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HIGH SPEED WIND UPLIFT RESEARCH ON GREEN ROOF ASSEMBLIES

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Abstract

The wind uplift behavior of vegetative (green) roof assemblies is not well understood and few resources exist for designing wind-resistant green roofs in hurricane-prone regions. While design guidelines have recently been published, they are not based on experimental studies. The lack of evaluation reports for green roofs, is contributing to relatively slow introduction of green roofs into the Florida construction market, where a state-wide product approval system is in place to ensure performance evaluation reports are provided for all building envelope components. The purpose of this research was to develop and perform wind resistance tests to evaluate the characteristic response of green roof systems to extreme winds. The two-year study investigated two green roof systems; a modular tray green roof (in 4 in. and 8 in. deep modular trays) and a 6 in. built-in-place green roof system. The roofs were installed on an 8 ft by 8 ft flat roof building mockup and subjected to wind speeds up to 120 mph. Green roof specimens were tested on the building mockup with and without parapets. Several plant species were included, consisting of native to Florida and more typical succulents used in green roof installations. The plants were grown in Gainesville, FL for periods of 3 months to 18 months before testing. Root uplift pull tests were performed on individual plants to determine the effect of high wind on the uproot resistance of various plant species. The effects of parapets, and excessive moisture in growth media (from simulated rain), duration of wind event, and wind direction were also investigated. The investigators observed that more robust plant growth occurs when plants were planted in deeper growing medium (8 in. modules). However, the wind resistance of plants in both the shallow and deep module trays was approximately the same. Unprotected growth media (i.e. unplanted modules with no erosion control) were highly susceptible to erosion or scour losses as compared to planted green roof modules. Parapets were found to reduce wind damage to plants but they also encouraged scour and redistribution of the growth media near the inside face of the parapet along the leeward wall.

It was concluded that maintaining a high roof vegetation coverage ratio is necessary to minimize media loss by scour. While taller plant species were found to experience higher degrees of damage during wind testing than shorter species, their uproot capacity may be greater due to their larger root systems.

Introduction

Designing a green roof system for Florida can be challenging, given the state's unique climate. Design considerations must account for the following: high temperature and humidity, periods of drought, occasional freezes in North Florida, periods of heavy rain, and hurricanes. Florida spans several Plant Hardiness Zones ranging from sub-tropical to tropical climates as determined by the United States Department of Agriculture (Zones 8 through 11a) (**7**), so plant selections must consider a wide range of conditions. The particular challenge for the construction industry is the limited available knowledge of how green roofs perform during a hurricane. While Florida's Building Code establishes standards for performance of products, materials, and systems, building departments face a difficulty in verifying Code compliance for green roof projects because no standard test or evaluation methods exist for determining the wind uplift resistance of a green roof.

The basis for wind loading of green roof systems can be found in previous (mainly wind tunnel) studies to determine wind loads on low-rise flat roof buildings. Those studies enabled development of models to explain gravel scour action on ballasted roofs and failure of roofing systems when buildings are subjected to cornering winds that can result in extremely high suction forces. Green roof systems behave like a ballasted roof, in that growth media can be displaced by strong wind, moving it from place to place, or it can blow completely off the roof. However, plants have been shown to reduce such debris generation at ground level, through their role in soil stabilization and momentum reduction. However plant foliage can be damaged or the entire plant can be uprooted by strong winds.

In recent years several organizations have developed the first North American design guidelines for green roofs. The RP-14 published by ANSI/SPRI in 2010 is a wind design standard for vegetative roof systems that references wind tunnel research reported by Retzlaff et al. at the 8th Cities Alive Conference (1, 8). RP-14 also draws from a Ballast Design Guide for Protected Membrane Roofs, Tech Solutions 508.1, published by Dow Chemical in 2009 (1, 3). In 2011, Factory Mutual Global published their FM 1-35 "Property Loss Prevention Data Sheets Green Roof Systems" that is associated with its FM 1-28 wind design guideline for low-rise buildings (4). These documents represent the state of knowledge for wind design of green roofs but there has been limited full-scale validation of these guides. Indeed, some provisions appear overly conservative, such as the FM 1-35's restriction for green roof systems to locations where the design wind speed is not greater than 100 mph (4).

The purpose of this research project was to develop wind resistance tests and to evaluate the characteristic response of green roof systems to extreme winds. The two-year study investigated two types of green roof systems; modular tray green roofs and built-in-place green roof systems.

Experimental Details

Sedums were one of the earliest plant selections for green roofs in Florida, but they failed to survive one season (2, 9). Subsequent plant selections over the years have been native and ornamental herbaceous perennials, annuals and native grasses. Plants were selected for this project based on their success in extensive green roof configurations around Florida, the University of Florida's (UF's) green roof, or within UF's field plots for a period of at least one year. Early experiences with Florida green roofs have suggested that all green roof applications in Florida should have some form of irrigation. Given the ANSI guideline for fire (VF-1), evergreen plant selections are also needed to limit plants that are semi-perennial and produce biomass fuel for fire.

The modular tray green roofs varied in depth as 4 in. extensive or 8 in. intensive modules while the built-in-place green roof systems were constructed to have nominally 6 in. of media depth. The roofs were installed on an 8 ft by 8 ft by 8 ft high flat roof building mockup and subjected to wind speeds up to 120 mph. The modular tray system, supplied by Manufacturer A, consisted of 2 ft by 2 ft plastic trays that were assembled in 3 by 3 grids on the roof. The built-in-place system was supplied by Manufacturer B, and it consisted of metal edge flashing, and a composite drainage system installed in accordance to manufacturer's specifications. The growth media used in both green roof systems were provided by their respective manufacturers. After plant selections were made, they were planted in the green roofs and set up at the UF Alachua County Extension Office to grow. Table 1 provides details of the experiment, which was conducted in two phases, as shown.

	Phase 1	**Phase 2**
Test Trials	6 – Repeats of 9 modular trays per test	8 – Repeats of 9 modular trays per test 8 – Built-in-place repeats
Wind Direction	90°	45°
Parapet Height	12 in.	0 in.
Plants Tested	A,B,C,D,E,F	A, B, C, D, E, F (retested) G, H, I, J, K, L, M, N
Plant Heights	Mixed	Mixed (retested), Tall & Short
Establishment	3 mo., 5 mo., & 9 mo.	1.5 mo. (built-in-place) 6 mo. & 13 mo.
Growth Media Depth	4 in. & 8 in.	4 in. & 8 in. 6 in. (built-in-place)
Wind Speed	20, 30, 50, 70, 90, & 120 mph	100 mph
Test Duration	5 min.	10 min. or 20 min. (extended)
Moisture Level	Natural	Natural & Wet
A *Aptenia cordiflora* B *Delosperma cooperi* C *Dianthus gratianopolitanus* D *Lantana montevidensis* E *Salvia rutilans*	F *Sedum rupestre 'Angelina'* G *Sedum rupestre* H *Delosperma nubigenum* I *Rosemarinus officianalis* J *Gaillardia aristata*	K *Coreopsis lanceolata* L *Bulbine frutescens* M *Lantana camara* N *Portulaca grandiflora*

Table 1. Wind test matrix summary

Plant Selection

Plant selections were made with the basis of determining suitability on the most common green roof assemblies found in Florida, as well as plants that were available from regional nurseries. Good performance of plants for at least one year in an extensive green roof representative of Florida conditions was an important criterion. Criteria for plant selection included the following characteristics:

1. The capacity to withstand high temperatures and humidity for extended periods of time
2. The ability for moderate to fast growth rates in response to short project timeline.
3. The capacity for extended drought tolerance and withstanding seasonally heavy rains
4. The capacity to withstand freezes of 25° F - 34° F, depending on location

Taller herbaceous ornamentals (30 in. – 36 in.), shorter ground covers (4 in. – 6 in.) and a variety of plant forms were included in the 14 species in these trials. The 14 species (shown in Table 1) selected include a variety of plant forms (orthotropic vs. prostrate), leaf area (small vs. large), stem composition (hard vs. soft), and root types (tap root vs. fibrous). Further, the list includes herbaceous perennial native plants, ornamentals, and succulents with good track records in Florida's climate. Two varieties of Sedums and other succulents were utilized in the study as species from UF field trials that offered promise for use in Florida. However, until further plant studies are performed, the selections made for this study should not be interpreted as recommended species for Florida green roofs.

Wind Testing Procedure

Wind uplift tests were conducted using a portable hurricane simulator, developed at the University of Florida (6). This device consists of eight 5 ft diameter fans and is capable of producing a 10 ft by 10 ft open jet of sustained wind speeds up to 120 mph. Although this is equivalent to a Category 3 hurricane, its longitudinal turbulence intensity falls between 5-6%, and is much smaller relative to realistic storm conditions. This limitation is noted as experience shows that plants are likely to experience far less damage from low-turbulence airflows. The wind speeds were measured using an RM Young anemometer positioned at roof height, 1 ft upstream of the building mockup.

Phase 1 consisted of six wind test trials; three with 8 in. deep modules and three with 4 in. modules, approximately 36 sq. ft of green roof per trial. Each trial used eight planted modules and one unprotected one (i.e. no plants or erosion control), installed on the roof deck surrounded by a 12 in. tall parapet. The planted modules had a mixed array of six species, and were wind tested on three different dates allowing specimens 3, 5 and 9 months' worth of establishment. The wind flow was perpendicular to the windward wall, and the speeds were varied from 20 mph to 120 mph for a total testing time of 5 minutes (Figure 1). Timing constraints prevented the investigators from testing built-in-place systems at this stage as well.

Figure 1. Test setup for Phase 1

Phase 2’s test setup was developed to evaluate green roof behavior under more severe wind loading conditions, by removing the parapet and exposing the green roof systems to cornering winds. Phase 2 also introduced a second roofing system type, built-in-place green roofs. The modular tray green roof systems were set up as before in Phase 1, except that the unprotected module tray was replaced with a planted module. It should be noted that the module trays tested in Phase 1 were retested in Phase 2. In this phase a sustained wind speed of 100 mph was used for all tests, and the time of testing extended to 10 minute and 20 minute intervals.

Figure 2. Test setup for Phase 2

The built-in-place green roof systems were designed and constructed on a wood deck with self-adhered waterproofing membrane according to the manufacturer’s specifications. First, a drainage layer was laid atop the deck, and aluminum edge restraints were installed to form a container for the green roof. Then, a drainage cup mat and filter fabric were placed before adding the growth media and plants. The green roof assemblies were planted as monocultures with tall and short plant species. Additional 2 in. by 10 in. wood boards were fastened to the deck along the perimeter of the edge restraints. Eight built-in-place green roof trials were wind tested: four with “normal” moisture conditions and four tested immediately after irrigating the 6 ft by 6 ft green roof with 55 gallons of water. This was done to simulate the expected heavy rainfall intensity likely to occur during a hurricane.

Video footage was taken during each test. Growth media erosion losses for the modular tray green roofs were quantified by weight measurements, before and after testing. In Phase 2 overhead photographs of the green roofs were taken before and after each 10-minute segment, and the plant coverage ratio was calculated. Growth media samples were taken from each trial (in Phase 2) to determine their moisture contents.

Plant Uproot Procedure

Extensive uprooting research has been conducted in the past in controlled lab experiments on mostly monocot plant species. However, little is known about the uproot potential of field-grown dicot species in modular green roof systems. A Plant Uproot Device was developed to determine the uproot resistance of the plants. The device consisted of an electric linear actuator, a 200 lb load cell, a steel wire cable, and a rubber grip device to hold the plants. The displacement rate of the actuator varied from 36 to 75 in/minute. Force-displacement graphs were plotted for each plant. The uproot tests were conducted until the plant's root system or stems detached from the green roof media, or the limit of the actuator was reached (6 in.). The parameters which were considered in the specimen selection were: plant species, system depth, establishment time, media moisture content, and effect of wind testing on the assembly.

Immediately following plant uproot testing, growth media was carefully removed from representative root systems, and the plants were cleaned off and placed on a white board to document their growth habit. This was done in order to determine the relationship (if any) between root spread, root establishment time, root uplift force, and wind-induced failure of a plant.

Results & Discussion

Phase 1 Wind Testing

Plant bending and losses were minimal up to 70 mph, but appeared to increase thereafter. Testing confirmed findings by Retzlaff et al. (2010) which reported that planted modules can effectively bind growth media and resist scour, even in corner regions of the roof (8). Due to increased exposure, taller plant species are more prone to wind damage than shorter plant species which remain low and close to the green roof surface. The 4 in modules were seen to undergo dynamic lift in the leeward corner during testing although none of the modules actually became airborne. One observation was that plants that are subject to dieback during the winter ought to be pruned to remove dry pieces that could become a fire-hazard.

The presence of the roof parapets appeared to limit the damage to plants. There was minimal loss of plants in these tests. However, a wind direction reversal occurred along the leeward parapet causing the plants to bend against the simulator's wind flow. When the leeward parapet was removed in one test, this behavior was not observed. It is expected this reversal in wind direction could occur on full-sized roofs, depending on parapet height and wind speed. Unprotected modules along the leeward edge of the roof experienced significant erosion of growth media reflected by significant losses (46% loss for 4 in. module and 16% loss for 8 in. module). These losses were most severe when the unplanted modules were placed in the leeward corner location.

Phase 2 Wind Testing

The growth media erosion patterns observed in Phase 2 confirmed the presence of strong suction forces below the conical vortices. This can be clearly seen in test trial S-T2, depicted in Figure 3(a). For the built-in-place green roofs, it was found that most of the growth media scour occurred along the leading edges and corner of the roof. Media build-up was found to occur at the far end (leeward) corners. It appears that growth media was also blown off the roof, indicated by buildup of growth media along the leeward aluminum edge restraint (Figure 3(b)).

The erosion pattern seen in the built-in-place green roofs was not as apparent in the modular tray green roofs, although some localized scour was seen in individual modules. The extent of growth media scour was highly dependent upon the plant coverage ratio and location of the particular module on the roof deck. Plant coverage ratio was found to play an important role in resisting growth media erosion for both the built-in-place and modular tray green roofs. Overall, the built-in-place assemblies had higher coverage ratios (average 81%) than the modular tray roofs (average 72%). However, the built-in-place green roofs suffered greater coverage ratio loss (about 18%) than the modular tray green roofs, which experienced only an averaged 8% loss in coverage ratio during the 10-minute test intervals. Two factors that may have accounted for this significant difference were: 1) the relatively short establishment time and growth of root systems allowed for the built-in-place green roofs (6-8 weeks), and 2) the modular trays, being more discontinuous than the built-in-place trays, provided more roughness and better protect the growth media. Further testing would be required to confirm or refute these theories.

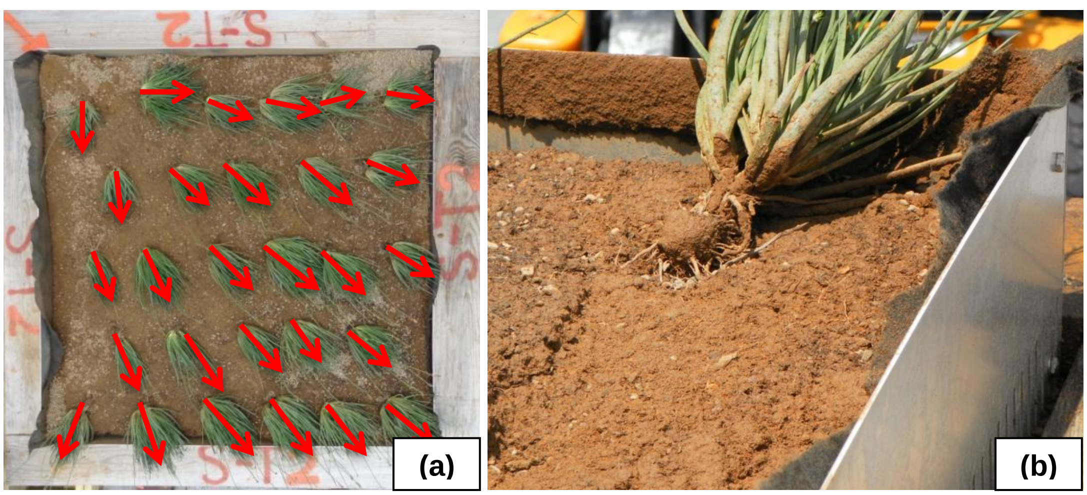

Figure 3. (a) Scour pattern observed over S-T2. **(b)** Growth media can be seen to have struck aluminum edge restraint. Root lodging is also witnessed in the Bulbine specimen.

Investigators determined that plants essentially provide a roughness layer, which disrupts wind flow from damaging the media surface. Further evidence supporting this was found in spot captures which showed regions within a built-in-place assembly completely devoid of coarse aggregate where plant coverage was minimal or non-existent, and other regions where coarse aggregate appeared undisturbed by the wind flow due to protection from bent over plants. Coverage ratio reduction does not occur at a constant rate, as extended testing durations only resulted in minimal reductions after the first 10-minute segment (an average of a 5% difference in coverage between the first and second 10 minute segments for test trials S-T1, S-T2, T7, and T11). Essentially,

Before Wind Testing **After 10 Minutes** **After 20 Minutes**

Coverage = 94% **Coverage = 68%** **Coverage = 56%**

Figure 3. Coverage ratio change of an extended, 20 minute test trial with saturated conditions for a Lantana monoculture

The most common plant failure observed, particularly within the built-in-place system, was root lodging. Root lodging is the failure means in which stresses cause collapse of the plant structure at the base, exposing the root system. The modular green roof assemblies, tested after 13 months establishment showed no signs of root lodging following each test trial, while those grown for 6 months had a few cases. The built-in-place green roof assemblies, on the other hand, were grown for 1.5 to 2 months and had occurrences of root lodging after each test trial. Observed losses involving uprooting of entire plants and occurrences of stem lodging were minimal.

Root lodging was limited to the individual plant specimens that were fully immersed in the wind flow; i.e. taller plants were more prone to root lodging over a more widespread area than shorter plants in built-in-place tests. Short plant species in the built-in-place tests (Portulaca and Aptenia) only displayed root lodging failure in high scour regions. In general, the taller plant species (Gaillardia, Lantana, Bulbine, & Coreopsis) all exhibited higher signs of stress (desiccation) after wind tests on both built-in-place and modular tray green roof systems.

Tests on built-in-place green roofs showed no significant difference in results between trials that were artificially saturated immediately before wind testing and those that had normal growth media moisture conditions. Despite the extensive wetting, the roofs drained quickly, resulting in moisture contents varying from 21% to 30%.

Uproot Resistance Testing

Sixty-three (63) uproot resistance tests were conducted on 5 of 11 available plant species in the modular tray green roofs: Aptenia, Delosperma, Dianthus, Gaillardia, and Lantana. The maximum resistance was an outlying case of 80 lb in the Gaillardia species. More than half of the test specimens displayed strong plant to media bonds – 36 of 63 exhibited no root or stem failure at all within the 6 in. displacement range of the actuator. The Lantana species, in both 4 in. and 8 in. substrate depths, accounted for 11 of those 36 cases. Its average measured peak force in those 11 cases was 28.12 lbs. of resistance, suggesting that despite its susceptibility to wind damage in its stem and leaf areas above the media surface, its plant structure is tough and its extensive root-system is well-anchored, providing acceptable uproot resistance.

The only trend recognized linking media depth and uproot capacity was shown in the Delosperma and Gaillardia species. Each had higher uproot resistance for tests conducted in the 8 in. deep modules, achieving 15 lbs and 22.5 lbs, respectively, versus the 4 in. modules that failed at 5 lbs and 10 lbs, respectively. For some other plants (e.g. Dianthus), however, there was no difference in uproot resistance with different media depths. As a result of the actuator's short extension, as uproot resistance increased, more cases of stem failures were likely to occur. The investigators suspect that given sufficient anchorage to a fixed base and an actuator with a longer extension, more stem failures would be witnessed as root capacities are reached.

Conclusion

The results obtained from the green roof wind tests and plant uproot resistance tests provided valuable knowledge on the wind performance for built-in-place and modular tray green roof systems when exposed to realistic wind flow conditions. The research has shown that past wind engineering knowledge for pavers and ballasted roofs is relevant to green roof systems, with regard to behaviors at roof corners and along edges. Green roof systems, both modular tray and built-in-place, can be extremely susceptible to wind uplift – particularly in extensive systems. Since there are several parameters that contribute to the creation of damaging corner vortices and suction forces on a roof, it is prudent not to rely solely upon the dead weight of the roof system itself to hold it in place. While individual anchors for each module is an option, this approach may require multiple penetrations through the membrane, or use of adhesives. Also, several modules can be tied together once sufficient anchorage points are provided to increase the combined weight and resist the expected uplift load. However, solely tying the modules together may not prevent module blow-off, and could result in failure of larger sections of the green roof, since the wind force on an airborne module could be sufficient to drag other modules off. The tests showed that roof parapets can potentially reduce the chance of green roof failure, but may still experience failures given a critical combination of wind speeds, parapet and building heights, and dead weight of the green roof. Fortunately, small changes can be beneficial; i.e. anchoring a 2 in. by 12 in. wood strip around the perimeter of the green roof was sufficient to prevent failure of the built-in-place green roof system. It was noted that anchored edging systems were not tested with the modular tray assemblies. Future testing of this conservative, worst-case scenario is needed to address potential benefits of edge restraint systems in both modular and built-in-place green roof systems.

It is evident that sub-tropical climates in Florida tend to enable rapid development of plants for green roof modules despite the elevated temperatures and dry conditions. It appears that irrigation is useful to ensure healthy plants in Florida's climatic conditions. The plants grown in the 8 in. deep modules were more robust and grew more rapidly than similar plants grown in the 4 in. modules. It was remarkable that the combination of proper care and the ideal growing conditions of a subtropical climate, plants tested after just 6 weeks had sufficient coverage and erosion resistance to retain much of the growing media. Green roofs will require maintenance if they are to perform year-round in Florida. During the winter, as herbaceous ornamental plants dieback, they should be pruned to remove dead materials that could be a fuel-source on the roof. A mixture of plant species may be the best approach if the characteristics of evergreens, combined root systems, and foliage profiles are coordinated. In doing so, the growth media should be matched to be appropriate for the mixture of plant species. Additionally, some plants develop roots that spread throughout the depth of the module, while other plants have roots that only extend locally below the foliage and in shallow depths. By combining plants with these two rooting habits, the growing media is well secured. Also, 2 – 3 months is sufficient time for plant establishment when considering a modular tray as ballast, meaning that it is unlikely to blow away in normal conditions.

Overall, plants grown in this study experienced root lodging failures, uprooting failures, and limited breakage in the green roof assemblies. Despite the plants undergoing stress due to the high winds, there is a good chance that the majority of them will survive 5, 10 or 20 minutes of extreme winds in a storm event. This experiment has shown, as expected, that the longer a plant is exposed to high wind, the more damage can be done. It also showed that the longer plants mature in the green roof assembly, the more extensive their root systems grow and provide anchorage. Thus, during a hurricane, where strong winds can last for more than three or four hours, plant damage is to be expected. The amount of damage can actually be *higher* than the results this study yielded due to the higher expected turbulence intensities in a real hurricane, which would cause a greater degree of unsteady movement of the plants. Photo documentation of root systems and root pull-out tests suggest that a more established green roof with an extensive root system (longer than the tests' 13 months) may provide the capacity required for post-event regeneration of plants that have experienced stem breakage. The survival of the root system suggests that even if plants die-off after extreme weather conditions (heat, flood, etc.), its presence provides adequate erosion control for preventing media blow-off for some period of time.

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