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Wind Performance Evaluation of Fully Bonded Roofing Assemblies

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ABSTRACT

Wind performance investigation is critical in the design of durable roofing assemblies. In North America, mainly two types of low slope roofs, conventional and inverted, are in practice depending on the placement of the membrane in the system. The present study focuses on the wind uplift performance of fully bonded single ply roofing assembly. Past studies focused on the wind uplift resistance evaluation of Mechanically Attached Systems (MAS) with different waterproofing membranes. However, no studies exist in the literature documenting the performance of fully bonded assembly (FBA). Recent field investigations of roof failures after major hurricanes indicated that these assemblies are equally susceptible to high wind events. The present study investigated three parameters that could influence the wind uplift performance of the FBA namely, curing time of the assembly, bonding strength between the membrane and insulation fastener plate and insulation thickness. The optimal curing time appears to be near 28 days, at which maximum adhesive bond is achieved between the membrane and the insulation facer. Use of metal fastener plates with smooth surface provides good bonding with the membrane compared to the plastic and textured plates, and thereby improves the wind uplift rating of FBA. Arranging the insulation in staggered fashion can minimize the airflow into the assembly and improve the wind uplift rating.

Key words

Wind, Roofs, Uplift, Fasteners, Curing Time, Loads, Dynamic Test, Failure Mode, Adhesive, Bond Strength.

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1. Introduction

Wind performance investigation is critical in the design of durable roofing systems. Wind flow around buildings creates both negative and positive fluctuations over a roofing system. Negative pressure on exterior surface is created by the flow separation on the outside of the roof. Positive pressure, known as building internal pressure, is dependent on the location of dominant openings in the building. It is generated by the wind flow into the building and the temperature difference across the envelope. These pressures are dynamic and can be separated into static and fluctuating components. The static component is simply the mean pressure. The transient component occurs as a random process and its dominant frequencies depend on the frequency of the upstream wind and the geometry of the building. Thus the wind effect on roofing and its response is dynamic. Wind pressure distribution varies spatially over a roof and it can have high suction at the corner and perimeter, due to vortex flow and separations. Figure 1 illustrates the pressure variation measured on a roofing assembly placed in a wind tunnel (Baskaran, Paroli and Booth, 1997).

Figure 1. Wind Pressure Distribution on a Roof

In North America, two main types of low slope roofs are in practice depending on the placement of the membrane in the assembly:

Conventional roofing assembly: The membrane is at the top of the insulation and is directly exposed to environmental elements. The conventional roofs may be either the Single-ply roofing system (SPR) or a Built up roofing system (BUR) Figure 2 illustrates typical cross-section of a conventional roof assembly

Inverted roofing assembly: It is also known as protected roofing assembly. The membrane is placed below the insulation and, thus is protected from environmental elements such as wind, rain, UV and temperature. Figure 3 shows typical cross-section of an inverted roofing assembly

Figure 2. Cross-Section of Typical Conventional Roofing Assembly

Figure 3. Cross-Section of Typical Inverted Roofing Assembly

Within the conventional single ply roofing assembly three types exist as follows:

Mechanically attached SPR: The membrane is attached to the structural substrate either along strips or at discrete points using fasteners. The attachments consist of the mechanical fasteners and plates or metal or polymer batten.

Fully Bonded SPR: The membrane is adhered to the insulation by solvent or water-based adhesive or hot bitumen and the insulation is mechanically attached to the structural deck.

Loose Laid SPR (ballasted configuration): The single-ply membrane is loose laid and held down by the weight of ballast or concrete pavers. However, at the building perimeters, the membrane is attached with the roof/wall junctions.

Figures 4 through 6 show the typical cross sections of these roofing assemblies.

Figure 4. Mechanically Attached SPR

Figure 5. Fully Bonded SPR

Figure 6. Loose Laid SPR

The present study focuses on the wind uplift performance of fully bonded single ply roofing assembly (Figure 5). The fully bonded single-ply roofing assembly (here after abbreviated as FBA) comprises of following components: deck, barrier, insulation, fastener plate, fastener, adhesive and membrane. Wind-uplift resistance of FBA depends on several factors namely, on the application and bonding strength of the adhesive, bonding strength of the membrane with insulation and fastener plates, fastener density of the insulation board, insulation thickness, and curing time of the assembly.

Wind uplift resistance of the FBA is different from that of the MAS. Figure 7 illustrates the wind effects on the FBA. As seen in the figure, the entire roofing assembly acts as a composite unit though each roofing component offers a certain resistance to the wind uplift force. This can be illustrated through a force-resistance link diagram. All resistance links should remain connected for an assembly to be durable and to keep the roof properly in place.

Figure 7. Wind Uplift Resistance of FBA

Existing studies in the literature focused on the wind uplift resistance evaluation of MAS with different membranes - Assemblies with PVC membranes (Baskaran and Lei, 1997), Assemblies with modified bituminous membranes (Chen and Baskaran, 1999) and Assemblies with TPO membranes (Baskaran, Lei and Richardson, 1999). However, no studies exist in the literature documenting the performance of the FBA. Recent field investigations of roof failures after major hurricanes indicated that these assemblies are equally susceptible to high wind events (NRCA, 2004 and RICOWI, 2006). Recent standard developed by the Single Ply Roofing Institute (SPRI, 2005) address only the bonding strength of insulation to the steel deck.

To understand the response of the FBA under dynamic environment, an extensive experimental study has been carried out by the SIGDERS – Special Interest Group for Dynamic Evaluation of Roofing Systems, at the National Research Council Dynamic Roofing Facility (Sexton and Baskaran, 2002 and 2003). Under this investigation more than 24 full scale mockups were constructed and exposed to simulated wind dynamics. This paper presents and discusses the experimental findings from this on going investigation.

2. Experimental Approach

Experimental work was carried out at the Dynamic Roofing Facility (DRF) established at the Institute for Research in Construction at the National Research Council of Canada (IRC/NRC). DRF consists of a bottom frame of adjustable height upon which the roof specimen and a removable top chamber are installed (Figure 8). The design allows for

the installation and study of roof assemblies of different thicknesses up to 500 mm (18") as well as the evaluation of sloped roofs. The bottom frame and top chamber are 6100 mm (240") long and 2200 mm (86") wide and 800 mm (32") high. The top chamber is equipped with six windows for viewing, and with a gust simulator, which consists of a flap valve connected to a stepping motor through a timing belt arrangement. Pressure suction as high as 10 kPa (209 psf) over the roof assembly is produced by a 37 KW (50HP) fan with a flow rate of 2500 L/sec (5300 cfm). A computer, using feedback signals, controls the operation of the DRF. The computer regulates the fan speed in order to maintain the required pressure level in the chamber. Operation of the flap valve simulates the gusts in the form of uniform cyclic pressure loading over the surface of the roofing system. Closing the flap valve allows pressure to build in the chamber, while opening the valve bleeds the pressure. Also, the test facility has instrumentation for measuring the dynamic response for the specimen. More information of the DRF features is given in Baskaran et al. (1999).

Figure 8. FBA on the Dynamic Roofing Facility

All assemblies were subjected to the simulated wind dynamics in accordance to CSA A 123.21-04 standard's load cycle. The CSA A123.21-04 load cycle (Baskaran et al 1999) was developed based on the wind-tunnel studies of full-scale roof assemblies. Studies were made of 3048 × 3048 mm (120" × 120") roof assemblies using the National Research Council's (NRC's) 9000 × 9000 mm (360" × 360") wind tunnel. Two series of investigations were carried out using two distinct roofing membranes. The first series dealt with a reinforced Poly Vinyl Chloride (PVC) membrane and the other with a non-reinforced Ethylene Propylene Diene Monomere (EPDM) membrane. Different configurations were tested for variation in building heights, wind speed and wind direction. The obtained unsteady histories of wind pressures were used for the load cycle development. The details of the developed load cycle can be found in a report by Baskaran et. al (1999).

Figure 9 shows SIGDERS load cycle and it has five rating levels (A to E). The test pressure on the Y-axis corresponds to the design pressure, in accordance with local building codes or wind standards. A summary of the load cycle follows:

- As shown in Figure 9, the SIGDERS dynamic protocol has five rating levels (A to E). To evaluate a roof assembly for a specific wind resistance, all the gusts corresponding to Level A should be applied.
- Each level consists of eight load sequences with different pressure ranges, depicted in Figure 9. The eight load sequences can be divided into two groups. Group 1 represents wind-induced suction over a roof assembly. It consists of four sequences, where the pressure level alternates between zero and a fixed pressure. Group 2 represents the effects of exterior wind fluctuations combined with a constant interior pressure on a building. Internal pressure variations are explicitly codified in the recent North American wind standards (ASCE 7-2004, NBCC 2005). The SIGDERS test protocol accounts for such variations. (Baskaran et al 1999)
- The test pressure ratios (y-axis) for a test can be calculated from the design

pressure, in accordance with local building codes or wind standards. The pressures for each load sequence are calculated as percentages of the test pressure. For the present investigation, all the tests started from Level A with a test pressure of 2.9 kPa (60 psf).

- To evaluate the ultimate strength of the roofing assembly, testing should be started at Level A and should be continued when moving from one level to another. To obtain a rating, all specified numbers of gusts in each level must be completed without any resistance link failure. As discussed in the Figure 7, the assembly is considered as “Failed”, even if one resistance link fails.

Figure 9. SIGDERS Dynamic Load Cycle

3. Experimental Set-up

This paper presents data from eight roofing assemblies (Table 1). Constructed assemblies were 2000 mm (79”) wide and 3048 mm (120”) length. These assemblies consisted of roofing components whose general physical and mechanical properties are grouped in Table 2.

Table 1. Mock-ups Details and Nomenclature

Table 2. Nominal Physical and Mechanical Properties of Components

Figure 10 illustrates a typical layout of the FBA. The installation is similar for all assemblies and the construction procedure can be described in four steps (Figure 11):

Figure 10. A Typical Layout of FBA

Deck Installation: Two deck pieces cut at length of 3048 mm (120”) and width of 1000 mm (39”) were overlapped and fastened to two 150 mm x 150 mm (6” x 6”) wooden beams spaced at 1830 mm (72”) o/c using 12 mm (½”) carriage bolts and 76 mm (3”) wood fasteners.

Figure 11. Mock-up Construction Process

Insulation Installation: Three insulation configurations were installed:

- A1 to A4: Two full insulation boards of 1219 mm x 2006 mm x 50 mm (48” x 79” x 2”) and two cut boards of 305 mm x 2006 mm x 50 mm (12” x 79” x 2”) were installed on top of the deck. The two full boards are installed in the middle with the long edges of the boards parallel to the width of the steel deck assembly and the cut boards are installed on the two sides as shown in Figure 11. The boards were fastened using 73 mm (2⅞”) diameter hexagonal metal plate.
- A5 and A6: The insulation dimensions and arrangement was similar to A1 to A4 with the exception that A5 uses a smooth surfaced 76 mm (3”) diameter circular metal plates, and A6 uses a 76 mm (3”) diameter circular plastic plates as fastener plates. The objective was to investigate the bonding strength of the membrane to the different plate configurations.
- A7 and A8: To investigate the effect of insulation thickness A7 was installed with two layers of 50 mm (2”) thick insulation boards in staggered arrangement, while

A8 was installed with one layer 100 mm (4") thick insulation boards. Both assemblies use 73 mm (2 $\frac{7}{8}$ ") diameter hexagonal metal plate as fastener plate.

- All the assemblies use # 15 - 127 mm (5") long fasteners for insulation attachment. Each insulation board has a fastener density of one fastener per 0.17 m² (1.8 ft²) as illustrated in Figure 12.

Membrane Installation: 1830 mm (72") wide 45 mil (0.045") TPO membrane were hot air welded together to form a continuous waterproofing layer. The membrane was then loose laid out squarely over the insulation boards along the width of the assembly, and clamped at one end, ensuring minimum overhang of 203 mm (8") of membrane along the width of the assembly. The membrane is then folded in half, so as to expose both the membrane underside and the insulation facer surface. Each surface was swept and cleaned (Figure 11).

Adhesive Application: The adhesive was applied on both surfaces, the membrane bottom and insulation top at a quantity of 4.4 Liters/6.5m² (1 Gal/70 ft²) using conventional paint rollers and sleeves. The surfaces were then left to cure for a period of approximately 30 minutes or until the surface is "tacky" to touch. At this point the membrane side is flipped and allowed to adhere to insulation using a spreading applicator as shown in Figure 11. All measures were taken to ensure that there was no air trapped between membrane and insulation. The same procedure is repeated for the other half of the membrane.

The above-mentioned systematic approach was followed for all assembly constructions. The amount of adhesive used per mock-up, the curing time prior to application, and the membrane-seaming weld parameters were specified by the material manufacturer. Further, all assemblies were constructed by the same roof applicator in order to minimize any errors resulting from differences in construction techniques and all assemblies were stored undisturbed under same lab ambient conditions.

After the specified curing time, the assembly is lifted with crane and placed into the SIGDERS test frame. With the test assembly in the middle of the test frame two dummy assemblies were placed on either side of the test assembly. To minimize any air leakage into the assembly the edges along the perimeter of dummy assemblies were sealed using insulation, air sealant tape, additional edge fasteners, and clamps as shown in Figure 11.

Figure 12 illustrates the instrumentation layout for the test assembly. A load cell, L1, capable of measuring force up to 700 lbf (3113 N) was installed on a center fastener of the middle insulation board to measure uplift load. P1 and P2 represent the pressure taps installed on the dummy to measure the pressure across the test assembly.

Figure 12. Instrumentation Layout for Wind Uplift Testing

4. Results and Discussion

The present study investigated three parameters that could influence the wind uplift performance of the FBA. The results obtained from these three investigative parameters are discussed below:

4.1 Effect of Curing Period

Curing period is defined as the number of days a assembly is allowed to cure after the construction and before it is subjected to the wind uplift pressures. The objective was to cure assemblies for different time periods and correlate the curing time with the sustained wind uplift pressure. All the assemblies were cured under standard lab conditions of 20°C and 65 % RH.

Starting with A1, which was allowed to cure for 14 days, A2 and A3 were cured in increments of 7 days i.e. 21 and 28 days respectively, and A4 was cured for 42 days. As indicated before, assembly construction and components were similar for the four assemblies and the only variable was the curing time. Figure 13 illustrates the measured pressure-time history response of the four tested assemblies.

Figure 13. Typical Time History Response Plots for Differences in Curing Time- Pressure

A1 with 14 days curing period sustained a maximum pressure of 1.4 kPa (30 psf) and passed only two sequences at the Level A of the CSA A123.21-04 protocol. When the applied pressure was 2.2 kPa (45 psf), the assembly failed at the loading sequence 3. A2's resistance increased to 2.2 kPa (45 psf), however, the assembly failed during the loading sequence 4, indicating that the increment of 7 days did not have major effect on the assembly's wind uplift performance. Conversely, A3 with 28 days and A4 with 42 days curing period showed comparatively a higher wind uplift performance by sustaining a maximum pressure of 2.9 kPa (60 psf).

Figure 14 shows similar comparison for the measured insulation fastener loads. A1 sustained a maximum force of 0.38 kN (88 lbf), A2 resisted a force of 0.69 kN (158 lbf) and A3 and A4 measured a similar load about 0.7 kN (160 lbf). The significant increase in the fastener loads from A1 to A3 is clearly due to the influence of curing time. In the case of A1, due to insufficient curing time period, the adhesive bond between the membrane and the insulation facer was not adequately developed resulting in the cohesive failure of the bonding agent. Whereas in A3, the 28 days curing time strengthened the adhesive bond between insulation facer and membrane, therefore moving the failure mode from adhesive level to insulation level where the insulation facer delamination was the failure mode. Figure 15 shows some of the typical observed failure modes. Evaluating the wind uplift performance of A3 and A4, the results indicate that increasing the curing period from 28 (A3) to 42 (A4) days did not have any major improvement in the wind uplift resistance. Both the assemblies sustained the same

pressure, similar fastener load and also had similar failure mode. Therefore the results obtained from the first investigative parameter indicates that there is a finite time for the curing of FBAs and the optimal time appears to be around 28 days, at which maximum adhesive bond is achieved between the membrane and the insulation facer.

Figure 14. Typical Time History Response Plots for Differences in Curing Time- Load

Figure 15. Failure Modes of the Wind Tested FBA after 14 and 28 Days Curing

4.2 Effect of Insulation Plate Configuration

During the failure mode investigation of A1, a weak adhesive bonding was noticed between the insulation plate and membrane. In some case, the failure mode appeared as if the failure might have initiated from the plate top and propagated. Based on that, it was decided to investigate the bonding strength of the insulation plate with the membrane. Two factors influence the bonding strength between the plate and the membrane, one is the plate geometry, and the other factor is the material compatibility of the plate with the adhesive. To identify the effect of plate configuration on the wind uplift resistance, three different insulation fastener plates were tested. Figure 16 shows the geometrical details of the three fastener plates.

Figure 16. Geometrical Details of the Three Types of Insulation Fastener Plates

A1 to A4 used the 73 mm ($2\frac{7}{8}$ ") diameter textured hexagonal metal plate, while A5 was constructed using 76 mm (3") diameter smooth circular metal plates and A6 was constructed using with the 76 mm (3") circular smooth surfaced plastic plates. Only with this exception, all the other components were similar for the three assemblies. The curing time for A1 to A4 varied from 14 to 42 days, while the curing time for A5 and A6 was 14 and 28 days respectively.

Figure 17 shows the comparison of the wind uplift performance of FBAs with three different plate configurations. The data shown in Figure 17 has been grouped based on the curing time. Going in the ascending order of the curing time, in period 1 with 14 day curing time the wind uplift rating of A5 with plastic insulation plate increased by two fold [2.9 kPa (60 psf)) when compared to A1 [1.4 kPa (30 psf)], which had the textured hexagonal metal plate. The same proportional increase in the fastener force was observed from A1 [0.4 kN (88 lbf) to A5 [0.8 kN (177 lbf)] as illustrated in Figure 17. Similar trend was observed in period 2 with 28 days curing time. A6 with smooth circular metal plate registered two-fold increase in both pressure and fastener load [5.7 kPa (120 psf), 1.5 kN (347 lbf)] when compared to A3 [2.9 kPa (60 psf), 0.7 kN (162 lbf)]., which had textured hexagonal plate. Figure 18 illustrates the observed failure modes for the four tested assemblies. Emphasizing on the bonding strength of the plates, in the case of A1 and A5 the area around the fastener plates indicated the cohesive failure of the bonding agent (adhesive on the underside of the membrane and on the insulation facer). Very minimal adhesive was found on the plastic plate (A5) compared to the textured metal plate (A1), however, the geometrical symmetry and larger contact

surface area (bonding area) of the plastic plate improved the wind uplift rating of A5 compared to A1. Similarly, the comparison of the bonding strength A3 and A6 revealed that the smooth circular metal plate in A6 had more adhesive accumulated compared to A3, which had the textured hexagonal plate. As illustrated in Figure 18, the concave surface of the smooth circular metal plate provides the larger bonding area or contact area to increase the bonding strength with the membrane, which results into high wind uplift resistance. Conversely the failure pattern of the textured hexagonal plate as depicted in Figure 18 indicates that only the outer and the middle rim of the plate offer the required contact area. The outline of the plate marked on the adhesive layer and the absence of adhesive on the plate (Figure 18) justifies this observation. This weak-bonding strength between the plate and membrane ultimately led to the cohesive failure of the assembly. The adhesive bonding of the smooth circular plate (A5) is a good candidate of both the geometrical and material compatibility.

Figure 17. Effect of Insulation Fastener Plate Configuration on Wind Uplift Rating

Figure 18. Failure Modes Observed with Different Plate Configurations

4.3 Effect of Insulation Thickness on Wind Uplift Resistance

The third investigative parameter was the effect of insulation thickness. Three different insulation layouts were investigated. Figure 19 shows the cross-sectional view of the three assemblies. A7 comprised of staggered arrangement of two layers of 50 mm (2") thick insulation boards with overall thickness of 100 mm (4") and A8 was installed with one layer of 100 mm (4") thick insulation boards. The data obtained from these two assemblies was compared with A3, which had one layer of 50 mm (2") thick insulation boards. The insulation boards used in the three assemblies are from the same manufacturer and all three assemblies used the common plate and fastener [73 mm ($2\frac{7}{8}$ ") diameter hexagonal textured metal plate and # 15- 127 mm (5") long fasteners] for attachment to the steel deck. Apart from the varying insulation thickness, the remaining roofing components were similar for all the three assemblies. A3 and A8 had a curing time of 28 days, while A7 had a curing time of 35 days. As discussed in section 4.1, the optimal curing time was found to be at 28 days, therefore the curing time of 35 days for A7 can be considered not to be an influential factor on the assembly's wind uplift performance.

Figure 19. Cross Sectional View of Assemblies with Different Insulation Thickness

Figure 20 shows the measured pressure and load time histories for the three tested assemblies. In terms of the wind uplift pressure, A3 (a layer of 2" ISO) and A7 (2 layers of 2" ISO) sustained a pressure of 2.8 kPa (60 psf) and 5.0 kPa (105 psf) respectively, while A8 (a layer of 4" ISO) passed 5.7 kPa (120 psf) without any failure. A8 was started with a target pressure of 2.9 kPa (60 psf) and when the test pressure reached 5.7 kPa (120 psf) no failure was observed and the test was stopped. Therefore the ultimate strength of the A8 might be greater than 5.7 kPa (120 psf).

Figure 20. Measured Response of the Assemblies with Different Insulation Thickness

After the wind uplift test, the test assemblies were examined for the failure modes as shown in Figure 21. In A3, the observed failure mode was the cohesive failure of insulation facer, while A7 failed by a combination of cohesive failure of insulation facer and foam cracking at the top layer of the insulation boards. Closer examination of the A7 indicated that the bottom insulation layer had no signs of damage and it was the top layer that underwent foam cracking. In A8, no failure mode was observed however the condition of the assembly was investigated as shown in Figure 22. Even though, A8 did not meet the failure criteria established for the present study, it is evident from the Figure 22 that A8 was at the verge of failure.

Figure 21. Failure Modes of the FBA's with Differences in Insulation Thickness

Figure 22. Condition of A8 after the Wind Uplift Testing

Comparing the failure modes of A3 (a layer of 2" ISO) and A7 (2 layers of 2" ISO) as shown in Figure 21 arises a question that if the bottom insulation layer of A7 is acting as a spacer, then how the assembly wind uplift rating was better than A3 as both have the same wind uplifting mechanism. Note that there is no bonding between the two insulation layers. As shown in Figure 19, A7 comprises of staggered arrangement of two layers of 2" (50 mm) thick insulation boards. When the assembly is subjected to wind uplift pressure, the top insulation layer, which is adhered to the membrane is subjected to deformation, while the bottom insulation layer is acting as a spacer in between the deck and top insulation layer. The staggered arrangement of insulation boards contributes to an air barrier effect restricting the air intrusion into the assembly. This type of air retarding effect reduces the stress on the adhesive interface, which lowers the failure propagation between the membrane and insulation and allows the assembly to sustain higher wind uplift pressures. At higher wind uplift pressures the wind-induced load at the fasteners might have exceeded the maximum compressive strength of the insulation board eventually leading to the foam failure. This failure mode highlights the phenomenon of air barrier effect and transferring of the weakest link from the adhesive interface to the insulation level.

The next question that arises is the higher wind uplift resistance of A8 compared to A3, though both had one layer of insulation boards with the exception of difference in thickness. With the increase in thickness the compressive strength of the insulation board increases and the deformation decreases. Though both A3 and A8 have the same insulation fastener density, A8 with thicker insulation board [100 mm (4")] deforms less than A3 [50 mm (2")] reducing air intrusion into the assembly. The combination of higher compressive strength and lower deformation, and reduction of air intrusion increased the wind uplift rating of A8 compared to A3.

5. Concluding Remarks

Research pertaining to the wind uplift performance of fully bonded assemblies (FBA) is still unfilled in the roofing literature. The current study provides the foremost research data in understanding this specific genre of conventional roofing assembly. These roofing assemblies are a combination of mechanical attachment and adhesive application. Curing time of the assembly plays crucial role in its wind uplift evaluation. The present study investigated eight mockups of fully adhered assemblies based on three influencing parameters. The first parameter being the curing time, the second parameter was the material compatibility and adhesive strength between the insulation fastener plate and the membrane, and finally the third parameter was the effect of insulation thickness. Based on the presented results and discussions, the following conclusions can be drawn:

- Fully bonded assembly with 28 days curing time showed an increase in the wind uplift resistance by 50% and 25% respectively compared to assemblies with 14 and 21 days curing time. The optimal curing time appears to be near 28 days, at which the maximum adhesive bond is achieved between the membrane and the insulation facer, and no changes in wind uplift performance was observed for assemblies with 42 days of curing time.
- In addition to the attachment function the geometrical configuration of the fastener plate played a major role in wind uplift resistance. With the same curing time, assembly with circular metal plate having smooth surface sustained 50 % higher wind uplift resistance when compared to assemblies with textured hexagonal plate and smooth plastic plate.
- Doubling the insulation thickness from 50 mm (2") to 100 mm (4") doubled the wind uplift resistance. This improvement can be attributed to the higher compressive strength and lower deformation of the thicker insulation board, which contributes to air leakage control into the assembly.

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<i>Manufacturers</i>	Atlas Roofing Corporation, Canadian General Tower Ltd., Carlisle Syn Tec., GAF Materials Corporation, GenFlex Roofing Systems, Firestone Building Products Co., IKO Industries Ltd., ITW Buildex, Johns Manville, Sarnafil Roofing, Soprema Canada, Stevens Roofing, Tremco and Trufast
<i>Building Owners</i>	Canada Post Corporation, Department of National Defence, Public Works and Government Services Canada.
<i>Industry Associations</i>	Canadian Roofing Contractors' Association, Canadian Sheet Steel Building Institute, National Roofing Contractors' Association and Roof Consultants Institute.

Figure 1. Wind Pressure Distribution on a Roof

Figure 2. Cross-Section of Typical Conventional Roofing Assembly

Figure 3. Cross-Section of Typical Inverted Roofing Assembly

Figure 4. Mechanically Attached SPR

Figure 5. Fully Bonded SPR

Figure 6. Loose Laid SPR

Figure 7. Wind Uplift Resistance of FBA

Figure 8. FBA on the Dynamic Roofing Facility

Figure 9. SIGDERS Dynamic Load Cycle

Table 2. Nominal Physical and Mechanical Properties of Components

Deck

Type	Profiled 22-gauge metal
Thickness	0.030" (0.76 mm), nominal
Overall Depth	1.5" (38 mm)
Flute Spacing	5.9" (150 mm)
Fastener Pullout as per ANSI/SPRI FX-1-2001*	510 lbf (1512 N)

Insulation

Type	Polyiso
Dimensions**	4' x 8' (1219 mm x 2438 mm) x 2" (50 mm) or 4" (102 mm)
Compressive Strength as per ASTM D1621(2004)*	25 psi (170 kPa)

Insulation Attachment

Type	Mechanical fasteners
Fastener	5" (127 mm) Long Type # 15
Plate***	2.875" (73 mm) Dia. Hexagonal metal plate
Fastener Layout	Refer to Figure 7
Fastener Density	1.8 Sq. ft./ Fastener (0.17 Sq. m/ Fastener)

Membrane

Type	TPO, Single-ply
Thickness*	45 mil (1.16 mm)
Tensile Property as per ASTM D 751 - 2000*	XD: Breaking strength = 3481 psi (24.0 MPa) XD: Elongation at break = 30.4 % MD: Breaking strength = 3597 psi (24.7 MPa) MD: Elongation at break = 31.0 %
Attachment	Fully Bonded
Amount of Glue Used	1 gal / 70 Sq.ft. (3.79 L / 6.5 Sq.m)

Seam

Type	Hot air welding
Seaming Width	Overlap = 3.5" (89 mm)

**Data measured at NRC*

*** Varied for A8: 4' x 8' (1219 mm x 2438 mm) x 4" (100 mm)*

**** Varied for A5 : 3" Dia. Smooth Circular Metal Plate*

**** Varied for A6 : 3" Dia. Smooth Circular Plastic Plate*

Figure 10. A Typical Layout of FBA

Figure 11. Mock up Construction Process

Figure 12. Instrumentation Layout for Wind Testing

Figure 13. Typical Time History Response Plots for Differences in Curing Time -Pressure

Figure 14. Typical Time History Response Plots for Differences in Curing Time - Load

Figure 15. Failure Mode of the Wind Tested FBA after 14 and 28 Days of Curing

Figure 16. Geometrical Details of the Three Types of Insulation Fastener Plates

Figure 17. Effect of Insulation Fastener Plate Configuration on Wind Uplift Rating

Figure 18. Failure Modes Observed with Different Plate Configurations

2" ISO - A3

2x2" ISO - A7

4" ISO - A8

Figure 19. Cross Sectional View of Assemblies with Different Insulation Thickness

Figure 20. Measured Response of the Assemblies with Different Insulation Thickness

Figure 21. Failure Modes of the FBA's with Differences in Insulation Thickness

Figure 22. Condition of A8 after the Wind Uplift Testing