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Effets du rétrécissement thermal sur les toitures composées

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Effects of Thermal Shrinkage on Built-up Roofing

William C. Cullen

The effects of thermal movement of bituminous built-up roof membranes are related to some common failures of built-up roofing observed in field exposures. A procedure for determining the amount of thermal movement of built-up membranes is described. Data are given for the thermal movement of various bitumens and reinforcing felts used in the construction of built-up roofs and for the composite membranes over a temperature range of +30 to −30 °F. The data obtained are related to field experience and suggestions are presented which will prove beneficial in reducing the incidence of built-up failure due to thermal movement.

1. Introduction

Asphalt and coal-tar-pitch built-up roofings are used throughout the world to protect large buildings having relatively flat roofs (slopes less than 2 in./ft). These roofing systems are exposed to various climatic conditions ranging from the hot, humid tropics to the cold polar regions. An expected life of 20 years is not always obtained due to premature failure of components of the systems. For example, an extensive survey of military roofing in Alaska in 1957 in which the author participated revealed that approximately 50 percent of the flat roofs had failed. The majority of these roofs had no slope and were installed after 1950. Many of the failures occurred when the roofs were only 1 or 2 years old. Similar performance of bituminous built-up roofings have been observed in other climates. Obviously, the maintenance, repair, and replacement cost of the prematurely failed roofs is quite large. The object of this research was to identify and study some of the factors involved in premature failures and to relate the pertinent factors to roof performance.

2. Some Causes of Failure

The author's experience over many years with built-up roof performance has indicated that many failures can be attributed to the following:

(a) Faulty workmanship.
(b) Faulty design.
(c) Application of roofing materials during inclement weather.
(d) Improper use of materials.
(e) Poorly designed or installed flashing systems.

These causes and their effects are easily recognized and can be avoided to a large extent by the use of available material and design criteria enforced by construction inspection. However, the causes of other serious failures common to built-up roofings, such as splitting or wrinkle cracking, are not as well known. The primary causes of splitting failures are believed to be different from those resulting in wrinkle cracking, although some factors as solar heating and radiative cooling are common to both. Splitting failures are postulated to result from shrinkage of the roof membrane while wrinkle cracks are attributed to fatigue of the roof membrane resulting from repetitive movements during the development and subsequent regression of wrinkles in the membrane.

A number of possible causes of wrinkling and subsequent wrinkle cracking failures have been suggested by Joy [1]* and Brotherson [2] as: Water-vapor pressure; expansion of roofing felts resulting from absorption of moisture condensed on felts over insulation joints; and movement in substrate (deck or insulation) with changing moisture content. Cullen and Appleton [3] suggested the thermal cycle produced by solar heating may contribute to the dimensional changes which occur in the system components and result in the formation of wrinkles and wrinkle cracking.

Although the seriousness of wrinkle cracking is recognized, it is believed that splitting results in a more serious failure. The author's experience with the performance of built-up roofs has confirmed the widespread incidence of splitting failures, especially in cold climates. Figures 1, 2, and 3 show schematically failures attributed to membrane shrinkage. Figure 1 shows the number of splits which were observed in the roof on one large structure, while figures 2 and 3 indicate the displacement of the flashings at an expansion joint and at the gravel stop, respectively, on the same structure, due to membrane shrinkage.

Although many membrane failures can be traced to the movement of a building component beneath the roofing [4] which is transferred to the membrane, evidence exists that thermal movement of the membrane is also involved [5]. Therefore, in order to allow for the movement and minimize the failures, the extent of the movement as well as the strength characteristics of a bituminous membrane must be known over the temperature range to which the roofing may be subjected.

*Figures in brackets indicate the literature references at the end of this monograph.

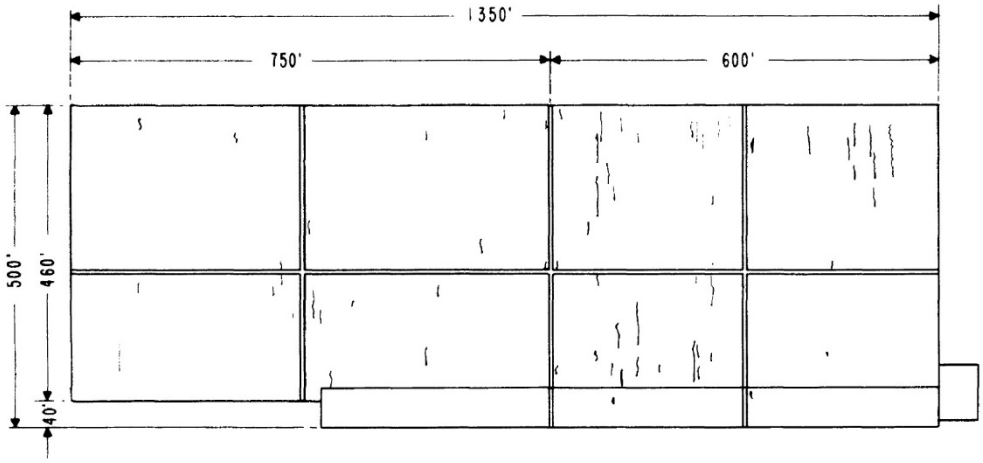

FIGURE 1. *Splitting failures attributed to membrane shrinkage.*
The four sections on the left were about 3 years old. The remaining sections on the right were approximately 9 years old.

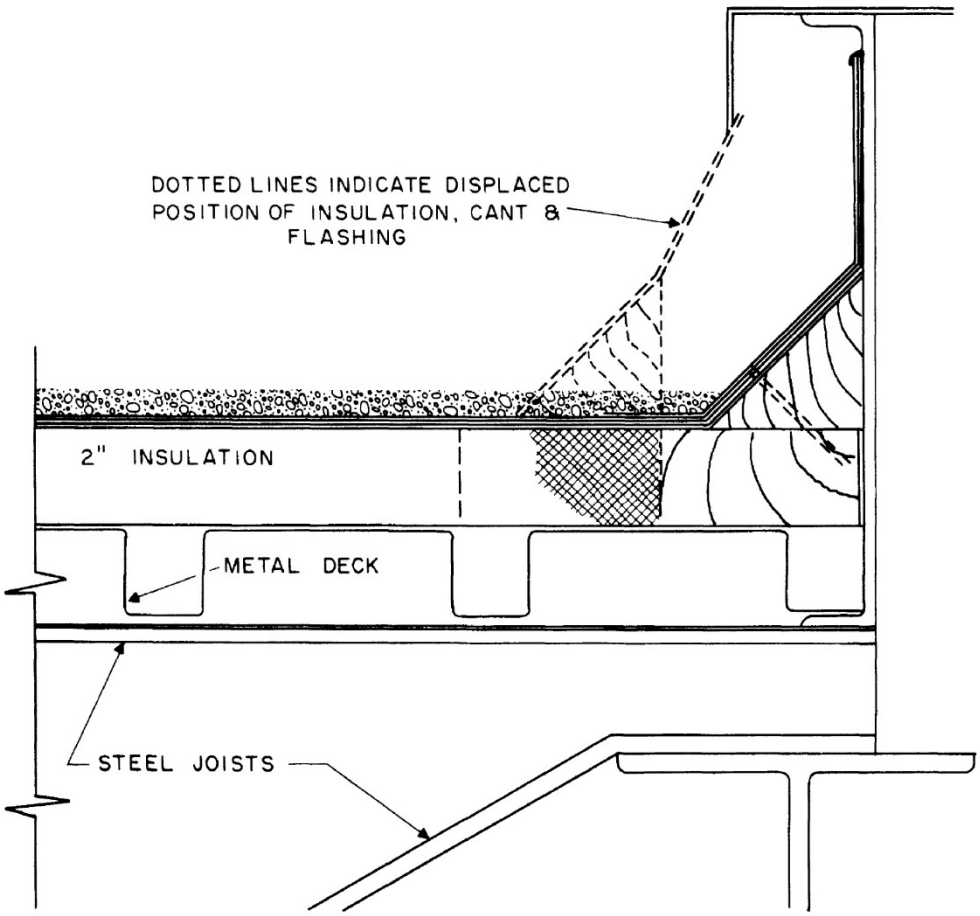

FIGURE 2. *Displacement of flashing at an expansion joint due to membrane shrinkage.*

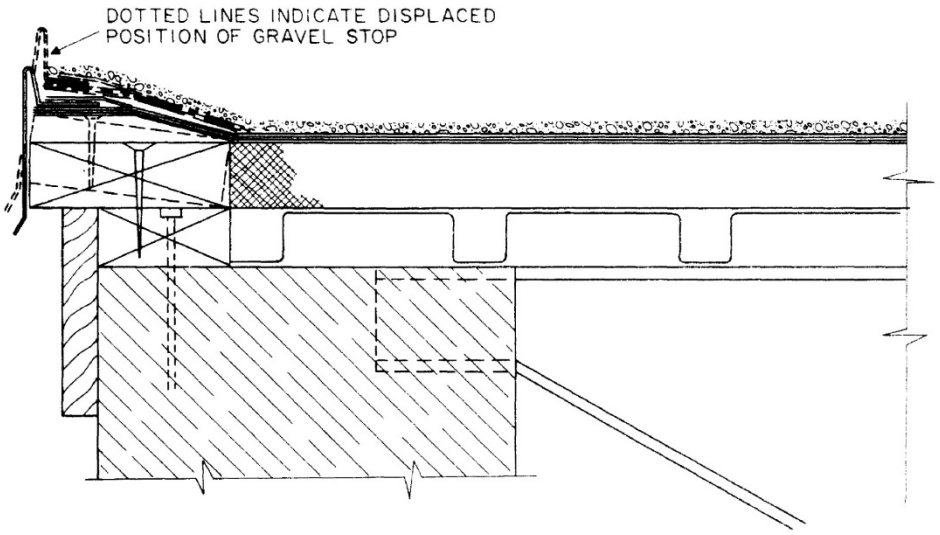

FIGURE 3. *Displacement of gravel stop due to membrane shrinkage.*

3. Strength Characteristics of Bituminous Built-Up Membranes

In attempting to relate the strength characteristics of a bituminous built-up roof to splitting failures, three factors should be considered: Breaking load, breaking strain, and thermal movement.

3.1. Breaking Load

After a comprehensive study on some strength characteristics of bituminous built-up roofing, Jones [6] reported the breaking load of an organic-felt built-up membrane tested in the length direction was double that tested in the across machine direction, while that of an asphalt-glass felt membrane was equal in each direction and roughly the same as that of the organic-felt membrane in the across machine direction. He further reported the breaking loads of the organic-felt membrane and of the glass-felt membranes increased 300 and 70 percent, respectively, when the temperature of the specimen was decreased from 75 to −20° F.

3.2. Breaking Strains

Jones [6] also reported that the breaking strains for various bituminous membranes varied with temperature. For example, coal-tar pitch and organic-felt membranes showed a marked decrease from 1.7 percent at 75 °F to 0.5 percent at --20° F, while the asphalt and organic-felt membranes decreased from 2.3 percent at 75 °F to 1.2 percent at −20 °F. The asphalt and glass-felt membrane decreased from 1.7 percent at 75 °F to 1.1 percent at −20 °F.

3.3. Thermal Movement

The dimensions of most substances increase as the temperature increases and decrease as the temperature decreases. The ratio of the increase in length of a body to the original length for a specified temperature rise is known as the coefficient of linear thermal expansion. The coefficient of cubical thermal expansion is defined in like manner except that the quantities are now volumes instead of lengths. In order to relate thermal movement of built-up roofing to its performance, it is necessary not only to know the linear expansion coefficient of the bitumen and the saturated felt, but also that of the composite built-up membrane constructed from these components.

The coefficient of cubical expansion of asphalt and coal-tar pitch was reported to be 3.5 to 3.9×10^{-4} per °F over the temperature range of 32 to 140 °F and 2.6×10^{-4} per °F over the range of 200 to 300 °F [7], respectively. If the assumption is made that the linear expansion is about ⅓ that of the cubical expansion, the linear expansion coefficient is 120×10^{-6} per °F for asphalt and 90×10^{-6} per °F for coal-tar pitch over the temperature ranges indicated.

Cullen [5] reporting on a limited study of the thermal movement in relation to solar heating indicated the coefficient of linear thermal expansion of composite built-up membranes increased markedly as the temperature decreased. He further reported the expansion coefficient to be in the range of 10 to 31×10^{-6} per °F for various composite bituminous built-up membranes over a temperature range of −60 to 0 °F when measured parallel to the machine direction of the reinforcing felt. However, no published information was available for the thermal expansion coefficients of roofing felts nor had data been found indicating the relationship between linear expansion and direction of the felt.

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4. Materials and Test Procedure

Four types of bituminous-saturated felts and two types of bitumen, which are conventionally used in the construction of built-up roofs, were selected for study. Table 1 lists the types of materials used. For the first test each specimen was cut from a sample that consisted of four plies of a felt fastened to each other, without the use of bitumen, by applying staples at each end, while for the second test the specimen consisted of four plies of felt cemented to each other with the appropriate bitumen.

The thermal movement measurements were made on four 12-in. long by 2-in. wide specimens of each sample, two of which were prepared with the 12-in. dimension perpendicular to the machine direction of the felt and the remaining two were prepared with the 12-in. dimension parallel to the machine direction of the felt. Brass reference plugs, ¼ in. in diameter, were inserted and sealed with an epoxy adhesive into holes drilled into the specimen near each end and spaced about 10 in. apart.

The specimens were placed in the conditioning chamber, unrestrained on a flat surface, which was dusted with talc to reduce friction. A copper-constantan thermocouple was inserted into one of the specimens to measure the specimen temperature during the test. The temperature of the chamber was lowered to −60 °F and then cycled from −60 to 140 °F and back down to −60 °F.

TABLE 1. *Materials used for specimen preparation*

Bitumens	ASTM Specification
Asphalt	D312–44
Coal-tar pitch	D450–41, type A
Reinforcing felts	
Felt, organic, asphalt-saturated, 15 lb	D226–60
Felt, asbestos, asphalt-saturated, 15 lb	D250–60
Felt, organic, coal-tar saturated, 15 lb	D227–56
Felt, glass fiber, asphalt-saturated, 8 lb	D2178–63T, type I

At 10 °F increments during the cycle while the specimens were in the chamber, the distance between the reference plugs was measured to the nearest ten-thousandth of an inch using a Whittemore Strain Gage, as shown in figure 4. The variation of specimen temperature during the period when the measurements were made was minimal due to the large mass of the conditioning chamber.

The temperature limits and the cycling procedure used in this program were based on previous work conducted at the National Bureau of Standards [5]. However, the apparent linear expansion coefficients were calculated from the data obtained over the range from 30 to −30 °F since it was believed that this was a realistic temperature range for roofs exposed in many areas where splitting failures have occurred.

5. Results

The averaged results, expressed as the apparent linear thermal expansion coefficient of felts and of the composite membranes obtained both "in the machine" and "across machine" directions, are shown in tables 2 and 3, respectively.

The results obtained compare favorably with previous results of thermal movement of composite built-up membranes in the machine direction [5].

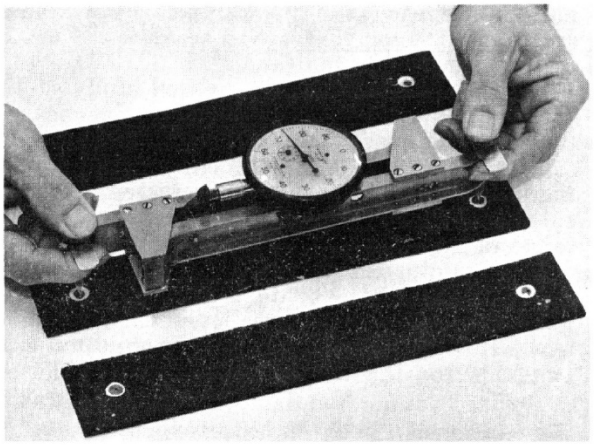

FIGURE 4. *Thermal movement measurement technique.*

TABLE 2. *Apparent linear thermal expansion coefficient of roofing felts*

(Temperature range 30 to −30 °F)

Description	Expansion coefficient per °F	
	With machine	Across machine
Felt, organic, asphalt-saturated	6.3×10^{-6}	13.3×10^{-6}
Felt, asbestos, asphalt-saturated	6.3×10^{-6}	13.0×10^{-6}
Felt, glass fiber, asphalt-saturated	14.5×10^{-6}	18.2×10^{-6}
Felt, organic, coal-tar-saturated	6.5×10^{-6}	15.2×10^{-6}

TABLE 3. *Apparent linear thermal expansion coefficient of built-up membranes*

(Temperature range 30 to −30 °F)

Description	Expansion coefficient per °F	
	With machine	Across machine
Asphalt—asphalt-sat. organic felt	10.9×10^{-6}	20.8×10^{-6}
Asphalt—asphalt-sat. asbestos felt	8.3×10^{-6}	20.3×10^{-6}
Asphalt—asphalt-sat. glass felt	18.1×10^{-6}	26.1×10^{-6}
Coal-tar pitch-coal-tar-sat. organic felt	19.4×10^{-6}	29.4×10^{-6}

6. Summary and Comment

The data reported in this paper show that the thermal movement of the composite membrane is larger than that of the felt from which it was constructed but less than that reported for similar bitumens used in the construction of built-up roofs [7]. Further, the data show that the apparent coefficient of linear thermal expansion obtained in the across machine direction is appreciably greater than that obtained for in the machine direction. Data obtained in a previous program [5] showed that bituminous built-up membranes undergo greater thermal movements than most other components of a roof system at subfreezing temperatures and that the thermal movement is not linear with temperature but increases as the temperature is decreased.

Investigations, by the author, of splitting failures due to membrane shrinkage over a period of 7 years on roofs protecting structures throughout the United States have revealed some factors which appear common to this type of failure, as follows:

1. The failures were most common in bituminous built-up membranes placed over substrates having high thermal insulating values.
2. The splitting generally occurred parallel to the machine direction of the felt.
3. The splits often coincided with long unbroken joints between the insulation boards. Seldom did they occur over staggered joints.
4. The incidence of splitting failures was much greater in the colder climates and the failures were frequently reported following periods of extremely cold weather with little or no snow cover.
5. The roofs having large areas which were infrequently broken by expansion joints were more susceptible to splitting and membrane shrinkage failures than roofs of smaller area.

These observations would certainly suggest that thermal shrinkage of the membrane may be involved in such failures.

It has been demonstrated experimentally that bituminous built-up roof membranes placed over insulation were subject to greater temperature fluctuations [3], and as a consequence, greater thermal movement [5] than similar membranes placed over other substrates. Further, it appeared to be more than coincidental that splitting failures in the membrane occurred more frequently parallel to the machine direction of the felt since the results of laboratory measurements given here establish that the thermal movement was larger in the "across machine" direction. Further, the strength of the composite membrane has been reported to be considerably less in this direction [6].

When a bituminous built-up membrane is subjected to a temperature change of 60 °F (+30 to −30 °F), it can contract as much as 0.18 percent as calculated from the data reported herein. Further, it has been demonstrated experimentally that a similar membrane has a breaking strain of 0.45 percent at −20 °F [6]. Therefore, it appears safe to assume that if the roof membrane were free to move, no splitting failure would occur from thermal movement in the membrane alone. On the other hand, if the membrane were solidly adhered to the substrate (as it will be in many cases), except for small areas over the unstaggered joints, it is conceivable that the cumulative movement resulting from the thermal shrinkage of the membrane and movement between units of the substrate may produce a stress concentration in the membrane over a joint of sufficient magnitude to cause rupture.

The thermal expansion coefficient of bituminous roofings increases as the temperature decreases [5]. Therefore, such membranes are especially susceptible to thermal shrinkage when exposed in cold climates.

The data regarding the thermal and strength characteristics of bituminous built-up roof membranes obtained in this and similar programs in other laboratories will prove useful in explaining and predicting the performance of built-up roofing systems during exposure. Further, it is believed that a better understanding of the fundamental factors involved in roofing performance may lead to changes in conventional practices of the built-up roofing industry regarding roof application and, thereby, increase the life of the roofing.

7. Suggestions

The data obtained during the investigation as well as the observations of splitting and shrinkage failures in the field suggest that thermal movement of the built-up roofing may be involved. The question, therefore, arises as to the precautions that can be taken to avoid or reduce the incidence of these failures. The alteration of the basic properties of bituminous roofing materials to overcome the effects of thermal movement is not economically feasible. However, the initiation of certain changes in standard roof design and roofing procedures based on data obtained in the studies of the engineering properties of roofing materials should prove helpful in preventing premature roofing failures involving splitting and membrane shrinkage. It is with that intent that the following suggestions are made:

1. The intelligent use of expansion joints in the roofing membrane (not structural joints) will reduce the incidence of failure due to thermal shrinkage of built-up membranes. The spacing of joints would vary with the climate to which the roof is exposed. The average January (Northern Hemisphere) temperature may be used as a guide to establish spacing of expansion joints.

2. When the use of insulation between the roof membrane and the roof deck is necessary, as it will be in the majority of the cases, the joints between the insulation boards should be taped. This practice will serve to eliminate areas of stress concentrations over the joints between insulation boards. It is interesting to note that at least one major roofing manufacturer has recommended this practice for a number of years.

3. The insulation should be applied to the deck so that the longitudinal (continuous) joint is parallel to the short dimension of the roof, while the roofing felts should be applied parallel to the long dimension of the roof and perpendicular to the longitudinal joints of the insulation. This practice would use the greater strength of the reinforcing felts "in the machine" direction to advantage while reducing the potential stress concentrations over joints due to the greater thermal movement of felts in the "across machine" direction.

4. The adhesive bond between the roof membrane and the substrate should be of optimum strength, i.e., strong enough to hold the membrane in place under conditions of exposure (wind uplift, etc.), but sufficiently distributed on finite areas of contact to permit the distribution of strains over larger areas of the membrane in the event of thermal shock. A requirement for spot, sprinkle, or strip mopping in lieu of solid mopping would serve to accomplish this end. The use of a laminated base sheet, in which both the elongation of the respective laminants and the strength of the adhesive bond between laminants could be controlled, may also produce the desired effects.

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8. References

[1] F. A. Joy, Better Building Report No. 5, College of Engineering, The Pennsylvania State University (Sept. 1963).
[2] D. E. Brotherson, Research Report 61–2, Small Homes Council—Building Research Council, University of Illinois (1961).
[3] W. C. Cullen, W. H. Appleton, The Construction Specifier **16,** 5, 35 (Oct. 1963).
[4] R. D. Marquis, Bulletin of Midwest Roofing Contractors, Vol. VII, Issue 1 (June 1963).
[5] W. C. Cullen, NBS Tech. Note 231 (1963).
[6] P. M. Jones, ASTM Symposium on Recent Research on Bituminous Materials (June 1963).
[7] Herbert Abraham, Asphalt and Allied Substances **IV,** 169 (1962).

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