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WIND UPLIFT RESISTANCE DESIGN OF A GREEN ROOF

Mike Gibbons, M.E.Sc.
RWDI Inc., Guelph, Ontario, Canada

Scott Gamble, P. Eng.
RWDI Inc., Guelph, Ontario, Canada

Shayne Love, Ph.D., P.Eng., MBA
RWDI Inc., Guelph, Ontario, Canada

ABSTRACT

Green roofs, also referred to as vegetated roofs, have increased in popularity in recent years in North America. Traditionally their use had been more prominent in European countries, such as Germany, however the North American design community have recently adopted them, thanks in part to programs such as LEED and the City of Toronto's Green Roof Bylaw. Toronto's Green Roof Bylaw mandates "green roofs on new commercial, institutional and residential development with a minimum Gross Floor Area of 2,000m^2 as of January 31, 2010". Also contained within the aforementioned Green Roof Bylaw is a requirement that the submitted green roof design explicitly state the uplift wind pressures that it has been designed for, and how the design addresses the stated pressures. This report needs to be stamped by a Professional Engineer.

This requirement has led to many questions regarding the wind resistance of a green roof, which is a unique building material in many ways - it is organic, living, porous, and has a variable weight (based on the amount of water it is retaining). Conventional building materials have strict tolerances and highly standardized, whereas the properties of green roofs change on a daily basis.

The intent of this paper is to discuss the design of a green roof in order to prevent lift off/fly away of a green roof assembly. The methods presented are based on applicable standards and building codes, as well as specific testing that has been undertaken on a green roof system to demonstrate its porosity and pressure equalization properties.

Keywords: Wind Uplift, Green Roof, Pressure Equalization, Full Scale Testing, Boundary Layer Wind Tunnel Testing

1. INTRODUCTION

Green roofs are becoming a common building typology in North America. Having been employed in Europe for decades, their adoption in North America over the past 5 – 10 years has been explosive. Much of this growth is due to the positive environmental aspects that green roofs bring to a building, such as better storm water retention and filtration, passive cooling and a reduction of the heat island effect in urban environments. The positive environmental aspects of green roofs are reflected in the allotment of LEED points for the installation of green roofs on buildings.

Due to the uniqueness of green roofs as a building product – no other product is a living, breathing organic system, whose weight and porosity changes by the hour – questions have arisen in terms of how they should be treated from a design standpoint. From a wind uplift perspective, green roofs present an interesting challenge, particularly due to their porosity. The low level of rigidity in a green roof also presents an interesting challenge when it comes to wind resistance, as the applicable wind load averaging areas are substantially less than conventional building products meaning that the probability of failure due to overturning, particularly at the edges and corners of green roof arrays, is heightened.

The purpose of this paper is to describe testing and analysis procedures that can be applied to the design of green roof systems, so that the risk of failure due to wind is minimized. The use of building code provisions, scale model boundary layer wind tunnel testing as well as full scale testing is described.

1.1 Review of Available Design Guidance

The following section details the available design guidance in the literature, pertaining to the wind uplift design of a green roof.

FLL Guideline for the Planning, Execution and Upkeep of Green Roof Sites (2008): This guideline is a holistic document which goes through the complete green roof design process, from initial design to installation to maintenance. Recommendations are made in regards to placement of green roof areas on a roof (i.e. high wind load areas to avoid), erosion control, and a calculation procedure to determine the required dead weight of the green roof assembly to resist uplift and overturning moment.

ANSI/SPRI RP–14 – Wind Design Standard for Vegetative Roofing Systems (2010): This design standard presents various building characteristics (height, exposure, parapet) and the recommended maximum design wind speed (referenced to 3-second gust, 10 m, open terrain) for three system classifications.

FM Global Property Loss Prevention Data Sheets 1-35 Green Roof Systems (2011): This data sheet details a number of loading conditions including wind, hail, gravity and seismic. For wind design, this data sheet largely references other FM Global Data Sheets (1-28 and 1-29), which largely reference the ASCE 7 design standard. Applicable wind load factors are recommended based on whether or not the green roof is used as ballast for roofing membrane/elements. The data sheet recommends an upper limit 50-year wind speed of 100 mph (45 m/s) 3-sec gust at 10 m in open terrain, for all building heights and terrains. At speeds above this level the data sheet recommends that green roofs not be installed.

Full-Scale Wind Loading on Green Roof Systems (Vo, 2013): This thesis details full scale testing completed at the University of Florida as well as a recommended calculation procedure that can be used to determine minimum green roof weight based on building geometry, exposure and design wind speed. This calculation procedure is largely based on the wind load coefficients for cladding and components in the ASCE 7 design standard.

While these documents provide some guidance to the designer of a green roof system, their applicability to real world buildings is thought to be somewhat limited. Furthermore, a remaining missing piece is how green roofs perform under wind loading conditions. In the sections that follow, the focus will shift from the determination of loading conditions to the assessment of wind resistance in green roofs.

2. PRESSURE EQUALIZATION

Traditional roofing systems incorporate a waterproofing layer that is impermeable to wind. Therefore, the net wind pressure, Δp, exerted on the roof is the difference between the wind pressure on the roof exterior, p_e, and the interior pressure within the building, p_i.

Green roof systems are permeable to air and water, and sit above the roof's waterproofing layer. While the overall pressure difference across the entire roof is unchanged when a green roof is used, the pressure differential experienced by the green roof assembly, Δp_{GR}, is some factor less than 1 of Δp owing to the porosity of the green roof which allows for pressure equalization. Therefore, one can relate the net pressure acting across a green roof assembly to the net pressure acting across the roof by Equation 1:

[1] $\Delta p_{GR} = EC \cdot p_e$

where EC is the equalization coefficient, which is some factor between 0 and 1. The green roof schematic in Figure 1 shows how the pressure differentials are defined.

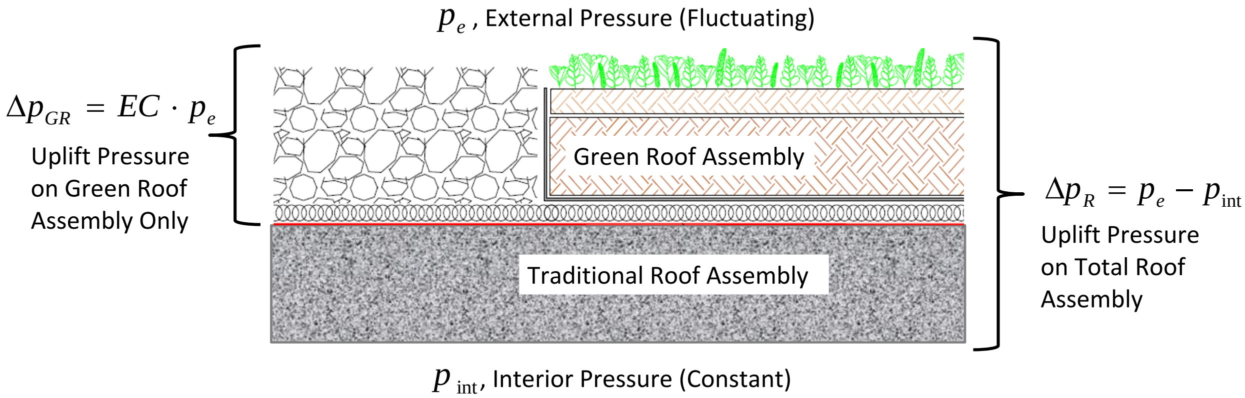

Figure 1: Schematic of green roof assembly pressure distribution

Clearly, a full scale test procedure is required to determine the equalization coefficient and resulting net pressure acting across a green roof assembly. In the literature, this has only been investigated implicitly. Full scale testing has been completed on a relatively small roof (8 x 8 ft) in a hurricane simulator facility (Vo et al, 2012). Similar testing was completed with the Wall of Wind facility at Florida International University, as described in Wanielista et al (2011). In the Vo et al tests, the pressure within the green roof assembly was not measured so it is not possible to determine an equalization coefficient from this test explicitly. Additionally, in both the Vo et al and Wanielista et al tests, it is not possible to separate the failure modes – namely failure due to uplift and failure due to overturning moment. The Vo et al study advocated for anchoring of the green roof assemblies in order to better resist uplift, as this was shown to greatly increase the survivability of the green roof in the as-tested 120 mph winds.

A pressure equalization testing procedure also exists within the CAN/CSA A 123.24 test standard (CSA Group, 2015). This test procedure applies a fluctuating pressure across the green roof assembly as well as the underlying built-up roof assembly. The deflection of the entire system is measured, and failure is said to occur when the deflection of the above-deck components (green roof assembly and built-up roofing assembly) exceeds L/120, where L is the structural span of the deck. This type of testing is described in greater detail by Baskaran (2002).

The authors of the current paper have developed a novel testing procedure which can directly quantify an applicable equalization coefficient for a given green roof assembly. This non-destructive testing procedure also readily allows different conditions of green roof assemblies to be tested. For example, the porosity, and therefore pressure equalization characteristics, of a green roof assembly could be different if the green roof is completely dry, saturated or frozen. This test procedure only looks at the pressure acting across the green roof assembly, so it can be readily applied to a green roof being installed on any roof type. This test procedure can be used in conjunction with the above mentioned testing procedure, or others, to allow for a better understanding of the performance of a green roof under wind uplift loading.

The test chamber allows for a green roof assembly test sample measuring 1 m by 1 m to be instrumented with pressure transducers. The pressure chamber and an example green roof sample are shown in Figure 2. Within the pressure chamber, a fluctuating pressure is applied to the green roof samples, varying in magnitude from 0 kPa to 1 kPa and in frequency from 1 Hz (~1 second gust duration) to 1/75 Hz (~1.25 minute gust duration).

Figure 2: Green roof sample within the pressure chamber (note the door has been removed for this photo)

In the tests conducted to date, pressure transducers were placed in five locations in the horizontal plane, with each of these five locations having pressure transducers at four levels within the sample. An example of the pressure transducers at the 4 layers are indicated in Figure 3. Two measurements of external reference pressure, p_e, were made within the pressure chamber: directly above the green roof sample and on the horizontal surface of the pressure chamber above the green roof sample. The placement of the transducers allowed pressure measurements to be made at various layers within the sample, and for pressure coefficients relative to p_e to be made. Using the collection of pressure measurements, the equalization coefficients could be calculated for the entire thickness of the green roof assembly and for sub-layers of the assembly.

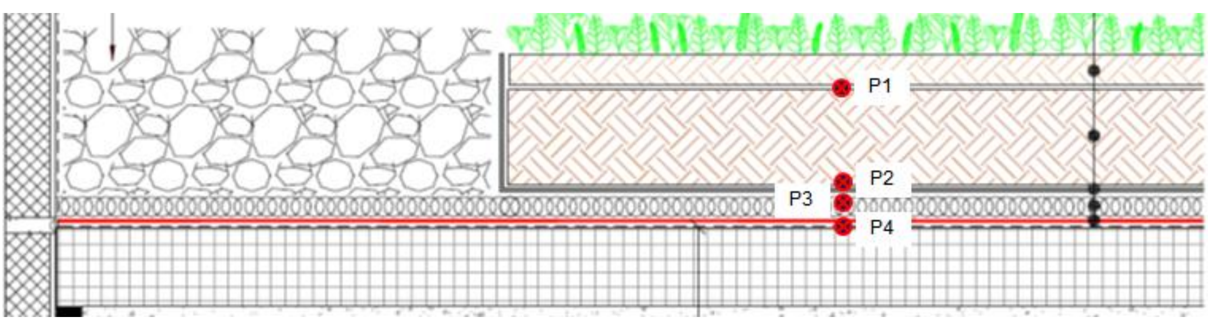

Figure 3: Sample Pressure Measurement Locations in Vertical Plane (Locations P1, P2, P3, P4)

This testing produces a set of pressure coefficients versus pressure fluctuation frequency. As mentioned previously, the pressure fluctuation frequency ranged from 1 Hz to 1/75 Hz. In this test methodology the quantity of primary interest is the difference in pressure between the layers of the green roof and external pressure, as these pressure differentials produce uplift forces that could potentially separate component layers of the green roof system or lift the entire system.

Equalization coefficients are used to express the pressure differentials across the green roof layers as a percentage of the external roof pressure calculated for structural roof loading. The equalization coefficients are frequency-dependent; since they are related to the time it takes for the pressure to equalize through a green roof sample. At each discrete frequency, the equalization coefficients, EC, are calculated using the formula in Equation 2:

[2] $$EC = \mathrm{stdev}(\Delta p_{GR}) / \mathrm{stdev}(p_e)$$

The testing completed to date has been confidential and therefore specific results cannot be shared, however, a generalized curved (with no value on the axis for EC) have been presented in Figure 4

One shortcoming of the above methodology is that the test procedure does not consider or account for the potential of system failure due to drag-induced failure of the green roof system. Failures of this type are typically related to improperly secured edges (roll-up) or wind erosion of the surface. The equalization coefficients calculated using the above methodology are only valid when the edges of the green roof system are appropriately secured or aerodynamically shielded. Other test methods can be used to assess the stability of the system to drag-induced failure.

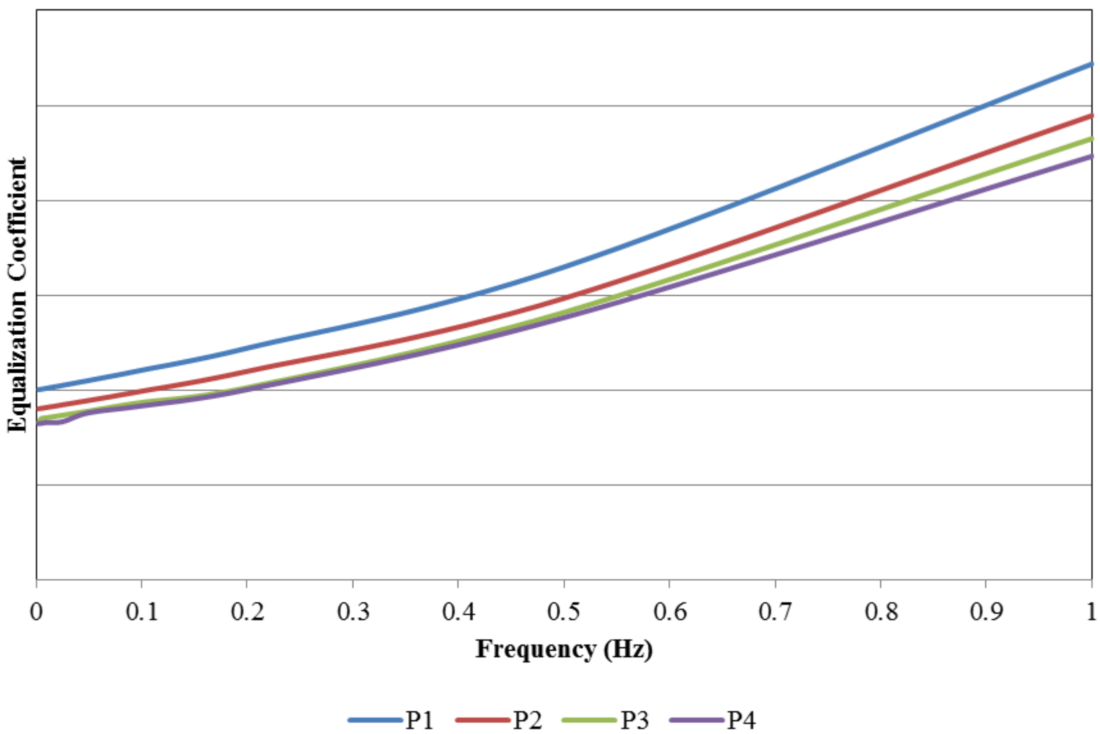

Figure 4: Sample plot of equalization coefficient versus pressure fluctuation frequency at four measurement points (P1, P2, P3, P4)

3. DRAG / WIND FLOW RESISTANCE

The previously mentioned testing completed by Vo et al (2012) and Wanielista et al (2011) explicitly test for the wind speed that leads to drag induced roll-over of the green roof assembly. Similar test procedures are also described within the CAN/CSA A 123.24 standard. As these test methodologies do not reflect a full-scale building, it is important that the as-tested wind speed is converted back to a real world wind speed appropriately. For example, the CAN/CSA A 123.24 test procedure calls for an oncoming wind that has very low turbulence (wind speeds must vary less than 3 km/h) and no mention of consideration for full scale wind spectra is made. Thus, it is inappropriate to make a direct correlation between the wind speed that a green roof assembly fails at in the CAN/CSA A 123.24 Wind Flow test procedure to a real world building. A test in a wall-of-wind test facility, where the spectral content of wind can be given due consideration, would allow more readily for a direct comparison to real world speeds, as the real world nature of the wind is simulated.

4. THE ROLE OF BOUNDARY LAYER WIND TUNNEL TESTING

Much of the discussion in this paper thus far has been on the role of full scale testing in determining the wind resistance of a green roof assembly. This, of course, is only one side of the equation. Traditionally, Boundary Layer Wind Tunnel Testing has been used to quantify the external pressures acting on a façade, as well as measure local wind speeds. Outlined below is a simple procedure that allows for a green roof assembly to be designed based on the results of boundary layer wind tunnel testing in conjunction with the resistances determined through the CAN/CSA A 123.24. Also provided is a modified procedure that allows for the use of equalization coefficients. Full details of boundary layer wind tunnel testing have not been provided in the current paper, as these have been described extensively in the literature. See Irwin et al (2013) or ASCE (2012) for further information.

From CAN/CSA A 123.24, a green roof designer has a wind uplift resistance, P_{up}, and wind flow resistance, V_{flow}. In order to determine wind uplift resistance, a cladding wind tunnel test is undertaken, which allows for the determination of peak external pressure coefficients. These external pressure coefficients are determined on a direction by direction basis, typically at wind direction intervals of 10° and at model scales in the 1:200 to 1:500 range. In order to determine full scale wind pressures, the pressure coefficients are combined with a representation of the local wind climate, which allows for an external wind pressure, P_{e50}, to be determined at a desired return period, such as 50 years. This procedure allows for the determination of external wind pressures at many locations on a roof surface, so it could be used as a pre-screening process in order to identify the areas on the roof that would be best suited for a green roof assembly.

Once the set of external pressures are determined (typically laid out in a cladding diagram), a simple comparison can be made to determine if the selected green roof assembly can resist the predicted wind load, as given in equation 3:

[3] $$P_{up} \geq P_{e50} \cdot \alpha$$

where α represents the contribution of any applicable load factors (such as wind load or dead load factors).

The equalization coefficient procedure relates the available wind uplift resistance to the dead load, W_{GR}, of the green roof assembly, according to equation 4:

[4] $$W_{GR} \cdot \alpha_D \geq EC \cdot P_{e50} \cdot \alpha_W$$

where α_D and α_W are the applicable dead load and wind load factors, respectively.

Drag / wind flow resistance can be determined using Irwin sensors (Irwin, 1981), which are conventionally used for the determination of pedestrian wind comfort. However, these same sensors can be used to determine local wind speeds at full scale heights of 0.25 m to 2 m above a roof surface. By instrumenting a building roof with Irwin sensors, gust velocity ratios can be determined on a direction by direction basis. As with the cladding pressure test, the gust velocity ratios are combined with a representation of the local wind climate which allows for local wind speeds, V_{e50}, to be determined for a desired return period. This procedure allows for the determination of local wind speeds at many locations on a roof surface, so once again it could be used to determine the best locations for a green roof assembly.

Once the set of local wind speeds have been determined, the following comparison can be made to determine if the selected green roof assembly can resist the predicted wind speeds, as given in equation 5:

[5] $$V_{flow} \geq V_{e50} \cdot \alpha^{0.5}$$

The applicable load factors are raised to the power of 0.5 as the relationship between wind speed and pressure is conventionally taken as P is proportional to V^2. As noted previously, the V_{flow} values determined through the CAN/CSA A 123.24 test procedure are steady speeds, with very little turbulence. Therefore, they should be treated as gust wind speeds rather than mean wind speeds in the comparison with V_{e50}.

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