ANALYSIS AND DESIGN OF ADHESIVE LAP SPLICES FOR ELASTOMERIC SINGLE-PLY MEMBRANES

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I. ABSTRACT

Lap splices for elastomeric sheet membranes have lacked the benefit of engineering study and design until recently. These efforts have already yielded new materials and adhesive formulations for improving lap splices: namely primers and self-adhering tape. Criteria for determining an improved adhesive have been the ultimate shear and T-peel tests.

Judged by this investigation, lap-splice performance should be evaluated at a low-elongation level (20%-50%), using a working stress design approach. Temperature-induced loads are used as the primary load criteria with a safety factor. Based on field observations, the testing of high-level elongation (in some cases, ultimate elongation) cannot discern the reserve capacity of an adhesive lap-splice joint.

Reserve capacities of 4-in. splices are less than 50% at the working stress level according to this study. Working-stress level has been defined as the product of load elongation in the 20% - 50% elongation range for a spliced joint.

Design recommendations include a safety factor (ranging from 2 to 4) for temperature-induced loads. This section also discusses how future work may quantify improvements in adhesive lap splice materials via reserve strain-energy capacity. Field and laboratory samples of adhesive lap splices were examined; aged field samples are sensitive to water-bath testing due to micro-voids existing within the splice.

II. LAP SPLICES FOR SINGLE-PLY MEMBRANES

Prefabricated single-ply roofing sheets undergo critical field-splicing when individual sheets are made into a continuous roof membrane. The lap-splicing technique depends largely on the nature of the single-ply sheet material.

Inherent strengths and weaknesses of lap splices are evident with each different single-ply material. Thermoplastic sheets such as polyvinyl chloride (PVC) are heat weldable and solvent fusible. These techniques make field-splicing of thermoplastic sheet lap joints relatively easy. Lap seams can be heat-welded at ambient temperatures below 40°F without affecting the lap splice. The solvent process, however, may be risky in cold weather, since condensation may occur in minute amounts within the lap as the solvent evaporates. Plastomeric single-ply roof sheets nonetheless exhibit excellent lap-splice strength. Under ultimate tensile stress, failure occurs within the membrane itself, not at lap joints. Ultimate elongation of the lap splice area ranges from 110% at −20°F, to well over 200% at 102°F (Ref. 1).

Some plastomeric sheets are also welded to clad metal flashings. Tested under similar conditions, the membrane again failed, this time adjacent to the metal flashing. Elongations for this type of splice are severely reduced (34% to 97%), depending on the test temperature.

Modified bitumen single-ply sheets can be spliced via several methods. Two common techniques are hot-asphalt (as an adhesive) and torching. As a generic class, modified bitumens exhibit a wide range of load-elongation behavior with respect to temperature. Previous research (Ref. 1) has shown that the type (ASTM D312) of asphalt may affect the ultimate strength and elongation of a lap splice. Like the hot-air welding of thermoplastic sheets, torching affects direct fusion between sheets. The torching method usually increases lap-splice elongation since a hot asphalt adhesive is less flexible than the modified bitumen. However, this difference in elongation is not very significant, since most modified bitumen sheets are fully adhered to a substrate. Some modified bitumen composite sheets are self-adhering by design. Lap splices of this nature have been found to possess adequate load-elongation properties for field fabricating a continuous roof membrane.

The third generic class of single-ply roof sheets is elastomeric: notably, ethylene propylene diene monomer (EPDM), butyl rubber (IIR), and polychloroprene (CR neoprene). The elastomeric single-ply roof sheets are cured, or chemically cross-linked material. These vulcanized sheets present unique difficulties for field splicing, since they lack the welding or fusion action of the plastomeric or modified-bitumen sheets.

Elastomeric membranes are specified with little regard to the engineering design or performance level needed of the field lap splice. The following section presents a technique for evaluating the performance of an adhesive splice, along with design guidelines. The strain-energy concept is introduced with temperature-induced loads as a basis for evaluating performance. Data will be presented to correlate the change in strain-energy loads with the ultimate shear and elongation behavior of adhesive splices.

III. SPLICING ELASTOMERIC SINGLE-PLY ROOF SHEETS

Synthetic rubber roof sheets (EPDM, butyl and neoprene) are normally spliced with polychloroprene-phenolic adhesives. This system is widely used for field splicing; some gum tape methods have also been used in conjunction with adhesives.

Factory splices of elastomeric roof sheets are also made via a tape and vulcanization process. Its advantages are two-fold:

- A wide roll of single ply roof membrane can be prefabricated under factory conditions,
- The factory splice is superior to an adhered field splice.

Since most synthetic rubber sheets are calendered and cured, as part of the vulcanization process, they require talcing or dusting to prevent "blocking" of the material as it is wound in a roll. The presence of talc dust may present a problem to field splicing work; i.e., the lap must be cleaned to assure good adhesion. Surface cleanliness significantly improves adhesion (Ref. 2); under rooftop conditions, dust and moisture must be removed as well as talc.

According to a study on the adhesive bonding characteristics of EPDM roofing membranes (Ref. 2) bonding conditions can also affect adhesion; i.e., working temperatures ranging from 40°F to temperatures in excess of 100°F. The nature of the EPDM substrate is another factor affecting adhesion. Different shear and peel test results were recorded for the various EPDM membranes sampled. Though EPDM sheet is quite inert, with good weathering characteristics, the shear and peel test results amply demonstrated that different EPDM sheets do not bond equally.

To improve the lap adhesion characteristics of EPDM roofing membranes, several alternatives have recently become available. In one, a primer is first applied to the cleaned EPDM lap splice, followed by the splice adhesive.

Another method growing in use is a self-adhering tape splice. Tape systems currently under development are made in two forms: cured and uncured. Tape systems may also use primers. In summary, elastomeric sheets can be spliced via solvent based contact adhesive, primer plus adhesive, tape or primer plus tape.

IV. LOAD-ELONGATION BEHAVIOR OF LAP JOINTS

Load

Like other membranes, elastomeric sheets must resist two types of stress: thermal and mechanical (i.e., dynamic wind and traffic loading, and large structural movements). Depending on the type of roof system, structural framing, and other factors, mechanical loading can vary widely. Thermal stresses, however, are predictable and measurable and, for elastomeric sheets, quite low (Ref.3).

As shown in Fig. 1, the upper bound and lower bound curves for these membranes range from 0.8 to 1.8 lb/in. over a 100°F temperature drop. Therefore one design variable for evaluating an adhesive lap-splice performance concerns its resistance to thermally induced loads. A reasonable safety factor should be applied to the thermally induced load for a spliced joint's design.

Ultimate shear and T-peel strengths are of little value in assessing performance of an elastomeric sheet splice subject to thermally induced and/or mechanical loads, because of the extreme test elongation required to realize these values. A lap shear test cannot be completely relied upon to indicated adhesive integrity, since a peel mechanism is part of the failure mode in a lap shear test. (This is not to be confused with a T-peel test.) As tension increases on the splice joint, a flexible adhesive will extend to accomodate the force. The splice joint goes into a free-body peel at the points of maximum stress. Since the splice begins the test in shear and then changes to a peel mechanism, the test result is neither representative of true shear or peel (Ref. 4, 5). Note, however, that ultimate shear and T-peel strengths of elastomeric sheet splices improve accordingly with the use of primers. Shear and T-peel test methods are thus best for evaluating adhesives, not lap joint performance.

Elongation

Field observation of elastomeric single-ply roof systems have shown them to be generally taut, with a small amount of elongation in loose-laid systems as well as a variety of mechanically attached membranes. When a 12x12-in. field-splice segment is cut from a membrane, the test specimen normally contracts a maximum of 1% to 3% of its linear dimension.

A primary performance requirement of the adhesive lap splice is to insure strain continuity in the roof membrane. Thus, the elongation behavior represents a more exact criterion for lap-splice performance. If a consistent relationship can be established between lap-splice elongation and load behavior, a test program could then be designed to correlate the load elongation behavior of unaged laboratory specimens with aged field splices.

A pilot study was undertaken to determine this load-elongation behavior, disregarding the ultimate shear, peel strength or elongation values of the lap splice. Test samples were nominal 5-8 in. sections containing a splice. Preliminary results show that a 2-in. splice (when tested over a 5" gage length) yielded a 4 - 5 lb/in. load at 20% elongation, and a 9 - 10 lb/in. load at 50% elongation. This load-elongation relationship was then compared with: (1) anticipated thermally induced loads and (2) anticipated membrane elongation. From a design and performance viewpoint, this load approach seems appropriate, since it allows for temperature-induced loads with a safety factor of 2.0 to 4.0. The 20% - 50% elongation range appeared reasonable, since no field study to date had indicated higher levels of lap-splice elongation (i.e., greater than 50%). Any elongation beyond that level would place the entire elastomeric roof sheet under duress.

A test program was then devised to evaluate lap splices for determining the following parameters:

- Load level achieved at 20% elongation
- Load level achieved at 50% elongation
- Retention of those load levels under a variety of environmental stresses and/or aging conditions.

This design concept parallels the working stress concept for a structural material such as concrete or steel. The only difference here is the need for relatively large elongations.

V. STRAIN ENERGY OF LAP SPLICES

The approach selected to evaluate lap-splice load-elongation behavior is that of strain energy. Units of strain energy are force times distance (which also represents work done). Strain energy is defined as the area under the load-elongation curve of a material under tensile stress. Ultimate strain energy for elastomeric materials (5-in. gage length) generally exceeds 300 lb-in. depending on test speed. (A low speed test at 0.05 inches/minute may yield a strain energy value around 100).

If a lap splice sample is subjected to some environmental stress, we can then run a tensile test and study the change in behavior between 20% and 50% elongation benchmarks. Retention of strain energy in this working-stress range is more significant as a performance indicator than an absolute test value such as shear or peel.

Rate of Loading

Elastomeric membrane data have been determined by test methods developed for synthetic rubber materials destined for consumer use. The test is run at an extremely high loading rate (jaw separation speed of 20 in./min.). As previously noted, loading rate affects the load-elongation behavior of these materials. Before the test program could proceed any further, a reasonable loading rate had to be determined. Then the effect of the actual strain rate (in./in./min.) had to be evaluated for different test sample lengths.

A test speed of 2 in./min, was selected since it reduced the normal test speed by one magnitude (20:2) and yet allows for reasonable economy of laboratory testing machine time. This rate is higher than the thermal movement rate of any building component; however when membranes are pulled or subjected to wind suction on a roof, stresses can be applied very rapidly to a lap joint. Also, the 2 in./min. test speed is recognized by ASTM D412 as appropriate for materials in the 20% elongation range.

Material samples were selected from two manufacturers and subjected to a constant rate of jaw separation (2 in./min.) for various test lengths. As shown in Table 1, actual strain rate decreases for membrane test-sample lengths above 5-in. A 5-in. gage length was used as the base sample length. Strain energy between the 20% and 50% elongation portion of the load-elongation curves was determined. A computation was also made for determining the strain energy of test samples in excess of 5-in. of length. As shown in Table 1, the experimental and computed values compared very closely, showing that for the test speed selected, the measured strain energy on a unit-length basis (lb-in./in.) is constant. Knowing that the actual strain rate would not affect the strain energy per unit length value, we could confidently use sample lengths of 5-in. to 8-in.

VI. LOAD AND STRAIN ENERGY FOR 2″ LAP JOINTS

A series of 2-in. lap splices were made from 45-mil EPDM sheets obtained from three different contractors' ordinary inventory, and each from a different manufacturer. Though recently purchased, the material's exact age was unknown. Lap samples were made according to the manufacturer's instructions for cleaning and splicing.

Although individual samples were identified by manufacturer, the purpose of the test was to determine the load, elongation and strain energy behavior for the generic group. Lap sealant was applied to one-half of the samples for comparative testing, since it is required by most specifications for elastomeric roofing. There is, however, very little comparative data on the lap sealant's mechanical effect on overall lap-joint behavior.

All samples were allowed to air cure at room temperature (70°F) before being introduced to a high-temperature cure. Nine samples (each manufacturer's material in triplicate) were subjected to a given time/temperature environment before testing. A similar number with lap sealant were also subjected to the same treatment.

As shown in Table 2, the load at 20% elongation ranged from 4.68 to 5.35 lb./in. The load at 50% elongation ranged from 9.26 to 10.68 lb./in. for the group. As expected, there were variations among the samples within each test group; each source (manufacturer) was clearly identifiable at the 50% elongation load. The strain energy (lb-in.) for each respective group is also shown.

All samples were tested to determine ultimate shear and elongation values. As shown in Table 2, ultimate shear strengths varied substantially. Samples with lap sealant normally exceeded the test values of laps without lap sealant. While we cannot determine or recommend an absolute level of strain energy at this time, ultimate shear values evidently cannot be relied on as a base indicator for performance.

Water Soak

Another set of specimens was similarly prepared and subjected to an air cure for a varying amount of time before submersion in a water bath. Again, samples with lap sealant were also tested. Compared with the samples shown in Table 2, those undergoing the water-bath treatment lost lap-joint strength in every test category, with a 3-6% loss in strain energy (see Table 3). However, in some cases, the ultimate shear values increased.

VII. LOAD AND STRAIN ENERGY FOR VARYING LAP WIDTHS

Another series of test samples, prepared to determine the change in strain energy for varying lap sizes, were not subjected to any environmental stress, but were simply air cured for seven days at room temperature (70°F). Test results were then compared with the base strain energy required by a membrane sample (unspliced) of the same length. As shown in Table 4, a 4-in. lap length offers a reserve capacity of 43%. A 2-in. lap joint only provides a 15% reserve capacity, when compared with the membrane itself. Adhesive joints (from a working stress viewpoint) have very little reserve capacity. These results quantify the notion that this type of lap splice is among the weakest of all generic systems in use today. Ultimate shear and peel tests cannot demonstrate this fact, due to the approach used.

VIII. LOAD AND STRAIN ENERGY FOR AGED FIELD LAPS

Field lap samples were procured from a four-year-old, 60-mil EPDM exposed roof system. One-half of the samples (five) were subjected to a 122°F water bath treatment for five days, followed by five freeze-thaw cycles with a two-hour minimum for each phase. During this time the samples were pre-elongated 20%. This test was similar to that conducted on the samples "H" as shown in Table 3.

The field samples contained a varying lap length (4.5-in. -4.9 in.). As shown in Table 5, the loads at the 20% and 50% elongation levels have increased over those shown in Table 4 for the samples "FA" due to: (1) a 25% increase in mil thickness, (2) an increase in lap length, and (3) aging. The samples "FB" showed marked decrease in load and strain energy levels within the 20% to 50% elongation level. A typical plot of the load-elongation curves for these samples is shown in Figure 2.

Close examination of the field laps revealed small unconnected void areas between the spliced sheets. They evidently result from field conditions present during splicing operations. In contrast, the lab samples were spliced under ideal conditions and rolled repeatedly with a 2-in. dia. steel roller.

IX. CONCLUSIONS AND RECOMMENDATIONS

This test program has demonstrated the need or using a **low elongation — working stress level** concept for evaluating the performance of adhesive lap splices. Ultimate shear tests should be used primarily as relative indecies for adhesive strength.

The strain-energy concept can be a useful tool for monitoring load-elongation behavior at the working-stress level of a lap splice. The working stress level should be defined as the load-elongation product used in the 20%-50% elongation range of a lap splice.

The following design recommendations for future lap splice specifications emerge from this study:

1. Any adhesive lap splice should have a minimum safety factor of 2.0 against temperature-induced loads. At higher elongations the safety factor against thermally induced load should increase to a minimum of 4.0.
2. The lap splice itself should be wide enough to offer at least a 50% strain-energy reserve capacity compared with an equivalent gauge length of unspliced membrane.
3. Lap splices should retain 75% of the strain energy (after water bath test) at low elongation levels (20%-50%).
4. Strain energy of aged EPDM membranes apparently increases. Adhesive lap splice materials should therefore be able to meet this increase as they age.
5. Future design work on adhesive and lap splices should attempt to quantify levels of performance based on strain-energy reserve capacity rather than an absolute strain-energy value.

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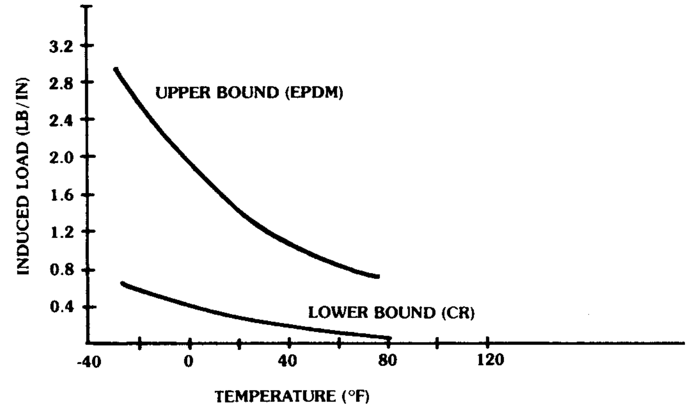

FIGURE 1
Temperature Induced Loads for Elastomeric Membranes (Ref. 1).

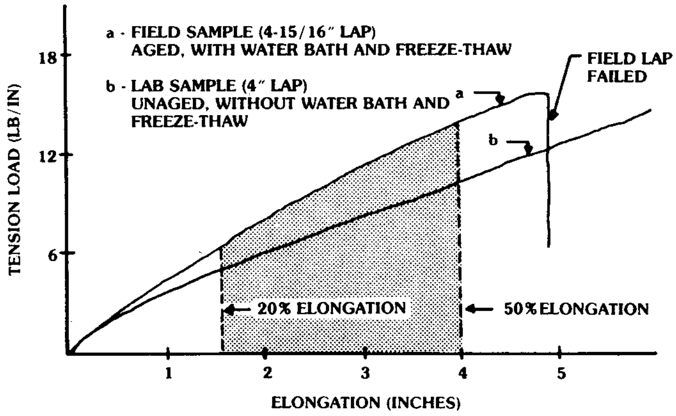

FIGURE 2:
Load-Elongation Behavior of EPDM Lap Splice.

Membrane Test Sample Length (in)	Actual Strain Rate (in/in/min)	Average Load (lb/in) At 20% Elongation	Average Load (lb/in) At 50% Elongation	Measured Strain Energy (lb/in) At 20-50% Elongation	Computed Strain Energy (lb/in) At 20-50% Elongation	Measured Strain Energy/ Unit Length (lb-in/in)
5	0.400	4.15	7.50	8.70	———	1.740
7	0.286	4.15	7.40	12.15	12.18	1.735
7.5	0.267	4.00	7.40	12.80	13.05	1.707
8	0.250	4.15	7.45	13.90	13.92	1.738

TEST SPECIFICATIONS: Straight specimens of plain membrane (no laps) of varying gage length; jaw separation rate 2″/minute; tested at room temperature (70°F) according to ASTM D412.

TABLE 1
Strain Rate vs. Strain Energy for EPDM 45 mil Sheet

Test Sample Key	Load (lb/in) At 20% Elongation	Load (lb/in) At 50% Elongation	Strain Energy (lb/in) At 20-50% Elongation	Ultimate Shear (PSI)	Ultimate Elongation (%)
A	4.68	9.26	10.45	7.82	104
AA	4.96	9.50	10.85	9.02	114
B	4.90	9.59	10.87	8.95	111
BB	5.04	9.73	11.09	10.90	126
C	5.01	9.64	10.99	9.95	123
CC	5.35	10.68	12.02	11.19	125
D	5.19	10.30	11.53	8.82	106
DD	5.12	10.23	11.52	11.10	125

TEST SAMPLE KEY: 45 MIL EPDM

A	70°F Air Cure for 7 Days
B	70°F Air Cure for 4 Days + 122°F Air Cure for 3 Days
C	70°F Air Cure for 34 Days
D	70°F Air Cure for 4 Days + 122°F Air Cure for 29 Days

A, B, C, D Series are without lap sealant.
AA, BB, CC, DD Series are with lap sealant.

TEST SPECIFICATIONS: Straight specimens with 5″ gage length containing 2″ lap; jaw separation rate 2″/minute; tested at room temperature (70°F) according to ASTM D412.

TABLE 2
Load-Elongation Behavior of 2″ Laps (air cure only)

Test Sample Key	Load (lb/in) At 20% Elongation	Load (lb/in) At 50% Elongation	Strain Energy (lb-in) At 20-50% Elongation	Ultimate Shear (PSI)	Ultimate Elongation (%)
E	4.62	9.00	10.30	8.30	109
EE	4.81	9.42	10.68	8.97	114
F	4.99	9.66	11.07	7.76	103
GG	4.94	9.83	11.11	9.56	117
H	4.43	9.83	10.70	10.80	124

TEST SAMPLE KEY: 45 MIL EPDM

E	70°F Air Cure for 4 Days + 122°F Water Bath for 3 Days
F	70°F Air Cure for 4 Days + 122°F Water Bath for 29 Days
G	70°F Air Cure for 4 Days + 122°F Air Cure for 29 Days + Five 2-Hour Freeze/Thaw Cycles
H	70°F Air Cure for 24 Days + 122°F Water Bath for 5 Days + Five 2-Hour Freeze/Thaw Cycles, elongated 20%.

E, F and H.Series are without lap sealant.
EE and GG Series are with lap sealant.

TEST SPECIFICATIONS: Straight specimens with 5″ gage length containing 2″ lap; jaw separation rate 2″/minute; tested at room temperature (70°F) according to ASTM D412.

TABLE 3
Load-Elongation Behavior of 2″ Laps (water soak)

Lap Width (in)	Load (lb/in) At 20% Elongation	Load (lb/in) At 50% Elongation	Strain Energy (lb-in)		Reserve Capacity (%)
			Measured	Required	
2	4.53	8.93	14.10	12.18	15.7
3	4.85	10.17	16.90	13.05	29.5
4	5.48	11.17	19.98	13.92	43.3

TEST SPECIFICATIONS: Straight specimens of plain membrane (no laps) of varying gage length; jaw separation rate 2″/minute; tested at room temperature (70°F) according to ASTM D412.

TABLE 4
Load-Elongation and Strain Energy Reserve for Varying Lap Widths 45 mil EPDM

Field Sample	Load (lb/in) At 20% Elongation	Load (lb/in) At 50% Elongation	Strain Energy (lb-in) At 20-50% Elongation
FA	10.43	19.87	36.36
FB	7.46	16.96	29.30

TEST SPECIFICATIONS: Straight specimens with 8″ gage length containing 4.5″ - 4.9 ″ laps, samples 4 years old. Jaw sepearation rate 2″/minute; tested at room temperature (70°F) according to ASTM D412.

KEY: FA - Tested As Is
FB - Subjected to Water Bath for 5 Days @ 122°F, Followed by 5 Days Freeze/Thaw Cycles; 2 Hours Minimum Each Phase, elongated 20%.

TABLE 5
Load-Elongation and Strain Energy Level of Aged Field Laps 60 mil EPDM