STUDIES ON MOVEMENT OF BUILT UP ROOFING MEMBRANES

Donald E. Brotherson

Research Report 65-2
UNIVERSITY OF ILLINOIS
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BUILDING RESEARCH COUNCIL
STUDIES ON MOVEMENT OF BUILT-UP ROOFING MEMBRANES

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ABSTRACT

"Splitting" or "shrinkage" failures in built-up roofing membranes have become a critical problem to the roofing industry. The problem is defined and examples are given. In order to understand and analyze the causes of these failures, laboratory studies were made to establish and measure the movement characteristics of various roofing membranes when subjected to thermal changes. The results of this work are reported and discussed for various membranes made up of No. 15 asphalt felts when attached to a variety of sub-strates.
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I. INTRODUCTION

In 1959, the National Roofing Contractors Association and the Small Homes Council-Building Research Council of the University of Illinois entered into a cooperative agreement to study failures in built-up roofing materials and systems. The results of the first studies were reported in the SHC-BRC Research Report 61-2, "An Investigation Into the Causes of Built-Up Roofing Failures". These studies dealt primarily with the failure termed "wrinkle-cracking" or "ridging".

Following this investigation, the Advisory Committee felt that the most critical problem being encountered was the failure of the roof membrane by splitting or by what appeared to be shrinkage of the membrane. At that time a new agreement between the NRCA and the SHC-BRC was approved to continue the studies of roofing failures with primary emphasis placed on the "splitting" or "shrinkage" problem.
II. THE PROBLEM

The failure termed as "splitting" can be described as one where the roof membrane is torn apart; the split or tear is generally in the direction parallel to the run of the felt and follows a straight line; no ridging or blistering is noted before the split occurs; and, no deterioration of the membrane is noticeable at the split. Splitting has been associated with sudden extreme changes in temperatures.

"Shrinkage" is somewhat akin to splitting except that the movement occurs at parapet walls, roof edges, curbs or flashings. The membrane does not tear but pulls away from the roof edge or curbs, leaving an entry for water to penetrate the building. The apparent movement does not always provide an entry for water penetration but may show up as a displacement of lead flashings around plumbing vents or clamping rings around roof drains as shown in Figure 1.

During the study, a limited number of field investigations were made. Most of the roofs investigated exhibited the shrinkage problem. Some had splits and some showed both types of failure.

In the roofs that had "shrunk," flashings had pulled out from under the counter­flashings enough so that the tin caps and nails were showing as in Figure 2. Lead flashings around plumbing stacks were completely pulled away from the stack and the lead torn. In one building, the force of the movement had been great enough to move pre-cast concrete slabs off of their supports. In another, cant strips had been displaced as much as two inches from the parapet walls, shown in Figure 3. In all cases investigated, the movement appeared to be toward the center of the structure.

For the most part, the roofs that split did not show the characteristics of the "shrinkage" problem. Flashings against parapets and around stacks were intact. In some cases, after the splits were repaired using conventional methods, the split would re-occur alongside the original split. In one case where the repair was in the form of an expansion or relief joint, the split did not re-occur except near the fascia where the joint had been tapered so that it would not be visible from the ground. In many of the roofs studied, no method of repair was successful and complete re-roofing was needed.

The exact cause, causes, or reasons for splitting failures has never been fully established. Many theories have been put forth, but as yet none have been proven either mathematically or by laboratory or field demonstration. The main reason for this inability to fully substantiate any theory is the lack of physical data about the roofing membrane.

For the initial phases of this project the Advisory Committee agreed that the major effort should be placed in establishing and measuring the movement that takes place in roofing membranes due to thermal changes.
Figure 1. Displaced Clamping Ring

Figure 2. Displaced Parapet Flashing

Figure 3. Displaced Cant Strip

Figure 4. Dial Indicator and Plug Arrangement
III. LABORATORY STUDIES

All of the samples made for this study were of low-melt-point asphalt and asphalt-saturated felts. All felt material was taken from the same roll. No surfacing material or top coating was applied to the samples.

SERIES I

The first series of tests were made on one-, two- and three-ply samples, both restrained and unrestrained. Restraint was imposed by securing the sample to a plywood base the same size as the sample, with hot asphalt of the same type used to make the multiple-ply samples.

For the first series, the samples were made 12 inches wide by 36 inches long. For samples "with the roll" the material was taken with the long dimension in the same direction as fiber grain and for samples "across the roll" the material was taken with the long dimension across the fiber grain.

In order to establish the fixed measuring points, two sets of brass reference plugs were fixed to each sample with an epoxy cement. Each set of plugs was set 10 inches apart for a 10-inch gauge length. The plugs were drilled to receive the pins of a modified Ames dial indicator as shown in Figure 4. The pins and plugs were carefully fitted to eliminate movement in the plug. A thermocouple was inserted between the plies of each sample to allow temperature measurements to be made during the testing period.

The distance between the two sets of reference plugs was measured with the sample stabilized at approximately 70 degrees F and then the sample was lowered into an open-top freezer chest in which the temperature was at about -25 degrees. Measurements between the reference plugs were made at 10 degree increments as the sample cooled to 10 degrees, and then at 5 degree intervals until the sample reached a temperature of -15 degrees. The sample was then allowed to return to room temperature and the measurements were repeated. Heat lamps were then used to raise the sample temperature to 120 degrees F.

Table I gives the average thermal expansion and contraction coefficients for the nine samples tested in the ranges of -15 degrees to zero; zero to 40 degrees; 40 degrees to 70 degrees; and 70 degrees to 120 degrees. Figures 5 through 13 give a graphic representation of the movement that occurred as the samples were cycled through the various temperature ranges.

As the figures show, the thermal movement is not linear with temperature changes. The movement that occurred in the samples followed the following general pattern: As the sample is cooled, the decrease in sample length is sharp at the start. In the low mid-ranges, the curve flattens out and movement is minimum. As the materials
Figure 5. 1-PLY WITH ROLL
Series I

Figure 6. 1-PLY ACROSS ROLL
Series I
Figure 7. 1-PLY WITH ROLL ON PLYWOOD

Series I

Figure 8. 1-PLY ACROSS ROLL ON PLYWOOD

Series I
Figure 9. 2-PLY ACROSS ROLL -
Series I

Figure 10. 3-PLY WITH ROLL
Series I
Figure 11. 3-PLY ACROSS ROLL
Series I

Figure 12. 3-PLY WITH ROLL ON PLYWOOD
Series I
Figure 13. 3-PLY ACROSS ROLL ON PLYWOOD
Series I

Figure 14. Sample on Heated Enclosure
<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>-15 to 0°F</th>
<th>COOLING</th>
<th>HEATING</th>
<th>AVER.</th>
<th>0°F to 40°F</th>
<th>COOLING</th>
<th>HEATING</th>
<th>AVER.</th>
<th>40°F to 70°F</th>
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<th>HEATING</th>
<th>AVER.</th>
<th>70°F to 120°F</th>
<th>HEATING</th>
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<td>3.3</td>
<td>4.4</td>
<td>4.8</td>
<td>4.6</td>
<td>13.8</td>
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<td>9.5</td>
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<td></td>
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<td>27.4</td>
<td>17.9</td>
<td>6.6</td>
<td>11.8</td>
<td>9.2</td>
<td>13.0</td>
<td>11.2</td>
<td>12.1</td>
<td>No Data</td>
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<td>3.6</td>
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<td>3.7</td>
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<td>4.0</td>
<td>3.8</td>
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<tr>
<td>WITH ROLL</td>
<td>17.2</td>
<td>24.5</td>
<td>20.9</td>
<td>5.9</td>
<td>4.6</td>
<td>5.2</td>
<td>6.1</td>
<td>2.6</td>
<td>4.3</td>
<td>11.7</td>
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<td>7.5</td>
<td>10.8</td>
<td>16.4</td>
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<td>9.1</td>
<td>11.4</td>
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<td></td>
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</tr>
<tr>
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<td>8.3</td>
<td>5.0</td>
<td>6.6</td>
<td>3.1</td>
<td>2.5</td>
<td>2.8</td>
<td>4.2</td>
<td>1.7</td>
<td>2.9</td>
<td>7.0</td>
<td></td>
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</tr>
<tr>
<td>ACROSS ROLL ON PLYWOOD</td>
<td>11.9</td>
<td>10.5</td>
<td>11.2</td>
<td>4.8</td>
<td>2.8</td>
<td>3.8</td>
<td>3.9</td>
<td>5.5</td>
<td>4.7</td>
<td>12.2</td>
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</table>
go below the 0-degree range, the movement again is very sharp and the sample size decreases more rapidly. As the sample is allowed to warm, the movement in the low range is again very sharp with a flattening out in the low mid-range and then a sharp increase in movement in the upper ranges.

This pattern of movement is most evident in the unrestrained samples, but still can be seen in the restrained samples. The relative amounts of movement are greater in the samples taken "across the roll" and seems to increase with an increase in the number of roofing felts in the sample.

The effect of restraint is evident in all temperature ranges and types of sample. The restraint effect is especially demonstrated in the difference between the unrestrained and restrained 3-ply "across the roll" samples where in the low and low mid-range the movement was reduced by a factor of more than three.

SERIES II

For the next series of tests, a heated box was constructed so that the underside of the samples could be subjected to temperatures similar to those in a heated building while the top surface was subjected to the ambient temperature of the freezer.

The box was constructed of plywood and equipped with a strip heater at one end controlled by a line-voltage thermostat. Adjustable supports were placed in the corners of the box so that samples of varying thickness could be used. A panel was cut out of one end of the box to allow access to the thermostat controls. Plywood strips four inches wide were made for the top edges of the box and were secured to the edges by bolts with wing nuts. This allowed the samples to be held in place without imposing restraint on the edges of the sample. For other tests, the wing nuts could be pulled up tight and the sample edges restrained. For Series II, restraint was not imposed on the samples and the edges of the box were lined with foil paper to insure that the samples would not bond to the box.

All of the samples were made of the same felt and asphalt as the samples in Series I. The samples measured 18 inches by 30 inches and were three-ply. Insulation and plywood bases were made 16 1/2 inches by 28 1/2 inches to allow for lapping the box edges.

Samples were made as follows:

1. 3-ply #15 felt on 1/2-inch plywood
2. 3-ply #15 felt on 1-inch fiberboard insulation
3. 3-ply #15 felt on 1-inch fiberboard bonded to 1/2-inch plywood

In the manner described earlier, brass reference plugs were cemented to each sample except that four sets of plugs were used on each sample so that two
measurements across the roll and two measurements with the roll could be made as each sample was subjected to the temperature variations. As in the first series, a thermocouple was inserted in each sample to monitor the sample temperature. Each sample was subjected to temperature variations similar to those in the first series. The sample was measured at approximately 70 degrees and then put in the freezer box. The sample was allowed to cool until it stabilized at its lowest temperature. This temperature varied with each sample, depending on whether it was insulated or not. The non-insulated samples reached a low temperature of 36 degrees while the insulated samples reached a low temperature of 15 degrees. These samples did not reach the low temperatures experienced in the first series because of the heat loss from the heated box.

Figures 15 through 20 show the thermal movement that occurred in the three samples in the same direction as, and across the grain of the felt. Table II gives the average thermal expansion/contraction coefficients in ranges similar to those given for Series I.

From the table and figures, it can be seen that as in the first series, movement across the roll is greater than movement with the roll.

The data presented in Figures 15 through 18 starts at room temperature and is varied through a high temperature of 120 degrees and then returned to the low temperature, which is a different temperature sequence than for the data in Figures 5 through 13. The tests on these two samples were done in this manner to reduce the time required to complete the cycle of temperature variation. In Figures 19 and 20, the data is presented in the same temperature sequence as the earlier data and the pattern of movement described earlier can be seen. The initial temperature drop causes a rapid movement, which then tapers off in the mid-range. On the warming part of the cycle, the initial movement is again sharp, with a leveling in the mid-range, and a sharp increase in the high range.

A study of Figures 15 through 18 indicates a similar performance pattern. Any initial change in direction of temperature variation causes a sharp movement to occur in the sample, with a corresponding tapering off in the mid-ranges.

The effect of changing the sub-structure from a rigid base (plywood) to a more flexible base (insulation) can be seen by comparing Figures 15 and 16 with Figures 19 and 20. The sample attached directly to the plywood had a greater movement in the mid-ranges than the sample attached to the insulation board. For the high range, the movement "with-the-roll" attached to the plywood is slightly greater and the cross fiber movement is somewhat less. The sample attached to insulation and plywood followed more closely the pattern of the sample on insulation only.

SERIES III

During the testing of the Series II samples, it was observed that when the sample
Figure 15. 3-PLY ON PLYWOOD WITH ROLL
Series II

Figure 16. 3-PLY ON PLYWOOD ACROSS ROLL
Series II
Figure 17. 3-PLY ON PLYWOOD AND INSULATION WITH ROLL
Series II

Figure 18. 3-PLY ON PLYWOOD AND INSULATION ACROSS ROLL
Series II
Figure 19. 3-PLY ON INSULATION WITH ROLL

Series II

Figure 20. 3-PLY ON INSULATION ACROSS ROLL

Series II
### TABLE II

**SERIES II - THERMAL CONTRACTION/EXPANSION COEFFICIENTS X10^-6**

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>RANGE</th>
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<tr>
<td>3 PLY ON PLYWOOD</td>
<td>70F to 120F</td>
<td>120F to 70F</td>
<td>70F to 40F</td>
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<tr>
<td>WITH ROLL</td>
<td>3.99</td>
<td>3.49</td>
<td>3.65</td>
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<td>ACROSS ROLL</td>
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<td>5.12</td>
<td>5.52</td>
<td></td>
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</tr>
<tr>
<td>3 PLY ON INSULATION</td>
<td>65F to 120F</td>
<td>120F to 70F</td>
<td>70F to 50F</td>
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</tr>
<tr>
<td>WITH ROLL</td>
<td>2.47</td>
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<td>2.62</td>
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<td>70F to 40F</td>
<td>40F to 20F</td>
<td>20F to 40F</td>
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<td>70F to 110F</td>
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<td>9.17</td>
<td>2.80</td>
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<td>5.50</td>
<td>4.83</td>
<td>5.37</td>
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</table>
was heated beyond 110 degrees it contracted and became smaller instead of expanding as was expected. This prompted a series of tests to see what effect continuous cycling of sample through the temperature variations would have.

As each of the three samples was cycled, the reversal of movement experienced with the sample on insulation was noted. If heating was continued beyond the 110 to 120 degree range, the sample would contract rather than continue to expand. A similar reversal occurred when the samples were allowed to remain at low temperatures for prolonged periods of time (usually overnight). Instead of continuing to contract or remain at the same dimension, the samples would expand.

This erratic behavior of the samples is difficult to explain. It is possible to assume that the behavior is the result of a moisture content change in the roofing felts. From previous experience, it is known that the roofing felts are dimensionally unstable and will vary in size as the moisture content of the felts vary, much the same as any product composed primarily of wood or wood fibers. (Roofing felts are composed basically of wood fibers). Since all of the samples were left with the top ply uncoated, they would tend to become smaller as they lost moisture and expand as they took on moisture. Heating the samples drove off moisture from the top felt. Cooling the samples brought them down below the dew-point of the ambient air, condensing moisture vapor on the sample surface, which was absorbed into the felts, causing them to expand even though the temperature of the sample was decreasing.

Figures 21 through 26 are a graphic representation of the effect of multiple cycles on the various samples and fiber directions.

For all three samples, the "across - the - roll" accumulation of "shrinkage" was greater than the shrinkage "with the roll". This, too, is typical of all wood products.

The total dimensional change of the samples was greater for the sample bonded directly to the plywood than for the sample bonded to the insulation. This was apparently influenced by the ability of the insulation board to "give" with the movement of the felt membrane more so than the stiffer plywood. For the sample where the insulation was bonded to the plywood base, the action approximated the movement of the sample bonded directly to the plywood. Here again, the plywood apparently did not "give" as readily and in turn restricted the movement of the insulation board.

As stated earlier in this report, these samples were not restricted from moving around the edges. Had restriction been imposed, it can be expected that the shrinkage characteristics might be somewhat different.
Figure 21. 3-PLY ON PLYWOOD WITH ROLL
Series III

Figure 22. 3-PLY ON PLYWOOD ACROSS ROLL
Series III
Figure 24. 3-PLY ON ONE-INCH INSULATION ACROSS ROLL
Series III

Figure 25. 3-PLY ON ONE-INCH INSULATION WITH ROLL
Series III
Figure 25. 3-PLY ON ONE-INCH INSULATION AND PLYWOOD WITH ROLL
Series III

Figure 26. 3-PLY ON ONE-INCH INSULATION AND PLYWOOD ACROSS ROLL
Series III
IV. CONCLUSIONS

1. From the three test series it is obvious that roofing membranes will contract and expand as the temperature of the membrane is varied. This fact has been substantiated by other works.

2. The amount of movement and the rate of movement is affected by the substrate, the number of roofing plies, the direction in relation to the roll of felt, and abrupt changes in temperature (either sudden cooling or heating).

3. Contraction or expansion of the felts can occur from conditions other than temperature changes. Changes in the moisture content of felts will cause dimensional changes that are large enough to over-ride changes occurring from temperature changes and cause reversal of thermal contraction or expansion.

4. As roofing felts are subjected to cyclic variations of temperature and/or moisture, they will exhibit a shrinkage characteristic that is cumulative and apparently irreversible. The initial cycles will cause the greatest shrinkage accumulation. As many as nineteen cycles have been performed without any indication of stabilization. No determination has been made as to the number of cycles needed to effect stabilization of the felts.
V. INSTRUMENTATION STUDIES

During the course of the investigations reported in this study, the samples did not always act in a uniform manner. As stated earlier, the movement at times was quite erratic and an exact graphic description is impossible to reproduce.

The modified Ames dial and brass plug system proved adequate as a measuring technique but, it was felt that a system should be devised that could be continuously monitored on automatic recorders. A better "picture" could be then drawn that would result in more precise measurements.

At the conclusion of the three test series, an effort was made to devise such a system. At first it seemed that the easiest method to use would be a strain-gauge system. A standard SR-4 strain gauge was bonded directly to the roofing sample. A second strain gauge was used in the circuit as a balance for the thermal changes that the gauge would have to undergo. A Leeds and Northrup strain gauge module and an Esterline-Angus recorder completed the equipment.

A sample was run in the same manner as the previous tests. The strain gauge system did not prove to be suitable. As was experienced with roofing felts, the SR-4 gauges were apparently affected by moisture. Efforts were made to devise shielding arrangements for the gauges but these, too, did not prove effective.

Some consideration was also given to the possibility that the gauge wire was stronger than the roofing it was to measure. To offset this effect the SR-4 gauges were bonded to a thin sheet of spring metal fitted with pivots at the ends. Small mounting blocks were bonded to the roofing sample with epoxy cement. The blocks were made with pins to accept the pivots at the ends of the spring. This was tested and did not prove successful. Apparently, the friction at the pivot points was great enough that the relatively small movements in the roofing sample could not overcome it. Prior to the set-up with the pivots, a similar system without pivots and with the spring slipped into slots machined in the mounting blocks was tried and it, too, was not successful for apparently the same reasons.

One more attempt was made using SR-4 gauges. In this system, the gauge was suspended between two mounting blocks. One of the mounting blocks was equipped with a movable grip on a finely threaded adjusting screw. It was planned that the gauge could be stressed by means of the adjusting screw so that it would always be in tension at any extreme of movement in the sample. A similar gauge was put into the circuit (unmounted) to balance any thermal effect. This system, as the others, was not successful. Here
again the problem of moisture was encountered and it became apparent that the gauges were stronger than the sample material and could not give a true answer of the movement taking place in the felts.

Currently under development is a system employing linear-variable differential transformers (LVDT). For this system, small plates will be cemented to the sample. Each plate will have a vertical post. The LVDT will be mounted on one post and the other post will support the end of a 10-inch Invar rod which will be threaded to the core of the LVDT. Any movement between the plates will cause the core to move in the transformer. Changing the core position will change the signal from the transformer which will be continuously monitored by the recorder. The recorder can be equipped with a "drag pen" so that the trace will not be broken as is common with multiple point recorders.

In a preliminary investigation using a Schaeitz Type 033S-L LVDT, excellent results were obtained. However, with this type LVDT, a correction must be made for temperature differences. To overcome this the next set-up will use manganin wound transformers.
VI. RECOMMENDATIONS FOR FUTURE WORK

This report covers a limited number of samples under one set of conditions. The number of samples and combinations of materials and operating conditions possible to test is, of course, quite large.

The testing should continue and the following series of tests should be performed:

1. Asphalt and asphalt felts with edges restrained.
2. Coal-tar pitch and tarred felts with and without restraint.
3. Asphalt and glass felts with and without restraint.
4. Asphalt and asbestos felts with and without restraint.
5. A special study on a limited number of samples where steep-roofing asphalt is used to bond the sample membrane to the plywood and/or insulation.

At the termination of these five series, a program should be initiated to study the effects of varying the insulation and substrate. For example: Glass fiber insulation on steel deck with and without taped joints in insulation, and perlite board insulation bonded to fire-resistant vapor barriers with mastic.

In all cases, the samples should be subjected to multiple cycling for a minimum of 30 days to perhaps 60 days until either stable dimensional conditions are obtained or until it can be established that "shrinkage" will continue to occur. The length of time each cycle will take will depend on the makeup of the sample. It is estimated that perhaps two complete cycles could be done each day with automatic programming equipment.

The data that will be generated by these tests is needed if the problem of shrinkage and splitting is to be understood and solved.
REFERENCES
