in/GR Area]	Will vary with storm event
O' [in/GR Area]	-
Ms [in/GR Area]	-
F' [in/GR Area]	Will vary with storm event
S' [in/GR Area]	-

www.cityoforlando.net/public_works/stormwater/

* Based on 2004 data, Inches per year

** Monthly average, Inches per day

The eighteen greenroof chambers were built with an area of approximately 16 ft^2; replicating the Student Union's greenroof. The design of each chamber differed only in soil media and vegetation, while all other construction parameters stayed true to the field study design. The two different types of growing media examined for this experiment were divided into two soil types:

- Soil A: Expanded clay-based media with 60% expanded clay, 15% peat moss, 15% perlite, and 10% vermiculite (E)
- Soil B: (Bold & Gold™) Tire crumb-based media with 40% tire crumb, 20% expanded clay, 15% peat moss, 15% perlite, and 10% vermiculite (B&G)

Two irrigation rates were also compared to determine the effects on stormwater quality based on regular irrigation of 1 inch of water per week compared to an over irrigation of 2 inches of water per week (separated into two weekly irrigations of 1 inch of water each). However, irrigation only occurred when, 24 hours prior, precipitation levels exceeded the volume being tested. When looking at vegetation and the added environmental benefits they ensure, Hardin designed sixteen chambers to compare Soil A with and without vegetation to Soil B with and without vegetation. By comparing all three of these variables in relation to one another, the most efficient design for stormwater runoff was qualified.

To study the effects of a cistern in relation to a greenroof, the biological processes were analyzed based on water quality tests that were routinely conducted on sampling from the Student Union greenroof cistern once a week. The following parameters were inspected: ortho-phosphorus, total phosphorus, nitrate + nitrite, ammonia, TKN, total nitrogen, total suspended solids, total dissolved solids, total solids, pH, and alkalinity through current methods outlined in Table 4.

Table 4: Water quality parameters and their respective testing methods [Source: (Hardin 2006)]

PARAMETERS	TESTING METHODS
Ortho-phosphorus	Standard Methods 4500-P E ascorbic acid method: Hach DR 5000 spectrophotometer
Total Phosphorus	Standard Methods 4500-P B 5 persulfate digestion method for the conversion of organic phosphorus to ortho-phosphorus
Nitrate+Nitrite	Standard Methods 4500-NO_3^- E cadmium reduction method: the Hach DR 5000 spectrophotometer
Ammonia	Standard Methods 4500-NH_3 D using the Accumet^{TM} AR50 Dual Channel pH/Ion/Conductivity Meter with the Thermo Electron Corporation Orion 9512 Ammonia selective probe.
TKN	Standard Methods procedure 4500-N_{org} B Macro-kjideal method
Total Nitrogen	Add up the nitrogen species
Total Suspended & Dissolved solids	Standard Methods 2540 D and C
pH	Accumet^{TM} AR50 dual channel pH/Ion/Conductivity Meter with the AccutupH^{+TM} selective probe
Alkalinity	Standard Methods titration method 2320 B

Based on the data collected from this field investigation, it was concluded that greenroof stormwater treatment can effectively reduce the volume of runoff by as much as 87% when using a cistern that stores a volume of 5 inches over a greenroof area in Orlando, FL; while, greenroofs that do not utilize a cistern only achieves a runoff reduction of about 43% for the same region (Hardin 2006). Furthermore, it was also shown that the UCF Student Union greenroof had a heat reduction of about 45% over the course of one year (Wanielista et al 2007b).

Results from the experimental chambers concludes that a greenroof has the ability to reduce the stormwater runoff by approximately 50% for 6 inches of water per hour for a 10 minute duration shown by the hydrograph in Figure 8 (Hardin 2006).

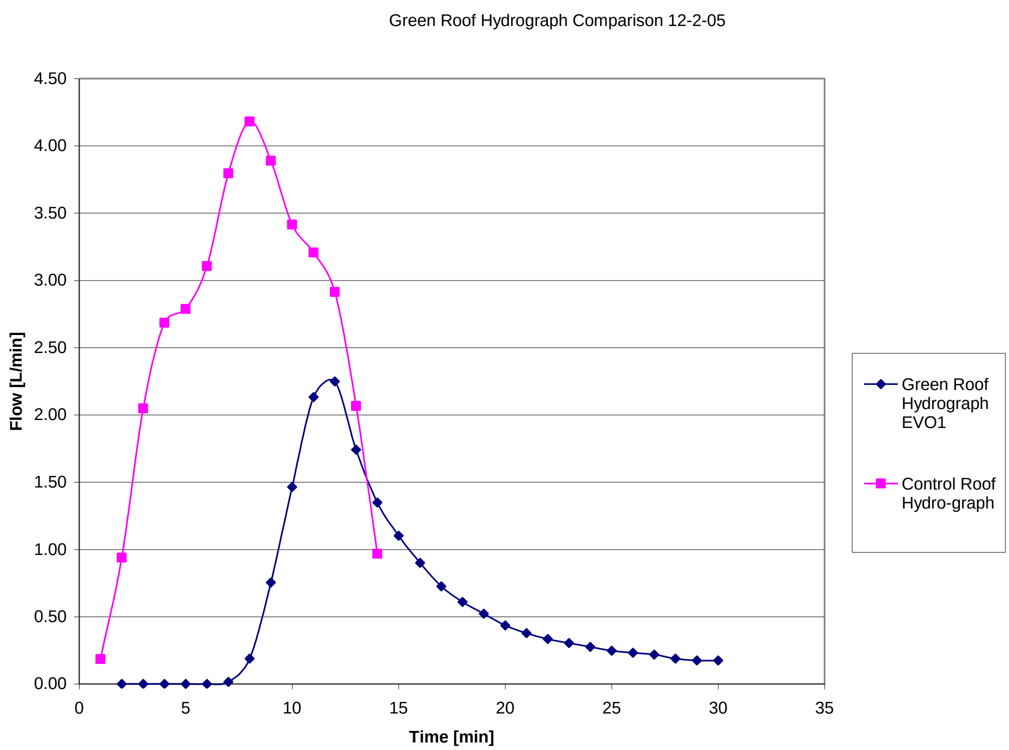


Figure 8: Hydrograph Comparison Control vs. Expanded Clay. [Source: (Hardin 2006)]

When looking at the stormwater quality effects of Soil A and Soil B (E and B&G respectively), the biggest nutrient removal is shown by Figure 9. Although both soils remove these nutrients significantly in comparison to the control beds (no greenroof), the Bold & Gold™ growth media reduces more nitrogen with respect to the expanded clay material. This is due to the recycled tire crumbs ability to absorb the nitrogen. However, it was also noted by Hardin that Soil A allowed the vegetation to flourish more abundantly in comparison to Soil B even though the Bold and Gold™ growth media removed more nutrients. In order to maintain the best greenroof design, it was concluded to utilize a 1 inch per week irrigation routine, with a greenroof constructed with expanded clay growth media with a 1 inch Bold & Gold™ (tire crumb base) pollution control media directly below it.

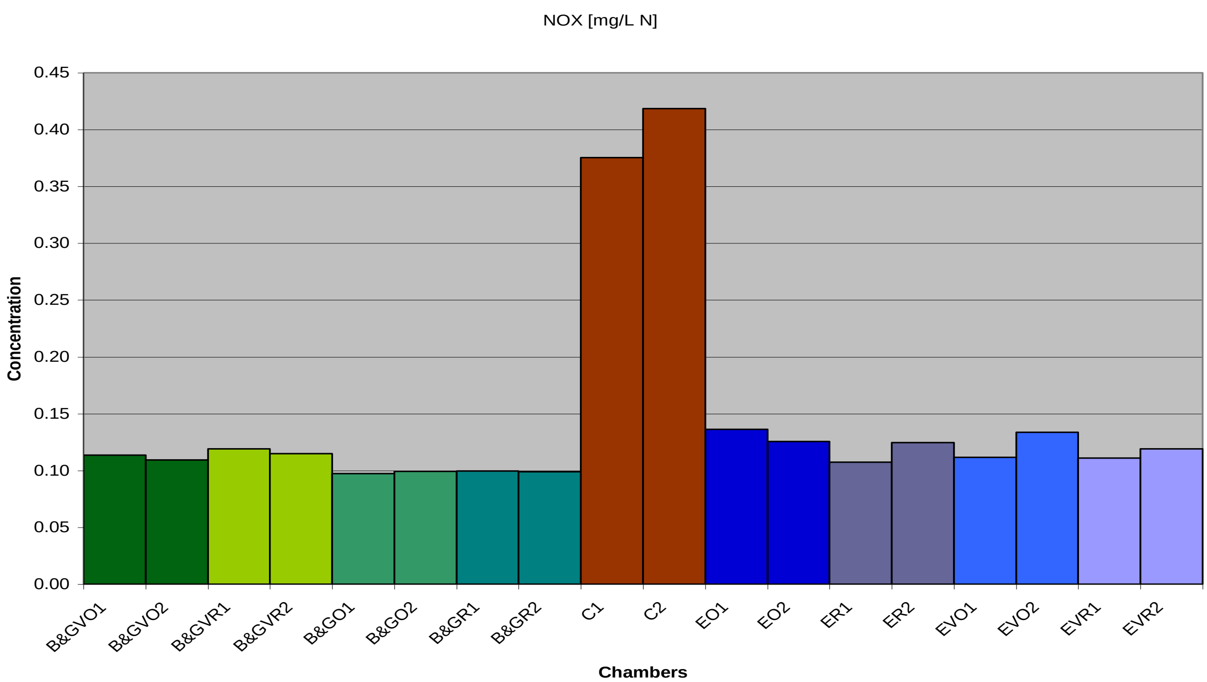


Figure 9: Nitrate+Nitrite concentrations (mg/L) of all greenroof testing beds [Source: (Hardin 2006)]

New American Home

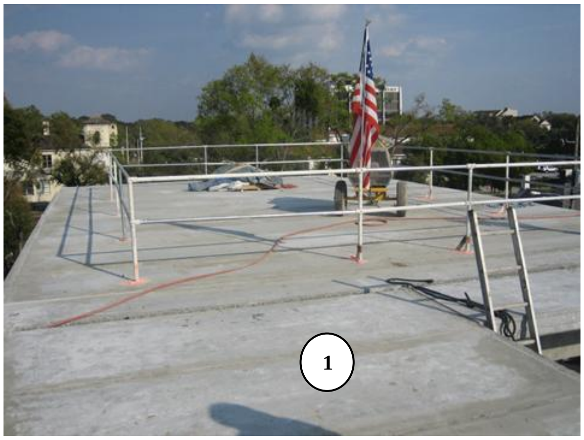
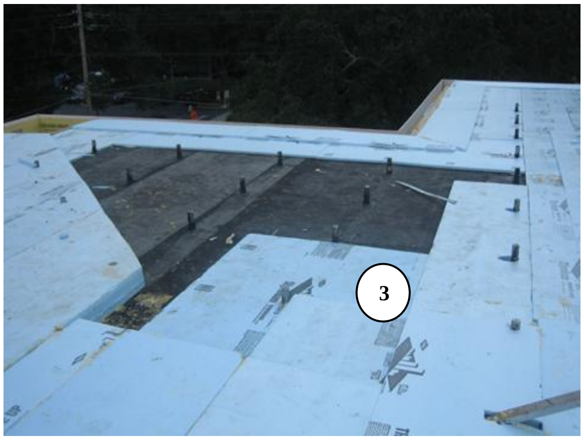
Completed in January, the house was the show home for the 2007 International Builders Show, which had an attendance of over 100,000 people (www.greenroofs.com). The single family home located in Downtown Orlando, FL has greenroofs on site sized at about 300 ft^2 and

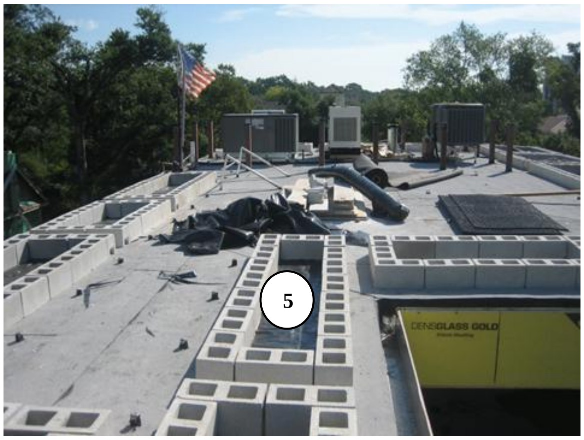
360 ft^2 of greenroof planters (represented by Figure 10) which acts extensively at a growing depth of approximately 5-6 inches. The design incentives for this research was to study a 95% retention of site runoff with underground water runoff collection cistern for pollution control and irrigation of the roof using primarily native vegetation and pollution control media beneath the growth media for each greenroof.

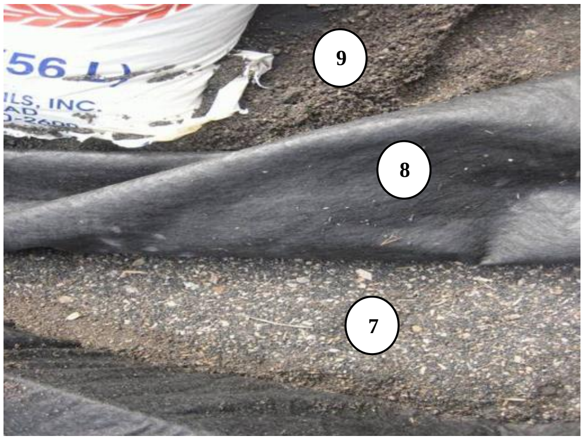
The main objective for the design of the stormwater treatment system was to minimize stormwater runoff from the cistern; which was anticipated to help improve water quality within that discharge. Another significant goal was to document greenroof construction methods for the public to educate those who aspire to go “green” by applying these innovative techniques as an alternative stormwater treatment system (Wanielista et al 2007a).

The construction methods used to build the New American Home (NAH) are shown in application order by Table 5 (a) through (h). Table 5 (i) and (j) represent the filter boxes and pump sump respectively. In relation to these discharge technologies, a cistern and drainage basin were also used.

Table 5: New American Home (NAH) under construction [Source: (Wanielista et al 2007a)]

Construction Techniques for the New American Home (NAH)		
Label	**Figure**	**Description**
(a)		1. *Conventional concrete roof deck at the New American Home in Downtown Orlando, FL.*
(b)		2. *Hydrotech waterproof layer is a rubber-asphalt material spread over the concrete roof deck at a temperature of 350^{o} F to 450^{o} F at a thickness of about 90 mm. A polyester fabric is imbedded into the material when warm and then finished with a 125 mm layer of rubber-asphalt material over the fabric. The material takes approximately 48 hours to cure.*
(c)		3. *Insulation installation atop the waterproof membrane has an R-value of 5 per inch. The insulation was used for a mild slope on the roof, insulating the middle of the roof more heavily than its perimeter. In the middle area of the roof, the thickness of the insulation was close to 6 inches, resulting in an R-value of 30.*

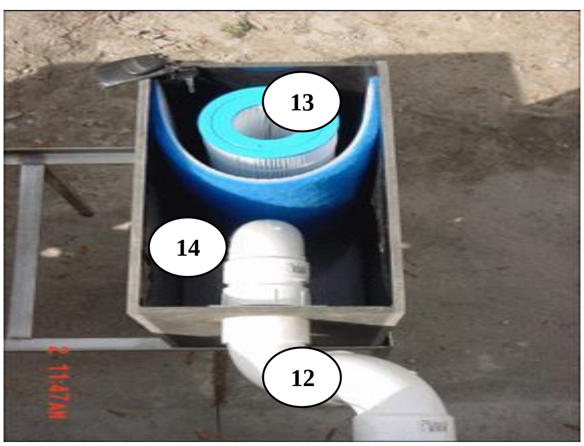
Construction Techniques for the New American Home (NAH)		
Label	**Figure**	**Description**
(d)		4. *The final layer of the roof deck before the greenroof material fitting of the media and vegetation is a second protection layer which is rolled out over the insulation to help protect the components from construction foot traffic and weather.*
(e)		5. *Concrete blocks used as planter boxes to contain the media and vegetation. The blocks were attached to the roof with a heavy duty adhesive and were spaced with a quarter inch space between them to aid drainage. Planter boxes only line the perimeter of the NAH as an aesthetic detail to be seen from the street.*
(f)		6. *2 cubic feet of the Bold & Gold™ pollution control media and growing media lifted on to the roof by a forklift.*

<table>
<tr><th colspan="3">Construction Techniques for the New American Home (NAH)</th></tr>
<tr><th>Label</th><th>Figure</th><th>Description</th></tr>
<tr><td>(g)</td><td>
</td><td>

7. *The pollution control media is spread into the planters at a depth of 1.5 inches.*
8. *A separation fabric was laid over top of the Bold and Gold™ Pollution Control media to prevent the buoyant materials in the Bold and Gold™ Pollution Control media from floating to the top and mixing with the growing media.*
9. *The growing medium has a depth of 6 inches.*

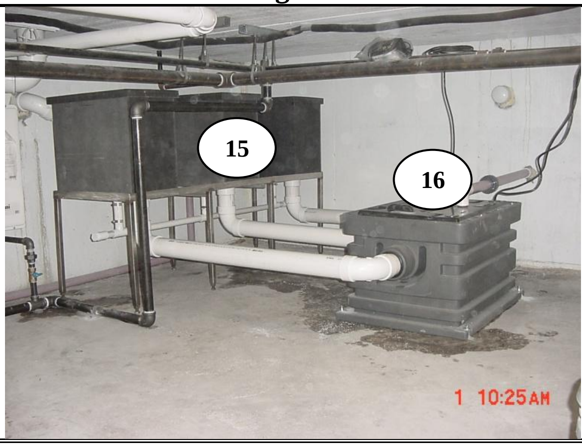
</td></tr>
<tr><td>(h)</td><td>
</td><td>

10. *Muhly Grass and Coontie Palm are planted*
11. *All plants are irrigated with flexible drip irrigation tubing which is intertwined between the plants.*

</td></tr>
<tr><td>(i)</td><td>
</td><td>

12. *Stormwater runnoff from rooftop.*
13. *The roof runoff travels into three 20 micron Unicell filter boxes.*
14. *Sampling location*

</td></tr>
</table>

Construction Techniques for the New American Home (NAH)		
Label	**Figure**	**Description**
(j)		*15. Three Unicell filter boxes discharges water to sump pump.* *16. A sump pump filters water to the cistern.*

Water quality in the cistern, drainage basin, sump pump, and before filtration was measured and compared to one another as outlined by Table 6 and Table 7. Based on the conclusions made by Wanielista et al (2007a), the nutrients and bacteria concentrations were lower in the cistern compared to the other locations. Furthermore, as stated by Wanielista et al (2007a), the greenroof stormwater management system designed for water quality improvement and stormwater volume reduction has been demonstrated to achieve water quality improvements and volume reductions as shown in Table 6 and Table 7.

Table 6: Average Values from Four Different Locations at the NAH [Source (Wanielista et al 2007a)]

Sample Location	pH	Alkalinity (mg/l)	TSS (mg/l)	TDS (mg/l)	Total Solids (mg/l)	Conductivity µS @ 25C	Turbidity NTU	BOD5 (mg/l)
Drainage Basin	6.27	45	12	107	119	129	2.96	7.13
Before Filter	6.81	45	24	134	158	140	1.72	11.68
Sump Pump	6.88	45	7	135	142	137	2.30	9.02
Cistern	7.45	88	2	161	163	216	0.76	1.37

Table 7: Average Values from Four Different Locations at the NAH [Source: (Wanielista et al 2007a)]

Sample Location	NH3 (µg/l)	NOx-N (µg/l)	Nitrite (µg/l)	TN (µg/l)	SRP (µg/l)	TP (µg/l)	Fecal Coliform (cfu/100 ml)	E. Coli (cfu/100 ml)
Drainage Basin	270	333	19	4706	24	118	733	2
Before Filter	481	1161	71	5190	39	216	337	71
Sump Pump	191	1437	113	6144	39	91	896	121
Cistern	48	185	12	329	46	76	60	37

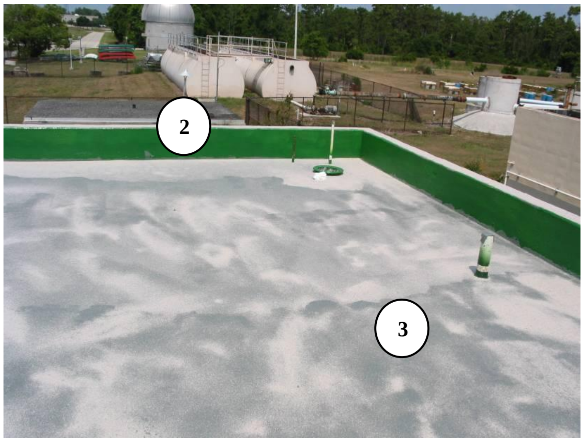
Based on this study, Wanielista et al (2007a) recommends the design, construction, and operation implemented in situ at the New American Home be considered for other greenroof stormwater treatment systems with the addition of a cistern for stormwater control. Additionally, it is concluded that stormwater collection on site (via cistern) should be used for irrigation and other non potable uses.

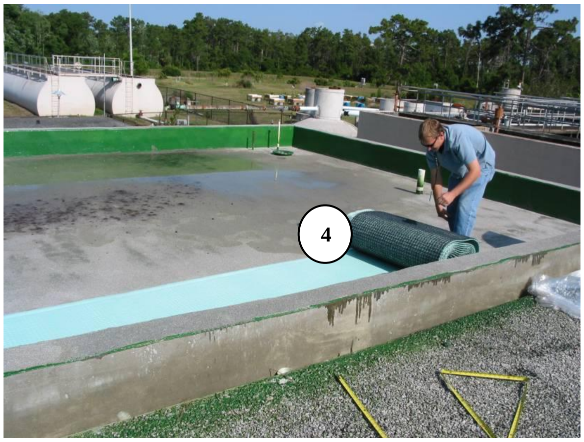
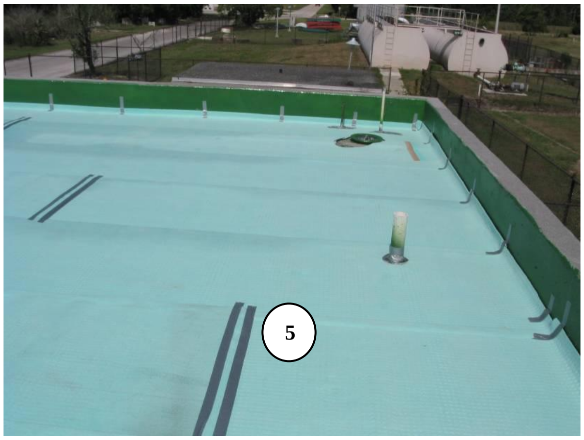
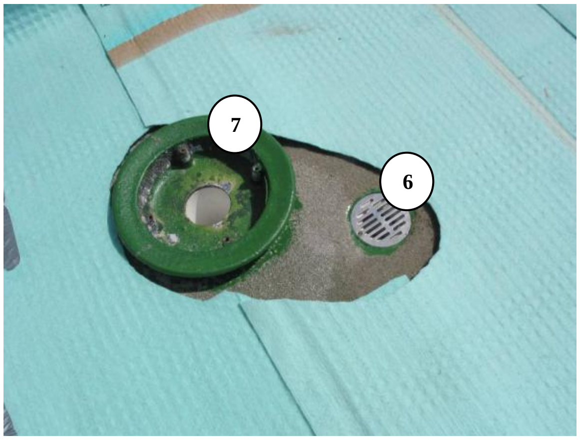
Figure 10: Greenroofs and Green Planters on site at the New American Home [Sourcehttp://www.greenroofs.com/projects/pview.php?id=744]

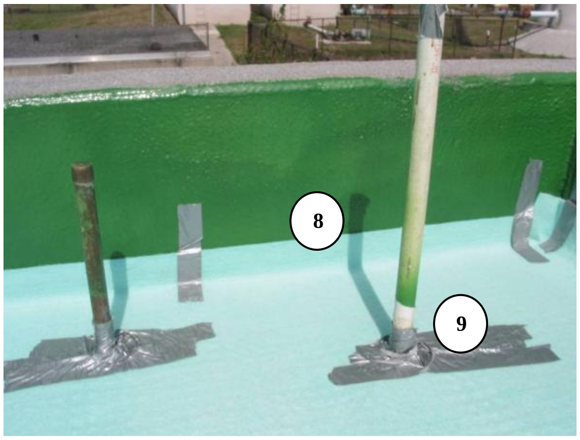
Stormwater Management Academy Laboratory

Like the New American Home, the Stormwater Management Academy Laboratory (SMAL) greenroof strives to minimize stormwater runoff through the use of a greenroof and cistern while also improving the water quality of the whole system. Outlined by Table 8, photos visually define the construction methods used to build the SMAL greenroof.

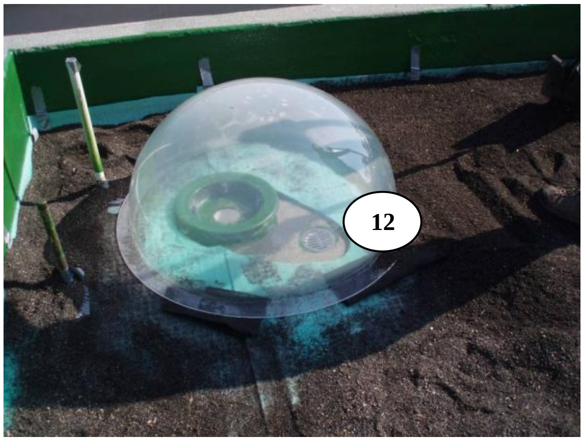
Table 8: Construction methods of the Stormwater Management Academy Laboratory (SMAL) [Source: Wanielista 2007a]

Stormwater Management Academy Laboratory (SMAL) Installation		
Label	**Figure**	**Description**
(a)		1. *Traffideck™ demonstration of application process. The water proof membrane used was Traffideck™ - a spray applied membrane which incorporates the water proofing, protection, and root barrier layers in one layer. When applied, the membrane is green in color.*
(b)		2. *Traffideck ™ membrane is applied to 800 ft^2 concrete deck of SMAL. The membrane is fully dried in four hours and can support heavy equipment.* 3. *Primer and sand over the membrane.*

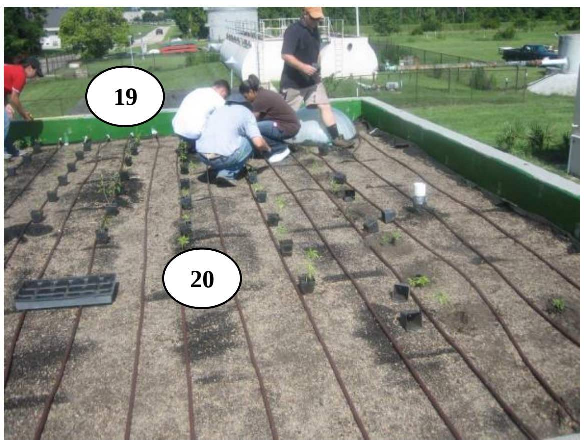
Stormwater Management Academy Laboratory (SMAL) Installation		
Label	**Figure**	**Description**
(c)		4. *The drainage layer selected was the Colbond Enkadrain & Retain™ due to it being light weight, having a high recycled content, and its ability to hold water for plant use while allowing excess water to freely drain off the roof, which is rolled for easy installation.*
(d)		5. *Duct tape or liquid nails are used to temporarily secure drainage layer sections to one another.*
(e)		6. *Greenroof drain (primary drain) is used to drain the stormwater runoff from the greenroof through the drainage layer to the cistern.* 7. *As an added precaution, an overflow drain (secondary drain) is used to collect stormwater runoff from the greenroof when the primary drain is full.*

<table>
<tr><th colspan="3">Stormwater Management Academy Laboratory (SMAL) Installation</th></tr>
<tr><th>Label</th><th>Figure</th><th>Description</th></tr>
<tr><td>(f)</td><td>
</td><td>8. Drainage layer is duck taped or liquid nailed along the perimeter of the roof wall, not flush to the roof top; but, with about a 2 inch lip from the surface.
9. Stand pipe detail in relation to the drainage layer.</td></tr>
<tr><td>(g)</td><td>
</td><td>10. The Bold & Gold™ pollution control layer is installed directly on top of the drainage layer by using a Bobcat and is approximately 1 inch thick.</td></tr>
<tr><td>(h)</td><td>
</td><td>11. Bold & Gold™ pollution control media is spread to a desired thickness by manually distributing evenly across the rooftop with a hoe or broom.</td></tr>
</table>

Stormwater Management Academy Laboratory (SMAL) Installation

Label	Figure	Description
(i)		*12. The drainage area was covered with a clear dome to protect the drain from debris and allow for regular inspection of the drain.*
(j)		*13. Even spread of 1" Bold & Gold™ pollution control layer.*
(k)		*14. The separation fabric is installed on top of the pollution control layer which is composed of granular recycled tires, expanded clay, and saw dust. This is done to prevent particle migration due to the buoyancy of the rubber tire and to ensure good contact with the water.*

Stormwater Management Academy Laboratory (SMAL) Installation		
Label	**Figure**	**Description**
(l)		*15. The bags of growth media placed on the separation fabric helps hold the fabric in place until the growth media can be installed.*
(m)		*16. The irrigation system is a surface drip irrigation system used to prevent the waste of irrigation water that occurs via overspray that is typical when using spray heads. Rather than placing the drip irrigation lines at the root ball where the water will migrate downward, placement of the drip lines on the surface encourages the plant roots to grow out and cover the roof.*
(n)		*17. The growth media consists of expanded clay, vermiculite, and peat moss. The media is light in color to ensure the media does not get too hot and has a high organic content to support healthy plant growth designed to be light weight and have a high water holding capacity while maintaining air voids.*

Stormwater Management Academy Laboratory (SMAL) Installation		
Label	**Figure**	**Description**
(o)		*18. It is desired to weave the wind blanket into the growth media for more stability. This is achieved by installing the growth media in rows with high points and low points (see where the wind blanket is rolled over the growth media with the rest of the growth media placed on top of it.*
(p)		*19. The drip irrigation lines (Netafim) are attached to the irrigation supply pipes shown and laid across the roof with a spacing of one foot on center.* *20. Plants used were Dune Daisy and Coral Honeysuckle. Planting was done by cutting an X in the wind blanket where the plant was to be placed, removing the media in that spot, placing the plant in the resulting hole, and replacing the media and wind blanket.*
(q)		*21. At a total greenroof depth of 4 inches, the SMAL greenroof is installed.*

The stormwater runoff from this greenroof is discharged into the cistern shown in Figure 11. The water quality analysis covers the same nutrients as outlined by both the Student Union greenroof as well as the New American Home greenroof. The stormwater quality results are represented by Table 9 and Table 10.

Figure 11: Stormwater Management Academy Laboratory (SMAL) cistern system [Source: (Wanielista et al 2007a)]

The water quality concentrations of the SMAL cistern are higher when comparing these concentrations to the filtration system at the New American Home. However, when comparing these concentrations to surface water standards of Class I potable waters and Class III recreational waters, the nutrient levels are relatively low for Solids, Turbidity, Nitrate, TP, SRP, Coliforms, and BOD_5 (Wanielista et al 2007a).

Table 9: Average Values from the SMAL Cistern [Source: (Wanielista et al 2007a)]

Site pH	Alkalinity (mg/l)	TSS (mg/l)	TDS (mg/l)	Total Solids (mg/l)	Conductivity µS	Turbidity NTU	BOD5 (mg/l)
7.90	180	5	352	357	516	1.18	2

Table 10: Average Values from the SMAL Cistern [Source: (Wanielista et al 2007a)]

NH3 (µg/l)	NOx-N (µg/l)	Nitrite (µg/l)	TN (µg/l)	SRP (µg/l)	TP (µg/l)	Fecal Coliform (cfu/100 ml)	E. Coli (cfu/100 ml)
70	30	5	4633	37	53	257	0.5

Construction Methods

The design and construction of a greenroof should be consulted with a structural engineer due to the load bearing capacity of saturated soil exceeding load restrictions as well as the process of retrofitting an existing conventional roof. The design of the greenroof should also be done in accordance to location, climate, and annual weather conditions while understanding that maintenance is needed with respect to the design of the roof. Typically, for residential homes in Florida, greenroofs are extensive for a low maintenance, cost effective, and energy efficient alternative to the typical rooftop covering. For general extensive greenroofs, they are composed of the following characteristics as shown in Figure 12 (not including the roof deck from the surface of the roof structure to the vegetation layer): root barrier, drainage layer, separation fabric, 1" pollution control media, separation fabric, 3" – 5" growth media, and vegetation native to Florida. Research done by the Stormwater Management Academy at UCF concludes that this construction design works best, both for economical and ecological purposes when building an extensive greenroof. Therefore, this section will discuss each greenroof layer in detail.

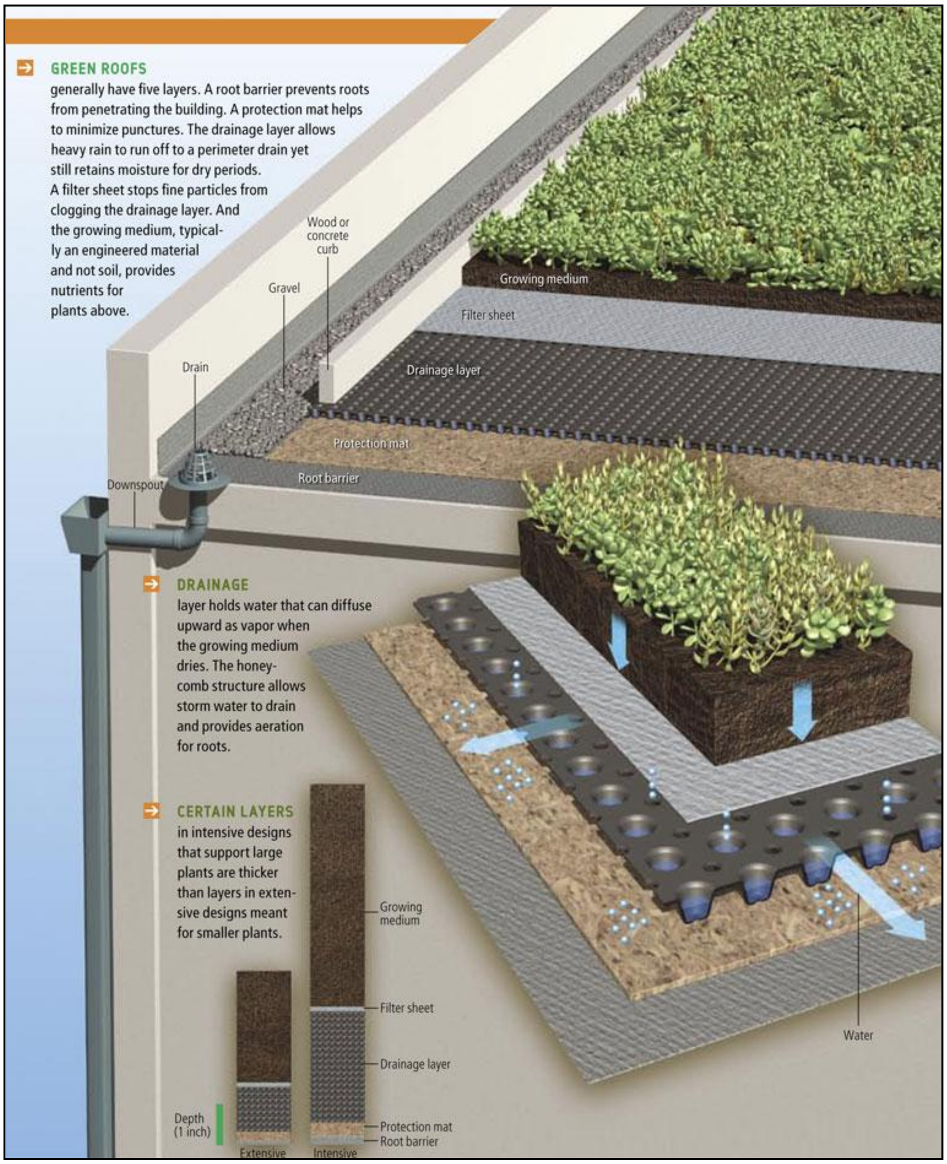


Figure 12: Typical construction schematic for greenroofs [Source: http://resosol.org/SolPass/toiturevegetalisee/Scientific-American.html]

Vegetation

In order to ensure lush vegetation growth, it has been observed that utilizing vegetation native to the greenroof location with a proper irrigation schedule and fertilization routine is ideal. An irrigation plan designed by Hardin (2006) for Orlando, FL recommends an irrigation schedule of 1 inch per week, fertilizing twice a year with a 10-10-10 slow releasing fertilizer.

There are many options available for Florida native plants; however the following plants are just some that have been tested and have shown successful growth atop roofing systems:

- Muhly Grass
- Sunshine Mimosa
- Dune Sunflower
- Railroad Vine

For this study, only Florida natives are used with an irrigation pattern of 1 inch per week and fertilization twice a year. The plants used for this research are muhly grass, railroad vine, blue daze, and lotus corniculatus which can be seen in Figure 13.

Figure 13: Florida native plants used for vegetation growth: (a) Muhly Grass, (b) Railroad Vine, (c) Blue Daze, (d) Lotus Corniculatus

Growth Media

Soil Type

The soil type chosen for greenroof construction is important for three reasons: structural load, stormwater quality, and vegetation growth. Generally, due to the heavy weight of typical soil, a greenroof growing medium utilizes expanded clay as it acts as a lightweight aggregate that has a high water holding capacity due to the large amount of void spaces; however, the structure holding the greenroof must be designed to carry a soil load of at least 25 lb/ft^2 (Hardin 2006). As outlined previously, Hardin's (2006) Student Union greenroof tested two types of growth media for greenroofs:

- Expanded clay-based media with 60% expanded clay, 15% peat moss, 15% perlite, and 10% vermiculite
- (Bold & Gold™) Tire crumb-based media with 40% tire crumb, 20% expanded clay, 15% peat moss, 15% perlite, and 10% vermiculite

The tire crumb is finely ground up recycled tires used to adsorb pollutants to its surface and the peat moss is used as a source of organics for plant life; where, the perlite and the vermiculite reduce the void spaces in the media.

In relation to these tests, the author recommends an expanded clay-based growing medium for ideal vegetation growth; however, the tire crumb-based growing medium performs better for stormwater treatment purposes. Based on this analysis, the expanded clay is used at each facility for this research with the pollution control media (which will be discussed later) directly beneath it to aid in stormwater quality.

Depth of Soil

As mentioned before, green roofs are grouped into two various categories based on the depth of growth media specific to passive and active greenroofs. For a passive greenroof, also known as an extensive greenroof, there is a soil depth of 2 to 6 inches. Active (intensive) greenroofs, on the other hand, have a growing depth of greater than 6 inches.

Studies conducted by Kelly (2007) at UCF show that soil depth influences the water quality with a significant difference in solids, conductivity, alkalinity, turbidity, and ortho-phosphorus concentrations; higher with the deep media depth than the shallow media depth for the majority of combination test beds tested. Furthermore, a UCF study by Hardin (2006) concludes that an eight inch greenroof soil media depth with a cistern retained 87% of the annual precipitation. This paper will focus on two different media depths. Although both roofs act extensively, one roof is constructed with a shallow depth of 3 inches while the other roof is constructed with 5 inches.

Bold & Gold™ Pollution Control Media

Bold & Gold™ pollution control media is a soil composite of recycled tires, expanded clay, saw dust, and peat moss developed at the University of Central Florida. The main component of the media is recycled tires in the form of tire crumb and has been shown to remove nitrogen species from golf course runoff (Lisi et al 2004). Investigated further by Hardin (2006) at UCF, results show that vegetated chambers are effective at reducing the concentration of nutrients like ammonia, nitrate + nitrite, ortho-phosphorus and total phosphorus compared to a conventional roof. Thus, each roof observed for this study utilizes 1 inch of the Bold & Gold™ pollution control media for environmental benefit.

Drainage Layer

The drainage layer is the element between the waterproof membrane and the pollution control media. Its primary function is to convey excess water toward the roof drains and gutters while also preventing water logging of the vegetation, excess water that may cause root decay, and increases the depth of the course available for root penetration (Wanielista et al 2008).

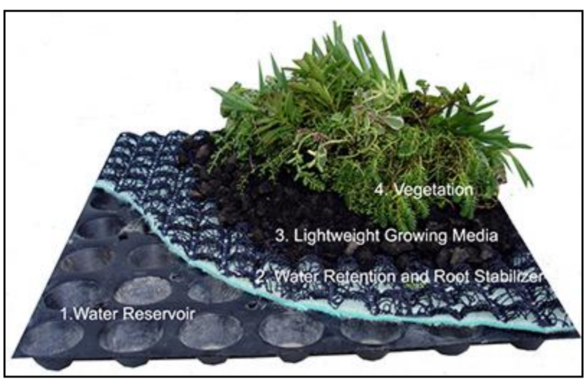


Figure 14: Geo-synthetic drainage mat (left) [Source: http://www.agreenroof.com/systems/grs/extensive.php/]; Gravel used for drainage (right) [Source: http://www.blackwoodplanthire.co.uk/products/drainage_gravel_10/index.html]

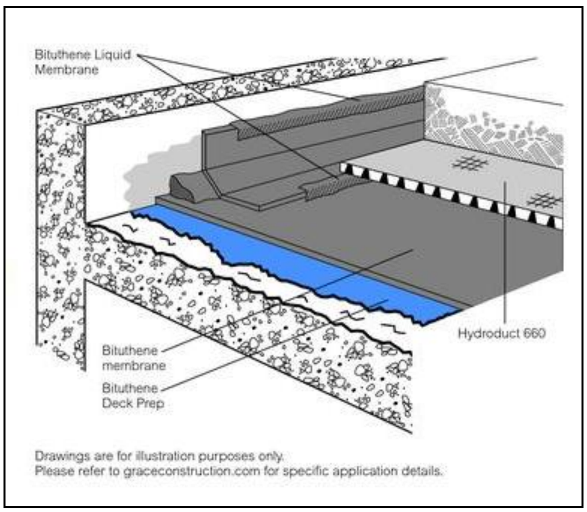
Two classes of drainage material are available, aggregate and geo-synthetic as shown in Figure 14. According to the FLL European standards or guidelines five different groups of materials may be used for the drainage layer. The five standards consist of an aggregate-type material (expanded clay and slate which may be broken or unbroken), recycling aggregate-type materials (brick, slag, foamed glass), drainage matting (textured non-woven matting, studded plastic matting), drainage boards (i.e. plastic foam boards, shaped rigid plastic boards), and drainage and substrate boards (boards from modified foam) (FLL 2002).

With geo-textiles, many companies, like Enkadrain, offer a multifunctional layer for the drainage of surplus water, protection and filtration without the risk of clogging. The nonwoven filter layer serves both to protect the sealing layer and as a separator from the substrate. Certain types of geo-textiles are designed for use in extensive or intensive green roofs; while others offer useful solutions for construction projects where greenroofs are intended to take heavy loads in which compression resistance becomes essential (Colbond).

A study tested the durability of a geo-synthetic drainage mat, Enkadrain, over the span of 10 years. Installed in 1985 and removed in 1995 – researchers tested a buried sample of Enkadrain and compared it to a new sample. After conducting a series of tests for tensile strength, permeability, discharge capacity, and thickness; it was concluded that there was very minimal difference between the two samples and in some cases they displayed identical properties (Hytiris & Berkhourt 1996). Therefore, for the purpose of this literature, geo-synthetic drainage layers are used for all facilities.

Root Barrier

For conventional roofing systems, various products for waterproofing liners are available. With the advancement of the green market, new products are accessible that defends against root penetration of the roofing deck as well as maintaining a waterproof seal. Two examples in Figure 15 show products available to fight against root penetration and water damage. The type of protection layer chosen for the greenroof is dependent on its specific design and budget for construction.



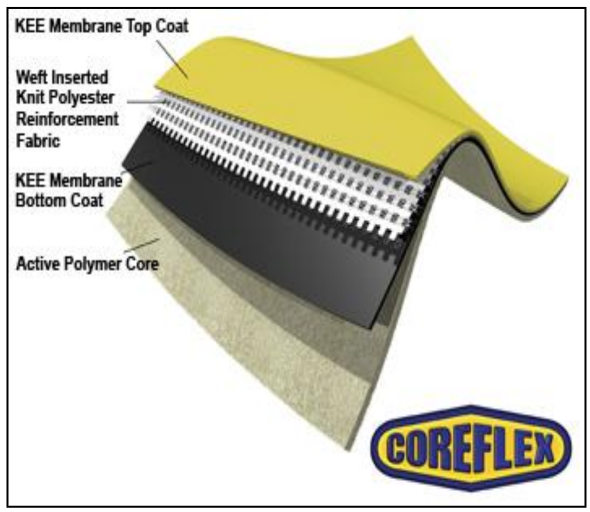


Figure 15: Example products for root rated barriers for greenroof application: Hydroduct (left) [Source: http://www.archiexpo.it/prod/grace-construction-products/membrana-drenante-bugnata-drenaggio-di-tetti-verdi-2545-154856.html] and Coreflex (right) [Source: http://www.cetco.com/BMG/Coreflex.aspx]

Wind Erosion & Control Methods

Wind erosion is an inevitable situation for nearly all soils as it carries the finest particles of earth at any given wind event. Other than moving soil from one place to another, wind erosion also reduces the ability for the soil to store nutrients and water for ideal vegetation growth. There are many factors affecting wind erosion like climate, soil texture and structure, state of the soil surface, vegetation, and soil moisture. In order to control this phenomenon, it is recommended to increase the reinforcement of the particulates by increasing soil cohesion, roughness of the soil surface, vegetation cover, and utilizing wind breaks (Roose 1996).

Geo-textiles

There are many options of wind control for greenroofs. Between the different types of geosynthetic technology, natural geo-textile, fiber reinforcements, and chemical polymers available, there are plenty of good sources to help combat wind uplift. For the purpose of this literature, geosynthetic geo-textiles are used for construction purposes.

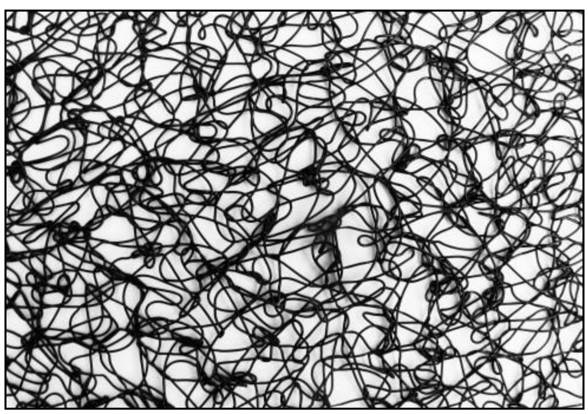


Figure 16: Colbond wind netting sample with over 95% open space [Source: http://www.stylepark.com/srv.do?site=stylepark&id=267032&lang=en&op=show_material_edition&choices=mw_materialeditionen:technische_textilien_1]

Geosynthetic wind nets are a long term alternative method of soil stability control in comparison to natural geo-textiles. In order to reduce soil erosion, geo-textiles are used during the initial phase of plant growth serving as a protective layer until the area has an established vegetation cover (Lekha 2003). Some argue that the use of natural geo-textile nettings like coir or jute serve a better purpose for temporary slope stability applications since they have the ability to absorb water and degrade over time. A case study conducted by Lekha (2003) concludes that vegetal cover with the aid of a natural geo-textile reduced soil erosion by 95.67%. (with respect to 56% rainfall) in comparison to a non protected soil. However, in applications where winds are high, long term use of geo-textiles with the addition of established vegetation is the ideal combination for maximum reduction in soil erosion – where the synthetic wind netting adds structural reinforcement with the establishment of the vegetal root system.

Based on studies conducted at UCF, it is desired to use an integrated technique where a geosynthetic wind blanket is weaved into the growth media for more stability like the application described in Table 8 for wind erosion stability control. This method of geosynthetic wind netting application is used at both facilities being tested in this research.

Vegetation Cover

According to Lekha (2003), an established vegetation canopy is an ideal method to preventing 90% of soil erosion problems. When wind blows across a surface and encounters large obstructions, a fraction of the wind's momentum is absorbed by the vegetation which causes a reduction in wind speed decreasing the shear force to the surface; in return, reducing possible wind erosion (Grant 2003). This reduction in speed decreases the available shear force to the surface thus decreasing possible wind erosion in the leeward side of the wind impediment.

Figure 17: Examples of Florida native plants: Muhly Grass (left), Dune Sunflower (middle), Sunshine Mimosa (right)

A study conducted on Tibetian soils by Zhang et al (2006), examined the effects of vegetation cover on unmodified alpine grassland steppe soil. Several tests were investigated for samples having vegetal cover by 45%, 40%, 30%, 20%, and 10% under wind loads ranging from 29.2, 39.0, 58.4, and 77.4 ft/s at 5 minute durations. Based on the results found visually in this study, Zhang et al concludes that soil erosion induced winds increased with the level of plant cover. This research analyzes the pressure distributions affected by the level of vegetation establishment in relation to other wind erosion control methods.

Wind Breaks

A typical wind break used for most structures is called a parapet which is a portion of the wall that exceeds above the roof line. The Building Code Requirements for Masonry Structures (ACI 530-02/ASCE 5-02/TMS 402) requires parapet walls to be a minimum of 8-inches thick and their height not to exceed three times their thickness. Many studies have observed that parapet height significantly influences the pressure distribution in the corner and along the perimeter of the roof where low parapets tend to increase peak suction on the roof when compared to a roof without a parapet; however, higher parapets create a considerable reduction in peak suction (Kopp 2005). For this research, two facilities are being monitored, one facility with a parapet wall and one without. In relation to vegetation cover and the use of a wind break, pressure distributions are analyzed.

Greenroof Cost

A Case Study: Life Cycle Cost Analysis

When looking at the initial costs of a greenroof, in comparison to conventional rooftops, there are costs ranging from three to six times more than a typical roofing system as shown by Figure 18. In the long term, however, greenroofs may be less expensive and outperform conventional roofing (Patterson 1998). A study in Singapore, conducted by Wong et al (2003), addressed the following objectives by creating two hypothetical case studies of an extensive roof (Case 1) and an intensive roof (Case 2):

- An examination of initial cost comparing a greenroof to a conventional flat roof.
- A life cycle cost analysis of greenroofs versus a traditional flat roof.
- To incorporate economic benefits like energy costs into life cycle costs.

Structural Costs of Installation

The initial costs proposed by Wong et al (2003) are compared in Figure 18 for an inaccessible, 4 inch extensive roof to a conventional flat roof including the roof deck. It was concluded that an extensive greenroof is roughly 50% more expensive for initial installation. However, when comparing an intensive greenroof with shrubs only, it was found that there was a price difference of 36%, while an intensive greenroof with trees had a price difference about 50% to that of a conventional flat roof.

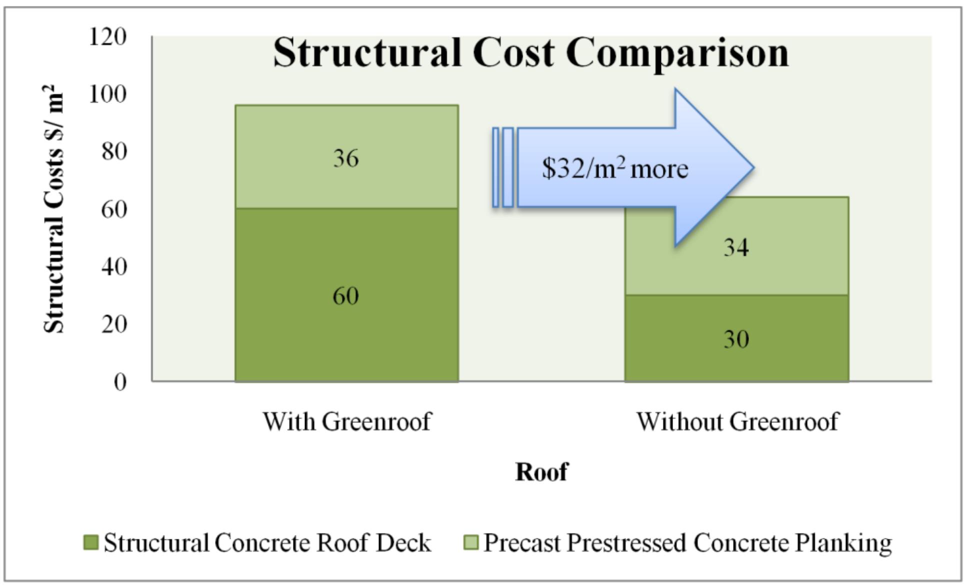


Figure 18: Cost comparison for an extensive roof compared to a flat roof [Source: (Wong et al 2003)]

Life Cycle Costs Including Energy Costs

In order to estimate the life cycle costs (LCC) including energy costs, Wong et al (2003) used the PowerDOE program to simulate energy consumption. However, it must be noted that this analysis does not include the following criteria:

- Intangibles such as improved productivity, improved health of building (air/water)
- Stormwater management savings

In the case of inaccessible rooftops, the life cycle costs of a conventional flat roof exceed that of an extensive green roof after the 10th year and exceeds minimally after the 35th year for an accessible intensive roof with 80% shrubs. It is concluded that an extensive roof sees a positive return over time with a reduction of energy costs by 14.6%, while the complexity of intensive roofing systems does not see a return in comparison to a conventional flat roof.

Greenroof Stormwater Price Comparison

Since greenroofs are primarily used for stormwater management, a study conducted by Wanielista and Hardin at UCF (2007) outlines a cost comparison for four locations located in Orlando, FL in comparison to utilizing a pond for stormwater runoff summarized in Table 11 by implementing a 100,000 ft^2 greenroof. The greenroof price includes the first year of maintenance while the pond price does not include maintenance; but, does include the price of land. As can be seen, out of the four locations compared, three of the greenroof locations see a positive return over $100,000; with Downtown Orlando producing a payback of $4.4 million in comparison to the use of a retention pond. Much of the cost for the pond comes from the price of land; therefore, greenroof use is definitely a cheaper alternative to conventional methods of stormwater collection.

Table 11: Pond Price vs. Greenroof Price in Orlando, FL area. Prices are in millions. [Source: (Wanielista and Hardin 2007)]

Greenroof Based on 100,000 ft^2 Roof Deck				
	Downtown Orlando [N. Magnolia]	Lee Road and I-4	University Blvd.	International Drive
Pond Price (Including Land Cost)	$5.8	$1.55	$1.2	$2.1
Green Roof Price	$1.4	$1.4	$1.4	$1.4
Realized savings	**$4.4**	**$0.15**	**-$0.2**	**$0.7**

Hurricane Damage Assessment

When Florida was hit by 4 hurricanes in 2004, many structures were severely damaged. In Lee County, specifically after hurricane Charley, a damage assessment conducted by the Florida Department of Environmental Protection (FDEP) concludes that at least 5 Gulf-front buildings sustained major roof damage and at least 10 single family homes were damaged due to severe winds, along with other damage along the coastal barriers. The aftermath that occurred due to a category 4 hurricane on conventional roofing systems in the area is exemplified in Figure 19.

Figure 19: Visual damage assessment of Lee County after hurricane Charley in 2004 [Source: http://www.dep.state.fl.us/beaches/publications/tech-rpt.htm]

Lee County also serves homage to the Bonita Bay greenroof in Shadow Wood Preserve. When comparing the greenroof photos (before and after in Figure 20), there is almost no damage visible on the greenroof, which can be seen, did not have established vegetation at the time. Based on visual observation, it is apparent that greenroofs under hurricane winds actually reduce potential roof deck uplift due to the heavy dead load of greenroof materials in comparison to the light weight conventional roof shingle. When looking at the damage assessed on the soil media itself, very little (if any) erosion of the soil occurred.

Figure 20: Bonita Bay greenroof: Before hurricane Charley (top) and After hurricane Charley (bottom 2)

Full-Scale vs. Wind Tunnel Tests

States like Florida, Louisiana, and Texas worry about the potential structural devastation that can occur with the possibility of a hurricane. In order to help eliminate these possibilities, researchers study the effects of wind on structures with the use of wind tunnels, boundary layer wind tunnels, and full-scale testing facilities (either simulating wind or on site with natural wind application).

Wind tunnels are commonly used by creating scaled models of the structure in question with the application of a scaled wind speed. It is difficult, however, to simulate atmospheric wind characteristics especially around structures with sharp edges and corners (Blessing 2007). According to Simiu and Miyata (2006), when comparing data between full scale testing and wind tunnel testing, wind flow in the simulated wind tunnel underestimates the load characteristics that actually occurs on site. Due to the complex behavior of atmospheric wind flow, it is difficult to replicate an accurate wind profile in a wind tunnel.

Many studies present the use of in situ testing opposed to wind tunnel testing in order to obtain realistic results. A study conducted on the Palazzo della Ragione roof in Padua, Italy compares full scale testing to wind tunnel results which is also cross referenced with Eurocode 1 for wind load design over a period of 3 years (Zonta 2000). Zonta claims that there are essentially three problems with full scale testing: (1) there are limited economic returns, (2) there is a difficulty in obtaining a reliable reference pressure for calculating pressure coefficients, and (3) the unpredictable actions of wind which are uncontrollable on site.

The building tested in Italy is over 98 feet (30 m) in height from ground level, above the city skyline – free from surrounding obstructions. The monitoring plan included eight differential pressure transducers measuring at the surface of the roof with an absolute pressure measurement identifying the reference pressure measured by the internal pressure of the building itself. Initial results collected over 5 second signals compare wind tunnel tests to full scale tests of winds to Eurocode 1 of wind application from the East direction. Preliminary analysis indicates that wind tunnel pressures are close to full scale tests; however, Eurocode 1 overestimates the theoretical pressure distribution.

Another full scale study was conducted by Florida International University (FIU) in 2007 at the Hurricane Research Center (HRC) on a 10 ft by 10 ft by 10 ft testing structure with simulated wind through the "Wall of Wind" (WOW). Blessing (2007) monitored the facility with 16 differential pressure transducers strategically placed in order to measure pressure in all three zones of the roof outlined by ASCE 7-05 components and cladding. By utilizing the WOW system, Blessing was able to control the wind speed and direction up to approximately 108 mph at 45° for 6 minutes at a sampling frequency of 10 Hz . When comparing the minimum pressure coefficients (maximum uplift) to ASCE 7-05 Method 2 design, results show pressures almost 4 times the predicted ASCE 7-05 calculations. Blessing argues that even though FIU has results much greater than that of the estimated ASCE 7-05 design provisions, the full scale study is consistent with recent findings of other full-scale studies and wind tunnel tests, suggesting that the pressure distributions collected on full scale sites are at least double the distributions found in the lab under similar conditions (Blessing 2007).

Summary

For this research, there are two separate studies analyzed: a controlled full-scale study through visual record (Chapter Three), and a long term monitoring study within an uncontrolled environment (Chapter Four). Based on current construction methods of greenroof design discussed in this chapter, both experiments implement greenroofs constructed with the same materials – a waterproofing membrane, a drainage mat, Bold & Gold™ pollution control media, and an expanded clay-based soil medium. Each greenroof, however, utilizes a different soil erosion method of integrated geosynthetic wind netting, wind breaks, and vegetation establishment as well as a varying soil depth.

CHAPTER THREE: CONTROLLED FULL-SCALE STUDY

Introduction

In order to accurately test greenroofs under wind loads, a full scale experiment is implemented for this research. Although wind tunnel testing methods were considered, it is difficult to scale down structures with the use of vegetation cover while maintaining a true replication for testing purposes. In this chapter, an extensive greenroof atop a basic flat roof structure is tested under high winds to evaluate the failure of the green materials used for construction.

The Wall of Wind Test Setup

To grasp a visual idea of how greenroofs act under hurricane induced loads, the same testing structure used by Blessing (2007) was covered with greenroof materials and tested at Florida International University's (FIU) Hurricane Research Center (HRC). Eighteen tests were initially planned to investigate the performance of the greenroofs as a function of various parameters such as anchorage, vegetation, wind netting, and parapet height as outlined in Figure 21. However, only one of these tests could be conducted due to the availability of the HRC.

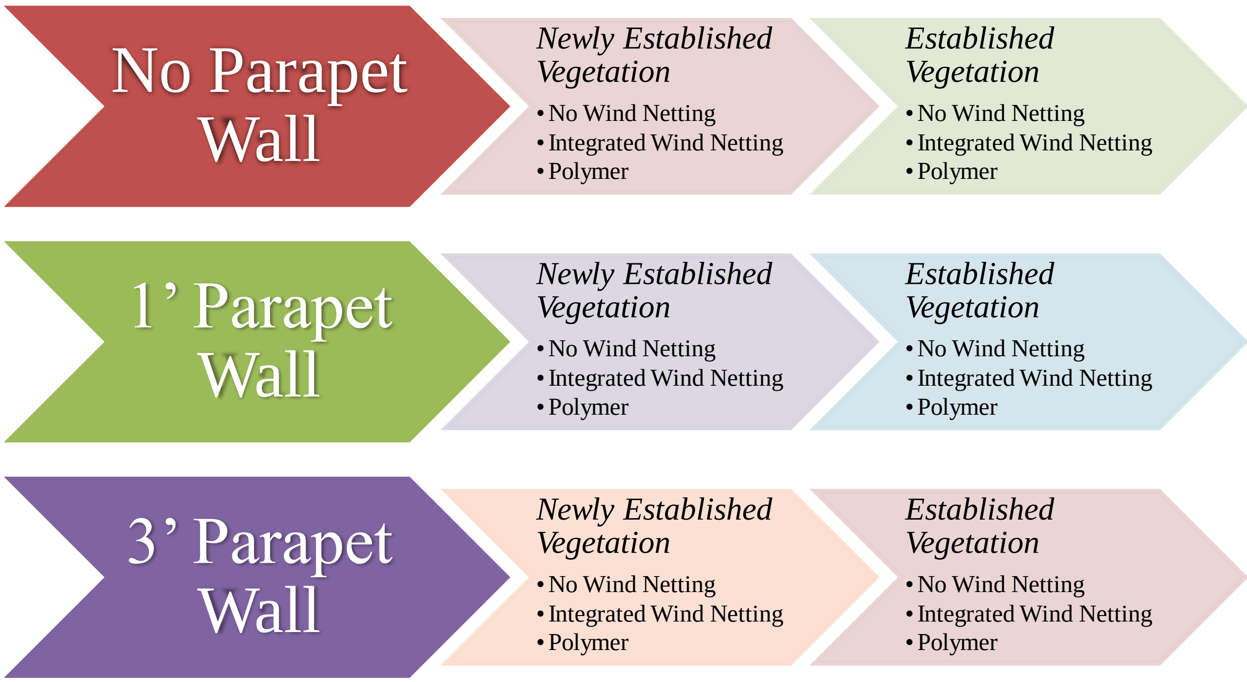


Figure 21: Proposed testing at Florida International University's Hurricane Research Center

The test conducted at Florida International University’s HRC was done using the facility’s WOW system. The large scale wind simulator consisted of six 2x3 array of Chevy 502 big block carburetor engines turning Airboat Drive Units CH3 2:1 propeller drives as shown in Figure 22 (a). Measuring 16 ft tall by 24 ft wide, WOW allowed for full-scale monitoring of a 10 ft by 10 ft by 10 ft building.

(a) Wall of Wind structure at FIU HRC

(b) Wind monitoring gauges for each WOW propeller

(c) Individual Chevrolet motor

(d) FIU HRC testing structure

Figure 22: Florida International University (FIU) Hurricane Research Center (HRC) equipment

FIU Test Structure

All testing for this experiment was done using a plywood test structure shown in Figure 22. The test structure rested on a square concrete pad and was secured to the ground placed at a 45° angle in order to simulate the worst case scenario, specified by ASCE Code 7-05 provisions, at 9 ft from the edge of the WOW diffuser section and 16 ft from the back propellers for all testing as shown in Figure 22 (d). This distance allowed for two things: a steady development of wind velocity and enough space for the structure to experience peak velocities (Blessing 2007).

Greenroof Construction

The roof deck of the FIU HRC structure was covered with a basic greenroof design to test for the worst possible scenario during a hurricane. The components of the greenroof consisted of the following layers starting from the deck with Live Edge roof restraint along the perimeter (illustrated by Figure 23): thermoplastic membrane with protection layer, drainage layer with integrated separation fabric, 1” Bold & Gold™ pollution control media, separation fabric, and 3” Bold & Gold™ growth media.

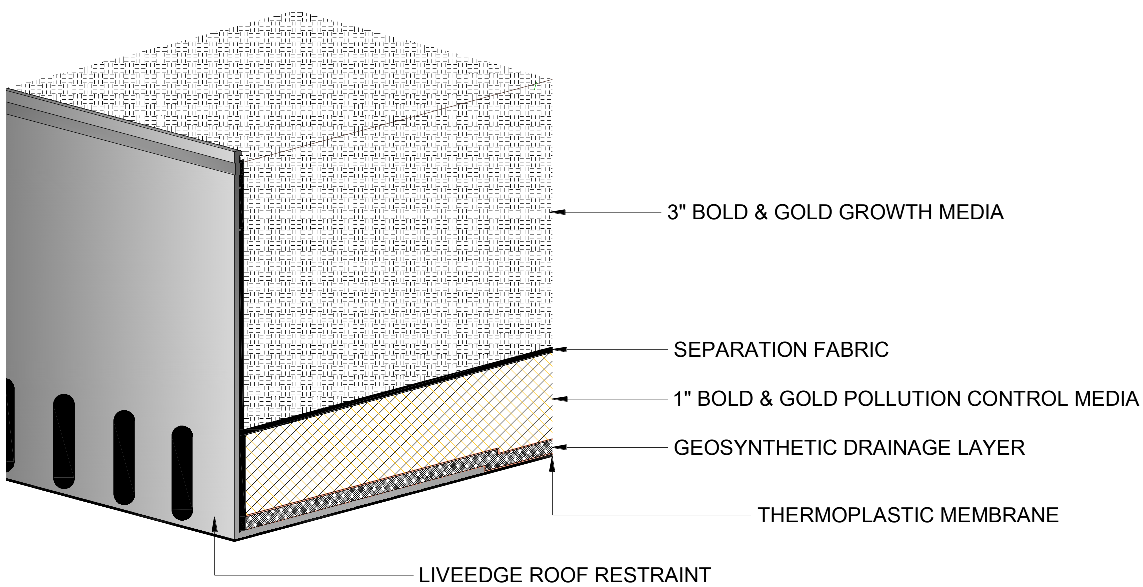


Figure 23: Greenroof cross-section of FIU HRF greenroof test

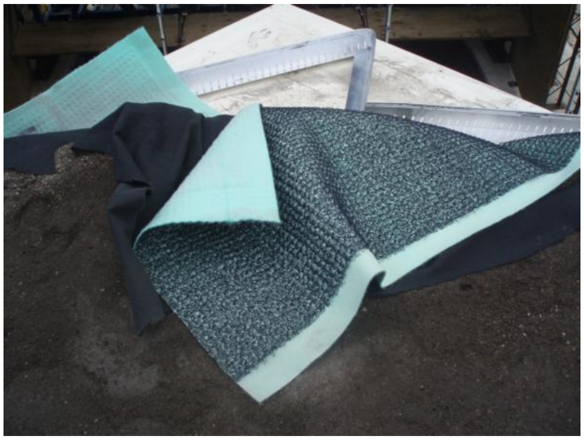
This test was conducted for a greenroof using unsaturated conditions, without the use of any wind erosion control methods, and no vegetation. Also, the Live Edge roof restraint was not structurally glued or bolted to the thermoplastic membrane in any fashion; only the weight of the greenroof materials held it in place for this particular test.

Visual Results

The following results are based on a time history of 1 minute and 30 seconds. The first 30 seconds are measured at 3600 rpm equivalent to 58.9 mph, where it then ramped up to 4400 rpm equivalent to approximately 77.8 mph for 1 minute. As soon as the WOW structure accelerated to77.8 mph, the greenroof suffered uplift at the corner of the roof. The visual analysis of the greenroof at the time of failure is outlined in Table 12 (when t = 90 seconds).

Table 12: Visual Results of controlled lab study at Florida International University (FIU)

Florida International University Hurricane Research Center: Greenroof Study		
Label	**Figure**	**Description**
(a)		• *10ft by 10ft by 10ft structure at 45° from WOW structure at t = 90 seconds.*
(b)		• *Forces at the windward corner of the roof (closest to the WOW structure) cause green material uplift from the roof deck.* • *Live Edge roof restraint is uplifted at 77.8 mph, 35 seconds after t = 0 sec.*

<table>
<tr><th colspan="3">Florida International University Hurricane Research Center: Greenroof Study</th></tr>
<tr><th>Label</th><th>Figure</th><th>Description</th></tr>
<tr><td>(c)</td><td></td><td>Colbond Enkadrain drainage mat and separation fabric flap over pollution control media and soil media.
Mound is created at the corner of the roof with synthetic materials atop the soil media protecting the soil mound.</td></tr>
<tr><td>(d)</td><td></td><td>Pollution control media is uplifted to the surface of the soil medium; however, it is protected by the synthetic layers covering the mound created by the wind load.</td></tr>
<tr><td>(e)</td><td></td><td>Furthest corner from the WOW structure sees minimal damage from the velocity profile.</td></tr>
</table>

Florida International University Hurricane Research Center: Greenroof Study		
Label	**Figure**	**Description**
(f)		• *Soil cracking occurs in various sections along the perimeter of the roof.*

Conclusions

It is interesting to see the reaction of the greenroof under a heavy wind event with minimum structural support. Photos in Table 12 (b) and (c) both illustrate material instability as the greenroof materials fail at approximately 78 mph. This is due to the fact that there is uplift on the aluminum Live Edge roof restraint used for greenroofs with no parapet wall or any anchorage. However, it needs to be noted that the edge restraint was not fastened to the roof membrane by any adhesive and was only structurally supported by the weight of the greenroof itself at about 20-25 lbs per ft^2 (Hardin 2006). Although failure occurs at the corner closest to the WOW structure, note the opposite corner of the facility in Table 12 (d), (e), and (f); there is no sign of significant projection from the roof due to the overlap of geosynthetic drainage material and separation fabric which acts as a wind shield during the remaining duration of the wind application. At the worst possible case of construction (and wind load), the greenroof is damaged; but, not a complete failure as the greenroof itself stays intact atop the roof deck.

CHAPTER FOUR: FULL SCALE FIELD MONITORING STUDY

Monitoring Facilities

In this chapter, two greenroof structures in situ are monitored long term and evaluated under natural wind loads. There are two field sites instrumented to collect data to determine the effects of high winds, including hurricanes, on green roofs. At 222.4 miles apart, both greenroofs are located in Florida; one on the East coast in Indialantic, FL and the other on the West coast in Port Charlotte, FL (see Figure 24).

Figure 24: Locations of each testing facility: (A) Port Charlotte Rays Stadium (PCRS) and (B) Florida Showcase Green Envirohome (FSGE)

Each greenroof is chosen specifically due to the fact that they are along opposite coasts of Florida. Since wind velocities are generally higher off the shoreline, it is hypothesized that these locations are ideal for maintaining the desired load conditions.

Florida Showcase Green Envirohome (FSGE)

The Florida Showcase Green Envirohome (FSGE) is a unique study as it is the first residential property to be constructed as a 95% energy efficient home in the state of Florida. With five greenroofs on the premises, they are all built with the same concept of minimal maintenance with maximum environmental benefits for the homeowners. The image represented by Figure 25 shows UCF researchers installing the greenroof atop the owner's pool storage facility – just one of the five greenroofs on site. Four of five extensive roofs are composed similar to the UCF Student Union roof at 4 inches of total green material.

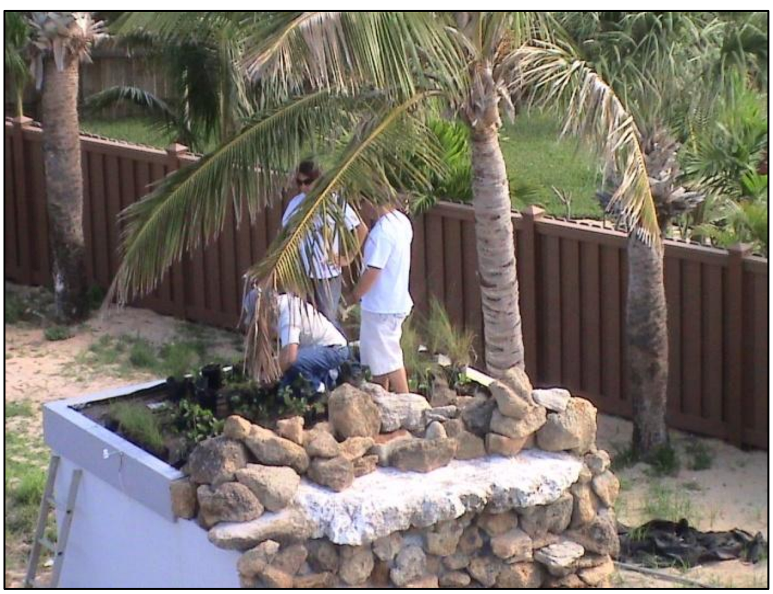


Figure 25: FSGE greenroof being studied for wind uplift

Illustrated in Figure 25, the FSGE greenroof is used for wind uplift research on location. Unlike the other four green roofs on site, this specific roof is built to a total depth of 6 inches; with 5 inches of growth media and 1 inch of pollution control media. The greenroof is approximately 8 feet in height with a total surface area of about 50 square feet with no parapet.

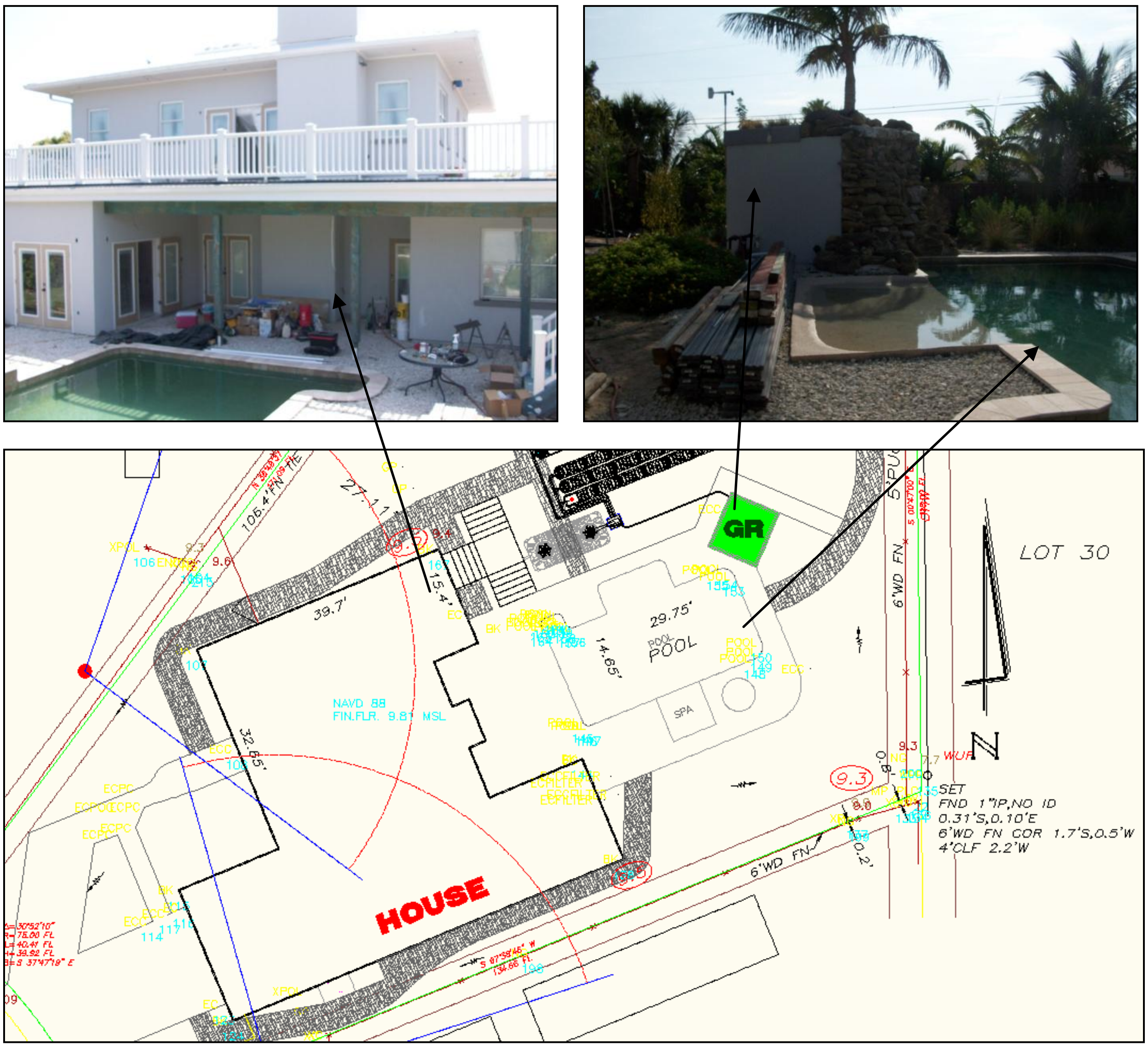


Figure 26: Florida Showcase Green Envirohome (FSGE) plan view [Drawn by: J. Morris Smith, Jr., PE, PSM]

An aerial view of the house on location illustrated in Figure 26 gives a perspective on the surrounding obstructions on the premises in relation to the greenroof being measured. Approximately west of the monitoring facility, there is a two story house impeding prospective wind loads from that direction. Furthermore, the entire lot is enclosed by neighboring trees and shrubbery which dampers the generally windy conditions experienced from the Florida coastline east of the FSGE greenroof. Due to these barriers, a significant wind history is difficult to come by in this specific area.

Greenroof Design

The greenroof itself was constructed in the summer of 2007 allowing for a well established vegetated roof (WEVR) and composed of the main greenroof components (starting from the roof deck):

- Thermoplastic membrane with protection layer,
- Drainage layer with separation fabric,
- 1" pollution control media, separation fabric,
- 5" Bold & Gold™ growth media,
- and Florida native vegetation (muhly grass and railroad vine)

Table 13: Greenroof construction at the Florida Showcase Green Envirohome (FSGE)

Construction Methods for the Florida Showcase Green Envirohome (FSGE)		
Label	**Figure**	**Description**
(a)		• *Homeowner installing the perimeter of the 2nd story greenroof (1 of 3)* • *The perimeter of the greenroof is lined with treated 5 stacked 5/8" Bluwood panels*
(b)		• *The deck, including the 5 Bluwood panels, is covered with Bituthene 300 membrane which acts as a waterproof root barrier.*
(c)		• *UCF Students laying the geo-synthetic drainage layer (in the direction of the longest length of the perimeter) after the root rated barier.*

Construction Methods for the Florida Showcase Green Envirohome (FSGE)		
Label	**Figure**	**Description**
(d)		• *After the drainage layer, 1" Bold & Gold™ pollution control media is evenly distributed and covered with separation fabric (not shown).* • *The separation fabric is not stretched flush to the Bluwood wall; but, with an excess lip over it.* • *The 3" growth medium is then distributed in rows at desired thickness with an integrated wind netting using techniques described in Table 8, Figure (o).*
(e)		• *Before planting vegetation, an irrigation network is installed at the surface of the soil media designed to irrigate at programmable times.*
(f)		• *Vegetation is planted in open spaces throughout the irrigation network.*

Visually outlined in Table 13, the construction process of the 2nd story greenroof located on site at FSGE is relevant to the assembly methods used when building the pool storage greenroof studied for this research; although, there is a variation in soil depth (at 5 inches of Bold & Gold™ growth medium instead of 3 inches). Thus, the specific schematic relative to the FSGE testing site for this experiment can be seen in Figure 27.

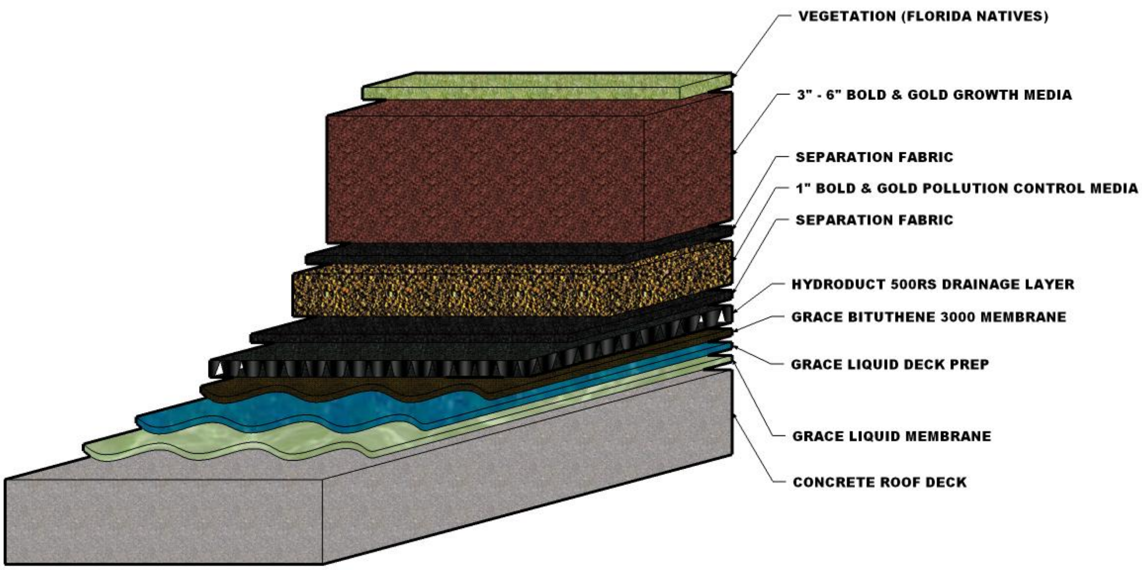


Figure 27: FSGE pool storage facility greenroof

<u>Instrumentation Plan for the Monitoring System</u>

This evaluation includes measurement of pressure, wind speed, and wind direction simultaneously to capture the effects of wind on the pressure distribution along the surfaces of a vegetated roof; where, the surface is considered to be flush to the soil media at the base of the vegetation.

In order to evaluate the pressure distributions on greenroofs due to wind, SETRA Model 265 very low bidirectional pressure transducers are used in a grid like pattern within the permitted area of the space provided. Each transducer has the capability to read ±50 inches of water column – equivalent to ±259.2 psf with an analog output of 0 to 5 V. The positive and negative signs refer to the downward and uplift (suction) forces on the structure respectively; where, 2.5 V is comparable to 0 psf.

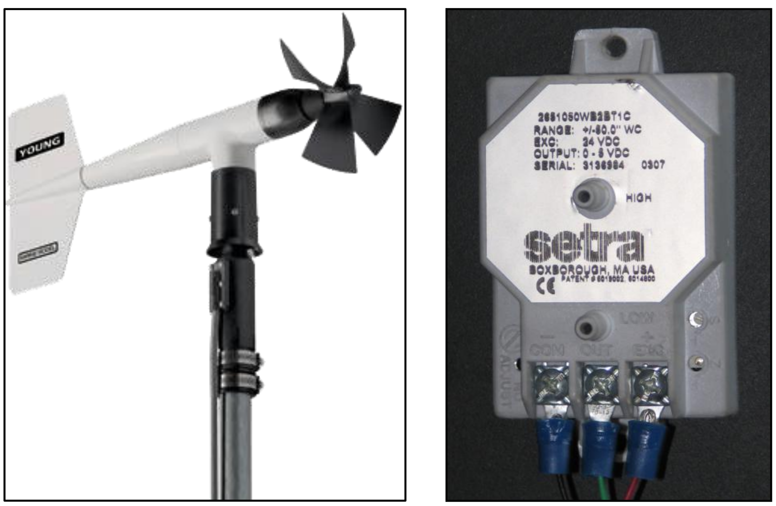


Figure 28: RM Young Wind Monitor (left) [Source: http://www.youngusa.com/products/11/8.html] and SETRA Model 265 pressure transducer (right) [Source: (Blessing 2007)]

Both locations suffer from typical Florida humidity; therefore, each pressure transducer is equipped with desiccant pouches to reduce the probability of moisture getting in the low port of the sensor. Given the limitations of each structure, instrumentation of each facility was challenging. The SETRA Model 265 very low differential pressure tap (with a long term stability of 0.5%) being used for the study is shown in Figure 28. For this specific pressure unit, two ports are read; where, the high end port is relayed to the surface of the greenroof growth medium (under the vegetation) via ¼" o.d. polyethylene tubing and the low end port is referenced within a static wind location to atmospheric air. Due to excessive exposure to the sun, the ¼" o.d. polyethylene tubing was later replaced with ¼" o.d. irrigation tubing.

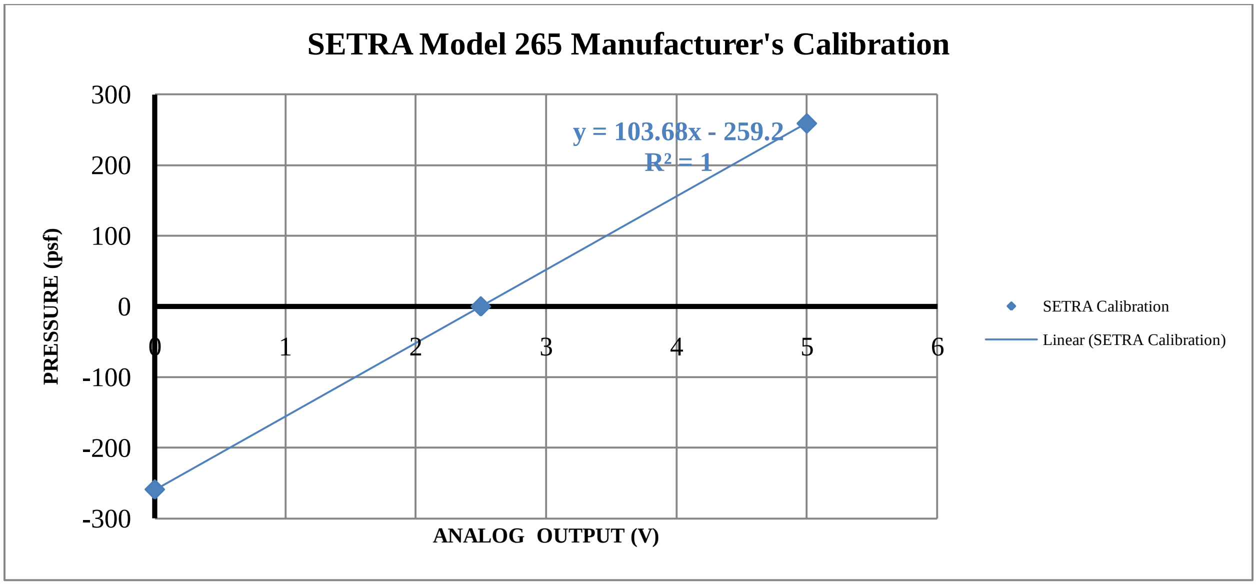


Figure 29: Manufacturer's calibration for SETRA Model 265 bidirectional pressure transducers

Each pressure transducer was checked in relation to the manufacturer's calibration curve (Figure 29). Since the SETRA pressure transducers measure pressure in inches of water column (in W.C.), a basic water column was created using ¾" o.d. PVC piping connected to ¼" o.d. polyethylene refrigerator tubing. Given that drifting occurs throughout time, the "zero correction" was checked upon visit for each sensor to ensure the correct calibration standard. Every 2 months, however, a new calibration curve was created for each pressure transducer.

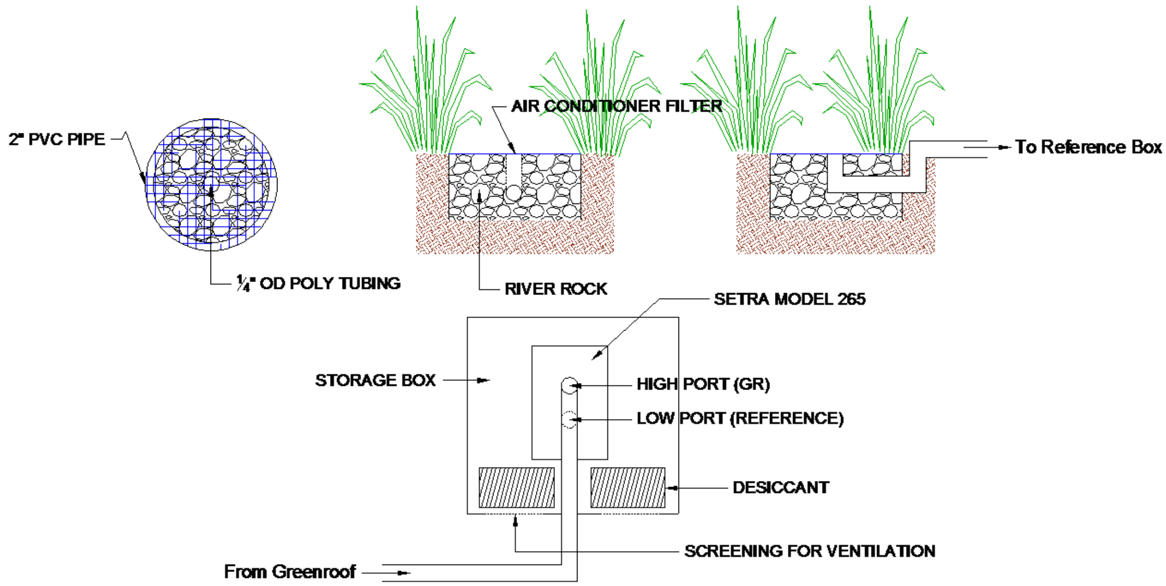


Figure 30: AutoCAD schematic for instrumentation application

The instrumentation design implemented to collect pressure readings is rendered in Figure 30. Since there were no capabilities to puncture or damage the roof of the building in any fashion, relaying the high end port to the location of interest was done in a way as described by Figure 30. A 2 inch diameter PVC pipe was cut at a length of approximately 3 inches for each tap location. The ¼ " o.d. tubing was then connected to the PVC "caddy" with the help of 90° irrigation elbows. In order to keep the tubing in place within the "caddy", small pebble rock was used and the PVC pipe was capped with a piece of blue air conditioning filter to avoid clogging of the high end port which were checked and replaced when necessary. The low end of the pressure transducer acts as the reference pressure for the sensor and is located inside of the structure.

The wind speed and direction is measured using an RM Young Model 05106 (Figure 28) wind monitoring system capable of measuring up to 150 mph as well as 0 to 360 degrees for direction given that zero degrees is facing the North producing an analog output of 1 to 5 V. Very accurate in measurement, the RM Young wind monitor has an accuracy of ±0.6 mph for wind speed and ±3 degrees for wind direction. Since FSGE has a large tree obstructing the building, it was decided to mount the wind sensor on the southwest corner of the roof approximately 1.5 feet above the roof deck to gather wind data.

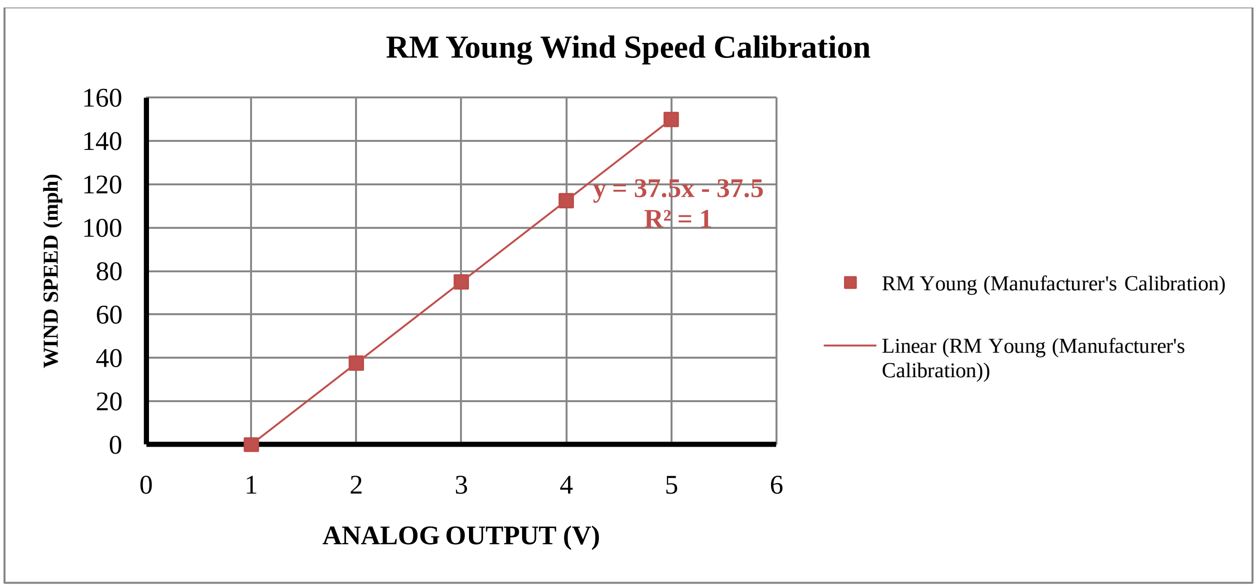


Figure 31: RM Young wind speed calibration curve according to the manufacturer.

After installing the wind monitor on site, a calibration check was made for both wind speed and direction. Since there is no wind tunnel on site to check the wind speed of the wind monitor, the voltage was first read at the minimum wind speed (0 mph) and the corresponding wind speeds were plotted given the manufacturer's calibration standard. In order to check that the calibration standard was accurate, a Skymate handheld wind meter (with an accuracy of

±3%) was used at the same time to compare the wind speed in real time in 30 second increments. To simulate wind in one direction, a general table top fan was used at a high setting for 2 minutes and 30 seconds. Since the RM Young wind meter is far more accurate than the Skymate hand held wind meter, an acceptable comparison for the installed wind speed calibration curve is shown by Figure 32.

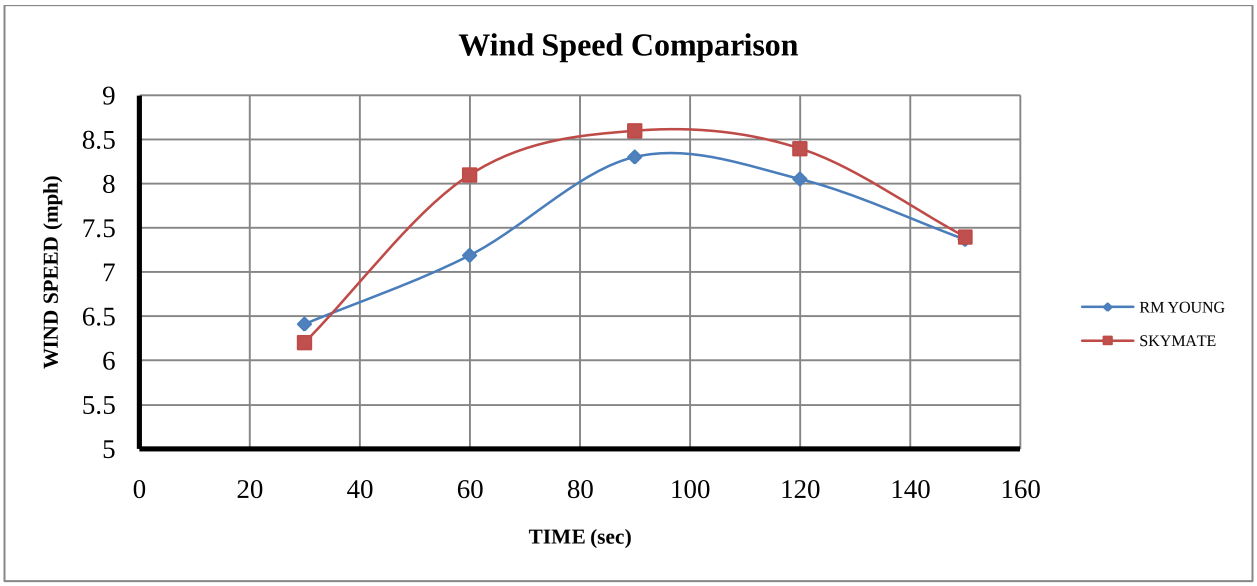


Figure 32: Florida Showcase Green Envirohome (FSGA) wind speed comparison

In order to check that the wind unit was properly installed for wind direction, the propeller of the system was moved (with the nose of the propeller in the direction of measurement) facing 0°, 90°, 180°, 270°, and 355° equivalent to the north, east, south, west, and northwest directions respectively (Figure 33).

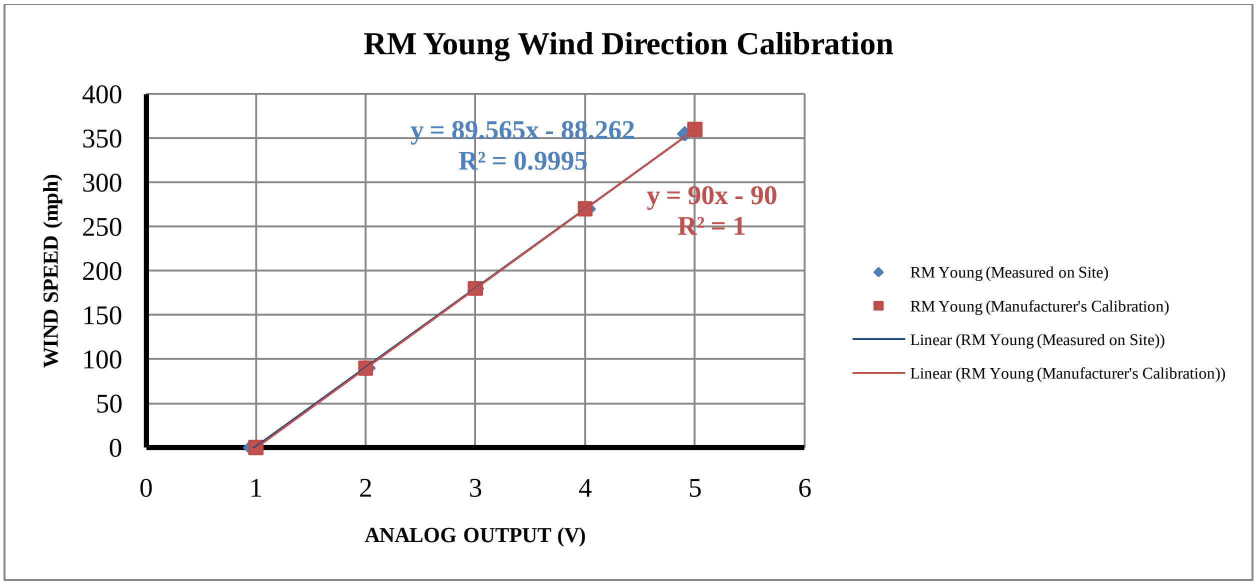
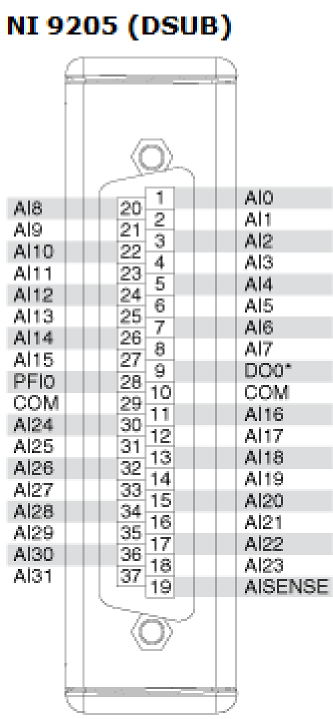


Figure 33: Florida Showcase Green Envirohome (FSGE) wind direction calibration curve

All sensors are connected to a National Instruments CompactRIO Integrated Systems with Real-Time Controller and Reconfigurable Chassis (NI CRIO) 9074 data acquisition system (Figure 34). This system was chosen for its integrated real-time chip, and the ability for compact storage as well as its durability in harsh conditions.

Figure 34: National Instruments CRio 9074 (left) and 9205 module for analog voltage readings (right) [Source: http://sine.ni.com/ds/app/doc/p/id/ds-204/lang/en and http://sine.ni.com/nips/cds/view/p/lang/en/nid/208800 respectively]

Since all units have analog readings, each sensor is connected to a National Instruments 9205 module. Each 9205 module is capable of reading up to 36 single ended units or 18 differential units. In order to ensure the most precise result, all sensors were wired differentially to the 9205 module, referencing each sensor to its individual common ground. Thus, the reference of each sensor as well as the output of each sensor was wired simultaneously to their respective channels in the NI module as illustrated in Figure 35.



<u>NOTE:</u> *To wire sensors to the NI 9205 (DSUB) differentially, the common wire connects to the reference port of each channel system, while the output of the device is wired to the output port. For channel AI0, the sensor common is wired to #20 and the output is wired to #1.*

Figure 35: NI 9205 Module schematic

Monitoring Design

Based on the area provided, as well as the budget for equipment, twelve SETRA Model 265 very low differential pressure transducers are planted for measurement purposes. The locations for the sensors were chosen based on a grid like pattern shown in the schematic outlined in Figure 36. Along the shortest sides of the building there are 3 pressure taps in a row about 1.8 feet by 4 pressure taps in a column approximately 1.5 feet apart.

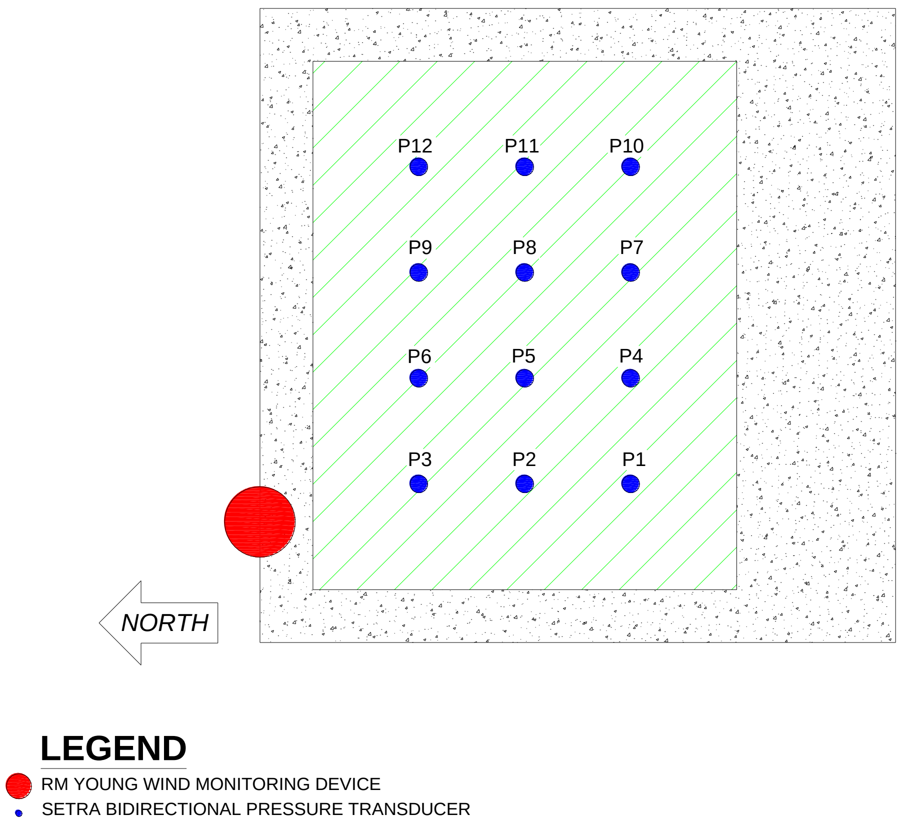


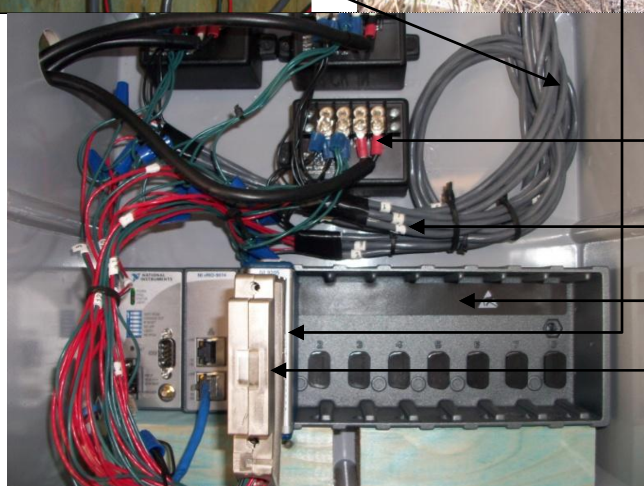
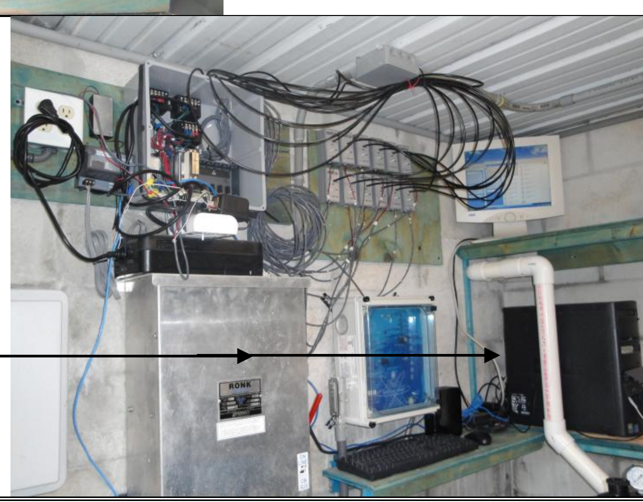
Figure 36: Schematic of pressure grid across FSGE roof

One of the main objectives of this research is to collect data during severe wind events; thus, data was collected from June 2009 to February 2010; where hurricane season is between June 1st – November 30th. Data is collected at a sampling frequency of 1 Hz, 5 Hz, and 10 Hz at a minimum 3 second average wind speed of 15 mph or more.

Presented in Table 14, the components of the data collection system are visually outlined. The sensors continually collected data as the data acquisition system transferred it to the host PC computer located on site. The NI CompactRIO was programmed by the National Instruments software, LabVIEW, enabling the data acquisition system to compile the records as a text file for later analysis.

To communicate from the sensors to the data acquisition system to the host computer, three different LabVIEW programs were created to relay information from the reconfigurable FPGA chassis to the embedded real-time control to the computer. The FPGA chassis set the sample rate of the whole system commanding the CompactRIO to read each sensor at the desired sampling frequency. The real-time processor then references the FPGA chassis and relays the data from each sensor simultaneously to the computer on site. The host computer communicates with the data acquisition system via an Ethernet cross over cable which organizes and compiles the data and stores it to an external hard drive as a text file.

Table 14: Monitoring hierarchy for Florida Showcase Green Envirohome

SETRA Pressure: Reference Pressure (Internal Pressure)	SETRA PRESSURE: Surface Pressure (External Pressure)	RM YOUNG Wind Monitor
		
	SETRA power supply 22 gauge wire NI Compact Rio 9074 NI 9205 Module	
Host PC Computer		

Port Charlotte Rays Stadium (PCRS)

Unlike FSGE, the green roof tested in Port Charlotte, FL consists of a section of a flat roof at 25 feet in height and 1600 sq. feet in area with a parapet height of 2 feet – 7 inches atop the club house located at the Port Charlotte Rays Stadium (PCRS) shown in Figure 37. Since this roof is much larger than the East coast roof, it was decided that only the two ends of the roof are to be monitored, with the corners of the roof the main concern,.

Figure 37: Port Charlotte Rays (Spring Training) Stadium. [Source: http://www.baseballpilgrimages.com/spring/portcharlotte.html]

Greenroof Design

The greenroof itself was constructed in the beginning of 2009 making it a newly established vegetated roof (NEVR) and composed of similar greenroof components as FSGE (starting from the roof deck):

- Thermoplastic membrane with protection layer,
- Drainage layer with separation fabric,
- 1" pollution control media,
- Separation fabric,
- 3" Bold & Gold growth media, and vegetation: blue daze and lotus corniculatus
- With a Live Edge roof restraint bonded to the thermoplastic membrane along the perimeter of the greenroof materials

Rather than covering the entire club house roof deck, the PCRS greenroof is approximately 6.4 feet from the parapet wall on the shortest side and about 16.9 feet from the parapet along the long side of the greenroof. Although the entire greenroof is covered in vegetation, the plants are sparsely covering the soil media at about 50% total coverage as shown in Figure 38.

Figure 38: PCRS greenroof before instrumentation

Instrumentation Plan for the Monitoring System

The same instrumentation plan for the FSGE greenroof is implemented for the Port Charlotte Rays Stadium greenroof with minor alterations. All of the equipment is exactly the same for both roofs; very low differential pressure transducers supplied by the Model 265 SETRA product, a wind monitoring device capable of reading up to 150 mph winds distributed by RM Young mounted about 2.5 feet above the roof deck, and an NI CompactRIO Model 9074 with two 9205 analog (Voltage) modules issued by National Instruments. The high end ports of the pressure sensors utilize the same PVC "caddy" approach as the FSGE greenroof. The same calibration techniques used at FSGE are also used at PCRS. The calibration curves for the RM Young Model 05106 wind monitor at PCRS are represented by Figure 31 and Figure 39 respectively.

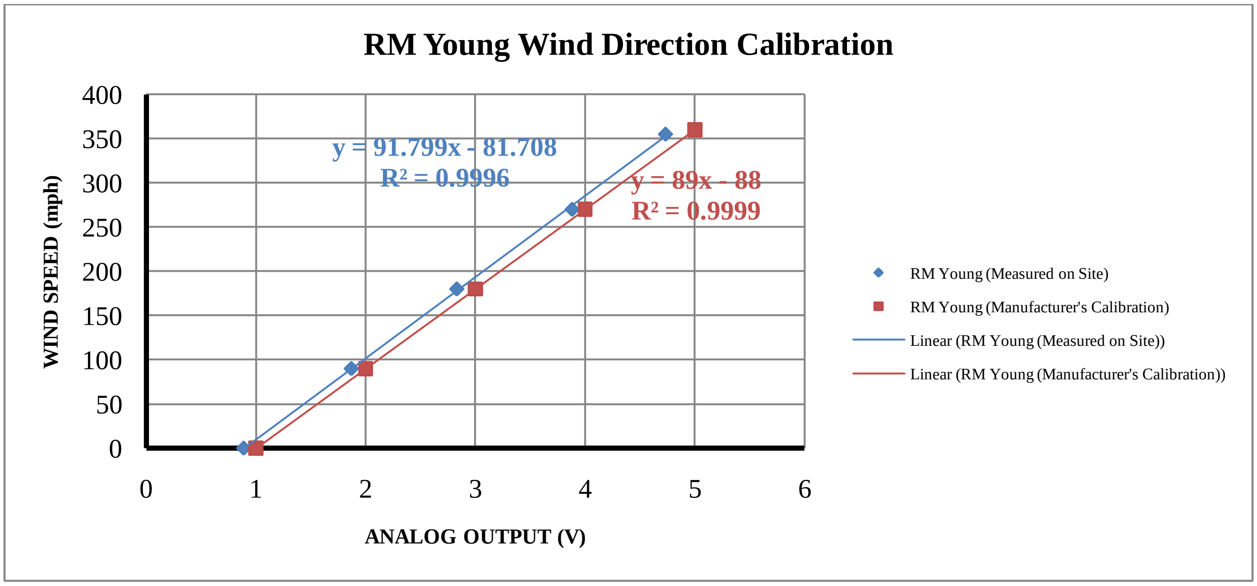


Figure 39: Port Charlotte Rays Stadium (PCRS) wind direction calibration curve

Like the FSGE location, the PCRS wind monitor was also checked for calibration upon installation. For the PCRS greenroof, however, the wind speed was checked every second for 15 seconds with a natural wind load on site. The same Skymate handheld wind meter was utilized on site in comparison to the RM Young wind monitoring system as shown in Figure 40. Although there are some differences in wind speed between the two wind monitoring devices, the calibration check at the time of installation are deemed satisfactory.

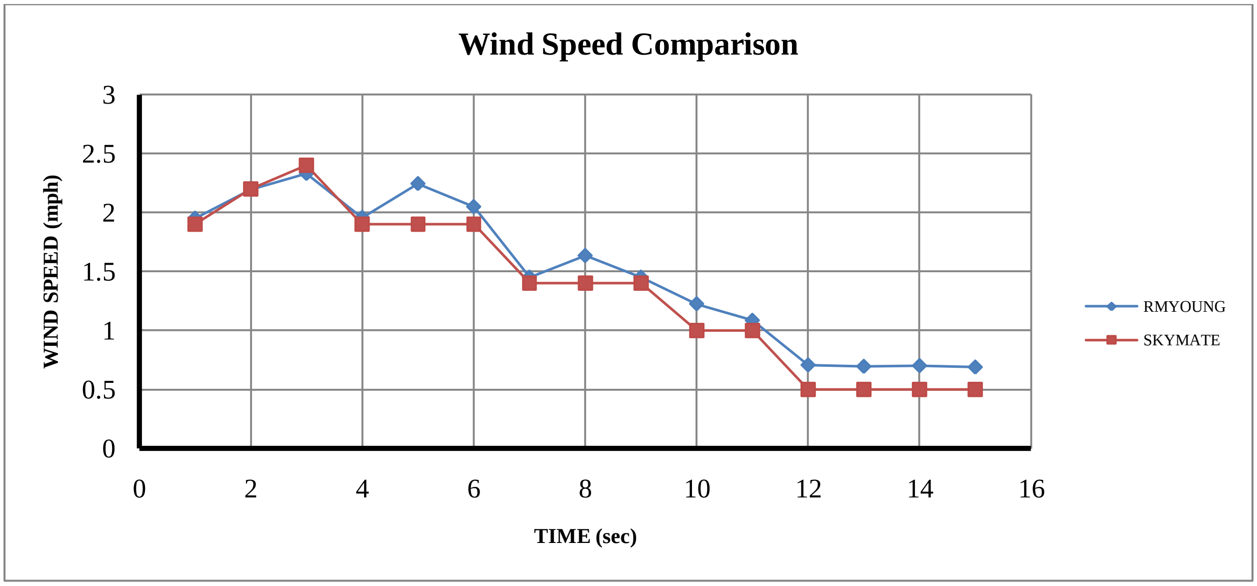


Figure 40: Port Charlotte Rays Stadium (PCRS) wind speed comparison

There are only two main differences between the two facilities in instrumentation setup. Rather than housing all of the sensors inside the monitored building like that of the FSGE system, all of the sensors are stored outside in junction boxes while the computer equipment is housed inside the building. Shown in Figure 41, there are 24 pressure transducers split between 4 junction boxes; each housing 6 transducers. Since the low end port cannot withstand any moisture, each box uses desiccant pouches to absorb all of the moisture which is checked and replaced when necessary. Another differing factor is the length of the ¼" o.d. refrigerator tubing used to measure the high end port of each pressure tap location; some tubes have a length of up to 100 feet (which was also later replaced by ¼ " o.d. irrigation tubing).

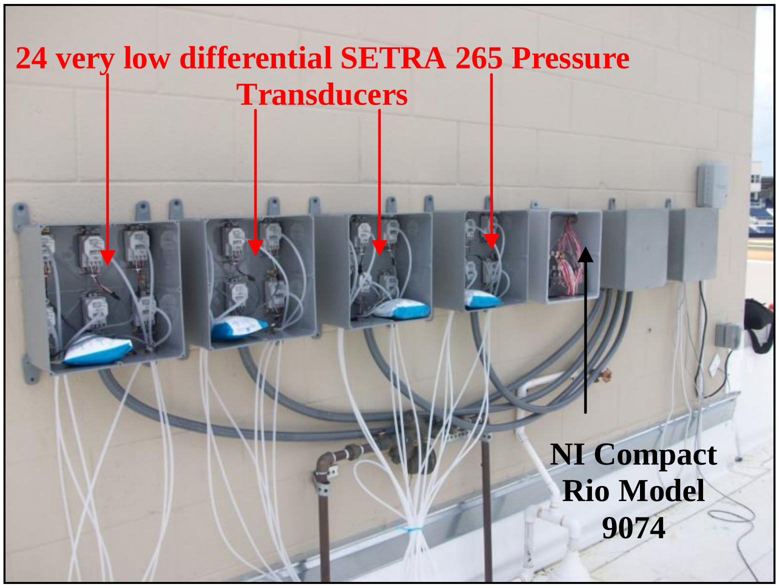


Figure 41: Sensor instrumentation for PCRS

Monitoring Design

In order to keep it consistent, the same data collection scheme used by the FSGE greenroof is implemented by the PCRS greenroof. Displayed by Figure 42, the locations of the pressure sensors with a 3 by 4 matrix; 3 pressure sensors in a row at approximately 5 feet apart by 4 pressure sensors in a column at about 5 feet apart in order to maintain a grid like pattern similar to the east coast greenroof. All programming methods for the NI CompactRIO are the same (except that there are more sensors being monitored) and data extraction methods for predicting pressure distributions for high speed winds are also identical. Data is collected from

June 2009 to February 2010 at a sampling frequency of 1 Hz, 5 Hz, and 10 Hz at a minimum 3 second average wind speed of 15 mph or higher.

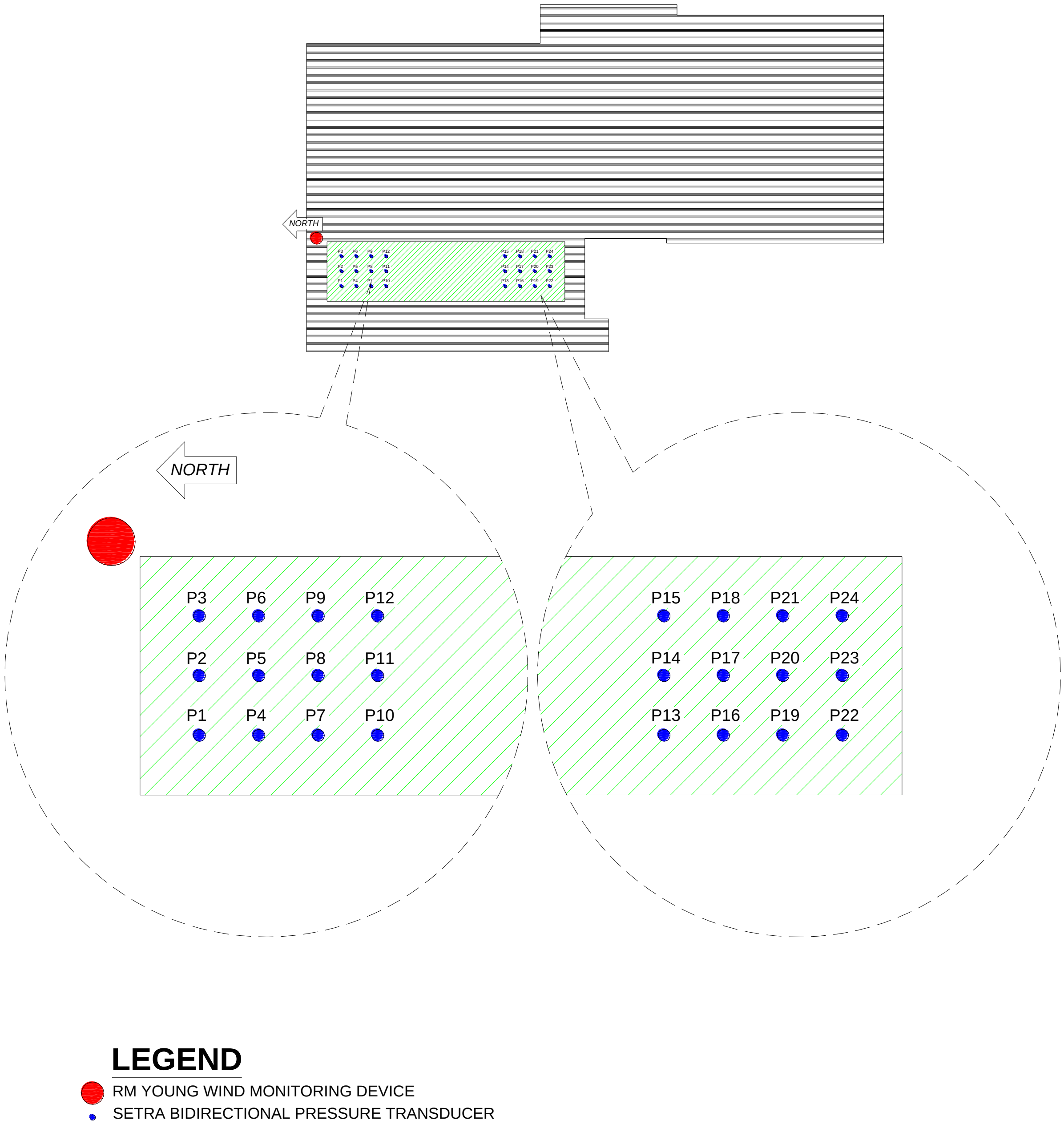


Figure 42: Schematic of pressure grid across PCRS roof

CHAPTER FIVE: RESULTS AND DISCUSSION

Generally, the characteristics of wind are sporadic in nature, constantly changing directions and velocities over time. When analyzing a wind load (on a structure), various factors affect the dynamic force. In order to efficiently evaluate a structure using an analytic approach, computational fluid dynamic (CFD) methods can be used in conjunction with finite element analysis. However, due to the complexity of such methods, standard design codes like ASCE Code 7 2005 are typically used to simplify the effects of wind application on a structure for design purposes. All standard codes are based on pressure data collected over time through scaled wind tunnel models, analyzing respective pressure coefficients across the structure. Although effective for estimation, wind tunnel studies make room for error through approximation of scale which can be rectified through the use of full scale testing. This chapter focuses on the results obtained from the monitoring of both greenroofs for wind speed, wind direction, and pressure distribution. Pressure measurements are also compared to American Society of Civil Engineers Code 7 2005 (ASCE 7-05) Method 2.

Measured Data

As described previously, the field monitoring in situ per site allowed for data collection over a time period of 9 months, from July 2009 – February 2010. During hurricane season, the data acquisition system collected one sample per second at a sampling frequency of 1 Hz continuously until a threshold of 50 mph was met; where, the sampling frequency jumps to collect data at 50 Hz. Unfortunately, significant wind events did not occur and a threshold of 50 mph was not achieved. In order to gather sufficient data, the sampling frequency was changed to measure at 5 Hz from November 2009 – December 2009 and 10 Hz from December 2009 – February 2010 continuously.

Data, collected instantaneously for all sensors used to monitor both greenroofs in question through data acquisition, was filed to a host computer on site for later analysis. With the Florida Showcase Green Envirohome (FSGE) utilizing 12 pressure transducers and the Port Charlotte Rays Stadium (PCRS) utilizing 24 pressure transducers, each pressure tap was analyzed for a minimum 3 second wind duration for velocities greater than or equal to 15 mph.

Since data was collected continuously over time, different time histories are spliced together (shown in Appendix A and Appendix B) to identify the 3 second gusts at or above 15 mph sampled at each location. An example of one time history is shown in Figure 43 for the FSGE greenroof. As it shows, a 17 minute window of data is collected at a sampling frequency of 10 Hz on January 16, 2010. The data is extracted for the desired wind speeds when a continuous wind event occurs continuously for at least 3 seconds and is then analyzed separately as one “sample”. Since all testing was done on site, wind events could not be controlled for neither wind speed nor wind direction; thus, maintaining even a 3 second time window of sustainable wind speeds and wind direction proved to be difficult.

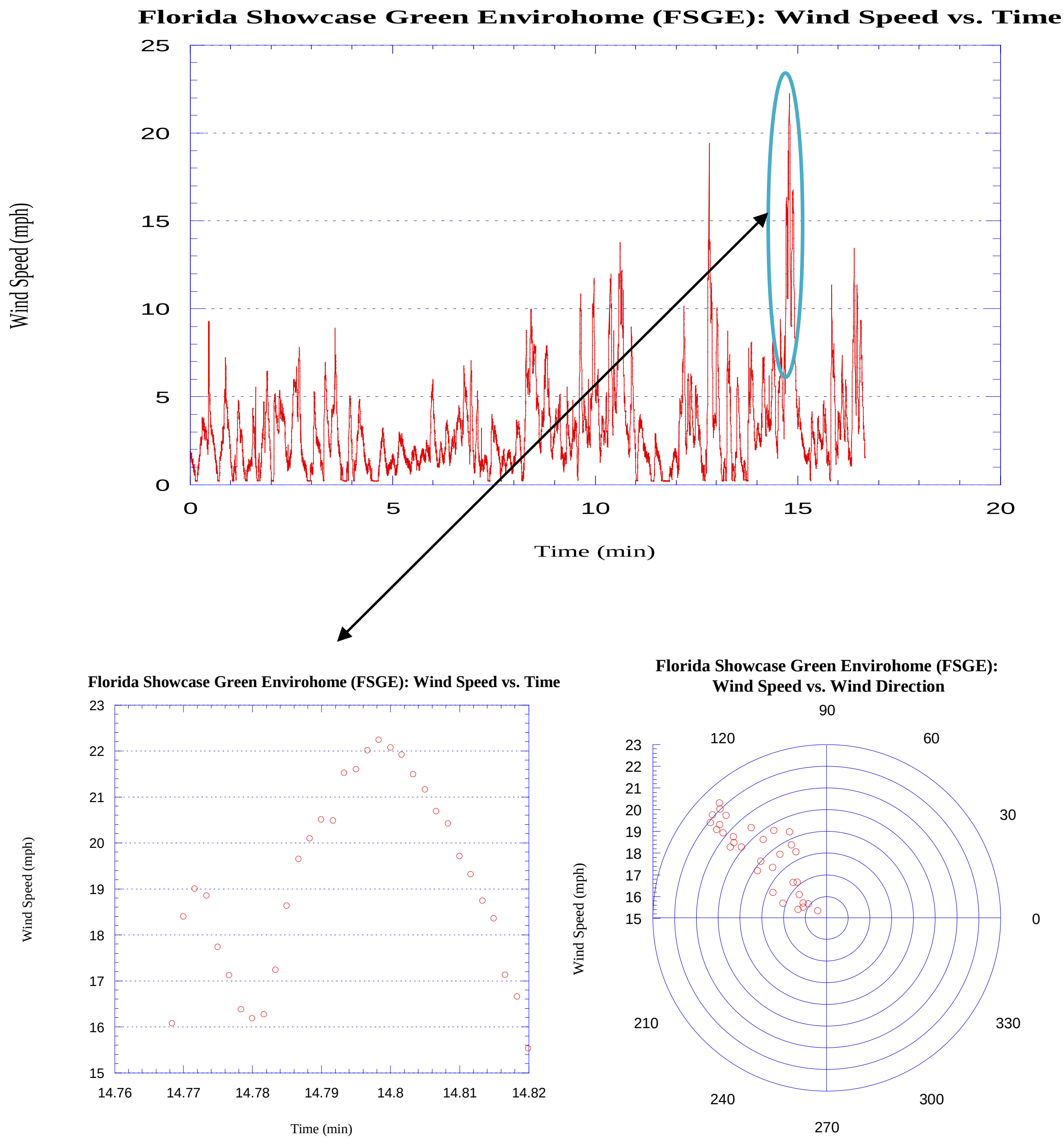


Figure 43: Sample wind speed time history for FSGE on January 16, 2010 at a sampling frequency of 10 Hz (top), filtered wind speed time history data from master wind speed time history (bottom left), and filtered wind speed time history data versus its respective wind directions (bottom right)

Florida Showcase Green Envirohome (FSGE) Measured Data

Although FSGE is located on the East coast of Florida, along the shoreline of Indialantic, continuous durations of wind loads were hard to come by. This problem has much to do with height of the storage facility only spanning 8 feet high as well as the neighboring single family dwellings with large trees surrounding the FSGE perimeter illustrated in Figure 44.

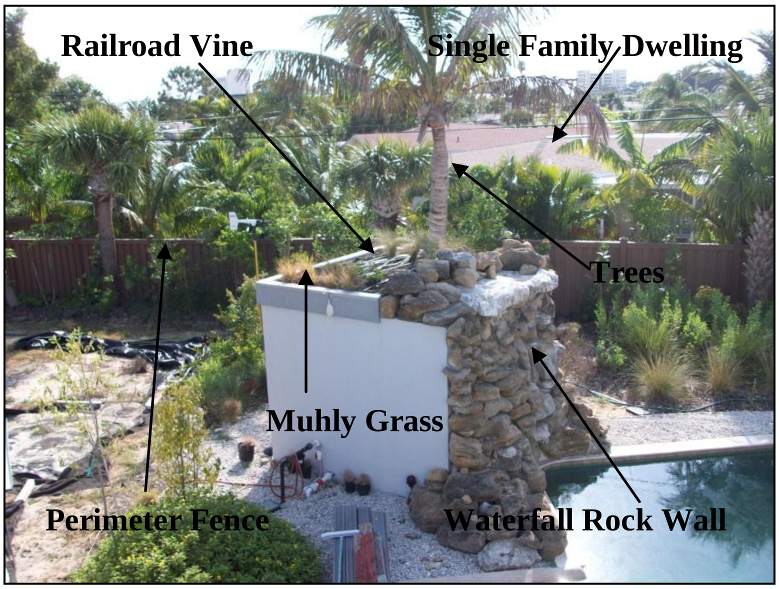


Figure 44: Florida Showcase Green Envirohome (FSGE) greenroof surrounding area

The FSGE greenroof utilizes the structural support of an integrated geo-synthetic wind netting with 5 inches of Bold & Gold™ soil media to combat the force of wind. Since the vegetation was planted in the summer of 2007, establishment of the Florida natives has occurred over 2 years time making it a well established vegetated roof (WEVR).

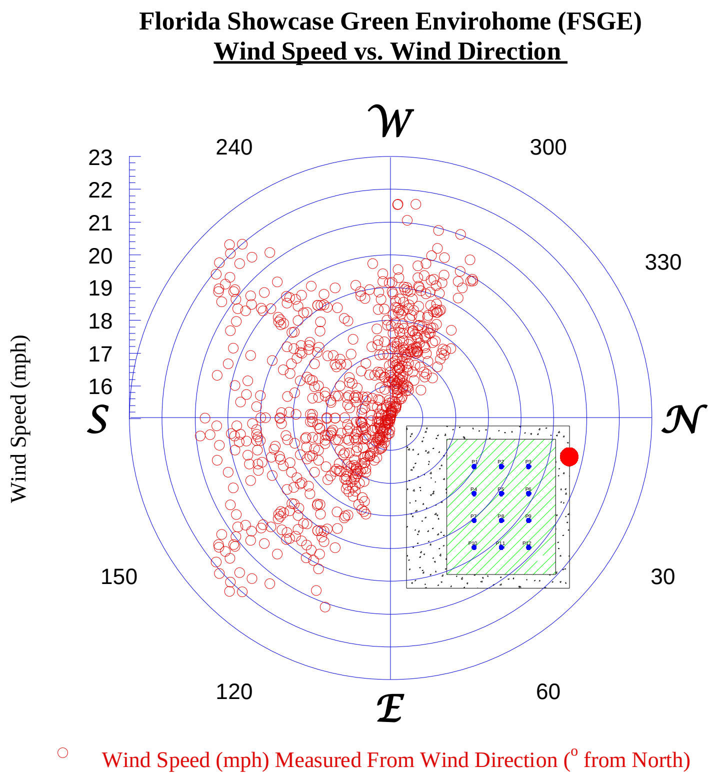


Figure 45: Florida Showcase Green Envirohome (FSGE) wind speed vs. wind direction

Although data was collected at three different sampling rates, only data collected at sampling frequencies of 5 Hz and 10 Hz were analyzed in order to ensure the highest level of accuracy. Based on this, collected winds at or above 15 mph for all data with sampling frequencies of 5 Hz and 10 Hz have an average directional trend coming from the Southwest with a maximum wind speed of about 22 mph shown in Figure 45, where each marker represents each wind speed collected instantaneously with respect to its coinciding wind direction for all 3 second samples spliced together for both sampling frequencies.

All pressure taps are located at the surface of the soil media to evaluate the external pressure of the structure with the addition of plant life, where pressure taps P1, P2, P3, P10, P11, and P12 are measured directly under fully established muhly grass. Pressure sensors P4 thru P9, on the other hand, are located flush to the surface under adult railroad vine which grows along the plane of the soil medium rather than orthogonal to the surface. With established vegetation in place and the pressure sensors located under the foliage, it is hypothesized that the pressure distribution across the surface of the greenroof is much less than across a conventional rooftop due to the dissipation of wind energy through the plant canopy.

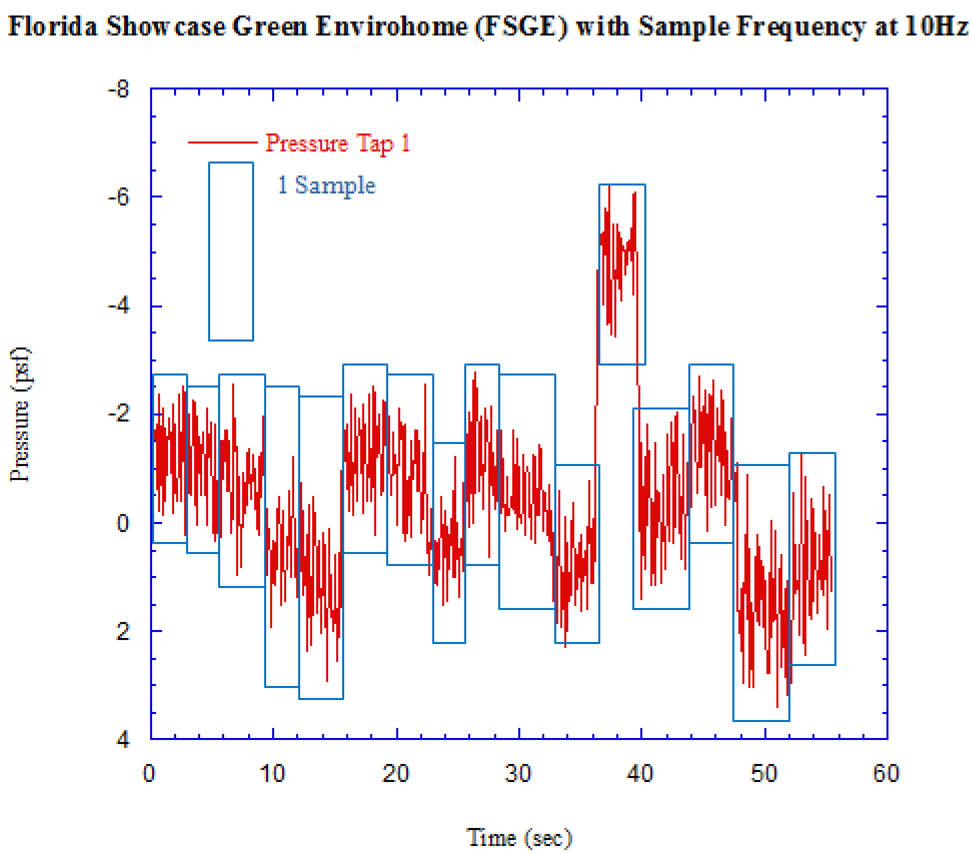


Figure 46: Spliced data for Florida Showcase Green Envirohome (FSGE) at a sampling frequency of 10 Hz

From November 2009 to December 2009, 7 total data sets were extracted over time for a data collection sampled at a frequency of 5 Hz. From December 2009 – February 2010, data was sampled at a frequency of 10 Hz for the remainder of 16 sample sets as shown in Figure 46. A combination of all 3 second gust time histories for the FSGE greenroof are outlined for each pressure tap on the roof in correlation to the wind speed and wind direction to illustrate the instantaneous pressure distributions across the surface of the greenroof in Appendix A and Appendix B for sampling frequencies of 5 Hz and 10 Hz respectively. Although data was also collected at a sampling frequency of 1 Hz, only data at higher sampling frequencies are considered for data analysis.

Both sampling frequencies illustrate varying pressures at each pressure node across the surface of the greenroof. The variation in pressure distribution between each pressure sensor is highly affected by the dynamic wind parameters of wind direction and time. However, due to the overall size of the structure supporting the greenroof, minimum variation between each pressure tap is observed with uniform pressure distribution across the soil medium.

Port Charlotte Rays Stadium (PCRS) Measured Data

Unlike FSGE, the Port Charlotte Rays Stadium (PCRS) is located on the West coast of Florida in Port Charlotte. Since the PCRS greenroof is atop a building with elevation of 25 feet and located in an undisrupted surrounding area, more wind data is available in comparison to the FSGE site.

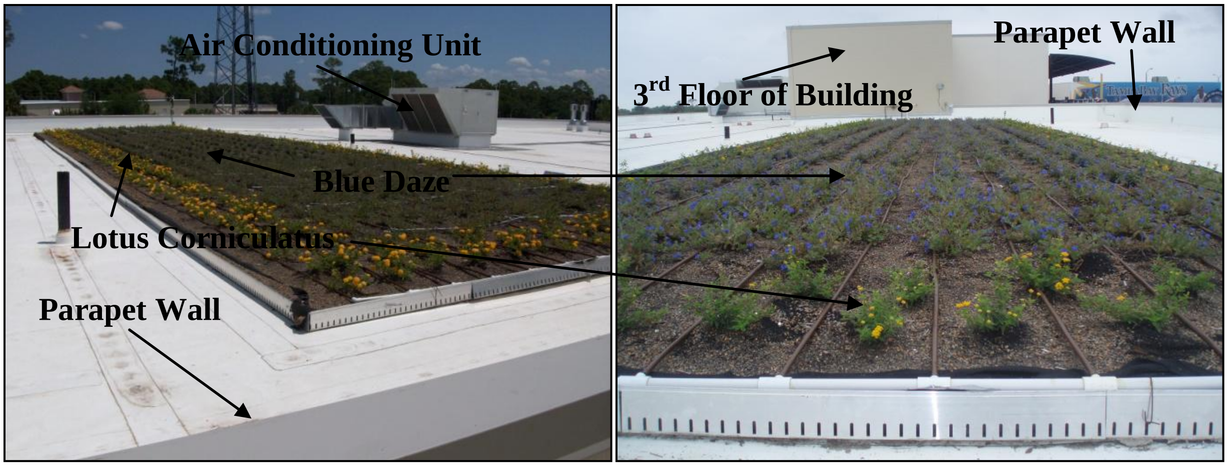


Figure 47: Port Charlotte Rays Stadium (PCRS) greenroof obstructions

Similar to the FSGE greenroof, the PCRS greenroof integrates geo-synthetic wind netting as a technique to combat wind erosion; however, the soil medium only has a depth of 3 inches. As an added prevention, a parapet wall of 2 feet – 7 inches is implemented. Rather than covering the entire area of the roof, the PCRS greenroof only covers a portion of the rooftop at a surface area of 1600 sq. feet as shown in Figure 38. Furthermore, given that the PCRS greenroof only covers a portion of the roof itself, mechanical units for the building are located on the bare portions of the roof (near the patch of greenroof) which effects the flow of wind near the section of interest, as shown in Figure 47, as well as a 10 foot wall of the 3rd floor of the building located south of the greenroof.

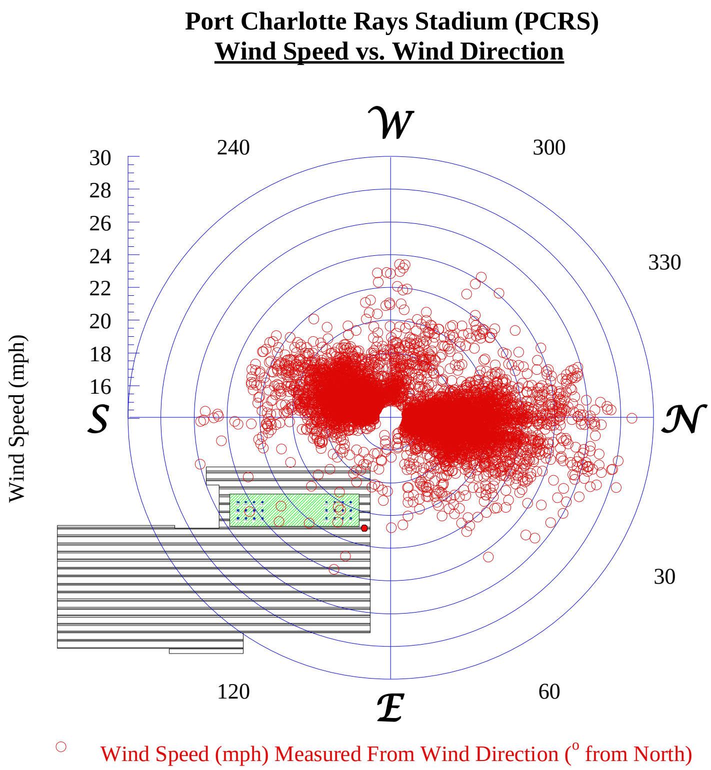


Figure 48: Port Charlotte Rays Stadium (PCRS) wind speed vs. wind direction

The vegetation was planted in 2009 with light coverage across the greenroof area, with less than 1 year of plant growth, making it a newly established vegetated roof (NEVR). All pressure taps are located at the surface of the soil medium under a light cover of blue daze and lotus corniculatus. Represented by Figure 48, winds at or above 15 mph for all data with sampling frequencies of 5 Hz and 10 Hz have average directional trends from the North and Southwest directions.

Unlike the FSGE site, the PCRS greenroof has more data collected over time due to the high elevation of the building and the topography of the region. A compilation of all 3 second gust time histories spliced over time for the PCRS greenroof for a sampling frequency of 5 Hz with a sample size of 62 is referenced in Appendix A. Next, data for the PCRS greenroof was sampled at a frequency of 10 Hz for the remainder of 119 sample sets which is shown in Appendix B.

Although similar in greenroof characteristics, the PCRS greenroof differs from the FSGE greenroof by size, geometry, and protective elements like a parapet wall and the large wall obstructing the Southwest end of the clubhouse greenroof. Due to this, all pressure taps are expected to have uncertain pressure distributions.

ASCE Code 7-05

The American Society of Civil Engineers (ASCE) provides techniques to determine the minimum load requirements in structural design through the use of the *Minimum Design Loads for Buildings and Other Structures* (ASCE Code 7-05). In this section, a brief review of ASCE Code 7 2005 is presented and later compared with the field data obtained from monitoring studies. Specifically for this study, the analytical method (method 2) for wind design is implemented.

Analytical Method

According to ASCE 7-05, all buildings designed using the analytical procedure are determined in accordance with the following provisions:

1. The building in question is considered to be a regular-shaped building or structure, having no unusual geometrical irregularity in spatial form.
2. The building or other structure does not have the response characteristics making it subject to cross wind loading, vortex shedding, instability due to galloping or flutter; or does not have a site location for which channeling effects or buffeting in the wake of upwind obstructions warrant special consideration.

Applying Wind as a Pressure

In accordance with ASCE 7-05, the base wind pressure of a structure in pounds per square foot (psf), q, can be calculated by the following equation:

[1]

where K_z is the velocity pressure exposure coefficient, which is a function of height, K_{zt} is a factor that accounts for wind speed increases due to hills and escarpments, K_d is a factor that accounts for the direction of winds which is only used when the structure is subjected to combinations of loads, V is the wind velocity in miles per hour (mph), I is the importance factor of the building (outlined by Table 16), and the numerical coefficient 0.00256 is used – except where sufficient climatic data are available to justify the selection of a different value of this factor for a design application.

The velocity pressure exposure coefficient, K_z, can be determined by the following formula:

[2]

[3]

Where, z_g and α are nominal height of the atmospheric boundary layer and the 3 second gust speed power law exponent respectively, tabulated by Table 15 based on exposure categories (B, C, and D) defined by ASCE 7-05 based on surface roughness of the surrounding topography where the structure is located.

Table 15: Terrain exposure constants for α and z_g [Source: (ASCE 2005)]

Exposure	α	z_g (ft)
B	7.0	1200
C	9.5	900
D	11.5	700

The topographic factor, K_{zt}, is equal to 1.0 and the wind directionality factor, K_d, for building is equivalent to 0.85. The wind velocity, V, is identified as the nominal design 3 – second gust wind speeds at 33 feet above ground for exposure Category C.

When identifying the importance factor (I) of the building, ASCE 7-05 establishes the coefficient into two categories based on hurricane prone regions with four subcategories classifying the use of the building itself as outlined in Table 16.

Table 16: Importance factor as described by American Society of Civil Engineers Code 7 2005

Category	Non-Hurricane Prone Regions, V=85mp to 100mph	Hurricane Prone Regions, V>100mph
I: Buildings and other structures that represent a low hazard to human life in the event of failure	0.87	0.77
II: All buildings and other structures except listed by I, III, and IV	1.00	1.00
III: Buildings and other structures that represent a substantial hazard to human life or have a potential to cause substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure	1.15	1.15
IV: Buildings and other facilities designated as essential facilities	1.15	1.15

Components and Cladding

There are three zones of concern when designing for roof loads in accordance to ASCE Code 7-05. The highest pressure occurs in Zone 3 which is denoted by the four corners of the roof as shown in Figure 49. Zone 2 is outlined as the perimeter of the roof which has the second highest load occurrence. Zone 1 is generally the largest area of the roof having the lowest pressure distribution of all three zones. In order to estimate the areas of these zones the following steps should be followed:

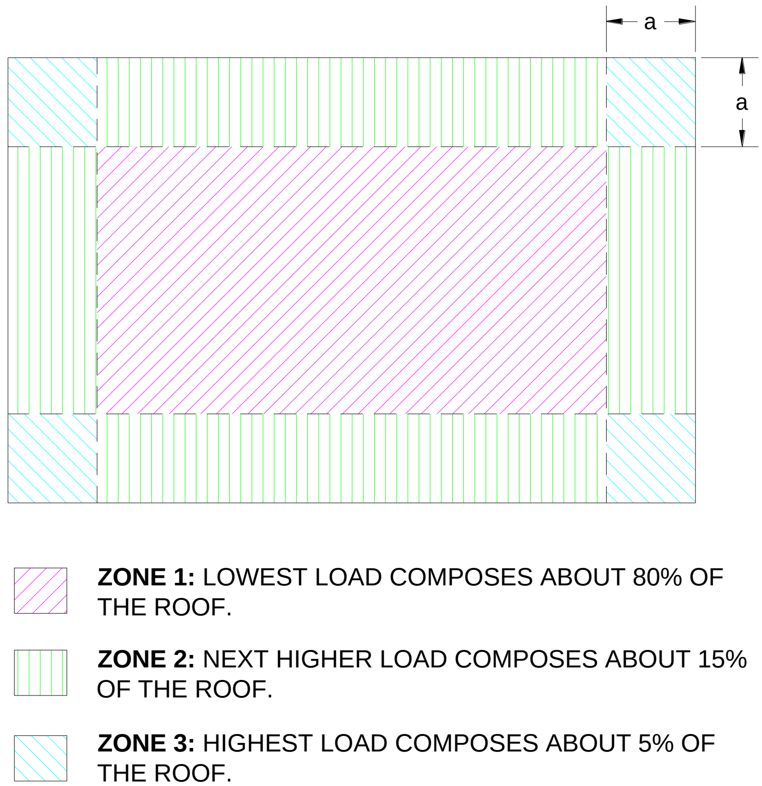


Figure 49: Components and Cladding

- "a" is calculated as the smaller of 0.10 times the least horizontal direction or 0.4 times the elevation
- But not less than 0.04 times the least horizontal direction or 3 ft

Based on the effective areas determined per zone, the pressure distributions of each section are then calculated using the following provisions:

– [4]

where, q is the base wind pressure calculated by Equation [1], G is the wind gust effect factor which depends upon exposure, C_p is the external pressure coefficient of the building surface where negative values represent pressure acting away from the surface, and GC_{pi} is the internal coefficient which depends on the type of openings in the building – for fully enclosed buildings GC_{pi} = +/- 0.18.

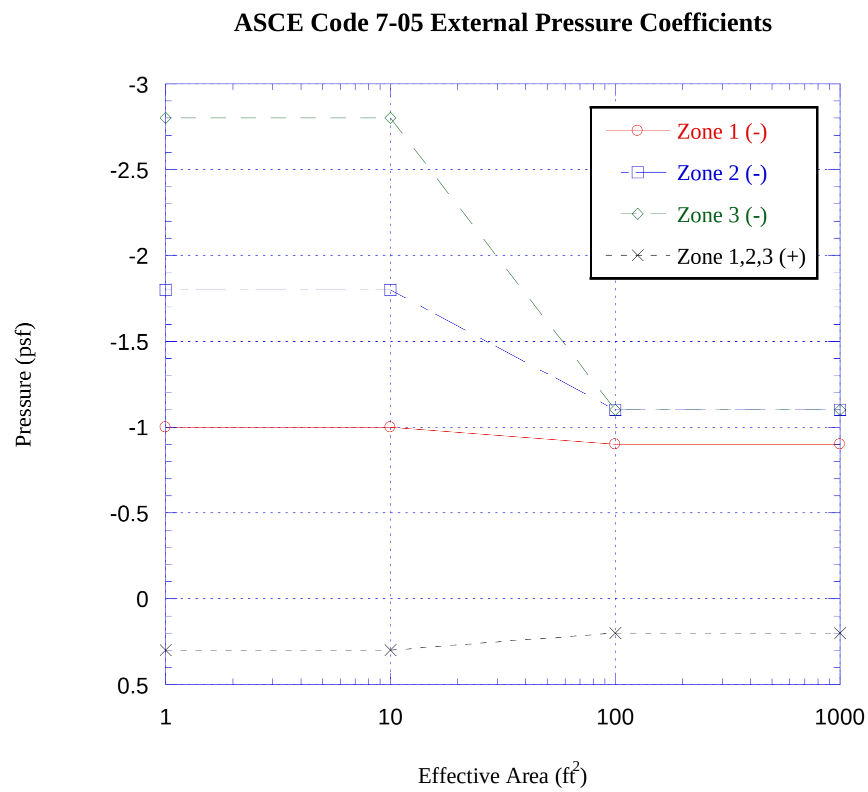


Figure 50: Relationship between GC_p (external pressure coefficient) with effective area for all negative and positive zones [Source: (ASCE 2005)]

For rigid structures, the gust effect factor, G, is calculated by the following formulation:

) [5]

[6]

where, , is the intensity of turbulence at height which is equal to the height of the structure defined as *0.6h* but not less than the z_{min} for all building heights where z_{min} and c are defined in Table 17 as the exposure constant and the turbulence intensity factor respectively.

Table 17: Terrain exposure constants for c and z_{min} [Source: (ASCE 2005)]

Exposure	c	z_{min} (ft)
B	0.30	30
C	0.20	15
D	0.15	7

As stated by ASCE Code 7 2005, coefficients (the peak factor for background response) and (the peak factor for wind response) are taken to be 3.4 and the background response Q is calculated by the following:

[7]

in which, B is the horizontal dimension of the building measured normal to the wind direction in ft, h is the mean roof height of the structure, and is the integral length scale of turbulence at the equivalent height given by the calculation where l and are tabulated in Table 18 :

— [8]

Table 18: Terrain exposure constants for *l* and [Source: (ASCE 2005)]

Exposure	(ft)	
B	320	1/3
C	500	1/5
D	650	1/8

It should be noted, however, that ASCE 7-05 uses Figure 50 to estimate GC_p in relation to the effective wind area calculated for components & cladding; where, the two variables cannot be separated.

Florida Showcase Green Envirohome (FSGE) – ASCE Code 7 2005 Method 2

Based on the specifications of the FSGE greenroof building, ASCE 7-05 was solved for components & cladding of the rooftop. The following characteristics were determined to solve ASCE 7-05 Method 2 for a 9 ft x 9ft x 8ft structure:

- Base, B = 9ft , Length, L = 9ft; Elevation, z = 8ft
- Velocity, V = 130 mph
- Wind directionality factor, K_d = 0.85
- Exposure Category = C
- Velocity pressure coefficient, K_z = 0.849
- Topographic factor, K_{zt} = 1.0
- Importance factor = 0.77; with an Occupancy of I
- Effective wind area = 9 sq. ft.

- External pressure coefficient with gust effect factor, GC_p
  - [Positive, Negative Zone 1] = [0.3, -1]
  - [Positive, Negative Zone 2] = [0.3, -1.8]
  - [Positive, Negative Zone 3] = [0.3, -2.8]
- Internal pressure coefficient with gust effect factor, GC_{pi}
  - Although the building is considered to be enclosed, the measured data on site referenced a static atmospheric pressure rather than the internal volume of the structure. In order to effectively compare ASCE 7-05 results to measured full scale data, it needs to be assumed that the building is not enclosed to account for the difference; thus, $GC_{pi} = 0.0$.

Referencing the characteristics outlined, ASCE 7-05 components & cladding were calculated and outlined in Table 19.

Table 19: ASCE Code 7-05 components & cladding results for FSGE

ASCE CODE 7 2005 Florida Showcase Green Envirohome (FSGE)			
Zone 1	**Zone 2**	**Zone 3**	**Positive all Zones**
-24.03 psf	-43.27 psf	-67.30 psf	7.21 psf

All three zones for components & cladding in relation to the FSGE structure being measured are illustrated by Figure 51. The effective area for all three zones is 9 sq. feet, where the design pressures found in Table 19 can be applied to their respective zones (for both the negative and the positive design pressures) for design purposes. Zone 1 encompasses pressure taps P4, P5, P7, and P8, Zone 2 includes pressure taps P1, P2, P6, P9 P10, and P11, and Zone 3 contains pressure taps P3 and P12.

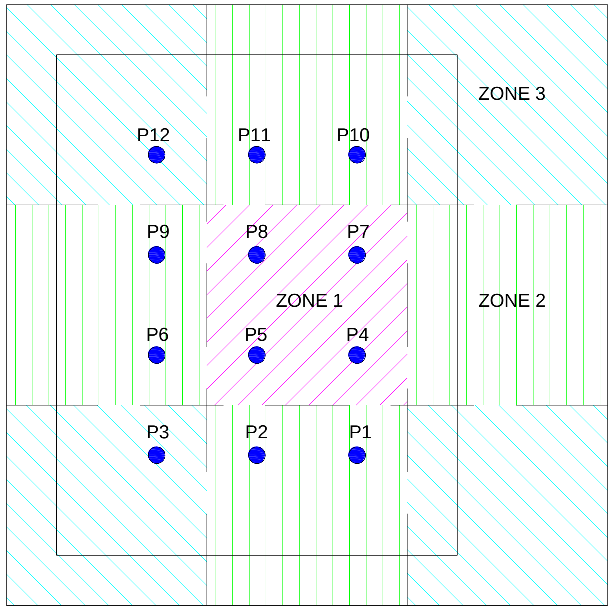


Figure 51: Florida Showcase Green Envirohome (FSGE) components & cladding

Port Charlotte Rays Stadium (PCRS) – ASCE Code 7 2005 Method 2

Based on the specifications of the PCRS greenroof building, ASCE 7-05 is solved for components & cladding of the rooftop. Since the greenroof only covers a section of the building itself, it is understood that it is located in Zone 1 of the entire building. The following characteristics are then determined to solve ASCE 7-05 Method 2:

- Elevation, z = 25 ft
- Parapet height < 3 ft; therefore Zone 3 ≠ Zone 2
- Velocity, V= 130 mph
- Wind directionality factor, K_d = 0.85
- Exposure Category = C
- Velocity pressure coefficient, K_z = 0.945

- Topographic factor, K_{zt} = 1.0
- Importance factor = 1.0; with an Occupancy of II
- Effective wind area > 1000 sq. ft.
- External pressure coefficient with gust effect factor, GC_p
    - [Positive, Negative Zone 1] = [0.2, -0.9]
- Internal pressure coefficient with gust effect factor, GC_{pi}
    - Although the building is considered to be enclosed, the measured data on site referenced a static atmospheric pressure rather than the internal volume of the structure. In order to effectively compare ASCE 7-05 results to measured full scale data, it needs to be assumed that the building is not enclosed to account for the difference; thus, GC_{pi} = 0.0.

Referencing the characteristics outlined, ASCE 7-05 components & cladding are calculated and outlined in Table 20.

Table 20: ASCE Code 7-05 components & cladding results for PCRS

ASCE CODE 7 2005 Florida Showcase Green Envirohome (FSGE)	
Zone 1	**Positive all Zones**
-31. 29 psf	6.95 psf

Pressure Coefficient Conversion

In order to compare collected data to ASCE7-05 design provisions, all data collected is converted to non dimensional pressure coefficients using Bernouilli's Equation [9].

[9]

where is the pressure coefficient, is the change in pressure measured on site measured in lbs/ft^2, is the wind velocity in ft/s, and is the specific density of air in slugs/ft^3. By converting the data collected for both sites to pressure coefficients, pressures can be predicted at higher wind speeds and compared to the minimum design pressures, assuming that it acts in a linear fashion. For both roofing systems, atmospheric references are used; therefore, the calculated pressure coefficients are actually external pressure coefficients of the structure.

Florida Showcase Green Envirohome (FSGE) Pressure Coefficients

In order to organize the data, the minimum, the average, and the maximum pressure coefficients of each 3 second (or more) sample are plotted in a histogram for each pressure tap as shown in Appendix C. Specifically, when analyzing the data, the minimum and maximum pressure coefficients are chosen per tap to evaluate the instantaneous worse case for each pressure location for their respective wind speed and wind direction. When plotting the pressure coefficients for review, both sampling frequencies are grouped together. However, for the FSGE greenroof, samples 1 thru 7 are sampled at a frequency of 5 Hz; whereas, samples 8 thru 23 are sampled at a frequency of 10 Hz.

Florida Showcase Green Envirohome (FSGE): Net Pressure Across Greenroof

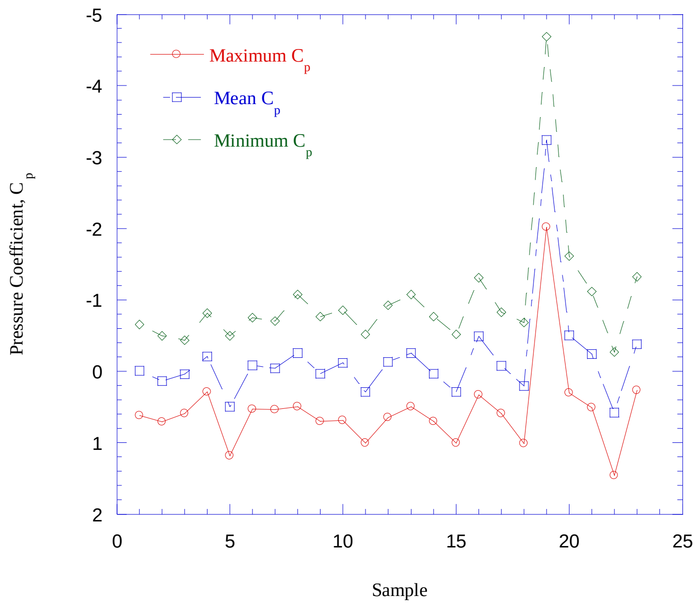


Figure 52: Florida Showcase Green Envirohome (FSGE) maximum, minimum, and mean pressure coefficients across greenroof

The graph represented by Figure 52 compiles the net pressure coefficients across the greenroof ; therefore, one marker represents the minimum, maximum, and mean pressure coefficient averaged across the entire roof. Since the structure itself is fairly small with a low elevation, a uniform pressure distribution is evident across the entire greenroof, with a minimal variation between sample sets.

Port Charlotte Rays Stadium (PCRS) Pressure Coefficients

The same analysis approach is taken in order to organize the data collected at the PCRS greenroof. The minimum, the average, and the maximum pressure coefficients of each 3 second sample are plotted in a histogram for each pressure tap as shown in Appendix C; where, samples 1 thru 62 are sampled at a frequency of 5 Hz and samples 8 thru 181 are sampled at a frequency of 10 Hz.

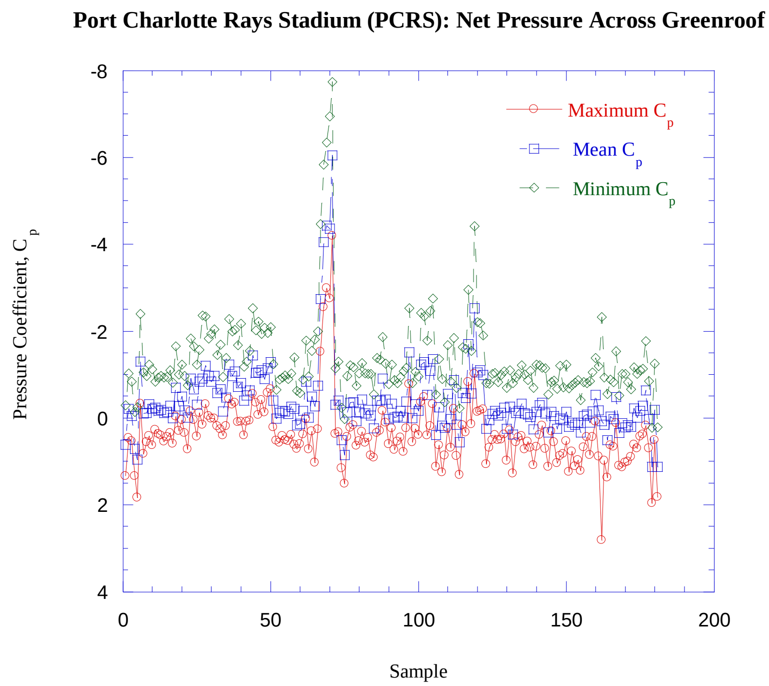


Figure 53: Port Charlotte Rays Stadium (PCRS) maximum, minimum, and mean pressure coefficients across greenroof

Unlike the uniformity of the FSGE greenroof, the PCRS greenroof displays variability between each sample across the greenroof as shown in Figure 53. This is due, as stated before, to the dimensional elements of the structure itself as well as the preventative techniques used for wind reduction.

Predicting a Pressure Based on Measured External Pressure Coefficients, C_p

Since wind speed and wind direction could not be controlled, the external pressure coefficients measured at each monitoring facility changes with direction of wind and location of each pressure tap. The minimum and maximum pressure (coefficient) distribution per pressure unit with respect to the wind direction (not a function of time) is illustrated in Appendix D. When comparing pressure coefficients to ASCE Code 7-05 provisions for components & cladding, it should be understood that the simplified methodology within the code does not account for wind direction per specific zone of the roof.

Although components & cladding measured by ASCE Code 7-05 accounts for wind speed as the main factor that affects the pressure distribution along the surface of the roof for design load calculations, results in Appendix D also suggest that wind direction has a large effect on the pressure distribution as well. With respect to the pressure coefficient comparison to wind direction, the FSGE greenroof has the largest uplift pressure coefficients around 280 degrees from the North. Like the FSGE greenroof, the PCRS greenroof data suggests that, when comparing the pressure coefficients on site to their respective wind directions in Appendix D, the wind direction affects the magnitude of the pressure distributions. After analyzing this data, the PCRS greenroof has the highest uplift pressure coefficients at about 200 degrees from the North.

In order to correlate the external pressure coefficients collected in situ to the pressures estimated by ASCE Code 7-05, the external pressure coefficients can be used to evaluate the predicted pressures at each pressure tap for the design wind velocity used in ASCE 7-05 by rearranging Equation [9] to be:

– [10]

Where, velocity, V, is taken to be the design wind speed and C_p is taken from measured data. It should be noted, however, that the design wind speed estimated by ASCE Code 7-05 is taken to be 130 mph for exposure Category C at an elevation of approximately 33 feet.

Florida Showcase Green Envirohome (FSGE) Pressure Prediction

When estimating the pressure distribution at a design wind velocity of 130 mph across the FSGE greenroof, the minimum pressure coefficient is averaged per pressure tap location and re-calculated to predict the pressures at a higher wind speed (Table 21). These results are then compared to ASCE Code 7-05 design provisions in Table 22. Since the main concern of this study is the uplift pressures across the roof, only the minimum pressures are predicted in accordance to ASCE Code 7-05. Rather than comparing the average minimum pressure per location, each pressure tap is averaged within their respective zones, which is then compared to the calculated pressures by ASCE Code 7-05.

Table 21: Florida Showcase Green Envirohome (FSGE) minimum external pressure coefficient conversions

Pressure Tap	Mean Minimum Pressure Coefficient, C_{pmean}	Predicted Pressure, P_{FSGE}
P1	-2.14	-93.52 psf
P2	-0.92	-39.94 psf
P3	-0.74	-32.42 psf
P4	-1.38	-60.15 psf
P5	-0.72	-31.45 psf
P6	-1.04	-45.36 psf
P7	-0.97	-42.51 psf
P8	-0.74	-32.25 psf
P9	-0.76	-33.26 psf
P10	-1.17	-50.88 psf
P11	-0.54	-23.60 psf
P12	-0.71	-30.82 psf

When evaluating each zone for the FSGE greenroof in Table 22, it is evident that the highest uplift zone is Zone 2 at an uplift pressure of 49.30 psf with Zone 3 having the least amount of uplift at 31.62 psf. This is due to the fact that both pressure transducers in Zone 3 are the farthest pressure taps from the direction of wind while Zone 2 and Zone 1 are closest to the force of wind.

Table 22: Measured minimum pressure predictions compared to minimum ASCE Code 7-05 calculations

Zone per Unit Area	Components & Cladding Zones (FSGE Measured)	Components & Cladding Zones (ASCE)
Zone 1 (P4, P5, P7, P8)	-41.60 psf	-24.03 psf
Zone 2 (P1, P2, P6, P9,P10, P11)	-49.30 psf	-43.27 psf
Zone 3 (P3, P12)	-31.62 psf	-67.30 psf

Since the pressure data collected across the greenroof are considered to be external pressure distributions, predicted uplift forces (based on measured pressure coefficients on site) are compared to the estimated design pressure in relation to ASCE Code 7-05. As shown in Figure 54, the predicted average pressures on site are within the estimated design loads calculated for components and cladding; however, the maximum and minimum pressures measured on location are not.

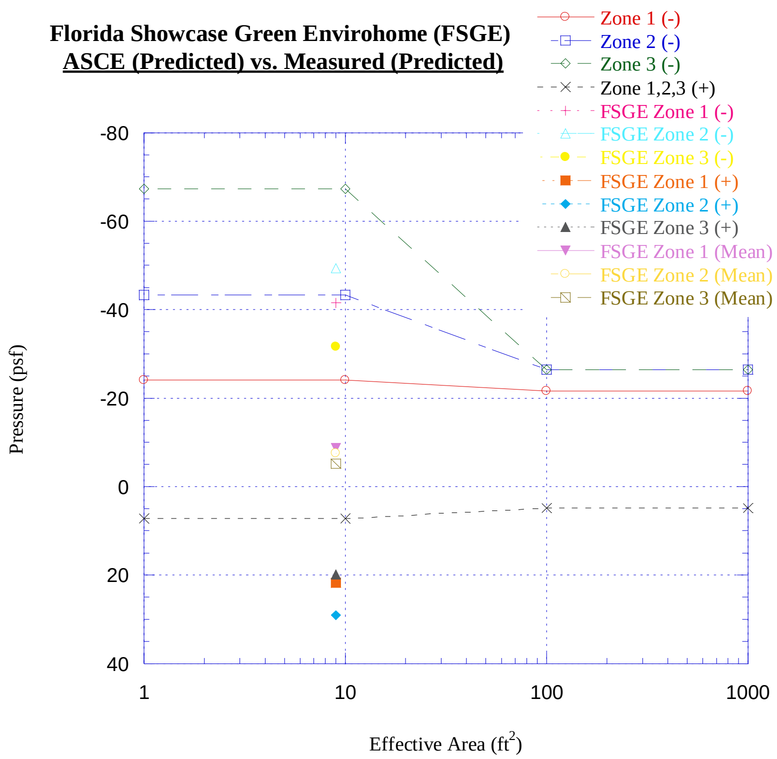


Figure 54: Florida Showcase Green Envirohome (FSGE) (measured) vs. ASCE Code 7-05 (calculated)

Port Charlotte Rays Stadium (PCRS) Pressure Prediction

When estimating the pressure distribution at a design wind velocity of 130 mph across the PCRS greenroof, the same methodology is used with respect to the FSGE greenroof where the minimum pressure coefficient is averaged per pressure tap location and re-calculated to predict the pressures at a higher wind speed (Table 23). These results are then compared to ASCE Code 7-05 design provisions in Table 24.

Table 23: Port Charlotte Rays Stadium (PCRS) minimum external pressure coefficient conversions

Pressure Tap	Mean Minimum Pressure Coefficient, C_{pmean}	Predicted Pressure, P_{PCRS}
P1	-4.10	-179.08 psf
P2	-1.32	-57.64 psf
P3	-0.92	-40.32 psf
P4	-0.39	-16.89 psf
P5	-0.90	-39.23 psf
P6	-3.77	-164.25 psf
P7	-1.84	-80.18 psf
P8	-0.92	-40.09 psf
P9	-2.32	-101.17 psf
P10	-0.74	-32.49 psf
P11	-1.92	-83.55 psf
P12	-1.04	-45.45 psf
P13	-0.80	-34.72 psf
P14	-1.24	-54.18 psf
P15	-0.49	-21.26 psf
P16	-2.93	-128.02 psf
P17	-1.03	-44.72 psf
P18	-0.86	-37.42 psf
P19	-0.57	-24.73 psf
P20	-0.61	-26.63 psf
P21	-0.40	-17.24 psf
P22	-1.38	-60.05 psf
P23	-1.28	-55.84 psf
P24	-0.91	-39.60 psf

When evaluating Zone 1 for the PCRS greenroof in Table 24, it is evident that the measured pressure is greater than that of the ASCE Code 7-05 prediction. This can be due to the assumption of linearity of velocity and its effect on pressure (since air flow acts in a nonlinear fashion with the change in velocity affecting turbulence) when using the pressure coefficient to predict the pressure distribution for a wind velocity of 130 mph.

Table 24: Measured minimum pressure predictions compared to minimum ASCE Code 7-05 calculations

Zone per Unit Area	Components & Cladding Zones (PCRS Measured)	Components & Cladding Zones (ASCE)
Zone 1 (P1-P24)	-59.36 psf	-31. 29 psf

Figure 55 displays the predicted maximum, minimum, and average pressures measured on location in comparison to the calculated ASCE Code 7-05 design loads. Although the minimum and maximum predicted pressures are above the design loads estimated by ASCE Code 7-05, the average predicted pressures are within design standards calculated by Method 2.

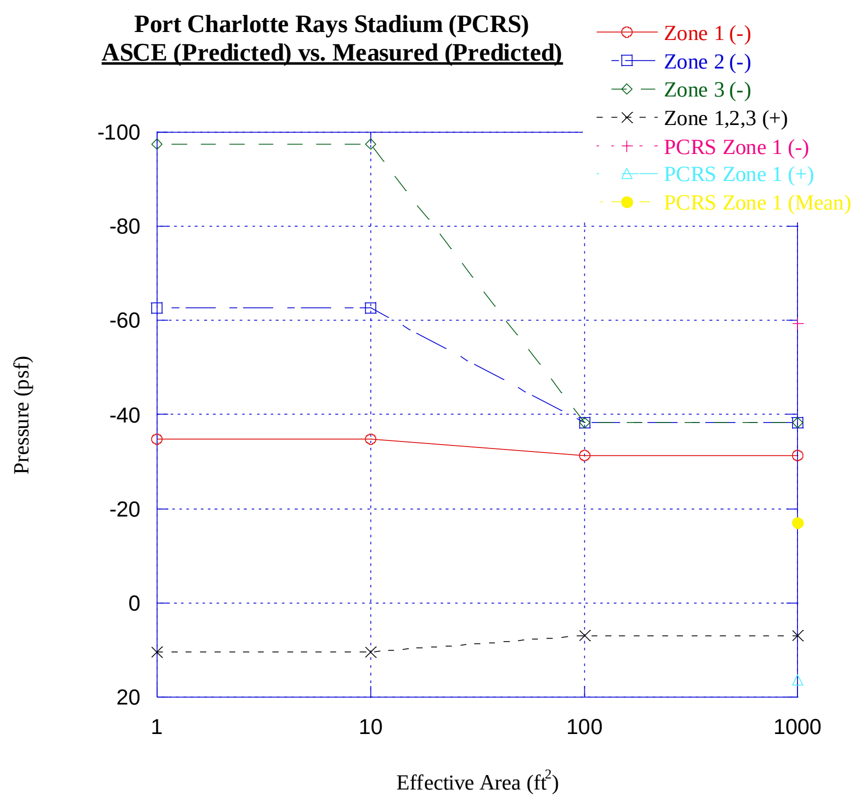


Figure 55: Port Charlotte Rays Stadium (PCRS) (measured) vs. ASCE Code 7-05 (calculated)

Greenroof Material Loss

Along with the pressure collection, a visual analysis was made to compare the level of vegetation establishment at both locations. The FSGE greenroof is considered a well established vegetated roof (WEVR) since the vegetation canopy has been growing over two years. The PCRS greenroof, on the other hand, is a newly established vegetated roof due to the lack of cover and establishment in less than one year. Photos of each greenroof taken over time are organized in Table 25, comparing the material loss in relation to vegetation establishment.

Table 25: Visual results of greenroofs over time

Greenroof Material Loss On Site		
Site	**Figure**	**Description**
FSGE	 	• *Planted in Summer 2007* • *Soil media depth of 5"* • *Integrated wind netting* • *Establishment with flourishing muhly grass and railroad vine increasing soil stability* • *About 75% of the greenroof is covered by vegetation* • *Significant soil loss is not evident*

<table>
<tr><th colspan="3">Greenroof Material Loss On Site</th></tr>
<tr><th>Site</th><th>Figure</th><th>Description</th></tr>
<tr><td>PCRS</td><td>
</td><td>Planted in Early 2009
Soil Media depth of 3”
Integrated wind netting
About 50% vegetation coverage
Soil material loss from the greenroof surface with an accumulation at the drain suggesting that the soil media does not necessarily project from the roof but accumulates across the surface.
Wind netting is exposed at the surface due to a lack of soil stability added by a strong vegetation cover (where it was once covered by soil)</td></tr>
</table>

CHAPTER SIX: CONCLUSIONS

For the purpose of this literature, two greenroofs were investigated under natural wind conditions in order to study the effects of wind on greenroof materials. Since there is a lack of research done specifically in relation to this study, there was a need to document the effectiveness of greenroofs under high wind conditions based on the following questions:

1. Do winds have an effect on green roof material loss?
2. Do greenroof materials modify local pressure conditions that would need a modification to current design codes?
3. Does the level of vegetation establishment affect the material loss and pressure distribution?

Winds Effects on Greenroof Material Loss

In 2004, the state of Florida underwent the devastation of four natural disasters known as Hurricane Charley, Ivan, Jean, and Frances. A damage assessment conducted by the Florida Department of Environmental Protection (FDEP) after the destruction of Hurricane Charley in Lee County, FL, concluded that the many (if not mostly all) of the conventional roofing structures along the shoreline sustained considerable roof damage. In that same county, a greenroof located in Shadow Wood Preserve in Bonita Bay was subjected to the same severe wind event. When comparing visual results of the greenroof before and after Hurricane Charley, it was evident that the greenroof reduced uplift for the structure itself by acting as a heavy dead load atop the structure. Furthermore, when comparing photos before and after the hurricane, it was also apparent that minimal damage occurred to the greenroof materials themselves, even without the use of any wind breaks or establishment in foliage.

In order to gather more information on the topic, a controlled full scale investigation was conducted at Florida International University's (FIU) Hurricane Research Center (HRC) using simulated wind up to 77.8 mph with the facility's wall of wind (WOW). The greenroof studied at FIU was only composed of the basic elements of green materials; such as, a thermoplastic membrane with protection layer, drainage layer with integrated separation fabric, 1" Bold & Gold™ pollution control media, separation fabric, and 3" Bold & Gold growth media. The only supportive feature along the perimeter of the greenroof itself was the use of a Live Edge roof restraint held in place by the weight of unsaturated greenroof components; where, no wind netting, vegetation, or additional wind breaks were used. Based on the visual results outlined in Chapter Three, although the greenroof components at the corner of the roof closest to wind application uprooted after 35 seconds of wind application up to 77.8 mph, it was considered a partial failure as the remaining portion of the greenroof stayed primarily intact after the additional 55 seconds of high speed winds.

In order to study the effect of wind on greenroof material loss, it is recommended to apply a similar procedure to the controlled field investigation outlined in this thesis while applying different parameters such as anchorage, vegetation, wind netting methods, and parapet height.

Greenroof Materials Effect on Local Pressure Conditions

Both vegetated roofs are located in the state of Florida, spanning alongside each coast from east to west. The East coast supplied a well established vegetated roof (WEVR) in the Indialantic, with a lush canopy of muhly grass along the perimeter of the small roof with adult railroad vine spread across the center. The structure supporting the roof canopy was simple in design; a square structure only 8 feet in elevation. Due to this, as well as the many obstructions enclosing the building like trees and single family dwellings surrounding the area, high winds were hard to collect for the desired time within a consistent direction.

The West coast greenroof in Port Charlotte, however, had the advantage of higher sampling of wind load application due to the structure's topographic features of open terrain surrounding the perimeter, as well as a higher elevation of 25 feet. This roof on the other hand, lacked in foliage as it supplied a newly established vegetated roof (NEVR) for comparison purposes with the addition of a 2 feet – 7 inch parapet wall as a preventative technique to aid in wind design. Furthermore, unlike the WEVR roof located at the Florida Showcase Green Envirohome (FSGE) on the East coast, the NEVR roof at the Port Charlotte Rays Stadium (PCRS) does not cover the entire surface area of the supporting structure; rather, only a partial 1600 sq. ft. section of canopy covers the clubhouse at PCRS.

In order to conduct an ideal experiment for this study, both greenroofs should be identical in frame; where, geometry, topography, construction materials, and load applications are the same – in which the only variant parameters desired are vegetation establishment and preventative wind techniques. However, due to the fact that both greenroofs vary significantly, and many of these factors could not be isolated – nor could they be controlled, many variables were introduced.

When conducting the full scale monitoring study on site, it was difficult to accurately compare the pressure distributions collected in situ to those used for design provisions in ASCE Code 7-05 for two reasons: wind speed and wind direction. Unfortunately, since natural wind conditions are stochastic in space and time, significant wind speeds were not sustained and the wind directions were highly variant from sample to sample; therefore, adding to the limitations of this research. In order to compare the pressure data collected on site to ASCE Code 7-05 design loads, the minimum, maximum, and mean pressure coefficients, C_p, were calculated for their corresponding wind velocities and pressures. By doing so, when re-evaluating the pressure for a higher wind speed using the pressure coefficients, a linear assumption was made which significantly influences the final pressure result.

The pressure coefficients for the WEVR roof at FSGE illustrate a fairly uniform trend from one pressure tap to another. Since the building itself is so simple in design and lacks in size, the pressure profile across the roof was observed to have a rather uniform distribution across the rooftop. The pressure coefficients for the NEVR roof at PCRS, however, display very random results between each pressure sensor reading. Due to the geometry of the building as well as the obstructions located on the open area of the rooftop itself, non-uniformity was evident at the finite level.

Since ASCE Code 7-05 calculates design loads for buildings and structures using pressure envelopes, the average maximum, minimum and mean pressure coefficients were tabulated across the effective areas of each zone authorized by components and cladding for each roof. By back calculating the pressure using pressure coefficients assuming a velocity of 130 mph, comparisons were made focusing on the average minimum (uplift) pressures measured on location to the calculated design loads from ASCE Code 7-05. Based on the results found in Chapter Five, the average pressure predictions for both greenroofs are within ASCE Code 7 2005 minimum design codes. The minimum pressure prediction for WEVR at FSGE are close to ASCE Code 7-05 estimated design loads; however, the NEVR at PCRS pressure predictions are double the estimated design loads allotted by ASCE Code 7-05.

Although pressure distributions analyzed in this research show higher predicted (measured) pressures in comparison to ASCE Code 7-2005, it is not considered to be due to the addition of greenroof materials atop the roofdeck; but, the geometry, size, and topography of the structure. Also, since the maximum wind speed collected at both greenroof locations was slightly above 20 mph, the assumption of linearity highly alters the predicted (measured) pressures calculated.

Vegetation Establishment and its Effect on Material Loss and Pressure Distribution

When comparing the two roofing systems used in this research, it becomes difficult to do so due to the lack of consistency in structural shape, location, and size. However, research has shown that rooftops with the addition of a wind break reduce the uplift forces across the surface. Although the NEVR greenroof at PCRS utilizes a parapet wall, the measured pressure coefficients are greater than those found at the WEVR greenroof at FSGE which only employs the use of vegetation establishment; suggesting that vegetation growth reduces the pressure distribution across the surface of the roof – in this case, the soil medium.

With the establishment of vegetation at FSGE, there was no sign of soil erosion at low wind speeds; whereas, the NEVR at PCRS had considerable soil loss accumulating across the surface of the roof. For newly established plants, along with the integrated geosynthetic (for long term use and establishment), it is recommended to also utilize a short term alternative for plant growth like a polymer which acts as a binding compound for soil until stability (by full vegetation cover) takes place.

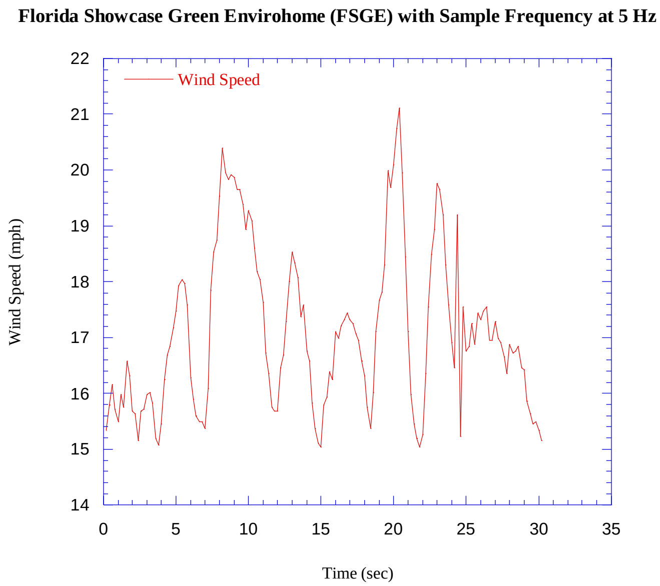
Future Work

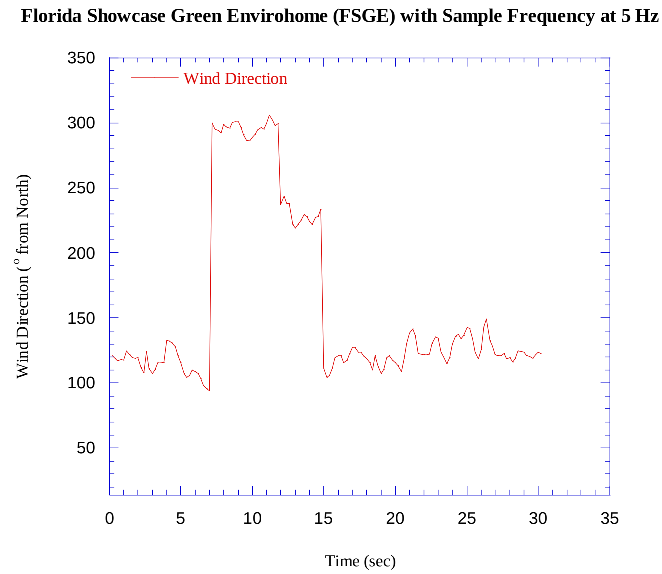
For testing purposes in the future, a controlled field investigation is the desired method of testing. By controlling the wind speed and wind direction (similar to a wind tunnel) in a full scale study, the limitations found in situ under natural conditions can be significantly reduced. Although this research illustrates the effect of greenroof materials under wind loads, it would be beneficial to study established and non-established vegetated roofs in relation to different wind erosion techniques like wind breaks, polymers, and geo-synthetic applications specifically in order to identify the best construction technique to reduce the maximum amount of soil erosion atop the greenroof under high wind events.

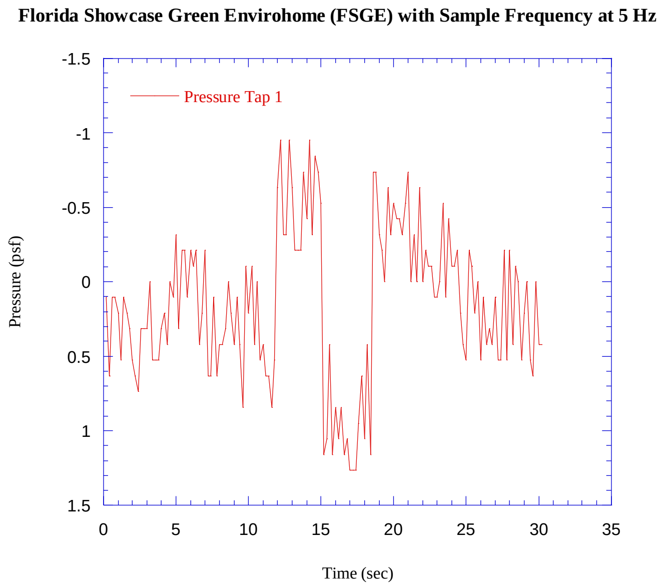
Furthermore, rather than comparing results to ASCE Code 7-05, it would be beneficial to instrument a control roof (with no green materials atop the surface) identical to the greenroof being tested. By doing so, pressure data influenced by greenroof materials can be directly compared to a conventional rooftop. Since ASCE Code 7-05 calculates structural design load, rather than collecting data at the surface of the soil layer, analyzing the effect of these materials on the structure itself under wind events would be the ideal method of testing.

APPENDIX A: SAMPLING FREQUENCY AT 5 HZ

Florida Showcase Green Envirohome (FSGE) Raw Data at 5 Hz







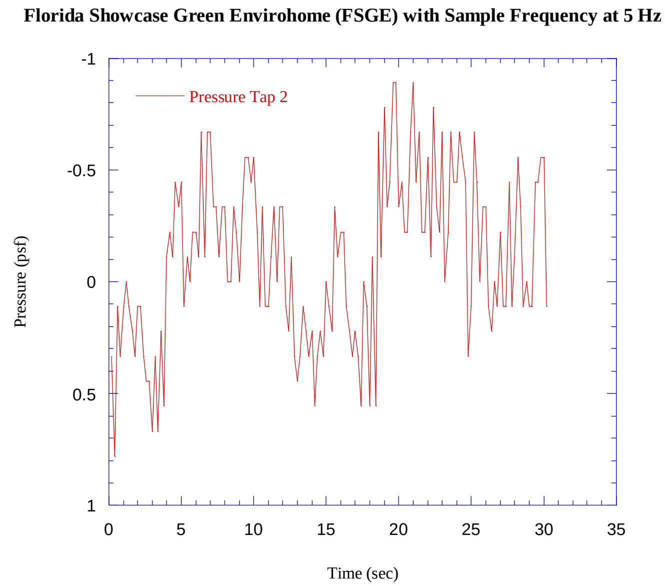
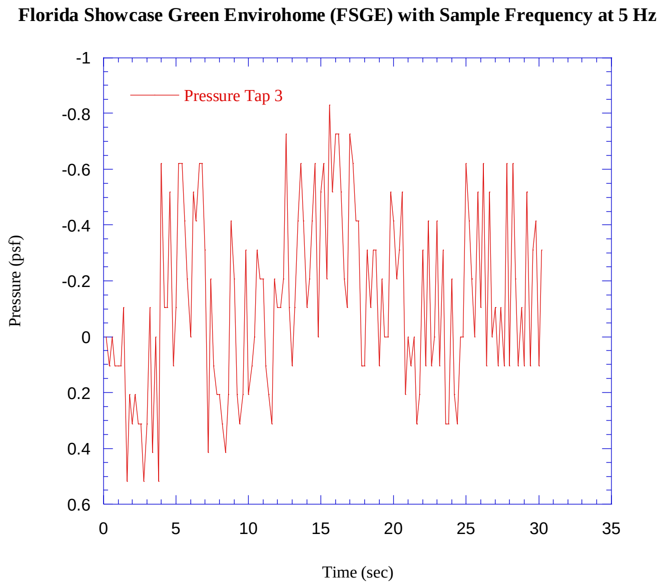
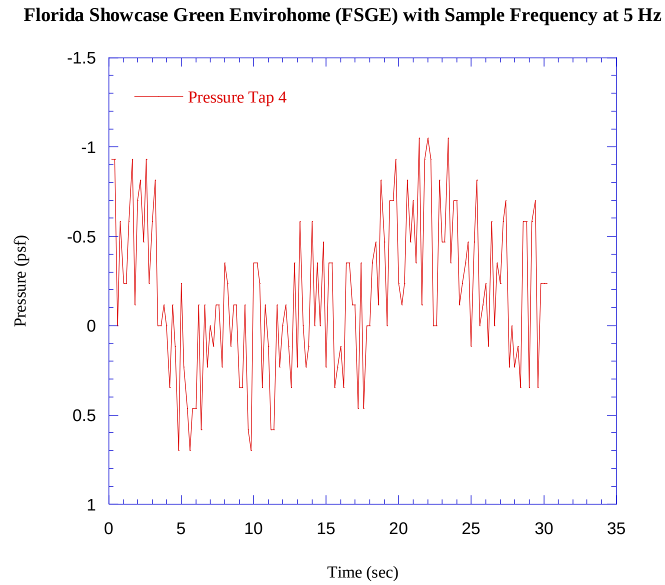
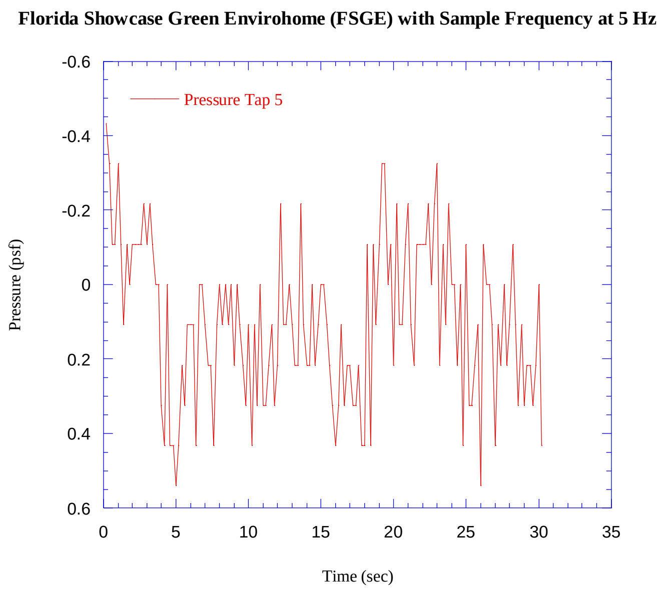


Figure 56: Spliced time histories for wind speed, wind direction, pressure tap 1 and pressure tap 2 at a sampling frequency of 5 Hz at Florida Showcase Green Envirohome







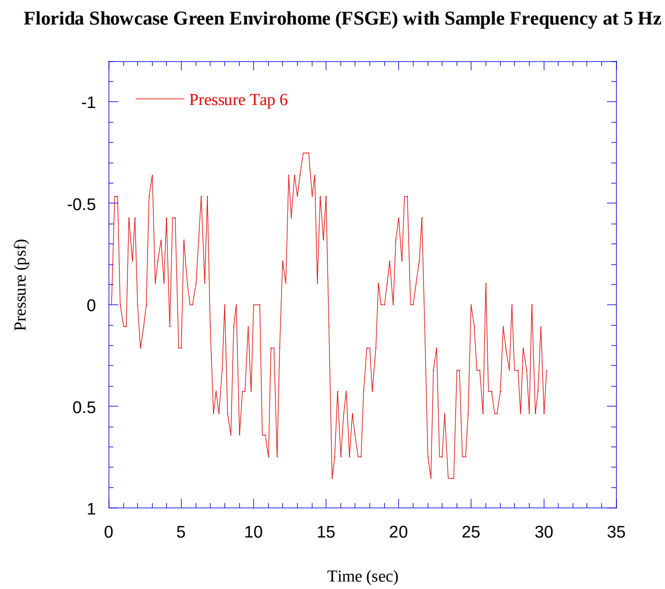


Figure 57: Spliced time histories for pressure tap 3 – pressure tap 6 at a sampling frequency of 5 Hz at Florida Showcase Green Envirohome

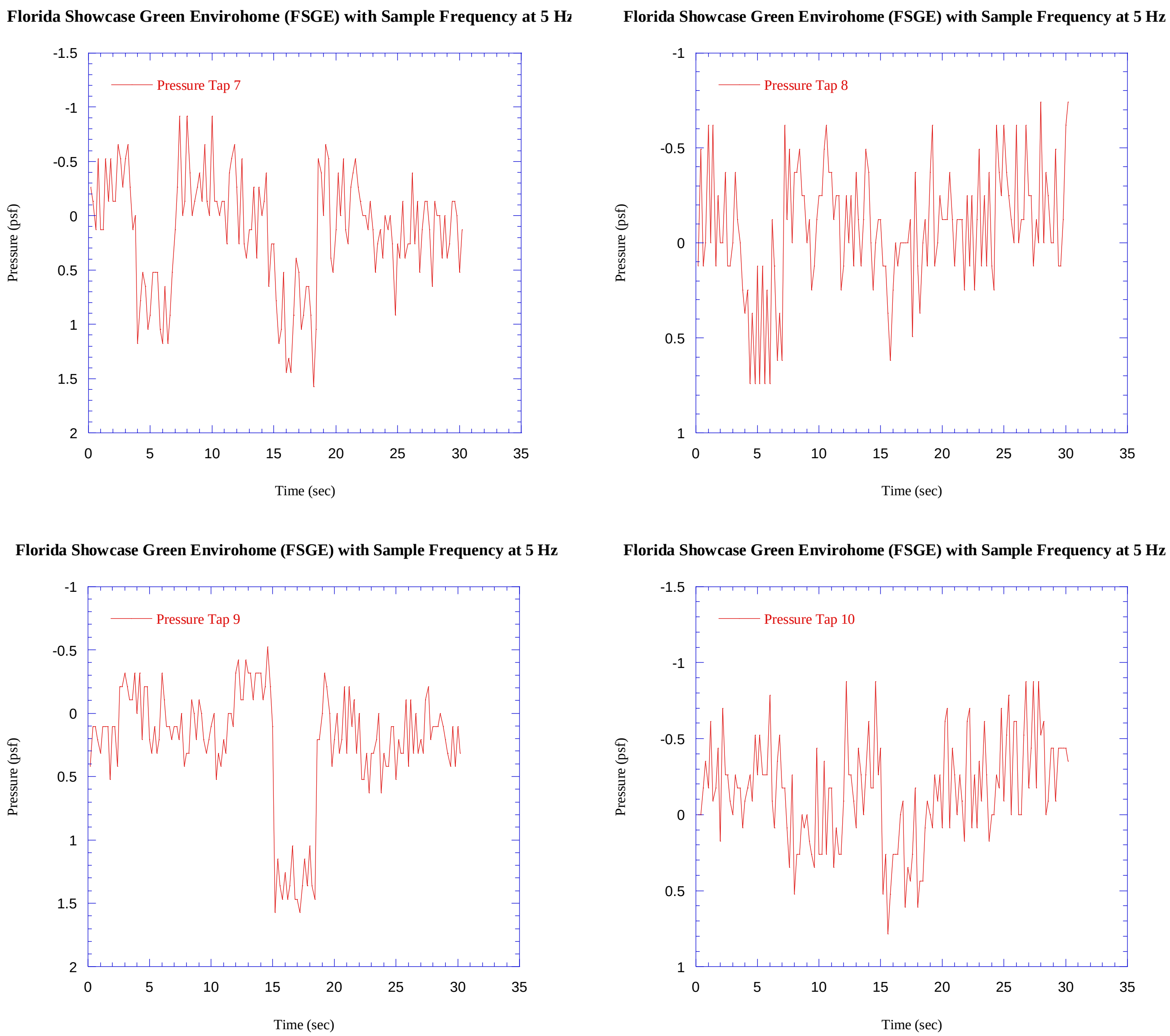
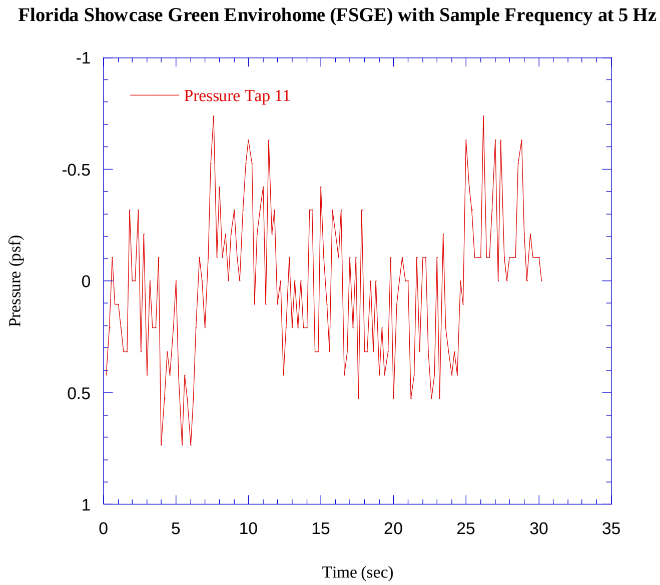


Figure 58: Spliced time histories for pressure tap 7 – pressure tap 10 at a sampling frequency of 5 Hz at Florida Showcase Green Envirohome



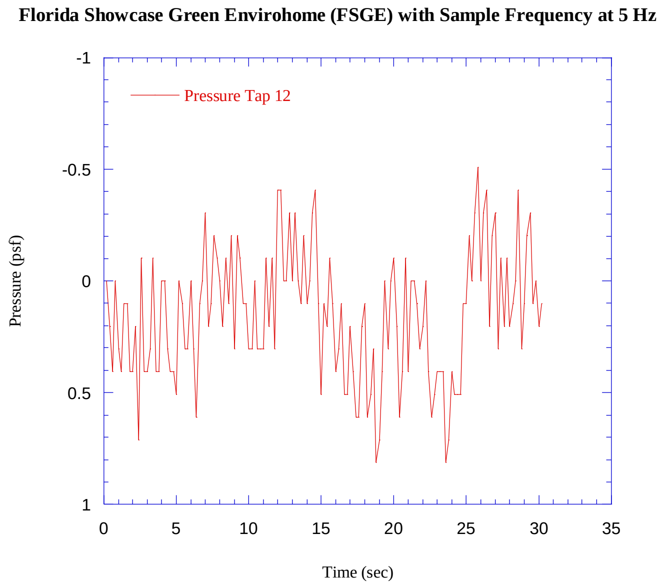


Figure 59: Spliced time histories for pressure tap 11 and pressure tap 12 at a sampling frequency of 5 Hz at Florida Showcase Green Envirohome

Port Charlotte Rays Stadium (PCRS) Raw Data at 5 Hz

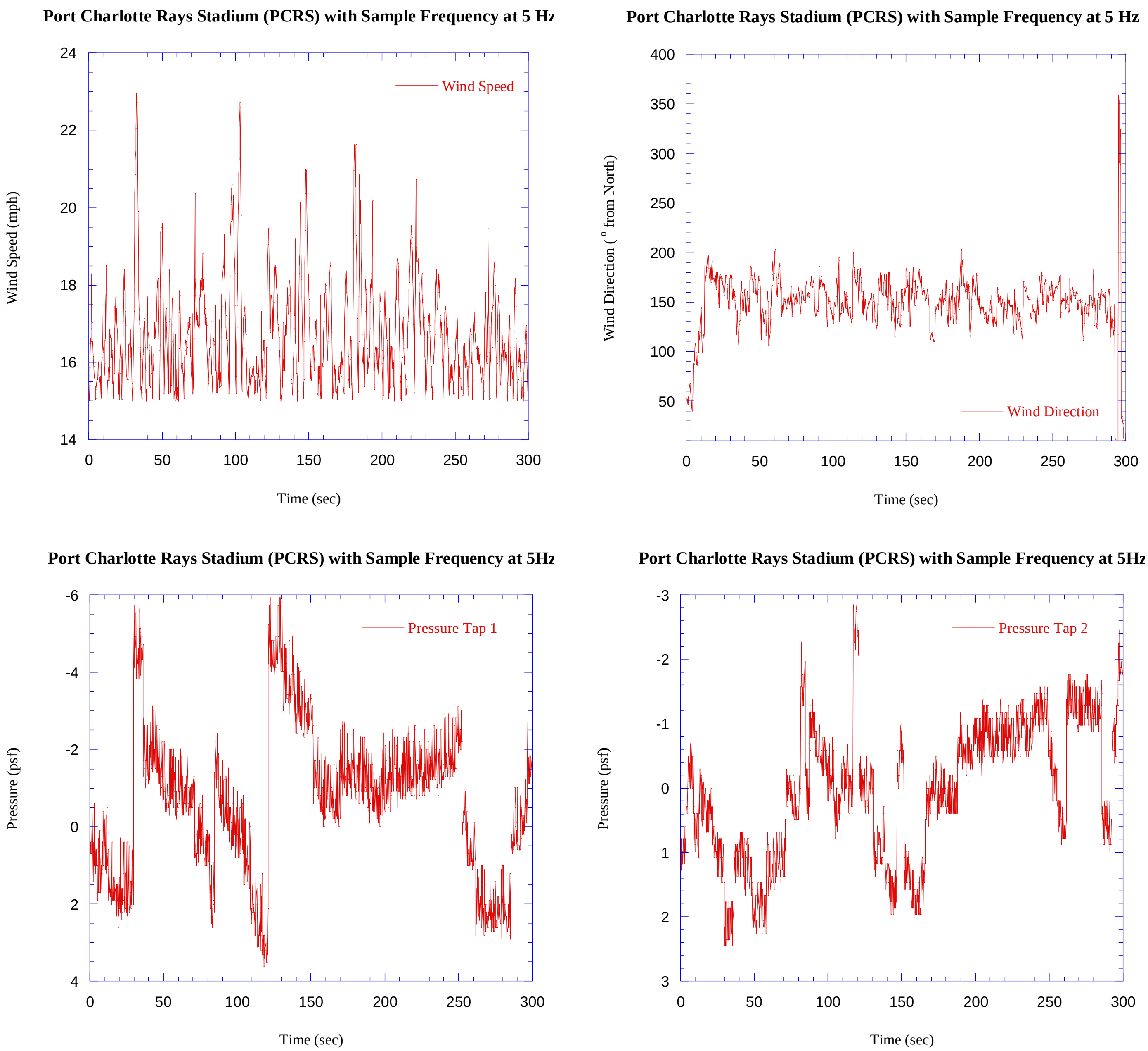


Figure 60: Spliced time histories for wind speed, wind direction, pressure tap 1 and pressure tap 2 at a sampling frequency of 5 Hz at Port Charlotte Rays Stadium

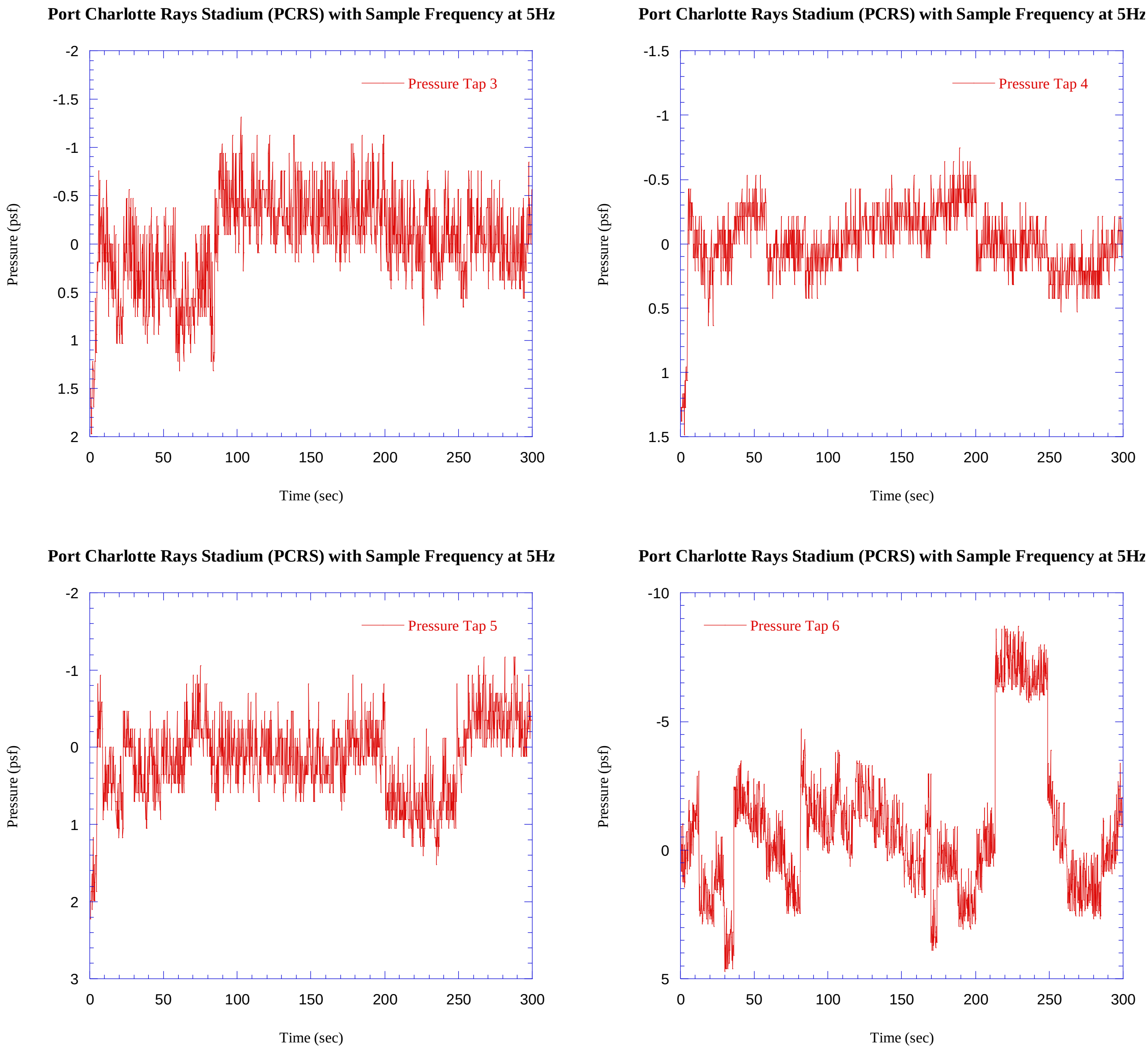


Figure 61: Spliced time histories for pressure tap 3 – pressure tap 6 at a sampling frequency of 5 Hz at Port Charlotte Rays Stadium

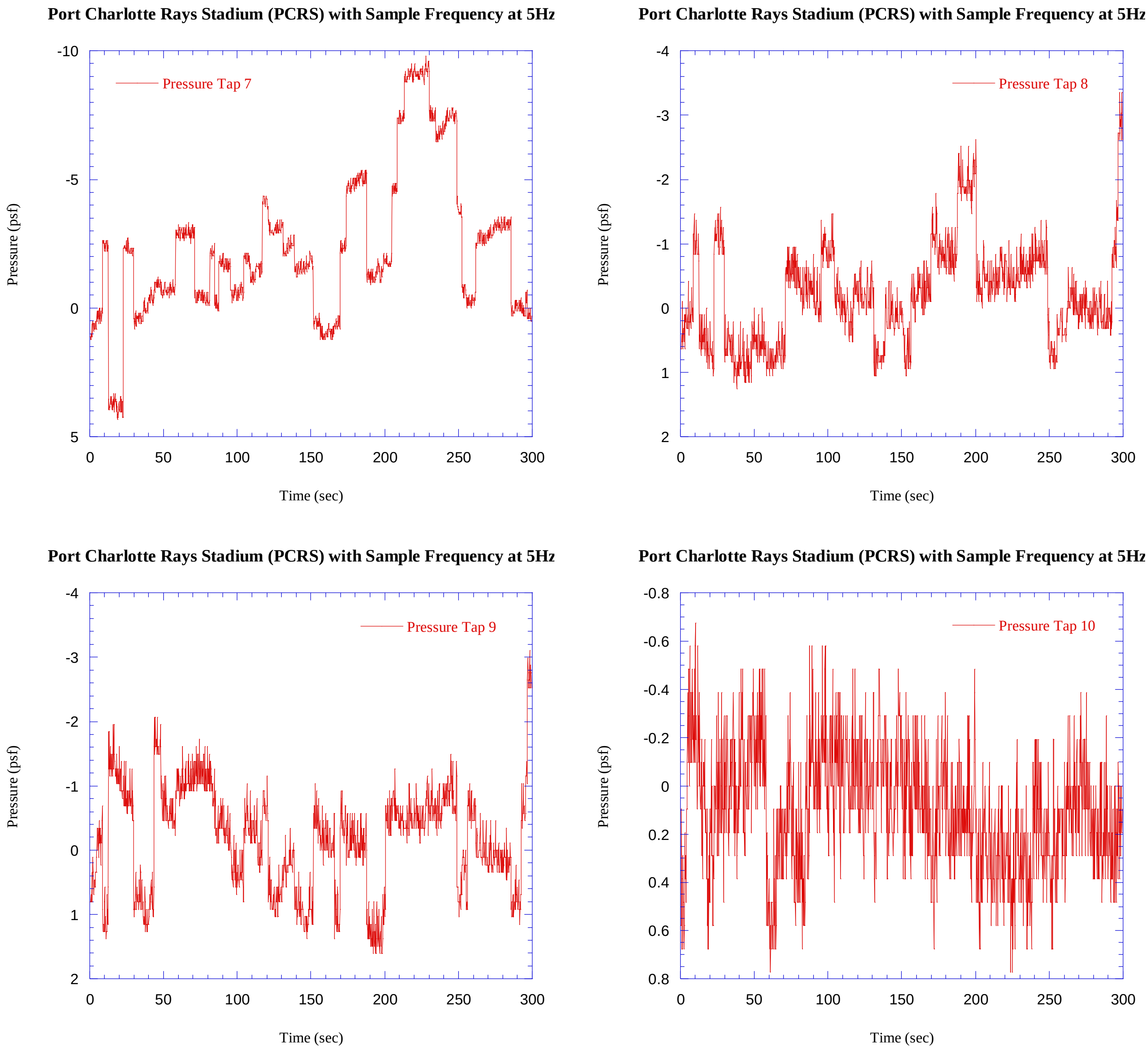


Figure 62: Spliced time histories for pressure tap 7 – pressure tap 10 at a sampling frequency of 5 Hz at Port Charlotte Rays Stadium

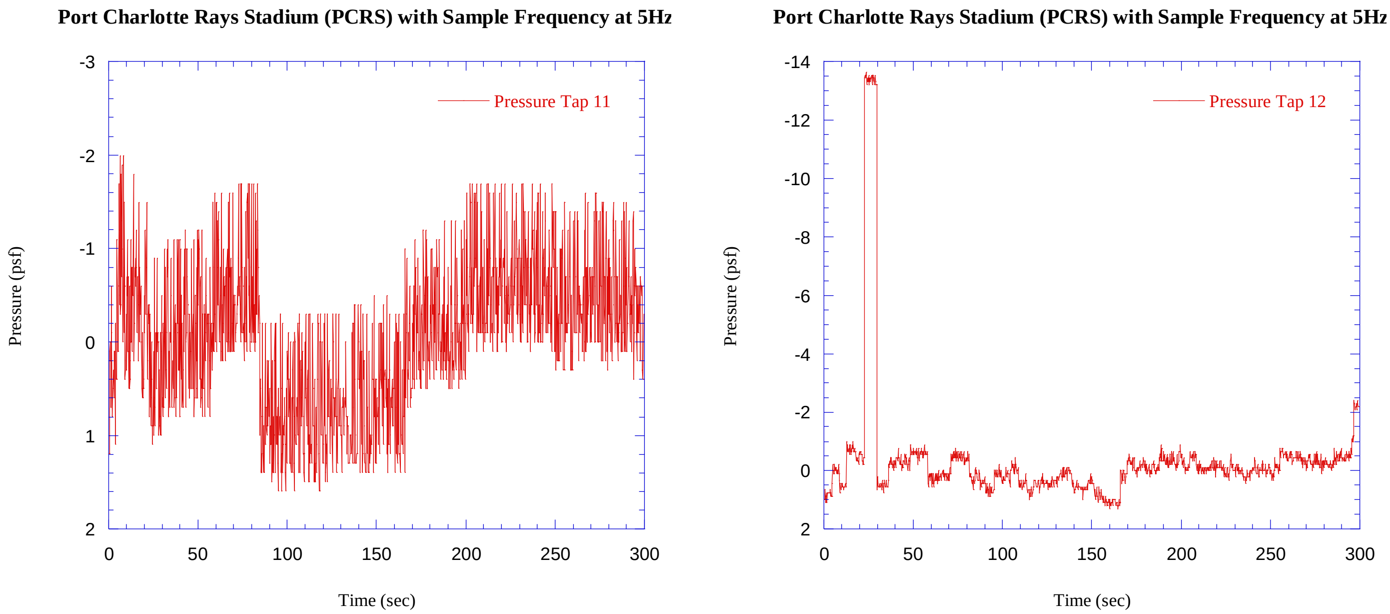


Figure 63: Spliced time histories for pressure tap 11 – pressure tap 14 at a sampling frequency of 5 Hz at Port Charlotte Rays Stadium

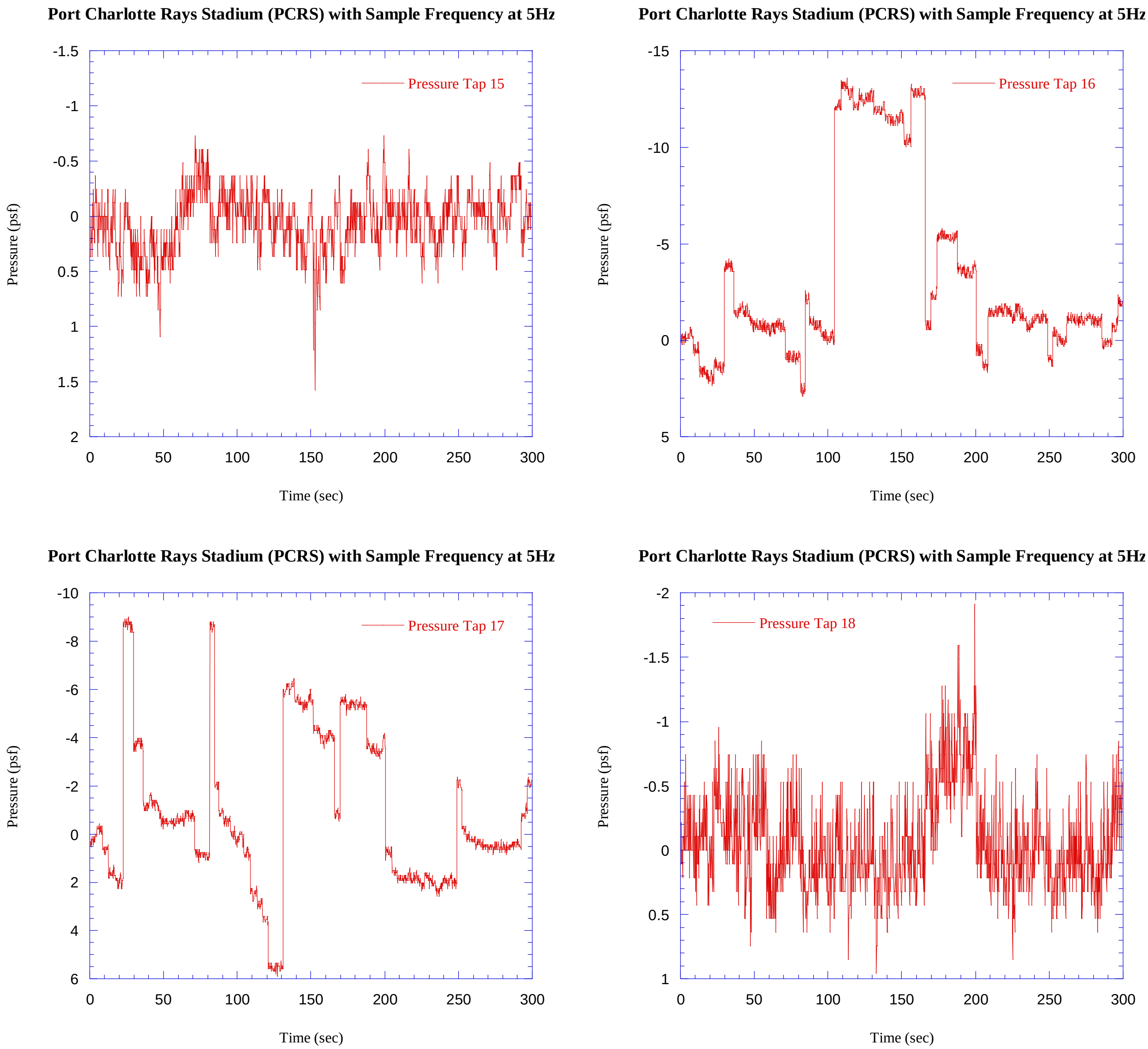


Figure 64: Spliced time histories for pressure tap 15 – pressure tap 18 at a sampling frequency of 5 Hz at Port Charlotte Rays Stadium

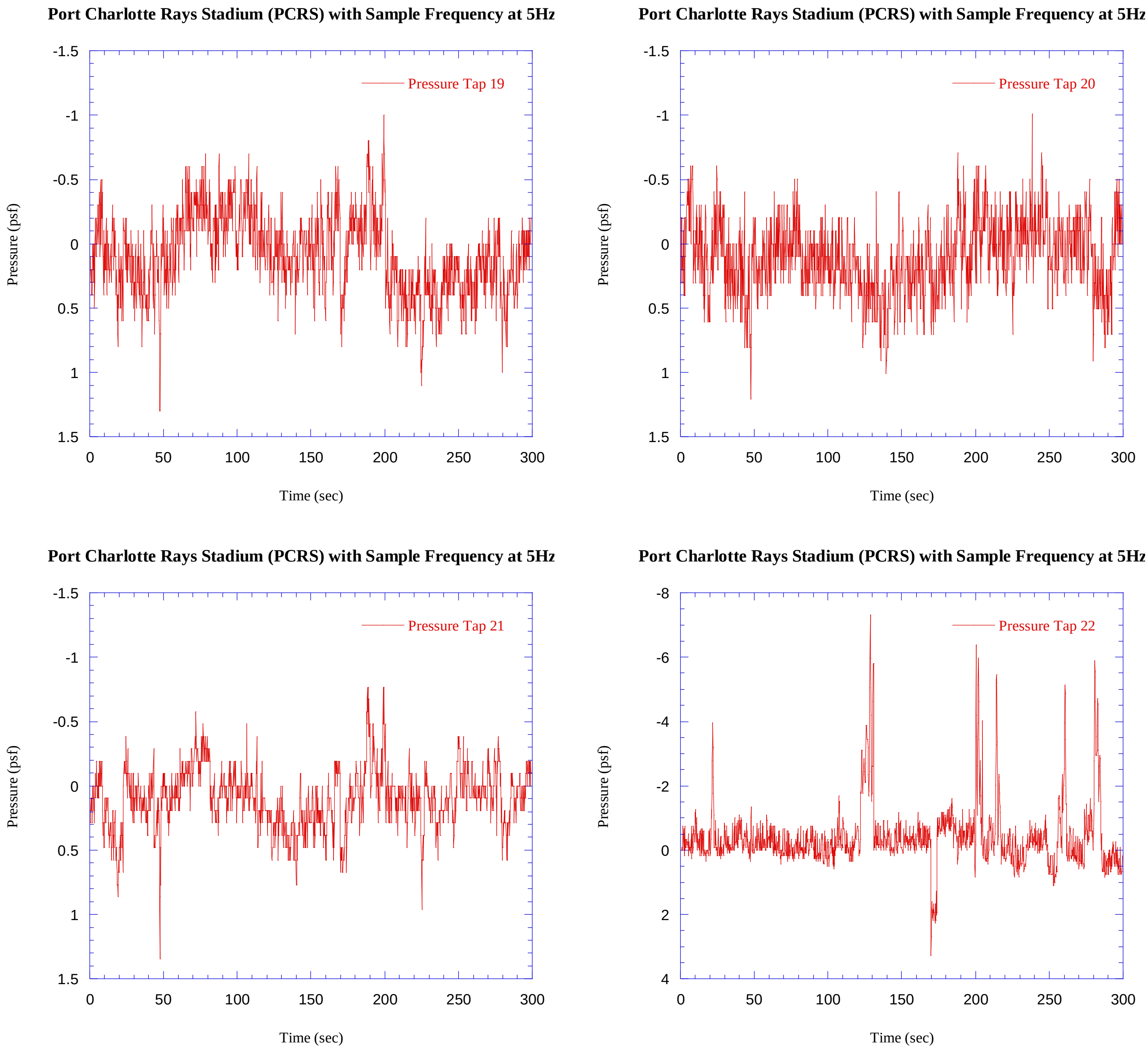


Figure 65: Spliced time histories for pressure tap 19 – pressure tap 22 at a sampling frequency of 5 Hz at Port Charlotte Rays Stadium

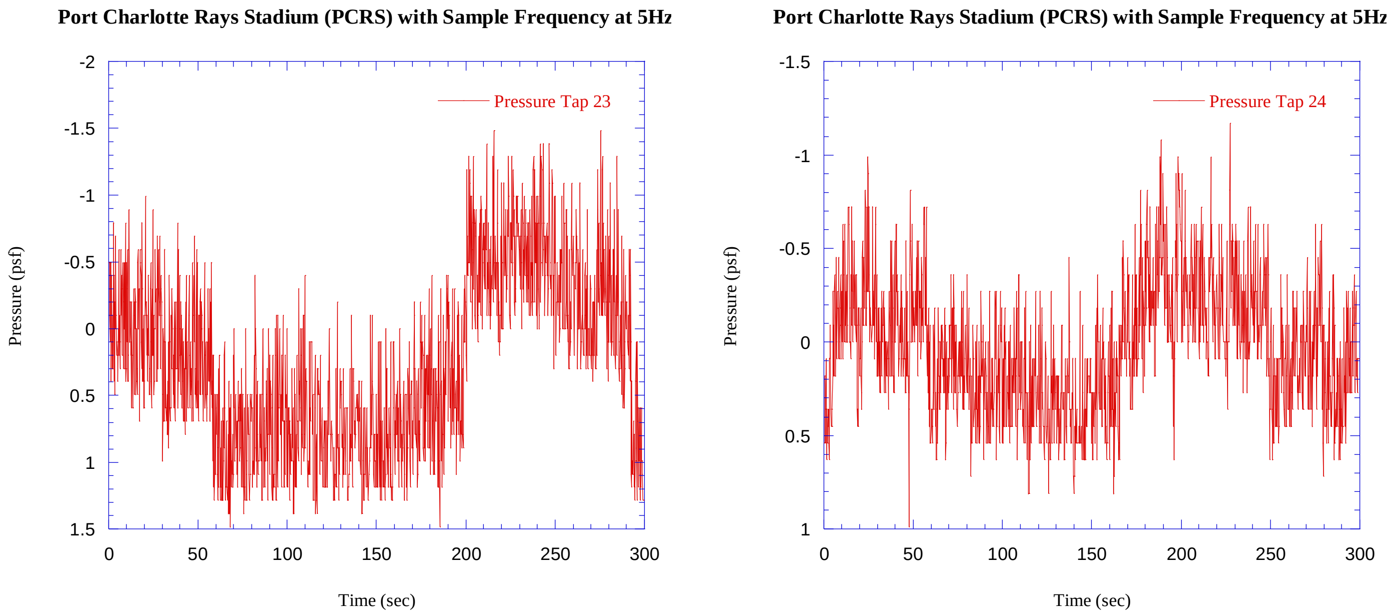
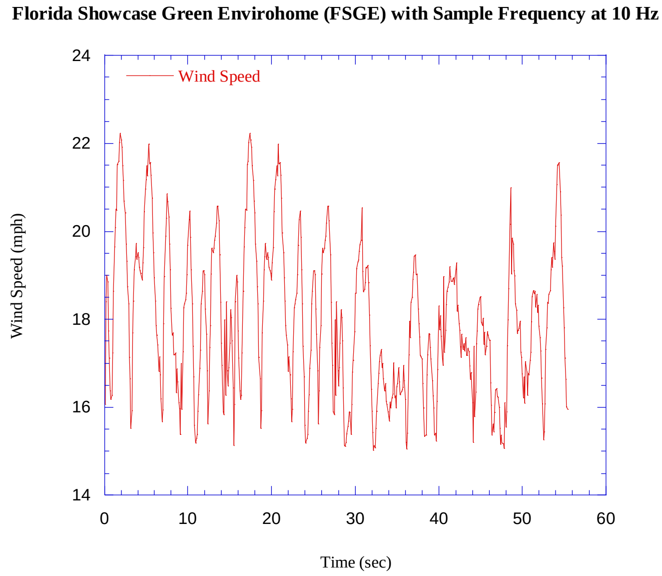
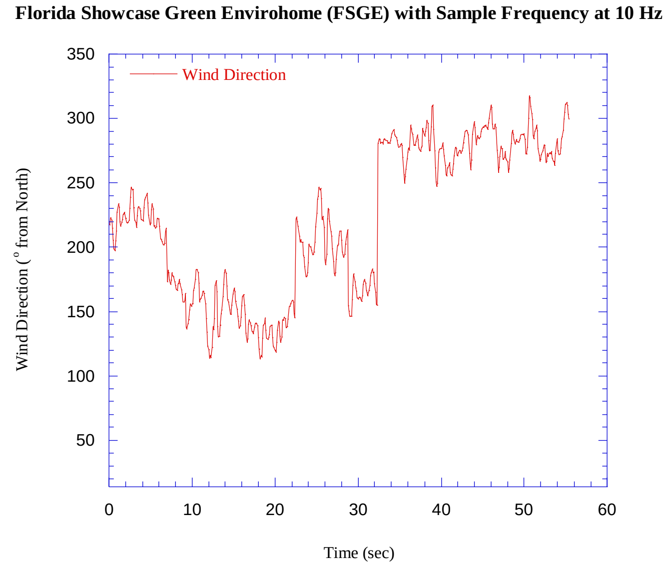


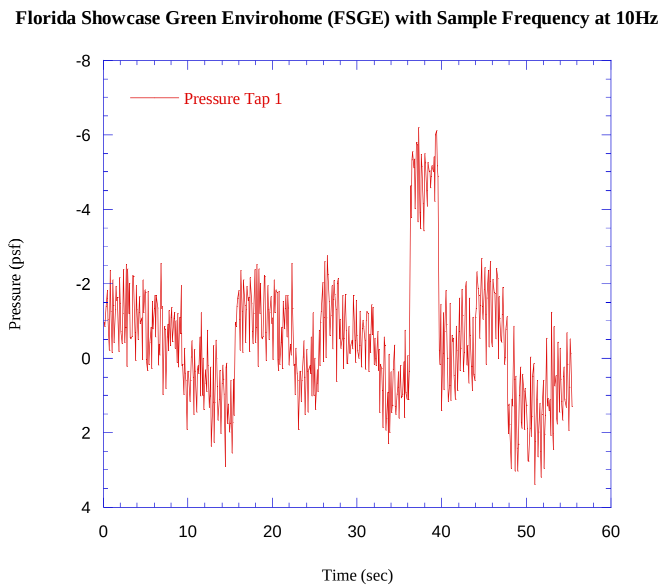
Figure 66: Spliced time histories for pressure tap 23 and pressure tap 24 at a sampling frequency of 5 Hz at Port Charlotte Rays Stadium

APPENDIX B: SAMPLING FREQUENCY AT 10 HZ

Florida Showcase Green Envirohome (FSGE) Raw Data at 10 Hz







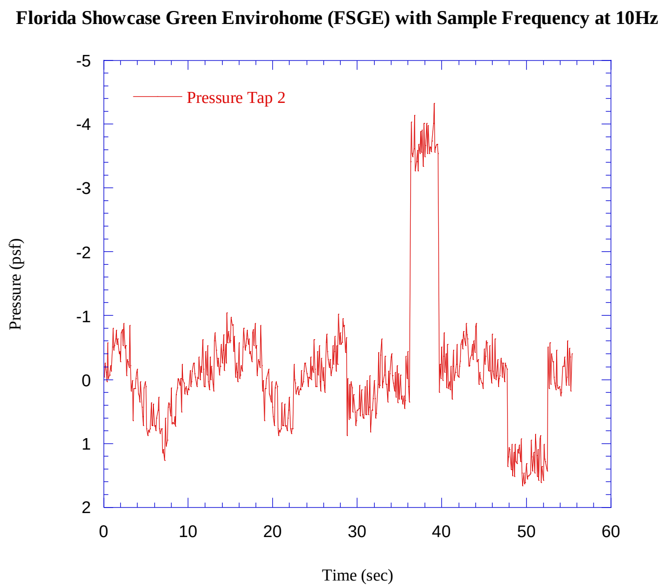
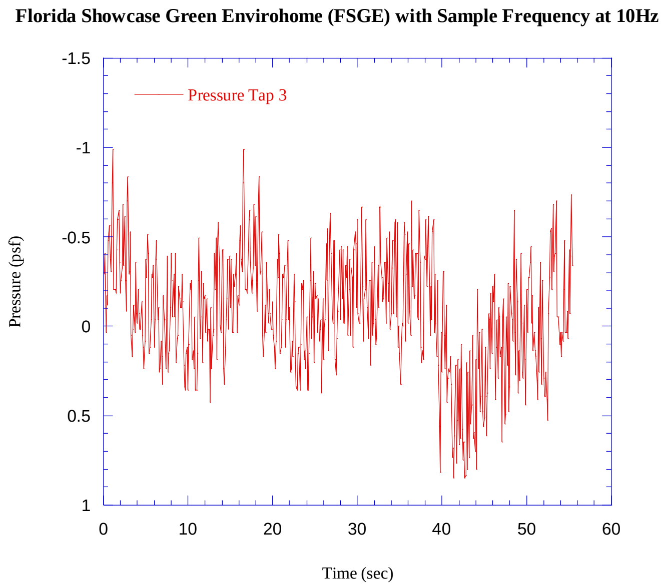
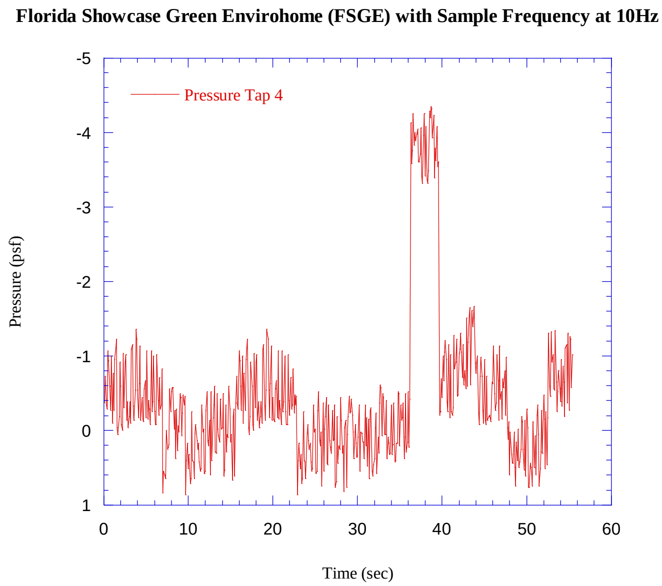
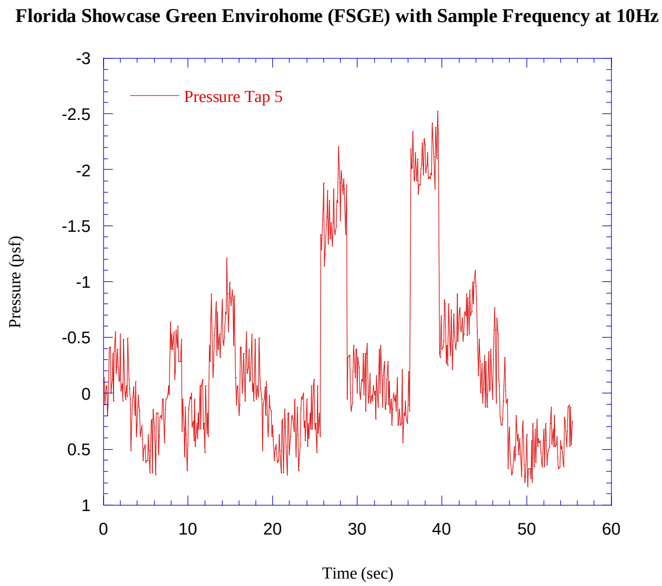


Figure 67: Spliced time histories for wind speed, wind direction, pressure tap 1 and pressure tap 2 at a sampling frequency of 10 Hz at Florida Showcase Green Envirohome







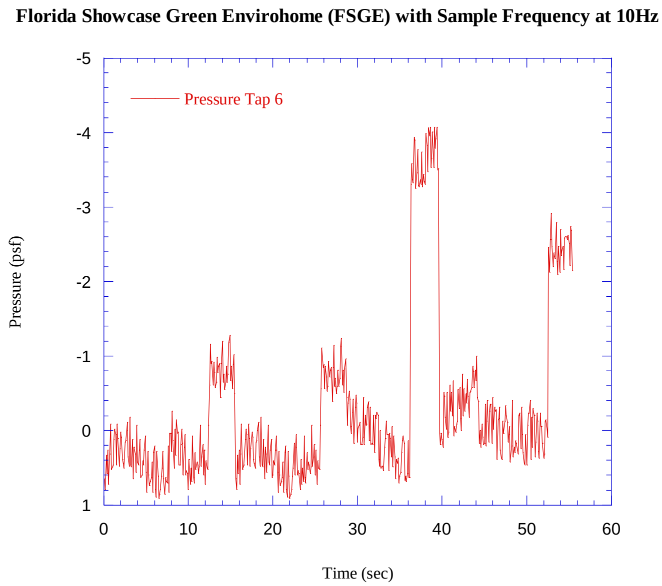
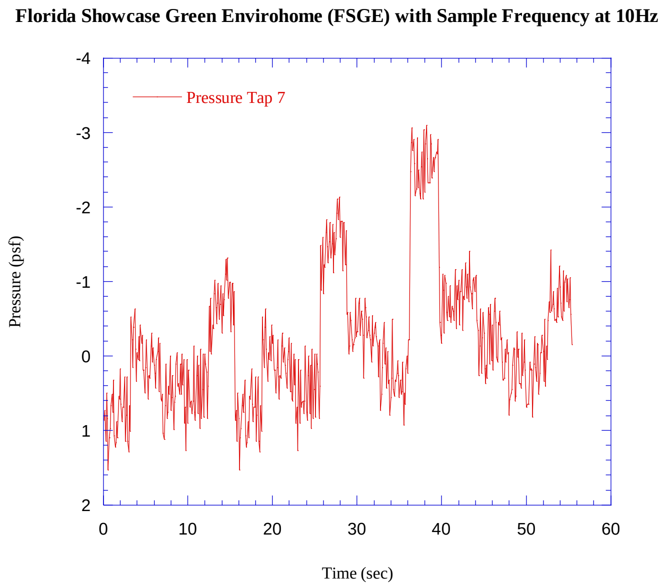
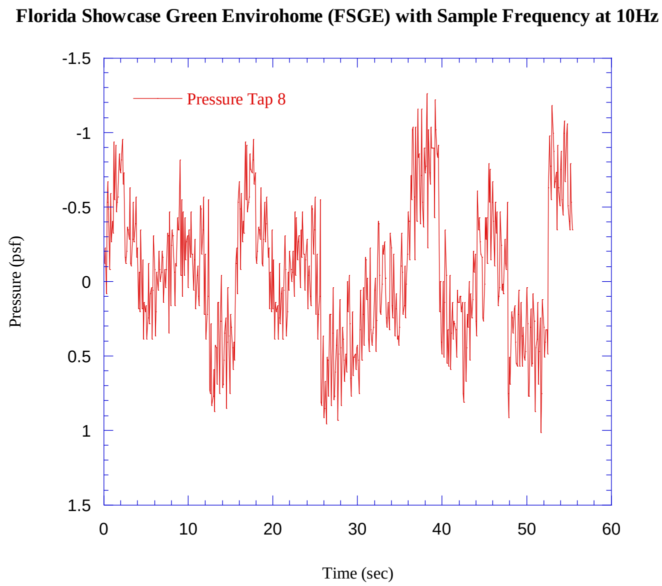
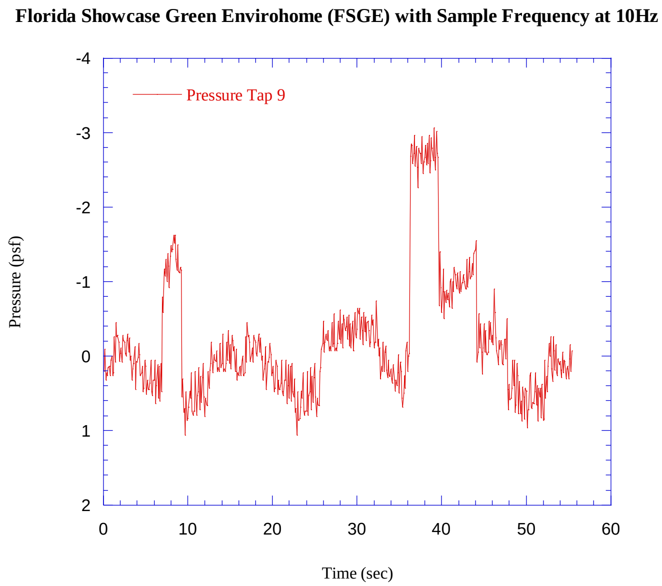


Figure 68: Spliced time histories for pressure tap 3 – pressure tap 6 at a sampling frequency of 10 Hz at Florida Showcase Green Envirohome







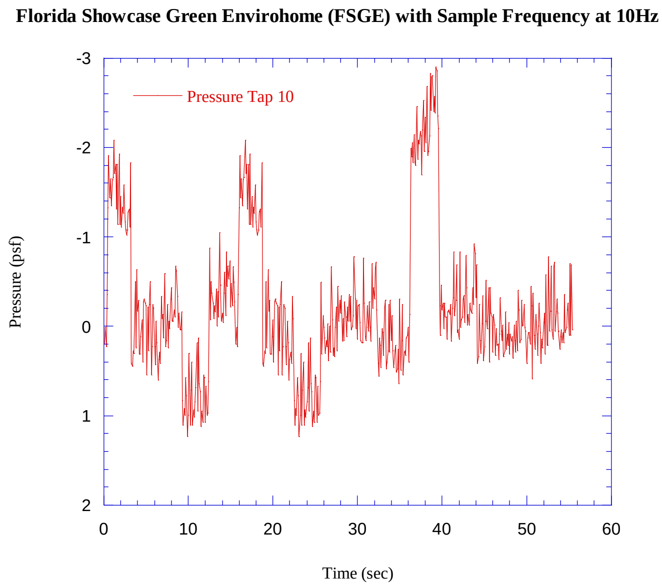
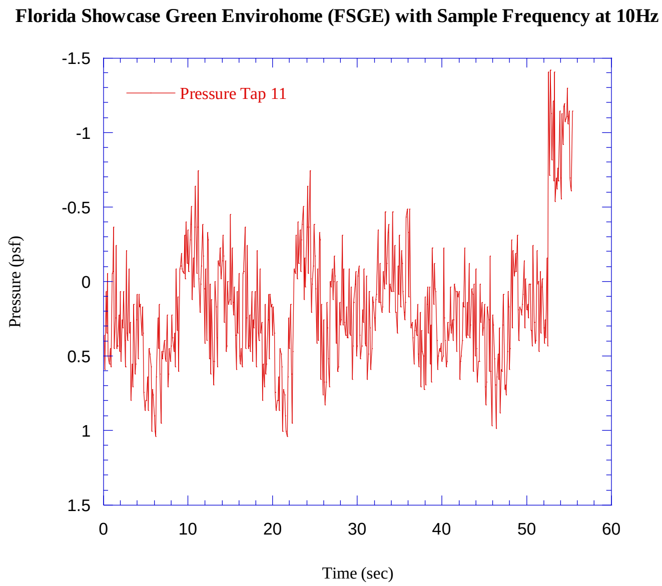


Figure 69: Spliced time histories for pressure tap 7 – pressure tap 10 at a sampling frequency of 10 Hz at Florida Showcase Green Envirohome



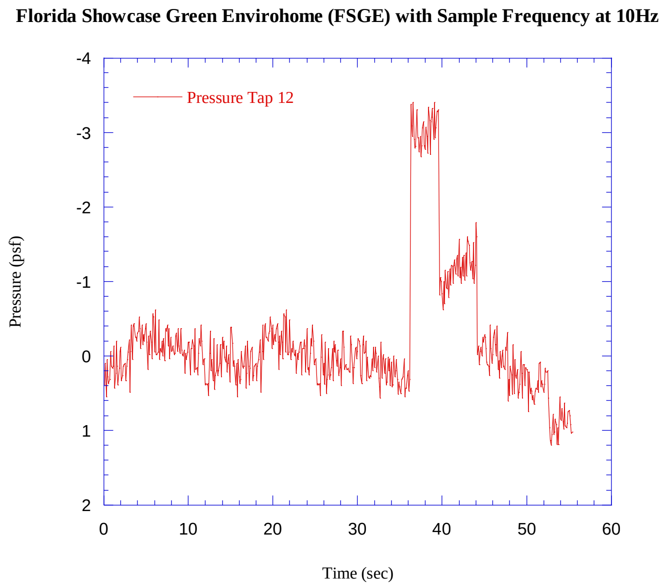
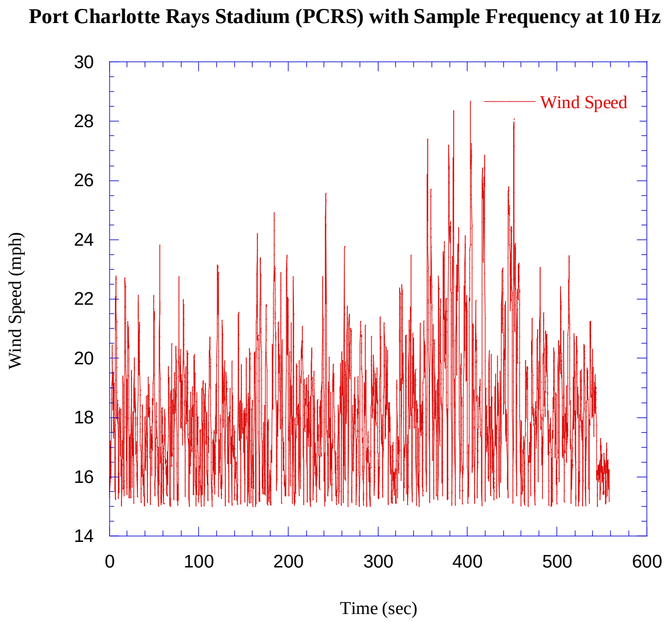
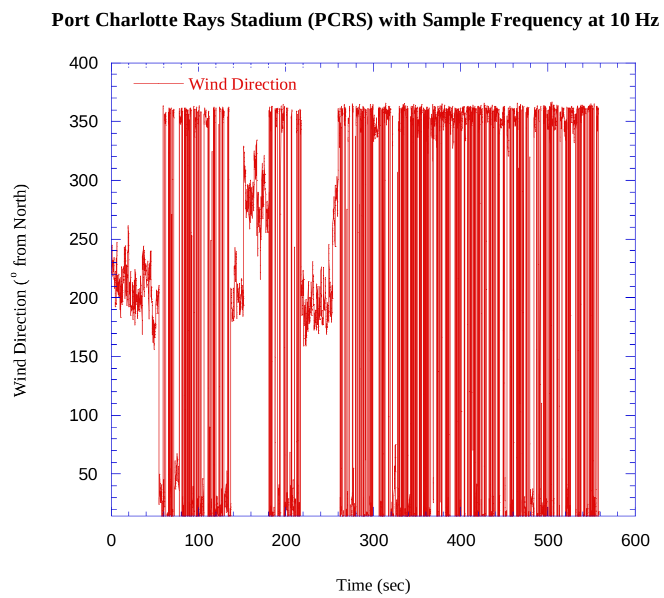
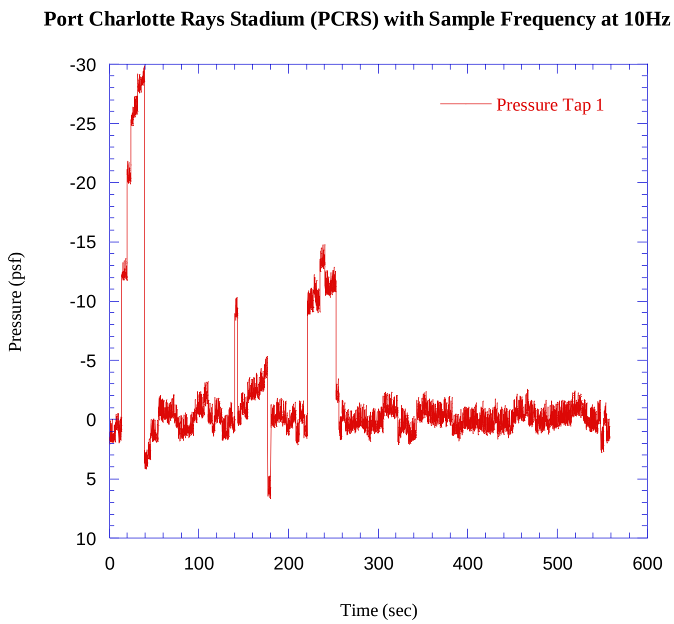


Figure 70: Spliced time histories for pressure tap 11 – pressure tap 12 at a sampling frequency of 10 Hz at Florida Showcase Green Envirohome

Port Charlotte Rays Stadium (PCRS) Raw Data at 10 Hz







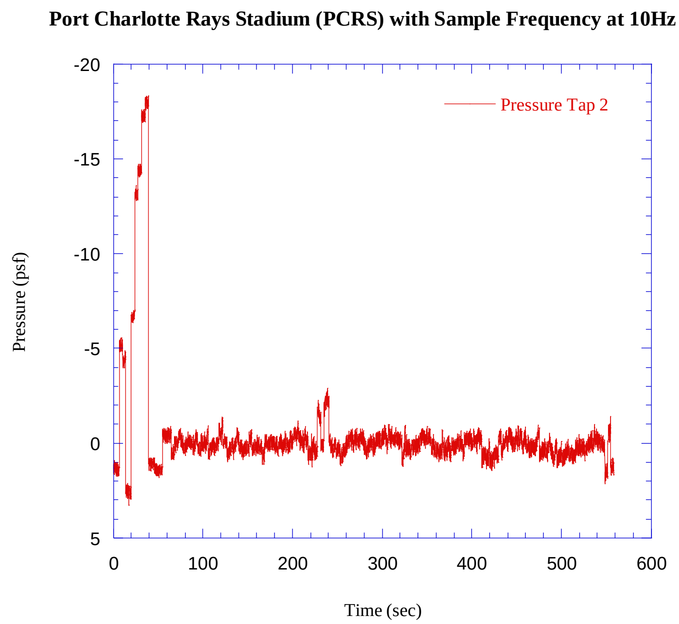


Figure 71: Spliced time histories for wind speed, wind direction, pressure tap 1 and pressure tap 2 at a sampling frequency of 10 Hz at Port Charlotte Rays Stadium

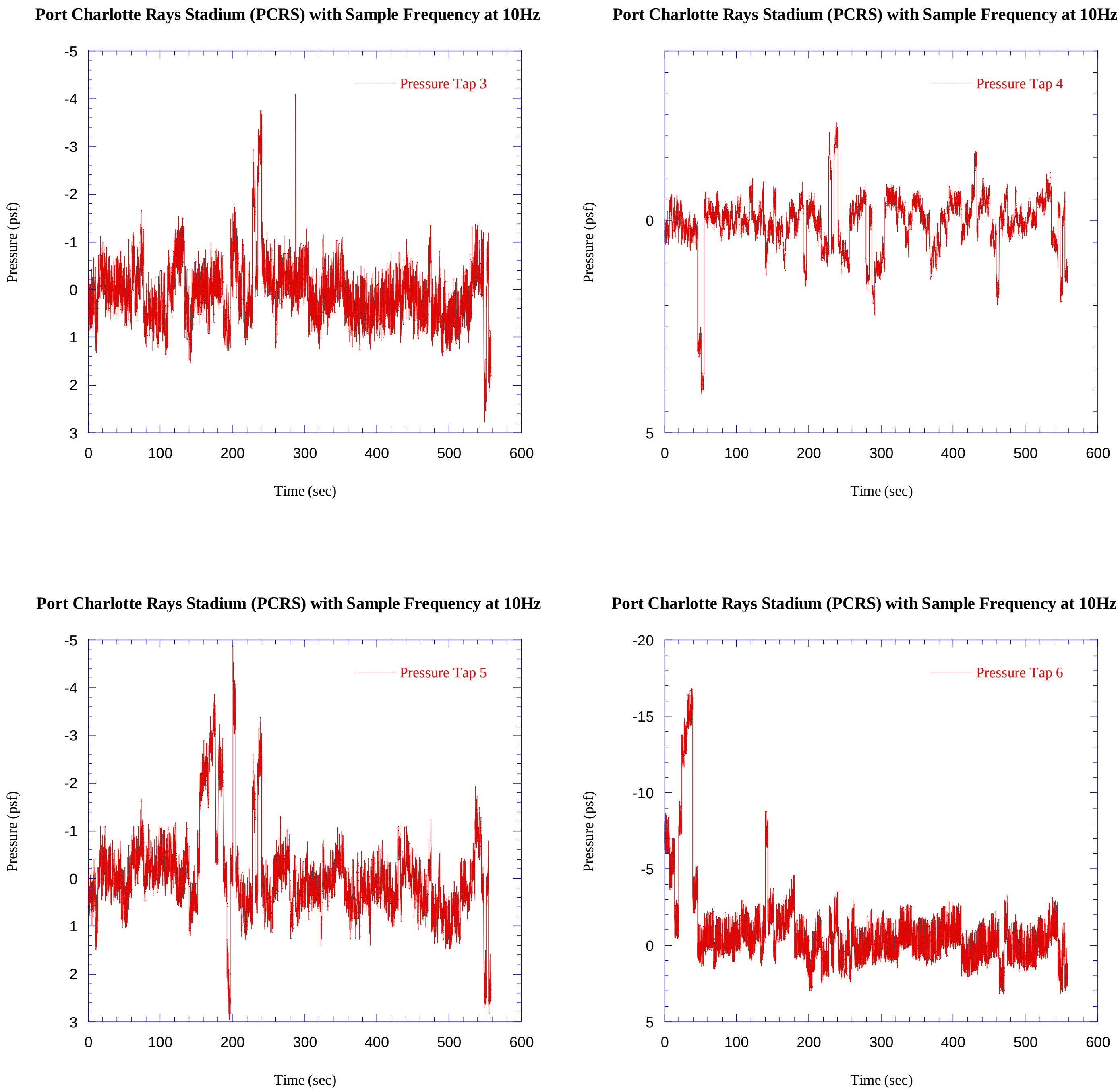


Figure 72: Spliced time histories for pressure tap 3 – pressure tap 6 at a sampling frequency of 10 Hz at Port Charlotte Rays Stadium

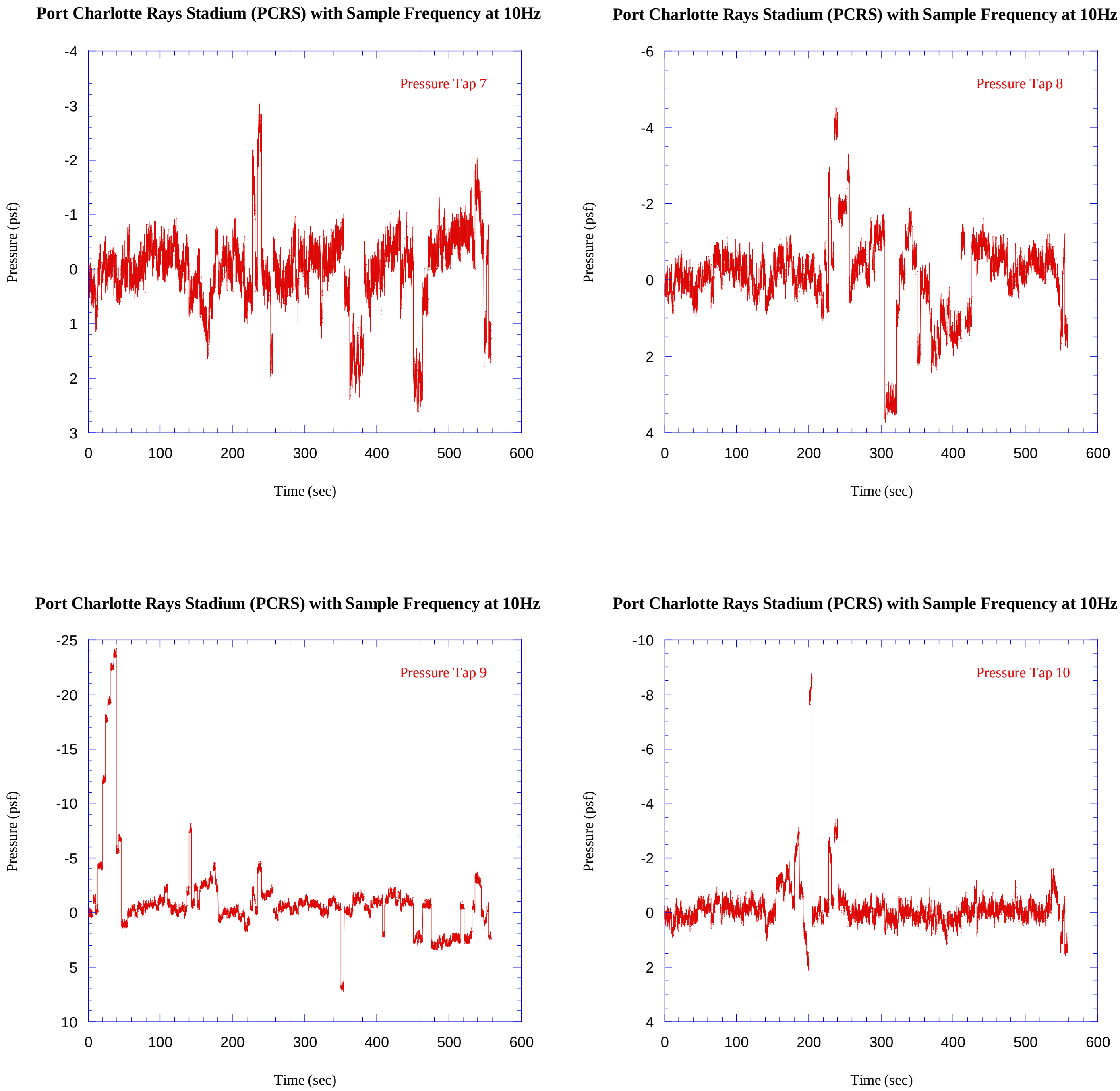


Figure 73: Spliced time histories for pressure tap 7 – pressure tap 10 at a sampling frequency of 10 Hz at Port Charlotte Rays Stadium

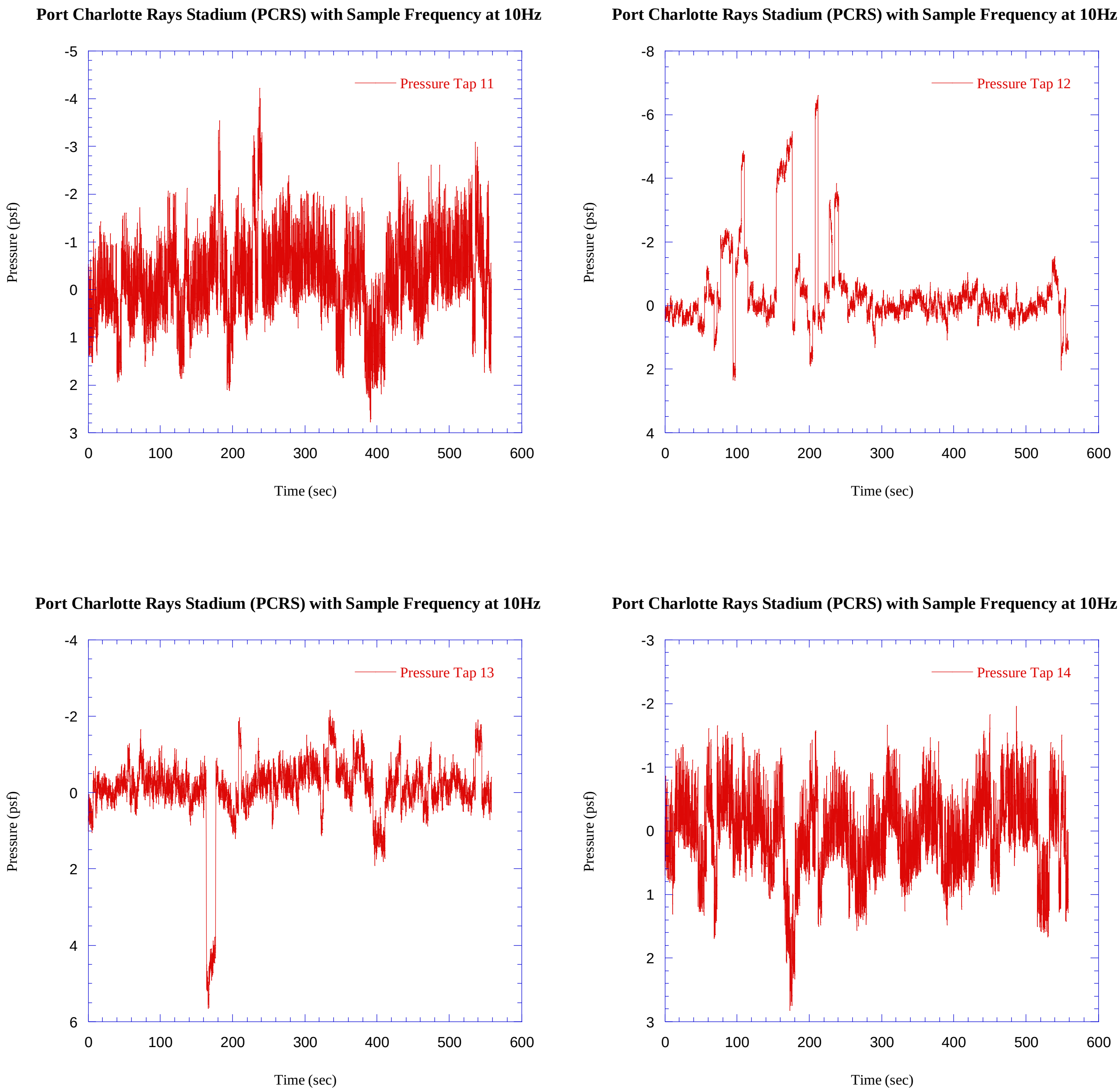


Figure 74: Spliced time histories for pressure tap 11 – pressure tap 14 at a sampling frequency of 10 Hz at Port Charlotte Rays Stadium

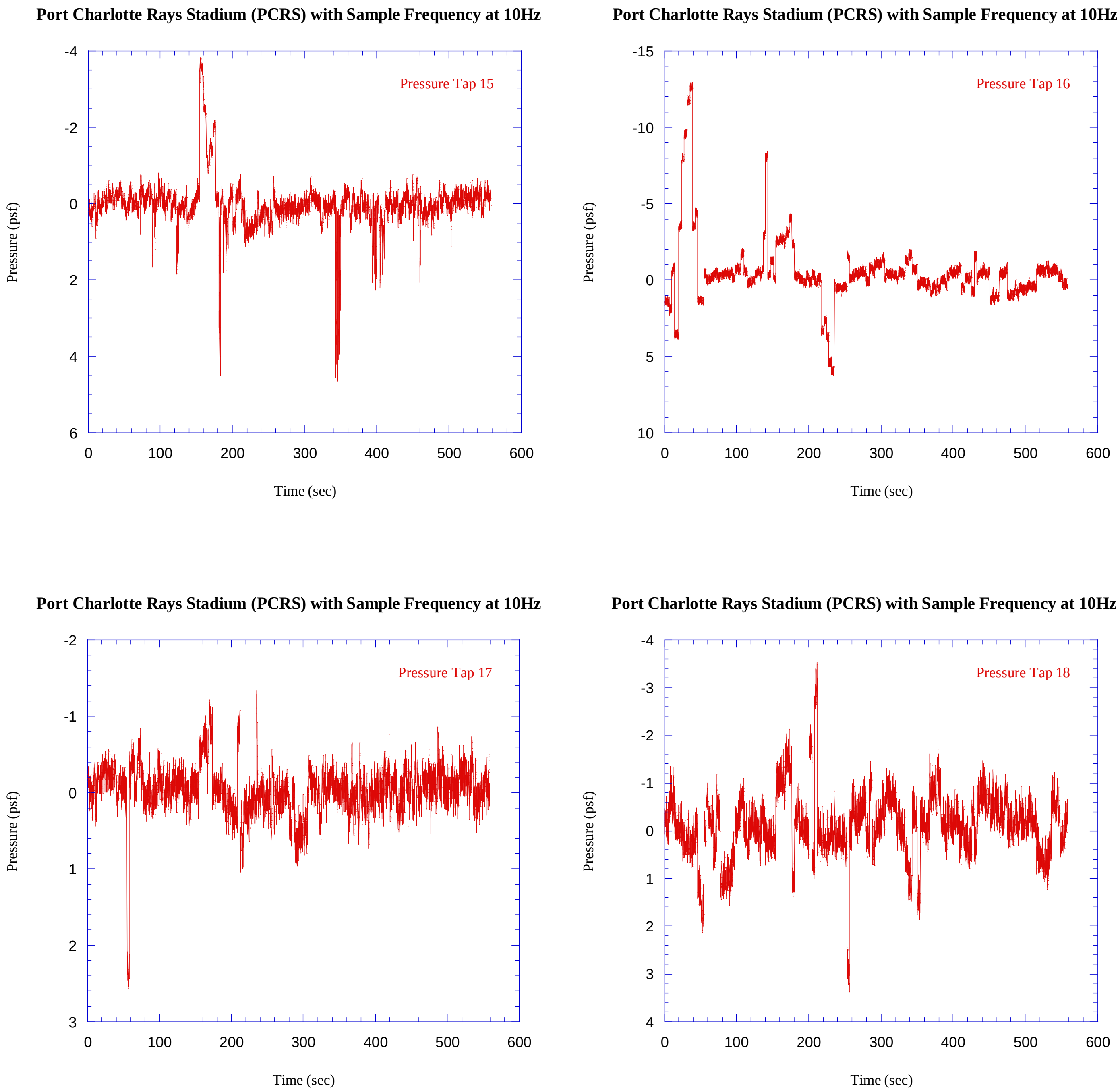


Figure 75: Spliced time histories for pressure tap 15 – pressure tap 18 at a sampling frequency of 10 Hz at Port Charlotte Rays Stadium

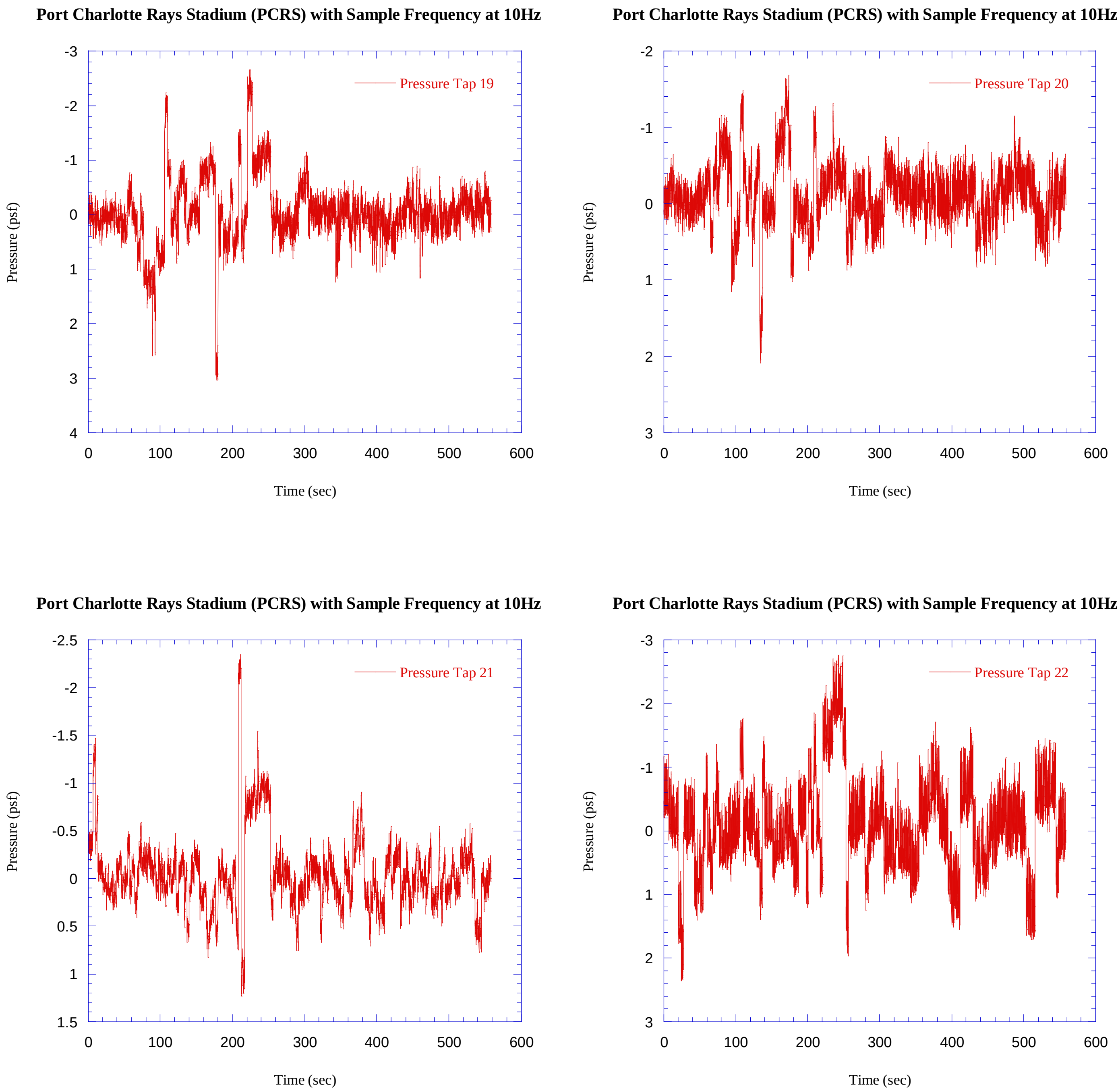
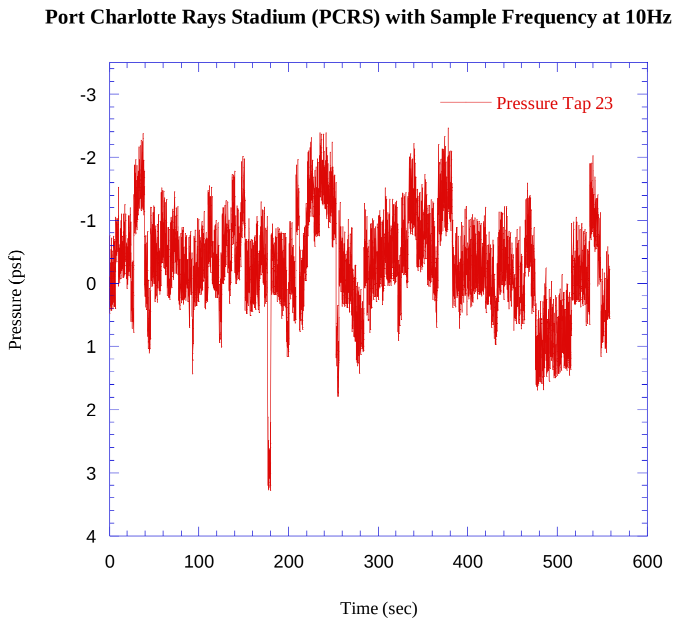


Figure 76: Spliced time histories for pressure tap 19 – pressure tap 22 at a sampling frequency of 10 Hz at Port Charlotte Rays Stadium



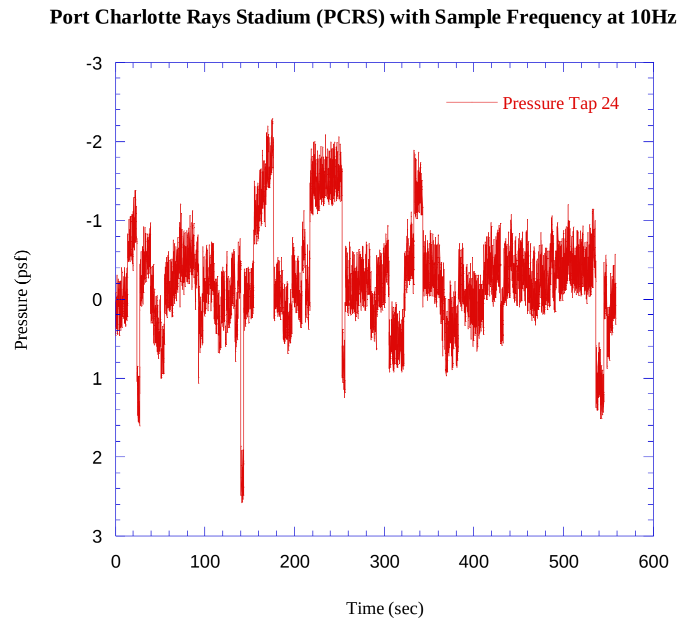


Figure 77: Spliced time histories for pressure tap 23 and pressure tap 24 at a sampling frequency of 10 Hz at Port Charlotte Rays Stadium

APPENDIX C: PRESSURE COEFFICIENTS

Florida Showcase Green Envirohome (FSGE) Pressure Coefficients

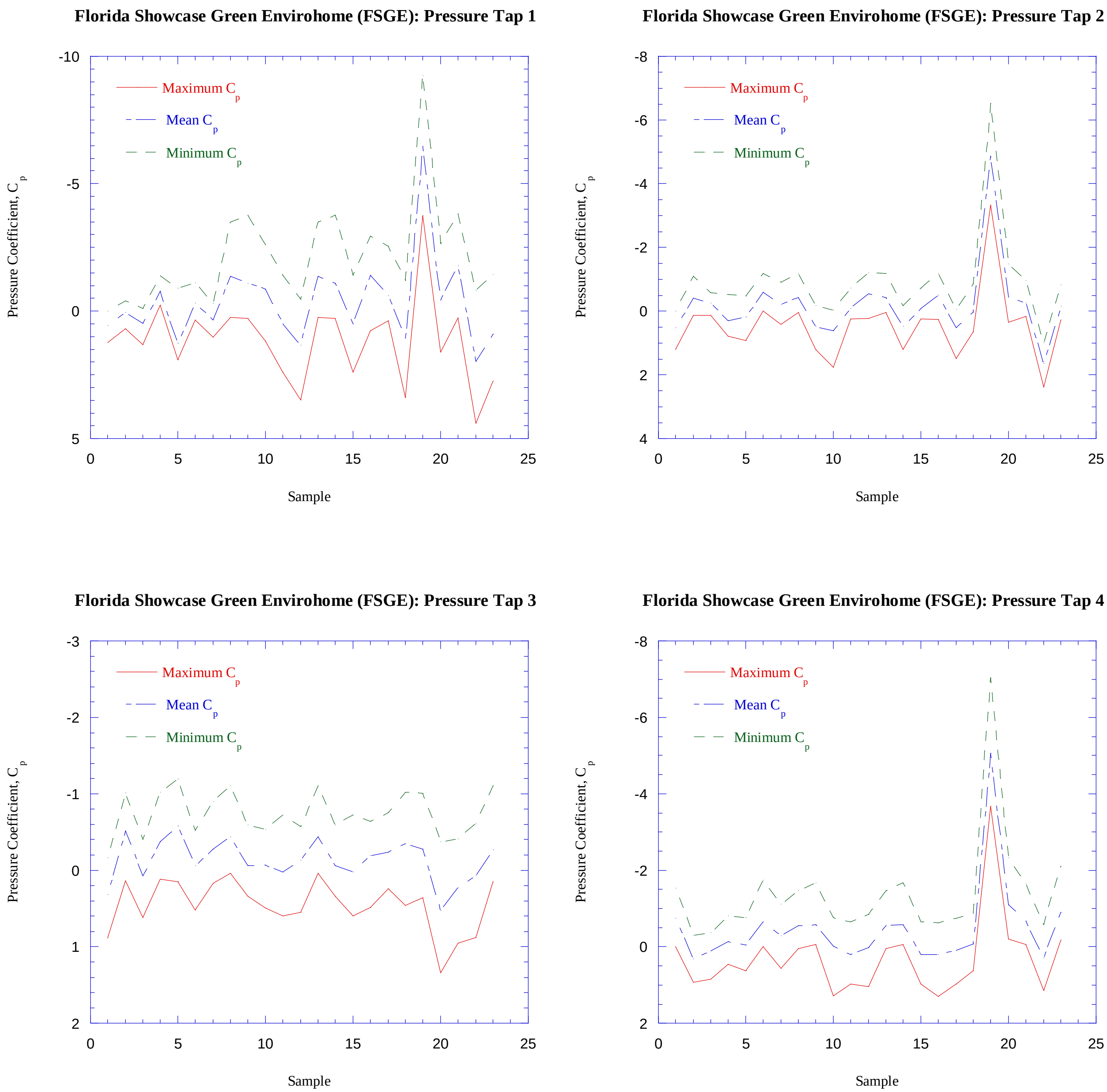


Figure 78: Florida Showcase Green Envirohome (FSGE) maximum, minimum, and mean pressure coefficients per pressure tap for pressure tap 1 – pressure tap 4

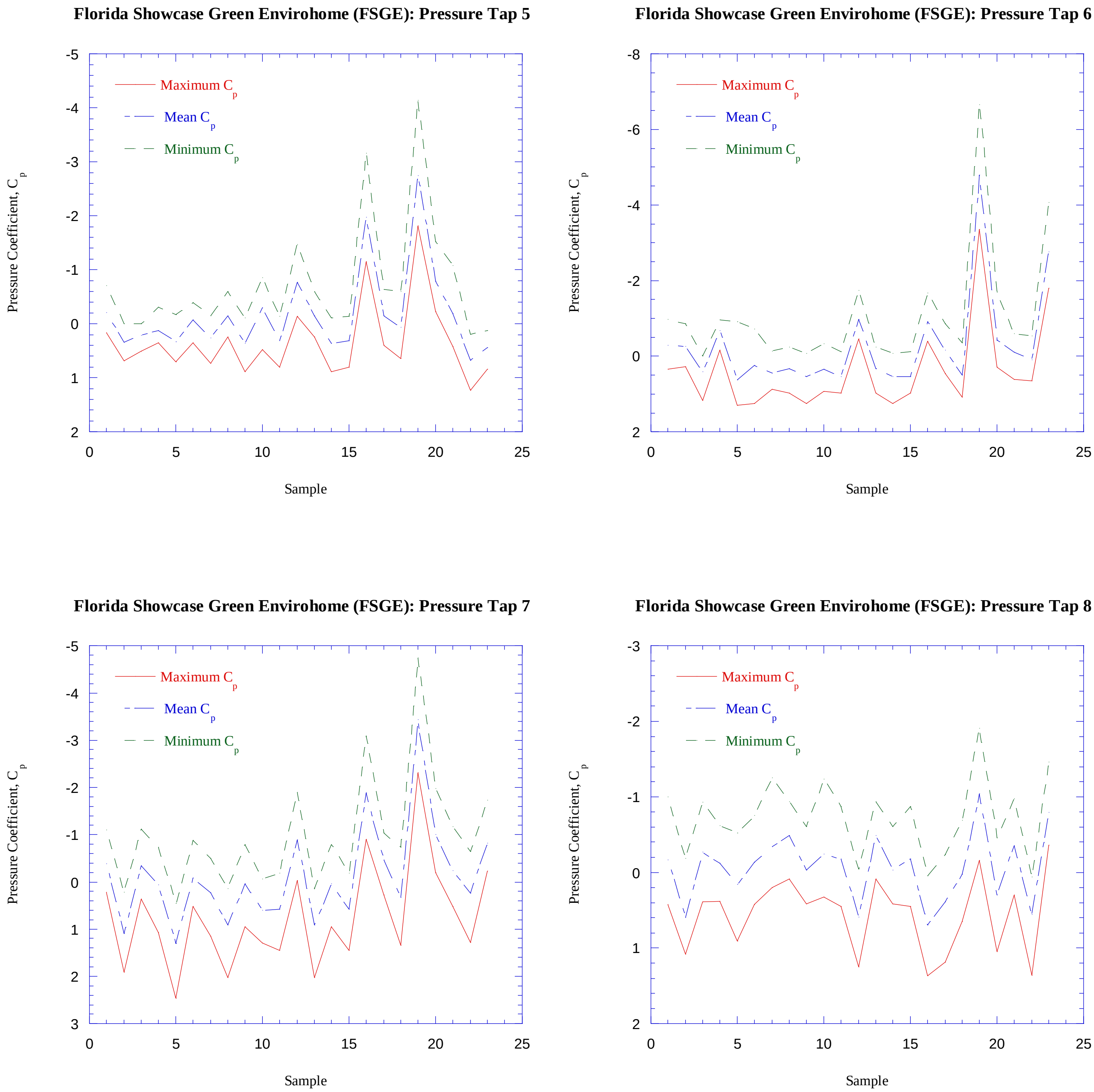


Figure 79: Florida Showcase Green Envirohome (FSGE) maximum, minimum, and mean pressure coefficients per pressure tap for pressure tap 5 – pressure tap 8

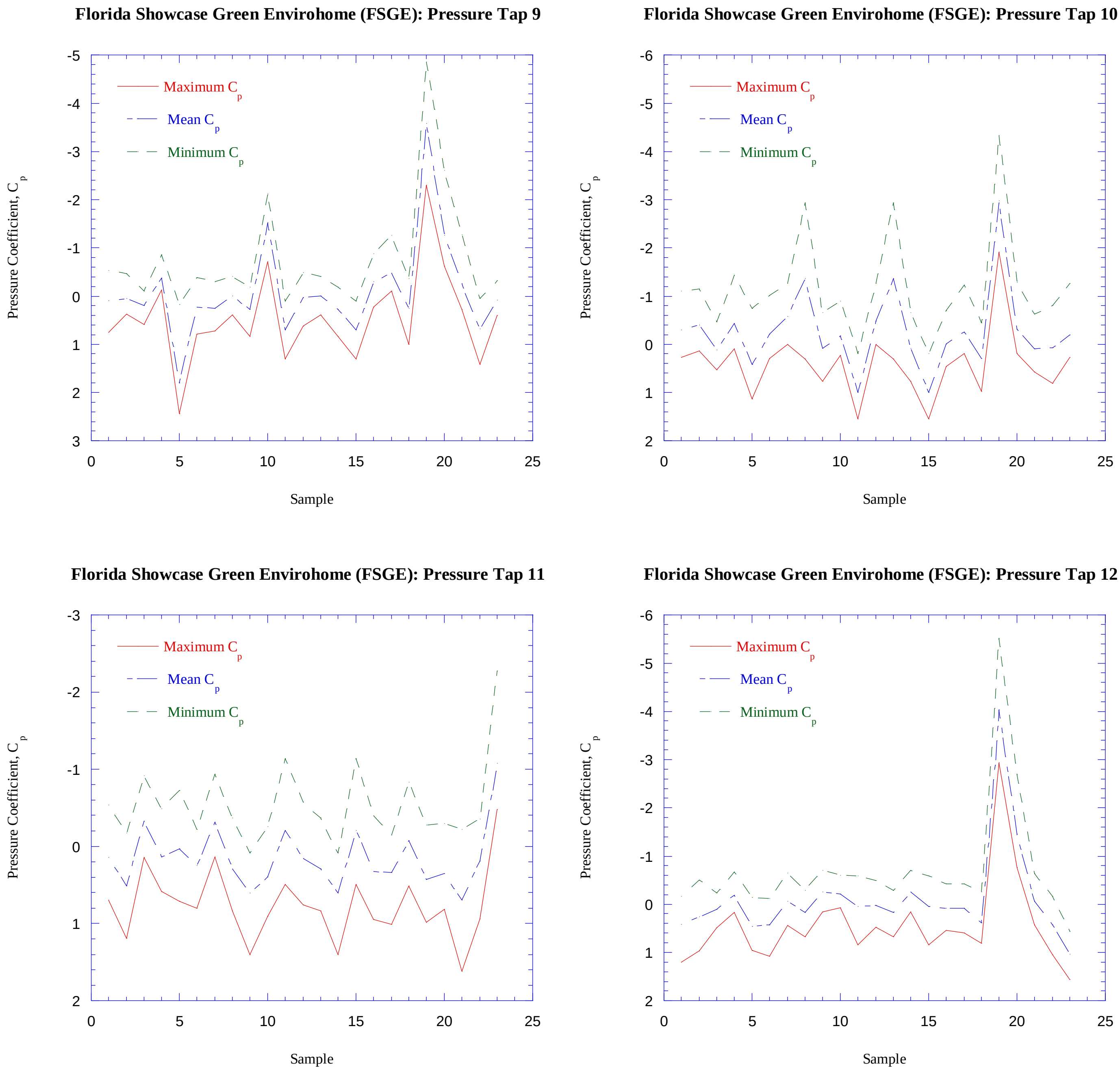


Figure 80: Florida Showcase Green Envirohome (FSGE) maximum, minimum, and mean pressure coefficients per pressure tap for pressure tap 9 – pressure tap 12

<u>Port Charlotte Rays Stadium (PCRS) Pressure Coefficients</u>

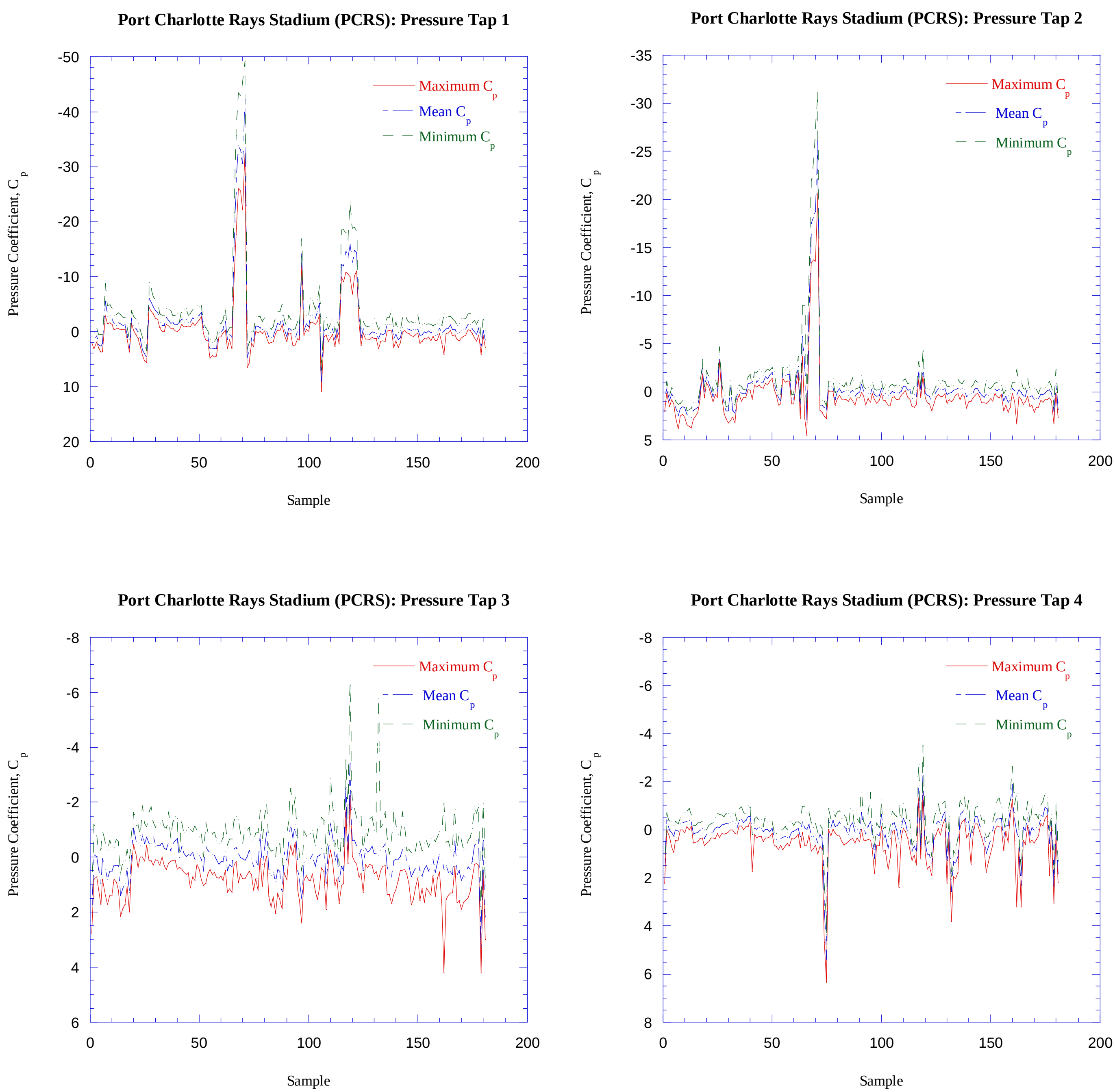


Figure 81: Port Charlotte Rays Stadium (PCRS) maximum, minimum, and mean pressure coefficients per pressure tap for pressure tap 1 – pressure tap 4

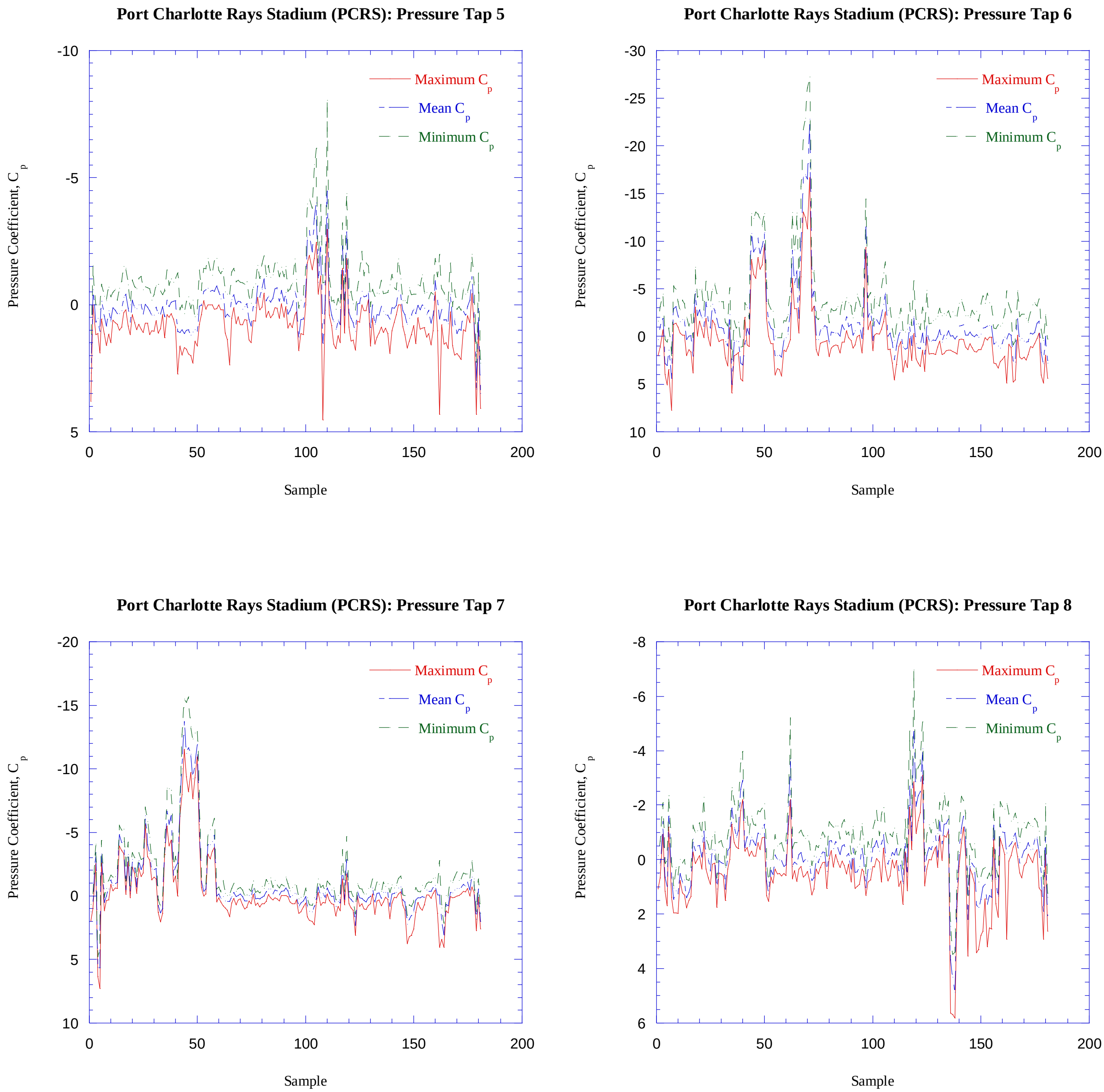
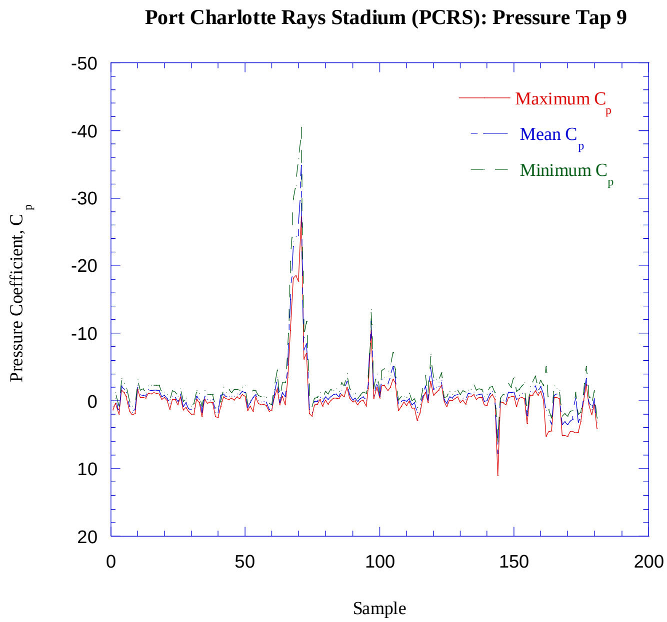
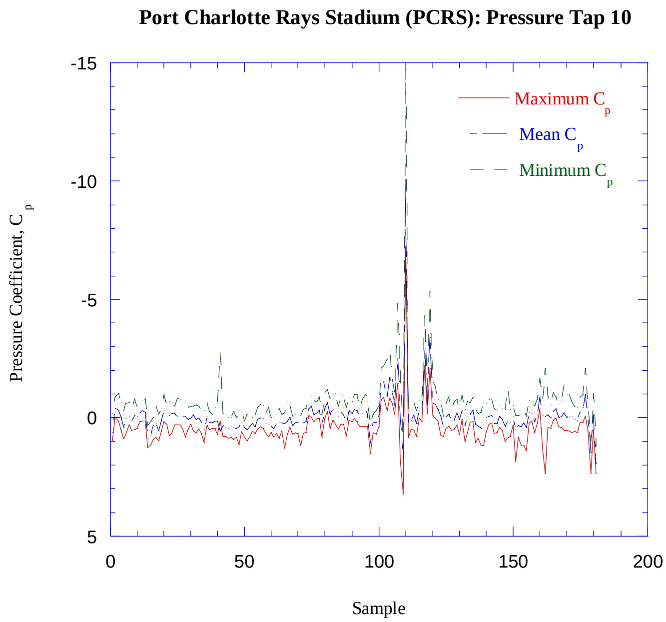
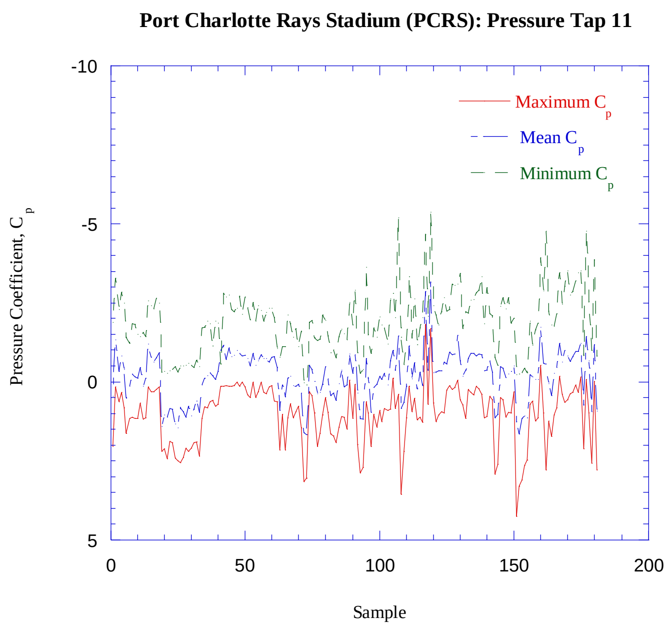


Figure 82: Port Charlotte Rays Stadium (PCRS) maximum, minimum, and mean pressure coefficients per pressure tap for pressure tap 5 – pressure tap 8







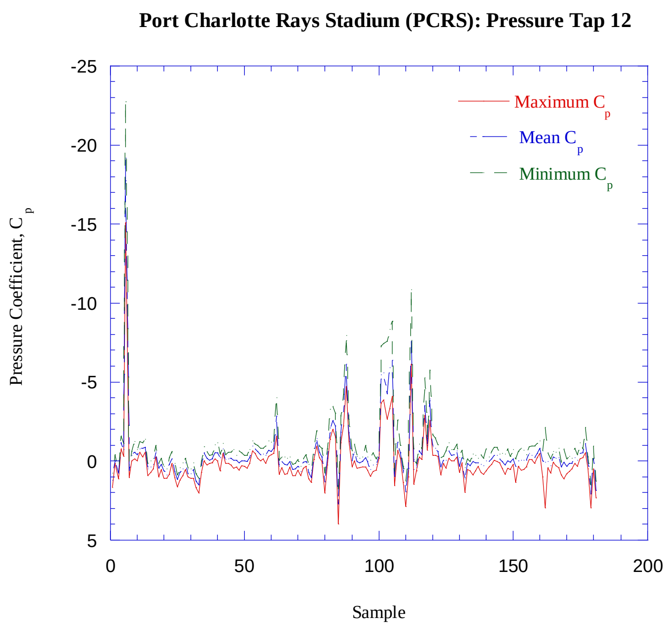


Figure 83: Port Charlotte Rays Stadium (PCRS) maximum, minimum, and mean pressure coefficients per pressure tap for pressure tap 9 – pressure tap 12

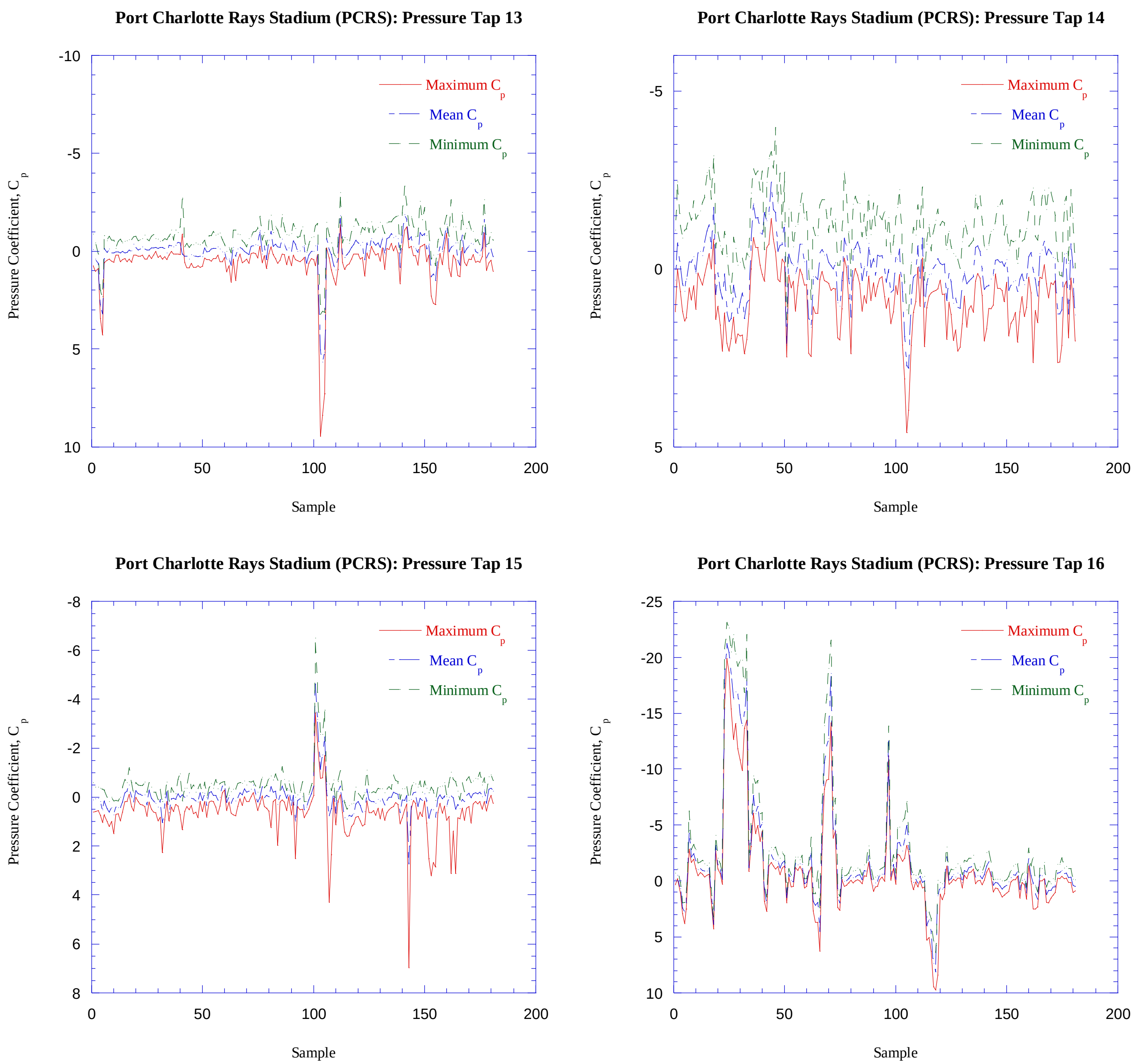


Figure 84: Port Charlotte Rays Stadium (PCRS) maximum, minimum, and mean pressure coefficients per pressure tap for pressure tap 13 – pressure tap 16

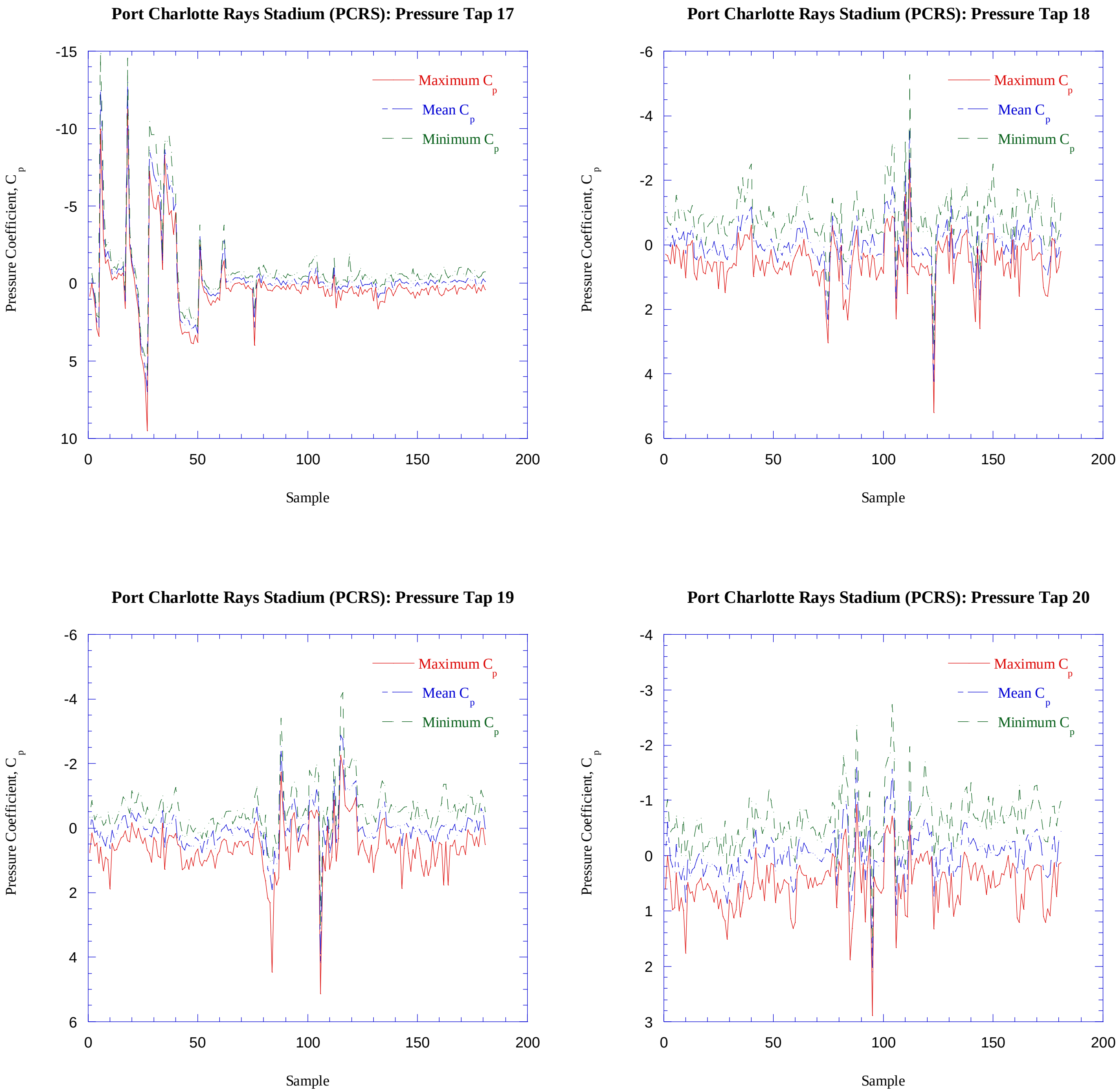


Figure 85: Port Charlotte Rays Stadium (PCRS) maximum, minimum, and mean pressure coefficients per pressure tap for pressure tap 17 – pressure tap 20

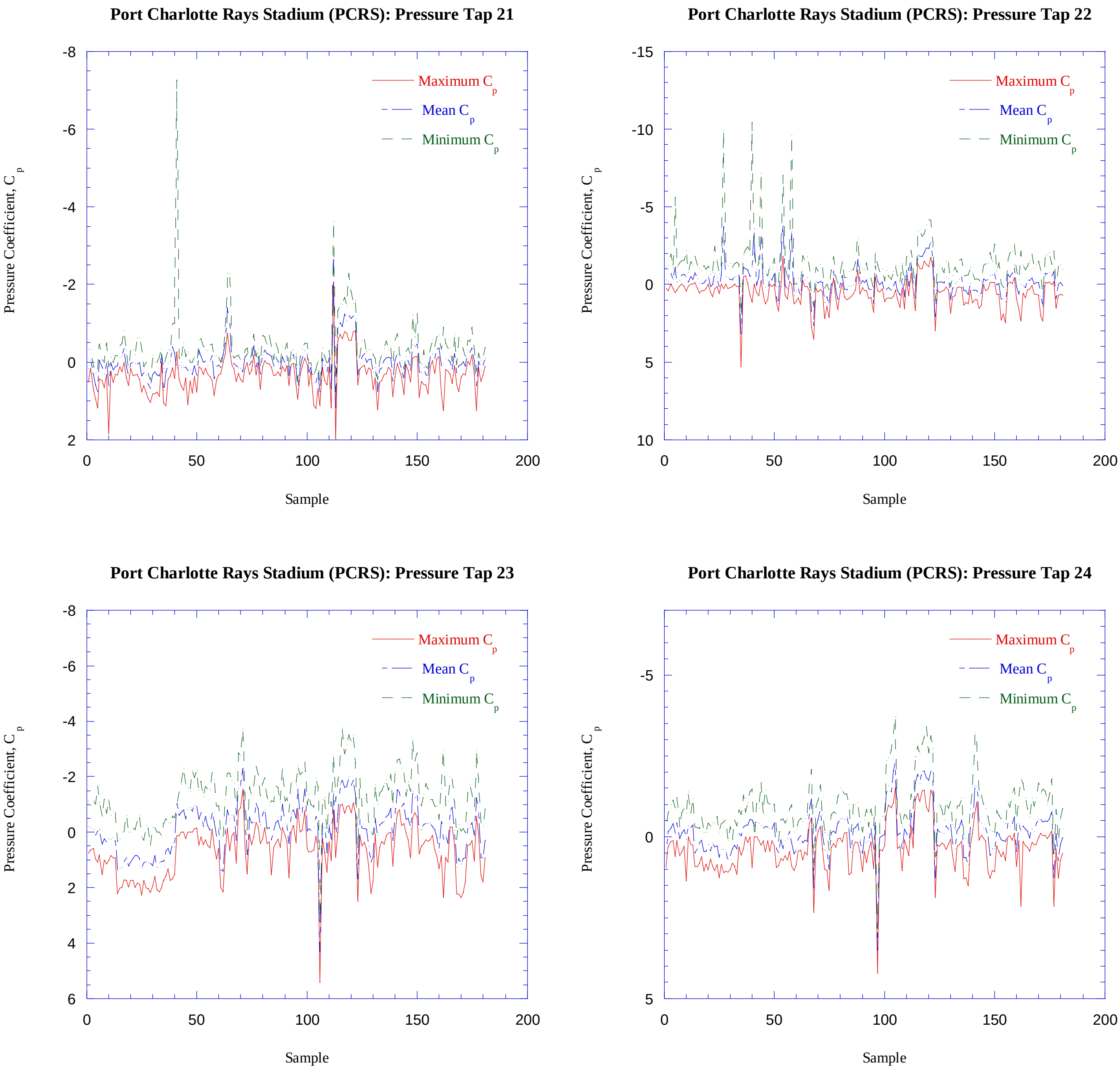
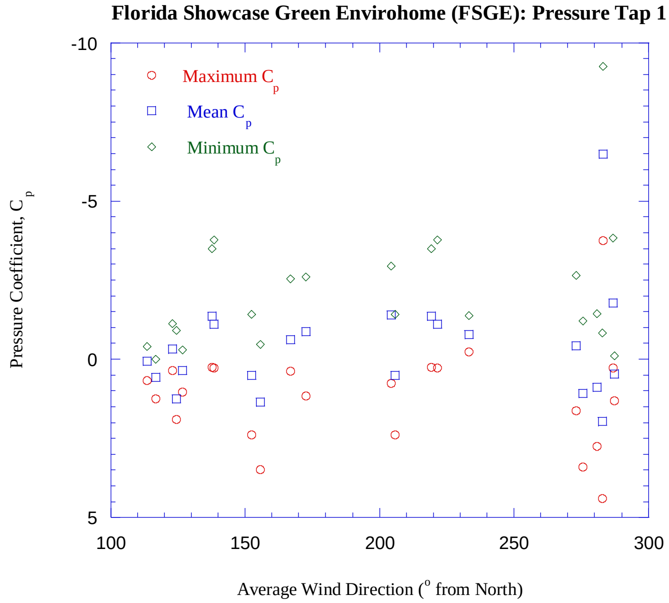
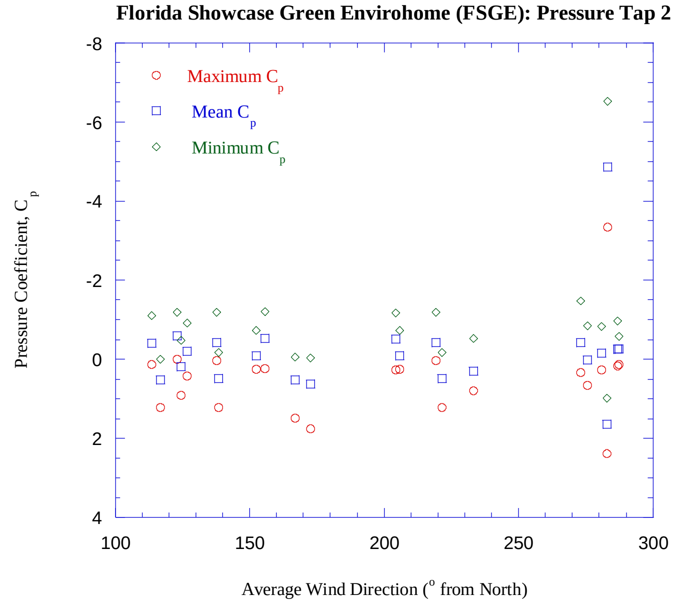


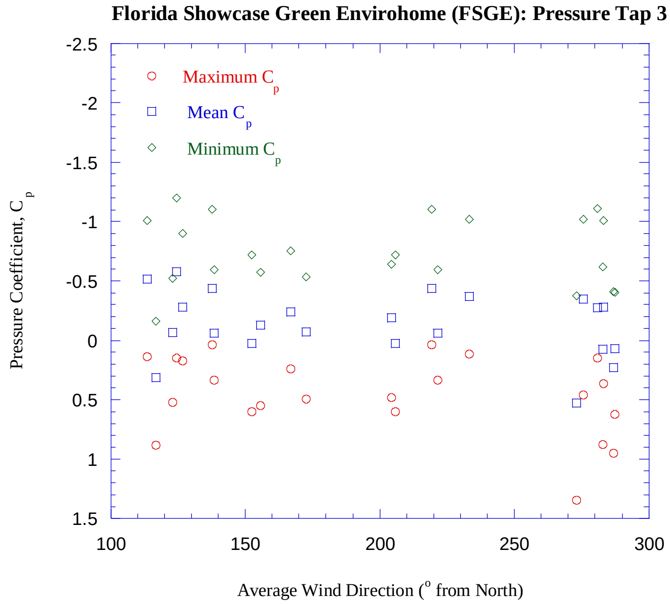
Figure 86: Port Charlotte Rays Stadium (PCRS) maximum, minimum, and mean pressure coefficients per pressure tap for pressure tap 21 – pressure tap 24

APPENDIX D: PRESSURE COEFFICENTS VS. WIND DIRECTION

Florida Showcase Green Envirohome (FSGE) Pressure Coefficients vs. Wind Direction







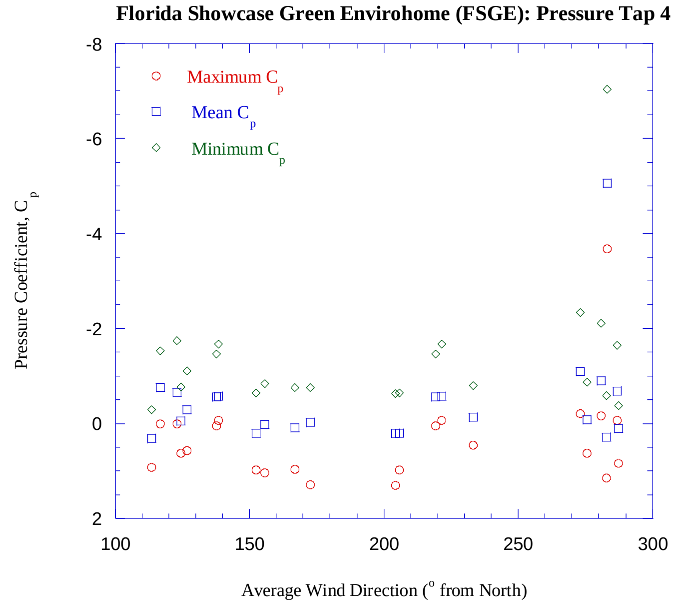


Figure 87: Minimum and maximum pressure coefficients measured at Florida Showcase Green Envirohome vs. average wind direction (0 ° from the North) for pressure tap 1 – pressure tap 4

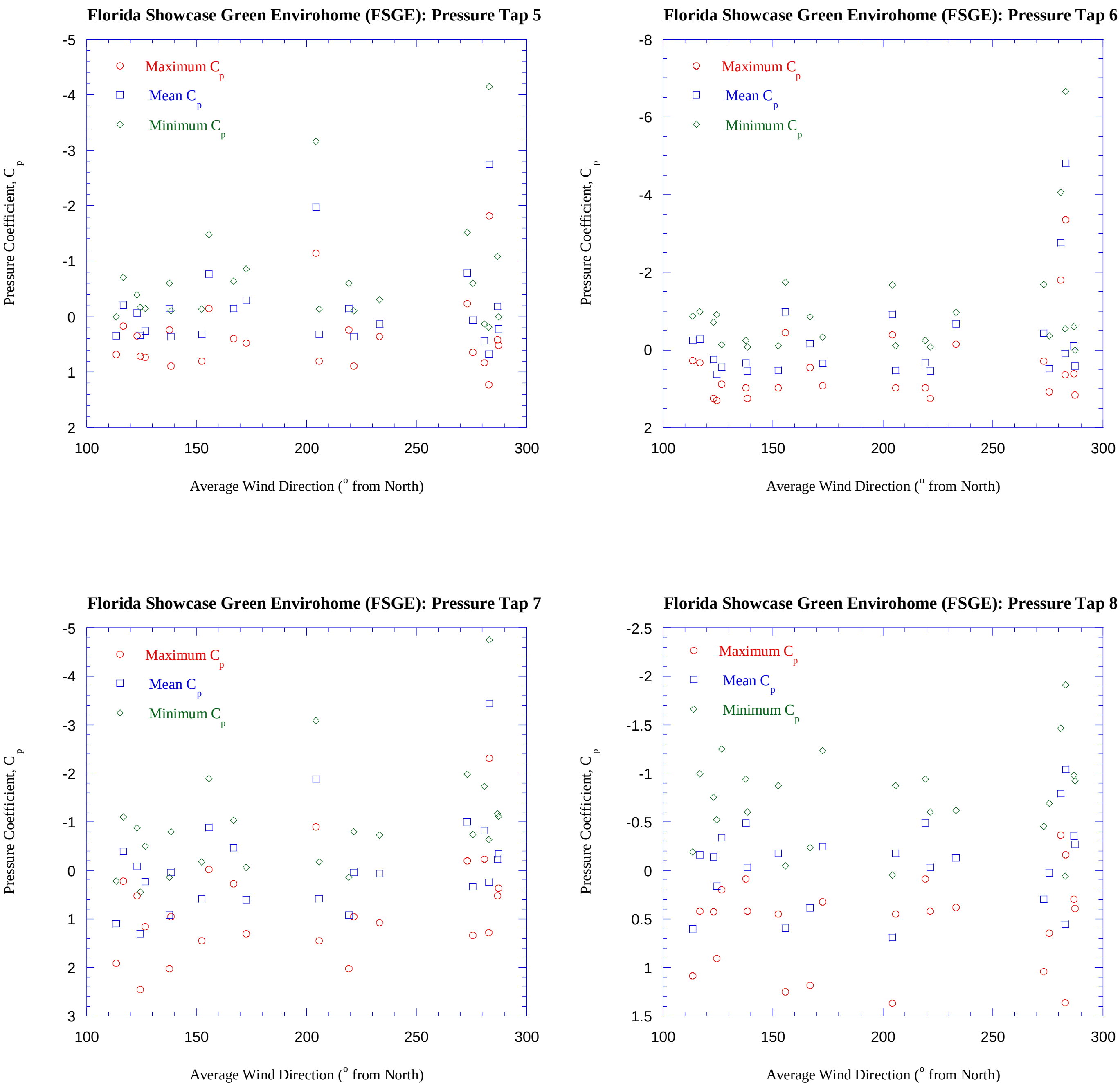


Figure 88: Minimum and maximum pressure coefficients measured at Florida Showcase Green Envirohome vs. average wind direction (0 ° from the North) for pressure tap 5 – pressure tap 8

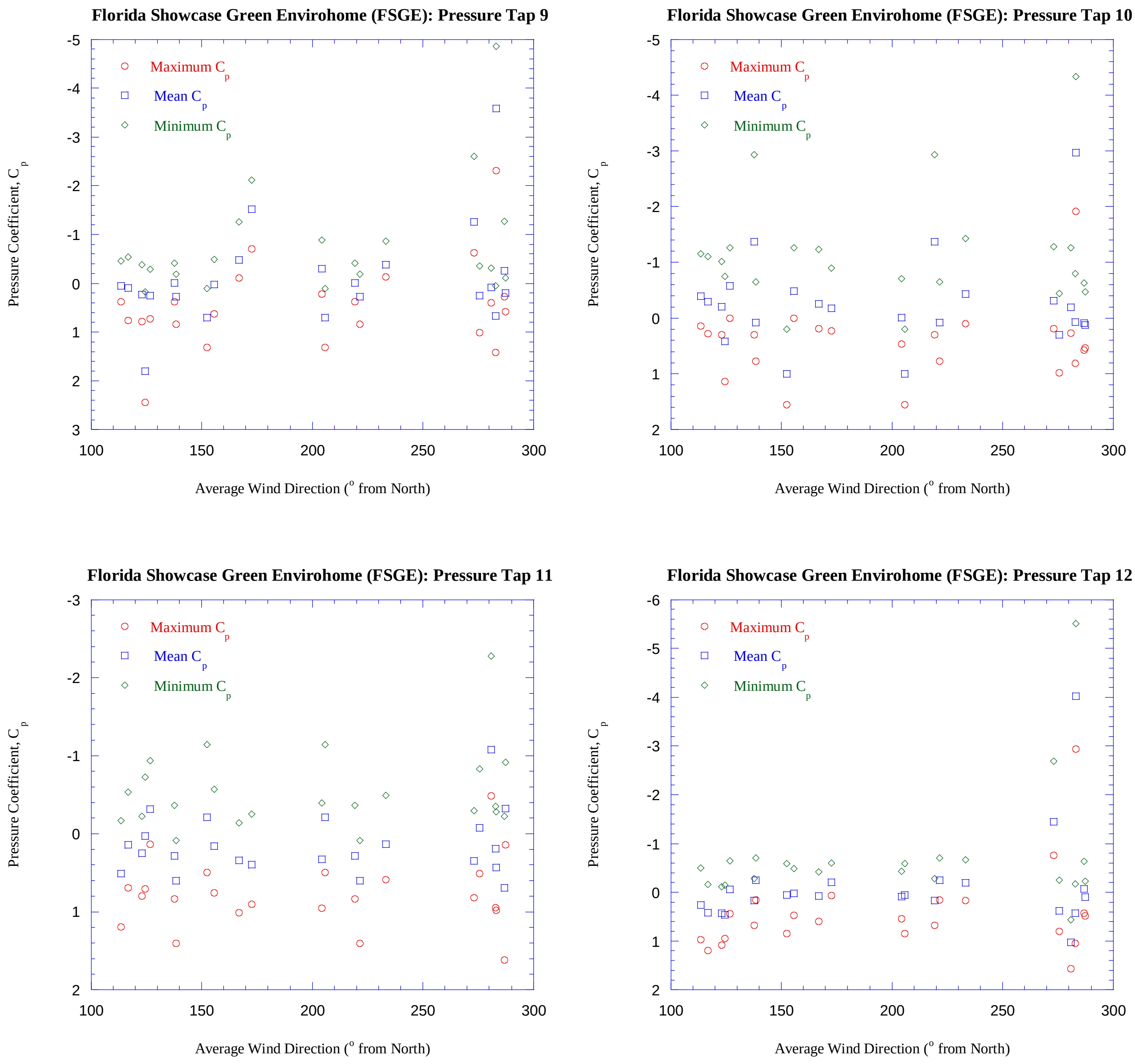


Figure 89: Minimum and maximum pressure coefficients measured at Florida Showcase Green Envirohome vs. average wind direction (0 ° from the North) for pressure tap 9 – pressure tap 12

Port Charlotte Rays Stadium (PCRS) Pressure Coefficients vs. Wind Direction

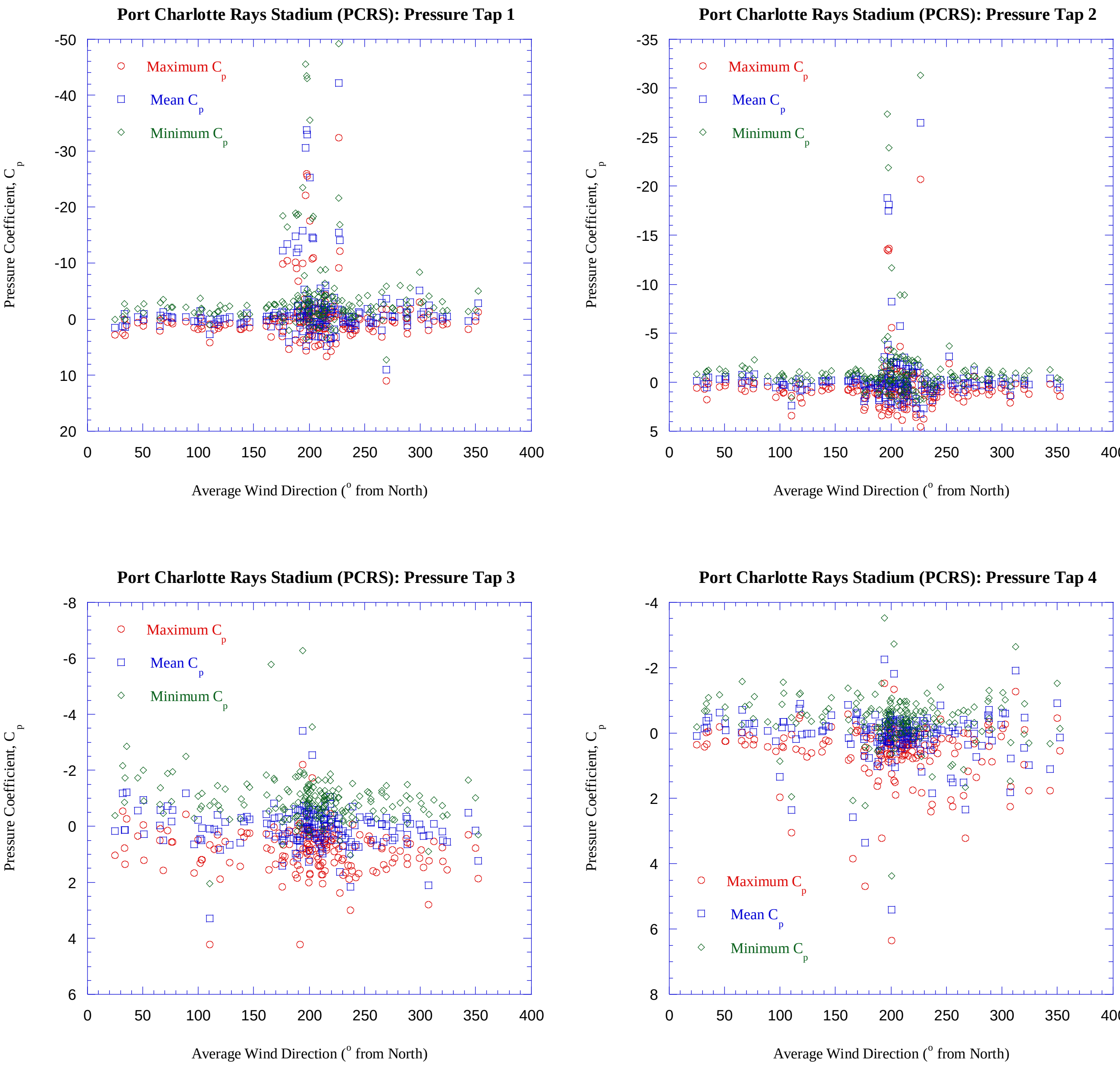
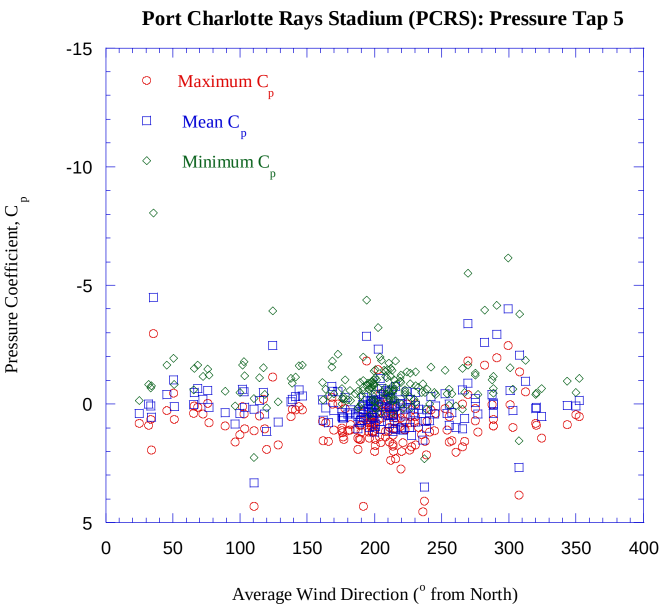
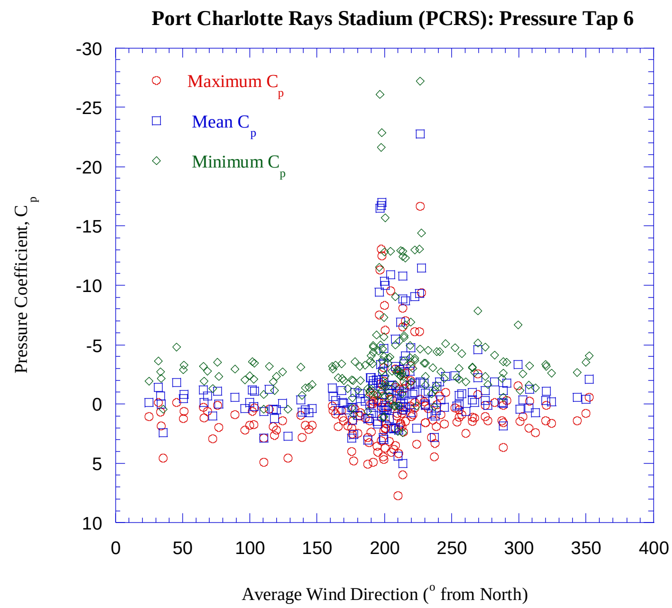
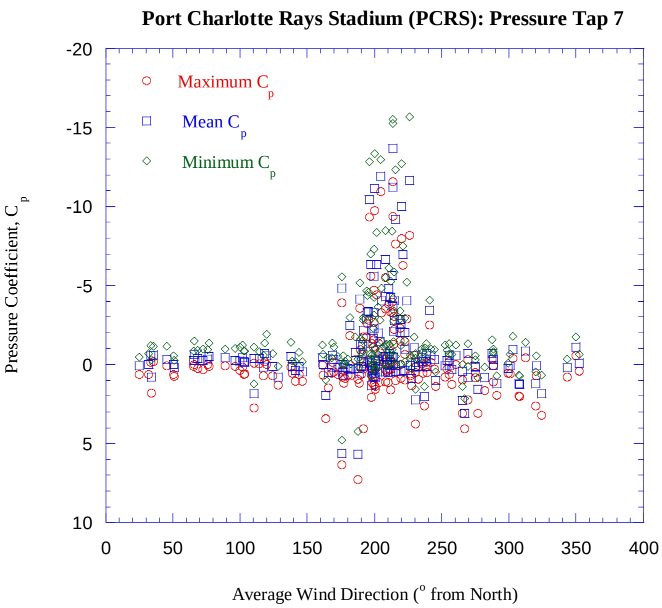


Figure 90: Minimum and maximum pressure coefficients measured at Port Charlotte Rays Stadium vs. average wind direction (0 ° from the North) for pressure tap 1 – pressure tap 4







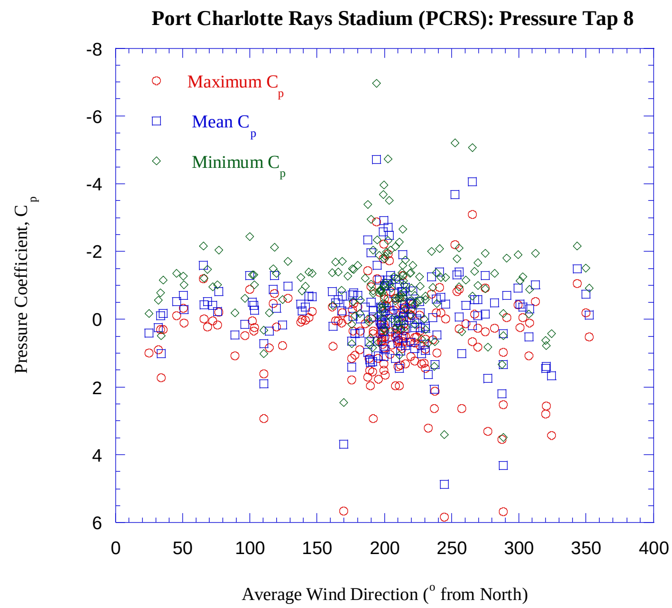


Figure 91: Minimum and maximum pressure coefficients measured at Port Charlotte Rays Stadium vs. average wind direction (0 ° from the North) for pressure tap 5 – pressure tap 8

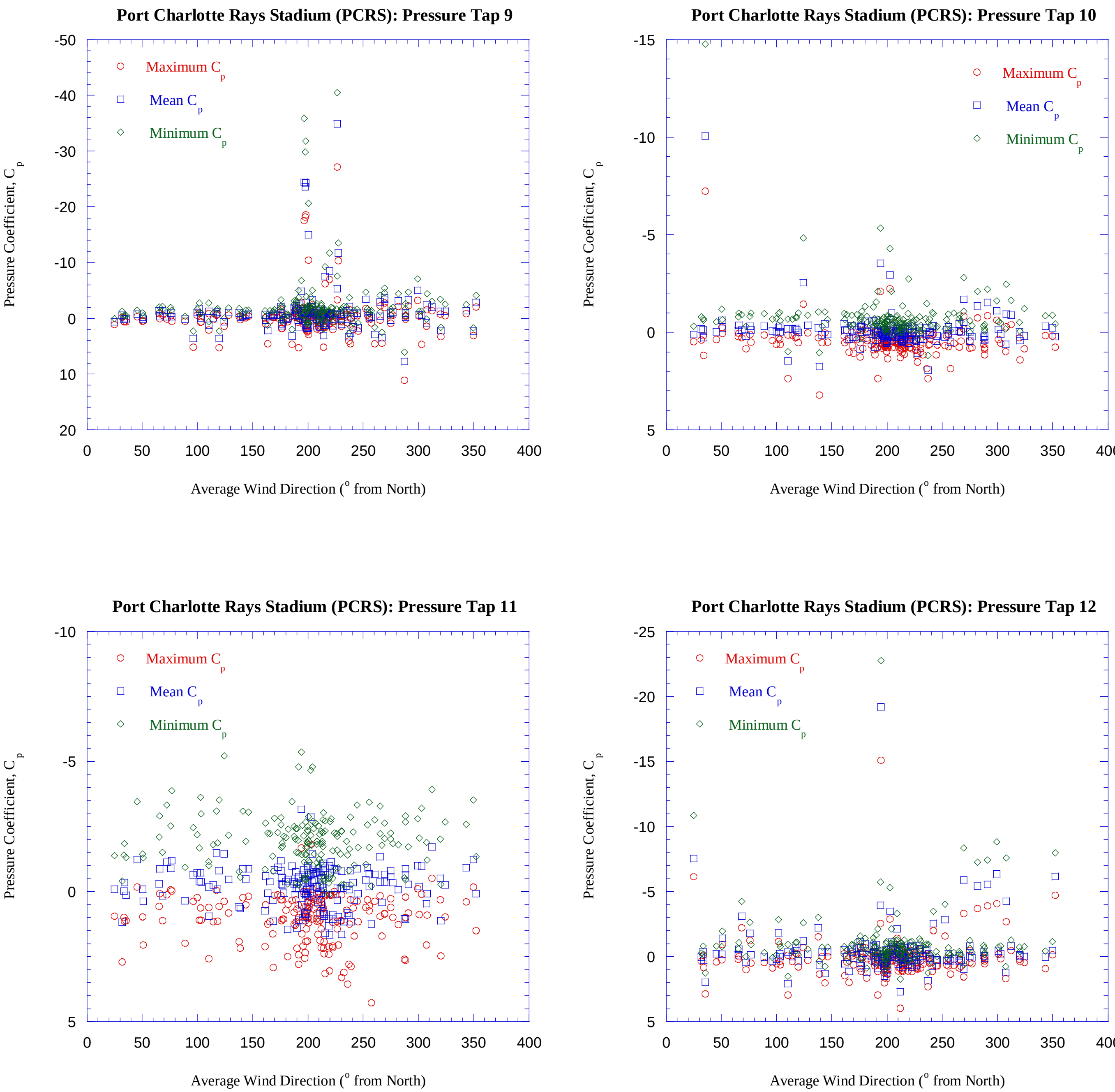


Figure 92: Minimum and maximum pressure coefficients measured at Port Charlotte Rays Stadium vs. average wind direction (0 ° from the North) for pressure tap 9 – pressure tap 12

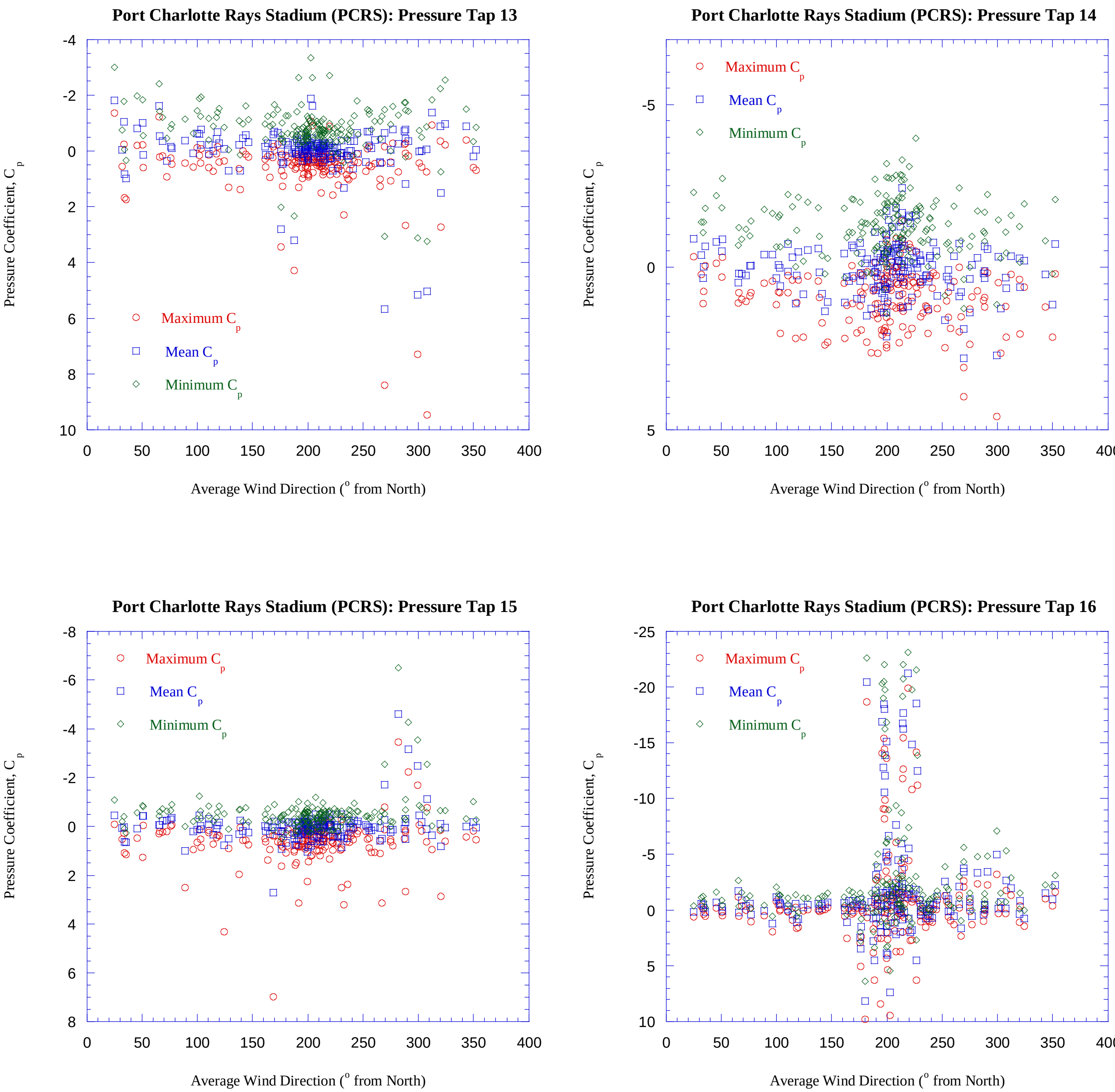
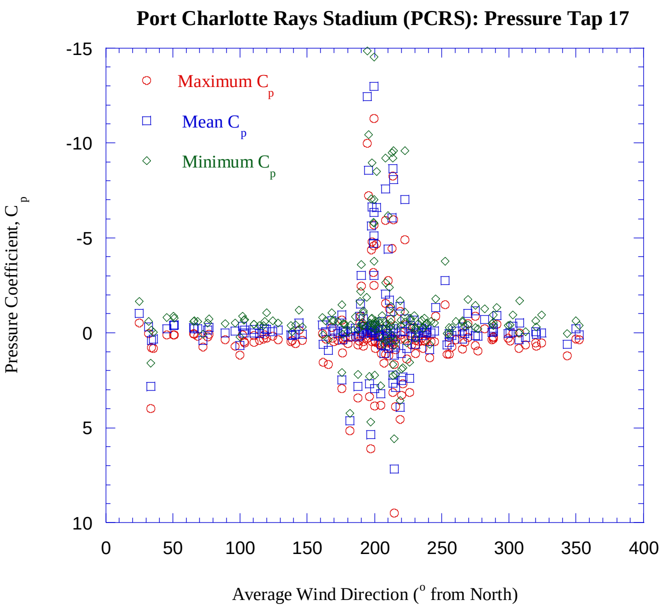
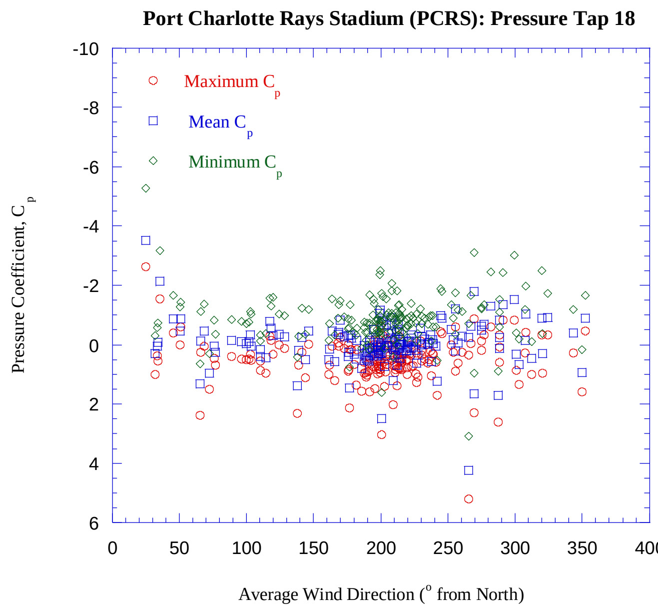
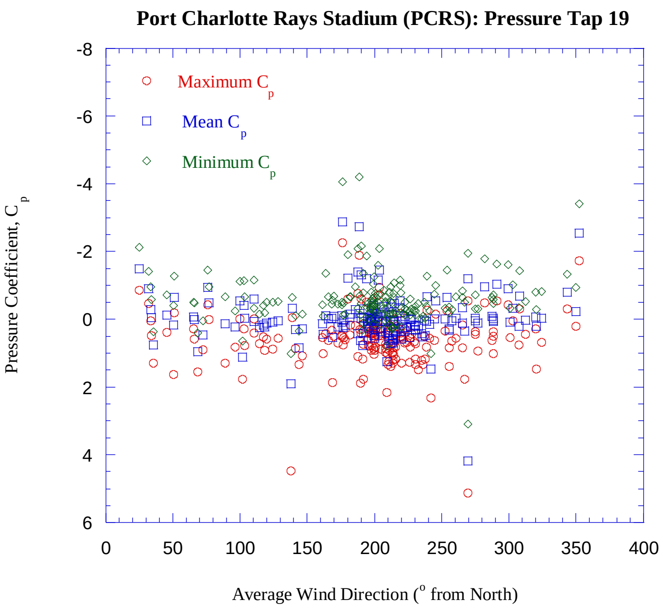


Figure 93: Minimum and maximum pressure coefficients measured at Port Charlotte Rays Stadium vs. average wind direction (0 ° from the North) for pressure tap 13 – pressure tap 16







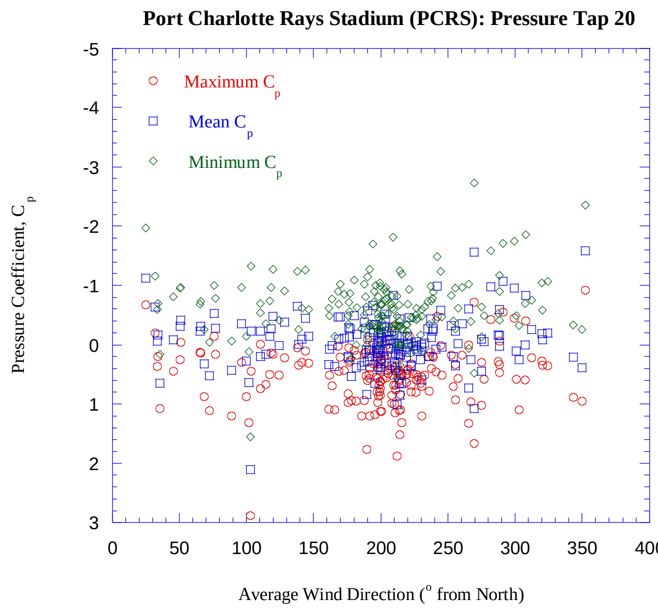
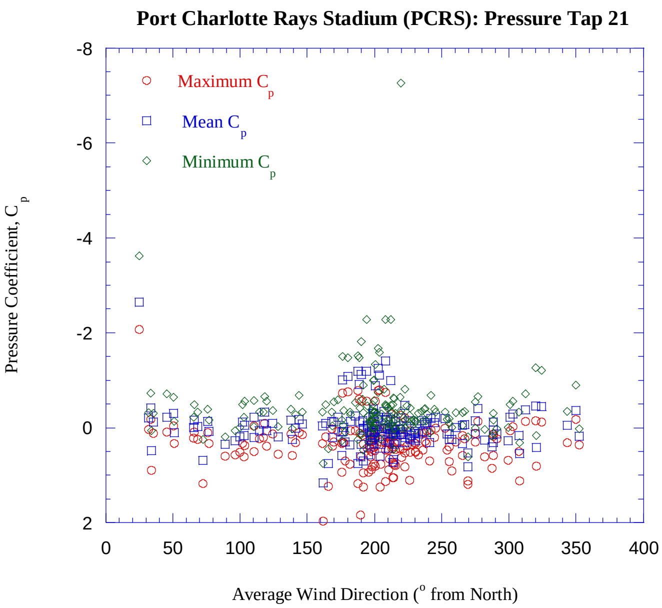
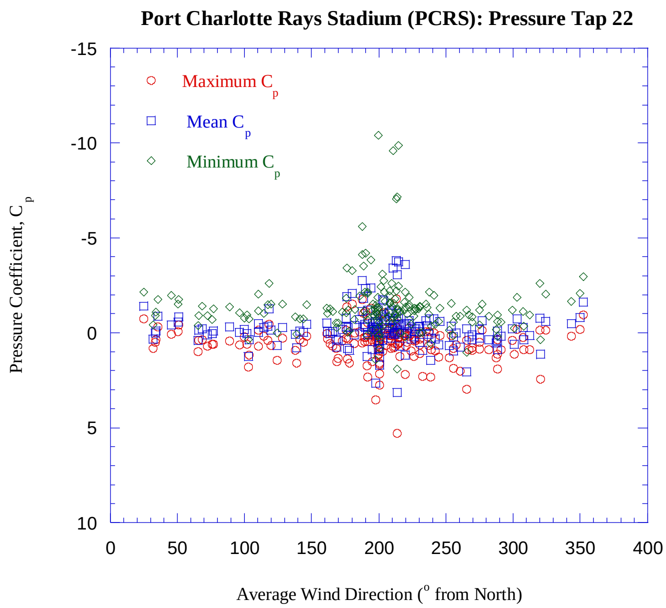
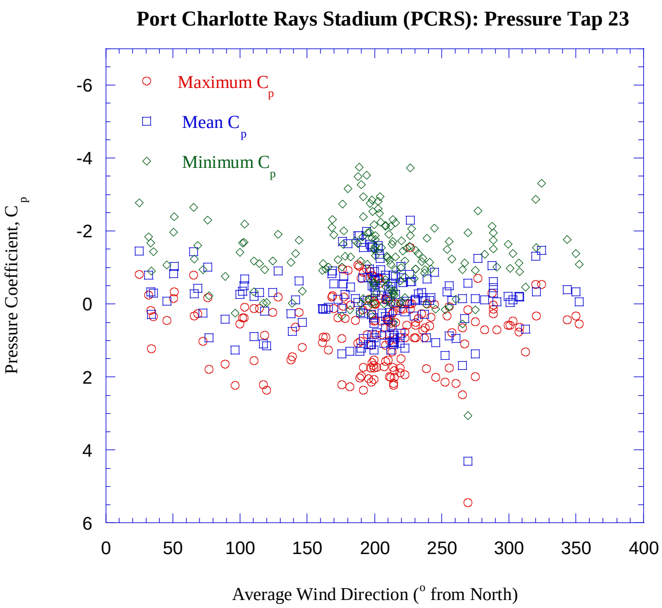


Figure 94: Minimum and maximum pressure coefficients measured at Port Charlotte Rays Stadium vs. average wind direction (0 ° from the North) for pressure tap 17 – pressure tap 20







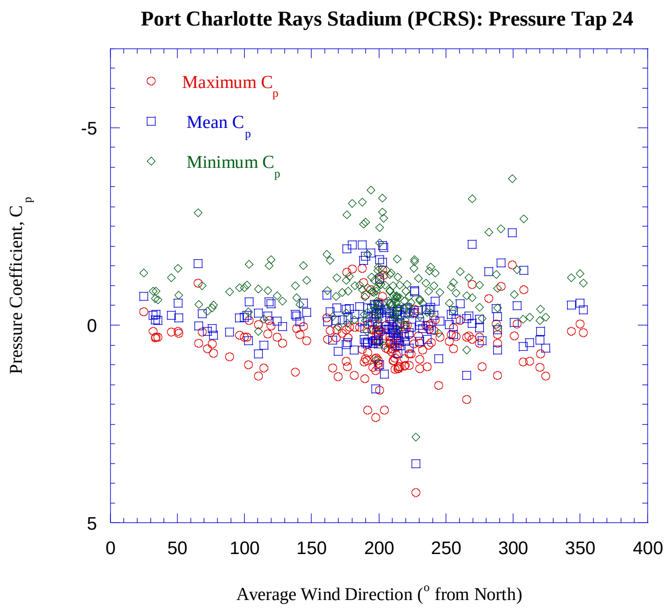


Figure 95: Minimum and maximum pressure coefficients measured at Port Charlotte Rays Stadium vs. average wind direction (0 ° from the North) for pressure tap 21 – pressure tap 24

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