PERFORMANCE OF MECHANICALLY FASTENED POLYMER MODIFIED BITUMEN ROOF MEMBRANE SEAMS SUBJECTED TO WIND UPLIFT

KOICHI OBA AND MANFRED N. PARTL
Swiss Federal Laboratories for Materials Testing and Research
Dübendorf, Switzerland

The aim of the study was to evaluate wind load resistance of heat-welded seams in polymer modified bitumen for roof membranes and to investigate failure characteristics of seams subjected to wind load.

Two commercial polymer modified bitumen roof membrane products were chosen for this study. One was a styrene-butadiene-styrene (SBS) copolymer modified bitumen product, and the other was an atactic polypropylene (APP) modified bitumen product. For performance-oriented evaluation of the welded seams, roof membranes were incorporated into a roof assembly designed in accordance with the Nordtest Method NT BUILD 307 wind load resistance test and tested. In order to study the particular behavior of the seams in mechanically fastened single-ply roof systems, seam specimens in which mechanical fasteners were built were mechanically tested with a seam opening test.

The results showed that for the SBS product, heat-welded seams with a width of only 30 mm (1.2 inches) could resist a dynamic wind load of more than 4900 N/m^2 (102 lbf/ft^2) at approximately 59°F (15°C). However, the welding of seams more than 100 mm (3.9 inches) wide, which is recommended by material manufacturers, is necessary to avoid critical peeling stress in the seam caused by wind uplift, because the peel strengths of polymer modified bitumen roof membranes are lower than their shear strengths. In addition, seams need to be welded at the full seam width.

The results also showed that the behavior of the seams could be studied with the seam opening test. The recommendations for optimal seam design were made by considering seam width and fastener position, which influence the mechanical strength of the seam.

KEYWORDS

Flat roof, polymer modified bitumen, roofing, seam, single-ply, T-peel test, wind load resistance.

INTRODUCTION

Wind load can have a great influence on the service life of the single-ply roof system by inducing stresses and strains on different components of the system. Wind loads on a low-slope roof may result in both depression and inflation of roof membranes. Roof perimeters and corners are exposed to higher uplift forces than the roof field.[1] According to studies done by Baxter and the National Roofing Contractors Association, a relatively high percentage of the wind-related problem jobs were mechanically attached single-ply roof membranes.[2,3] Hence, through re-evaluation and scientific research, a reassessment of mechanically attached roof systems is necessary.[3]

In Figure 1, an example of a mechanically fastened modified bitumen system is schematically shown. A single ply of the sheet is mechanically fastened to the roof structure along one of the long edges, with the second sheet overlapping the fastened edge of the first.[4] At this overlap, a watertight seam is made by heat-welding or by the use of an adhesive. Sometimes the sheets are joined not only to each other at this overlap, but also to the underlay (e.g., an insulation material, an older roof being re-covered). From a financial point of view, mechanically fastened single-ply roof systems are preferable to conventional built-up roof (BUR) systems because they reduce labor and materials costs.[5] In addition, polymer modified bitumen roof membranes replacing the conventional BUR membranes not only have a wider application temperature interval but also may possess better durability and mechanical properties, such as E-modulus and elasticity.[6]

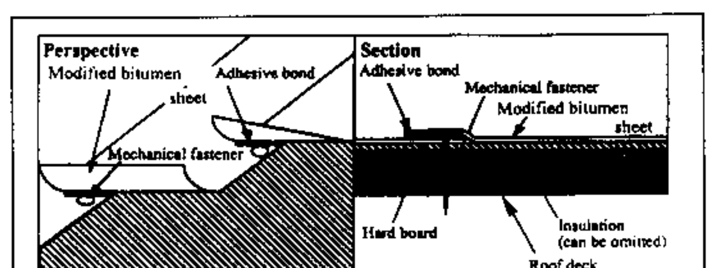

Figure 1: Example of a mechanically fastened modified bitumen roof system.

When a roof system is subjected to wind uplift, the seams are subjected to both peeling and shearing stresses, as shown in Figure 2. Such behavior has been studied by different kinds of wind load resistance tests. Paulsen used wind load resistance tests to study the difference in the fracture mode between differently designed roof assemblies.[7] The results showed that the failure is mainly the back out of the screw or the tearing of the membrane by the stress plate.

Therefore, the design of the seam, such as seam strength and seam width, plays an essential role in the performance of modified bitumen membrane roof systems when under the influence of wind load.[8] The seam is usually designed according to a technical proposal without any consideration to the

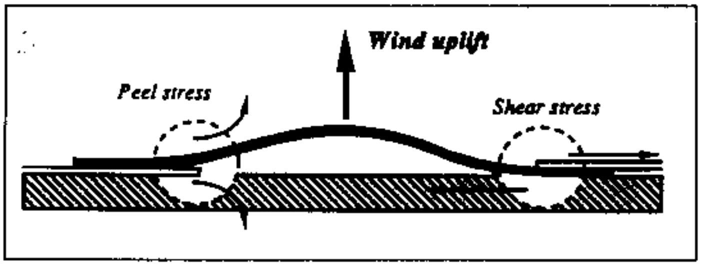

Figure 2. *Peel and shear stresses on the overlapping seams caused by wind uplift.*

nature of the membrane materials. However, because the components of polymer modified bituminous roofing products differ, the application method and design must be adjusted to the nature of the product.[9] The mechanical strength, which is usually studied by lap-shear test and T-peel test, and design of the seams need to be considered when predicting the performance of mechanically fastened single-ply roof systems.[10]

The purpose of this study is to investigate the influence of seam strength, which is usually studied with the lap-shear test and the T-peel test, and seam design on the behavior of a roof system when subjected to wind uplift. The wind load resistance test was performed using the apparatus at A/S Jens Viladsens Fabriker in Denmark in April 1994. In addition, a mechanical seam opening test was carried out to study the behavior of the seams in mechanically fastened modified bitumen roof systems. The correlation between the results obtained by those tests may offer information for designing satisfactory seams in regard to seam strength and width. The adhesion strengths of the seam samples used for both the wind load resistance test and the seam opening test were also evaluated by T-peel test to compare with the conventional test method.

MATERIALS

Two different commercial products that are normally seamed by heat welding, were chosen for this study: one styrene-butadiene-styrene (SBS) copolymer modified bitumen product and one atactic polypropylene (APP) modified bitumen product. These products are specified in Table 1.

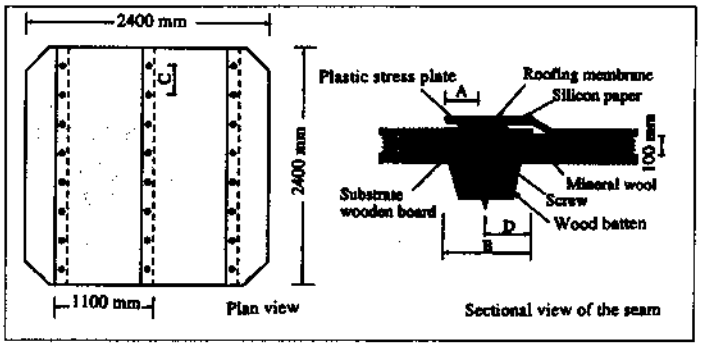

Figure 3. *Schematic view of roof assembly.*

EXPERIMENTS

Wind Load Resistance Test

Preparation of the roof assembly

For each test, a roof assembly was prepared in accordance with the dimensions listed in Table 2. The scheme of the assembly is shown in Figure 3. In all, six different assemblies were tested.

For the preparation of an assembly three strips of membrane material approximately 3 m (9.8 feet) long and 1.1 m (3.6 feet) wide were cut from the rolls. One of the strips was divided lengthwise into two equal halves. All of the membranes were placed on the roof assembly base, as shown in Figure 3. Plastic fasteners [one-piece socket and stress plate, 35 mm (1.4 inches) long, 45-mm (1-inch) diameter] were mounted at the edges of the sheets. The sheets were then mechanically fastened to the roof assembly base using steel screws. To study the influence of seam width on seam strengths when subjected to wind load, the sheets were mechanically fastened at several places so that the roof membrane could not loosen from the underlay. The distance between fasteners was either 100 mm (3.9 inches) or 300 mm (11.8 inches), as listed in Table 2. The sheets then were joined by heat-welding, using either hot air or gas, as

Product	Specification	Thickness	Coating	Reinforcement
SBS	Bitumen modified with approx. 13% styrene-butadiene-strene copolymer	4.0 mm	Granule on the surface; polypropylene film on the reverse side	Non-woven Polyester 210 g/m² + aluminum foil 40 g/m²
APP	Bitumen modified with approx. 30% atatic polypropylene	4.0 mm	Sandcoating on the reverse side	Fiberglass mat 50 g/m² + Non-woven Polyester weighing foil 160 g/m²

Table 1. The products tested.

Test No.	Product	A: Seam width (mm)	B: Overlap (mm)	C: Distance between fasteners (mm)	D: Position of fasteners (mm)	Welding	Speed (m/min)
1	SBS	60	140	300	40 from the edge	Hot air	approx. 1
2	SBS	30	140	100	70 from the edge	Hot air	approx. 1
3	SBS	80	140	100	60 from the edge	Hot air	approx. 1
4	APP	60	240	300	140 from the edge	Hot air	approx. 1
5	APP	130	130	100	60 from the edge	Gas	approx. 1
6	APP	130	130	300	60 from the edge	Gas	approx. 1

Table 2. Specification of the method of constructing roofing assembly.

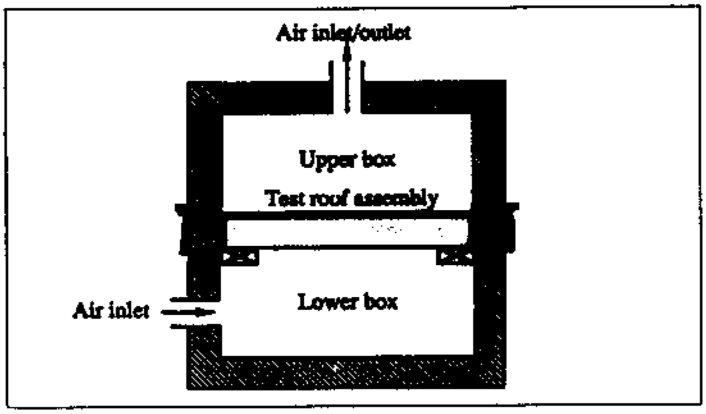

Figure 4. *Schematic view of wind load resistance test apparatus.*

described in Table 3. The welding speed was kept at approximately 1 m/min. (3.3 ft./min) so that the 5- ~ 20-mm (0.2- ~ 0.8-inch) bleed line of modified bitumen could be observed along the edge of the lap. Buttering of the lap edge, which some APP modified bitumen membrane manufacturers recommend, was not carried out. For Tests 1, 2 and 4, silicon papers were laid between overlapping membranes, as shown in Figure 3, to limit the seam width.

Procedure

The wind load resistance test was carried out at approximately 15°C (59°F) in accordance with Nordtest Method NT BUILD 307 *Roof coverings: Wind load resistance*[11] using the apparatus at A/S Jens Viladsens Fabriker in Denmark. The apparatus consisted of two boxes, one upper and one lower (Figure 4). The roof assembly was mounted in the middle test section for each test. The boxes were airtight, and the pressure was regulated in accordance with the appropriate pressure program. In all, six different roof assemblies were tested as prepared in accordance with the procedure listed in Table 2 and Figure 3.

All the roof assemblies except for Test 3 were tested according to Procedure B in Nordtest Method NT BUILD 307, which is a pressure program, as shown in Table 4. Each interval is a combination of 5 minutes of static load and 20 minutes of pulsating load. For Test 3, the assembly was tested according to Procedure A, which is a pressure program of only static pressure load intervals. At each interval, the peak height of the inflated roof membrane was registered as a result. The experiment was terminated when the roof assembly began to leak air, and the pressure was recorded as σbreak (N/m²).

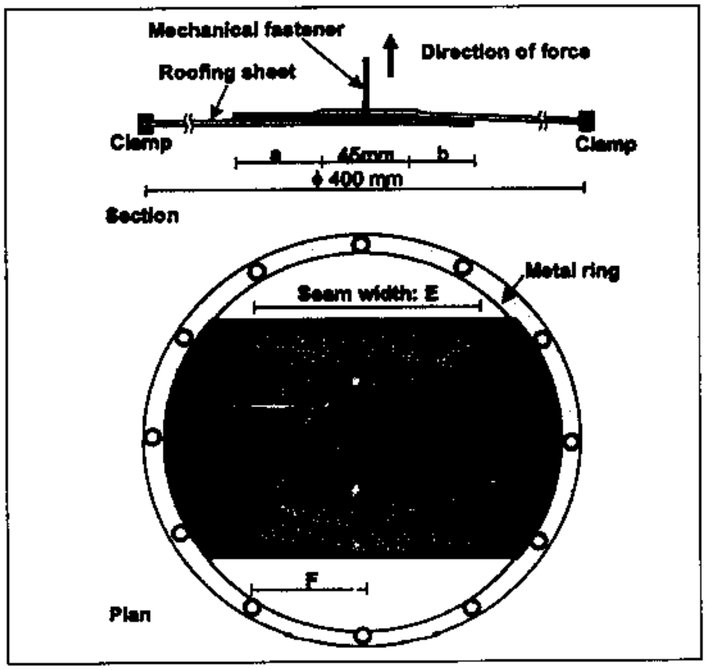

Figure 5. *Schematic view of seam opening test.*

Seam Opening Test

Preparation of the seam specimens

Seam specimens were produced by welding two 5-m- (16.4-foot-) long membrane sheets. Then, the resultant seams were cut into specimens of 250 mm (9.8 inches) (specimen width)

Method	Temperature of the medium	Effect of the heating medium	Weight of pressure roller
Hot air	ca 600°C	3.3kW at maximum	5 kg
Gas	ca 800-850°C	changeable up to 10KW by connecting an extra compressor	10 kg

Table 3. Welding method.

Test	Tensile speed	Seam width E	Distance F
Constant extension	-100mm/min	-200mm	-25mm -50mm -70mm
Constant force	-300N/min -500N/min -750N/min -1000N/min -1250N/min	-200mm -250mm	-25mm -E/2mm

Table 5. Formulation of the seam specimen for seam opening test.

Procedure A	Each interval includes static load 5min.										
Interval No.	1	2	3	4	5	6	7	8	9	10	11
Static load (kPa)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0
Procedure B	Each interval includes static load 5min and pulsating load 20min.										
Interval No.	1	2	3	4	5	6	7	8	9	10	11
Static load (kPa)											
Highest limit	.07	1.4	2.1	2.8	3.5	4.2	4.9	5.5	6.9	8.3	9.7
Lowest limit	0.3	0.6	0.9	1.2	1.5	1.8	2.2	2.5	3.1	3.7	4.3

Table 4. Loading conditions for wind load resistance test.

by 500 mm (19.7 inches) (length). They were welded using gas (Table 3). As shown in Table 5, specimens of different seam design E (seam width) and F (distance between fastener and edge) were prepared to study the difference in results. In each specimen, a plastic fastener (one-piece socket and stress plate, 35 mm [1.4 inches] long, 45-mm [1.8-inch] diameter) was placed. A schematic view of a specimen is shown in Figure 5. The welding work was carried out under dry conditions at 8°C (46°F) air temperature and 70 percent relative humidity by an experienced roofing contractor.

Procedure

The seam opening test was carried out at EMPA either at constant extension or at constant force. For both tests, a specimen was clamped in the middle of a metal ring (ϕ400 mm [ϕ15.7 inch]) fixed in a tensile test machine and pulled by attaching a mechanical fastener built in the seam to the bar, which was then moved. The mechanical load required to open the seam specimen during the test and the rate of deformation were recorded. For a constant deformation test, a specimen was tested at the constant extension rate of 100 mm/min. (3.9 in./min). For the constant force test, a specimen was tested at different speeds (e.g., 67, 112, 168, 224, 280 lbf/min. [300, 500, 750, 1000, and 1250 N/min]). Both tests were carried out at 23°C (73°F) and -10°C (14°F) in duplicate.

After the test, the area around the seam was cut and visually inspected. The seam surface that was opened by the test was then measured.

T-peel Test

Preparation of the T-peel specimens

After the wind load resistance test, three T-peel specimens of 50 mm (2.0 inches) by 150 mm (5.9 inches) were cut from each roof assembly. Three T-peel specimens were also taken from the seam samples prepared for the seam opening test. The specimens were conditioned in a climate chamber at 20°C (68°F) air temperature and 50 percent relative humidity for a week and then tested for seam strength by a T-peel test on a tensile testing machine.

Procedure

The two ends of a specimen were clamped in the grips and stretched at a constant deformation rate of 100 mm/min. (3.9 in./min) in the direction indicated by the arrows in Figure 6. The mechanical load required to peel the seam specimen during a constant extension rate was recorded. From these data, stress and strain were calculated. Tests were carried out at room temperature, 20°C (68°F), in accordance with a testing proposal, CEN/TC 117 N. T-peel strengths were calculated as tensile load divided by specimen width (N/mm).

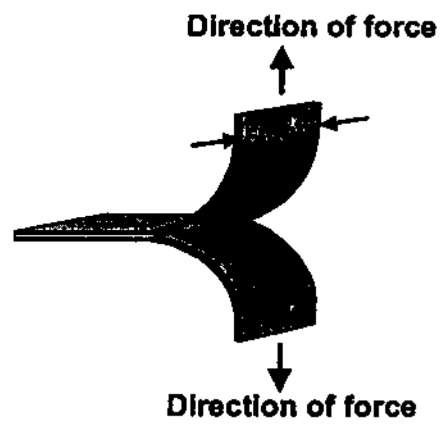

Figure 6. *T-peel test.*

RESULTS AND DISCUSSIONS

Wind Load Resistance Test

The results of wind load resistance tests are summarized in Table 6.

SBS modified bitumen

In Test 1, seam width was 60 mm (2.4 inches) (A in Figure 3), and the distance between the fasteners was 300 mm (11.8 inches). The fasteners were placed 40 mm (1.6 inches) (D in Figure 3) from the edges of the underlying sheet, so that peeling action in the seams was expected due to wind uplift. However, the test was disturbed by the tearing of the membranes. Approximately 6 minutes after Pulsating Load Interval 4,

Test No.	Static pressure levels 1	2	3	4	5	6	7	Pulsating negative pressure levels 1	2	3	4	5	6	7	σbreak (N/m^2)
1	60	90	125	155				55 75	90 110	130 150	150 170				2800
2	55	80	100	115	130	150	200	40 70	80 95	95 110	105 130	120 145	160 190	185 220	4900
4	60	80						55 70	100 115						1400
5	55	70	85	95	115	130		35 60	65 80	85 100	95 115	110 130			4200
6	50	80	100	150				45 65	75 95	90 115	145 165				2800

Test No.	Static pressure levels 1	2	3	4	5	6	7	8	9	10	11	Pulsating negative pressure levels	σbreak
3	45	75	95	110	120	135	145	155	175	195	220	-	

σbreak: Load at fracture or stop of experiment caused by air leakage through seams.

Table 6. Peak heights of the inflated roofing membranes by wind load (mm).

membrane began to tear because of the force induced at the stem of the plastic fastener. Hence, the stress obtained here (σbreak=2800 N/m² [58 lbf/ft²]) is related to the tear strength of the membrane. Deformation of the membrane around the stress plate was also observed, possibly caused by the fixation force of the stress plate against the suction of the membrane. The result agreed with what was observed at A/S Jens Viladsens Fabriker: When the seam was made using the full seam width (i.e., 140 mm [5.5 inches]), the membrane was pulled out as a result of the stress plate making a hole. Similar results have also been observed by other studies.[7,12] This type of fracture is common to thermoplastic roof membranes. Deformation of the plastic fastener was also noted, but no back out of the screws was observed.

In order to avoid tearing of the membrane, the distance between the fasteners was reduced to 100 mm (3.9 inches) for Test 2. Although the seam width was only 30 mm (1.2 inches), the test could be continued up to Pulsating Load Level 7 (σbreak=4900 N/m² [102 lbf/ft²]). In Test 1, where no fasteners were included in the seam area, peeling occurred. Therefore, the wind load resistance of 4900 N/m² (102 lbf/ft²) is related to the T-peel strengths. At Pulsating Load Level 4, delamination of the seam was observed. At Pulsating Load Level 5, the delamination movement of the seam seemed to change to gliding (i.e., shearing). Because of the relatively low ring and ball (R&B) softening point temperature of SBS modified bitumen, this "gliding delamination" may result in slippage of the SBS polymer modified bitumen membrane when it is heated to a high temperature by solar radiation. Slippage is a frequent problem for SBS polymer modified bitumen membranes, especially when they are applied with mopped asphalt.[13,14] At Static Load Level 6, a 15-mm- (0.6-inch-) wide fishmouth (a half-cylindrical opening formed by an edge wrinkle) was observed. At Pulsating Load Level 6, the gliding of the seam continued, and the seam width decreased drastically. After 13 minutes at Pulsating Load Level 7, the test was terminated because of pressure leakage through small holes in the SBS polymer modified bitumen membrane that were elongated by the extension in the seam.

Test 3 (seam width 80 mm [3.1 inches] and distance between fasteners 100 mm [3.9 inches]) was carried out according to Procedure A in Nordtest Method NT BUILD 307. Unlike in Tests 1 and 2, the stress applied in the seams caused a shearing action because the fasteners were placed inside the seam area. This type of roof assembly did not show any air leakage, even at Level 10. However, after Level 10, gliding in the seam was noted. Inspection of the seam area after the test showed that the roof membrane was still adhered to the stress plates.

APP modified bitumen

Test 4 [seam width 60 mm (2.4 inches) and distance between fasteners 300 mm (11.8 inches)] was disturbed at Pulsating Load Level 2 (σbreak=1400 N/m² [29 lbf/ft²]) by the opening of the seam in the middle of the roof assembly. The opening was approximately 250 mm (9.8 inches) long. Inspection showed that the opening occurred because of adhesive fracture, while the rest of the seam area was cohesively joined. In Test 4, fasteners were not included in the seam area, and the seams tended to fracture by peel stress, as shown in Figure 7.

This means that for APP products, the dynamic wind load

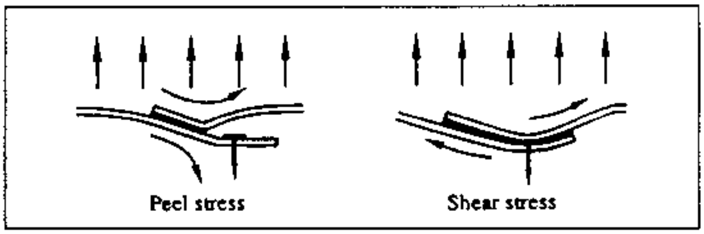

Figure 7. *Peel and shear stresses revealed by wind uplift.*

resistance of 1400 N/m² (29 lbf/ft²) is related to the T-peel strengths. The peel strengths of seams for polymer-modified bituminous roofing materials are lower than their shear strengths,[4] and the peel strengths of APP products are much lower than those of SBS products. Therefore, the design of seams promoting peeling action should be avoided, especially for APP products. Furthermore, the results of this test suggest that hot-air welding may be unsuitable for welding APP polymer modified bitumen roof membranes. Lack of fusion at the overlap for weldings was attributed to insufficient heat applied for joining the seam, resulting in seam separation.[13] APP polymer modified bitumen has a higher R&B softening point than SBS polymer modified bitumen and requires more latent heat to achieve adhesion.[14] Thus, the other two test assemblies, Tests 5 and 6, were prepared using a gas welding apparatus. This welding method did not allow limitation of the seam width using silicon paper.

Test 5 (seam width 130 mm [5.1 inches] and distance between fasteners 100 mm [3.9 inches]) was terminated when the seam was opened at Pulsating Load Level 6 (σbreak=4200 N/m² [88 lbf/ft²]). The dynamic wind load resistance (4200 N/m² [88 lbf/ft²]) was much higher than in Test 4, perhaps partly because of using the full seam width and partly because of using gas welding. When seams are welded using full seam width, wind uplift should promote shearing action in the seam, as shown in Figure 7. At Pulsating Load Level 4, splitting of the membrane along polyester fibers was noted. This membrane splitting is recognized as a common problem for APP products.[13] Inspection showed that the opened seam area had an adhesive fracture; the other area had a cohesive fracture.

Test 6 (seam width 130 mm [5.1 inches] and distance between fasteners 300 mm [11.8 inches]), the test was terminated by the opening of the seam after 5 minutes at Pulsating Load Level 4 (σbreak=2800 N/m² [58 lbf/ft²]). The fracture was caused by delamination along the reinforcement layer (i.e., cohesive fracture). Delamination of the seam at the reinforcement is likely to be related to the overheating of the membrane during welding work, which can destroy membrane integrity and displace the reinforcement fabric.[9,14] At Static Load Level 3, delamination of the seam was noted. Delamination is likely to start at the area around the stress plates, because the adhesion between stress plates and membrane is weaker than between the sheets. At Pulsating Load Level 3, the delamination accelerated along seams. At Static Load Level 4, delamination spread along the seam. This mechanism is illustrated in Figure 8.

Seam Opening Test

Figure 9 shows the results of testing APP polymer modified bitumen membrane seams using the seam opening test at constant deformation. The distance between the mechanical fastener and the edge (F in Figure 5) played an important

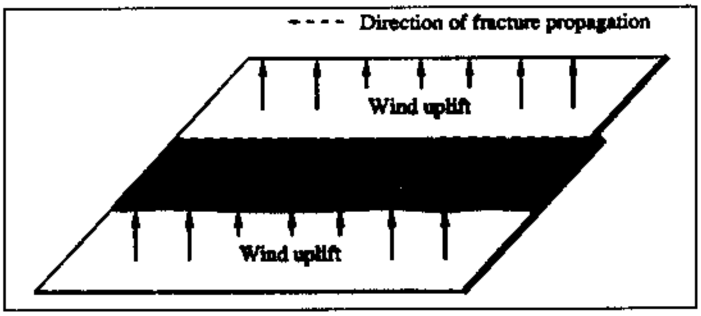

Figure 8. *Delamination mechanism observed in the seam for Test 6.*

role, as demonstrated by the delamination mechanism shown in Figure 8. The seam started to open when the diameter of the opened area became greater than the distance F. Figure 8 illustrates this diagonal-shaped critical zone. The diameter of the opened area varied between 30 mm (1.2 inches) and 50 mm (2.0 inches). However, after a certain extension, the tests were terminated when the mechanical fastener pulled through the sheets at approximately 1300 N (23°C) (291 lbf [73°F]) and 1700 N (-10°C) (381 lbf [14°F]), respectively. When the distance F was greater than 50 mm (2.0 inches), the opened area in the seam didn't reach the seam edge.

Figure 10 shows the results of testing SBS polymer modified bitumen membrane seams using the seam opening test at constant extension. With APP specimens, the diameter of the opened area varied between 25 mm (1.0 inch) and 45 mm (1.8 inches). When the distance F was 50 mm (2.0 inches), the test was terminated when the mechanical fastener pulled through the sheets. Therefore, for SBS specimens also, distance F needs to be more than 50 mm (2.0 inches) to avoid the opening of the seam along the seam edge.

Figure 11 shows the results of testing APP polymer modified bitumen membrane seams using the seam opening test at constant force. The test revealed that the diameter of the opened seam area tended to increase at higher tensile forces. When the seam specimens were subjected to a constant force of more than 1000 N/min (224 lbf/min), mainly the pulling of the mechanical fastener through the sheets was observed.

For SBS polymer modified bitumen membrane seams, only the pulling of the mechanical fastener through the sheets was observed.

T-peel Test

The results of measuring the T-peel strengths of seam specimens from both the wind load resistance test and the seam opening test are summarized in Table 7. The seam strengths of well-joined seam specimens (produced in laboratory) that show cohesive type of fracture by T-peel test are usually 6~8 N/mm (34~46 lbf/inch) for SBS products and 2~3 N/mm (11~17 lbf/inch) for APP products.[15] The results obtained here are approximately 1~2 N/mm (6~11 lbf/inch) lower for all products. All specimens failed in adhesive type of fracture. However, the results agree substantially with those from an earlier study, where the same products were tested.[16]

CONCLUSIONS

- When mechanically fastened modified bitumen seams are subjected to wind load, the following failure modes are commonly experienced:
  - Seam opening
  - Tearing of the membrane
  - Pull out or back out of the fasteners from the substrate
  - Deformation in fasteners

  The design of the seam must be planned so that the potential for all of these failure modes is minimized. To avoid tearing of the membranes, using the full seam width is necessary, and the number of fasteners must be sufficient to ensure that pull out of fasteners and membrane tearing by the stress plate or fastener do not occur.
- Seams of full width are necessary. When fasteners are not included in the seam area, the stress caused by wind uplift promotes peeling action in the seams. On the other hand, when fasteners are included within a seam area of full width, the stress is likely to cause shearing action. The shear strengths of the seams for polymer modified bituminous roofing materials are higher than the peel strengths.[16]

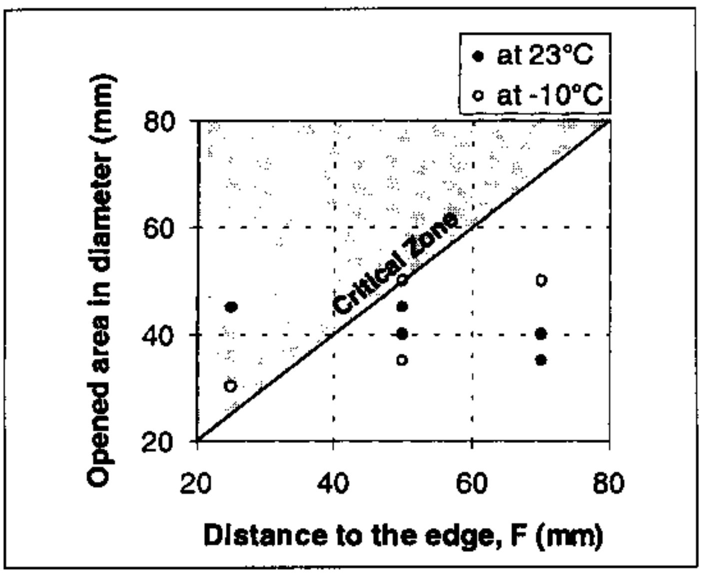

Figure 9. *Results of seam opening test at constant extension (APP modified bitumen membrane).*

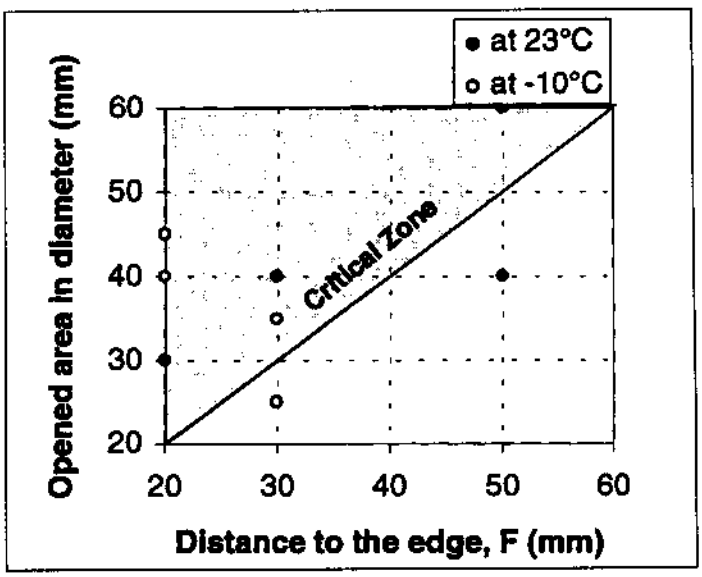

Figure 10. *Results of seam opening test at constant extension (SBS modified bitumen membrane).*

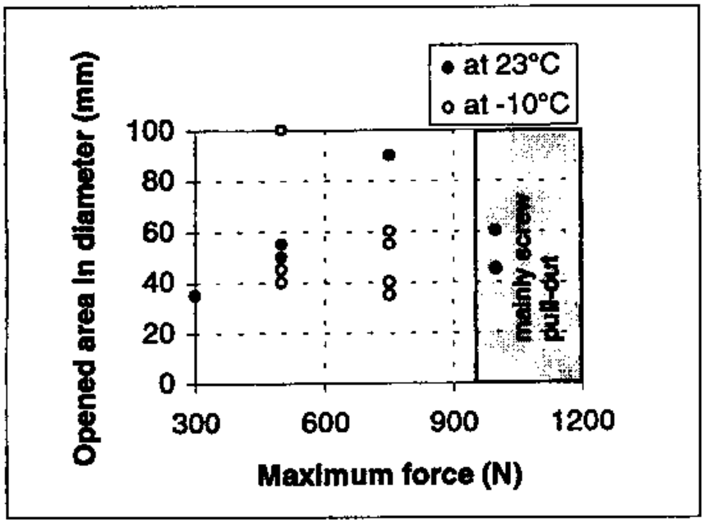

Figure 11. *Results of seam opening test at constant force (APP modified bitumen).*

Therefore, seams likely to peel because of wind uplift should not be designed. This is especially true for APP polymer modified bitumen roof membranes whose T-peel strengths are much lower than those for SBS polymer modified bitumen roof membranes.

- Not only the seam width, but also the position of the fastener in the seam is important. When the fasteners are placed far enough from the edge of the underlying sheet, the risk of promoting peeling action by wind uplift will be small. When the distance between the mechanical fastener and the seam edge is greater than 50 mm (2.0 inches), the mechanical fastener tends to pull out through the membrane before the seam is fully opened. The seam area outside the stress plate must also be wide enough to prevent water penetration.
- Seams of full width are also necessary to meet the considerable risk of delamination at places with narrow seams.
- Seams of SBS polymer modified bitumen roof membranes tend to glide as well as peel when subjected to wind load, while those of APP polymer modified bitumen roof membranes are likely to peel.
- For SBS products, a seam of only 30 mm (1.2 inches) width could resist a dynamic wind load of 4900 N/m^2 (102 lbf/ft^2) at 15°C (59°F) when the roof membrane was fastened by mechanical fasteners 100 mm (3.9 inches) apart. Safety factors need to be considered for the application of the result. The result can also be attributed to peel strength because the fasteners were not included in the seam area and did not cause peeling action in the seams. This corresponds to a seam strength of approximately 5 N/mm (29 lbf/in.) as measured by the T-peel test.

Test No.	T-peel strength	SD	Min
Wind load resistance test			
SBS-membrane	4.7	1.3	2.8
APP-membrane	1.5	0.3	0.9
Seam opening test			
SBS-membrane	6.2	0.6	5.5
APP-membrane	1.1	0.2	0.9

Table 7. T-peel strengths of seam specimens [N/mm].

- The welding work for APP products must be carried out more carefully by taking into account the pressure roller weight and welding speed, so that the seams will always be of full width, thus reducing the risk of delamination at areas of narrow seams. When an unsuitable welding method is used for welding APP products, peeling of the seam is more likely. In this study, the seams resisted dynamic wind loads of only 1400 N/m^2 (29 lbf/ft^2). This corresponds to a seam strength of approximately 1.4 N/mm (8 lbf/inch) as measured by the T-peel test.
- A clear correlation between T-peel strengths and the results obtained from the dynamic wind load resistance test was not observed. However, when the seam opening was in the peeling mode, there was a fair correlation between T-peel strength and dynamic wind load resistance. The T-peel test is a quick method of measuring seam strength and of comparing different specimens (e.g., aged and unaged, different products).
- The wind load resistance test and the seam opening test used in this study are useful methods for studying the performance of mechanically fastened polymer modified bitumen roof membrane seams subjected to wind uplift. However, these test methods need to be further improved in order to give recommendations concerning seam design to designers, manufacturers and roofing contractors. By T-peel test, the assessment of fastener pull out or back out from the deck is not possible.

ACKNOWLEDGMENTS

Financial support by the Swedish Building Contractors Development Fund (SBUF Project No. 2115) and the permission for the publication of the results is gratefully acknowledged. Many thanks are also due to Mr. Kim Worre at A/S Jens Villadsens Fabriker, Denmark, Mr. Kjell Larsson at Icopal AB, Sweden, and Mr. Johnny Poulsen at Eurotag Danmark A/S, Denmark for their assistance in the experimental work.

REFERENCES

1. Murphy, C. "Lap attachment of mechanically fastened roof membrane systems," *Proceedings of the 9th Conference on Roofing Technology*, National Roofing Contractors Association, 1989, 38-49.
2. Cullen, W. C. *Project Pinpoint Analysis: Ten-Year Performance Experience of Commercial Roofing 1983-1992*, National Roofing Contractors Association, 1993.
3. Baxter, D. "Mechanically/partially attached roof systems: Time for reassessment," *Professional Roofing*, March 1994, 30-34.
4. Oba, K. and F. Björk. "The influence of water on the mechanical strength of seams in single-ply coverings for low-slope roofs," Kautsch. Gummi, Kunstst. 45 (3) (1992) 195-202.
5. Rossiter, W. J. Jr. "Single-ply roofing—a decade of change," *ASTM Standardization News*, September 1985, 32-34.
6. Braun, E. "Bitumen," Rudolf Müller GmbH, Köln, 1987.
7. Paulsen, E. M. "Dynamic loading test for mechanically attached roofing systems," *Proceedings of VIII International Roofing & Waterproofing Congress*, International Waterproofing Association, 1992, 431-443.

8. Rossiter, W. J. Jr. and R. D. Denchfield. "A field study of the performance of polymer-modified bitumen roofing," *Proceedings of the 10th Conference on Roofing Technology*, National Roofing Contractors Association, 1993, 48-58.
9. Baxter, D. "Applicators must adjust to differences among modified bitumens," *Professional Roofing*, February 1991, 52-60.
10. Hanson, R., B. G. Johnson, and S. Nilsson. "Renoverade flacka tak: Erfarenheter från 500 omläggningar," Swedish Council for Building Research Technical Report R86, 1990.
11. Nordtest Method NT BUILD 307, "Roof coverings: Wind load resistance," Nordtest Finland, 1986.
12. Hoher, K. "Performance of mechanically-fastened roofing systems under cyclic-test conditions," *Roofs and Roofing*, J. O. May (Ed.), Ellis Horwood Ltd., Chichester, 1988, 93-105.
13. Baxter, R. P. "Field performance of polymer-modified bituminous roofing membranes," *Proceedings of the 8th Conference on Roofing Technology*, National Roofing Contractors Association, 1987, 85-90.
14. Dupuis, R. M. "Concerns in the application of modified bitumen," *Proceedings of the 9th Conference on Roofing Technology*, National Roofing Contractors Association, 1989, 73-77.
15. Oba, K. and F. Björk. "The relationship between welding temperature and T-peel strength of heat-welded seams in single-ply roof-coverings," *J. Adhesion Sci. Technol.*, Vol. 7, No. 9, 1993, 987-999.
16. Oba, K. and M. N. Partl. "Seam performance of polymer-modified bituminous roofing sheets," EMPA-Forschungs- und Arbeitsbericht No.113/6: FE 147 135, Swiss Federal Laboratories for Materials Testing and Research, 1994.
17. Oba, K. and F. Björk. "Dynamic mechanical properties of single-ply roof coverings for low-slope roofs and the influence of water," Polymer Testing 12, 1993, 35-56.