WIND UPLIFT RESISTANCE OF LOW-SLOPE MECHANICALLY FASTENED ROOFS WITH ATTACHED AND LOOSE-LAID INSULATION BOARDS

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Significant advancements through research and development are continuing to improve the characteristics of single-ply roof membranes. When these new membranes are integrated with other components of a roof assembly, what is missing is the understanding of the roof system's performance. Because of the lack of this advancement, existing roof system design procedures are not significantly different from those of conventional built-up roofs. The purpose of the paper is to explore one aspect of wind uplift design, namely, the need for attachment of insulation boards in a mechanically fastened membrane roof system. It has been demonstrated that neither the number of insulation fasteners nor their layout affects the wind performance of the roof system.

KEYWORDS

Wind Uplift, Low Slope Roofs, Single Plies, Insulation Attachment, Static Test, Dynamic Test, Fastening Layout.

INTRODUCTION

Single-ply roof (SPR) membranes are enjoying market growth in North America for low-slope roofing applications. The National Roofing Contractors Association's (NRCA's) 1997 market survey reported about 40 percent market share for SPR systems used in low-slope new construction [1]. During the 1980s when SPR systems started penetrating the market in low-slope applications, design concepts and evaluation procedures were adapted by modifying those that existed for conventional built-up roof (BUR) systems. Factory Mutual Research Cooperation- (FM-) tested SPR systems using the 5-foot-by-9-foot (1524-mm-by-2438-mm) wind table that had been used for the BUR systems for its wind uplift ratings. Significant advancements through research and development are continuing to improve the membrane characteristics of SPR systems [2]. Typically, this includes:
- modifying membrane chemical composition to develop environmentally adaptable membranes such as TPO
- increase in the membrane width to reduce the installation cost, such as 10-foot- (3048-mm-) wide sheets
- increasing the choice of membrane colors for aesthetic considerations

Only a few modifications in the design concepts and evaluation procedures were developed to account for the changes in membrane characteristics. Designing seams for thermoset membranes with tapes rather than liquid adhesives and FM's move towards a 12-foot-by-24-foot (3658-mm-by-7316-mm) wind uplift procedure are examples of some of these changes.

What is missing is the advancement of knowledge in the SPR system performance when these new sheets are integrated with other components of the roof system. Because of the lack of this advancement, existing SPR system design procedures are not significantly different from those of the conventional BUR system. The main purpose of this paper is to explore one aspect of wind uplift design, namely, the need for attachment of insulation boards in a mechanically fastened SPR system. As shown in Figure 1, the wind-induced pressures on a roof system can vary across the surface of the roof. The effects of wind can also vary with time, because pressure fluctuates with wind speed. Thus, all roof system designs must account for wind effects.

In this paper, experimental data are presented from a study that has been completed to quantify the influence of insulation board attachment. Two types of roof systems were tested. The first system had sheets narrower than the insulation board; 39¾-inch- (1-m-) wide modified bituminous sheets on 48-inch- (1219-mm-) wide polyisocyanurate (ISO) boards. The second system had sheets wider than
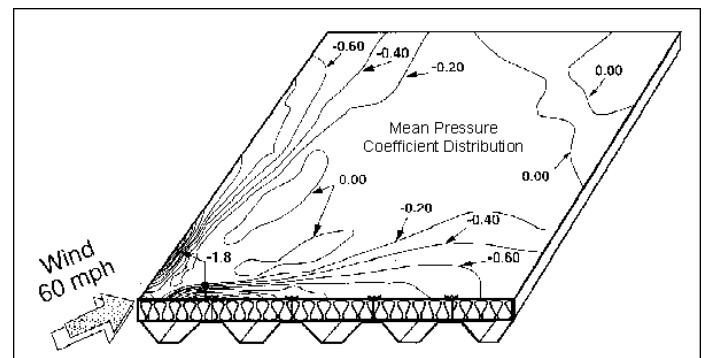

Figure 1. Wind pressure distribution on single-ply, mechanically attached roof systems.

the insulation board; 72-inch- (1829-mm-) wide PVC sheets on 48-inch- (1219-mm-) wide ISO insulation boards. For each system, two specimens were tested for wind uplift performance. In the first specimen, insulation boards were loose-laid, whereas in the second specimen the insulation boards were attached with six fasteners per board. In addition, two different (static and dynamic) test protocols were applied to investigate the influence of wind dynamics. A modified bituminous system was investigated using a static load cycle, whereas a PVC system was studied by applying a dynamic load cycle. A summary of the test protocols and descriptions of the dynamic roofing facility (DRF) in which these investigations have been completed are presented in the next section. System responses are also documented and discussed. Based on the discussion, the present study advances the design knowledge of SPR systems by concluding that there is no benefit in the wind-uplift rating because of mechanical attachment of insulation boards, and this has been found true irrespective of the SPR system and test protocol used. Further research areas that are needed for the development of design guidelines are also identified.

EXPERIMENTAL SETUP

Dynamic Roofing Facility

All the experiments described in this paper were carried out using the DRF established at the Institute for Research in Construction at the National Research Council of Canada (IRC/NRC). Baskaran and Lei documented details of the DRF features [3]. The DRF, shown in Figure 2, consists of a bottom frame of adjustable height upon which roof specimens are installed and movable top chamber. The bottom frame and top chamber are 240 inches (6100 mm) long, 86 inches (2200 mm) wide and 32 inches (800 mm) in height. 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 209 psf (10 kPa) over the roof assembly is produced by a 50 HP (37 kW) fan with a flow rate of 5300 cfm (2500 L/sec). A

computer uses feedback signals to control the operation of the DRF. The computer regulates the fan speed to maintain the required pressure level in the chamber. Operation of the flap valve simulates the gusts. Closing the flap valve allows pressure to build in the chamber, and opening the valve bleeds the pressure.

Applied Load Procedure

Static Test: Currently, in North America, FM 4470 is used as a test protocol for wind uplift resistance of SPR systems [4]. FM 4470 is not a consensus-based test protocol. In this static test, a pressure of 30 psf (1436 Pa) is applied from the bottom of the test specimen and held for one minute. The pressure is increased by 15 psf (718 Pa) each minute until the test specimen fails. A test assembly that successfully sustains a pressure of 90 psf (4309 Pa), for example, is given a windstorm classification of I-90. Another North American wind uplift approval standard is Underwriters Laboratories (UL) UL 580, and it is an approved American National Standards Institute (ANSI) standard developed based on a consensus approach [5].

Dynamic Test: A North American roofing consortium, the Special Interest Group for Dynamic Evaluation of Roof Systems (SIGDERS) has been established at the National Research Council of Canada to develop a test standard for evaluating roof systems under dynamic conditions. Research efforts by SIGDERS have led to the development of a new dynamic load cycle for the evaluation of roof systems. The SIGDERS load cycle was based on extensive wind-tunnel studies of full-scale roof systems measuring 10 feet by 10 feet (3048 mm by 3048 mm). These studies were carried out in NRC's 30-foot-by-30-foot (9-m-by-9-m) wind tunnel. Details of the method by which the load cycle was developed can be found in the paper "Wind Performance Evaluation Procedures for Roof Systems: Current Status and Future Trends" [6]. SIGDERS load cycle consists of eight load sequences with different pressure ranges, depicted in Figure 3. The maximum pressure (y-axis) for a test corresponds to the design pressure, in accordance with local building codes or wind standards.
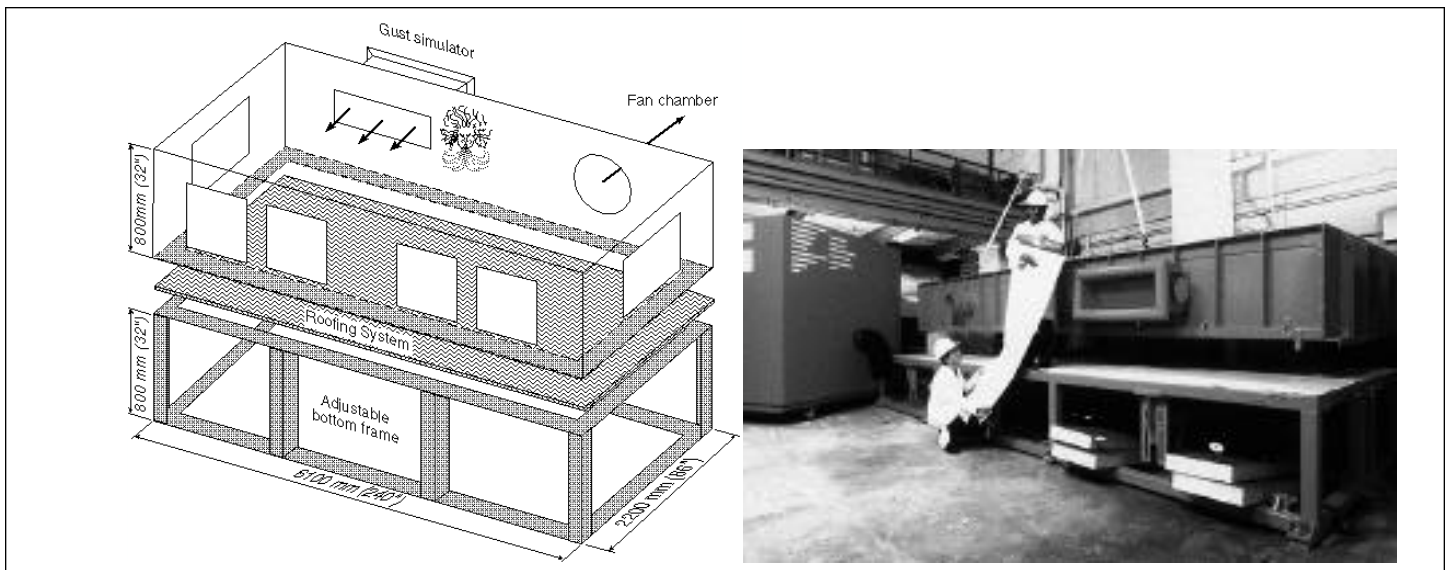

Figure 2. Dynamic roofing facility.

The pressures for each load sequence are calculated as percentages of the maximum pressure for the test. 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:

- Step 1 applies 400 gusts at 25 percent of the maximum pressure.
- Step 2 applies 700 gusts at 50 percent of the maximum pressure.
- Step 3 applies 200 gusts at 75 percent of the maximum pressure.
- Step 4 applies 50 gusts at the maximum pressure.

Group 2 represents the effects of exterior wind fluctuations combined with a constant interior pressure on a building. Internal pressure variations are codified explicitly in the North American wind standards American Society of Civil Engineers and the National Building Codes of Canada [7, 8]. Development of a test protocol should account for such variations. In Group 2, a constant minimum static pressure component is applied to the roof system, and the pressure level alternates between this minimum and the maximum pressure for each sequence. For example, in Step 5, a constant suction of 25 percent of the maximum pressure is applied and the gusts are applied above this constant static component. The roof sheets are lifted by the static pressure component, and thus Group 2 mimics the membrane tension effects that is aimed to simulate fatigue at the fastener locations. Similar to Group 1,

Group 2 consists of four sequences:

- Step 5 applies 400 gusts from 25 percent to 50 percent of the maximum pressure.
- Step 6 applies 400 gusts from 25 percent to 75 percent of the maximum pressure.
- Step 7 applies 25 gusts from 25 percent to 100 percent of the maximum pressure.
- Step 8 applies 25 gusts from 50 percent to 100 percent of the maximum pressure.

INVESTIGATED ROOF SYSTEMS

Two types of roof systems using the above test protocols have been investigated. The first type had modified bituminous membranes as their waterproofing component, whereas a PVC membrane was used in the second type.
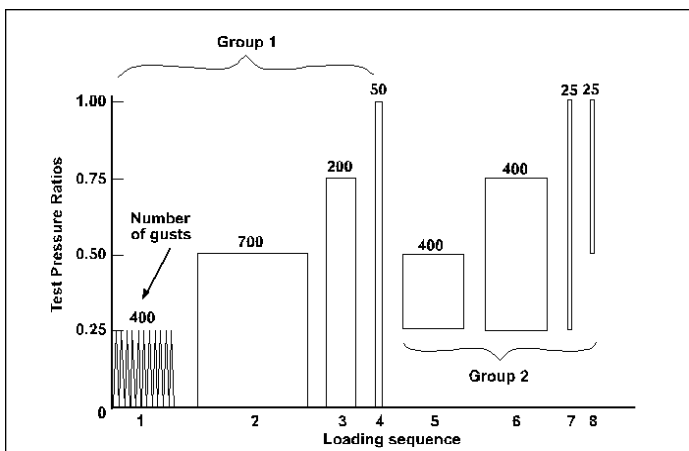

Figure 3. SIGDERS Dynamic Load Cycle.

Both systems were installed on the top of 4-foot-by-8-foot (1219-mm-by-2438-mm) insulation boards. Modified bituminous and PVC sheets were 39¾ inches (1 m) and 72 inches (1829 mm) wide, respectively, and they typically represent the response of narrow and wide sheets with respect to the width of the insulation boards.

System with Narrow Membranes

Modified bituminous sheets of 39³⁄₃₄ inches (1 m) wide, ⅛ inch (3.5 mm) thick were used. They were reinforced with a non-woven 180-gram polyester. An illustration of a typical mechanically attached system is shown in Figure 4. Systems of this type are common in Europe and have started to be used in the North American market. In general, first the base sheet is unrolled over the insulation. Two base sheets are placed side by side to form overlaps (seams). At the overlaps, the sheets are mechanically fastened to the deck. To maintain the continuity and provide a second line of defence for waterproofing, the base sheet seams are sealed by torch heating to melt and fuse the two sheets. Cap sheets are placed off center on top of the base sheets. The whole width of the cap sheet is adhered to the base sheet by torch application. This system can be installed on several deck types. For the present investigation, ⅝ inch (16 mm) plywood decks were used over 2-inch-by-10-inch (51-mm-by-254-mm) wooden joists. Joists were spaced 24 inches (600 mm) apart and fastened to the wood frame of the DRF. The plywood was fastened to the joists every 6 inches (152 mm) with #10 round head screws.

Figures 5 and 6 depict the detail of a seam. Each base sheet seam had an overlap of 4 inches (102 mm), with the fastener placed 1.5 inches (38 mm) from the edge of the under sheet, and 2.5 inches (64 mm) from the edge of the overlapping sheet. Fasteners were 5 inches (127 mm) long with a metal barbed plate 2 inches (51 mm) in diameter. For the tested system, base sheets were fastened at every 18 inches (457 mm) along the seam. Base sheets were not adhered to the insulation and were torched only at the seams. Cap sheets of identical size and type were placed over the base sheets, such that every cap sheet was centered over a seam. As mentioned before, the cap sheets were fully adhered to the base sheet by torch application.

Two specimens were evaluated using the FM test load cycle on the SIGDERS platform. For the first specimen, the insulation boards were loose-laid. In the second specimen, the insulation boards were mechanically attached to the deck with six fasteners per board. Insulation fasteners were
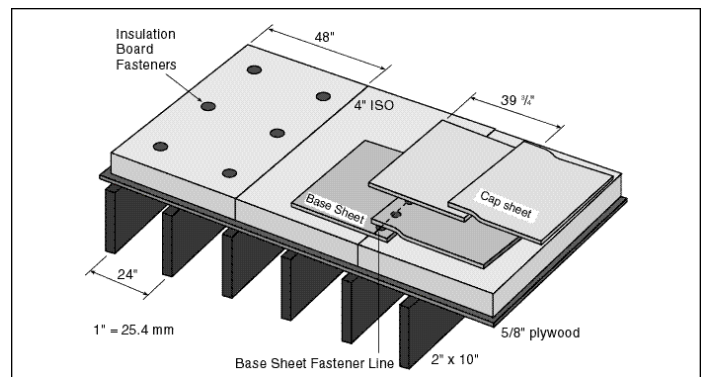

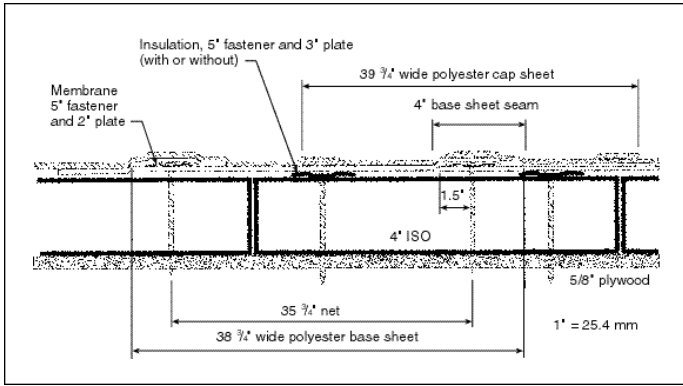*Figure 4. Mechanically attached modified bituminous system.*

Figure 5. Seam details of the tested modified bituminous system with insulation board fastened.
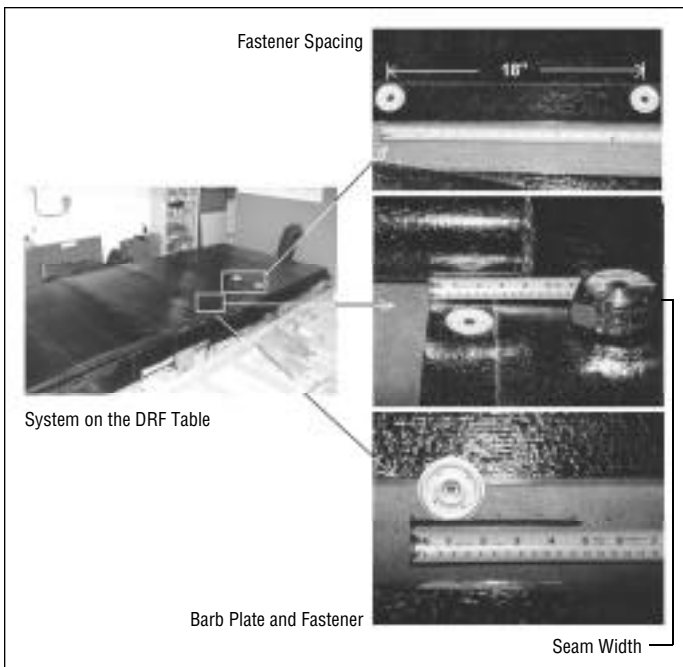

Figure 6. Photographs of the tested modified bituminous system.

Specimen	Number of Fasteners				
	Board #1	Board #2	Board #3	Board #4	Board #5
Insulated Board Loose Laid	10	5	5	10	5
Insulated Board Attached	16	11	11	16	11
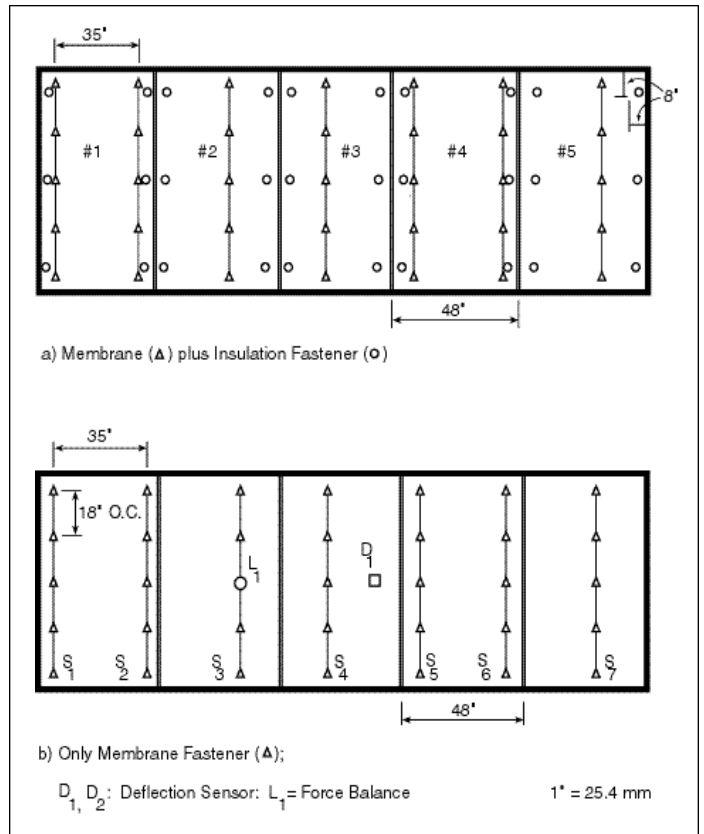
Figure 7. Loose-laid and fastened insulation boards on the modified bituminous system.

5 inches (127 mm) long with a plastic plate 3 inches (76 mm) in diameter. The system details, layout and instrumentation locations were identical for both specimens. Figure 7 shows the difference between loose-laid and mechanically fastened insulation boards specimens. As mentioned before, sheets were 39¾ inches (1 m) wide with 4-inch (102-mm) seams. This resulted in a fastener row spacing of 35¾ inches (897 mm) and membrane fasteners were installed over the insulation boards. The numbers of fasteners on each insulation board are tabulated below. With this arrangement, the second specimen had a minimum fastener density of one fastener per 2.9 square feet and a maximum fastener density of one fastener per 2.0 square feet.

The FM test carried out in the DRF conforms to the FM-4470 standard requirements discussed previously, with the difference being specimen size. In other words, the test applied a pressure level of 30 psf (1436 Pa) and maintained this level for 60 seconds before reaching the next level of 45 psf (2151 pa). Figure 8 shows the system response for the FM test. Note that the FM standard does not specify:

• The time requirement to increase the pressure from one level to another (i.e., after maintaining the pressure for 60 seconds at 30 psf (1436 Pa), how quickly should the pressure of 45 psf (2151 Pa) be reached; or

• The acceptable tolerance at each pressure level. For the present study, the applied pressure lies within 5 percent of the target pressure, e.g., if the target pressure is 30 psf (1436 Pa), the applied pressure lies at 30 psf Å 1.5 psf (1436 Pa Å71.7 Pa).

Figure 8 also compares the time histories of the measured responses of a specimen where the insulation boards are mechanically attached with a similar specimen in which the insulation boards are loose-laid. Not only is the applied pressure virtually the same at various tested levels, but also the measured fastener forces and deflections are similar between the two specimens. The fastened specimen sustained the applied pressure level of 60 psf (2868 Pa) and
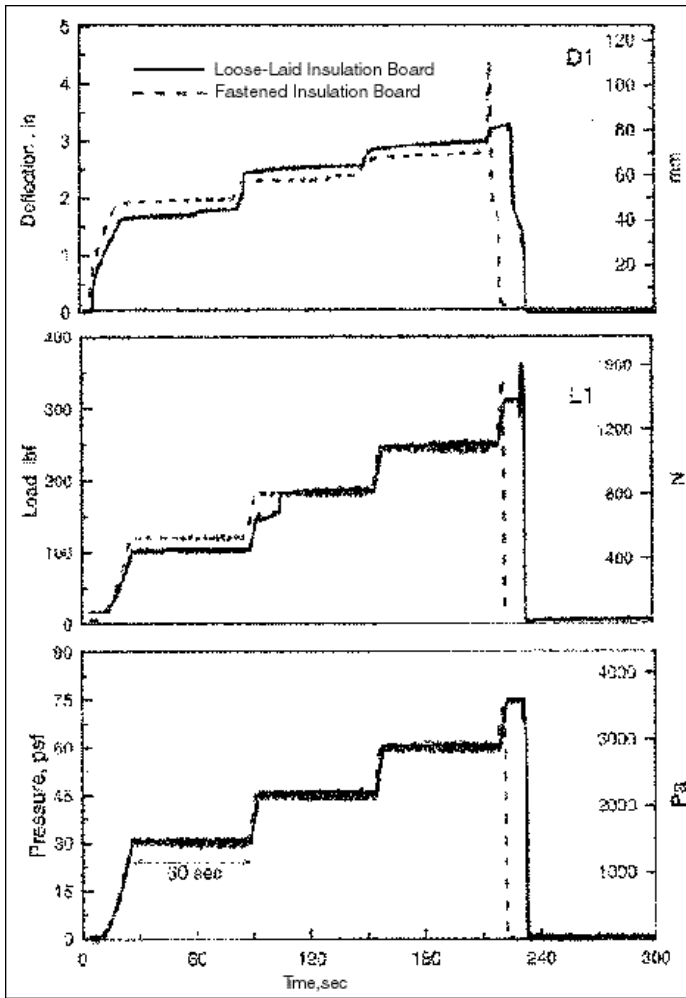
Figure 8. Response of the modified bitumen system with attached and loose-laid insulation boards shen tested using the FM load cycle.
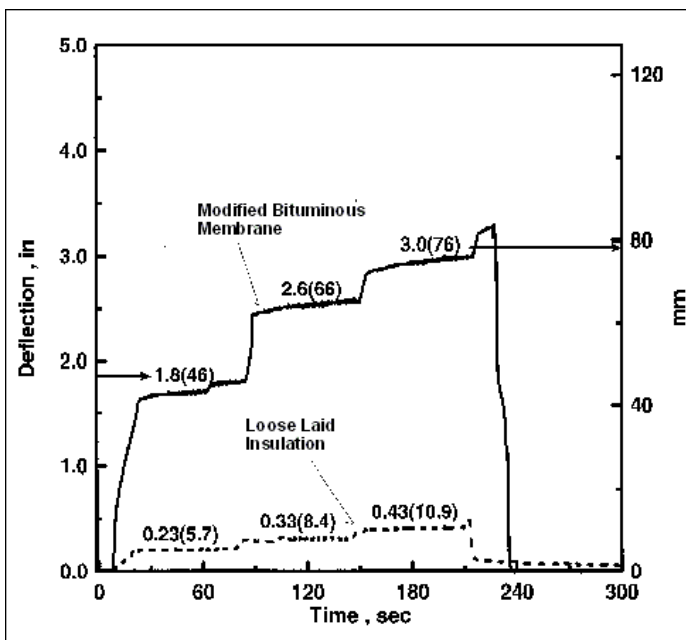

Figure 9. Measured uplift of a loose-laid insulation board when tested using the FM load cycle.

failed as the pressure was building towards 75 psf (3585 Pa). For this specimen, the measured fastener force and membrane deflection at 60 psf (2868 Pa) were 248 lbf (1103 N) and 2.8 inches (72 mm), respectively.

After sustaining the 60 psf (2868 Pa) level, the loose-laid specimen maintained 75 psf (3585 Pa) pressure for 8 seconds only and failed. The measured fastener force and membrane deflection at 60 psf (2868 Pa) were 255 lbf (1134 N) and 3 inches (76 mm), respectively. Upward movement of the insulation board was also monitored during the testing for this system. Figure 9 displays the upward lift of an insulation board at different pressures. These deflections are significantly lower than the membrane deflections irrespective of the pressure levels. At the sustained pressure (60 psf [2868Pa]), the loose-laid insulation board lifted only about 14 percent compared to the membrane uplift (0.4 inches [11mm] vs. 3 inches [76 mm]). Note that when the FM tests were carried out at the DRF, suction (negative) pressures were induced at the membrane top surface by developing a vacuum on the chamber and maintained constant at specified pressure levels of 30 psf (1436 Pa), 45 psf (2151 Pa) and 60 psf (2868Pa).

Wind effects on roof systems induce both suctions (negative) and pressures (positive). This depends on the wind direction, roof geometry and building's dimensions. Positive pressures mainly push the loose-laid insulation boards downwards. Therefore, the reported upward movement by the present study can be viewed as the worst-case scenario. Further discussion of this phenomenon is made under Figure 15.

Investigation of the failure mode of both specimens clearly indicated that the systems failed only because of membrane fasteners' pullout from the deck, as shown in Figure 10. The membrane remained intact, and no damages to the seams and insulation boards were observed. The fastener pullout failure occurred in seam number 4 of the test sample (refer to Figure 7). From the presented system response (fastener load and failure mode), it is clear that there is no significant difference between the specimen with loose-laid insulation boards and the specimen with mechanically fastened insulation boards. In other words, there is no benefit in wind uplift resistance for modified bituminous system arising from mechanical attachment of the insulation boards.
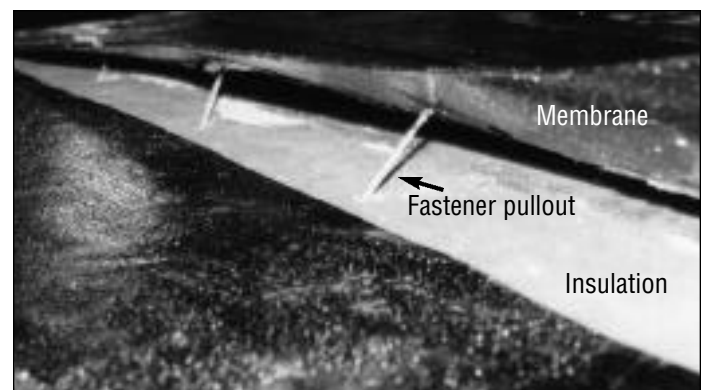

Figure 10. Failure mode of the modified bitumen system after the FM load cycle static test.

System with Wide membranes

In the majority of the mechanically attached SPR systems, the width of the sheet exceeds that of the insulation. To investigate the wind performance of such a system, the above exercise was repeated with 72-inch- (1829-mm-) wide PVC sheets. For the PVC system, not only is the sheet wider than the modified bituminous sheet but the sheet is also thinner (0.05 inches [1.2 mm] compared to about 0.24 inches [6 mm]). As shown in Figure 11, a steel deck was used to test the PVC system such that influence of the deck, if any, can also be identified. The deck is 22 Ga (0.76 mm-) thick with a profile height of 1.5 inches (38 mm) and a flute width of 5.9 inches (150 mm). It was fastened at every flute to the wooden beams of the DRF with #10 round-head screws. The wooden beams are 6 inches by 6 inches (152 mm by 152 mm) in size and spaced 72 inches (1829 mm) apart.

Reinforced PVC sheets, 6 feet (1829 mm) wide were used. Each seam had an overlap of 5 inches (127 mm), with the fastener placed 1.5 inches (38 mm) from the edge of the under sheet and 3.5 inches (89 mm) from the edge of the overlapping sheet. The portion of the seam beyond the fastener row was welded with hot air such that a water-proof top surface was obtained. The width of the welded portion varied between 1.5 inches and 1.75 inches (38 mm and 45 mm).

Figure 12 differentiates between the two PVC specimens. In one specimen, the insulation boards were loose-laid and in the other they were mechanically attached to the steel deck with six fasteners per board. The four seams are marked as S1, S2, S3 and S4 in Figure 12 and they indicate the membrane fastener locations. For the tested system, membrane sheets were fastened every 12 inches (305 mm) along the seam. Fasteners were 5 inches (127 mm) long with a metal plate 2 inches (51 mm) in diameter. Similar to the modified bituminous system, 4-inch-thick-by-4-foot-by-8-foot (100-mm-by-1500-mm-by-3000-mm) polyisocyanurate (ISO) boards were used. Insulation board fasteners were 5 inches (127 mm) long with a plastic plate 3 inches (76 mm) in diameter. Numbers of fastener on each board is tabulated below. For the specimen where the insulation boards were loose-laid, there was a board with no fastener and other boards with a fastener density of one fastener

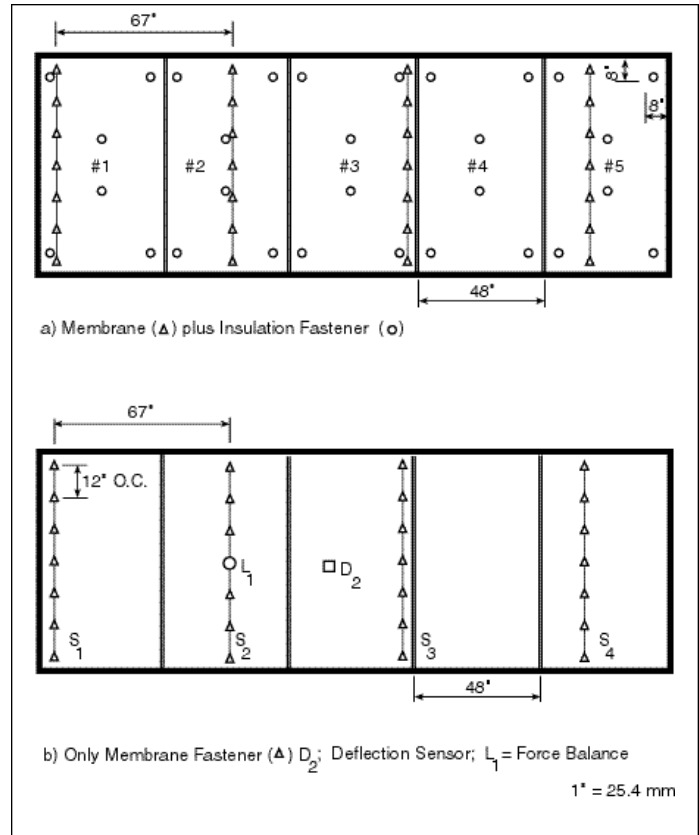| Specimen	Number of Fasteners				
	Board #1	Board #2	Board #3	Board #4	Board #5
Insulated Board Loose-Laid	7	7	7	0	7
Insulated Board Attached	13	13	13	6	13

Figure 12. Loose-laid and fastened insulation boards on the PVC system.

per 4.6 square feet. For the specimens with attached insulation boards, the fastener density was increased and it was one fastener per 2.5 square feet.

Response of the PVC System Subjected to the SIGDERS Load Cycle

Figure 13 shows the force and deflection data from the SIGDERS load cycle. In the graph, D1 indicates the membrane deflection at the center of the membrane fastener row spacing, 67 inches (1701 mm). Both specimens sustained a maximum pressure of 45 psf (2151Pa) and passed all gusts of the first, second and third sequences of the SIGDERS test. The specimen where the insulation was loose-laid failed at gust number 13 (out of 50) of sequence four, whereas the specimen with the insulation boards attached failed at the same sequence after 11 gusts (out of 50). This means that neither specimen passed the sequence four nor the gusts that can be applied over a constant static pressure component in Group 2 (refer to Figure 3).
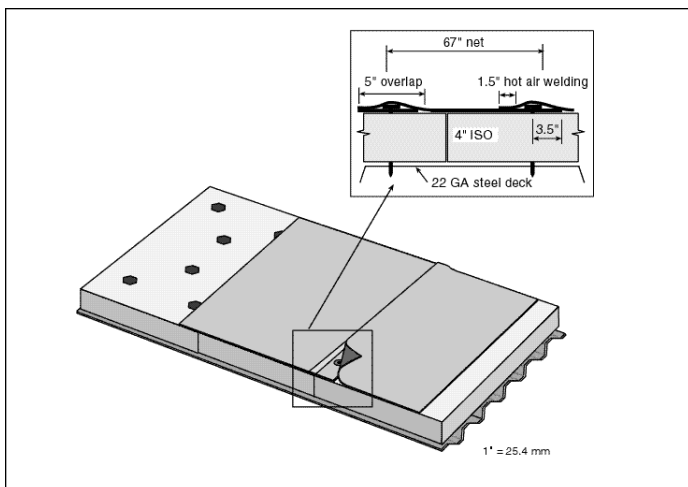

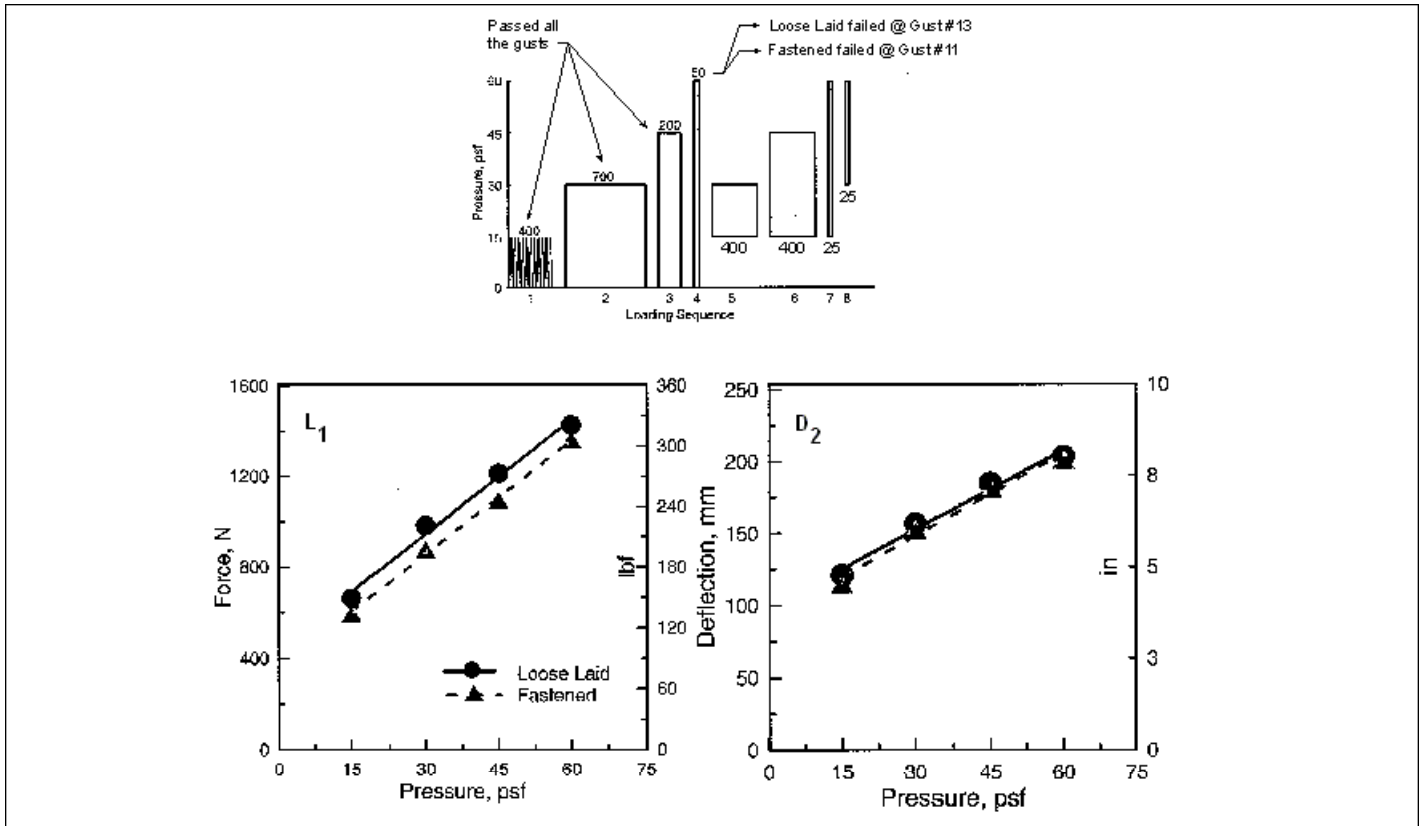*Figure 11. Details of the tested PVC system.*

Figure 13. Response of the PVC system with attached and loose-laid insulation boards when tested using the SIGDERS load cycle.

The graph in Figure 13 compares the measured membrane fastener loads of the two different specimens. They compare favorably, although the fastener loads measured for the specimen with fastened insulation boards were slightly lower than at the same pressure level of the loose-laid specimen. To quantify the difference between two data pairs, the mean difference is calculated as follows:

$$\Delta \varnothing = \sum_{i=1}^{4} \left\{ \frac{\varnothing_{Fsi} - \varnothing_{LLi}}{\varnothing_{Fsi}} \right\} \times 100 \qquad (1)$$

Where:
$\varnothing_{Fsi}$ = Membrane fastener force (deflection) from fastened specimen at an applied pressure.
$\varnothing_{LLi}$ = Membrane fastener force (deflection) from loose-laid specimen at an applied pressure.

For the fastener force the mean difference is about 9.8 percent. Similarly for the membrane deflection the difference is only 2.6 percent. A comparison of this nature clearly reveals that the predicted system responses are similar between the two specimens. It is worth mentioning that not only was the system responses similar between the two specimens, but also both specimens had similar failure modes, as discussed below.

Examination of both specimens after the test revealed that the membrane had experienced some stretching, as shown in Figure 14. The stretching along the fastener indicates that the system's failure is membrane tear. This stretching effect corresponds to field roof failure observations. Kramer quoted the most common observed wind failure for membrane roof systems as, "Slippage of roof membrane from below attachment plate leading to loss of compression between roof membrane, insulation substrate, and fastening elements and ultimately to membrane failure by way of tear spread around the fastener shaft" [9]. This observation coincides with the SIGDERS failure mode and indicates that the SIGDERS load cycle is simulating actual wind dynamics on roof systems. The FM static test, however, did not produce this effect on the membrane and therefore did not reveal the weakest link of the system's wind-uplift resistance. This membrane tear corresponds with failure modes observed in other field investigations [10, 11, 12, 13].
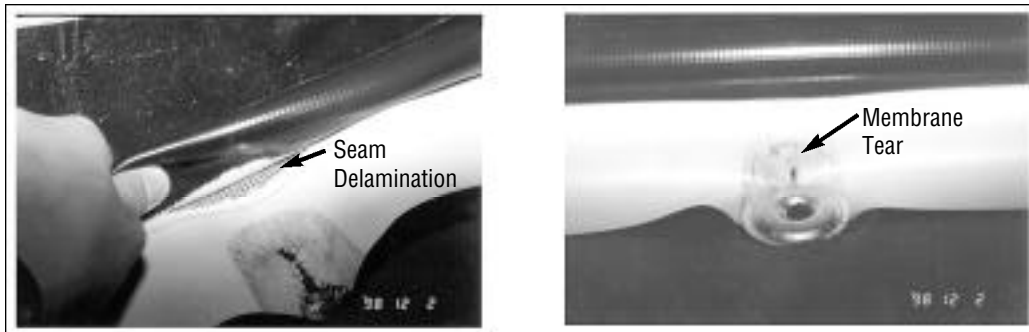

Figure 14. Failure mode of the PVC systems after the SIGDERS dynamic test.

Discussion

When the wind blows; it can cause suction (negative pressure) over a roof. As shown in Figure 15, for roof systems in which the membrane is mechanically attached, negative pressure can lift the membrane. Due to restrained seams, the lifted membrane billows and transfers the uplift loads to the seam fasteners and then into the deck. This load transfer path is known as structural load path. In this process, the fluctuation of the external wind pressure is slower than the membrane response time and the insulation boards are unrelated to the membrane response time. Thus, the insulation attachments are outside of the load transfer path. Moreover, the pressure difference between the top and bottom side of the insulation boards on a mechanically attached system is negligible (i.e. air below the boards is able to vent through the board joints and create similar pressure difference above and below the board). Hence, neither the number of insulation board fasteners nor the fastening layout will be beneficial for the wind-uplift resistance. This has been clearly demonstrated by the present data.

On the other hand, for the fully adhered systems, the load transfer path is completely different from the above. This is also illustrated in the Figure 15. In such a system, the surface area of the membrane is adhered to the insulation and the insulation boards are mechanically attached or adhered to the deck. The load transfer for this kind of roof assembly is known as pneumatic load path. That is, the load is shared among the components (membrane, insulation and deck) of the roof system by pressure differences across the components.
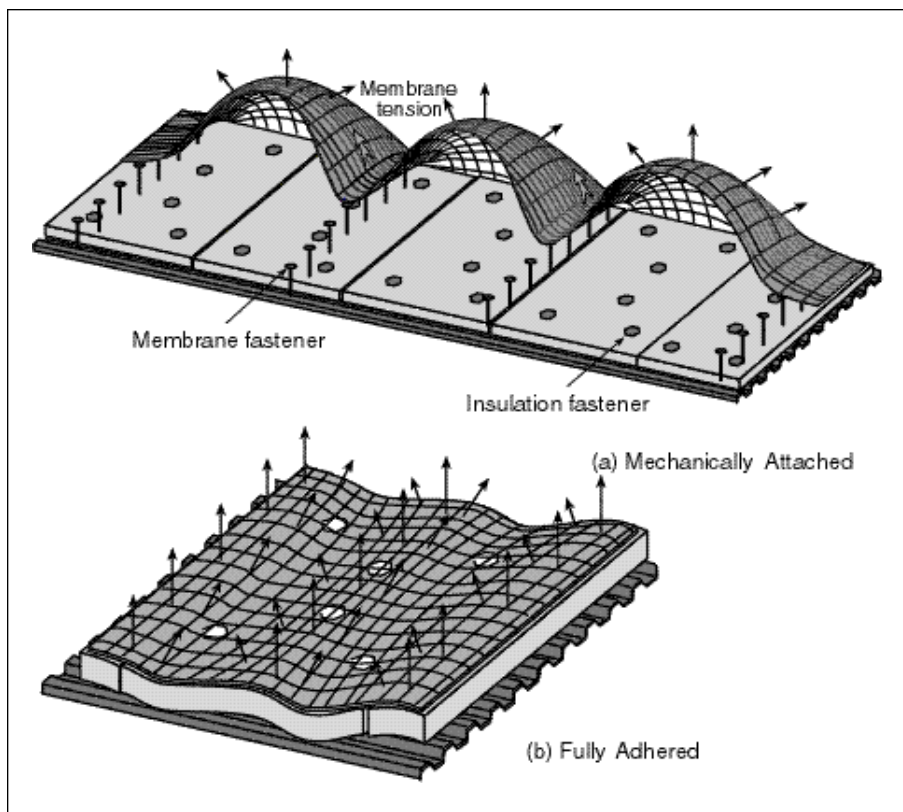
Fastening or adhering the insulation board is not only necessary in this case to resist wind uplift but also the insulation fastening layout is critical for the wind performance of the system. However, what is followed in the design of the mechanically attached SPR system is specifying the attachment to the insulation boards similar to those of the conventional fully adhered BUR systems. As a result, it is not surprising that the application of conventional design concepts to the newly developing system does not offer any additional improvements in the wind performance.

Inherent advantages of minimizing the number of fasteners on a mechanically attached SPR system are numerous. First, there will be significant reduction in the overall system cost due to reduction of material and installation cost. Second, a system with fewer fastener holes can facilitate better control of moisture vapor movements, reduction in thermal bridging potentials and increase the air tightness of the system. Such a system can reduce the heat loss and increase the energy efficiency of the building. Nevertheless, one should keep in mind, irrespective of the wind performance; a certain minimum number of insulation fasteners for each board are required. This is to keep the boards in place during the field installation and may heat to avoid shuffling (one board lifting and moving on top of another), and to minimize the insulation warping that may happen during the service life of the roof system. Also, depending on fastener row spacing and insulation board size, the membrane fasteners alone may or may not be sufficient. Therefore, the present study recommends a minimum of two fasteners for the insulation attachment in the SPR system. These two fasteners can be installed at the center along the length of the insulation board. Four fasteners may be needed for insulation boards that are susceptible to warping or insulation boards that are thin.

Questions may arise for tongue-and-groove insulation boards, whether the above-recommended minimum fastening is required. Also, advancements in material technology introduced into the market membranes that are wider (120 inches [3048 mm]) than the ones tested here (72 inches [1829 mm]). A detailed research investigation is needed to identify the pros and cons of these factors, as well as the following parameters on the insulation attachment of the SPR system before modifying the current design procedures:

- Method of attachment of vapor barrier/retarder
- Method of attachment of air barrier/retarder
- Size and type of insulation boards
- Use of insulation boards in multi-layers
- Effect of warped insulation boards
- Repeated foot traffic
- Snow drifting causing uneven loads on insulation boards
- Use of non-reinforced membranes
- Roof top equipment that can cause non-symmetrical loads

Figure 15. Comparisons of load transfer mechanism between mechanically attached vs. adhered systems.

- Installation of insulation boards parallel to the sheet width

CONCLUSIONS

- Two mechanically attached systems, one with modified bituminous membranes and the other with PVC membranes, having different fastening layout were investigated for wind uplift performance.
- In each system, the influence of the loose-laid insulation boards on the system response were quantified and compared with that of mechanically attached insulation boards.
- Experimental data supported the passiveness of the insulation attachments on the wind-uplift ratings in single-ply systems.
- Several inherent advantages becauase of the reduction in the number of fasteners on the single-ply systems are listed for discussion. First, there will be significant reduction in the overall system cost due to reduction of material and installation cost. Second, a system with fewer fastener holes can facilitate better control of moisture/vapor movements and reduce thermal bridging potentials, which reduces heat loss and increases the energy efficiency of the building.
- Further research needs are identified to recommend the minimum number of insulation fasteners for single-ply roof systems.

ACKNOWLEDGMENTS

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