EFFECTS OF HURRICANE FORCE WINDS ON MODULAR GREEN ROOF SYSTEMS

By

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To Patricia and Clifford Ellis

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LIST OF ABBREVIATIONS

ASCE	American Society of Engineers
IBC	International Building Code
LEED	Leadership in Energy and Environmental Design
LRFD	Live and Resistance Factor Design
NHC	National Hurricane Center's
NOAA	National Oceanic and Atmosphere Administration
NRCA	National Roofing Contractors Association
SIUE	Southern Illinois University, Edwardsville
UHI	Urban Heat Island Effect

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By

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Green roofs are becoming increasing popular system to conserve energy in buildings. However, there is very little data or research on the best strategy to ensure that these systems perform when subjected to hurricane force winds. Green roof systems can be either modular, a series of individual trays, or built in place. Green roof systems built in the Eastern and Gulf Coast region of the United States, have their own set of challenges as between the months of June and November is hurricane season, and this region is very susceptible to hurricanes. The severity of the winds that hurricanes produce make wind design criteria for roofs in regions prone to hurricanes very stringent. Modular green roof systems, because of their design, would be more likely to experience the effects of wind generated by hurricanes. Commercial building, especially the high rises in the heart of a city is best suited green roof systems because of their contributions to sustainable efforts. Green roof systems reduce the Heat Island Effect of the city and provide ecological advantages such as improving air quality and converting carbon dioxide into oxygen. The problem with modular green roof systems is that they have the potential to produce an arsenal of projectiles when exposed to hurricane strength winds. Since green roof systems are typically being installed on high

rise buildings in densely populated, there is the potential for a green roof system to cause devastating effects to the surrounding area. This research focuses on the performance of the modular green roof systems when subjected to hurricane force winds. Commercial builders, especially roofing contractors, in cities along the Eastern and Gulf Coast would benefit extremely from this research. Based on provisions outlined in the ASCE 7-05 and ASCE 07-10 Standards, a theoretical model with clearly defined parameters was developed and wind load design criteria were established. How wind forces would affect the modular green roof trays was based on the premise that the modular tray would be subjected to both horizontal and vertical forces that would overturn them at the pivot point furthest from where the lateral force hits the side panels of the tray. The theoretical model evaluated the typical design of a modular green roof system and considered how each component affects the modular green roof system's ability to resist being overturned. This research concluded that both extensive and intensive modular green roof systems can be installed on commercial and residential building in the Eastern and Gulf coasts, but intensive modular green roof systems provide better resistance to wind uplift for very tall structures.

CHAPTER 1
INTRODUCTION TO THE STUDY

Introduction to the Problem

As the world braces for the impending energy crisis, many industries are taking initiative to conserve energy. In the built environment, one of the strategies for reducing the energy consumption in a building is to install a green roof system. Green roof provides economic benefits to the owner by providing savings on energy heating and cooling cost, depending on the size of the building, the climate, and type of green roof. Green roof systems can be either modular or built in place. Green Roof systems have the biggest impact in buildings located in cities as they can reduce the urban heat island (UHI) effect. Temperatures in cities are usually 2º F to 10º F hotter than rural areas, thus the cooling requirements for the buildings in urban areas are much higher (Kibert 2008). UHI can be contributed to the removal of vegetation and replacing it with buildings and other structures. Green Roofs serve to replace the vegetation up heaved when the building is constructed. According to the Green Roofs for Healthy Cities website, green roofs can facilitate a significant improvement in the LEED^{TM} rating of a building, contributing as many as 15 credits under the system, depending on design and level of integration with other building systems. In some instances, while green roofs may not contribute directly to achieving points under the system, they contribute to earning LEED^{TM} credits when used with other sustainable building elements. Green roofs can be categorized as intensive or extensive systems depending on the plant material and planned usage for the roof area. Green roof systems can either be modular or built-in place. The type of green roof system depends on the vegetation needed to be supported. Extensive systems have a very shallow depth of soil or growing medium compared to intensive systems that have a greater depth of soil and growing medium which allows for greater diversity in size and type of vegetation (Weiler and Scholz-Barth 2009). Built-in-place roof systems are more traditional and are constructed by layering materials in place over the roof surface. According to the Green Roof Research Program at Michigan State University, intensive green roofs utilize a wide variety of plant species that may include trees and shrubs, require deeper substrate layers usually greater than 4 in (10 cm), and are generally limited to flat roofs. Extensive roofs are limited to herbs, grasses, mosses, and drought tolerant succulents such as *Sedum*, and can be sustained in a shallow substrate layer less than 4 in (10 cm). The incentives for installing a green roof in a new or renovation project are significant; however, one of the concerns of green roof systems is whether or they can withstand wind up lift. Modular green roof systems, due to their design, have a greater potential to be vulnerable to wind uplift sine there rest on the roof sub structure with no means of securing them to roof.

Background to the Problem

Every year the East and Gulf Coast of the United States is threatened by hurricanes. Winds produced by hurricanes can sustained range between 74 miles per hour (mph) for a Category 1 hurricane, to greater than 155 mph for a Category 5 according to the National Oceanic and Atmosphere Administration (NOAA), National Weather Service, National Hurricane Center's (NHC) new 2009 Saffir-Simpson Wind Scale. The Saffir-Simpson categorizes hurricanes based on wind strength and the 1 to 5 scale provides examples of the type of damages and impacts associated with winds of an indicated intensity. A maximum sustained wind is considered to be the maximum wind speed measured 33 ft (10 m) above the earth's surface. The NHC uses the Saffir-

Simpson scale to also estimate how much damage each category of hurricane will inflict once it reaches land. According the scale, roof damage does not become a concern until a hurricane reaches Category 2, where wind speeds are estimated between 96 and 110 mph. Research done by the NHC shows that high rise buildings are most susceptible to hurricane winds, as the strength of the wind increases with elevation. Commercial buildings located in major cities along the East and Gulf Coasts are typically greater than two stories.

Currently there is no set guidance for wind uplift as it pertains to green roof systems. ASTM Standard E2397-05 (Practice for Determination of Dead and Live Loads Associated with Green Roof Systems) does not address live loads associated with wind loads. Other ASTM Standards, E2399-05 (Maximum Media Density of Dead Load Analysis of Green Roof Systems) and E2400-06 (Guide for the Selection, Installation, and Maintenance of Plants for Green Roof Systems), do not factor the effects of severe wind condition in their recommendations and guidance. In Florida, where hurricanes are prevalent, the building code does not specifically address green roof systems nor does the ASTM Standard.

Problem Statement

Modular green roof systems are trays filled with growth media and vegetation that are placed on the roof of buildings without any mechanism in place to anchor them to the roof structure. If these green roof systems are to be installed in areas prone to hurricanes, they need to be able to withstand the forces that these winds produce. The objective of this research is to determine the survivability of these systems on roofs of various heights and at various hurricane wind speeds. Building height is an important factor in this evaluation as wind speed increases with elevation.

Statement of Purpose

This study will examine the likely hood that modular intensive and extensive systems will be able to withstand hurricane wind speeds by formulating a model using the wind design criteria established in the ASCE 7-05 and ASCE 7-10 standards. The survivability of modular green roof system under hurricane conditions is vital in the pursuit of this sustainable application in the Eastern and Gulf Coast Regions.

Rationale

Green roof systems installed on high rise buildings would produce the most benefit to as these buildings are typically located in urban settings. Not knowing how they will perform during hurricane conditions may be a cause for concern for many owners and buildings who want to pursue sustainable measures in the building design or renovation. A modular green roof system is a series of trays with vegetation and growth media resting on a roof surface. One of the advantages of a modular green roof system is the ease of which it can be moved to allow for easy access to the roof surface for repairs and maintenance. It is the ease of which modular green roofs can be moved that begs to question whether they can withstand hurricane force winds. The design/build community in these cities may want to incorporate and promote green roofs, however, they may be discouraged from doing so due to the threat that hurricanes pose each year. If modular green roof systems cannot withstand hurricane force winds and it is blown away, it will leave the substructure of the roof vulnerable which will create further damage to the roof. As an owner, knowing whether or not there is a risk associated with installing green roof systems in this region is important. Insuring buildings with modular green roofs may become more expensive if they are susceptible to wind uplift. If the modular tray is blown away by hurricane force winds, this leaves the underlying roof surface exposed and will cause more damage to components of the roof that were not meant to be exposed to high wind and rain.

To evaluate the effects of wind uplift on modular green roof systems, this research analyzes the effects strong winds have on the main components of a modular green roof system. The two components under scrutiny are the vegetation, to include growth media, and the trays. Strong wind forces, along with saturation, may make the vegetation easier to uproot depending on the plant's root structure and the type of soil the roots are embedded in. Without the weight of the vegetation, the trays will be more susceptible to the effects of the hurricane strength winds. This research also evaluates the modular green system as a whole. The system when viewed holistically should be able to withstand wind uplift forces regardless of vegetation, soil type, and saturated condition. Figure 1-1 provides a detailed cross section of a typical modular green roof.

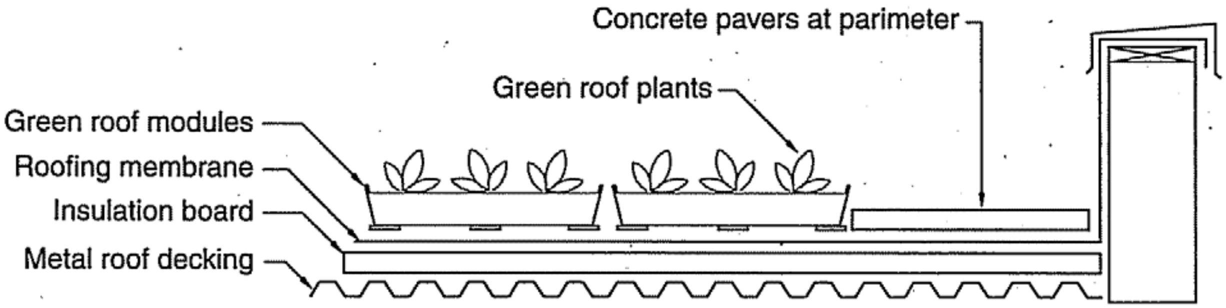


Figure 1-1. Typical cross section of a modular green roof (source: Lucket 2009)

The type of roof membrane used on a modular green roof system will determine the coefficient of friction that can resist the lateral forces produced by hurricane force winds. The roofing membranes and their characteristics are as follows:

- EPDM is the most commonly used membrane. It is low in cost and its large sheet size minimizes seams. EPDM's poor chemical and oil resistance makes it a poor choice for restaurants and rooftops with exhaust hoods ventilating airborne oils.

- TPO is increasing becoming a popular membrane. It is identified by its reflective white surface and is joined together by heat-welded seams. The expense of heat-welding equipment can limit the number of qualified contractors, reducing the competition and increasing the cost of the project. TPO has excellent durability and provides good root, chemical, and oil resistance.

- PVC has a reflective white surface with heated-welded seams. The expense of heat-welding equipment can limit the number of qualified contractors, reducing the competition and increasing the cost of the project. It has excellent durability and provides good root, chemical, and oil resistance.

- Modified Bitumen is commonly used roofing membrane as a cap sheet for built-up roofing systems. It is available in torch down (APP) and adhered (SBS) formulations. It is low cost, but is poor at root resistance and requires the use of a root barrier to prevent plant root from growing into the asphalt surface. Poor chemical and oil resistance makes modified bitumen a poor choice for restaurants and rooftops with exhaust hoods ventilating airborne oils.

- Liquid-Applied Membrane is an increasingly popular waterproofing strategy for green roofs. It is available in hot rubber-modified asphalt formulations and synthetic liquid membrane formulations. It is excellent for monolithic concrete substrates, but its poor root resistance requires the use of a root barrier to prevent plant roots from growing into the asphalt. Poor chemical and oil resistance makes liquid-applied membrane a poor choice for restaurants and rooftops with exhaust hoods ventilating airborne oils.

Aims and Objective of Study

The aim of the study is to determine the approximate wind speed and building height intensive and extensive green roof modules are able to remain on a roof structure. The study also evaluates how vegetation and growth media are affected by wind uplift. The study proposes a method for designers to evaluate the performance of a modular green roof system under hurricane conditions based on plant type, growth media, roofing membrane, building location, and building height.

Research Method

The study was based on scholarly articles and books on green roof design and maintenance, wind design for buildings, plant root structure, and soils. The study used the methods for calculating wind loads on buildings and roof top structures based on the provisions outlined in ASCE 7-05 and ASCE 7-10.

Assumptions and Limitations

Several assumptions and limitations pertain to this study. This study assumes that the modular green roof trays will act similarly to rooftop structures and equipment when exposed to wind forces. The study also assumes that no vegetation or growth media will be disturbed when the modular trays are exposed to hurricane force winds. The study assumed that the modular green roof system being evaluated is located on top of a rectangular shaped building. The study is limited to a singular metal modular intensive and extensive tray on an EMPD roof membrane surface. Modular green roof trays can be made of materials other than metal and EMPD is just one type of roofing membrane that these trays can rest. Modular trays arranged in a grid system will perform differently under hurricane system as the pivot point of the tray will change. The square area of the tray will determine how much of an impact the vertical forces produced by winds will have on it. The model developed for this study does not account for a parapet wall. According to ASCE 7-05, parapet wall higher than 3 ft (91.4 cm) will reduce the wind velocity pressure on a roof at the corners of the roof of a building.

Description of Research Organization

The research is comprised of five chapters, the first of which presents the reason why this researcher saw the need to investigate the effect of hurricane force winds on modular green roof systems. The first chapter also discusses the limitations to the study and the selected methodology for the study. The second chapter reviews literature that support the need for this study and how best to evaluate wind uplift on modular green roof systems due to hurricane force winds. The third chapter discusses the methodical approach and strategies used to obtain the results of the study while acknowledging the limitations associated with the study. The fourth chapter presents the results of the study by graphically illustrating the horizontal and vertical forces experienced by the intensive and extensive modular trays at various building heights and the failure height of both intensive and extensive modular systems at various wind speeds. The fifth chapter concludes the research by presenting the research findings, strategies that could be employed to prevent wind uplift of modular roof systems due to hurricane force winds, and recommendations for future research.

Conclusion

The study shall focus on the how hurricane strength winds will affect modular green roof systems and why this determination is important in the Eastern and Gulf Coast regions of the United States. The next chapter presents the literature reviewed for this study.

CHAPTER 2
LITERATURE REVIEW

Introduction

The literature reviewed for this research comes from various academic disciplines to include botany, meteorology, architecture, and engineering. This chapter reviews the literature authored by green roof industry experts in order to ascertain what methods the green roof industry has in place to combat hurricane strength winds. An in depth knowledge of the components of a modular green roof was crucial to this research, thus literature on plant root structure as it pertain to wind forces was reviewed. Since it was determined that soil strength is a factor in the ability for plants to resist wind uplift, literature on soils typical of green roofs was reviewed. Studies on the frequency on hurricanes along the Eastern and Gulf Coast regions was reviewed to establish the likely hood that buildings in this region will be subjected to hurricane wind speeds that would cause damage to roof structures. ASTM Standards used to evaluate wind loads, along with literature on wind design on structures was reviewed in order to develop a model that could simulate how hurricane force winds would affect modular green roof systems.

Making the Case for this Study

In an article written by Kelly Luckett, the president of Green Roofs Blocks, he discusses his concerns with wind uplift and green roof systems. His concerns came about after completing a project in Orlando, Florida, and nothing was mentioned of how the green roof compiled with wind uplift in the building code. Since the Florida Building Code does not address green roofs, there was no need to ensure it meets the wind uplift requirements of a traditional roofing system. According to Luckett, the building inspectors turned a blind eye to the green roof portion of the project. The biggest issue with wind uplift and green roof systems is the potential debris that a green roof systems will generate when exposed to high winds. A modular green roof is not attached to a roof and its resistance to normal wind uplift loads is due to its own weight (Weiler and Scholz-Barth 2009). The issue of wind uplift affects most roof systems. The perimeter of the roof is affected by a phenomenon known as wind vortex. Wind travels up the wall of the building and creates negative pressure at the roof surface as it swirls along the roof edge. In a meeting hosted by the Single Ply Roofing Industry, Mark Graham, Technical Director of the National Roofing Contractors Association (NRCA), told a group that the NRCA had proposed changes to the International Building Code (IBC) that would require green roofs to meet the same requirements for wind uplift as all other roofing assemblies (Luckett 2009). Mr. Graham felt that the lack of clear direction in the building code for green roof construction would leave the roofing contractor liable if a catastrophic failure should ever occur. Opponents to having a standard to green roofs site Europe as evidence that green roofs structurally safe. According to the website greenroofs.com, green roofs have been in use in Germany for the past 30 years and the Germans have been credited as being the originators of green rood technology. The argument the opponents to green roofs standards try to construct is that Europe has been installing green roofs for over 30 years and have not had any issues with them. But unlike the Eastern and Gulf Coast of the United States, European countries are not subjected to hurricanes and the green roofs being installed on the roofs in those countries do not have to account for wind uplift compared to the green roof system being installed roofs located Eastern and Gulf Coast. Another argument these opponents to green roof standards put forth is that there are too many variations of green roof design and planting schemes to test them all (Retzlaff 2009). The American National Standards Institute in conjunction with Green Roofs for Healthy Cities and the Single Ply Roofing Industry have been working together to develop guidelines for wind up lift on green roofs. The premise in the roofing industry is that vegetated growth media will perform similarly to other form of roof ballasts when subjected to winds. Many in the roofing industry agree with this statement despite the lack of empirical evidence to support this claim (Luckett 2009).

SUI Research

In June 2009, Southern Illinois University Edwardsville performed wind uplift a test on green roof modules that was sponsored by the NRCA. The modules were tested at various wind speeds and at a wind speed of 120 mph, began to slide. The module was tested again with a metal sheet deflector on the front side of the module and the result was the module being stable for 5 minutes at wind speeds 140 mph. The NRCA made available to the university René Dupuis, an engineer with “relevant” experience, and when consulted, suggested to set the module with the corner facing the wind source. According to the Mr. Dupuis, this would allow for a more realistic representation of wind forces acting on the surface of a green roof. When the module was initially tested, it was oriented perpendicular to the wind force and although this set-up was valuable in determining the fail point of the module, did not properly assess the wind uplift resistance to the growth media and vegetation. The subsequent test with the module oriented with the corners facing the wind force resulted in minor media displacement and minor loss of plant material when subjected to wind speeds of 140 mph for 5 minutes.

The effort by Dr. Retzlaff is commendable and is a start to addressing the wind uplift issue for green roof systems, the tests does not factor the effect moisture has on the modular green roof systems. The next step in the progression of research on green roof systems is to subject modules to hurricane condition and evaluate their performance. If green roof modular systems can withstand hurricane conditions, this may alleviate any concerns designers/builders may have in using green roof systems in this region.

Hurricanes Winds

Hurricanes are generated by low-pressure centers above the ocean at 5 to 20 degree latitudes and they typically last between one and three weeks, with an average of ten days. Moisture is the driving force that provides hurricanes their energy. Hurricanes are fed by evaporation over the ocean, but will lose strength over land due to the decrease in moisture and an increase in surface resistance to wind. It is for this reason hurricanes are strongest over the ocean and areas close to coast. A hurricane is a large body of rotating air which is a primary function of the Coriolis force produced by the rotation of the earth. The flow of air of a hurricane circles around the eye and spirals inward to low heights. The speed of the air increases as it reaches the eye and upon reaching the wall rushes upwards to large heights. The air then spirals outward from the upper region of the hurricane. The wind speed and distribution of pressure in hurricane systems can be modeled by Rankine vortex theoretical model. The graph in Figure 2-1 depicts the horizontal distribution of wind speed and pressure according to Rankine vortex theoretical model. Based on Figure 2-1(A), wind speeds in a hurricane reach a maximum at a distance *R* from the center, where *R* corresponds to the radius of the eye. Figure 2-1(B) shows that the pressure in a hurricane is minimal at the center and rises with *r*, where *r* represents the radial distance from the hurricane's center (Liu 1991).

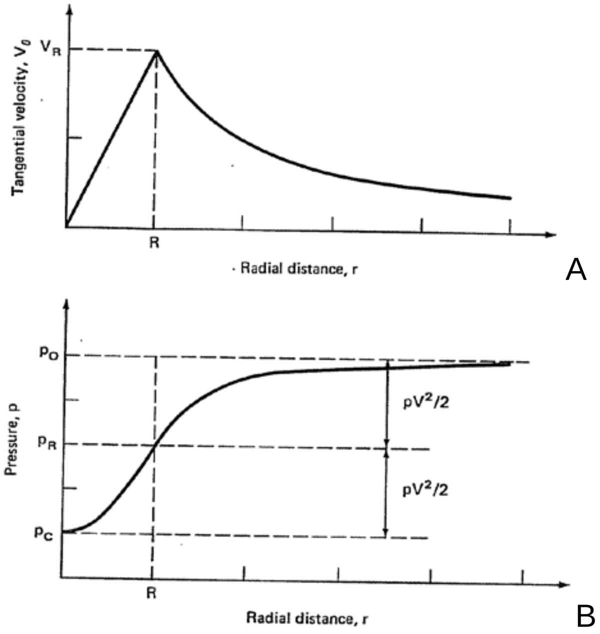


Figure 2-1. Horizontal distribution of wind speeds and pressure in a hurricane or tornado according to Rankine Vortex theoretical model. A) Velocity Distribution. B) Pressure Distribution. (source: Liu 1991).

Wind speed is measured by anemometers mounted normally at a height of 33 ft (10 m) above the ground. This measurement is considered to be surface wind and should not be confused with the wind measurements by aircrafts at high altitudes as wind speed in hurricanes decreases with a decrease in height, reaching zero velocity at ground level. Surface wind is the wind that is normally experienced by structures unless the structure is very tall (Liu 1991).

The National Hurricane Center (NHC) uses the Saffir-Simpson scale categorizes a hurricane based on wind speeds and the damage those wind speed will cause. Table 2-1 depicts the classification of hurricanes.

Table 2-1. Classification of hurricanes by the Saffir/Simpson Scale (adapted from Simiu and Miyata 2006).

Saffir-Simpson Number	Wind Speed (mph)	Damage Potential
1	74-95	Minimal
2	96-110	Moderate
3	111-130	Extensive
4	131-155	Extreme
5	156 and above	Catastrophic

Category 1

Some structural damage to houses and buildings will occur with a minor amount of wall failures. Mobile homes (mainly pre-1994 construction) are destroyed. Many windows in high rise buildings will be dislodged and become airborne. Many trees will be snapped or uprooted.

Category 2

Some roofing material, door, and window damage of buildings will occur. Considerable damage to mobile homes (mainly pre-1994 construction) is likely. A number of glass windows in high rise buildings will be dislodged and become airborne. Numerous large branches will break. Many trees will be uprooted or snapped.

Category 3

Some structural damage to houses and buildings will occur with a minor amount of wall failures. Mobile homes (mainly pre-1994 construction) are destroyed. Many windows in high rise buildings will be dislodged and become airborne. Many trees will be snapped or uprooted.

Category 4

Some wall failures with some complete roof structure failures on houses will occur. All signs are blown down. Complete destruction of mobile homes (primarily pre-1994 construction). Extensive damage to doors and windows is likely. Numerous windows in high rise buildings will be dislodged and become airborne. Wind-borne debris will cause extensive damage. Most trees will be snapped or uprooted.

Category 5

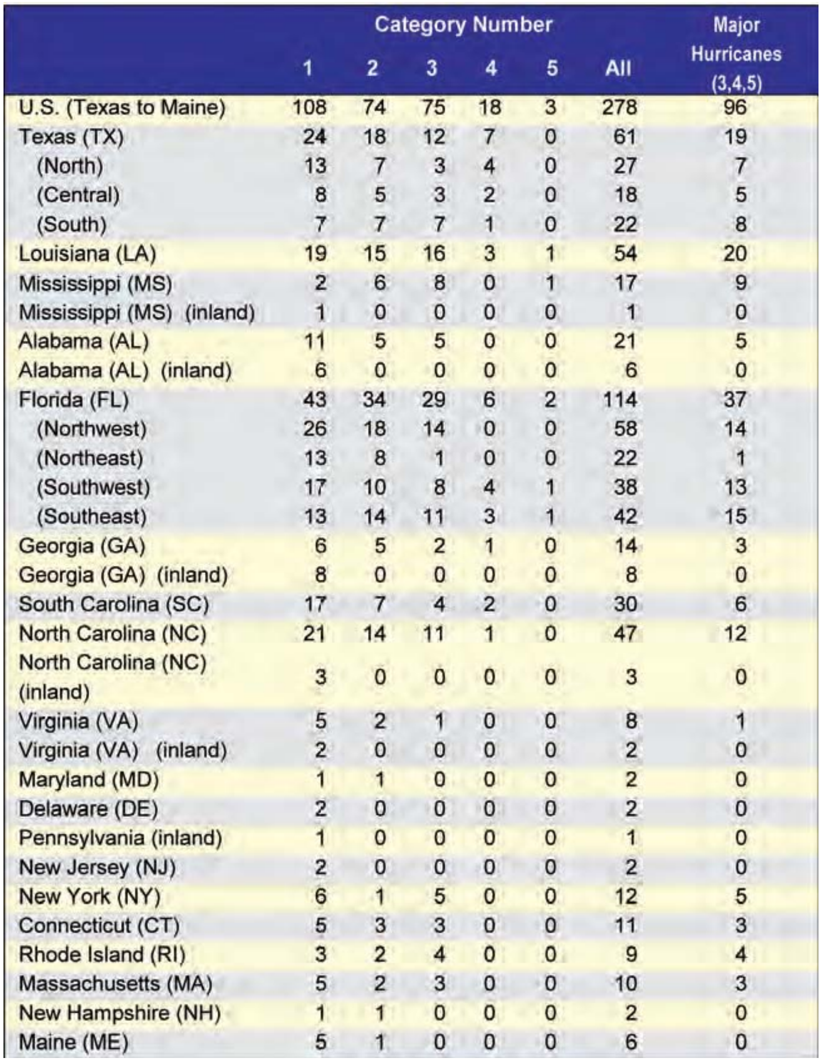
Complete roof failure on many residences and industrial buildings will occur. Some complete building failures with small buildings blown over or away are likely. Complete destruction of mobile homes (built in any year). Severe and extensive window and door damage will occur. Nearly all windows in high rise buildings will be dislodged and become airborne. Nearly all trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas.

Eastern and Gulf Coast Hurricane Frequency

The NHC has been recording hurricane data since 1851. In their publication entitled “Tropical Cyclones of the North Atlantic Oceans, 1851-2006” the agency reports the number and category of hurricane reaching the Atlantic Coast. Figure 2-1 depicts the highest category reached by hurricanes along coastal states between 1851 and 2006. According to the data, between 1851 and 2006, there have been 546 hurricanes that have made it to the Gulf and Atlantic Coast that were at least a Category 2. This highlights the frequency of hurricanes that reach the Eastern and Gulf coast have the strength to damage roofing structures. This validates the concerns that owners/builders/designers may have with installing a green roof system.

Wind Design

In order to analyze how wind will affect green roof modular system, the provisions in the ASCE 7-05, need to be consulted. Chapter 6 of this standard is dedicated to wind loads and it provides the methods to calculate wind loads on structures based on predetermined parameters. Modular green roof systems should have a minimum critical depth and weight to effectively serve as roof ballast to be able to withstand certain wind loads. The parameters that are pertinent to this research are wind speeds, building categories, exposure categories, and enclosure classification.



	Category Number						Major Hurricanes (3,4,5)
	1	2	3	4	5	All	
U.S. (Texas to Maine)	108	74	75	18	3	278	96
Texas (TX)	24	18	12	7	0	61	19
(North)	13	7	3	4	0	27	7
(Central)	8	5	3	2	0	18	5
(South)	7	7	7	1	0	22	8
Louisiana (LA)	19	15	16	3	1	54	20
Mississippi (MS)	2	6	8	0	1	17	9
Mississippi (MS) (inland)	1	0	0	0	0	1	0
Alabama (AL)	11	5	5	0	0	21	5
Alabama (AL) (inland)	6	0	0	0	0	6	0
Florida (FL)	43	34	29	6	2	114	37
(Northwest)	26	18	14	0	0	58	14
(Northeast)	13	8	1	0	0	22	1
(Southwest)	17	10	8	4	1	38	13
(Southeast)	13	14	11	3	1	42	15
Georgia (GA)	6	5	2	1	0	14	3
Georgia (GA) (inland)	8	0	0	0	0	8	0
South Carolina (SC)	17	7	4	2	0	30	6
North Carolina (NC)	21	14	11	1	0	47	12
North Carolina (NC) (inland)	3	0	0	0	0	3	0
Virginia (VA)	5	2	1	0	0	8	1
Virginia (VA) (inland)	2	0	0	0	0	2	0
Maryland (MD)	1	1	0	0	0	2	0
Delaware (DE)	2	0	0	0	0	2	0
Pennsylvania (inland)	1	0	0	0	0	1	0
New Jersey (NJ)	2	0	0	0	0	2	0
New York (NY)	6	1	5	0	0	12	5
Connecticut (CT)	5	3	3	0	0	11	3
Rhode Island (RI)	3	2	4	0	0	9	4
Massachusetts (MA)	5	2	3	0	0	10	3
New Hampshire (NH)	1	1	0	0	0	2	0
Maine (ME)	5	1	0	0	0	6	0

Figure 2-2. Number of Saffir-Simpson category events for specified coastal states, 1851-2006 (source: McAdie et al. 2009).

Wind is defined as a turbulent flow, characterized by the random fluctuations of velocity and pressure (Liu 1991). The ASCE 7-05 specifies three procedures for determining design wind loads: the simplified procedure, the analytical procedure, and the wind tunnel procedure. To apply the standard, the engineer must know the basic wind speeds, importance factors, exposure categories, and topographic factors (Simiu and Miyata 2006). Wind speed changes constantly so in order to determine wind speed, averages are obtained using different averaging times or durations. Gust is the instantaneous velocity wind. Ordinary structures are sensitive to peak gusts with the duration of 1 second, therefore the use of a mean wind speed value over one second for structural design must account for gust (Liu 1991). According to the ASCE 7-05 standard, the basic wind speed is defined as the 3 second peak gust at 33 ft (10 m) above the ground in open terrain. In hurricane prone regions the basic wind speed is defined as the speed with a mean recurrence interval (MRI) of 500 years instead of 50 years for winds outside hurricane prone regions. The MRI is the probability that wind speeds occurring in any one year exceeds an expected value (Simiu et al. 2006).

ASCE 7-05 divides buildings into four categories based on the risk these buildings pose to human life if failure occurs.

- **Category I:** agricultural facilities, minor storage facilities, and certain temporary facilities.
- **Category II:** all categories not defined in categories I, III, and IV.
- **Category III:** buildings and other structures where more than 300 people congregate in one area.
- **Category IV:** structures designated as essential facilities.

The importance factor coefficient varies depending on the category of the structure and whether or not the region it resides in is prone to hurricanes.

In order to properly evaluate the wind loads, the surface roughness category needs to be assigned. The surface roughness categories are as follows:

- **Surface Roughness A:** omitted from standard due to the practical impossibility of defining reliably the surface roughness of centers of large cities

- **Surface Roughness B:** urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of the single-family dwelling or larger.
- **Surface Roughness C:** open terrain with scattered obstruction generally less than 30 ft (10 m) high and flat open country, grasslands, and water surfaces in hurricane prone regions.
- **Surface Roughness D:** flat, unobstructed areas, including smooth mudflats, salt flats, and unbroken ice, and water surfaces outside hurricane prone regions.

See Appendix A for a visual depiction of the different exposure surfaces. Other factors that the ASCE standard considers that are pertinent in this study are whether the building being evaluated is open, enclosed, or partially enclosed. The enclosure classifications are as follows: 1) Open: a building having each wall at least 80 percent open; 2) Partially Enclosed: A building that complies with the following conditions. The total area of the openings in a wall that receive positive external pressure exceeds the sum of the areas of openings in the balance of the building envelope (walls and roof) by more than 10 percent. The total area of the openings in a wall that receives positive external pressure exceeds 4 ft^2 (0.37 m^2) or 1 percent of the area of that wall, whichever is smaller, and the percentage of openings in the balance of the building envelope does not exceed 20 percent; and, 3) Enclosed: A building that does not comply with the requirements for open or partially enclosed buildings. For the purposes of enclosure classification, glazing and doors are not considered defined as openings except under certain conditions (Simiu and Miyata 2006).

The topography of the land has an effect on wind speed due to rising slopes. Over rising slopes, wind speeds are higher for any given height above ground compared to winds traveling over horizontal terrain (Simiu and Miyata 2006). This effect has to be factored into the wind design calculations.

Green Roof Design Considerations

The benefits of green roof systems are more pronounced in commercial buildings located in an urban setting. Commercial and residential buildings in the heart of major cities along the Eastern and Gulf Coasts tend to be over 3 stories in height. Since wind speed increases with height, over 3 stories will experience a stronger wind force and will be more susceptible to wind uplift. This provides yet another deterrent for owners/builders/designers to install a green roof system in a building over 3 stories in an area prone to hurricanes as the green roof systems will likely experience scouring. Scouring is the blowing of the particles in the growth media from the surface of the green roof (Luckett 2009). This effect reduces the volume and weight of the growth media and its ability to ballast the green roof components below. Scouring has a greater effect on intensive green roof systems as those systems are designed to hold larger vegetation. Taller, upright plants catch wind easier and thus are easier to uproot. Hurricane conditions will only magnify the effect of scouring on extensive systems as plants in saturated soil will not be anchored as well and it will be blown away easier when subjected to hurricane force winds. To limit the effect of scouring on taller plants, Luckett, in his book “Green Roof Construction and Maintenance”, suggest planting these trees away from the roof edges where winds tend to be stronger. He also suggests the use of anchors to allow for these taller plants to establish roots capable of withstanding wind loads, however, under hurricane conditions, the soil will be saturated and the roots of these taller plants will be loosen and any technique used to ensure proper anchoring will be negated.

The International Green Roof Association Global Networking for Green Roofs recommends that plant materials can be broken down in these basic categories for the purpose of structural load calculations:

- Sedums and succulents – 2 lb/ft2
- Grasses and bushes up to 6 inches – 3 lb/ft2
- Shrubs and bushes up to 3 feet – 4 lb/ft2

For design purposes the weight of green roofs are comparable to stone ballast used to protect and preserve the water proofing membrane on traditional roofing systems. The structural engineer of a green roof will break up the vegetation into three main categories: lawns; short grasses; shrubs; and trees. The depth of the soil required to promote growth, and the weight of the vegetation itself, is the distinguishing factor for each category. Soil densities and loads vary depending on the type of soil, its level of compaction, and its moisture content. Table 2-2 lists the soil density for commonly used growth media.

Table 2-2. Weights of commonly used growing media components (adapted from Weiler and Scholz-Barth 2009)

Growth Media	Pressure
Loamy soils (saturated)	100-120 pcf
Clayey soils (saturated)	105-125 pcf
Silty soils (saturated)	100-120 pcf
Humus	80-85 pcf
Mulch	90-95 pcf
Lightweight aggregates	45-55 pcf
Sand (saturated)	120-130 pcf
Prefabricated lightweight soils (saturated)	6.5-8 psf per inch of depth

Engineers will most likely use the lightest growth media in green roof design to reduce the cost associated with the materials needed to support more weight. The problem with this philosophy is that the lighter the green roof system, the bigger the impact wind uplift will have on it. However, hurricanes produce a lot of rain and the saturation of the soil will provide additional weight to the system that will prevent some uplift.

It is not necessary to calculate the wind loads on grass and shrubs as these loads are typically negligible. Wind loads should be taken into consideration for any trees or vegetation planted over the structure. When wind pressure acts against the tree canopy and surface, a tree firmly rooted in the soil acts as a cantilever and has to resist overturning forces. The survivability of trees when exposed to wind forces is dependent upon how well their roots have been established. The horizontal forces acting on a structure due to the wind pressure on a trees area (canopy and trunk) can be significant to the structure's lateral force resisting system design, depending on the building's size, and should be considered in the developing structural systems for green roof systems. (Weiler and Scholz-Barth 2009).

The Vegetation Component

The type of vegetation that makes up the green roof system is important to its effectiveness. The vegetation used should be similar to the natural vegetation of that region. Modular green roofs systems are basically planters that are arranged on rooftops and are comprised of engineering soil blends and plants based on the regional climate. It is recommended that green roof plants be able to withstand extremes of heat and cold, low growing, shallow roots, and long life expectancy (Lucket 2009).

Plant Root Structure

Engineers evaluate root structures in plants because roots provide anchoring and absorb water and nutrients from the soil. This research focuses on the anchoring function of roots. The force that plants commonly experience is the horizontal force by the wind which results in overturning. Roots therefore have to be able to transmit rotational torque to the soil effectively. Fibrous root systems are effective at preventing uprooting but not as effective at avoiding overturning. Tap and plate root systems tend to have at least one rigid element at the base of the stem to act as a lever which can provide resistance to rotation. There are two other root systems that provide effective resistance to horizontal forces that result in overturning (Gregory 2006). Figure 2-3 depicts how common root systems fail when exposed to horizontal forces.

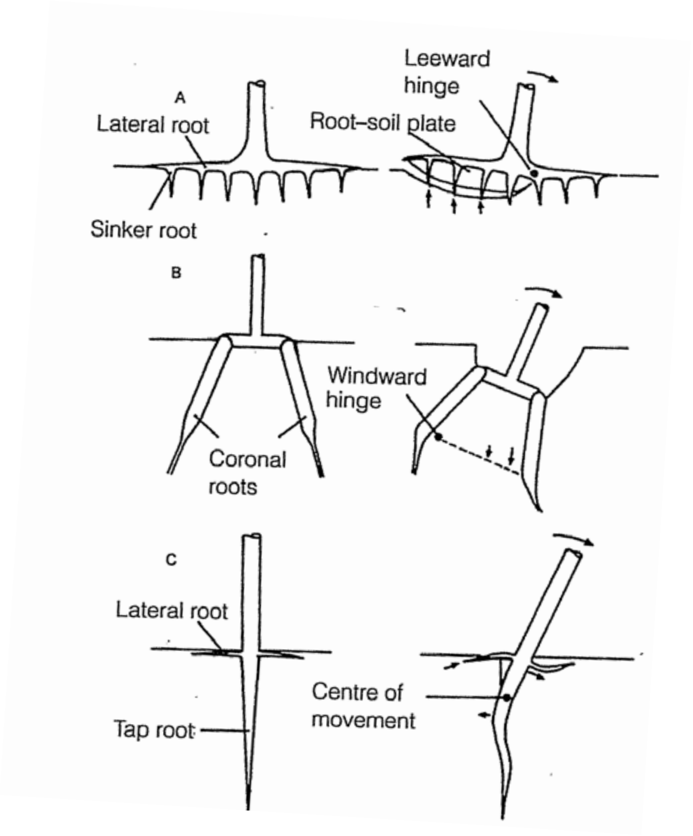


Figure 2-3. Failure modes due to horizontal forces in three types of root systems (source: Gregogy 2006).

In sinker roots, the roots system rotates up around a leeward hinge, while in narrower systems the rotation occurs about a windward hinge. In tap root systems, overturning occurs as the tap root bends about a point directly beneath the stem at some distance below the soil surface.

Tap roots is a characteristic of most small flowering plants that are in the dicotyledon class of plants. The anchoring mechanism of tap roots is twofold: (1) the resistance of the soil to compression on the leeward side; and, (2) the bending resistance of the tap root. If the tap root is acting like a foundation pile so that the plant can resist overturning, then the maximum resistance (R_{max}) to lateral loading can be predicted by the equation:

$$R_{max}=4.5\sigma DL^2 \tag{2-1}$$

where D and L are the diameter and the length of the rigid rod and σ is the shear strength of the soil. Based on this equation, soil properties have a significant influence on the failure.

A study of vegetation, particularly grasses, shrubs, herbs, other small dicotyledons, found in the Cárcavo catchment, located about 25 miles (40 km) northwest of the city of Murcia in Spain, was conducted to evaluate the root tensile strength and root reinforcement. The study excavated 50 roots of the different types of plants all with a diameter less than 0.3 in (8 mm) and a minimum root length of approximately 4 in (0.10 m). The roots were carefully preserved and tested for tensile strength using a universal tensile and compression test machine. The following formula was used to calculate the tensile strength of the root, T_r:

$$T_r=\frac{F_{max}}{\pi\left(\frac{D^2}{4}\right)} \tag{2-2}$$

where F_{max} is the maximum force (N) needed to break the root and D is the root diameter. Figure 2-4 shows the result of the laboratory test of root tensile strength for different types of vegetation.

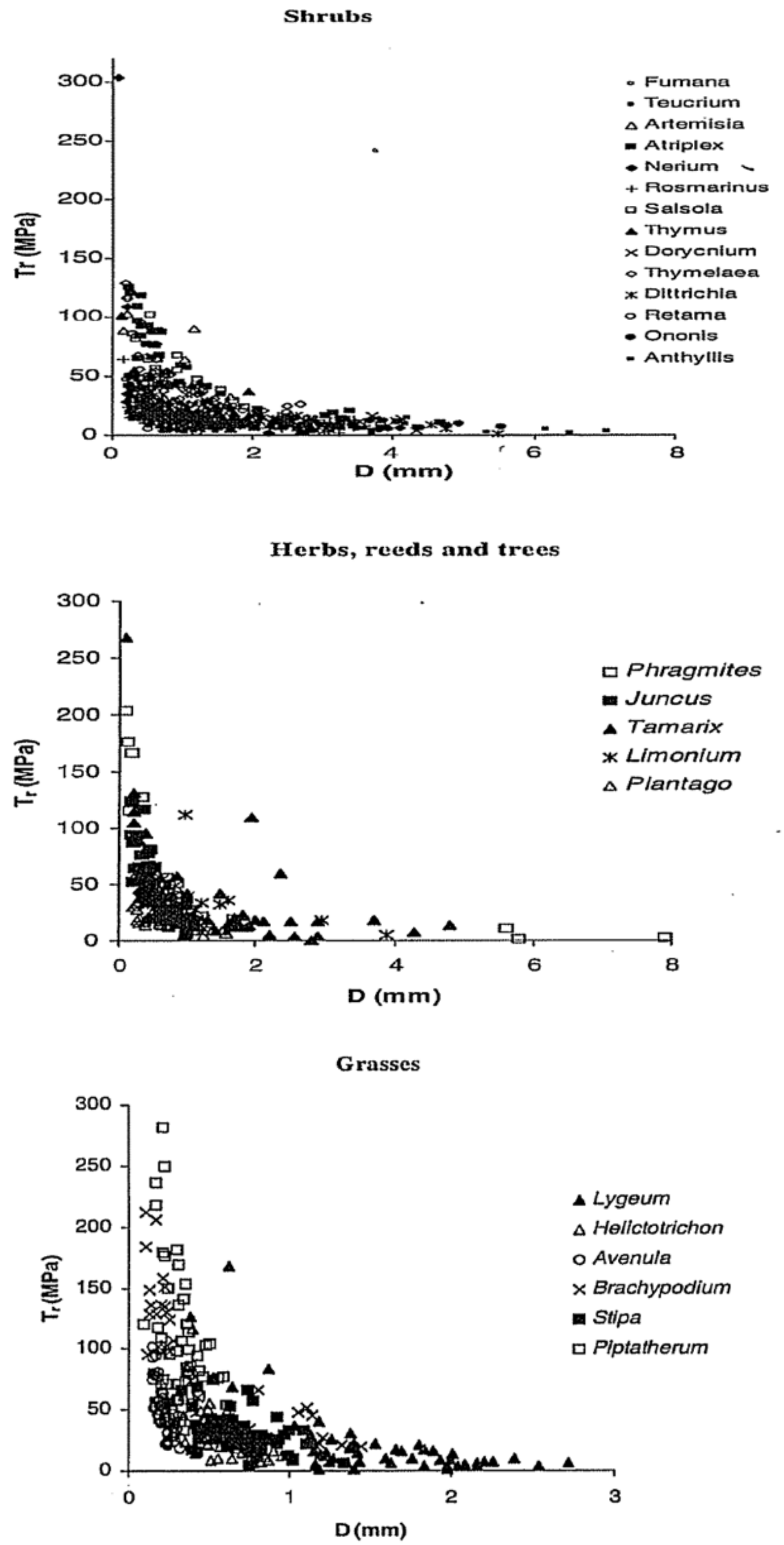


Figure 2-4. Root tensile strength plotted against root diameter. A) Shrubs. B) Herbs, reeds, and trees. C) Grass. (source: De Baets et al. 2008)

The maximum root tensile strength recorded in the test was 303 MPa with a root diameter of 0.09 mm. The test results also showed that the plant species Atriplex halimus had the strongest roots among the shrubs and Brachypodium retusum had the strongest roots among the grass (De Baets et al. 2008).

The study also assessed the contribution root area concentration to soil strength. Root area ratio (RAR) was calculated using root length density (RLD) and the diameter of the root. The notion is that there is an increase in soil shear strength due to the presence of roots. Plant roots act as a cohesive agent in the soil, binding the soil together in a "monolithic mass" which contributes to the soil strength (De Baets et al. 2008). Plants with a large RAR value will have serve to strengthen the soil it inhabits. Figure 2-5 shows the RAR of different species of plants.

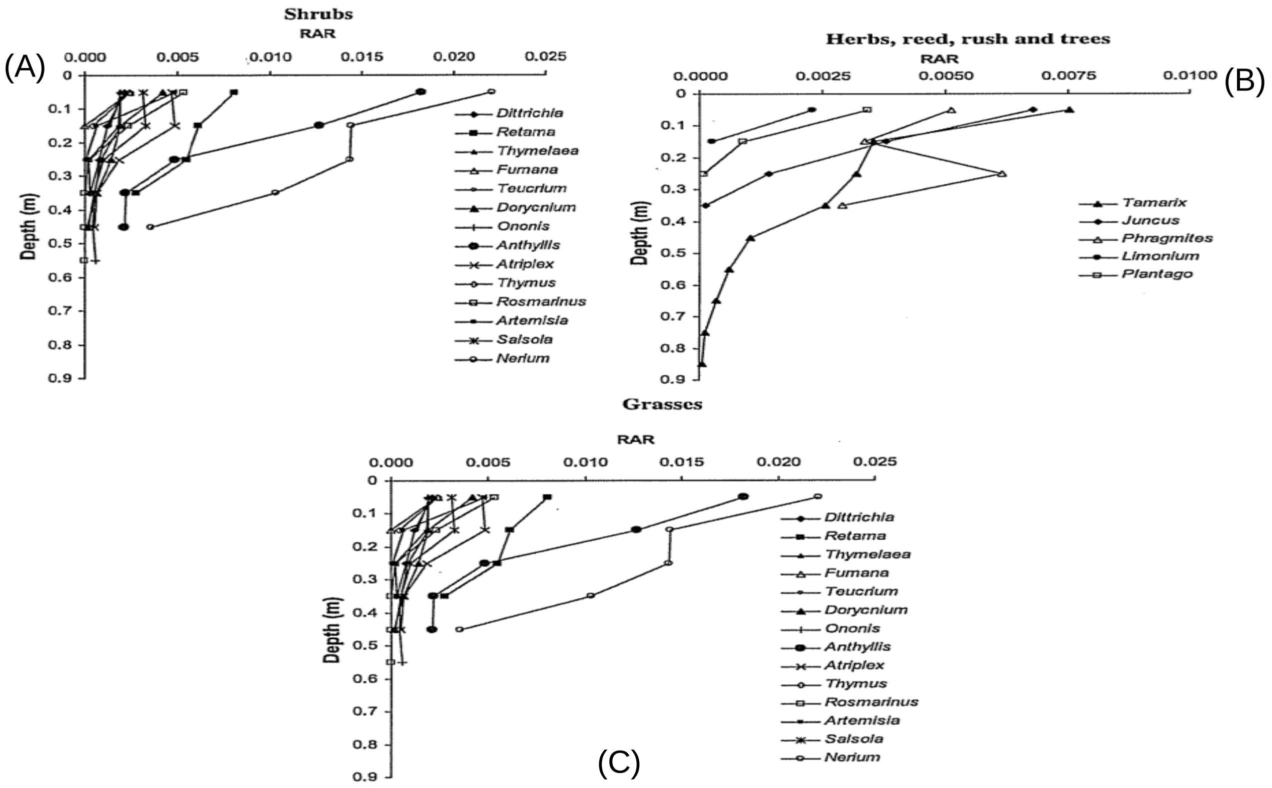


Figure 2-5. Root area ratio (RAR) distribution with depth. A) Shrubs. B) Herbs, reeds, and trees. C) Grass. (source: De Baets et al. 2008)

To comprehensively evaluate how a plant root system will perform under lateral loading, plants need to be evaluated with based on root length, root diameter, RAR, and soil type. Evaluating the combination effect of root length, root diameter, and RAR on lateral loading resistance is beyond the scope of this research. This researcher however recommends evaluating this combination effect if green roof modules are tested in a wind tunnel as it is still important to determine the survivability of the vegetation component if exposed to hurricane force winds.

Wind Loading

The effect on wind loading on vegetation is only significant if the wind is stronger than 11 m/s (24.6 mph). Wind tunnel experiments have shown that wind blowing parallel to a level surface can be expressed by the equation:

$$p=0.5p_aV^2C_D \tag{2-3}$$

Other experiments have developed an equation to determine shear forces and overturning moments due to wind. The equation is based on the assumption that the wind is only acting on individual trees and any dynamic effects are ignored. A single tree being exposed to a wind parallel to the slope can be expressed by the equation:

$$p_s=p\cos\beta\cos\beta \tag{2-4}$$

p_s represents the wind pressure and β is the slope angle normal to the wind pressure (Coppin and Richards 1990).

Growth Media

The type of growth media selected on a green roof is important to the longevity of the system. The type of growth media selected has more implication than how long the plant is going to last. It may also determine the survivability of the system under hurricane conditions. How well roots perform the function of anchorage depends on the soil the roots are embedded. Soil shear strength decreases and increases with moisture content hence plants are more susceptible to overturning in waterlogged soil. When the soil is waterlogged, critical shear stress is reached as the soil particle looses cohesion (Stokes 2002). The growth media on a green roof is generally lightweight and able to support plant life. Expanded aggregates, pumice, and volcanic rock are used as foundation for the growth media for green roofs because these minerals will not break down over time, thus contributing to the longevity of the green roof. The plant requires some amount of nutrients and this provided be added organic material to the growth media. The ratio of mineral to organic material that will contribute to a successful green roof is 80% mineral and 20% organic. A Michigan experiment attempted to determine the right organic to mineral blend. The experiment used 60% - 100% expanded slate as the inorganic substrate. For blends that had less than 100% expanded slate, the remaining volume was filled with a mixture of peat, sand and aged compost. The result showed that a growth media mix can be comprised of 80% of inorganic material and still produce healthy plants. Another study conducted by Southern Illinois University, Edwardsville (SIUE) did a similar research in an attempt to determine the best growth media mix. The experiment involved using four different types of inorganic components: Arkalyte, Haydite, lava, and pumice. The inorganic to organic ratio was kept at 80:20 with pine bark making up the organic component. The study found that pumice blend provided the best roof coverage after six months. Typically, traditional soil is too heavy, especially when wet to use on rooftops, so a green roof growing substrate was developed that had water holding capacity, degree of drainage, fertility for vegetation and growth. A firm in Atlanta is using growth media that is primarily sand based with expanded clay or slate and compost. Other common growth media used on green roofs are expanded shale, expanded clay, and crushed roofing tiles (Lucket 2009).

The ability for plants to avoid being overturned by the wind is a function of the plant's diameter, its length, and the shear strength of the soil. The shear strength of the soil is defined as the maximum resistance which it can offer to shear stress (Bell 1992). Two common growth media are peat and shale. The shear strength of peat is influenced by humification and mineral content (Bell 1992). Humification is essentially an oxidation process in which complex organic molecules are broken down into simpler organic acids, which may subsequently be mineralized into simple, inorganic forms suitable for uptake by plants (Allaby 2004). Shear strength is directly proportional to these two factors. Increased moisture content of peat has the effect of lowering its shear strength. Peat is also found to be prone to rotational failure or failure by spreading, especially when subjected to horizontal seepage forces. Peat has been found to behave similarly to normally consolidated clay, despite its extremely high water content. When fully saturated the strength of peat is negligible, as water is removed, it increases to values between 20 kN/m^2 (417.7 lb/ft^2) and 30 kN/m^2 (626.6 lb/ft^2) (Bell 1992).

The strength of shale decreases exponentially as the void ratio and moisture increases. Shale strength can be as weak as 15 kN/m^2 (313.3 lb/ft^2) or as strong as 23 MN/m^2 (480,365 lb/ft^2) depending on when it was formed. Shales formed in the Cambrian period showed to be the strongest. Desired use of the shale in the design would determine the needed strength, however, it is not recommended to use shale with strength lower than 20 kN/m^2 (417.7 lb/ft^2) (Bell 1992).

Conclusion

There is little study in the roofing industry on how wind forces affect modular green roof systems. One possibility for the lack of research is the myriad of variations to green roof systems that can be installed on a roof. Each configuration will perform differently when exposed to hurricane force winds. Another reason is the different parameters involved in determining wind load calculation. The building height and type of roof can affect the performance of the modular roof systems when exposed to high wind speeds. The literature review did show a strong possibility for the Eastern and Gulf Coast region to experience at least Category 2 hurricane each year. This data further validates the need to evaluate modular green roof systems in this region and promotes the need for standards to be in place that specifically address wind design criteria for green roof systems.

CHAPTER 3
METHODOLOGY

Introduction

In order to evaluate the effect of hurricane force winds, a theoretical building with an intensive and extensive modular green roof system was developed. The model was developed based on the Florida Building Code, ASCE 7-05, and ASCE 7-10. The building is located in an urban setting in the Florida. Florida was chosen because the State covered the range of wind speeds used in calculating wind loads on a building. The building type was based on buildings typical metropolitan area in Florida. The Florida Building Code was used to determine if any building height restrictions existed, while the ASCE Standards where used to determine the parameters needed to calculate wind loads based on the building type and location.

Developing the Model

Building

Green roofs are going to be most effective in very densely populated areas where there is a lot of hardscape. The theoretical model will be based on the types of buildings typical of densely populated urban areas. Since wind force increases with elevation, the building types being theoretical modeled are high rise commercial and residential buildings. These buildings typically have a flat roof top surface with a parapet, thus the wind load calculations will also based on this assumption.

Florida Building Code

The Florida Building Code was consulted to determine building height and parapet restrictions for the theoretical model. The Florida Building Code was used as the state has coastlines located in the eastern most part of the United States and the Gulf of

Mexico. In order to determine height constraints on the theoretical model, the building group needs to be known. The height restriction of the theoretical model is based on the Group B, Group R-1, and Group R-2 classification of buildings. Section 304.1 defines Group B as buildings that occupancy includes among others, the use of a building or structure, or portion thereof, for office, professional or service-type transactions, including the storage of records and accounts. Based on this definition, high rise commercial buildings of a densely populated urban area will fall into this category. Section 310.1 defines Group R as buildings that occupancy includes, among others, the use of a building or structure, or portion thereof, for sleeping purposes when not classified as an Institutional Group I or when not regulated by the Florida Building Code. Buildings in the Group R-1 are those that contain sleeping units where the occupants are primarily transient in nature. An example of a building in this category is a hotel. Group R-2 buildings are building that contain sleeping units or more than two dwelling units where the occupants are primary permanent in nature. Example of a building in this category is a condominium. Section 503 in the building code governs the height and area limitations for buildings and it states that the height and area for a building will be governed by the intended use of the building and shall not exceed the limits in the Table 503 of the Florida Building Code. The height and area limitations for Group B, R-1, and R-2 are listed in Table 3-1.

Table 3-1. Height and area restrictions on Group B, R-1, and R-2 buildings in the Florida Building Code

Group	Height	TYPE I	
		A	B
B	Story	Unlimited	11
	Area	Unlimited	Unlimited
R-1	Story	Unlimited	11
	Area	Unlimited	Unlimited
R-2	Story	Unlimited	11
	Area	Unlimited	Unlimited

Type I construction are those types of construction in which the building elements such as: structural frame; nonbearing walls; partitions; floor construction; and roof construction are of noncombustible materials or treated with a fire retarding agent. If the building is over two stories are 20 ft in height, fire treated wood is not permitted in the construction of the roof. Type I-A are typical of high rise buildings and Type I-B are typical of mid-rise buildings. The most appropriate type of construction for the theoretical model would be Type I-A, however, this construction type is unrestricted in height and area. The wind load calculations will be based on the highest building in the State of Florida. According to Emporis.com, a website that provides building information for buildings around the world, the Four Season Hotel in Miami in not only the tallest building in Florida, but it is also the tallest building south of Atlanta, Georgia. This building is approximately 788 ft 9 in (240.41 m) tall with an approximate building footprint of 1500 ft^2 (139.4 m^2). The building footprint information was gathered from talking to the engineering department of the hotel. The theoretical model will have a roof plan area of 1000 ft^2 (92.9 m^2) since the graph in Figure 6-15 depicts the GC_p coefficient as that is the maximum value on the effective wind area axis on that chart and a height of 790 ft (240.8 m).

A parapet is typical of high rise buildings and according to Section 2121.2.5.2 of the Florida Building Code, a parapet wall exceeding 5 ft (1.534 m) in height above a tie beam or other point of lateral support shall be specifically designed to resist horizontal wind loads.

Modular Trays

In order to properly calculate wind loads on the modular green roof system, the dimensions of trays will be needed. Modular trays vary in length and width, and can range in depths depending on the type of vegetation in needs to support. The dimensions being used in the theoretical model will be based on Weston Solution's GreenGrid® System. According to the specification summary of the products the weights in Table 3-2 are based on bulk density at maximum water holding capacity.

Table 3-2. Intensive and Extensive GreenGrid® modular green roof system

Module Type	Size	Weight of Planted Modules
Extensive	2 ft x 2ft x 4 in 60.96 cm x 60.96 cm x 10.16 cm	18 – 22 lb/ft^2 87.9 – 107.4 kg/m2
Intensive	2 ft x 2 ft x 8 in 60.96 cm x 60.96 cm x 20.32 cm	36 – 44 lb/ft^2 175.7 – 214.7 kg/m2

The theoretical model will use the 22 lb/ft^2 and the 44 lb/ft^2 weight to predict the best chance for the modular trays not to be influenced by hurricane force winds.

ASCE 7-05/10, Wind Load Calculation

Any reference made to figures, sections, and formulas are from ASCE 7-05, Chapter 6, Wind Loads unless stated otherwise. In order to use the analytical procedure for calculating wind loads on buildings, the building has to meet the following conditions:

1. The building or the other structure is a regular-shaped building or structure as defend in section 6.2.
2. The building does not have response characteristics making it subject to across wind loading, vortex shedding, instability due to galloping or flutter; or does not have site location for which channeling effects or buffeting in the wake of upwind obstructions warrants special consideration.

Calculation for velocity pressure will be based on the following equation:

$$q_z=0.00256K_zK_{zt}K_dV^2I \tag{5}$$

Section 6.5.7.1 states that isolated hills, ridges, and escarpments constituting abrupt changes in the general category, located in any exposure category, shall be included in the design. If site conditions and locations of the structures do not meet all the conditions specified in Section 6.5.7.1, K_{zt} = 1.0. Florida is a relatively flat state with little hills especially in the areas close to the coast, where you will find most of the state's major cities.

Section 6.5.8.1 states that for rigid structures as defined by section 6.2, the gust-effect factor, K_d shall be taken as 0.85. A rigid building is defined as having a negligible wind induced resonance. The theoretical model will be rigid as it is representative of a typical high rise residential or commercial building.

Section 6.5.4.4 states that the wind directionality factor, K_d, shall be determined from Table 6-4. Using the table, the K_d value will be 0.85 as the structure type being evaluated is a building.

Table 6-1 provides the value for the Importance Factor, I. The building category for the theoretical model will be Category II. For Category II, I is 1.0 for hurricane prone regions with wind speed greater than 100 mph.

The values for V, wind speed, will be based on the Figure 6-1A. Based on Figure 6-1A, the design wind speed for the State of Florida range from 100 mph to 150 mph, and is representative of the range of design wind speeds in the Eastern and Gulf Coasts.

Section 6.5.6.6 outlines the use of the Velocity Pressure Exposure Coefficient, K_z. According to Table 6-3, K_z may be determined by the following formula:

For 15 ft (4.6 m) $\leq z \leq z_g$

$$K_z=2.01\left({}^{z}/_{z_g}\right)^{2/\alpha} \tag{3-1}$$

The values z_g is 1200 and α is 7.0 based on exposure category B. Exposure category B characterized as urban area with numerous closely spaced obstructions having the size of a single family dwelling or larger. The values for z will be start at 33 ft since wind speed is defined at that height. The values will range from 33 ft (10 m) to 790 ft (241.8 m).

A value for velocity pressure, V will be calculated with the z value increasing at 15 ft increments, representing an additional story, for the different ranges of hurricane wind speeds.

The approved but unpublished newest version of the ASCE 7-05 standard, ASCE 7-10, outlines how to evaluate rooftop structures and equipment. This research assumes that the modular green roof trays will act similarly to rooftop structures and equipment when exposed to wind forces. Section 29.5.1 of the ASCE 7-10 breaks the forces acting on roof top structures and equipment into two components. Lateral force F_h and uplift force F_v. Figure 3-1 below illustrates how these forces will act on the modular green roof trays.

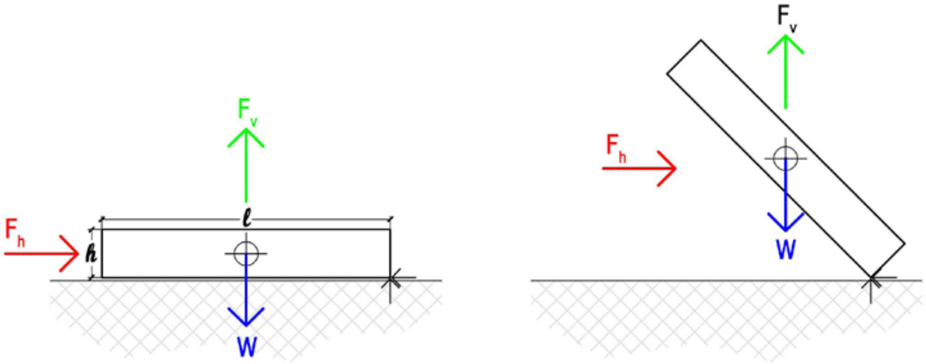


Figure 3-1. Lateral and uplift forces on modular green roof trays.

The modular green roof tray will lift up about an axis and can be represented by the equation:

$$\sum M_0 = F_h\left(\frac{h}{2}\right) + F_v\left(\frac{l}{2}\right) = W\left(\frac{l}{2}\right) \qquad (3\text{-}2)$$

where F_h is the net force in the horizontal and F_v is the net force in the vertical. For the modular green roof tray to be displaced, the lateral force produced by the wind will have to overcome the frictional force of the roofing membrane, while the uplift force will have to overcome the weight of the modular green roof tray. The coefficient of friction is the ratio of the frictional force between two bodies, parallel to the contact surface, to that of the force normal to the contact surface. Breakaway friction is the threshold friction coefficient as motion begins, and running friction is the steady-state friction coefficient as motion continues. EPDM is the most common type of roofing membrane and the coefficient of friction used in force calculations will assume that the modular green roofs are resting on an EPDM surface. The Mechanical Engineering Handbook states the theory of dry friction is the maximum frictional force that can be exerted on dry contracting surfaces that are stationary relative to each other (Marghitu et al. 2001). The value for coefficient of friction for EPDM is based on study on the dry friction and sliding wear of EPDM rubbers. The friction and wear characteristics were determined with a steel pin being pushed against the rubber plate with different loads (POP-L). Figure 3-2 shows the values for the coefficient of friction for different EPDM thicknesses.

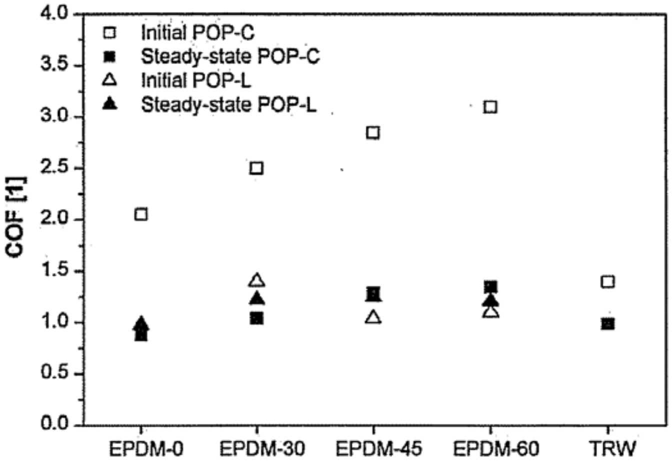


Figure 3-2. Initial and steady state coefficient of frictions for EPDM rubbers (source: Karger-Kocsis 2007).

The coefficient value for the model will be 1.25 as that value would represent the strongest coefficient of friction force for Initial POP-L. Steady-state POP-L values where ignores as those values represent the coefficient of friction as the steel pin is being dragged against the rubber which is not applicable to this research (Karger-Kocsis et al. 2007). This research assumes that the modular green roof trays will become airborne once the lateral and uplift forces overpower become greater than the frictional force and the weight of the modular green roof tray respectively. Table 3-3 lists the frictional force of the extensive and intensive modular green roof tray.

Table 3-3. Frictional Force for the maximum weight of GreenGrid® modular green roof system

Module Type	Weight	Coefficient of Friction (μ)	Frictional Force (F_f)
Extensive	88 lbs (39.9 kg)	1.25	110 lb (489.3 N)
Intensive	176 lbs (79.8 kg)	1.25	220 lb (978.6 N)

According to section 29.5.1 of the ASCE 7-10 standard, the lateral force F_h shall be determined by the equation:

$$F_h=q_h(GC_r)A_f \tag{3-3}$$

The variable q_h is the velocity pressure evaluated at the mean roof height of the building. The variable A_f is the vertical projected area of the rooftop structure or equipment on a plane normal to the direction of the wind. GC_r is 1.9 for rooftop structures and equipment with A_f less than the 10% of the building's base and height (0.1Bh). The smallest Bh value for the theoretical model is 1042.8 ft^2 (97 m^2), based on a 33 ft (10 m) height and base of 31.62 ft (9.6 m). The horizontal A_f value needed to calculate the lateral force for both the extensive and intensive modular trays are shown in Table 3-4.

Table 3-4. Extensive and intensive GreenGrid® modular green roof system horizontal A_f value for lateral force

Module Type	Horizontal A_f
Extensive	0.67 ft^2 (622.5 cm^2)
Intensive	1.33 ft^2 (0.12 m^2)

Since A_f will always be less than 10% of the building's base and height, the horizontal GC_r value for the theoretical model will be 1.9.

According to section 29.5.1 of the ASCE 7-10 standard, the lateral force F_h shall be determined by the equation:

$$F_v=q_h(GC_r)A_f \tag{3-4}$$

The variable q_h is the velocity pressure evaluated at the mean roof height of the building. The variable A_f is the vertical projected area of the rooftop structure or equipment on a plane normal to the direction of the wind.

GC_r is 1.5 for rooftop structures and equipment with A_f less than the 10% of the building's base and height (0.1Bh). The smallest Bh value for the theoretical model is 1042.8 ft^2 (97 m^2), based on a 33 ft (10 m) height and base of 31.62 ft (9.6 m). The horizontal A_f value needed to calculate the uplift force for both the extensive and intensive modular trays are shown in Table 3-5.

Table 3-5. Extensive and intensive GreenGrid® modular green roof system horizontal A_f value for uplift force

Module Type	Horizontal A_f
Extensive	4 ft^2 (0.37 m^2)
Intensive	4 ft^2 (0.37 m^2)

Since A_f will always be less than 10% of the building's base and height, the vertical GC_r value for the theoretical model will be 1.5.

Root Structure and Growth Media

To determine the survivability of vegetation on green roofs under hurricane conditions, a range of values for D, root diameter, and L, rod length, in the equation $R_{max} = 4.5\sigma DL^2$ will need to be evaluated for a tap root system. When determining R_{max} value for the shear strength of the soil, σ, the shear strength of the soil type when wet should be used since hurricanes typically produce a lot rain. This R_{max} value will then be compared to the horizontal force, F_h, produced by the wind at that specific height. If F_h is greater than R_{max}, overturning will occur. Due to the infinite combination of L and D for vegetation typical to a green roof, a realistic model for the survivability of the different types of vegetation when subjected to hurricane force winds will be an enormous undertaking and would take years of research. Conducting additional research will only be applicable for intensive green roof modular systems as extensive green roof modular systems are not designed to support the type of vegetation where this analysis is needed.

Summary

The model in which the modular green roof system will be evaluated is based on a 790 ft (240.8 m) building with a footprint of 1500 ft^2 (139.4 m^2), a roof top area is 1000 ft^2 (92.9 m^2), and located in a urban setting in the State of Florida. The module being evaluated is based on Weston Solution's standard extensive and intensive GreenGrid® modules. The max saturated weight for the modules will be 22 lb/ft^2 for the intensive and 44 lb/ft^2. The modules will be resting on an EPDM roofing membrane which has a coefficient of friction of 1.25 against a metal surface. The modules will be evaluated on their ability to survive the different design wind speeds for the State of Florida which range from 100 mph to 150 mph. The model assumes that the both the intensive and extensive modular trays will overturn when the combination of both the horizontal and vertical components of the wind force overcome the weight of the respective module along with its frictional force that exist between the metal trays and the EPDM roof membrane.

CHAPTER 4
RESULTS

Introduction

The results of this study are presented in a series of graphs that show the net horizontal and net vertical forces on both the modular extensive and intensive trays from a building height of 33 ft (10.1 m) to 790 ft (240.8 m) at wind speeds ranging from 100 mph to 150 mph. The net horizontal force is the difference between the frictional force of the modular tray and the lateral force produced by the hurricane wind. The net vertical force is the difference between the force supplied by weight of the modular green roof tray and the wind uplift force produced by the hurricane wind. Another series of graphs illustrate the failure height of the modular green roof at wind speeds ranging from 100 mph to 150 mph. The line of failure depicts when the net moment created by combination net horizontal and net vertical forces on the modular trays become greater than zero. If the summation of moments of an object about an axis is greater than zero that object is motion. Therefore the line of failure for the extensive and intensive modular trays is at a moment of 88 lbs·ft and 176 lbs·ft respectively.

Extensive Modular Trays

Figure 4-1 shows the net horizontal and net vertical forces at 100 mph wind speed. The minimum net horizontal and net vertical force produced by the 100 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -90.1 lbs (-401 N) and 5.9 lbs (26.2 N) respectively. The maximum net horizontal and net vertical force produced by the 100 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height were -60.6 lbs (-269.6 N) and 144.9 lbs (644.5 N). Figure 4-2 shows 363 ft (110.6 m) as the maximum building height this type of modular tray can remain on the roof top without being affected by the force produced by the wind speed.

Figure 4-3 shows the net horizontal and net vertical forces at 110 mph wind speed. The minimum net horizontal and net vertical force produced by the 110 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -85.9 lbs (-382.1 N) and 25.7 lbs (114.3 N) respectively. The maximum net horizontal and net vertical force produced by the 110 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height is -50.2 lbs (-223.3 N) and 193.8 lbs (1.25 kN). Figure 4-4 shows 183 ft (55.7 m) as the maximum building height this type of modular tray can remain on the roof top without being affected by the force produced by the wind speed.

Figure 4-5 shows the net horizontal and net vertical forces at 120 mph wind speed. The minimum net horizontal and net vertical force produced by the 120 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -81.3 lbs (-361.6 N) and 47.4 lbs (210.8 N) respectively. The maximum net horizontal and net vertical force produced by the 120 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height is -38.9 lbs (-173 N) and 247.3 lbs (1.10 kN). Figure 4-6 shows 93 ft (28.3 m) as the maximum building height this type of modular tray can remain on the roof top without being affected by the force produced by the wind speed.

Figure 4-7 shows the net horizontal and net vertical forces at 130 mph wind speed. The minimum net horizontal and net vertical force produced by the 130 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -76.3 lbs (-339.4 N) and 70.9 lbs (315.4 N) respectively. The maximum net horizontal and net vertical force produced by the 130 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height is -26.8 lbs (-119.2 N) and 305.6 lbs (1.36 kN). Figure 4-8 shows 33 ft (10.1 m) as the maximum building height this type of modular tray can remain on the roof top without being affected by the force produced by the wind speed.

Figure 4-9 shows the net horizontal and net vertical forces at 140 mph wind speed. The minimum net horizontal and net vertical force produced by the 140 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -70.9 lbs (-315.4 N) and 96.2 lbs (427.9 N) respectively. The maximum net horizontal and net vertical force produced by the 140 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height is -13.15 lbs (-60.1 N) and 368.4 lbs (1.64 kN). Figure 4-10 shows 33 ft (10.1 m) as the maximum building height this type of modular tray can remain on the roof top without being affected by the force produced by the wind speed.

Figure 4-11 shows the net horizontal and net vertical forces at 150 mph wind speed. The minimum net horizontal and net vertical force produced by the 150 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -65.1 lbs (-289.6 N) and 123.5 lbs (549.4 N) respectively. The maximum net horizontal and net vertical force produced by the 150 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height is 1.17 lbs (5.20 N) and 436 lbs (1.94 kN). Figure 4-12 shows that the line of failure is below the starting evaluation height of 33 ft (10.1).

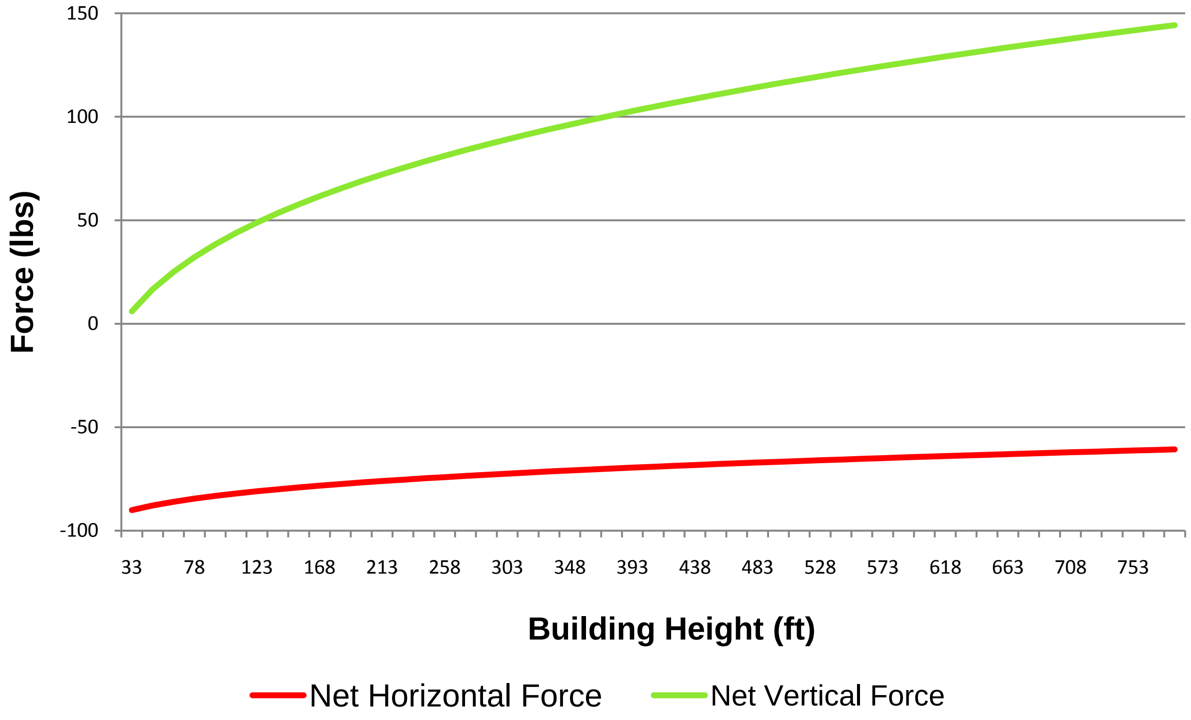


Figure 4-1. 100 mph wind net force on extensive modular trays

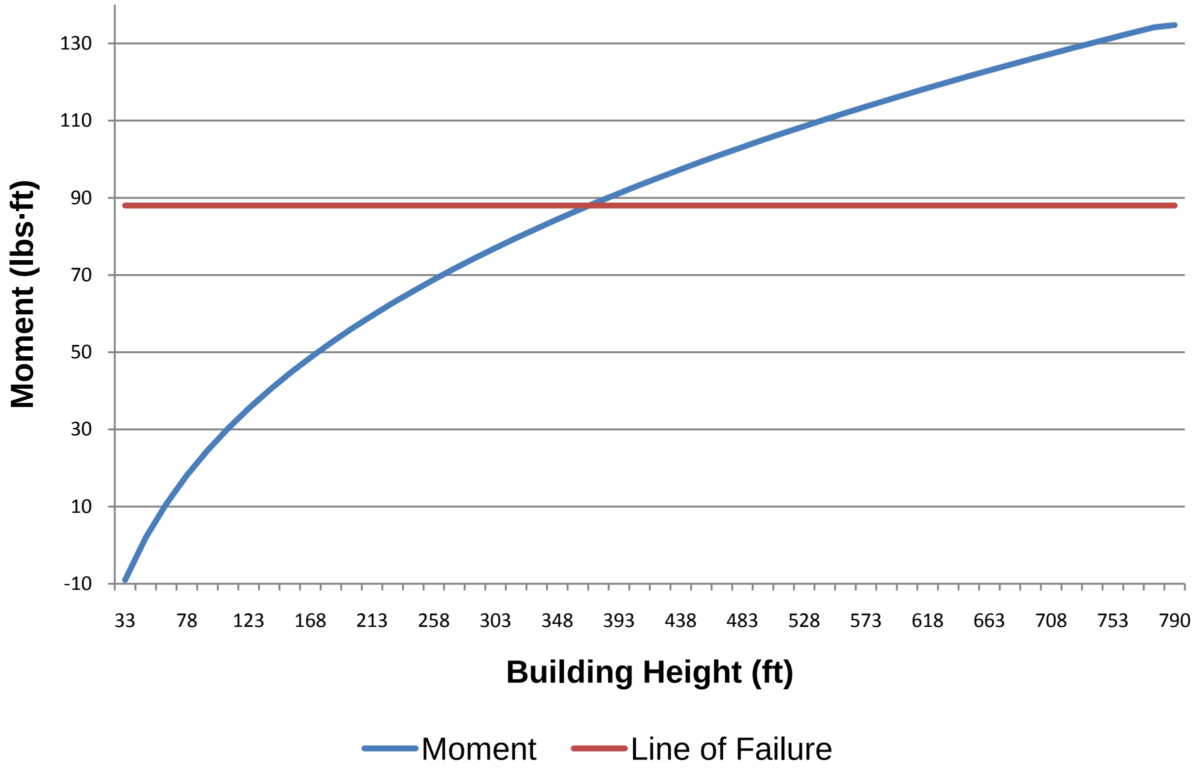


Figure 4-2. Extensive modular tray performance in 100 mph wind

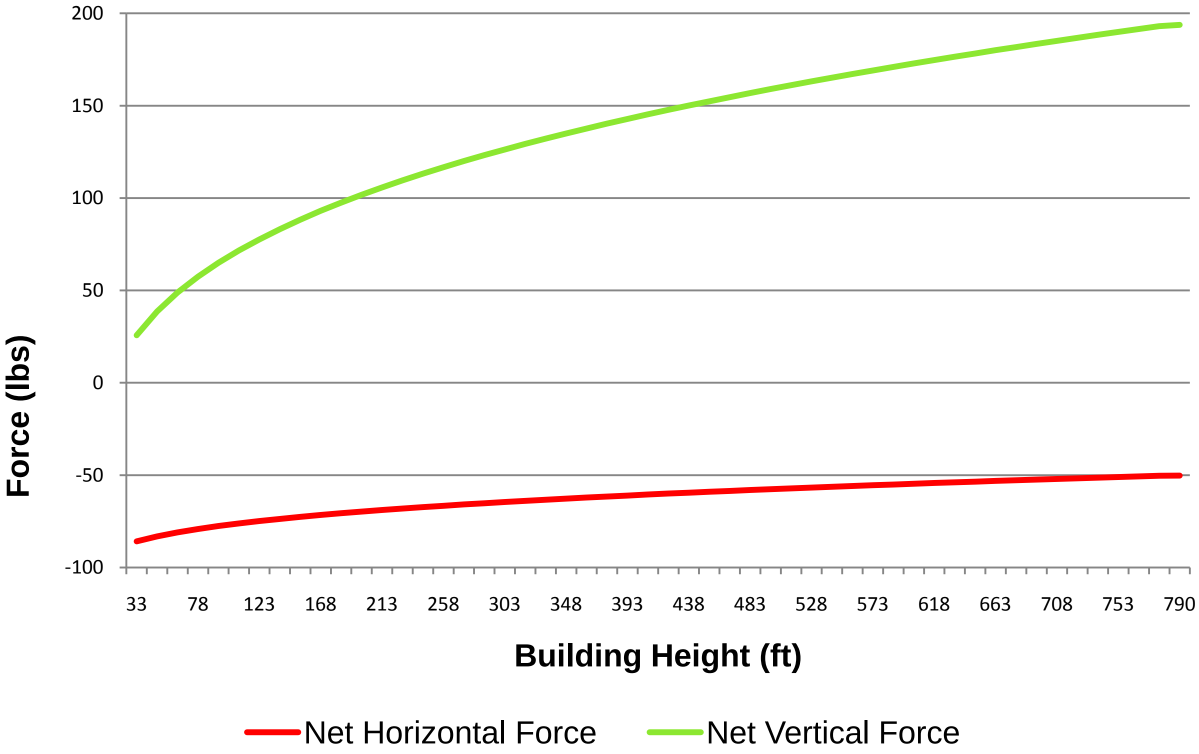


Figure 4-3. 110 mph wind net force on extensive modular trays

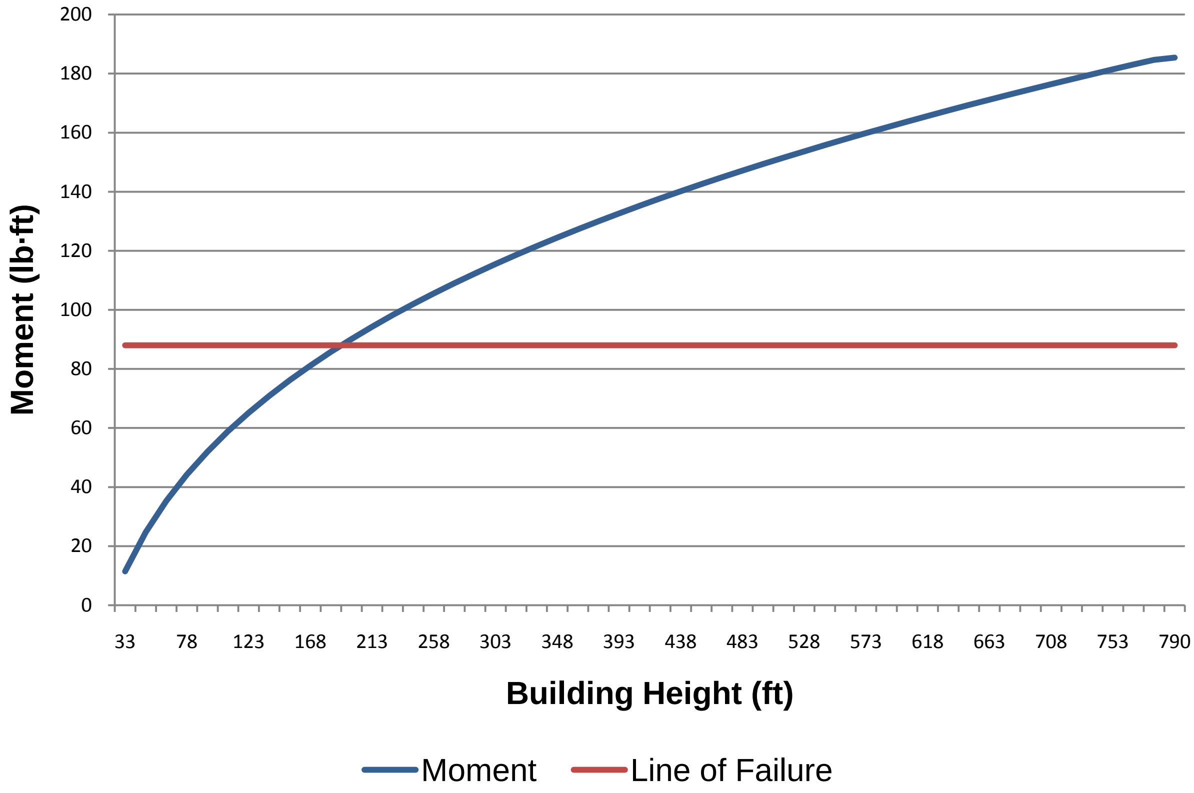


Figure 4-4. Extensive modular tray performance in 110 mph wind

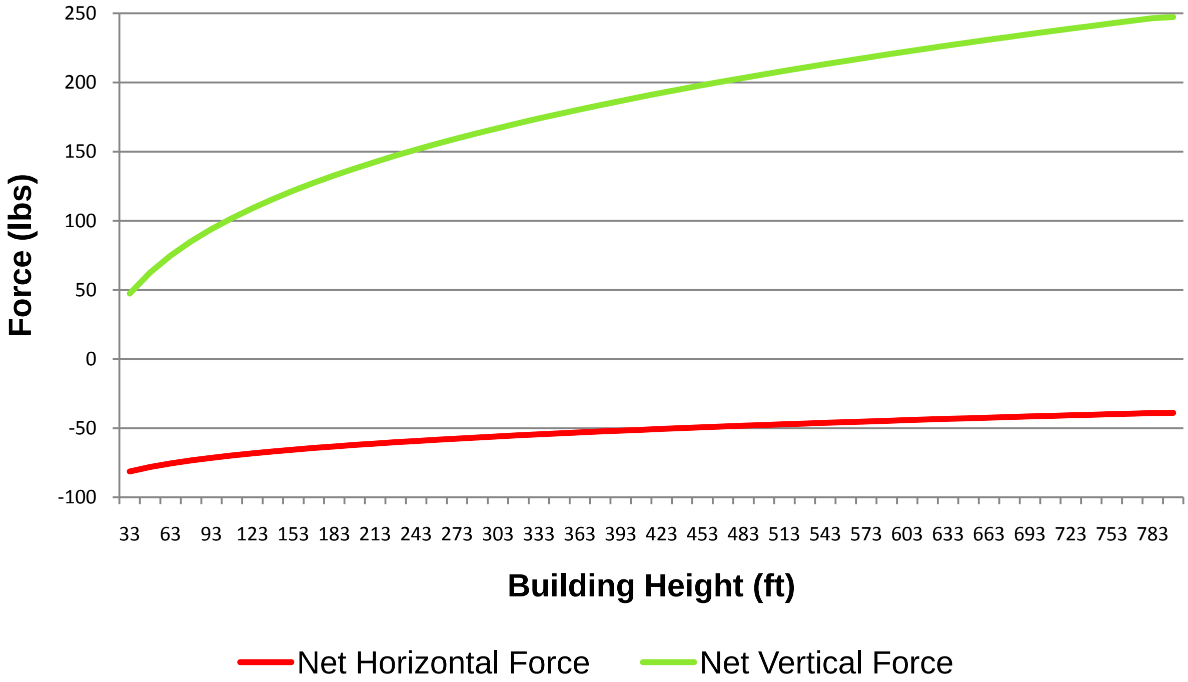


Figure 4-5. 120 mph wind net force on extensive modular trays

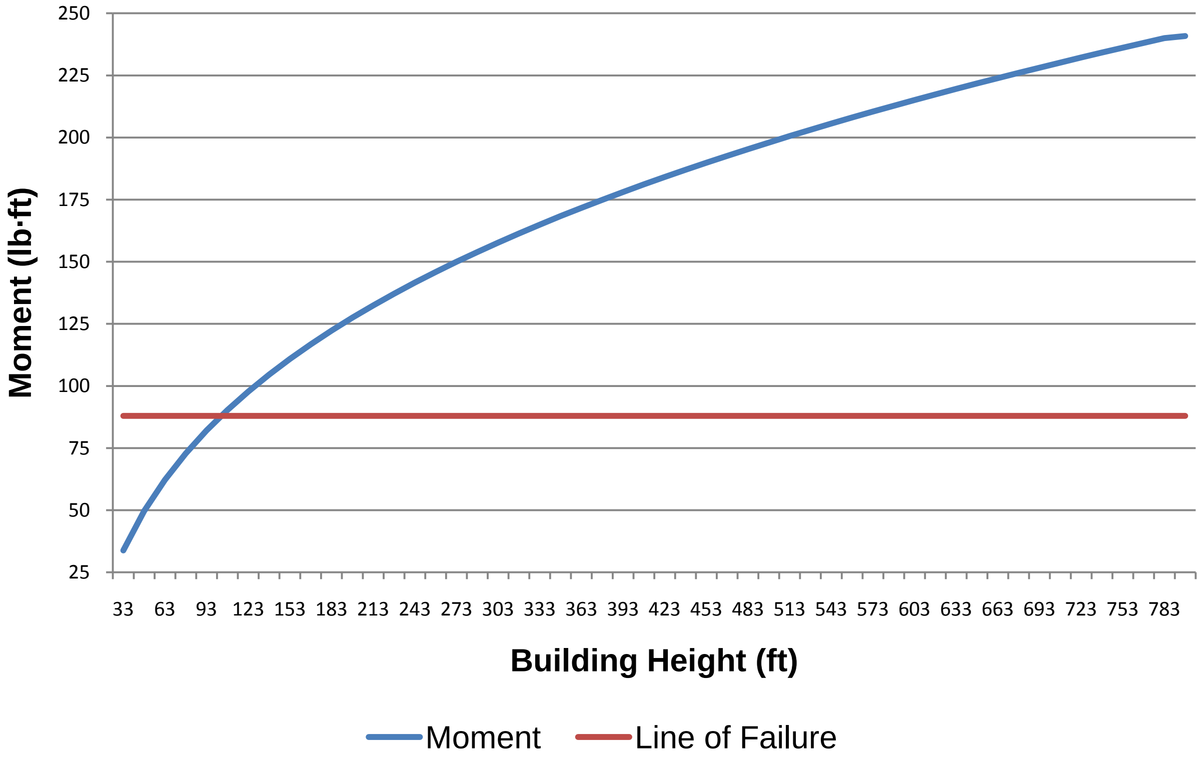


Figure 4-6. Extensive modular tray performance in 120 mph wind

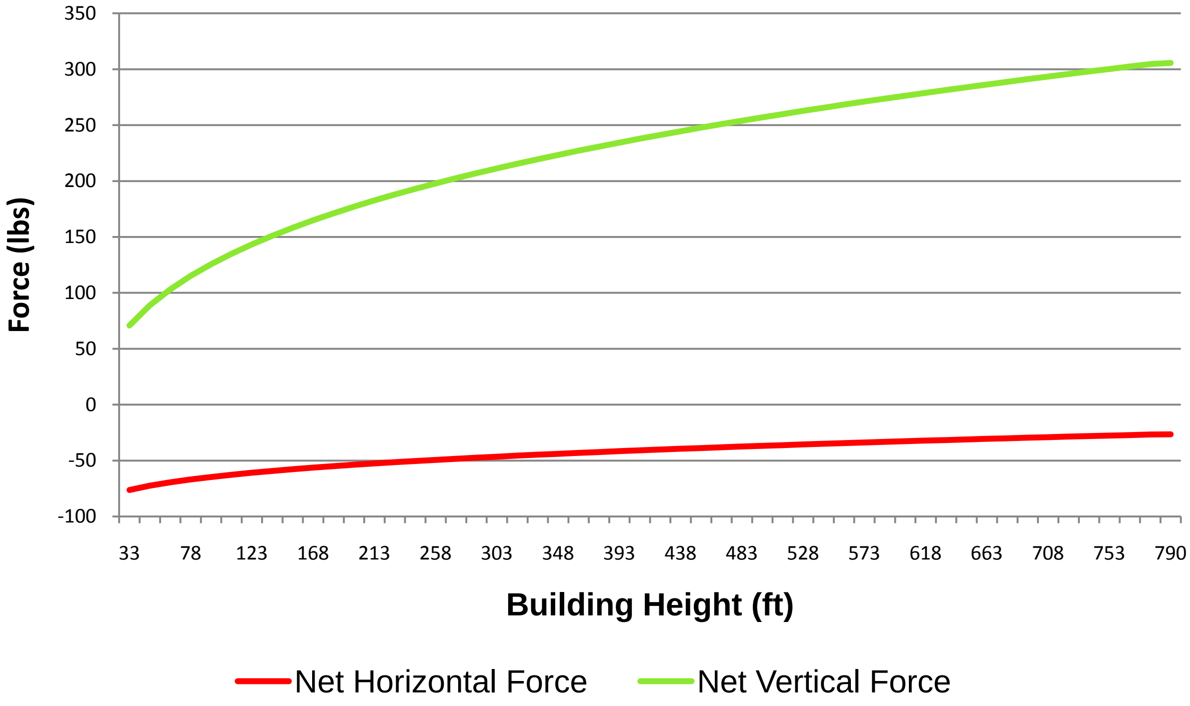


Figure 4-7. 130 mph wind net force on extensive modular trays

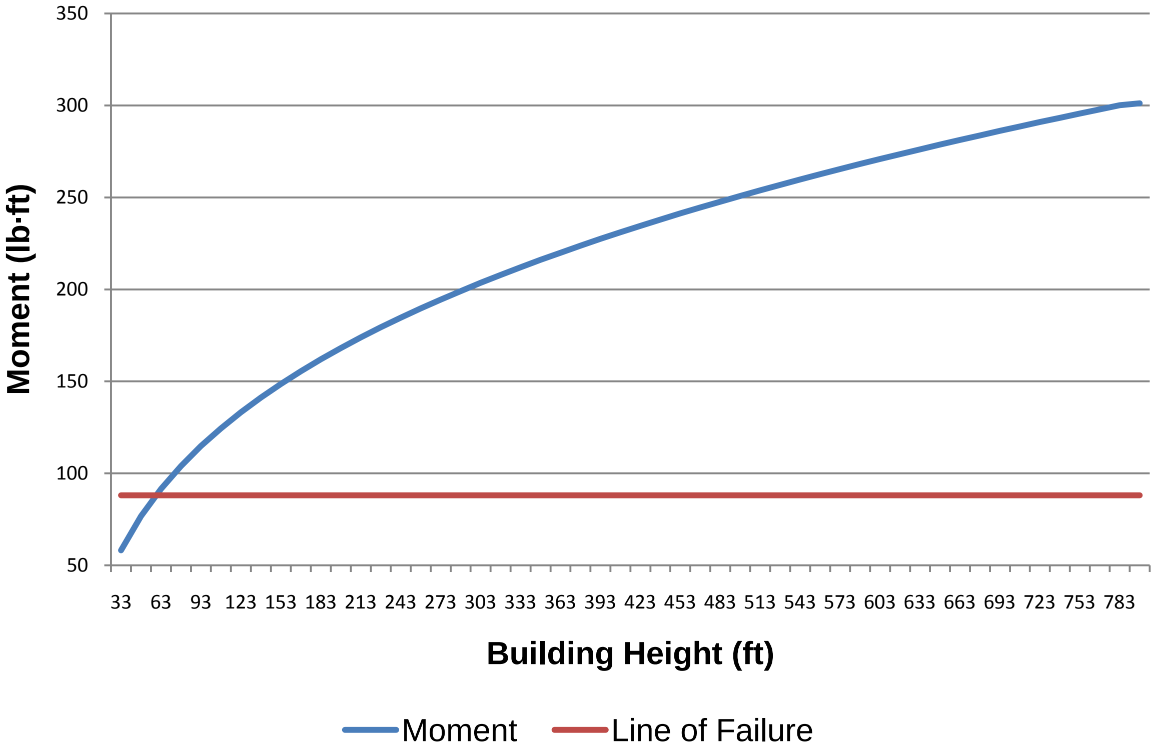


Figure 4-8. Extensive modular tray performance in 130 mph wind

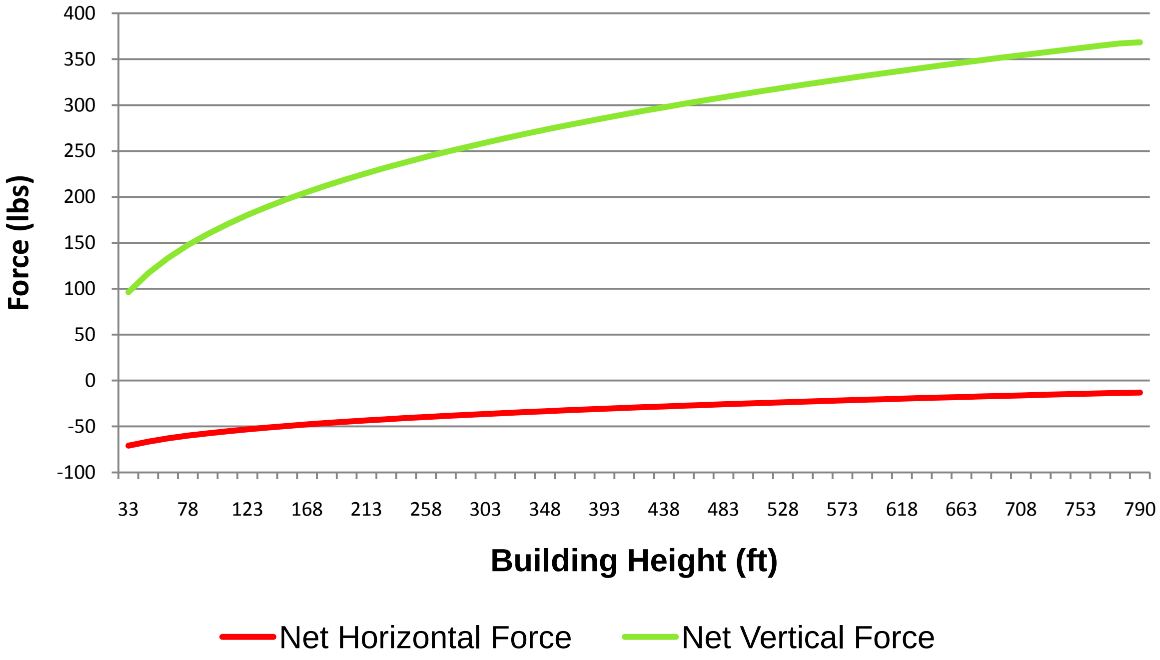


Figure 4-9. 140 mph wind net force on extensive modular trays

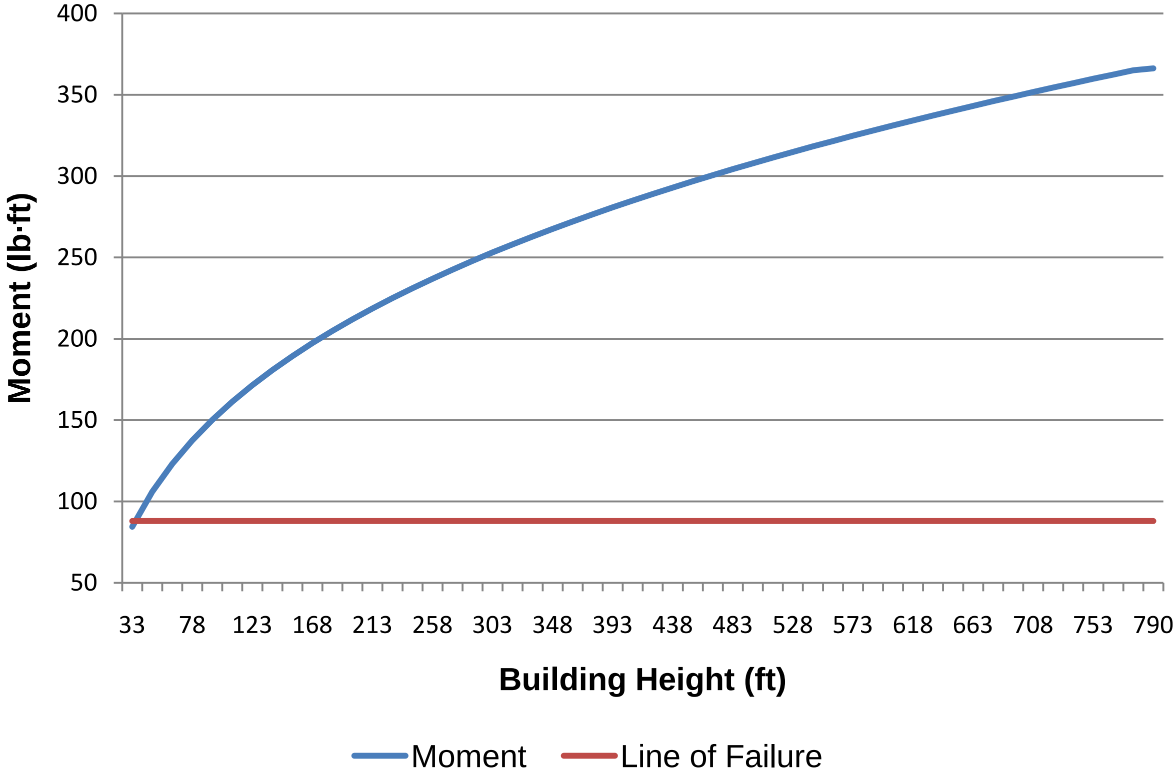


Figure 4-10. Extensive modular tray performance in 140 mph wind

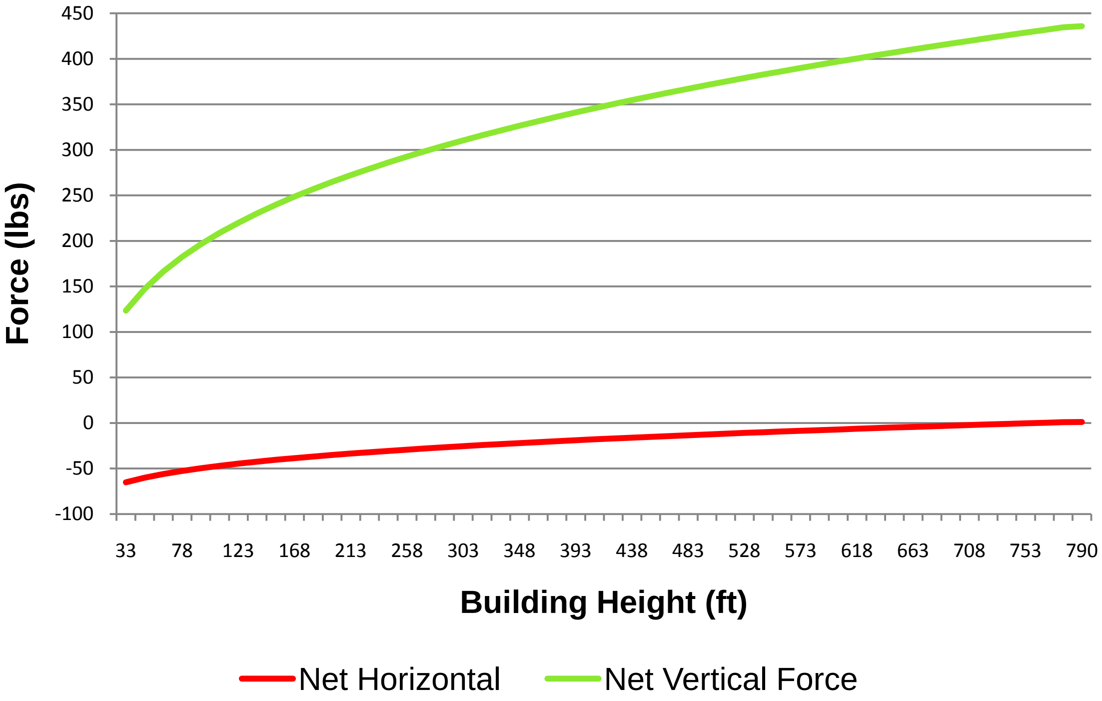


Figure 4-11. 150 mph wind net force on extensive modular trays

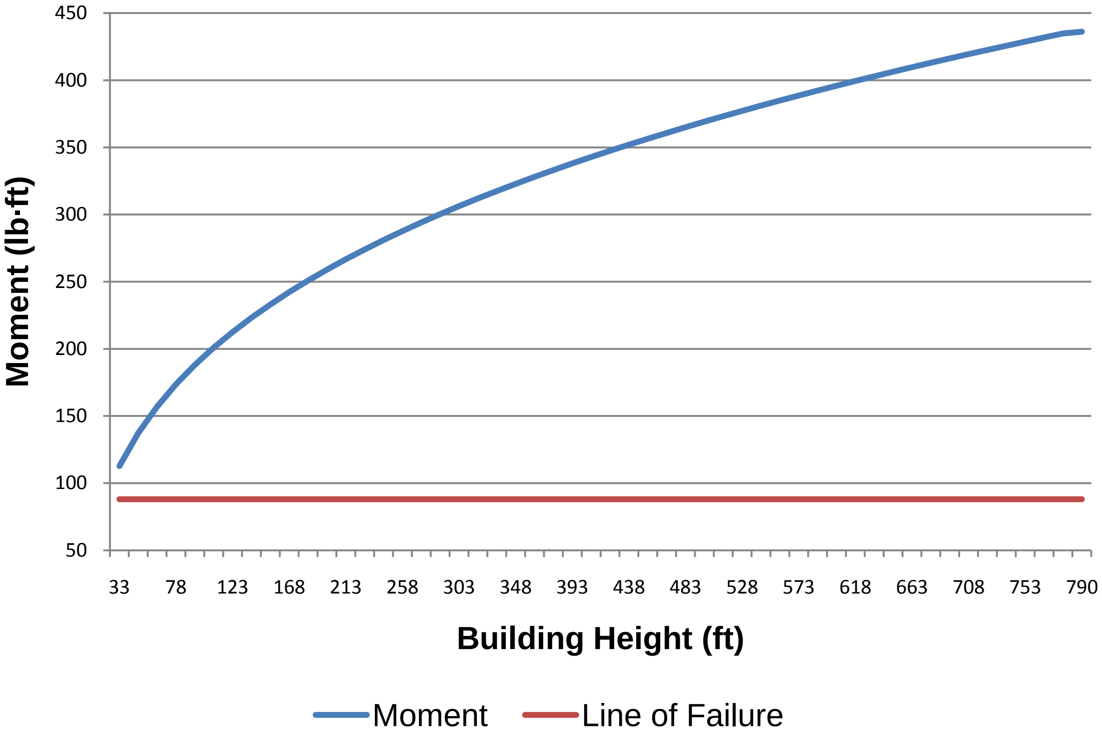


Figure 4-12. Extensive modular tray performance in 150 mph wind

Intensive Modular Trays

Figure 4-13 shows the net horizontal and net vertical forces at 100 mph wind speed. The minimum net horizontal and net vertical force produced by the 100 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -180.4 lbs (-802.5 N) and -82 lbs (-364.8 N) respectively. The maximum net horizontal and net vertical force produced by the 100 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height were -121.9 lbs (-542.2 N) and 56.9 lbs (253.1 N). Figure 4-14 shows the intensive modular trays do not fail for any given building height.

Figure 4-15 shows the net horizontal and net vertical forces at 110 mph wind speed. The minimum net horizontal and net vertical force produced by the 110 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -172.1 lbs (-765.5 N) and -62.3 lbs (-277.1 N) respectively. The maximum net horizontal and net vertical force produced by the 110 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height were -101.3 lbs (-450.6 N) and 105.8 lbs (470.6 N). Figure 4-16 shows the intensive modular trays do not fail for any given building height.

Figure 4-17 shows the net horizontal and net vertical forces at 120 mph wind speed. The minimum net horizontal and net vertical force produced by the 120 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -163 lbs (-725.1 N) and -40.6 lbs (-180.6 N) respectively. The maximum net horizontal and net vertical force produced by the 120 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height were -78.8 lbs (-350.5 N) and 159.3 lbs (708.6 N). Figure 4-18 shows the intensive modular trays do not fail for any given building height.

Figure 4-19 shows the net horizontal and net vertical forces at 130 mph wind speed. The minimum net horizontal and net vertical force produced by the 130 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -153.1 lbs (-681 N) and -17.1 lbs (-76.1 N) respectively. The maximum net horizontal and net vertical force produced by the 130 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height were -54.2 lbs (-241.1 N) and 217.6 lbs (967.9 N). Figure 4-20 shows 648 ft (197.5 m) as the approximate building height where the net moment is less than 176 lbs·ft.

Figure 4-21shows the net horizontal and net vertical forces at 140 mph wind speed. The minimum net horizontal and net vertical force produced by the 140 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -142.4 lbs (-633.4 N) and 8.22 lbs (36.6 N) respectively. The maximum net horizontal and net vertical force produced by the 140 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height is -27.8 lbs (-123.7 N) and 280.4 lbs (1.25 kN). Figure 4-22 shows 378 ft (115.2 m) as the maximum building height this type of modular tray can remain on the roof top without being affected by the force produced by the wind speed.

Figure 4-23 shows the net horizontal and net vertical forces at 150 mph wind speed. The minimum net horizontal and net vertical force produced by the 150 mph wind was noted at the 33 ft (10.1 m). The net horizontal force and vertical force at that building height were -130.9 lbs (-582.3 N) and 35.5 lbs (157.9 N) respectively. The maximum net horizontal and net vertical force produced by the 150 mph wind was noted at the 790 ft (240.8 m). The net horizontal force and vertical force at that building height is 0.68 lbs (3.02 N) and 348 lbs (1.55 kN). Figure 4-24 shows 228 ft (69.5 m) as the maximum building height the modular tray can remain on the roof top without being affected by the force produced by the wind speed.

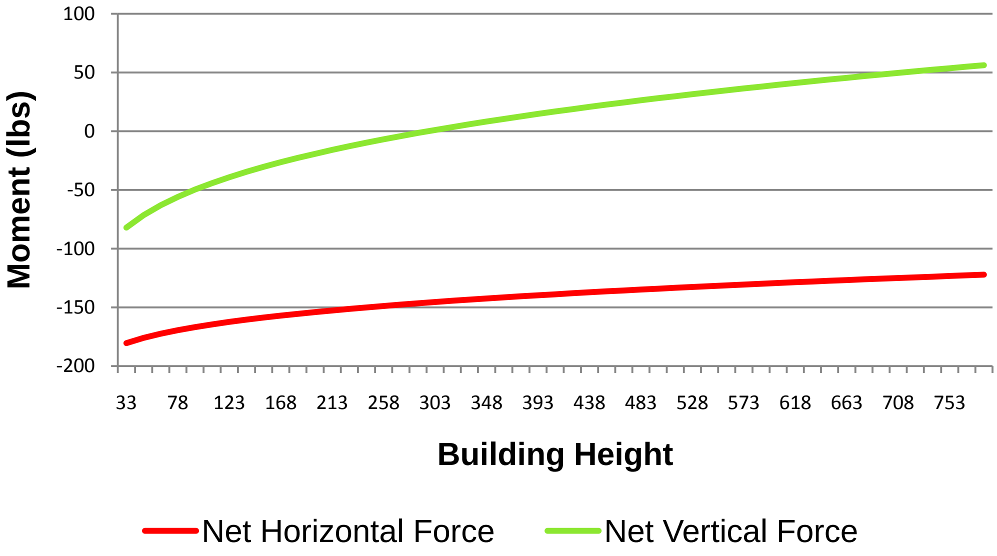


Figure 4-13. 100 mph wind net force on intensive modular trays

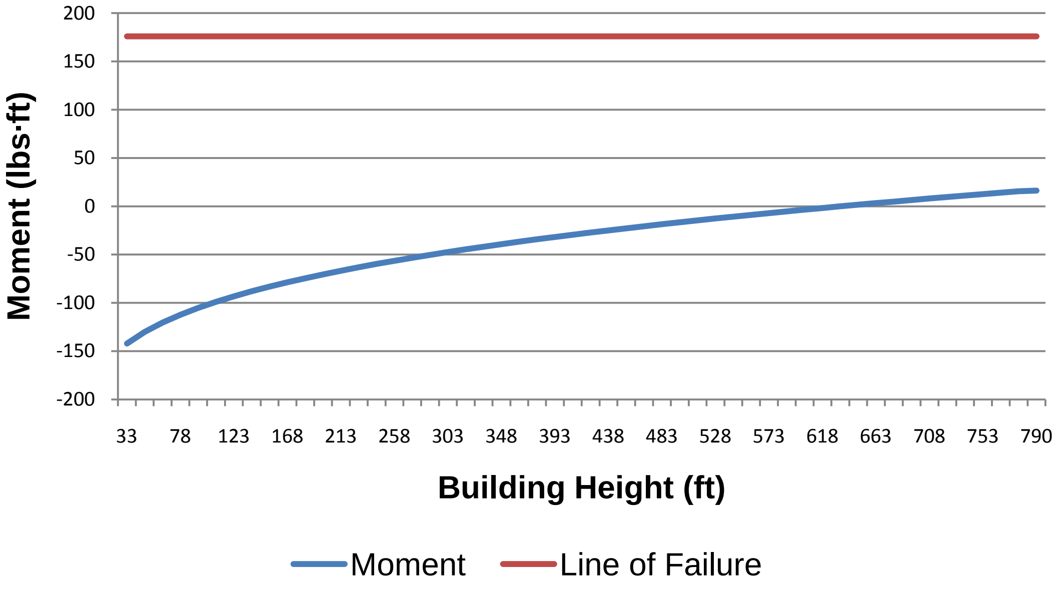


Figure 4-14. Intensive modular tray performance in 100 mph wind

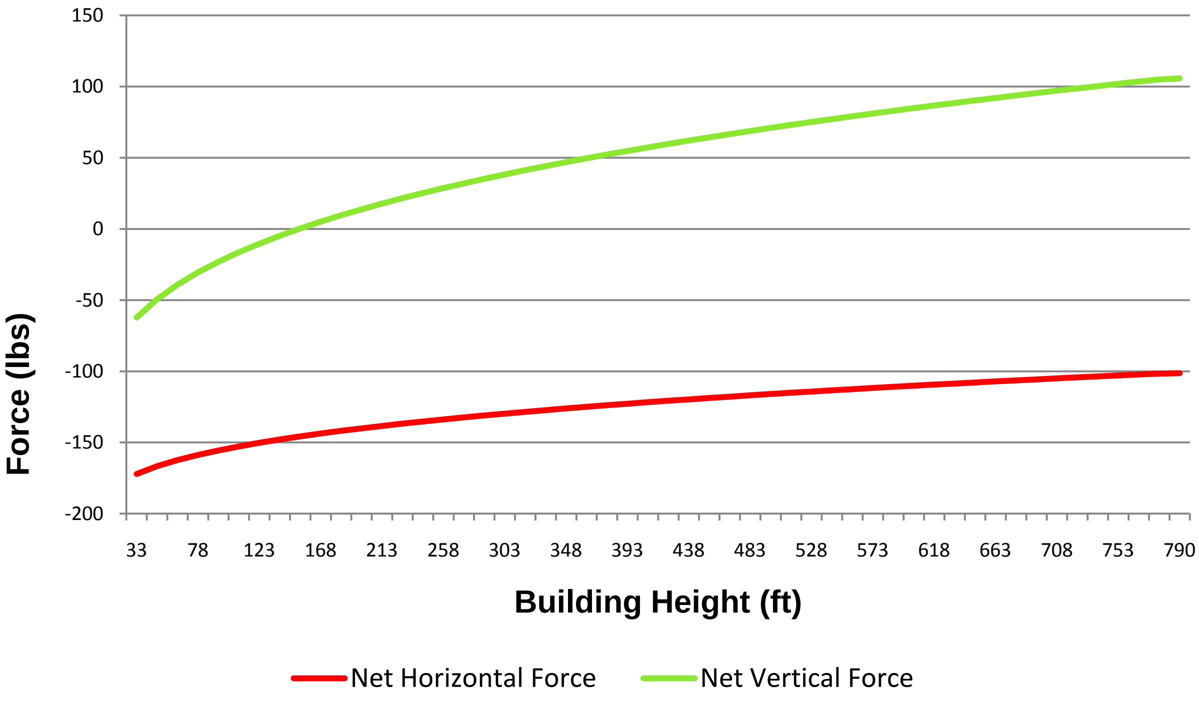


Figure 4-15. 110 mph wind net force on intensive modular trays

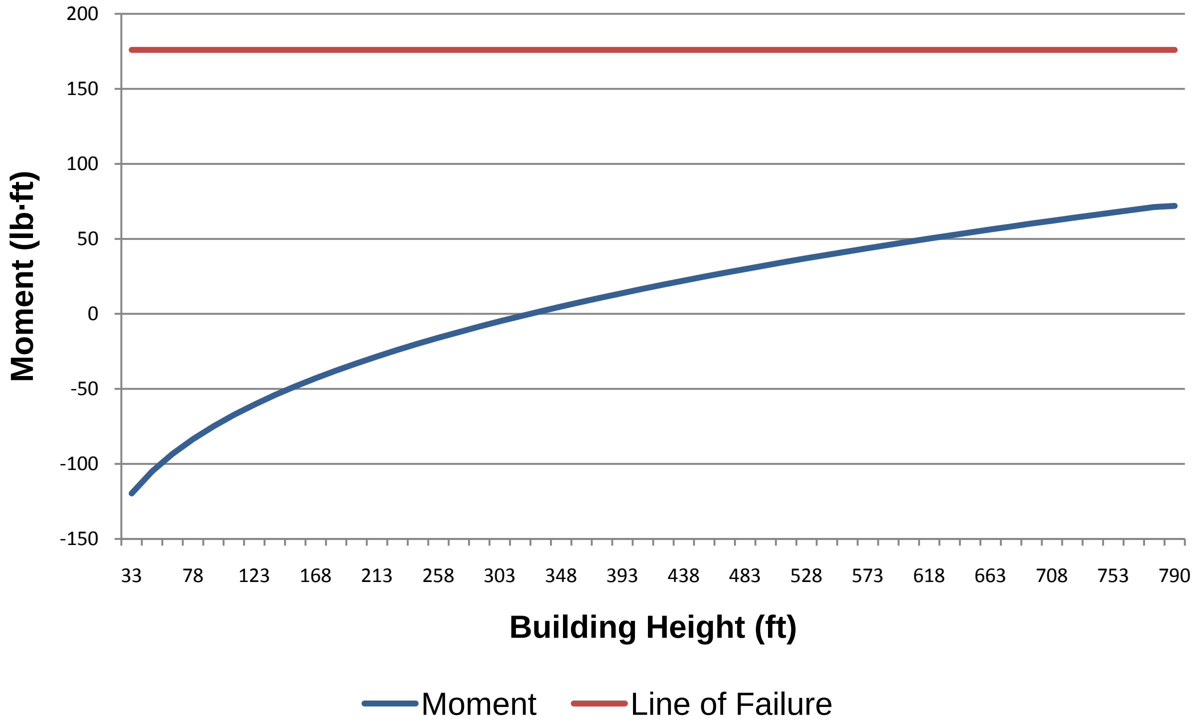


Figure 4-16. Intensive modular tray performance in 110 mph wind

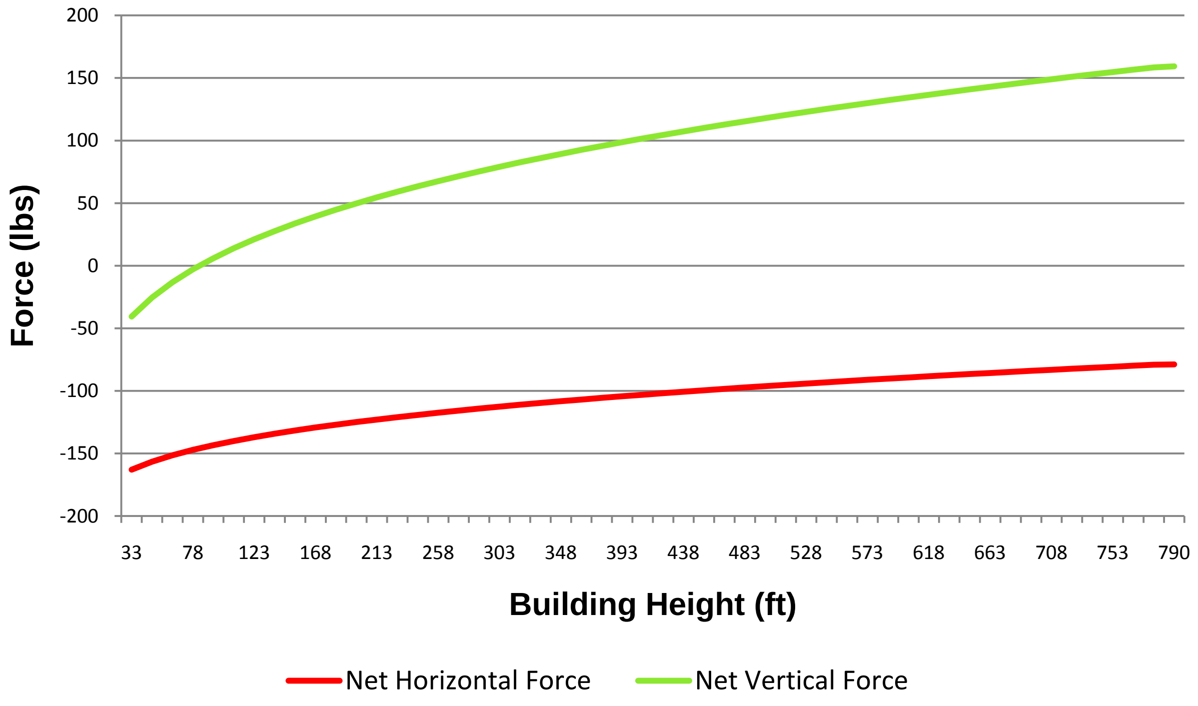


Figure 4-17. 120 mph wind net force on intensive modular trays

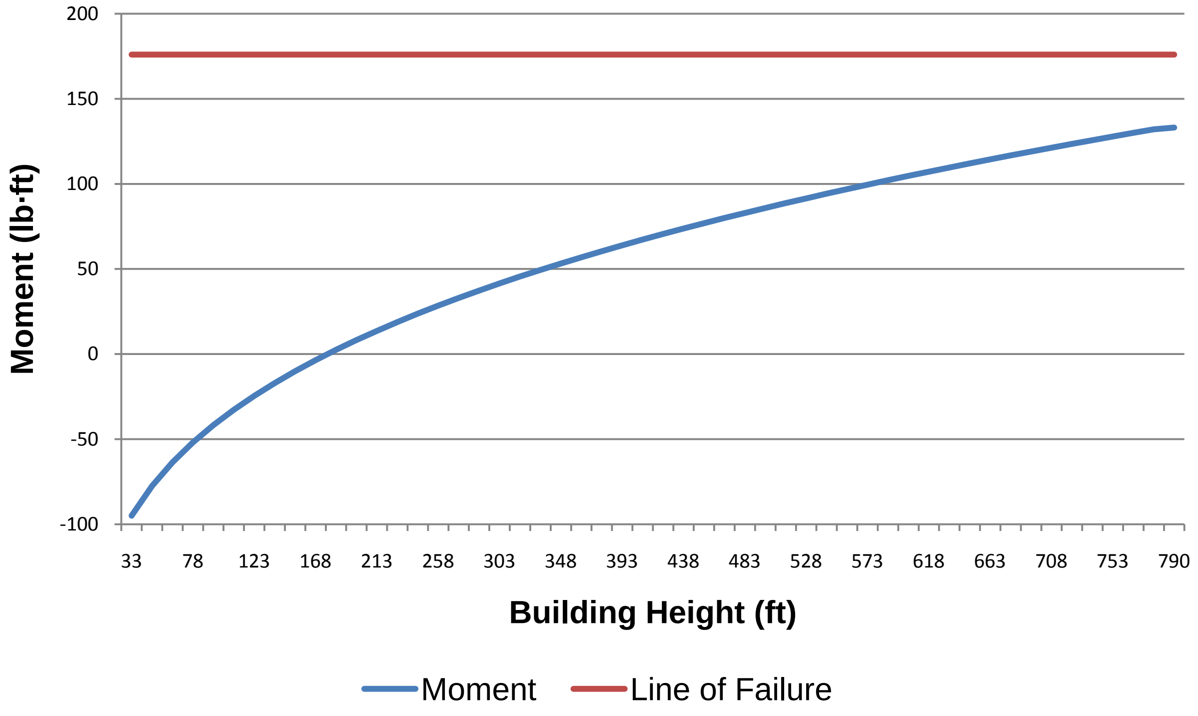


Figure 4-18. Intensive modular tray performance in 120 mph wind

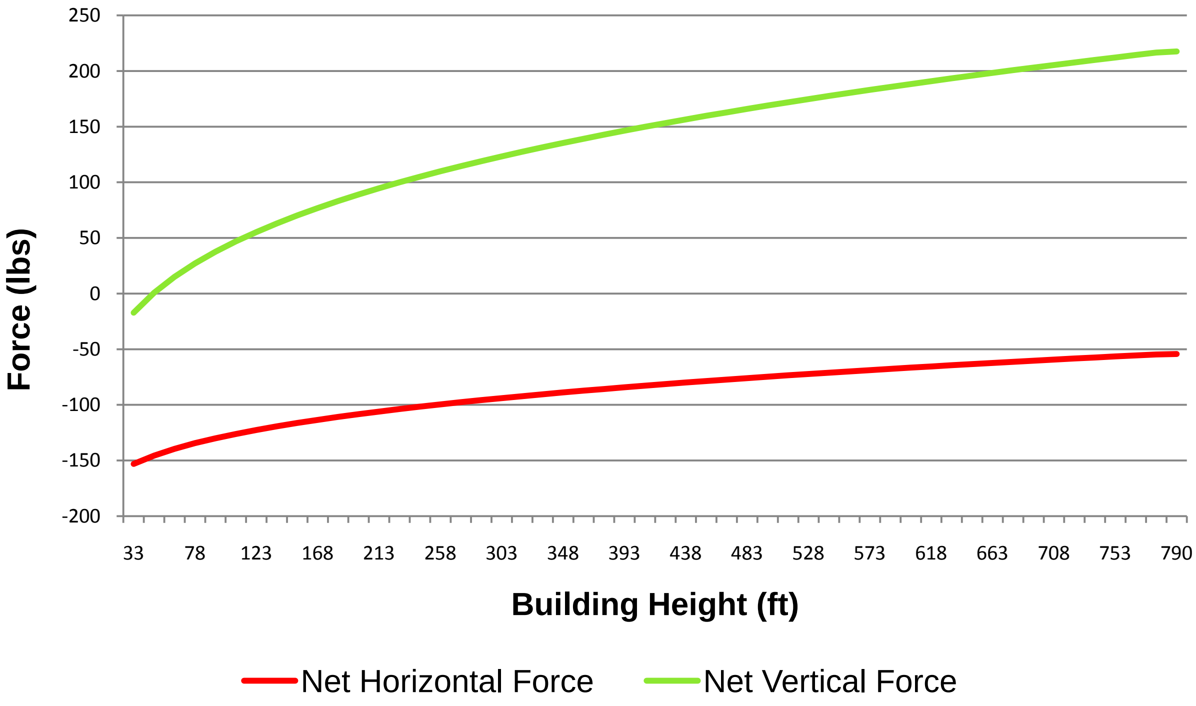


Figure 4-19. 130 mph wind net force on intensive modular trays

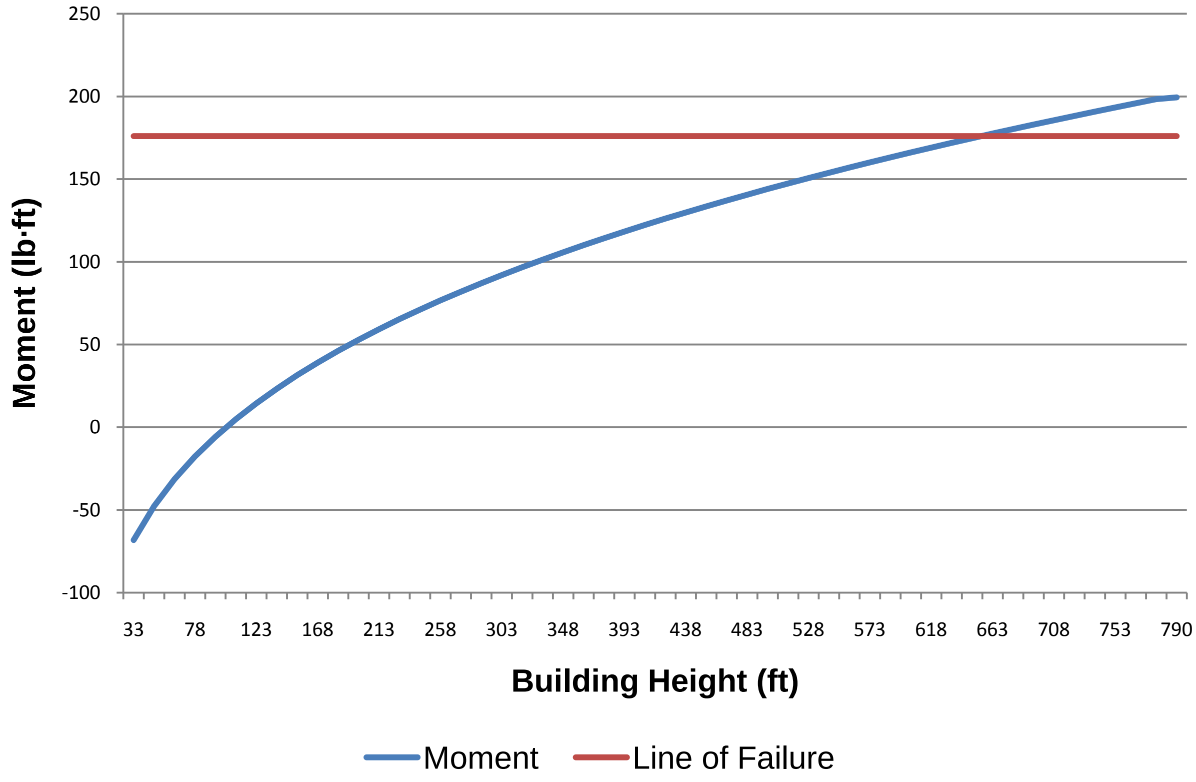


Figure 4-20. Intensive modular tray performance in 130 mph wind

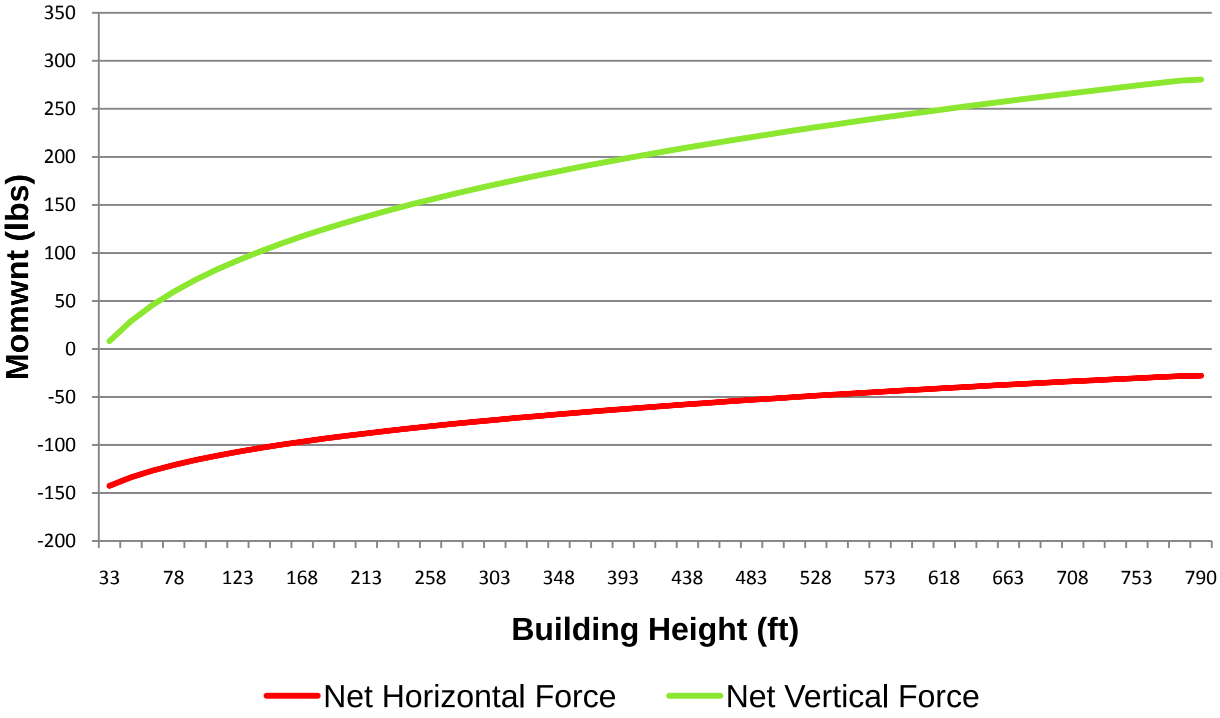


Figure 4-21. 140 mph wind net force on intensive modular trays

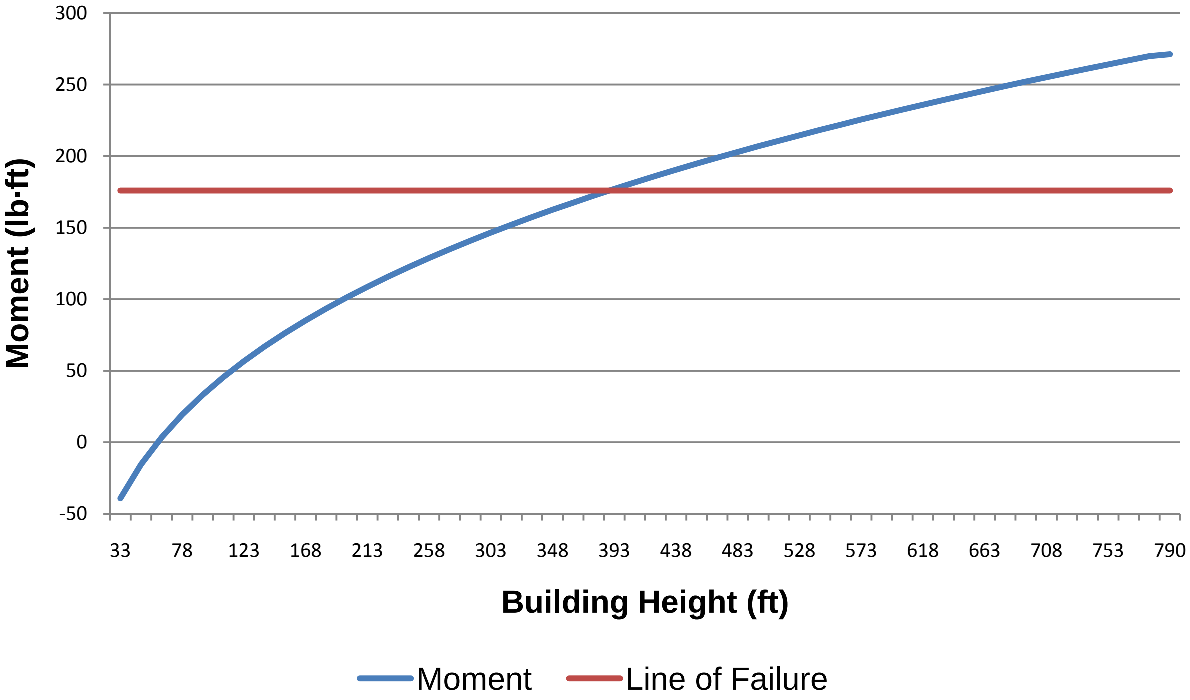


Figure 4-22. Intensive modular tray performance in 140 mph wind

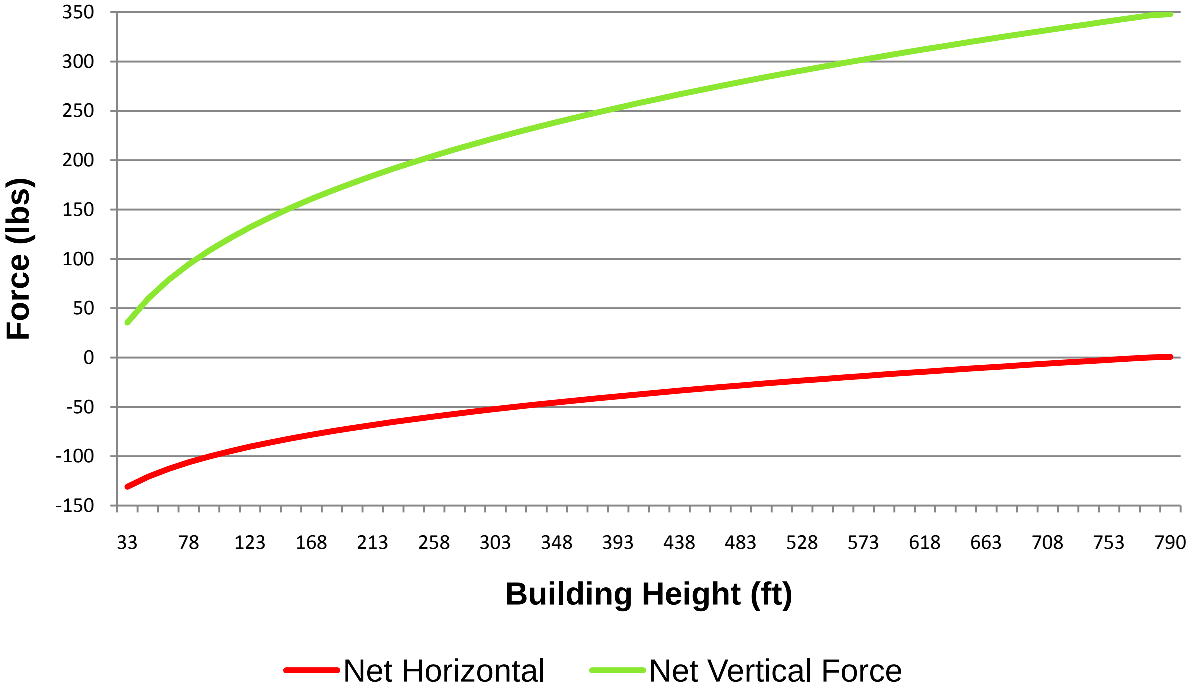


Figure 4-23. 150 mph wind net force on intensive modular trays

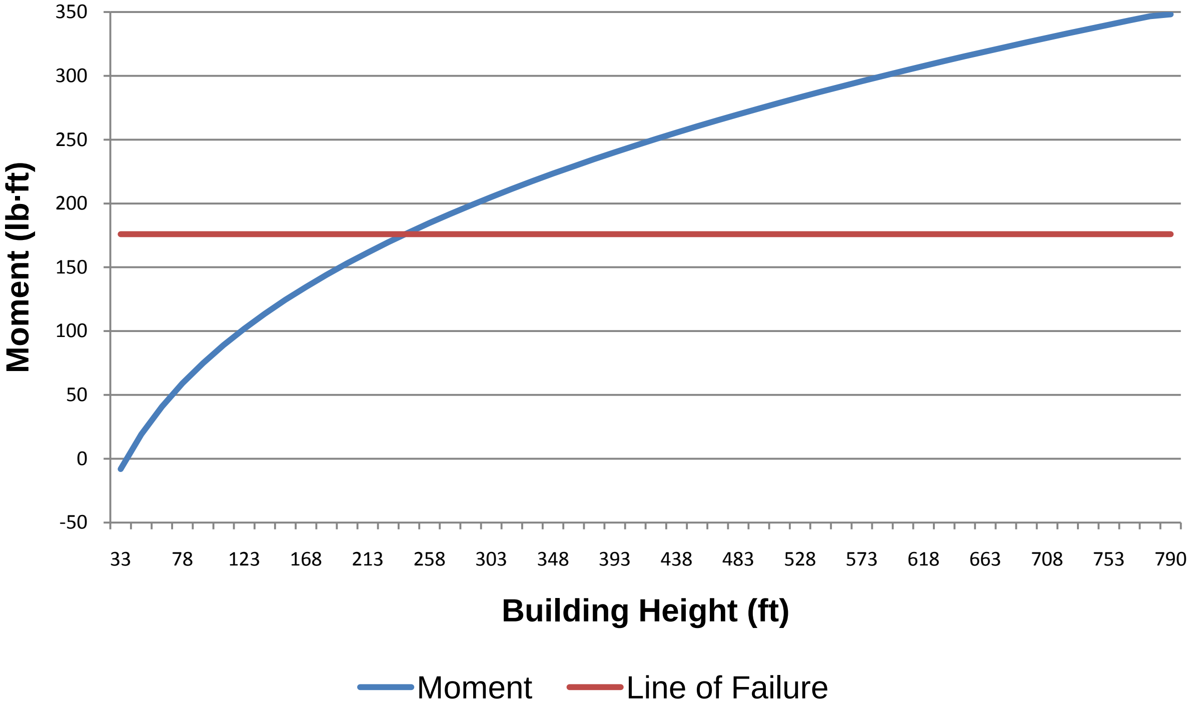


Figure 4-24. Intensive modular tray performance in 150 mph wind

CHAPTER 5
ANALYSIS OF RESULTS

Summary of Findings

Based on this analysis, an extensive modular green roof system on the theoretical model building can survive up to a Category 4 hurricane at 140 mph at an approximate building height of 33 ft and an intensive modular green roof system can survive a Category 5 hurricane at a 150 mph at an approximate building height of 228 feet. The study only determines when the modular trays will lose contact with the roof and not necessarily when the modular will become completely airborne. This study assumes that none of the vegetation was displaced, thus the maximum weight of the modular green roof system was maintained throughout the duration of the hurricane. In both the extensive and intensive modules, the contributing factor to the overturning of the trays was the vertical force. The net horizontal forces for all building heights and at all ranges of wind speeds were mostly negative. The uplift forces in the vertical are extremely great and overcame the horizontal component eliminating any contact with the EPDM roofing membrane. The values obtained for the net vertical force are of primary concern when evaluating this data or pursuing similar research.

Table 5-1 summarizes the failure building height for both the extensive and intensive modular trays at different wind speeds.

Table 5-1. Actual maximum height for extensive on intensive green roof models for theoretical building

Wind Speed (mph)	Modular Tray Maximum Height (ft)	
	Extensive	Intensive
100	363	790
110	183	790
120	93	790
130	48	648
140	33	378
150	N/A	228

The ASCE 7-05 standard allows only 60% of the dead load to be used when designing for wind when using the Live and Resistance Factor Design (LRFD). Using this approach to the roof design would effectively decrease the height green roof modules can be placed on the theoretical model building. Table 5-2 depicts the effect this requirement would have on the building height limit that extensive and intensive modular trays can be placed on without being affected by hurricane wind forces.

Table 5-2. Design maximum height for extensive and intensive modular green roof modules for theoretical model

Wind Speed (mph)	Modular Tray Maximum Height (ft)	
	Extensive	Intensive
100	63	790
110	33	498
120	N/A	273
130	N/A	153
140	N/A	93
150	N/A	48

Wind Uplift Prevention Strategies

This research presented a case that modular green roofs can be installed in high rise commercial and residential buildings in areas prone to hurricanes, particularly cities located along the Eastern and Gulf Coasts of the United States. Intensive modular green roof systems, due to weighing more than extensive modular systems, would be more suitable for these areas. Extensive modular green roof systems should be limited to medium to low-rise buildings. Growth media with higher densities would increase the weight of the modules and would offer greater resistance to hurricane force winds, however, increase weight of the modules involves more structural support for the roof, leading to an increase in construction cost. Applying fasteners to the modules would also serve to better secure modules to the roof. Wind uplift test conducted on mechanically fastened single-ply roof systems involved bolting the fasteners an insulation board lined with 50 mm thick EPDM. The results of the fastener strength are shown in Table 5-3.

Table 5-3. Failure Fastener Loads (adapted from Prevatt et al. 1999)

Specimen	Measured Fastener Failure Load	
	(kN)	(lbs)
12x24 EPDM	2.0	455
10x10 EPDM	1.9	432
8x8 EPDM	1.8	401
7x7EPDM	1.8	409
5x20 EPDM	1.8	410
5x9 EODM	1.8	403

The force applied to the fastener would be added to the weight of the modular green roof trays in the calculation of net vertical force. The resulting equation would be:

$$\sum F_y=0=F_v-(W+F_{fasteners}) \qquad (5\text{-}1)$$

F_y represents the forces along the vertical axis. Another 403 lbs to 455 lbs applied to would dramatically improve the performance of the modular green roof as the greatest F_v value achieved in the theoretical analysis was 523.98 lbs at a building height of 790 and wind speed at 150 mph. Although fasteners would help prevent uplift, this would not be a practical alternative as one of the most important features of a modular green roof system is its ability to be moved in the event maintenance to the roof structure is needed.

Another strategy being considered to mitigate the effects of strong winds on modular green roofs is the use of wind blankets. Wind blankets are a geo-textile material that is anchored in place and the plants are propagated through small openings cut in the geo-textile material. These wind blankets are designed to decompose as the plants on the green roof reach mature and develop strong roots to be anchored securely to the growth media (Lucket 2009). Xero Flor manufactures of XF300 and XF301 vegetation blankets tested the XF301 in an independent, certified testing laboratory familiar with green roof systems. The results showed that the uplift resistance of the XF301 mat was 5.5 psf. WGS Engineering, the certifying laboratory, concluded that the XF301 System is secure against wind uplift displacement at building heights of up to 328 ft (100m). The report did note that there was a limitation to the analysis due to the different averaging time used for dynamic wind speed in Germany compared to the United States. In Germany, roof design is based on mean hourly wind speed, while in the United States roof design is based on three second peak gust speed. The report recommends using a factor of 1.54 to convert for converting three second peak gust to mean hourly wind speed.

Using the XF301 on the modular green roof system used in the theoretical analysis with a 4 ft^2 area would provide a wind uplift resistance for 22 lbs. 22 lbs would do little to prevent wind uplift for extensive modular green roof trays when exposed to hurricane force winds. The least amount of uplift force produced in our theoretical model was 93.99 lbs for a building height 33 ft and wind speed of 100 mph and the weight of the module plus the resisting force of the wind blank would only produce negative net force of 16.01 lbs in the mildest condition.

Conclusion

There are general strategies that could be incorporated in building/designing a green roof that would help mitigate the effects of wind uplift. Concrete pavers have been used as additional weight to counter wind uplift forces as the weight of the modular green roof trays have the biggest impact on preventing wind uplift. Unfortunately, additional weight on the roof structure complicates matters for the structural engineer and the owner it terms of design and material costs respectively. Companies that manufacture modular green roof systems will need to overcome the problem wind uplift poses on their product if it is going to be a staple in the Eastern and Gulf coast areas that annually braces for hurricane force winds during the months of June and November.

Recommendations for Future Study

This study presents a very rudimentary approach to evaluating the viability of modular green roof systems when exposed to hurricane conditions. In order to fully evaluate how hurricane force winds effect modular green roof systems more research is needed. This study proposes a worst case scenario for modular trays being on a roof top but is not very realistic. It does however provide a baseline for how modular green roofs will perform under the most adverse of conditions. A model green roof capable of supporting both intensive and extensive trays subjected to wind speeds typical of a Category 2 and higher could be better evaluated how well they perform when exposed to hurricane conditions. The University of Florida's Civil and Coastal Engineering Department has hurricane simulator that simulates both wind speeds and rain typical of a hurricane. Subjecting a modular green roof system to this machine would provide very realistic conditions. The test could include how a parapet wall could not only help prevent wind uplift but can also serve as a mechanism to catch the modular trays if they do become airborne. The ability of a parapet wall to prevent the modular green roofs from being blown off a roof top prevents damage to surrounding structures in addition to being able to salvage the modular green roof trays.

Another research opportunity to better establish the effect of hurricane force winds on modular green roof systems would be to determine what plant type and growth media combination is best suited to withstand hurricane conditions. As discussed in this research, the type of root structure a plant possess, the size of the plant, and the growth media the plant is in has a direct effect on the plants ability to prevent overturning. The results of such a research could establish better design criteria for modular green roof systems being installed in hurricane prone regions.

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BIOGRAPHICAL SKETCH

Duane Andre Ellis earned his Master of Science in building construction from the M. E. Rinker, Sr., School of Building Construction at the University of Florida. While at the University of Florida he worked as a graduate teaching assistant for the BCN 3281C Construction Mechanics course. Prior to earning his MSBC degree, Duane graduated from the University of West Florida in 2008 with a Bachelor of Science degree in engineering technology, with a concentration in construction. He also holds certifications as a LEED AP and a Construction Document Technologist.