LAP SHEAR AND T-PEEL TESTING OF SEAMS IN EPDM, CSPE AND PVC FOR SINGLE-PLY ROOFS

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A series of lap shear and T-peel tests were conducted utilizing standard ASTM testing procedures on laboratory-developed seams for single-ply roof membranes utilizing EPDM, reinforced CSPE (also known as Hypalon) and unreinforced PVC membranes. The objective of the procedure was to develop the finite width of seam for the various membranes. Consequently, the seams started with seam widths of ¼ in. (6mm) and were increased in increments to 3 in. (76mm). The results clearly indicated that the required seam width for a successful shear lap was different for each material, and that a seam width of at least 1½ in. (38mm) must be maintained for PVC and CSPE with a greater seam width being required for EPDM seams. The average lap shear stress as developed from the various widths of laps was shown to have a lap shear stress in the order of 50 psi (0.34 MPa) for 1/4 in. (6mm) laps and decrease to a magnitude of 20 psi (0.14 MPa) for 3 in. (76mm) wide laps in EPDM membranes. The same phenomena was found to exist in the PVC and CSPE laps tested.

T-peel test results indicate EPDM seams yield relatively low T- peel results in comparison to PVC and CSPE. CSPE yields the highest T-peel results of all three materials, and is in order of 19 lb./in. (3.3 N/mm) as compared to EPDM which is 3.8 lb./in. (0.67 N/mm) and PVC which is 4.3 lb./in. (0.75 N/mm).

Test results of laps indicate, that with the seaming techniques utilized, EPDM yields lower lap shear stress values in comparison to PVC and CSPE's heat welding procedure yields the highest lap shear stress of the seams examined. It was also observed that the failure of laps leads to the conclusion that seaming technique does alter the stress-strain and ultimate stress characteristics of the membrane at the seam interface. This lowering of the ultimate stress consistently leads to the failure of the membrane, but always within the zone of the membrane influenced by seaming technique. Ultimate stress tests of the membrane clearly indicate that membrane stresses at failures at the seams was always lower than the unaltered stress of the membrane.

Test results indicate the safe width of the lap for the three membranes are different.

KEYWORDS

CSPE, EPDM, lap shear testing, PVC, seams, T-peel testing.

SYMBOLS

A	Area (in^2) (mm^2)
A_w	Area of lap bond (in.^{2}) (mm^2)
b	Longitudinal length of seam (unit strip)
C,D	Empirical constants
F_R	Empirical Load Ratio
L	Width of lap (in.) (mm)
P	Load (lbs.) (N)
P_s	Shear load (lbs.) (N)
P_p	Peel load (lbs.) (N)
R_m	Membrane stress ratio
t	Membrane thickness (in. or mils) (mm)
σ_m	Membrane stress (psi) (Pa)
σ_{m_p}	Membrane ultimate stress (psi) (Pa)
σ_m	Membrane stress under peel conditions (psi) (Pa)
σ_s	Lap shear stress (psi) (Pa)

CONVERSION FACTORS

1 in. = 25.4mm
1 in.^{2} = 645.2mm^2
1 lb. = 4.448 N
1 psi = 6.895 X 10^3 Pa

INTRODUCTION TO FACTORS INFLUENCING LAPS

Extensive research into the factors that influence laps leads to a relatively surprising result; all the data being reported is for adhesive bonded laps, whereas very little exists for heat welded seams. Rossiter[1] presents a summary of work in the area, as well as providing the major summary of work conducted at the National Institute of Standards and Technology (formerly the National Bureau of Standards) relative to laps of the adhesive types for neoprene, PVC and EPDM membranes. Rossiter[1] (in this and other work) points out that a simple leak at an improperly applied seam may result in extensive damage to insulation and building contents. Consequently, the seam techniques of adhesively bonded seams is critical in the design of these types of single-ply roof systems.

Rossiter[1] reports that experts in the EPDM field have identified the principal factors that influence laps in adhesively bonded seams. The primary factors identified as influencing the performance of the lap are:

- The behavior characteristics of the adhesive materials and the membrane.
- Environmental conditions such as:
  - Stress
  - Moisture
  - Heat and/or low temperatures
  - Temperature cycling
  - Chemical contamination
  - Workmanship

- Fabrication techniques, i.e., in factory versus field applied seams.

As a result of industry perceptions, two basic tests have been developed for testing the strength of laps. The lap procedure utilizes basically the configuration shown in Figures 4 and 5. However, instead of reporting either the tensile stress in the membrane or the shear stress at failure for the adhesive in the lap, the results are generally reported in the load per unit length at failure. The unit length generally being taken as one in.. Thus, in order to evaluate the membrane stress, the membrane thickness (t) as defined in Figures 4 and 5 is required. Unfortunately, this key item in many cases is left out of the reporting process.

When the membrane thickness is known and the load P is developed, the membrane stress σ_m can be computed by Equation 1 or

$$\sigma_m = \frac{P}{t} \tag{1}$$

and if the width of the seam is known, then the average shear stress can be developed from Equation 1 or

$$\sigma_s = \frac{P}{A_w} = \frac{\sigma_m t}{L} . \tag{2}$$

Rossiter[1] presents data in which the load P is known for a membrane thickness (t) and for width of the lap (L), and is tested at ambient conditions (i.e., T = 70°F (20°C)). The Rossiter[1] values are shown in Table 1.

Rossiter's[1] data shown in Table 1 is included in Figure 1. This data reveals that for EPDM laps, in comparison to independent data developed at Northeastern University by the authors, the primary control of a lap becomes the membrane stress. All of the data clearly indicates for a given membrane the shear stress in the lap is governed by a certain critical tensile stress in the membrane. Also, the shear stress in the lap will develop a value that is solely dependent upon a certain constant membrane stress.

The data in Figure 1 shows the critical stress in the membrane is solely a function of membrane thickness. The critical membrane stress versus thickness, from the Rossiter data, is shown in Figure 2. Thus, the membrane thickness via the Rossiter data is shown to influence the lap shear stress.

The test results and data clearly illustrate that as the membrane is stressed to a critical value shown in Figure 1, the shear stress in the lap adjusts to the values shown in Figure 1.

During the course of installation of a lap in the field various investigators, manufacturers, engineers, designers and contractors have identified numerous factors that have been thought to influence the strength of a lap. A partial list of these factors is shown in Table 2.

Rossiter[1] did the first singular work done to evaluate these factors that could potentially describe the strength of laps on single-ply EPDM membranes. For details of testing procedures and conditions see reference 1. This work, due to its surprising findings, was confirmed by the authors of this paper. The work for EPDM is best summarized in Figure 3.

Rossiter[1] utilized the two inch lap as the basis for comparison. For this reason, a two inch width was selected as the reference datum for comparison purposes. The data used to prepare Figure 3 was from an EPDM with a thickness of 50 mils (1.3mm). As can be seen in Figure 3, the influence of the various factors from an experimental viewpoint appears negligible. This demonstrates that good seams in single-ply membranes can be obtained with reasonable efforts in the field by keeping the material clean, dry and with surfaces being reasonably prepared according to the manufacturer's instructions. If reasonable care is taken and reasonable moisture and dirt are eliminated at the seam, relatively sound seams can be developed. The list of potential detracting factors for sound seam widths, when reasonable care is utilized, are not a major influence in the strength of the seam according to this early work. Thus, the primary guiding factor in seam strength becomes the membrane strength, σ_m, as given in Equation 1.

LAP MODEL

Single-ply roof membranes are joined by chemical or heat welds into a simple lap with a width of weld, L, as shown in Figure 4.

For purposes of analysis, the longitudinal length, b, of a strip of weld is taken to be a unit distance of one in. (25.4mm). Since the membrane is thin, it is reasonable to assume that an applied tensile stress, σ_m, is evenly distributed over the membrane thickness, t. Then the applied force may be written as

$$P = \sigma_m A = \sigma_m tb = \sigma_m t \tag{1A}$$

or

$$\sigma_m = \frac{P}{t} . \tag{1B}$$

A force diagram of the membrane on one side of the seam is shown in Figure 5.

Summing forces in the horizontal direction, the shear force may be written as

$$P_s = P = \sigma_m t. \tag{2A}$$

Distributing the force over the area of the weld gives us the lap shear stress

$$\sigma_s = \frac{P}{A_w} = \frac{P}{bL} = \frac{\sigma_m t}{L} \tag{2B}$$

which relates membrane stress to the average lap shear stress in the weld.

LAP TESTS

Specimens of EPDM, CSPE and PVC roof membrane material were joined together in a lap configuration according to the manufacturer's instructions. For chemical welds, proprietary adhesives provided by the manufacturer were used and heat welds were made using equipment provided by the manufacturer. A series of specimens were prepared in increments of seam width, L, of 0.25, 0.50, 1.00, 1.50, 2.00 and 3.00 in. (6, 13, 25, 38, 51, and 76mm). Ten samples of each were tested to failure on an Instron testing machine using a low rate of load application (i.e., 0.06 cm/min. at 70°F (20°C)). Results of average lap shear stress, σ_s, versus lap width, L, are shown in Figure 6.

The results show the average shear stress at the failure of the seam decreases as the width of the seam increases. This indicates a failure mechanism other than shear stress is occurring as the maximum shear strength is not developed at failure as the width L increases. The data in Figure 6 indicate the shear stress versus width are related by a power equation of the form

$$L = C\sigma_s^{D}. \qquad (3)$$

The values of C and D are given in Table 3.

The relationship of membrane stress, , at seam failure versus lap width, L, is shown in Figure 7.

The results show at some critical seam width for each membrane, the curve flattens out indicating that for stresses greater than at the critical length the membrane stress, not the shear stress, is the controlling factor in the strength of the seam. Therefore any increase in L beyond the critical point does not contribute to the strength of the seam.

Another approach to determine a critical width of lap is to examine the graph of lap shear stress at failure versus membrane stress at failure as shown in Figure 8.

The trend for each membrane is that as membrane stress at failure increases, the average lap shear stress decreases until it drops off at some limiting membrane stress value. The point at which the drop starts is the critical lap shear stress value.

For EPDM the value is about 21 psi (0.15 MPa), for CSPE about 63 psi (0.63 MPa) and for PVC about 40 psi (0.28 MPa). It represents the point at which the membrane stress becomes the controlling factor. The limiting membrane stress and critical shear stress values are shown in Table 4.

The values of σ_m/σ_s are fairly close. By taking the average value, it is possible to develop a relationship between the membrane stress and the critical shear stress or

$$\sigma_{m\ max} \approx 30\ \sigma_{s\ critical} \qquad (4)$$

or

$$\sigma_{s\ critical} \approx \frac{\sigma_{m\ max}}{30}\,. \qquad (5)$$

The test data also revealed the membrane stress, which occurred at failure at the lap consistently, was less than the maximum membrane stress the membrane would take under simple axial conditions as a pure membrane without a lap. This factor clearly indicates the seaming procedure, be it a chemical or heat weld, substantially influences the maximum membrane stress at the lap. Utilizing the definition of the ultimate membrane stress as $\sigma_m{}'$ the ratio of the membrane stress (σ_m) at the lap joint at failure is evaluated in Table 5, where the membrane stress ratio (R_m) is defined as $\sigma_m/\sigma_m{}'$.

By combining the results of Table 5 with Equations 5 and 3, it is possible to obtain a relationship which identifies the minimum critical width L of a lap for the three materials examined. This relationship takes the form of

$$L = C\,\frac{R_m\sigma'_m{}^{D}}{20}\,. \qquad (6)$$

Utilizing Equation 6, it is possible to examine the minimum widths of laps potentially required by the three membranes examined. These minimum widths are shown in Table 6.

The data in Table 6 indicates the minimum critical widths of laps is substantially lower than the 2 in. to 4 in. (50mm to 100mm) laps found in industry. It should be noted that the data base for Table 6 is for laboratory welded procedures on very clean materials under ideal temperature conditions.

The question of how the Rossiter[1] data for EPDM compares to other data, such as the data promulgated by the authors of this paper, is best answered by presenting the data on one single comparison plot. This comparison of the Phalen-Allen and Rossiter[1] data is shown in Figure 9.

Clearly the data of two independent sources are yielding shear stresses versus lap widths that are very compatible with the Rossiter data being placed at the high end of lap width. This indicates the data in this report is compatible with other responsible data.

T-PEEL TESTING

The early results of lap shear testing by Rossiter as noted earlier indicated the influence of various factors such as moisture and dirt had little or no influence on the strength of laps. The fact that dirt on an adhesive seam did not appear to influence the strength of the lap gave numerous investigators cause for concern. This quite naturally lead to seeking another method of evaluating seams in a quantitative fashion so that numerical values could be utilized to demonstrate the influence of contaminants, and simultaneously provide a base line to obtain minimum strength values for laps. Out of this concern came the T-peel test which has the configuration shown in Figure 10.

The test results for the T-peel are reported in units P (pounds (newtons) per unit longitudinal length of sample which is conventionally taken as 1 in. (1mm). Thus, it is possible to evaluate the membrane stress ($\sigma_m{}^P$) under peel conditions by

$$\sigma_m{}^P = \frac{P_p}{(1)\,t} = \frac{P_p}{t}\,. \qquad (7)$$

The results of lap shear tests and T-peel tests, as developed in tests conducted at Northeastern University, are shown in Figure 11 utilizing Equations 1 and 7.

This data allows the comparison of loads under shear conditions to be compared to the lap shear loads by a simple load ratio F_p or

$$F_R = \frac{\sigma_m}{\sigma_m^P} = \frac{P}{P_p}\,. \qquad (8)$$

Thus, the lap shear membrane stress can then be developed from Equation 8 as follows

$$\sigma_m = F_R\sigma_m^P. \qquad (9)$$

Based upon the test results from Northeastern University, the approximate load ratios (F_R) for the three membranes tested are shown in Table 7.

It should be noted that the data shown in Figure 10 and Table 7 were developed utilizing laps that were clean and developed according to manufacturer's specifications, and would be considered as seams clean when the laps were made. Also, the rate of loading was considered by examining results of Rossiter as shown in Figure 12.

As can be seen, the membrane stress increases as the rate of loading increases. This is to be expected from dynamic loading. The rate of loading for the samples tested for this paper was chosen to be 0.05 cm/min. which gives the lowest stress values and therefore conservative results.

Kendall[3] developed a relationship relating the lap shear force to the T-peel force utilizing considerations of the fracture process and the energy required for debonding to occur. The evidence, describing the fracture process for a lap discussed earlier, clearly indicates that the failure process is not a stress process, but is an energy related process. This factor gives credibility to the Kendall relationship which is defined as

$$P = (8EbtP_p)^{1/2} \tag{10}$$

where b is the unit length and is taken as 1 in., t is in the order of 20-40 mils (1 mil = 0.001 in. = 0.0254mm), and E can be obtained from the stress-strain characteristics of the membrane material. Utilizing these values yields load ratios (P_R) that are similar to Table 7. This shows the use of the values in Table 7 are reasonable for design considerations.

T-PEEL TEST RESULTS

The T-peel test can be used to quantify the influence of cleaning the membrane surface prior to placing the adhesives on the seam or heating the seam in a "welded" connection. One of the earliest works of merit relative to "clean" and "uncleaned" laps on single-ply membranes was described by Rossiter[1] and others.[3,4,5] This study was conducted on an existing government facility that originally was found to have hairline cracks in the lap sealant of the laps. Close inspection revealed that the delamination was occurring along the edge of the laps of a fully adhered roof. As a result, a series of T-peel tests were conducted in-situ and laboratory samples to evaluate the seams. This was done even though inspection and field results indicated the basic seams had maintained their integrity. Rossiter and Seiler's[4] work describing the results are summarized in Table 8, where the peel load (P_p) shown are for in-situ samples and laboratory samples on clean and uncleaned samples. These tests[4] were conducted utilizing a portable testing machine with a loading rate of 5 cm/min for the 60 mil (1.5mm) thick EPDM membrane. It should be recognized that these results were conducted with a rate of loading (i.e., 5 cm/min).

By combining Equation 9 with Equation 3, it is possible to relate the peel load to the width of the lap. Making the appropriate substitutions yields

$$L = C\,\frac{F_p P_p^{\,D}}{30t} \tag{11}$$

Utilizing Equation 11 with the results shown in Table 8 for EPDM in the in-situ case, the uncleaned samples and clean laboratory samples leads to the width of weld criteria shown in Table 9.

The results of Table 9 clearly indicate the cleanliness of a weld is significant. From a practical standpoint for EPDM seams, it would appear that 3 in. to 4 in. (75mm to 100mm) seams become a reasonable safe lap width.

These results from T-peel tests are important from a design viewpoint in that two major design considerations are clearly and quantitatively developed.

- Field seam strength of laps will develop membrane stresses in the order of magnitude of 37 psi (2.2/0.06) (0.26 MPa) for the peel conditions. This yields (utilizing Table 7 and Eq. 9) a membrane stress of about 282 psi (7.7 x 37) (1.9 MPa). This indicates the field developed seams appear adequate to carry most loads.
- Peel loads in laps, when they are developed without good cleaning operations, are about 2.7 lb./in. (0.47 N/mm). However, when the laps are cleaned the increase in load carrying capacity is almost doubled.

Clearly this demonstrates the merit of specifying a sound cleaning procedure for laps even though the evidence indicates that membrane stresses control lap shear failures.

CONCLUSIONS

The data developed in this study indicates the average shear stress in the lap decreases as the load increases, and the controlling feature of a lap is the membrane stress at the lap. The study indicates the welding process, either chemical or heat welding, alters the ultimate stress of the membrane. It also demonstrates that the width of the lap is related to the average shear stress in the lap by a single power relationship. Finally, it indicates the critical width of clean laps is generally less than most specified widths, and the lack of cleanliness of the seams as developed from T-peel testing substantially influences the width of a lap to the extent of almost doubling the width to consider the influence of contaminants may be necessary.

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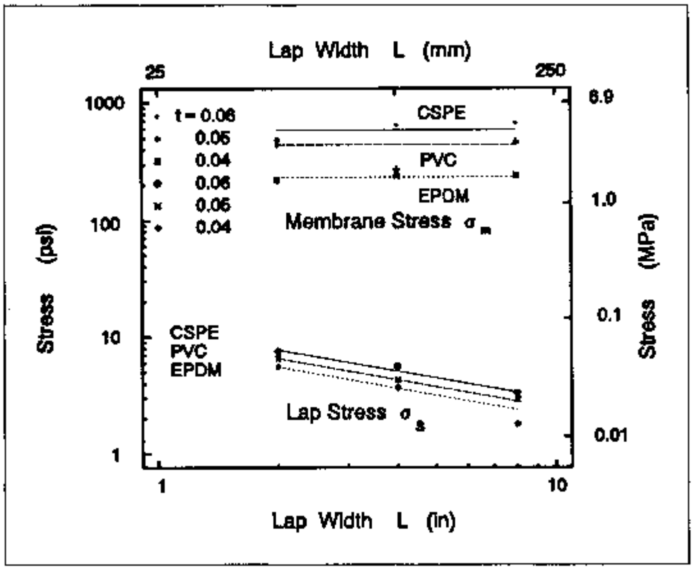

Figure 1

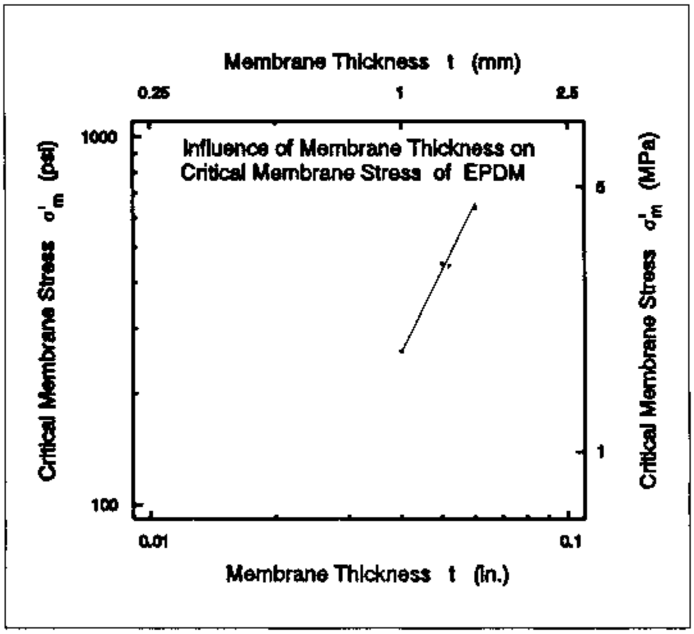

Figure 2

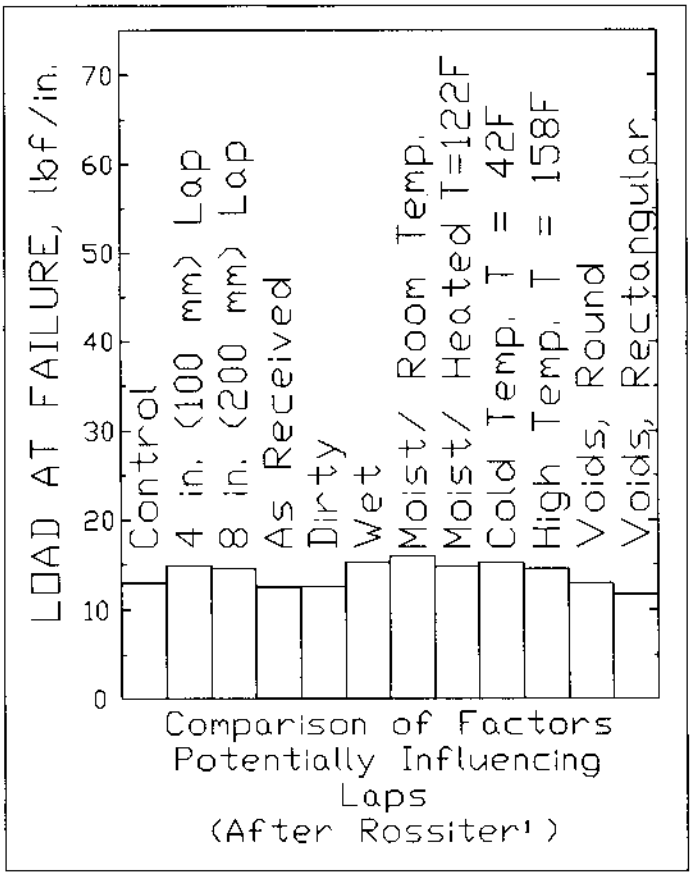

Figure 3

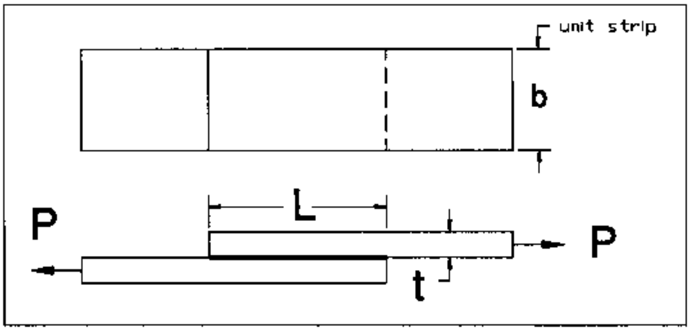

Figure 4 *Lap model.*

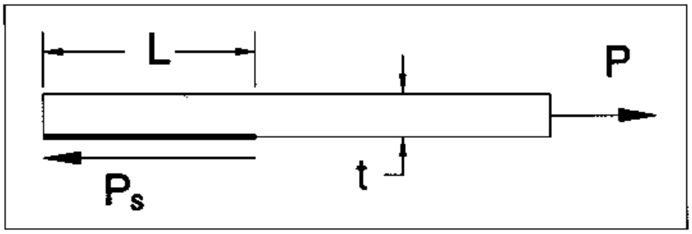

Figure 5 *Force diagram.*

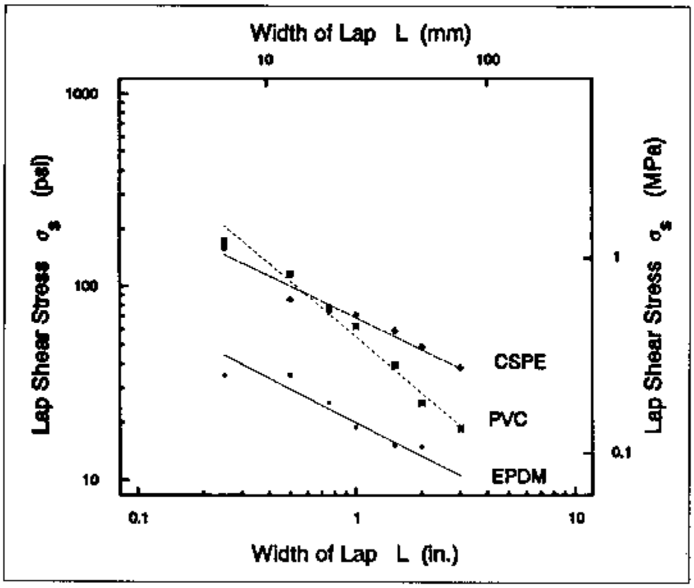

Figure 6 σ_s *vs. L.*

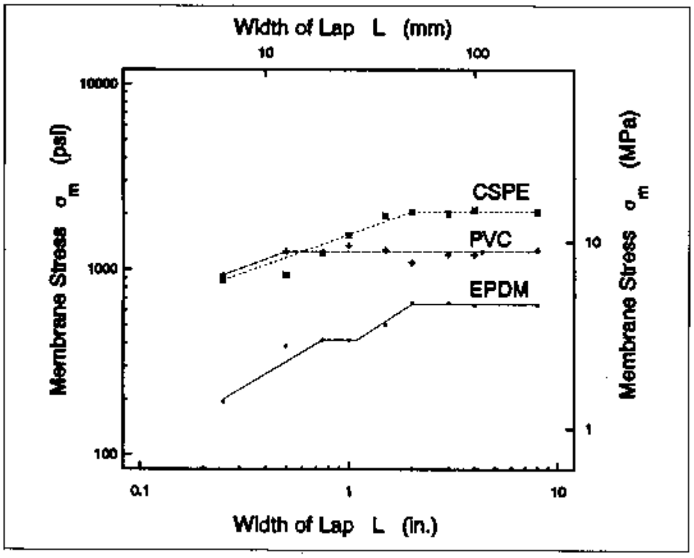

Figure 7 σ_m *vs. L.*

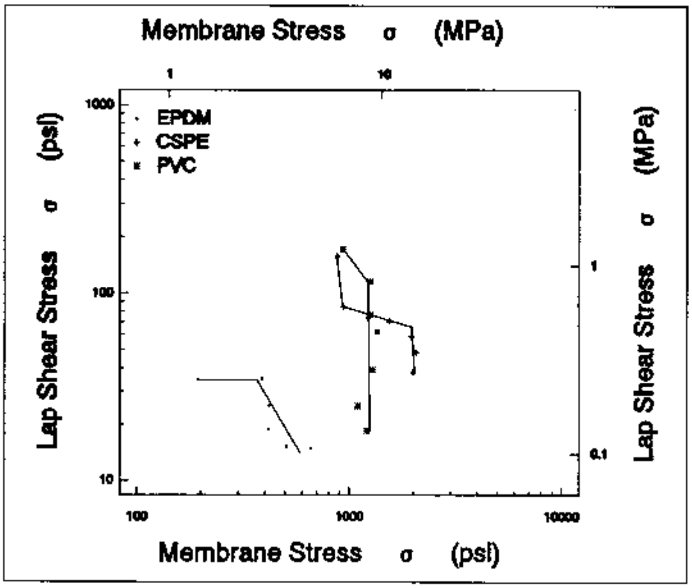

Figure 8 σ_s *vs.* σ_m.

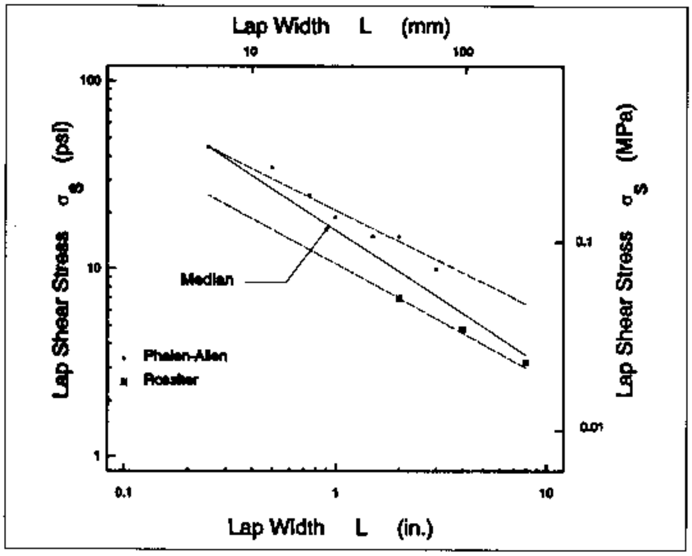

Figure 9 σ_s *vs. L for EPDM.*

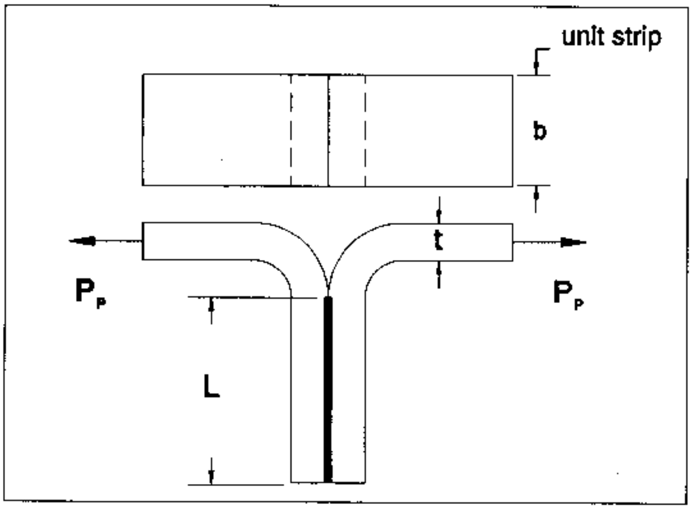

Figure 10 Configuration of T-peel test.

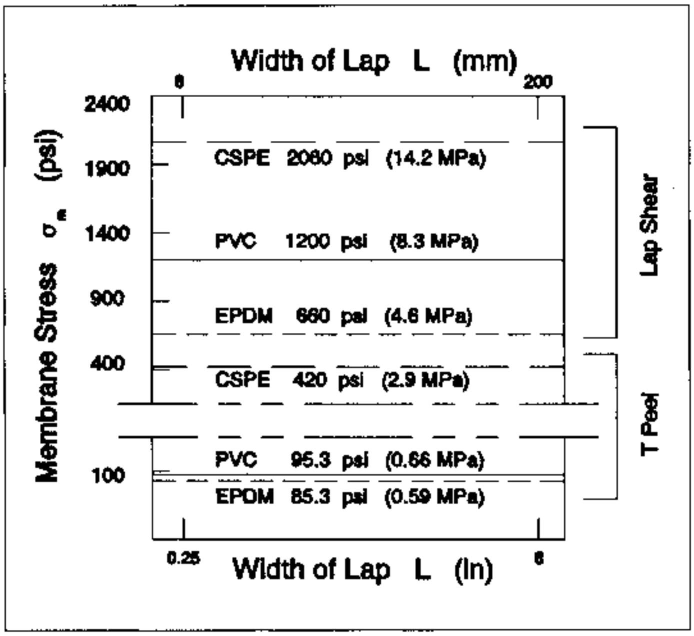

Figure 11 *T-peel test results.*

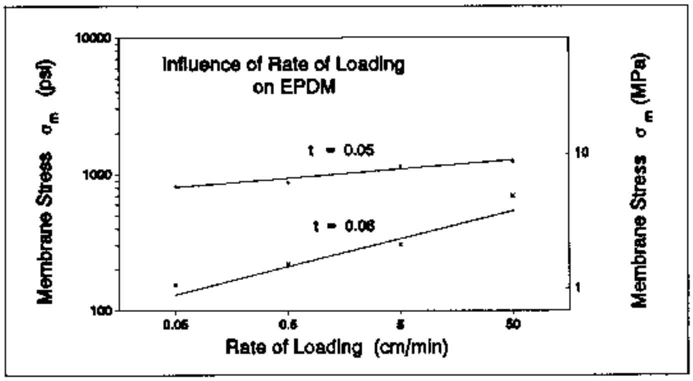

Figure 12

Sample	2 in.	(50mm)	4 in.	(100mm)	8 in.	(200mm)
Thickness in. (mm)	P lbs (σ_m) psi (σ_s) psi	(N) (MPa) (MPa)	P lbs (σ_m) psi (σ_s) psi	(N) (MPa) (MPa)	P lbs (σ_m) psi (σ_s) psi	(N) (MPa) (MPa)
0.04 (1.0)	17.2 430 8.6	(76.5) (3.0) (0.060)	26.0 650 6.5	(116) (4.5) (0.045)	26.8 670 3.35	(119) (4.6) (0.023)
0.05 (1.3)	24.3 486 12.2	(108) (3.4) (0.084)	17.9 358 4.48	(79.6) (2.5) (0.031)	23.2 464 2.9	(103) (3.2) (0.020)
0.06 (1.5)	(13.0) 217 6.5	(57.8) (1.5) (0.045)	14.9 248 3.73	(66.3) (1.7) (0.026)	14.6 243 1.63	(64.9) (1.7) (0.011)

Table 1 *Test results for laps via Rossiter for EPDM load (P), membrane stress (σ_m) and lap shear stress (σ_s).*

Number	Item
1	Dirt or other foreign matter
2	Release agent used during manufacturing process
3	Moisture (water)
4	Temperature (hot)
5	Temperature (cold)
6	Voids in adhesive layer

Table 2 *Factors potentially influencing laps in single-ply membranes.*

Material	C	D
EPDM	56.3	−1.3
CSPE (reinforced)	3930	−1.98
PVC (unreinforced)	40.4	−1.1

Table 3 *Constants relating L and lap shear stress (σ_s) in Equation 3.*

Material	$\sigma_{m\ max}$ psi (MPa)	$\sigma_{s\ critical}$ psi (MPa)	σ_m/σ_s
EPDM	630 (4.3)	21 (0.14)	30
PVC	1260 (8.7)	40 (0.28)	31.5
CSPE	2000 (13.8)	63 (0.43)	31.7
		Median	31.0

Table 4 *Critical membrane and shear stresses.*

Membrane Type	Ultimate Membrane Stress (σ_m') psi (MPa)	Membrane Stress at Lap (σ_m) psi (MPa)	Membrane Stress Ratio R_m
EPDM	1760 (12.1)	500 (3.4)	0.28
CSPE	1550 (10.7)	1300 (9.0)	0.84
PVC	2100 (14.5)	2000 (13.8)	0.95

Table 5 *Determination of membrane stress ratio (R_m).*

Material	Type of Weld	Minimum Critical Width L in. (mm) (Eq.6)
EPDM	Chemical	1.3 (33)
CSPE	Heat	1.0 (25)
PVC	Heat	1.4 (36)

Table 6 *Minimum critical widths at laps for various single-ply materials.*

Material	Load Ratio F_R
EPDM (unreinforced)	7.7
CSPE (reinforced)	4.9
PVC (unreinforced)	12.6

Table 7 *Approximate load ratios for common single-ply membranes.*

Classification	Peel Load lb./in. (N/mm)	Range lb./in. (N/mm)
In-Situ Samples	2.2 (0.39)	0.9 - 3.2 (0.16 - 0.56)
Uncleaned Laboratory Samples	2.7 (0.47)	1.9 - 4.4 (0.33 - 0.77)
Clean Laboratory Samples	4.6 (0.81)	3.3 - 6.6 (0.58 - 1.16)

Table 8 *T-peel test results for P_p for EPDM.*

Classification	Median Width in. (mm)	Range of Width in. (mm)
In-Situ	1.1 (28)	3.5 - 0.7 (89 - 18)
Uncleaned	0.9 (23)	1.3 - 0.3 (33 - 8)
Cleaned	0.4 (10)	0.7 - 0.3 (18 - 8)

Table 9 *Width of weld for EPDM from T-peel test results.*