Developing Tests and Evaluation of Wind Resistance
Wind Uplift Research on Sub-Tropical Vegetated Roof Assemblies

Text, photography, and diagrams by Glenn Acomb, David Prevatt, and Tuan Vo

	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 inch	0 inch
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 and Short
Establishment	3 month, 5 month, and 9 month	1.5 month (built-in-place) 6 month and 13 month
Growth Media Depth	4 inch and 8 inch	4 inch and 8 inch 6 inch (built-in-place)
Wind Speed	6 – Repeats of 9 modular trays per test	6 – Repeats of 9 modular trays per test
Test Duration	6 – Repeats of 9 modular trays per test	6 – Repeats of 9 modular trays per test
Plant Species Specified	A – *Aptenia cordiflora* B – *Delosperma cooperi* C – *Dianthus gratianopolitanus* D – *Lantana montevidensis* E – *Salvia rutilans* F – *Sedum rupestre* "Angelina" G – *Sedum rupestre* "Lemon Coral" H – *Delosperma nubigenum* I – *Rosemarinus officianalis* J – *Gaillardia aristata* K – *Coreopsis lanceolata* L – *Bulbine frutescens* M – *Lantana camara* "Gold Mound" N – *Portulaca grandiflora*	

A. Wind Test Matrix Summary

Although vegetated roofs have gained international acceptance and are being implemented throughout the world, majority of their installations have occurred in temperate climates, owing to their origins in European temperate climates, and far less in tropical climates. With the majority of tropical-climate vegetated roofs being installed in the past 10 years, understanding of their long-term performance, growth media, and plant selections is more limited. Of particular importance, there is far less knowledge about their performance in extreme weather conditions, particularly in the high winds of tropical storms.

As a part of a grant from the State of Florida Building Commission, a research team from the University of Florida performed field-testing to assess the forces of wind uplift on vegetated roof assemblies of built-in-place and modular tray systems. The potential for damages to vegetated roofs due to wind uplift appears real, but there is little evidence available to measure the forces and potential for damage and airborne debris in high-wind events.

Designing a vegetated roof system for humid tropical and sub-tropical climates must accommodate the unique climate. In Florida, which spans several Plant Hardiness Zones and sub-tropical to tropical climates, design considerations must also account for: high temperature and humidity; periods of drought; occasional freezes (in North Florida); periods of heavy rain; and tropical storms (Zones 8 through 11a) (PRISM Climate Group 2012). Therefore, plant selections must consider a wide range of conditions with a particular challenge in the limited experience of vegetated roof performance during a tropical storm. While Florida's Building Code establishes standards for the performance of products, materials, and systems, building departments face a difficulty in verifying code compliance for vegetated roof projects because no standard test or evaluation methods exist yet for determining the wind uplift resistance of a vegetated roof.

The basis for wind loading of vegetated roof systems can be found in previous (mainly wind tunnel) studies to determine wind loads on low-rise flat roof buildings. Those studies enabled the development of models to explain the 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. Vegetated roof systems behave like a ballasted roof, in that growth media can be displaced by strong wind, moving it from place to place, or blown completely off the roof. Plants have been shown to reduce such debris generation at ground level, through their role in soil stabilisation and momentum reduction. However plant foliage can be damaged and the entire plant can be uprooted by strong winds.

In recent years, several organisations have developed the first North American design guidelines for vegetated roofs, but there has been limited full-scale validation of these guides.[1] Indeed, some provisions appear overly conservative, such as FM 1-35's restriction for vegetated roof systems to locations where the design wind speed is not greater than 100 miles per hour. The purpose of this research project was to develop wind resistance tests and evaluate the characteristic response of vegetated roof systems to extreme winds. The two-year study investigated two types of vegetated roof systems: modular tray systems and built-in-place vegetated roof systems.

Experimental Details

Plant selection

Plant selections were made on the basis of determining their suitability on vegetated roof assemblies in Florida, as well as their availability at regional nurseries. Criteria for plant selection included the following characteristics:

1. Capacity to withstand high temperatures and humidity for extended periods of time
2. Ability for moderate to fast growth rates in response to short project timeline
3. Capacity for extended drought tolerance and withstanding seasonally heavy rains
4. Capacity to withstand freezes of 25 degrees Fahrenheit to 34 degrees Fahrenheit, depending on location

Taller herbaceous ornamentals (of 30 to 36 inches), shorter ground covers (of 4 to 6 inches) and a variety of plant forms were included in the 14 species in these trials. The 14 species (shown in Table A) 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. After plant selections were made, they were planted in

A – *Aptenia cordiflora*.
B – *Delosperma cooperi*.
C - *Dianthus gratianopolitanus*.
D - *Lantana montevidensis*.
E – *Salvia rutilans*.
F – *Sedum rupestre* "Angelina".
G – *Sedum rupestre* "Lemon Coral".
H – *Delosperma nubigenum*.
I – *Rosemarinus officianalis*.
J – *Gaillardia aristata*.
K – *Coreopsis lanceolata*.
L – *Bulbine frutescens*.
M – *Lantana camara* "Gold Mound".
N – *Portulaca grandiflora*.

1. Plants Selected for the Experiment

the vegetated roof assemblies and set up in field areas to grow. Table A provides details of the experiment, which was conducted in two phases.

Wind testing procedure

Wind uplift tests were conducted using a portable tropical storm simulator, developed at the University of Florida. This device consists of eight five-feet diameter fans and is capable of producing a 10-foot-by-10-foot open jet of sustained wind speeds up to 120 miles per hour. Although this is equivalent to a Category 3 tropical storm, its longitudinal turbulence intensity falls between five to six percent, and is much smaller relative to realistic storm conditions. The wind speeds were measured using an RM Young anemometer positioned at roof height, one foot upstream of the building mockup.

In Phase 1, each trial used eight planted modules and one unprotected one (meaning no plants or with erosion control), installed on the roof deck, surrounded by a 12-inch-tall parapet. The relatively short testing time for wind speeds of five minutes prevented the investigators from testing built-in-place systems (Fig. 2). In comparison, the Phase 2 test setup was developed to evaluate vegetated roof behaviour under more severe wind loading conditions, by removing the parapet and exposing the vegetated roof systems to cornering winds (Fig. 3). Phase 2 also introduced built-in-place vegetated roofs and longer testing times of 10 or 20 minutes. The unprotected module tray was replaced with a planted module and the module trays tested in Phase 1 were retested in Phase 2. Eight built-in-place vegetated roof trials were wind tested: four with "normal" moisture conditions and four tested immediately after irrigating the six-foot-by-six-foot, vegetated roof with 55 gallons of water to simulate the expected rainfall during a tropical storm.

Video footage was taken during each test. Growth media erosion losses for the modular tray vegetated roofs were quantified by weight measurements, before and after testing. In Phase 2, overhead photographs of the vegetated 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 monocot plant species. However, little is known about the uproot potential of field-grown dicot species in modular vegetated 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-pound 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 inches per 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 vegetated roof media, or the limit of the actuator was reached (6 inch media depth). 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 habits. 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 and Discussion

Phase 1 wind testing

Plant bending and losses were minimal up to 70 miles per hour, but appeared to increase thereafter. Testing confirmed findings reported by Retzlaff et. al that planted modules can effectively bind growth media and resist scour, even in corner regions of the roof (2010). Due to increased exposure, taller plant species are more prone to wind damage than shorter plant species, which remain low and close to the vegetated roof surface. The four-inch modules were seen to undergo dynamic lift in the far end or leeward corner during testing although none of the modules actually became airborne.

The presence of the roof parapets appeared to limit the damage to plants, with 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 behaviour was not observed. It is expected that this reversal in wind direction could occur on full-sized roofs, depending on parapet height

2. Test setup for Phase 1.

3. Test setup for Phase 2.

and wind speed. Unprotected modules along the leeward edge of the roof experienced significant erosion of growth media, reflected by significant losses (a 46- and 16-percent loss for a 4-inch and 8-inch module respectively). 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 4. For the built-in-place vegetated roofs, it was found that most of the growth media scour occurred along the leading edges and corner of the roof. Media buildup 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 (Fig. 5).

The erosion pattern seen in the built-in-place vegetated roofs was not as apparent in the modular tray vegetated roofs, although some localised 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 vegetated roofs. Overall, the built-in-place assemblies had higher coverage ratios (81 percent on average) than the modular tray roofs (72 percent on average). However, the built-in-place vegetated roofs suffered greater coverage ratio loss, of approximately 18 percent, compared to the modular tray vegetated roofs, which experienced only an average of 8 percent loss in coverage ratio during the 10-minute test intervals. Two factors that may have accounted for this significant difference are: first, the relatively short establishment time and growth of root systems allowed for the built-in-place vegetated roofs (of six to eight weeks); and second, the modular trays, being more discontinuous than the built-in-place trays, provided more roughness and better protection of the growth media. Further testing would be required to confirm or refute these theories.

Investigators determined that plants essentially provide a layer of roughness, 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 nonexistent 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 (with an average of a five-percent difference in coverage between the first and second 10-minute segments for test trials S-T1, S-T2, T7, and T11).

The most common plant failure observed, particularly within the built-in-place system, was root lodging. Root lodging is a means of failure in which stresses cause collapse of the plant structure at the base, exposing the root system. The modular vegetated roof assemblies, tested after 13 months of establishment, showed no signs of root lodging following each test trial, while those grown for six months had a few cases. The built-in-place vegetated roof assemblies, on the other hand, were grown for one and a half to two months and had occurrences of root lodging after each test trial. Observed losses involving the 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. Taller plants over a more widespread area were more prone to root lodging than shorter plants in built-in-place tests. Short plant species in the built-in-place tests (*Portulaca* and *Aptenia*) only displayed root-lodging failures in high-scour regions. In general, the taller plant species (*Gaillardia*, *Lantana*, *Bulbine*, and *Coreopsis*) all exhibited higher signs of stress (desiccation) after wind tests on both built-in-place and modular tray vegetated roof systems.

Tests on built-in-place vegetated 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 percent to 30 percent.

Uproot resistance testing

63 uproot resistance tests were conducted on 5 of 11 available plant species in the modular tray vegetated roofs: *Aptenia*, *Delosperma*, *Dianthus*, *Gaillardia*, and *Lantana* (see Table A for botanical reference names). The maximum resistance was an outlying case of 80 pounds 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 six-inch displacement range of the actuator. The *Lantana* species, in both four-inch and eight-inch substrate depths, accounted for 11 of those 36 cases. Its average measured peak force in those 11 cases was 28.12 pounds 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 recognised that links media depth and uproot capacity was shown in the *Delosperma* and *Gaillardia* species. Each had higher uproot resistance for tests conducted in the eight-inch-deep modules, achieving 15 pounds and 22.5 pounds respectively, versus the four-inch modules that failed at 5 pounds and 10 pounds respectively. For other plants (*Dianthus* for example), 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.

Vegetated roof systems behave like a ballasted roof, in that growth media can be displaced by strong wind, moving it from place to place, or blown completely off the roof.

4. Scour pattern observed over S-T2.

5. Growth media can be seen to have struck aluminum edge restraint. Root lodging is also witnessed in the plant specimen. Plants in this test trial are *Bulbine frutescens*.

While high-wind events may result in damage, post-generation of plants is likely in an established vegetated roof with extensive root systems.

Conclusion

Vegetated 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 on the dead weight of the roof system to hold it in place. While individual anchors for each modular tray is an option, this approach may require multiple penetrations through the membrane or the use of adhesives. Several modules can also 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 failures in larger sections of the vegetated roof, since the wind force on an airborne module could be sufficient to drag other modules off. The tests showed that roof parapets have the potential to reduce the chance of vegetated roof failure, but may still experience failures given a critical combination of wind speeds, parapet and building heights, and dead weight of the vegetated roof. Fortunately, small changes can be beneficial. For example, anchoring a two-inch-by-12-inch wooden strip around the perimeter of the vegetated roof proved to be sufficient to prevent failure of the built-in-place vegetated roof system (although anchored edging systems were not tested with the modular tray assemblies).

It is evident that sub-tropical climates can enable the rapid development of plants and root systems despite the elevated temperatures and dry conditions. The plants grown in the eight-inch-deep modules were more robust and grew more rapidly than similar plants grown in the four-inch modules. Further, vegetated roofs will require maintenance if they are to perform year-round in Florida and other similar tropical climates. A mixture of plant species' foliage, root systems, and foliage profiles may be the best approach if the growth media is matched to the mixture of plant species. By combining plants with different rooting habits, the growth media is well secured and a combination of aboveground foliage height can interlock. It was also noted that two to three 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 some root lodging failures, uprooting failures, and limited breakage in the vegetated roof assemblies. Despite 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 vegetated roof assembly, the more extensive their root systems grow and provide anchorage. Thus, during a tropical storm, where strong winds can last for more than three or four hours, plant damage is to be expected. The amount of damage may be higher than the results this study yielded due to the higher expected turbulence intensities in a real tropical storm, which would cause a greater degree of unsteady movement of the plants.

While high-wind events may result in damage, post-generation of plants is likely in an established vegetated roof with extensive root systems (longer than the tests' 13 months) as evidenced in the photo documentation of the root systems and root pull-out tests. The survival of the root system is likely even if plants die off after extreme weather conditions (of heat, flood, or high winds) and its presence provides adequate erosion control for preventing media blow-off for some period of time.

The research has shown that past wind engineering knowledge for pavers and ballasted roofs is relevant to vegetated roof systems, with regard to behaviours at roof corners and along edges. Looking to the future, testing should investigate higher wind flows, longer test durations, different media depths, and plants of greater variety and maturity. From this foundation, we can build a body of knowledge of the performance of vegetated roof assemblies in tropical climates and their extreme events, and lead to safer design and selection of assembly components. CG

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1 Published by ANSI/SPRI, *RP-14* 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 (ANSI/SPRI 2010; Retzlaff et al 2010). *RP-14* also draws from a Ballast Design Guide for Protected Membrane Roofs, *Tech Solutions 508.1*, published by Dow Chemical (ANSI/SPRI 2010, Dow 2009). In 2011, Factory Mutual Global published its FM 1-35 *Property Loss Prevention Data Sheets Vegetated roof Systems*, which is associated with its FM 1-28 wind design guideline for low-rise buildings (FM Global 2007).

Before Wind Testing
Coverage = 94%

After 10 Minutes
Coverage = 68%

After 20 Minutes
Coverage = 56%

6. Coverage ratio change of an extended 20-minute test trial, with saturated conditions for a monoculture, using *Lantana species "Gold Mound"* plants

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