

PROCEEDINGS

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WIND UPLIFT RESISTANCE EVALUATION OF COMMERCIAL ROOFS WITH AND WITHOUT ADD-ONS

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ABSTRACT

Wind-induced effects on roofing systems are dynamic because of the wind's variations with respect to time and space. The National Research Council of Canada (NRC), in collaboration with the Special Interest Group for Dynamic Evaluation of Roofing Systems (SIGDERS), has been investigating low-slope roof assemblies for wind uplift performance. In recent years, commercial roofs have been used (abused) as a platform with several add-ons. These add-ons include but are not limited to photovoltaic rocks, pavers to hold the rocks, photovoltaic films bonded to the membrane, garden roofs with extensive or intensive media, and, in some extreme cases, wind turbines. This paper will present and discuss these observations to facilitate the designer in developing guidelines.

SPEAKER

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WIND UPLIFT RESISTANCE EVALUATION OF COMMERCIAL ROOFS WITH AND WITHOUT ADD-ONS

BACKGROUND

Wind uplift forces acting on a roof system can be the cause of severe roof damage. Irrespective of the roofing system, the wind dynamics introduce stresses within the roofing system, causing fatigue, which may result in catastrophic failure over time. Depending on the magnitude and frequency of the wind events, this could lead to costly insurance losses.¹ For this reason, wind uplift testing of roofing systems has become a critical design consideration for insurance-approval agencies, architects, engineers, roofing contractors, and manufacturers. Furthermore, this type of testing acts as a key performance indicator of the materials used and provides insight into the expected longevity of a particular roof system. Once the system successfully resists a desired level of wind uplift pressure for a particular roof, the wind load design requirements have been met and the system can be approved for use. Wind uplift testing in many cases also identifies the mechanisms or weakest links in the roof system responsible for failure, and can help facilitate manufacturers in addressing those susceptible failure components directly.

Objective of the Paper

The objective of this paper is to demonstrate how rooftop add-ons influence the performance of roof systems under dynamic wind conditions. This has been accomplished through three case studies:

1. Concrete pavers as add-ons over the mod-bit membrane, (i.e., wind uplift performance of protected membrane systems). In such systems, the waterproofing membrane is protected from the environmental weather conditions. The investigation focused on systems that utilize interconnected concrete pavers to integrate roofing components and provide resistance against wind uplift.
2. Photovoltaic (PV) modules as add-

ons over the thermoplastic membrane (i.e., wind uplift performance of loose-laid PV modules over TPO membrane systems)

3. Vegetated trays as add-ons over the mod-bit membrane (i.e., wind uplift performance of vegetated roof systems)

The paper will present the first two case studies with side-by-side comparisons, but the presentation will elaborate on all three case studies.

CASE STUDY 1: WIND UPLIFT PERFORMANCE OF PROTECTED MEMBRANE SYSTEMS

Experimental Setup

For this study, evaluations were carried out in accordance with CSA A123.21-10² dynamic test protocol (Figure 1); the details are documented in Baskaran *et al.* (1999).³ Experiments were carried out at the NRC's Dynamic Roofing Facility (DRF)⁴ (see Figure 2), the features of which are documented by Baskaran *et al.* (2009).

- System #1: Consists of steel deck,

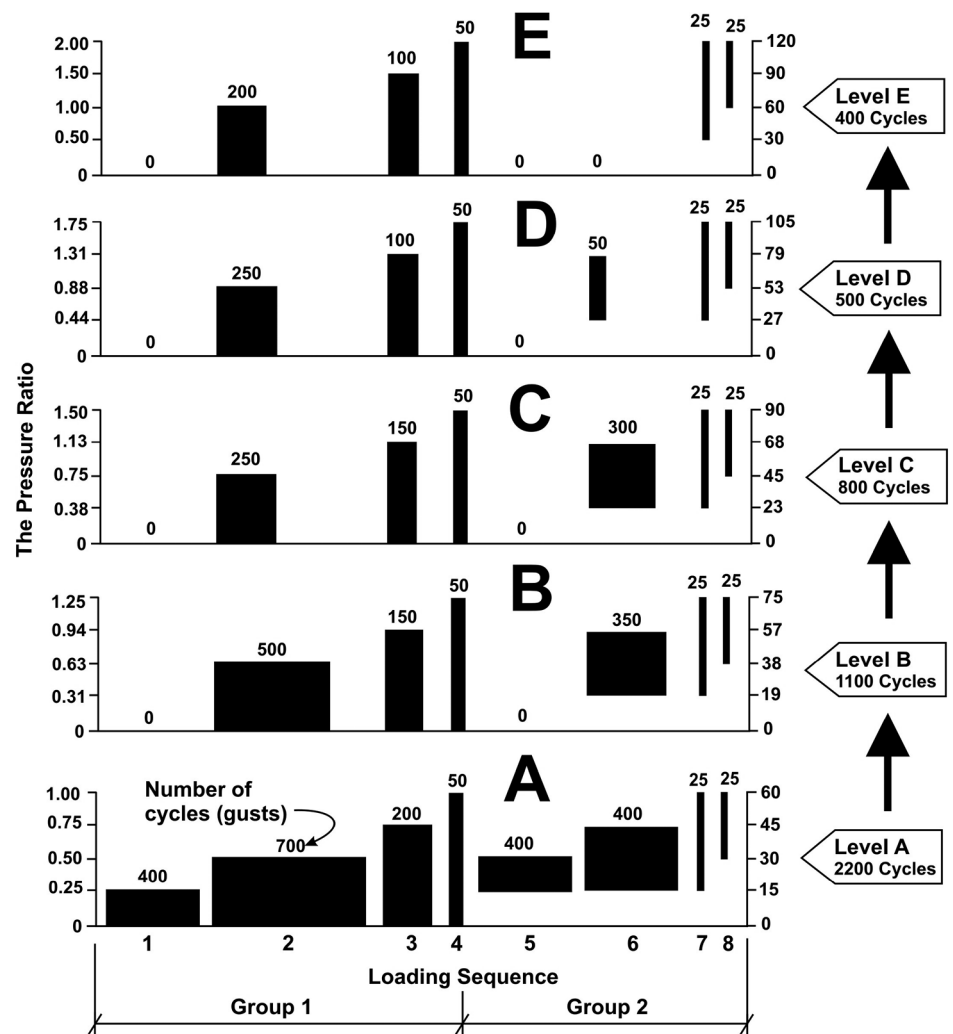


Figure 1 - CSA Dynamic Loading Cycle.



Figure 2 – A protected membrane system with a width of 16 ft. (4.9 m) and a length of 32 ft. (9.8 m) is ready for testing at the Dynamic Roofing Facility.

Figure 3 – Component details of System 1 and System 2.

plywood, support board, modified-bitumen membrane (cap and base sheets), woven polyethylene fabric, two layers of polystyrene insulation, and concrete pavers with H-clips.

- System #2: Consists of poured-in-concrete composite deck, modified-bitumen membrane (cap and base sheets), woven polyethylene fabric, two layers of polystyrene insulation, and concrete pavers with H-clips.

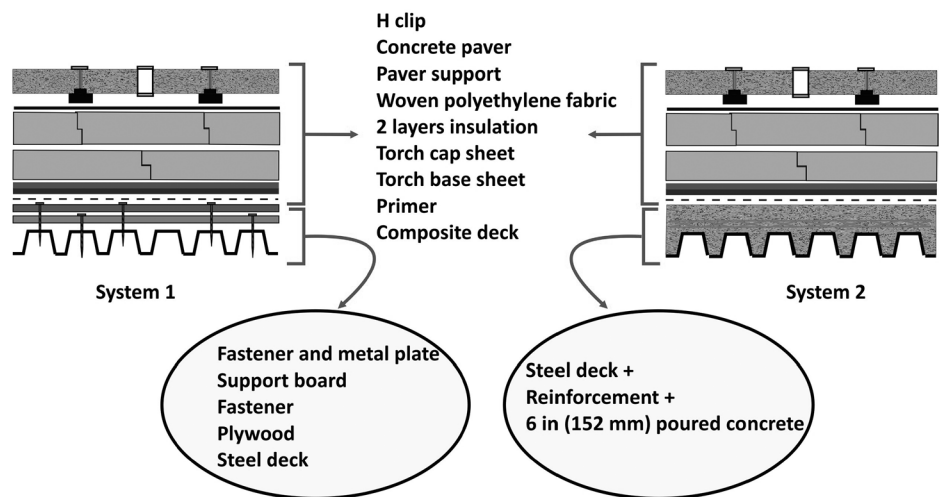


Figure 3 provides an isometric view of the components used. Figures 4 (System 1) and 5 (System 2) show a step-by-step photographic document of the system con-



Figure 4A – $\frac{3}{4}$ -in. x 4-ft. x 8-ft. (19 mm x 1219 mm x 2238 mm) sheets of plywood were placed on top the steel deck. Sheets were then attached with eight fasteners per board to steel deck using #14, $2\frac{3}{4}$ -in. (70-mm) fasteners.



Figure 4B – Over the plywood, support boards were attached with 15 fasteners per board, using #14, $2\frac{3}{4}$ -in. (70-mm) fasteners and 3-in. (76-mm) metal plates.

Figure 4C - A coat of primer (0.15-0.25L/m²) was applied on the top surface of the support board and cured for four hours. Base sheets were then torched to support the board layer.

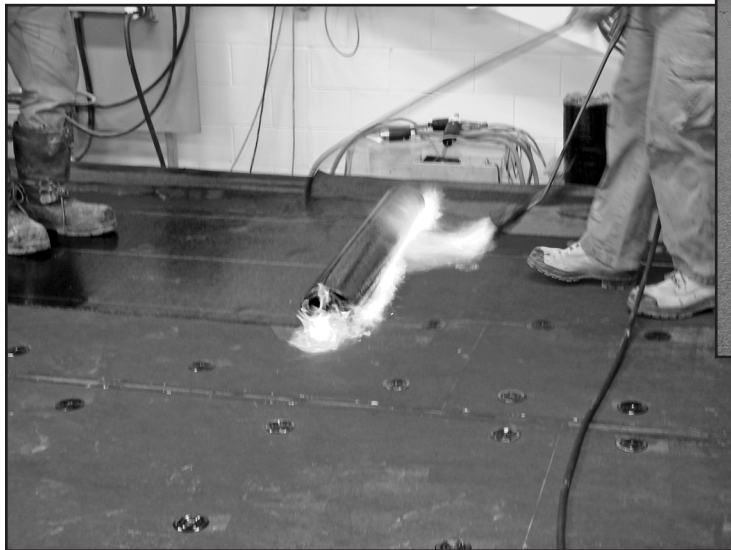


Figure 4D - Cap sheets were torched to the base sheet layer.



Figure 4E - Two layers of 3-in. x 2-ft. x 4-ft. (76-mm x 1219-mm x 2238-mm) insulation boards were shipped on top of the cap sheet.

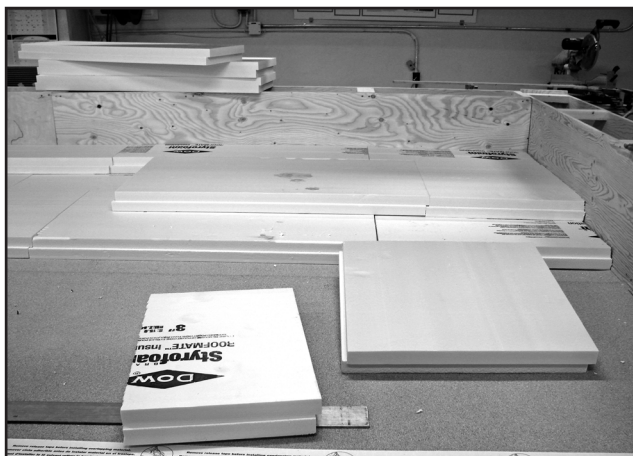


Figure 4F - 2-in. x 2-ft. x 2-ft. (51-mm x 1219-mm x 1219-mm) concrete pavers were placed on the top of the woven polyethylene fabric with paver supports 6 in. (152 mm) in diameter and 3/4 in. (19 mm) thick.



Figure 4H - Inside view during dynamic wind testing.

Figure 4G - Pavers were interconnected with 5-in. x 3 3/4-in. x 2 1/2-in. (127-mm x 83-mm x 64-mm) plastic H clips.

Figure 5A – Steel mesh was loose-laid on top of the welded steel deck.



Figure 5B – Six inches (152 mm) of concrete was poured on top of the steel deck with broom-finished surface, and the concrete was cured for 17 days.



Figure 5D – Cap sheets were torched to the base sheet layer.



Figure 5C – A coat of primer, 100-400 gal/ft² (0.4-1.6 L/m²), was applied on the top surface of the concrete deck. Base sheets were then torched to the concrete deck layer.

Figure 5E – An 18-in.- (457-mm-) high wooden parapet was installed all around the perimeter. Two layers of insulation were shipped and placed on top of the cap sheet.

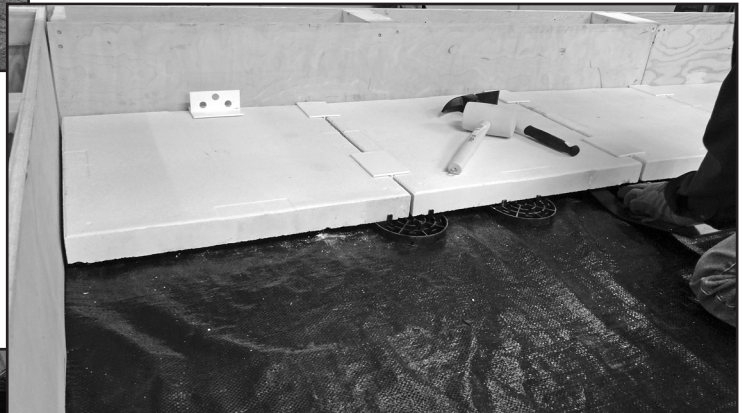


Figure 5F – One layer of woven polyethylene fabric was placed on the top of the insulation. 2-in. x 2-ft. x 2-ft. (5-mm x 1219-mm x 1219-mm) concrete pavers were placed on the top of the woven polyethylene fabric.

Figure 5G - Pavers were placed on the paver supports and interconnected with H clips.



Figure 5H - During dynamic wind testing (inside view).



struction at the DRF. During the test, time histories of the target and induced suction pressures and movement of the concrete pavers were collected. Observations of the system performance were video recorded and photographed at various points throughout the test period.

Experimental Data

Generally, the “roof wind” design is based on the following well-established engineering procedure:

System Resistance > Design Load Requirement (1)

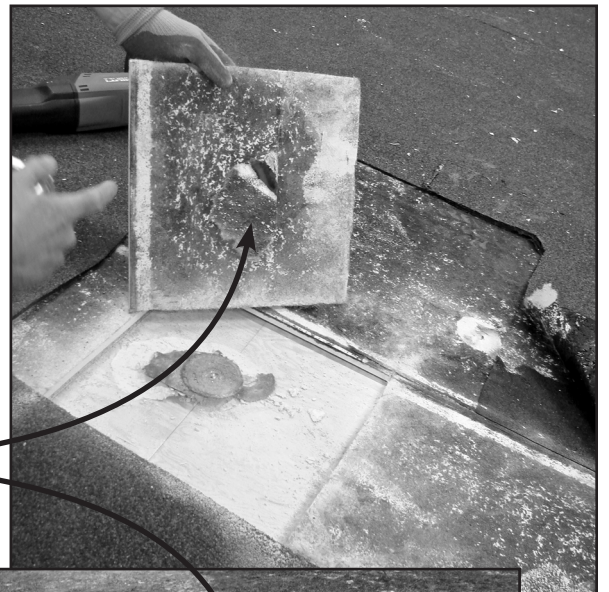
Flexible Membrane Roofs” (Baskaran and Smith, 2005). Professionally:

- Design load can be calculated using the Canadian model Building Code, “NBCC 2010 – National Building Code of Canada – Structural Commentaries (Part 4 of Division B)” or ASCE 7 - 2010.
- System resistance is evaluated in accordance with the consensus-based national standards such as CSA A123-21-10, Standard

Test Method for the Dynamic Wind Uplift Resistance of Membrane Roofing Systems.

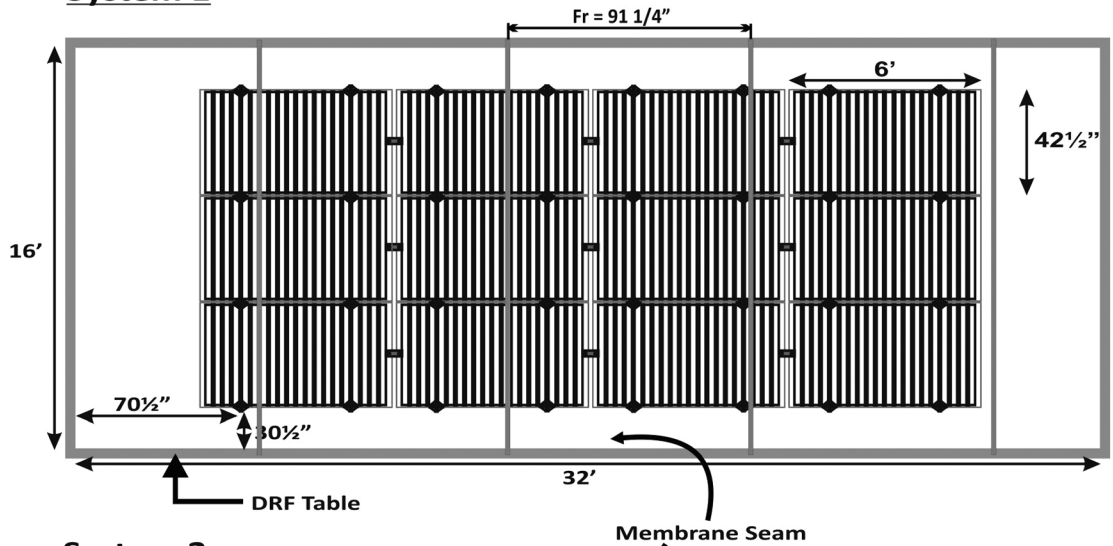
This paper focuses only on the system resistance evaluation, and no attempts were made to calculate the design load.

- System #1 had a resistance of 67 psf (3.2 kilopascals [kPa]). It sustained 100 psf (4.8 kPa) with a maximum measured paver uplift of 1.1 in. (28 mm). The sustained pressure level for each test refers to the highest



Figures 6A, 6B, and 6C - Failure mode of System 1. The add-on remains on top of the membrane after the dynamic wind test. Only fasteners and metal plates pulled through the support board.

System 1



System 2

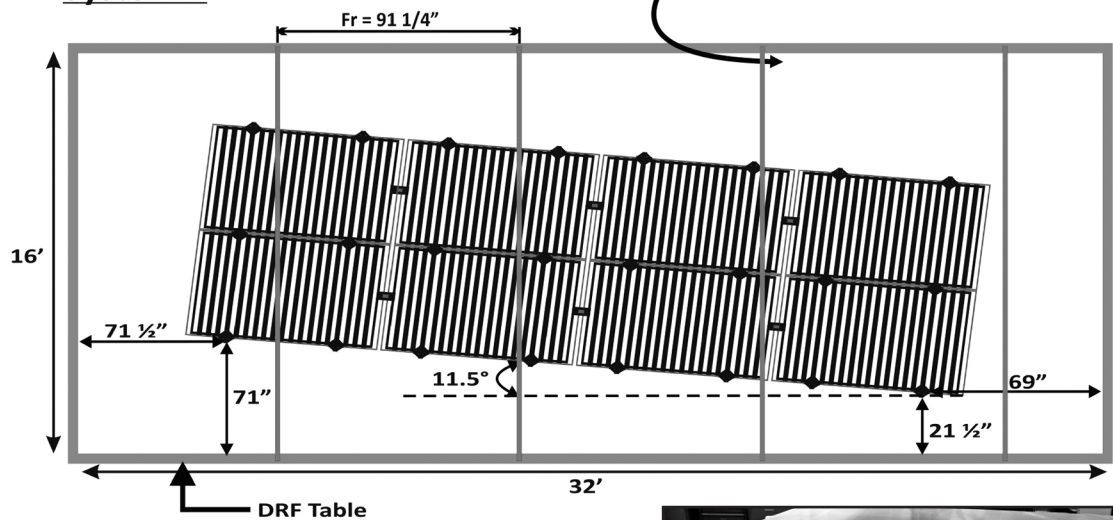
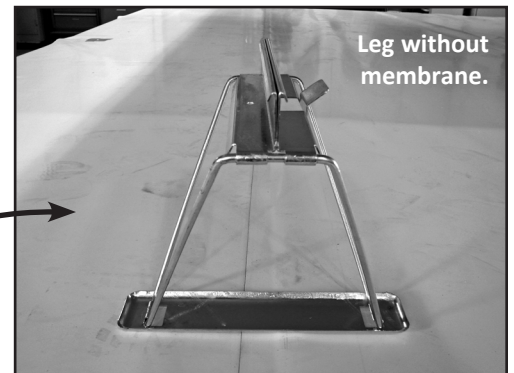
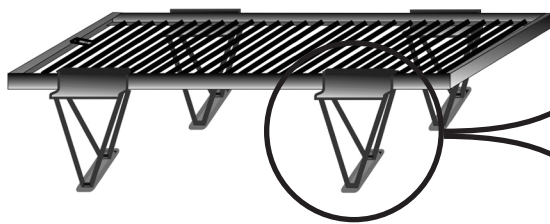


Figure 7 - PV module arrangement for Systems 1 and 2.



pressure level tested at which no noticeable failure had occurred to the roof system. System resistance was obtained by dividing the sustained test pressure with an experimental safety factor of 1.5 as per the CSA A123.21-10 standard.

- System #2 had a resistance of 180 psf (8.6 kPa). It passed 270 psf (12.9 kPa) with a maximum measured paver uplift of 1 in. (25 mm).

Discussion

This study presented wind uplift performance of a protected membrane roofing system subjected to the CSA dynamic wind uplift test protocol. System #1 failed at a wind suction pressure of 125 psf (6.0 kPa). During the failure investigation (refer to *Figure 6*), it was noticed that the weakest link in the system was the support board attachment to the structural deck (steel deck). The metal plates and fasteners pulled through the support board, causing the delamination of the membrane. This delamination resulted in discontinuity in the load transfer path, allowing air intrusion into the system. The lifted membrane was subjected to a pressure difference of 125 psf (6.0 kPa), which is greater than the self weight of the paver 23 psf (1.1 kPa). As the H clips maintained the interconnection of the pavers, the whole paver setup was uplifted during wind gusts.

The roofing system #2, constructed similarly to the field condition with a poured-in-place monolithic concrete deck, performed exceptionally well in resisting the extremely high wind pressures greater than 270 psf (12.9 kPa). With an air-sealed concrete deck, the air intrusion into the system is completely negated; therefore, the suction pressures are transferred equally across all the surfaces of roofing components (no pressure gradient) without any uplift forces acting on them. The applied uplift force is resisted by concrete deck and its attachment to the joist, which in this case was the strongest link, thus allowing the system to sustain high uplift pressures.

Conversely, if any air intrusion into the system occurs, it can break the load transfer path within the system components, and their response might induce significant uplift movement of the pavers. This was evident in System #1, which demonstrated the necessity for airtightness in the system at the deck level. It should be noted that in cases where the failure of the roofing components led to the uplift of the pavers, the lifted pavers settled back to their original position without any damage to themselves or to the clips.

When testing a roofing system for dynamic wind uplift performance, many component details and construction methodologies are considered. Some considerations for component details include the deck type, deck attachment, insulation compressive strength, membrane tensile

strength, and air permeability (leakage) of the individual components and the roof system collectively. For this reason, the reported wind uplift ratings from this study only apply to systems built at the NRC in the manner described in this report. Although this study provides some insight into the behavior of a protected membrane roof system when exposed to wind uplift pressures, further research efforts are required for any changes to be made in field construction methodologies or component selections. It is worthwhile to mention that preventing air intrusion into the assemblies is a key factor for these systems to be durable against wind uplift.

The need for incorporation of an air retarder/barrier into the system depends upon design wind speed and/or system design. For example, with a loose-laid membrane and Lightguard, an air retarder is critical. But in the system tested, an air retarder would not be needed where the speed is not too high (such as most of the continental U.S. outside of hurricane-prone regions). For additional details, refer to the ANSI/SPRI RP-4 standard.

CASE STUDY 2: WIND UPLIFT PERFORMANCE OF LOOSE-LAID PV MODULES OVER TPO MEMBRANE SYSTEMS

Experimental Setup

For this study also, all evaluations were carried out in accordance with the CSA A123.21-10⁵ dynamic testing protocol, and experiments were carried out at the NRC's DRF. To calculate wind loading on PV-mounted systems, refer to "Wind Design for Low-Profile Solar Photovoltaic Arrays on Flat Roofs," Wind Subcommittee on Solar Photovoltaic Systems (SEAOC Report PV2-2012, Structural Engineers Association of California).

- System #1 (refer to *Figure 7*): System consists of steel deck, polyisocyanurate insulation, and 8-ft.- (2438-

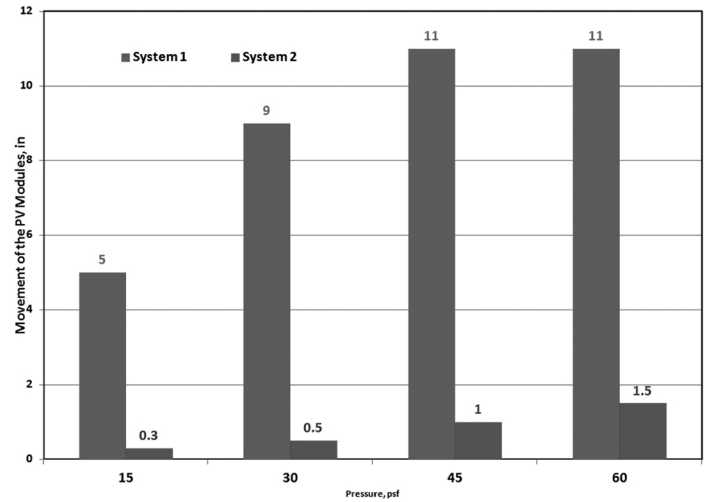


Figure 8 – PV module movement for Systems 1 and 2.

mm-) wide TPO membrane attached with fastener spacing of 12 in. (305 mm) on center. Twelve PV modules were interconnected using clips to form an array, which was loose-laid over the membrane with support legs. The module was installed with longer-dimension, 6-ft. (1830-mm) perpendicular-to-the-membrane seams. The overall dimension of the array was approximately 24 by 11 ft. (7300 mm by 3350 mm).

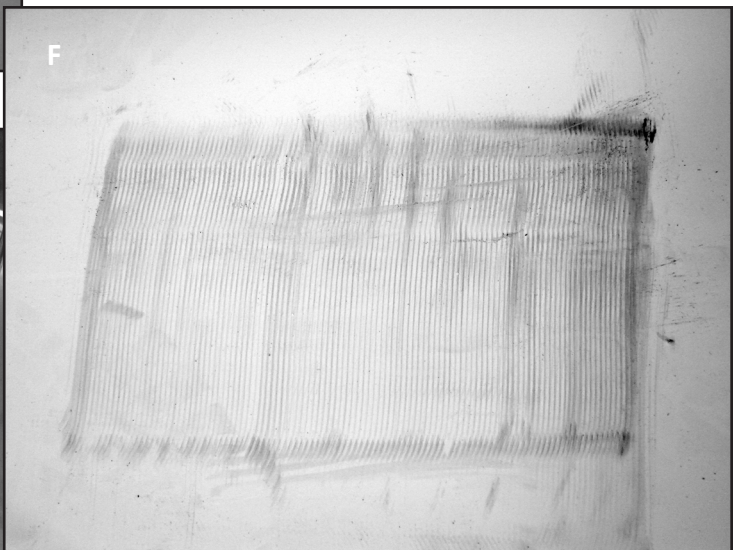
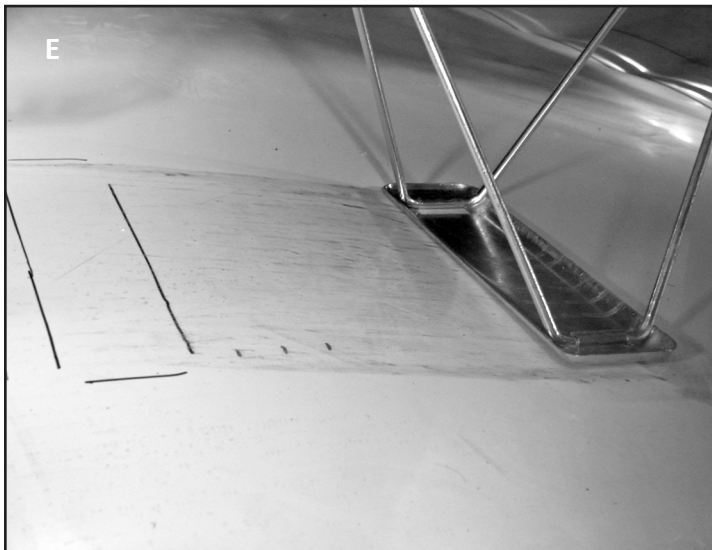
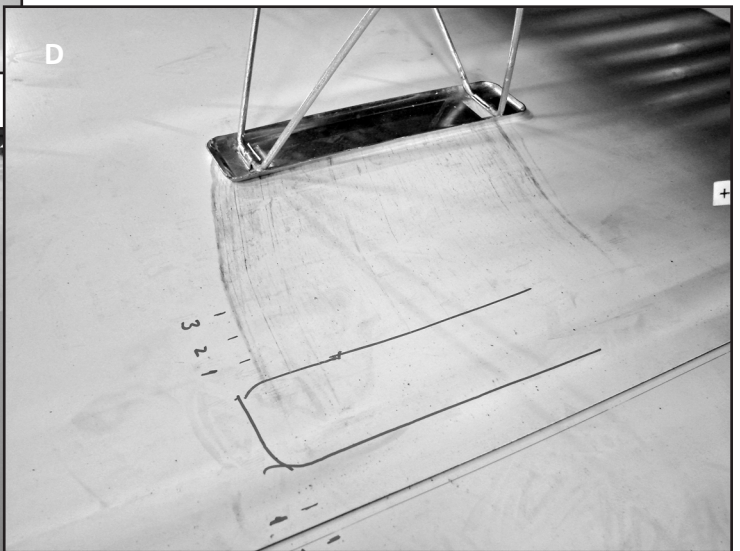
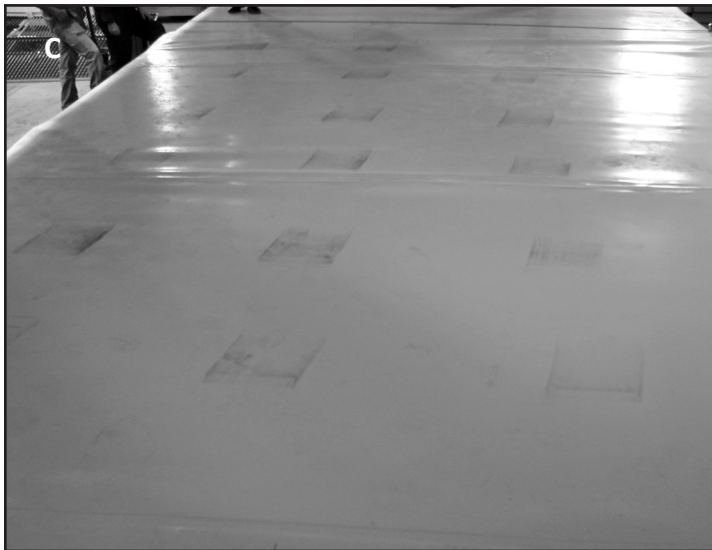
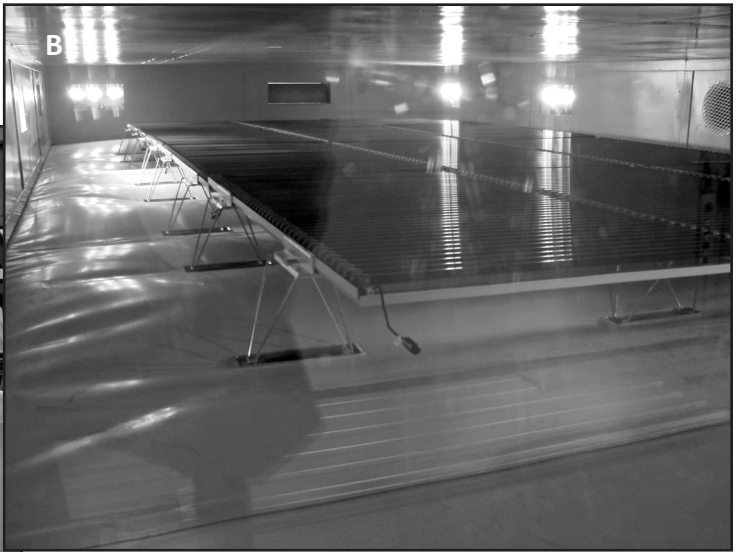
- System #2: Roof system components were the same as System #1, with module arrangement (longer dimension) placed at an angle of 11.5° to the membrane seams. A piece of rubber membrane was integrated to the support legs to offer friction on the membrane surface.

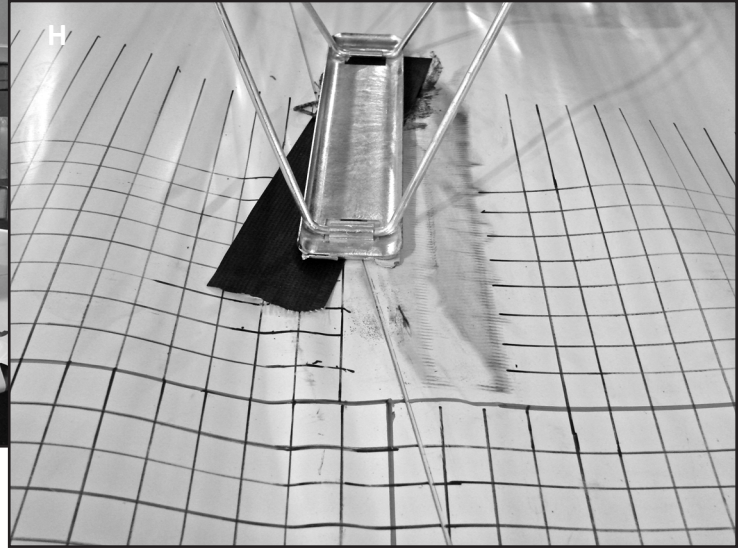
Experimental Data

Both systems were tested only to Level A of the CSA A123.21-10 load cycle, with 60 psf as the maximum test pressure. *Figure 8* compares the movement of the PV modules at various pressure levels.

- System #1 had a maximum longitudinal movement of 11 in. (279 mm) along the length of the module arrangement and a maximum lateral movement of 3 in. (76 mm). In other words, the translation movements of 11 in. (279 mm) and 3 in. (76 mm) represent sliding of the array perpendicular and parallel to the membrane seams.
- System #2 had a maximum longitudinal movement of 1.5 in. (38

Figure 9A - 9H - PV module response for Systems 1 and 2 during dynamic wind testing.





mm) along the length of the module arrangement and a maximum lateral movement of 3.5 in. (89 mm), which represents sliding of the array perpendicular and parallel to the membrane seams.

Discussion

This side-by-side system investigation provided knowledge on the contribution of two influence parameters—namely, membrane deformation and self-weight (70 lb.) of the modules. Equally important, the study confirmed the adverse effects created by the PV modules on the waterproofing membrane.

In comparing the two systems, the following observations can be made:

- Significant reductions of the module movements were measured by integrating pieces of rubber membrane on the leg supports. The rubber membrane provides additional friction at the membrane-to-leg interface, thus minimizing the movement of the PV modules.
- Arrangement of the PV modules at 11.5° slope to the membrane seam did not have any significant impact on the movement of the PV modules.

Figure 9 documents the photographic records of the PV modules' response on the roofing system due to wind uplift pressure. Some of the observations are summarized as follows:

- The clips used to integrate the PV modules to form an array cracked at pressure levels well below 60 psf. These polymeric clips failed to with-

stand the wind fatigue induced by the dynamic suction pressures.

- Irrespective of the arrangement, the adverse effects created by the PV module's legs on the waterproofing membrane are evident.
- The lateral movement or sliding of the array is significantly higher than the acceptable limit due to membrane billowing.
- Localized polymer losses were observed on the membrane where PV support legs were loose-laid. However, when tested according to ASTM D1474, the membrane met the water absorption requirement.

CONCLUSION

The paper presented two case studies with side-by-side comparisons for the wind uplift performance of add-ons on rooftops. For those who will be attending the presentation, the case study on the vegetated roofing will also be elaborated upon. ©

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