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Dynamic Wind Uplift Performance of Thermoplastic Roofing System with New Seaming Technology

A. Baskaran¹

Abstract: Wind dynamics, on a conventional roofing system, lift the membrane and cause fluttering, introducing stresses at the attachment locations. To identify the component of the system that has the weakest resistance against wind uplift forces, a dynamic method of evaluating roofing systems is beneficial. A recent industry survey predicts significant growth for thermoplastic polyolefin (TPO) membranes. Among others, hot-air-weld ability is an advantage of the TPO. In mechanically attached TPO roofs, seams are formed by welding one side of the bottom sheet with the top sheet using hot-air machines. Advancements in welding technology have led to double-side weld procedures or encapsulated seams for the TPO membranes. Wind uplift evaluations are being carried out on the TPO systems with one-side weld and double-side weld. Experiments have been conducted at the dynamic roofing facility (DRF) of the National Research Council of Canada, using the SIGDERS (special interest group on dynamic evaluation of roofing systems) wind test protocol. Systems with double-side weld performed better than the systems with one-side weld. Use of double-side weld minimizes asymmetrical stress concentration and improves the wind rating of the mechanically attached TPO roofing systems.

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Introduction

The design of a roofing system must account for the effects of wind. Wind-induced pressures on a roof system can vary across the surface of the roof. The wind's effects can also vary with time since pressure fluctuates with wind. This is particularly important in conventional roofing systems, where the waterproof component of the system, a flexible membrane, is on the outer surface and exposed to external environmental conditions such as wind and temperature changes. The present study focuses on the behavior of such roof systems, in which thermoplastic membranes are used as the waterproof component. Two main kinds of thermoplastic membrane, polyvinyl chloride (PVC) and thermoplastic olefins (TPO) are used in single-ply roofs. In PVC, both reinforced and nonreinforced varieties are available on the market, whereas only reinforced TPO membranes are used in roof assemblies.

In the early 1990s, TPO was introduced into the roofing market because of its environmental profile (Beer 1997). TPO membranes are positioning themselves well among the new generation of single-ply roofs. TPOs may be produced either by a reactor process using a specific catalyst or from a physical blend of the olefin phase and an ethylene propylene rubber. Polyester scrim has been primarily used as the reinforcement in these membranes. Relatively new to the North American roofing market, TPOs claim excellence in UV and tear resistance. Hot-air weldability is also an advantage for rooftop applications of these membranes. The weathering resistance of the membrane is mainly derived from the

presence of the ethylene propylene rubber, while the olefin phase imparts chemical resistance, tear resistance, and hot-air weldability.

Sheet width of TPO membranes varies from nominal 1.8 m (6 ft) to 3.6 m (12 ft). As shown in Fig. 1, membranes are placed on the rooftop and attached to the structural deck using mechanical fasteners. The attachment locations are then overlapped as seams. Wind-induced suction lifts the member between the attachments and causes membrane elongation and billowing. The magnitude of the wind-induced suction and the membrane elastic property determines billowing shape. Fig. F1 also shows the components of a mechanically attached single-ply roof assembly. Each component offers certain resistance to the wind uplift force. This can be illustrated through a force-resistance link diagram. All resistance links should remain connected for the system to be durable and to keep the roof in place where it belongs. Failure occurs when wind uplift force is greater than the resistance of any one or more of these links. For example, the roof assembly is considered failed when a fastener (link 6) pulls out from the deck although the membrane and its seams are in good condition. Similarly, a system is considered failed when a seam (link 2) opens under gusting wind while other components are intact. Conventionally, to maintain water tightness in roof assemblies with TPO membranes, one-side weld (OSW) seaming methods are applied. OSW is known as traditional seaming. It normally has an overlap of 127 mm (5 in.), with the fastener placed 38 mm (1.5 in.) from the edge of the under sheet and 89 mm (3.5 in.) from the edge of the overlapping sheet. The portion of the seam beyond the fastener row is welded with hot air such that a waterproof top surface is obtained. The width of the welded portion varies between 38 and 45 mm (1.5 and 1.75 in.). Advancements in welding technology have led to double-side weld (DSW) procedures (Russo 1998; Baskaran and Xu 2001). DSW is known as encapsulated seams. Mostly, it is used in conjunction with metal or plastic batten strips. The strip, usually 25 mm (1 in.) wide, is centered inside a 100 to 127 mm (4 to 5 in.) lap seam. A double-nozzle hot-air robotic machine is used to create an approximately 34-mm-wide

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Fig. 1. Wind effects on single-ply mechanically attached roof assemblies

(1.25 in.) weld on either side of the strip. The welding quality mainly depends on the temperature, speed, and compacting pressure (weight).

DSW systems are expected to strengthen the link 2 (seam) on the force resistance chain. This can increase the wind uplift rating. An experimental program has been completed at the NRC/IRC on a variety of TPO systems to quantify this concept. This paper presents and discusses data from this investigation. All the specimens were subjected to the SIGDERS load cycle. By constructing field mock-ups in the DRF, systems with OSW and DSW were tested under dynamic environment. System responses are measured based on three design factors: pressure, force, and deflection. By presenting the comparison between the OSW and DSW systems, the paper quantifies the benefits of DSW systems.

Theory

When roofing systems are subjected to various levels of wind dynamics during their lifetime, wind forces cause membrane billowing and introduce stresses at the attachment locations. In conventional roof assembly, wind loads are mainly transmitted in one of two ways. In a mechanically attached system where the fluctuation of the external wind pressure is slower than the membrane response time, the wind-induced load will be transmitted through the fasteners to the structural deck. This is known as the structural load path. In the fully bonded system, the load is transmitted through the 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 (Cook

1992). Since the wind's effects on the roof systems are dynamic, it is useful to evaluate them using a dynamic procedure.

Fig. 2 shows a simplified force diagram of OSW and DSW systems. In OSW systems, tensile forces cause tear forces along the direction of the weld. With a weld on each side of the fastener, tensile forces cause tear forces that are developed along the two opposite directions of the welds. During wind gusting, at a given time these forces can be expressed as follows:

Systems with one-side weld:

$$F_x = F_{\text{tensile}} \cos \sigma \quad (1)$$

$$F_z = F_{\text{tensile}} \sin \sigma \quad (2)$$

Fig. 2. Force diagram of OSW and DSW systems

Fig. 3. Dynamic roofing facility

Systems with double-side weld:

$$F_x = F_{\text{tensile}} \cos \sigma_1 - F_{\text{tensile}} \cos \sigma_2 \quad (3)$$

$$F_z = F_{\text{tensile}} \sin \sigma_1 + F_{\text{tensile}} \sin \sigma_2 \quad (4)$$

where F_x and F_z = the respective horizontal and vertical forces and σ , σ_1 , and σ_2 are the membrane orientation angles due to wind uplift.

It is evident from Eq. (3) that part of the forces developed on the fastener in the horizontal direction for the DSW system can cancel each other because of their quasimmetrical stress distribution pattern. On the other hand, the stress distribution is asymmetrical in the OSW system. This means that the induced force along the horizontal direction would be higher for the OSW system than the DSW system. Consequently, the degree of fastener being rocked sideways and causing membrane tearing would be reduced by the DSW technology. Data from the present experimental investigation confirmed this theory.

Experimental Approach

Dynamic Roofing Facility

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). The DRF is shown in Fig. 3, and Baskaran and Lei (1997) document detailed facility features. The DRF consists of a bottom frame of adjustable height upon which roof specimens and a movable top chamber are installed. The bottom frame and top chamber are 6,100 mm (240 in.) long, 2,200 mm (86 in.) wide, and 800 mm (32 in.) 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. Wind suctions as high as 10 kPa (209 psf) over the roof assembly is produced by a 37 kw (50 HP) fan with a flow rate of 2,500 L/s (5,300 cfm).

Fig. 4. SIGDERS wind load cycle

A computer uses feedback signals to control 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 having frequencies range from 0.5 to 5 Hz. Closing the flap valve allows pressure to build in the chamber, and opening the valve bleeds the pressure. A photograph of the DRF during an OSW system installation is shown in Fig. 3. To monitor the response of the roof system, typical design parameters of pressure, force, and deflection were measured.

Wind Test Protocol

Based on the wind tunnel results, a review of existing standards, and computer simulations, and using DRF, devised a test loading procedure that allows a roofing system to be tested at any design wind pressure (Baskaran and Chen 1998). This procedure, represented in Fig. 4, includes eight loading sequences in which a roof system is subjected to simulated gusts. The loading sequences are grouped into five different levels (Levels A to E). There are two groups of cycles at each test level: Group 1 cycles, which simulate wind-induced suction over a roof assembly, and Group 2 cycles, which simulate the effects of exterior wind fluctuations combined with a constant interior pressure on a building. Each group consists of four loading sequences in which the pressure level alternates between zero and a fixed pressure. Allowable internal pressure variations are explicitly specified in recent North American wind standards (ASCE 1997; NBCC 1995) and are taken into account in the SIGDERS test protocol.

Each loading sequence is performed at a pressure that is a percentage of the design wind pressure stipulated by the building code for a given type of building and a particular location, starting with lower pressures and increasing gradually with each level. For example, the Level A tests include one sequence of 400

Table 1. Features of SIGDERS, UEAtc, and FM Load Cycles

Parameter	UEAtc	SIGDERS	FM
Source data	Wind climatic data	Roof pressure time histories	N/A
Relationship with wind speed	No	Yes	Yes
Relationship with code	No	Yes	No
Internal pressure	No	Yes	Yes
High-frequency fluctuations	Yes	No	No
Membrane flutter	No	Yes	No
Testing time	55 h	5 h	<0.5 h
Maximum number of gusts	N/A	5000	N/A
Number of low-intensity gusts (<40%)	71% per cycle	18%	N/A
Number of medium-intensity gusts (40–75%)	28% per cycle	68%	N/A
Number of high-intensity gusts (>75%)	1% per cycle	14%	N/A
Correction for temperature	Yes	No	No
Correction for specimen size	Yes	Yes	No
End product	Fastener design force	Dynamic evaluation	Static evaluation

cycles (gusts) at 25% of the design wind pressure, another sequence of 700 cycles at 50% of the design wind pressure, and so on, for a combined total of 2,200 cycles. To evaluate the ultimate strength of the roofing system, testing begins at Level A. If all the resistance links (Fig. 1) remain connected, the roof is considered to have “passed” and obtains a rating. Testing then proceeds to the next level, where the pressure is increased (Fig. 4).

At present, mainly two test standards are being used in North America to assess wind uplift performance of membrane roof systems. They are the Factory Mutual Research “Approval” (1990) and Underwriters Laboratories (“Standard” 1991) test standards. In Europe, Gerhardt and Kramer (1988) developed the UEAtc 551 test procedure. It is the only available international standard for fatigue evaluation of roof assemblies. The FM, UEAtc, and SIGDERS load cycles were developed under different environments and time periods. The general characteristics of these load cycles are grouped in Table 1. A discussion of these features has been published by Baskaran et al. (1999). Specifically, the FM test method has the advantage of being simple and quick. An entire test may take less than 10 min to complete. Since, however, the FM procedure applies pressures statistically and not dynamically, its effects on roof systems do not represent the pressures induced by actual wind conditions in the field. The UEAtc load cycle produces failure modes representative of those observed in field conditions, but its major drawback is that it is time-consuming. One cycle with 1,415 gusts takes nearly 3 h to apply, and the UEAtc testing performed by the present study took more than 55 h to complete one system investigation. The SIGDERS load sequence produces failure modes similar to the UEAtc load cycle but takes much less time to complete. The test on the TPO system took less than 5 h to complete.

The tested system consisted of all three main roofing components, whose general physical and mechanical properties are summarized in Table 2.

- Deck: 22-Ga-(0.76 mm)-thick steel deck with a profile height of 38 mm (1.5 in.) and a flute width of 150 mm (5.9 in.). The steel deck was fastened at every flute to the wooden beams of the DRF with size-10 round-head screws. The wooden beams are 152.4 × 152.4 mm (6 × 6 in.) in size and spaced 1,829 mm (72 in.) apart.
- Insulation: 2 Polyisocyanurate (ISO) boards each of 50 mm thick × 1,500 mm × 3,000 mm (2 × 48 × 96 in.) were mechanically attached to the steel deck. Fasteners were 127 mm (5 in.) long with a plastic plate 76 mm (3 in.) diameter.

- Membrane: Reinforced TPO membrane sheets were used for both OSW and DSW systems.

OSW System: Details of the tested OSW system are depicted in Fig. 5. It shows the top view of the test assembly installed in the DRF with three full-width sheets and a dummy sheet at either end. The four seams shown in Fig. 5 indicate the fastener locations. For the tested system, membrane sheets were fastened at 305 mm ($F_s=12$ in.) spacing along the seam, resulting in seven fasteners per seam. The distance between any two fastener rows is known as fastener rows spacing [$Fr = 1,790$ mm (70.5 in.)]. Fasteners were 127 mm (5 in.) long with metal plates of 61 mm (2 3/8 in.) diameter. Fig. 5 also depicts the details of a typical seam. Each seam had an overlap of 111 mm ($S_w=4\frac{3}{8}$ in.), with the fastener placed 38 mm ($1\frac{1}{2}$ in.) from the edge of the under sheet, and 73 mm ($2\frac{7}{8}$ in.) from the edge of the overlapping sheet. The portion of the seam beyond the fastener row was welded with hot air such that a waterproof top surface was obtained. The width of the welded portion varied between 38 and 45 mm ($1\frac{1}{2}$ in. and $1\frac{3}{4}$ in.). P, L, and D represent respectively, pressure, force, and deflection measurement locations.

DSW System: The DSW system layouts and component details are the same as those of the OSW system with the exception of seaming. Instead of fastener plates, polymer batten strips 25 mm (1 in.) wide and 57 mil (0.057 in.) thick were used. As shown in Fig. 6, the batten strip was continuously placed at the bottom membrane and the system was fastened to the metal deck using mechanical fasteners. These batten strips come with factory-drilled holes 152 mm (6 in.) apart. Using these preset holes, fasteners can be installed at 152 mm o/c (6 in.) or its multiples. To compare the data of DSW with OSW system, the same fastener spacing of 304 mm o/c ($F_s=12$ in.) was maintained. Similarly, the seam width was also maintained constant at 111 mm ($S_w=4\frac{3}{8}$ in.). Hot-air process was used to form the seams with 32-mm-(1 1/2 in.)-wide welds on each side of the batten strip. The fastener row spacing was also maintained at $Fr=1,790$ mm (70.5 in.)

Result and Discussion

OSW System's Responses

Fig. 7 shows the measured response data for the OSW system. The roof system sustained a maximum pressure of 2.9 kPa (60

Table 2. Nominal Physical and Mechanical Properties of Components

Deck			
Type	Profiled metal sheeting 22-gauge		
Thickness	0.76 mm (0.030 in.)		
Depth	38 mm (1.5 in.)		
Flute Spacing	150 mm (5.9 in.)		
Fastener Pullout as per ANSI/SPRI FX-1-1996	2120 N (470 lbf)		
Insulation			
Type	Polyiso		
Dimension	2 boards of 1218 mm × 2436 mm (4 in. × 8 in.) × 50.8 mm thick (2 in.)		
Compressive Strength as per ASTM D1621-94	130 kPa (18.8 psi)		
Insulation Attachment			
Type	Mechanical fasteners with plates		
Fastener	Assembled 128 mm (5 in.) screws & plates		
Plate	77 mm (3 in.) plastic lock plate		
Fastening Pattern	4 fasteners per board		
Air/Vapor Barrier/Retarders			
None used			
Membrane			
Type	TPO		
Width	1902 mm (74 ⁷ / ₈ in.)		
Thickness	45 mil (0.045 in.)		
Tensile property as per ASTM D 751-98 (Grab)		MD	XD
	Breaking strength, kN (lbf)	1.3 (293)	1.1 (248)
	Elongation at Max. load, %	29	29
Membrane Attachment			
Type	Mechanical fasteners with Plates or Batten		
Fastener	128 mm (5 in.) #15		
Plate	61 mm (2 ³ / ₈ in.) Dia. metal plate		
Batten Strip	25.4 mm (1 in.) wide, 1.45 mm (0.057 in.) thick		
Fastener Row Spacing	1790 mm (70 ¹ / ₂ in.)		
Fastener Spacing	305 mm (12 in.)		
Seam			
Type	Hot air welding		
Seaming	Overlap: 111 mm (4 ³ / ₈ in.)		
	Type: One Side Weld or Double Side Weld		
	Temperature: 950 °C (510 °C)		
	Speed: 2.4m/min (7.9 ft/min)		
	Weight: 1 weight (6 lbs)		
Weld Condition			

psf) and passed all eight steps of Level A of the SIGDERS test. This means that the system configuration passed the gusts applied over a constant static pressure component in Group 2 (refer to Fig. 4), as well as those in Group 1. When the applied pressure was 3.6 kPa (75 psf), the system failed at the loading sequence 4 during gust number 12. The maximum sustained fastener force at the location L (see Fig. 5) was about 1,223 N (278 lbf). This was measured at the sequence 4 of the Level A.

Measured membrane deflection at the center (Fig. 5) of the 1,902-mm-(75 in.)-wide sheet is also shown in Fig. 7. Each sequence has a minimum and maximum deflection value. Except for sequence 1, the minimum deflection is always greater than zero, because the membrane has already been stretched by the previous sequence. Moreover, for loading sequences 5 to 8 (Group 2), the membrane was lifted and gusts were imposed over a static component. This induces membrane stretching to a greater degree than Group 1. The maximum sustained membrane deflec-

tion was about 175 mm (6.9 in.) for Group 1 during loading sequence 4 and about 183 mm (7.2 in.) for Group 2 during loading sequence 8.

The system failed when the membrane tore around the fastener plate. Examination of the failure at seam #2 showed that the membrane had been stretched around the plate and then torn completely away from around the plate, while the fasteners remained engaged with the deck. There was also an instance of delamination failure, as the membrane peeled slightly at one fastener location. Fig. 8 shows a typical example of the failure mode. Examination of the system's seams after the test revealed that the membrane had experienced some stretching, and bore teeth marks from the metal fastener plates. This is similar to field observations of roof failures.

Kramer (1994, 1995) quoted the most commonly observed failure for membrane roofs as "slippage of roof membrane from below attachment plate leading to loss of compression between

Fig. 5. Layout and sectional view of tested roof assembly with OSW

roof membrane, insulation substrate, and fastening elements and ultimately to membrane failure by way of tear spread around the fastener shaft.” This observation coincides with the SIGDETS failure mode and indicates that the SIGDETS load cycle is inducing wind fatigues on roof systems. Previous tests conducted using the FM static procedure, however, did not produce this effect on

the membrane, and therefore did not reveal the weakest link of the system’s wind-uplift resistance (Baskaran et al. 1999).

To validate the above findings, a second specimen (OSW2) was tested with one-side weld configuration. Such components as the membrane, insulation fastener and plates, and membrane fastener and plates (as shown in Fig. 5), with similar physical and

Fig. 6. Layout and sectional view of tested roof assembly with DSW

Fig. 7. Measured response of OSW system

mechanical properties (Table 2), were used for the reproducibility tests. However, OSW2 components were not from the same batch of the manufacturing process. Every effort was also made to have identical system layouts and instrument locations. Moreover, the

Fig. 8. Failure mode of OSW system

same roof installer was engaged to install the OSW2 specimen on the DRF.

A comparison of the OSW1 and OSW2 is performed in Fig. 9 for the measured deflection and force data. These data correspond to the Group 1 load sequences of the SIGDERS load cycle. The graph indicates that the measured fastener forces from OSW1 system compare favorably with those from the OSW2 system, although the OSW2 shows slightly higher forces at the same pressure level. To quantify the difference between OSW1 and OSW2, deflection and force data pairs are selected. The mean difference is calculated as follows:

$$\Delta = \sum_{i=1}^n \left\{ \frac{R1_i - R2_i}{R1_i} \right\} \times 100 \quad (5)$$

where $R1_i$ = measured response (fastener force or deflection) from OSW1 at a given applied pressure; $R2_i$ = measured response (fastener force or deflection) from OSW2 at a given applied pressure; n = number of pressure increments on the SIGDERS load cycle; and δ = mean deviation (%). The mean

Fig. 9. Reproducibility test response of OSW system

Fig. 10. Measured response of DSW system

difference is about 6% for the measured fastener force. At the membrane central location where the maximum deflections are expected, the mean difference for deflection is only 1%. A comparison of this nature clearly reveals that the system responses are reproducible for experiments conducted at the DRF.

Fig. 11. Fastener pullout failure mode of DSW system

DSW System's Responses

Fig. 10 presents the measured response of the DSW system in a format similar to that of Fig. 8. Several factors are evident from the figure, some of which are mentioned below:

- The DSW system sustained a pressure of 4.3 kPa (90 psf) and failed at 5 kPa (105 psf). It passed all the gusts from Level A to C of the SIGDERS load cycle. Note that the OSW system passed only the Level A.
- Maximum measured fastener force at the sustained pressure was 1,707 N (388 lbf). This is about 40% higher than the OSW system's 1,223 N (278 lbf).
- The sustained deflection of DSW system was 210 mm (8.3 in.), slightly higher than the OSW's 206 mm (8.1 in.). However, the maximum deflection of the DSW occurred under a much higher pressure.

Of particular interest is the failure mode observation of the DSW system. Fig. 11 shows an inverted view of a failed seam. Fastener pullout was the only observed failure mode. Neither the seam nor the membrane was damaged by the wind gusts. In comparing the failure mode of the DSW system with the OSW system, the theoretical concepts presented are found to be true. In other words, the DSW transforms force to the deck through a structural load path with minimal asymmetrical forces. (This is further discussed under Fig. 15, where the measured fastener horizontal forces are compared.)

The fastener pullout failure mode indicates that the weakest link was the fastener engagement with the deck. There are two ways to strengthen this link. The first is to use a high-tensile-strength deck, and second, to adapt a fastener that has a differently engineered thread design. In terms of the latter, the present study used #15 fasteners (Table 2), which is one of the high-end fasteners in the industry for roofing applications. To avoid the observed weakest link, the experiment was repeated by using a high-tensile-strength deck.

By maintaining all other parameters constant to that of the tested DSW system (DSW1), metal decks with minimum 551 Mpa (80 ksi) tensile strength were used to construct a new mock-up (DSW2). The DSW1 decks had a tensile strength of minimum 30 ksi (207 Mpa). The tensile strength values were not measured in the present study. They are reported as specified by the manufacture in accordance with the ASTM A 653 specification for the metal decks. However, pullout tests were carried out as part of this present study. With a #15 fastener, the pullout resistance with the 207 Mpa (30 ksi) deck was 2,068 N (470 lbf) and that with 551 Mpa (80 ksi) deck was 3,036 N (690 lbf).

Fig. 12. Measured fastener force for DSW2 system

The DSW2 system sustained a pressure of 5 kPa (105 psf) and failed at 5.7 kPa (120 psf). As shown in Fig. 12, the system passed all the applied gusts from Level A to D, and the maximum measured fastener force at Level D was 2,226 N (506 lbf). At Level E, the system failed during sequence number 4. Thus, using a 551 Mpa (80 ksi) deck increased the system rating by 0.7 kPa (15psf) by strengthening the engagement between the deck and fasteners.

Data from the DSW2 system can also be used to validate the reproducibility of the DSW1 test. The measured fastener forces and membrane deflections are compared between DSW1 and DSW2 at various pressure levels, in Fig. 13. The mean difference

Fig. 13. Reproducibility test response of DSW system

calculated using Eq. (4) is 5% for the fastener force and 1% for the membrane deflection. A comparison of this nature clearly reveals that the predicted system responses are similar among the DSW1 and DSW2 systems.

To evaluate the full potential of the DSW system, mock-ups with asymmetrical membrane layouts were constructed for extended investigations. A typical situation is shown in Fig. 14. Low slope roofs are, conventionally, divided into zones of corner, edge/perimeter, and field. This is a design procedure followed for wind load calculation to differentiate the high-suction corner

Fig. 14. Layout of DSW system for simulating asymmetrical loading

Table 3. Comparison of System Performance of OSW with DSW Systems

Type	System	Pressure ^a		Fastener Force ^a		Membrane Deflection ^a		Failure Mode
		psf	Pa	lbf	N	in.	mm	
Symmetrical	OSW	60/75	2900/3600	278/255	1223/1122	7.7/8.4	195/213	Membrane delamination and tear at B4
	DSW	105/120	5000/5700	506/555	2226/2442	9.2/9.4	233/238	Fastener pullout
Asymmetrical	OSW	60/75	2900/3600	273/213	1201/937	6.9/7.4	175/188	Membrane delamination and tear at B4
	DSW	120/X	5700/X	500/X	2200/X	9.7/X	246/X	Passed 120 psf

^aValue before forward slash is system's sustained parameters; value after forward slash refers to value at which system failed.

zones from the moderate field zones. So in construction, narrow membrane sheets are used at the high-wind-suction zones. Typically, full-width sheets are used at the field zones and narrow sheets are used for the perimeter zones. When wind gusts over the roof different billowing shapes can occur due to variation in the membrane width, as shown in Fig. 14. This can induce asymmetrical forces at the fastener attachment locations. In the OSW system, these asymmetrical forces are in addition to that due to seaming, and it can demand high resistance among the various component links.

To quantify how much the DSW can minimize the discussed asymmetrical forces, additional experiments were carried out on OSW and DSW systems with the layout shown in Fig. 14. All other parameters were kept the same as before. Table 3 summarizes the system response from all the tests. For the OSW system the 60/75 in the pressure column means the system sustained a pressure of 2.9 kPa (60 psf) and failed at 3.6 kPa (75 psf). Note that DSW system did not fail at 5.7 kPa (120 psf). The test was terminated because 5.7 kPa (120 psf) is the maximum attainable pressure at Level E when 2.9 kPa (60 psf) is applied at Level A.

The symmetrical DSW system failed at 5.7 kPa (120 psf) apparently because it had fewer fastener seams in the test mock-up—4 seams with 28 fasteners, compared with 5 seams and 35 fasteners of the asymmetrical system. Increase in attachment location is also true in the case of the OSW systems. However, a higher number of fasteners did not help the OSW system as the

failure mode of the OSW systems was membrane tear and increase in the number of fastener attachments cannot elevate this weakest link. Data presented in the Table 3 further encourages the application of the DSW seam technology.

During the wind uplift testing, induced fastener forces were measured using a force balance specially developed at the NRC. The force balance has the capacity to measure simultaneously both vertical and horizontal forces. As discussed, one should expect reduction in the horizontal force for systems with DSW seams. This theoretical concept has also been verified by the present study. For the horizontal component, comparisons between the OSW and DSW systems are shown in Fig. 15. They are presented as ratios at different pressures. These ratios are obtained by dividing measured force at each loading sequence with the maximum measured force from the OSW system. The data indicate that the horizontal forces were reduced by about 50% because of the double-side welding technology. This is due to the force transfer mechanism of the batten strips in the DSW systems, as explained below. The stress distribution along the mechanically fastened seams is different between the two systems when wind suctions are applied. In the DSW systems, the batten strips can spread the wind uplift along the length of the seam rather than localizing it at the fasteners or in the membrane around the vicinity of the fastener plates. On the other hand, in an OSW system the stress localization causes either an early fastener pullout if the membrane is strong enough, or membrane tearing around the plates.

Fig. 15. Comparisons of fastener force at X direction between OSW and DSW system

Conclusions

Based on the presented results and discussions, the following conclusions can be drawn:

- Double-side weld systems performed better than the systems with one-side weld. An improvement of about 50% was measured in the wind uplift rating. This is found true for all the response comparisons between one-side weld systems with double-side weld systems.
- Use of double-side weld minimized stress concentration at the fastener attachment locations of mechanically attached TPO roofing systems. During the failure mode investigation, neither the seam delamination nor the membrane tear was observed in the double-side weld systems. Use of high-tensile-steel deck increased the wind uplift rating.
- Data from reproducibility tests also validated the above observations.

- One of the most common layouts from field application was constructed and tested in the lab mock-up. Therefore, the above double-side weld concept may also be valid for other roof assemblies with thermoplastic membrane, such as the PVC.
- The SIGDERS test protocol used in this study is able to reproduce known failure modes and has potential to replace current certification tests. However, to have a fully quantitative acceptance of the SIGDERS test protocol, it is necessary to benchmark the test data with those obtained from full-scale data (for example, duplicate a failure observed during a real windstorm where the speed is known). Being involved in a wind investigation program (Baskaran et al. 1997), the writer would appreciate receiving such data from the readers.

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