MEMBRANE INTEGRITY DEPENDS ON CHARACTERISTICS OF ENTIRE ROOF ASSEMBLY

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I. ABSTRACT

Membrane splitting ranks second in frequency only to blistering among the major premature roof problems, which afflict about 9% of the nation's applied roofs.[1] Moreover, splitting is a more serious failure mode than blistering, for it generally results in early, if not immediate leakage.

Our investigation of membrane splitting has revealed a complex of contributing factors, a refutation of the common tendency to attribute splitting failure entirely to membrane defects. This paper accordingly has a dual purpose:

1. to show how different roof-system components affect membrane splitting resistance.
2. to identify low-cost safety features that can reduce splitting risk.

As key conclusions from this study, membrane-splitting resistance can be dramatically improved via the following low-cost techniques:

- Use of mechanical fasteners, not hot-mopped asphalt (or cold adhesives) to anchor insulation boards to steel decks.
- Use of more rigid deck (especially important for steel decks)
- Use of Type I or Type II asphalt for membrane interply moppings, not Type III asphalt.
- Specifications of four-ply instead of three-ply (or worse yet, two-ply) membranes.

II. PROBLEM SOURCES SUGGESTED BY NRCA PROJECT PINPOINT

Information supplied by member contractors to the National Roofing Contractors Association (NRCA) on the type of roofing systems being installed (called "baseline" data) and on "problem jobs" encountered is called Project Pinpoint. The effect of various elements of the entire roofing assembly on the integrity of the membrane is indicated by the ratio of problems-to-baseline for any given assembly specification. Our analysis of roof assemblies involving asbestos membranes indicated that membrane splitting was dependent on the following variables:

1. Deck type and deflection characteristics.
2. Insulation anchorage technique.
3. Number of felt plies in membrane.
4. Type of mopping asphalt used in membrane.

1. **Deck type** significantly affects membrane splitting. Figures 1 and 2 show the importance of deck type and metal deck spans for all membrane types. Here are the major findings:

- Frequency of membrane splits is 3-3½ times as great over metal decks as over wood decks, for all membrane types.
- Frequency of membrane splits increases almost fourfold when roof spans exceed 6 ft., for all membrane types.
- Deck type has much more impact on the incidence of splitting than membrane type.

Roof deck designers and general contractors or deck subcontractors must accept a major share of responsibility for membrane splits over marginal-quality decks.

2. **Insulation anchorage technique** has a big impact on membrane splitting, as indicated in Fig. 3a.

Frequency of membrane splits is 3.3 times as great with hot asphalt attachment of insulation as with mechanical attachment (Figure 3a). Use of mechanical fasteners is the most economical way to minimize roofing splitting. Their use over the entire roof, not just the perimeter, is recommended, especially in colder climates.

3. **Number of felt plies** has an important effect on membrane splitting (see Fig. 3b).

Frequency of membrane splits is 2.8 times greater on 3-ply roofs than on 4-ply roofs (figure 3b). Although 3-ply roofs have proven successful on many jobs, their use is not recommended over marginal decks.

40% of all asbestos roof splits reported in Project Pinpoint had only 2 plies. Use of 2-ply roofs is not recommended.

4. **Type of mopping asphalt** is also important (see Fig. 3c).

Frequency of roof splits is 60% greater with Type III asphalt than with either type I or Type II asphalt (Figure 3c). Use of Type III asphalt on low-slope roofs (½ in./ft or less) in the northern portion of the United States should be avoided.

Although data are excluded from this report, Project Pinpoint showed that the use of Type III asphalt had an even more adverse effect on roof problems other than splitting. Compared with the best overall performance achieved with Type II asphalt, other grades showed the greater percentages of roof problems:

- Type I - 4% more problems
- Type III - 127% more problems
- Type IV - 308% more problems

III. EXPERIMENTAL STUDIES ON ATTACHMENT OF ROOFING COMPONENTS

To resist thermal and mechanical stresses while it acts as an effective moisture barrier, a BUR membrane must be properly attached to the insulation and substrate assembly. Regardless of physical size or generic specification, all BUR system assemblies depend on reliable attachment.

Asphalt serves a two-fold purpose in the roof system assembly, acting both as waterproofing agent and adhesive. Consequently, effective attachment of the roof system assembly depends on the asphalt layer providing adhesion. Lack of attachment can result in membrane splitting, just as lack of felt adhesion because of improper asphalt viscosity can originate membrane blisters.

There is a crticial need to study attachment since attachment can only be made during the very short time span of construction, while its obligation to the roofing system lasts as long as the waterproofing function. The objective of this experimental work was to study the mechanism of attachment by asphalt adhesive.

Previous studies [2,3] have identified cold-weather construction (below 40°F) of BUR systems as critical because of asphalt cooling rate. Rapid cooling of Type III asphalt (ASTM D312-78) was determined; the data indicated a temperature decay time of eight to twenty seconds for hot asphalt to drop to 200°F when applied to steel decks.

Laboratory-produced membrane splits, with a preload applied to simulate accumulation [4], showed that a membrane and insulation board, when unattached to a deck, will split in the identical fashion (over a butt joint, bottom ply first) as found in actual roof splits in the field. Samples of a 32-year-old weathered membrane, showing little relaxation, experienced a higher temperature-induced load in this test. Therefore, for this aged embrittled membrane, **uniform** attachment of the membrane and insulation system was needed to withstand successive thermal strain cycles.

The objective of the current research program was to:

1. Verify and add additional data to the existing field measurements on rate of asphalt cool-off.
2. Assess the effect of asphalt cooling rate on proper attachment of rigid board insulation to steel deck.
3. Identify a practical and useful alternative method for achieving insulation board attachment if adhesion by hot asphalt was found questionable.

To assure general validity, this research program required different job-site conditions and work crews wherever possible along with extensive laboratory work.

Study Results

Among the known determinants of asphalt cooling rate are application temperature, quantity of asphalt, ambient air temperature, the respective thermal conductivities of the substate and roofing materials, wind velocity and solar conditions. Field measurement of asphalt cooling rates have found all of the above variables occurring either simultaneously or intermittently. Researchers have attempted to mathematically characterize the factors influencing asphalt cooling rate during construction. Because the parameters are difficult to separate in the real world of BUR construction, it was decided to conduct further experimental investigations, both in the field and laboratory, wherein all factors influencing attachment could be dealt with, including workmanship.

The field study conducted in 1979 and 1980 confirmed the short period of time available for attachment of BUR systems with hot asphalt. Additional data were generated for cooling variations of wind, solar load, and materials have little overall effect on the cool-off rate during cold weather construction (below 40°F). Essentially a short period of time is available for attachment, especially on steel decks with hot asphalt.

The actual attachment mechanism of insulation board to steel deck as next studied, both in field and laboratory. Horizontal (shear) loads were applied to insulation boards (see Fig. 4). The primary goal: to determine what horizontal attachment strength and stiffness an insulation board offered to a BUR membrane (see Table 1 for test results).

Variations in an adhesive asphalt quantity can produce a six-fold difference in attachment strength. An attempt was made to use 12-15 lb/square, but control of this parameter was difficult. Therefore, after each board was pulled, actual adhesive contact area was determined. Light mopping usually produced low shear strengths, while heavy moppings produced high strengths. Mechanically attached boards attained only one-third of the shear strength that heavy asphalt mopping produced, **but** the mechanically attached boards are far more consistent in strength.

Actual shear attachment behavior for 1 in. perlite board (2 ft. x 4 ft.) is shown in Figure 5. Twenty-five laboratory tests form the basis for the plot. The effect of different asphalt types, different asphalt temperatures at which the board is placed, and different quantities of asphalt were studied. Test averages in each category were used in this plot.

The results of the horizontal shear tests indicate that ultimate load and ultimate deflection are directly related to the quantity of asphalt used or the asphalt-to-insulation board contact area. The board attachment properties in shear are unaffected by using different asphalts or placing the board at various asphalt temperatures, because all failures occurred in the insulation rather than in the asphalt or at the deck-asphalt interface. Since the deck-asphalt shear strength was greater than the insulation-asphalt shear strength, the effect of different asphalt properties do not affect these test results.

Judged by the results of Table 1 and Figure 5 regarding ultimate shear strength versus ultimate horizontal deflection, perlite boards with light or medium moppings cannot withstand much horizontal movement (less than 0.15 in.). However, average horizontal deflection of the mechanically attached boards (with screw-type anchors) as 0.88 in. Mechanically attached boards (as tested) offer consistent shear strength and more horizontal flexibility than asphalt adhered insulation boards. Furthermore, in view of Factory Mutual Class I asphalt usage limitations (12 lb/sq.) and the available asphalt cool-off time in cold weather construction, the results of Figure 5 indicate mechanical fasteners should be used. Substantial attachment requires heavy moppings (as they relate to ultimate horizontal deflection or movement) of the board under shear load.

Since horizontal shear capacity was linearly proportional to contact area (asphalt-to-insulation) the ultimate shear capacity of perlite was calculated at 5 psi horizontal shear strength when attached by asphalt to a steel deck. Contact temperature and type of asphalt do not directly affect this shear strength. However, the attachment of an insulation board to a steel deck is affected by the cooling rate of asphalt, since rapidly chilling asphalt experiences a loss of flowability across the steel deck. Therefore, unless each individual insulation board is walked in with a vertical load, rapidly cooling asphalt may congeal and not spread out underneath the board of increase the asphalt to insulation board contact area. Moreover, the viscosity of the particular asphalt being used can directly affect the flowability of the cooling asphalt.

Insulation boards attached with hard asphalt can be disbonded through vertical loading. In laboratory studies undertaken to determine the effects of wheel loads, impact and foot traffic, audible fracturing of asphalt could be heard. Examination of individual insulation boards revealed that impact loading (e.g. dropping a roll of felt) can begin to disbond an insulation board at the edges. This disbondment due to vertical load was characterized by a failure at the asphalt-steel deck interface, and not at the asphalt-perlite interface. Therefore, construction loads on light gauge, long-span steel decks can break loose properly bonded insulation boards. If mechanically fastened (screw-type) methods are used, vertical disbondment is virtually impossible.

Finally, the effect of asphalt type on attachment strength was studied. Horizontal shear strength (for a board undamaged by vertical load) was found to be unaffected by asphalt type. The type of asphalt (hard vs. soft) becomes a factor when a board is loaded vertically by gravity loads, etc. To study the effect of vertical loading on the asphalt-to-deck interface, a split beam test as developed (Table 3). Judged by the test results, Type III asphalt can tolerate only one-fourth the load deflection that Type II asphalt can tolerate, both a 73°F and 20°F.

In summary, mechanical anchoring of insulation boards during cold weather construction is recommended. Attachment by Type III asphalt can be successful (for horizontal shear strength) in helping to restrain the BUR membrane, provided no vertical load damages the asphalt bond. Since this cannot be guaranteed, mechanical fasteners (screw-type) provide the most dependable attachment.

IV. THE ROLE OF STRAIN ACCUMULATION AND CONCENTRATION IN MEMBRANE—SPLITTING FAILURE

Membrane strength is generally overrated as a factor in membrane splitting. Preliminary membrane strength criteria were proposed by Mathey,[5] but the function of a membrane is not to provide strength to hold a building together, and the proposed criteria fail to account for the many membranes with less strength that have provided many years of successful performance even in very harsh climates. Membrane function and integrity are more realistically associated with **strain**. In 1966 Jones[6] reported that the breaking strain of all types of built-up roofing membranes was 2% or less at low temperatures (0°F to −40°F). Proper design and construction of the entire roofing assembly is required to prevent membrane splitting.

Although stress and strain are interrelated and cannot be completely separated, strain relationships are easy to visualize whereas stress relationships usually required calculation to be understood. Roof splitting mechanisms fall into two seemingly contradictory categories of "too much attachment" and "insufficient attachment" involving strain accumulation and concentration phenomena.

A. Strain Concentration — "Too Much Attachment"

In moisture-sensitive decks, e.g. wood, drying-induced shrinkage exceeds membrane movement, and the differential strain concentrates at a joint in the substrate. Solid mopping a membrane to an uninsulated wood deck (figure 6a) will cause splitting.

Koike[7] developed a mathematical relationship showing the crack-bridging capability of built-up roofing proportional to the product of membrane strength and membrane elongation. The illustration in Figure 6a assumes that the 8 in. wide wood decking installed with 1/16 in. joints experienced a typical 3% drying shrinkage, widening the deck joint to 5/16 in. A solidly mopped membrane would have to stretch 400% to accommodate this deck-joint expansion. Neither conventional built-up membranes nor the new modified asphalt roofing products have this elongation capability.

Proper membrane attachment is required to prevent membrane splitting. **Uniform, controlled** attachment is easily achieved with a nailed base sheet. The illustration in Figure 6b assumes a nail spacing of 22 in. across the felt. The base felt nail spacing lessens the net deck shrinkage movement by more than 50% because nail location does not correspond to board joints where deck movement is greatest. In addition, this lesser deck strain is distributed over a 22 in. width of membrane. Thus, the membrane is required to stretch less then 1/2%, which it is able to accommodate. Our industry does not attach built-up roofing to wood decking with nails merely because nailing is convenient. It is done because of the absolute necessity to distribute strain and prevent splitting.

B. Strain Accumulation — "Insufficient Attachment"

Membrane splitting over moisture stable decks, e.g. steel involves strain accumulation producing strain concentration.

In his analysis of the strain-accumulation mechanism of splitting, Turenne[8] recommends that all components of a roofing system must be attached uniformly and securely. Unfortunately, from a practical roof application viewpoint proper attachment to steel deck is not easily or consistently achieved with either hot-applied or cold-applied adhesives. Most roofs achieve, at best, a combination of loosely laid and adhered areas side by side. Attachment difficulties with steel deck are even evidenced by high insurance wind losses when perimeter nailing is omitted.

The illustration in Figure 7a assumes that an 8 ft. section of insulation is not attached to the steel deck. With the 37.5×10^{-6}/°F coefficient of expansion-contraction reported by Mathey[5] for an asbestos membrane in the cross machine direction, the 8 ft. section of membrane segment in the unattached area would want to shrink 1/8 in. with a temperature from 0° to −30°F.

The illustration assumes that the membrane is attached to the insulation, which reinforces it and restricts movement except over the insulation joint. Therefore, the strain accumulation concentrates over an insulation joint near the end of the unattached segment, and this strain concentration then acts just as shown previously with the wood deck illustration. If we assume that the insulation was installed with a 1/16 in. wide joint, the 1/8 in. strain accumulation at this joint would require a membrane with 200% elongation in this localized area to prevent rupture.

Mechanical attachment of insulation over the entire roof area, and not just around the roof perimeter, is the most practical way to provide needed **uniform, controlled** attachment on a steel deck, especially during cold weather roof application. The use of mechanical fasteners (Figure 7b) assures that no insulation board is unattached and, thus, strain can not accumulate. The thermal strain from a 30°F temperature drop and 37.5×10^{-6}/°F coefficient of expansion-contraction is approximately 0.1% and well within the elongation capability of a conventional built-up roofing membrane. Although this small amount of strain is added to mechanically induced strain, the principal cause of roof splits on roofs with proper attachment is due to membrane deflection from roof loading, especially over substrates with inadequate rigidity to provide membrane support.

C. Strain Relief

Davis[9] has inadvertently shown the importance of strain, rather than stress, as the principal roof splitting mechanism. The data in Figures 1 and 7 of Davis' paper on cold-applied built-up roofing show that it takes 3 to 5 years of exposure on a roof to evaporate enough solvent out of the roofing to reach a membrane tensile strength at 0°F of 200 lb./in. (the preliminary performance criteria level proposed by Mathey[5] to resist roof splits). Obviously, the cold-applied membranes described by Davis[9] would have failed during the first few years of service if the 200 lb./in. strength criteria were meaningful. On the contrary, cold-applied built-up roofing has a relatively low incidence of splitting problems.

Use of the softest asphalt commensurate with roof slope and climate has been considered good roofing practice for years. Hard, brittle bitumens do not provide strain relief. Warford[10] observed that Type I[11] asphalt has eight times as much elongation at 77°F as Type III[11] asphalt. The 77°F and 32°F penetration values of a bitumen are a better indicator of its brittleness than the softening point. Unfortunately, built-up roofing asphalt used in the United States has the dubious distinction of being lower in penetration and more brittle than asphalt used in Europe. Recently, there has been a trend toward using the less brittle polymer-modified asphalts, but they are much more expensive and have unproven long term, weatherability. Softer grade (Type I and II)[11] conventional asphalt can provide necessary strain relief on most roofs unless the deck construction is of marginal quality.

V. CONCLUSIONS AND RECOMMENDATIONS

NRCA Project Pinpoint roof performance survey data and experimental studies of insulation attachment methods show that the quality of the entire roofing assembly has a large effect on long term membrane integrity. The importance of substrate rigidity, including the deck, is apparent from the relatively high incidence of problem roofs encountered with steel decks, especially as spans increase beyond 6 ft.

Uniform, controlled attachment of all roofing components is important to accommodate strain limitations of all conventional built-up roofing membranes. Mechanical fastening of insulation over the entire roof, and not just the perimeter, is recommended on steel deck, at least during cold weather application. Unnecessary use of hard, brittle mopping asphalts increases the risk of roof performance problems.

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11 ***ASTM D312-78.***

Attachment Method	# of Boards Tested	Low Load (lb.)	High Load (lb.)	Ave. Load (lb.)
Hot Asphalt	25*	560	3670	1800
Screw-Type Fasteners	4**	960	1160	1025

NOTE: *All boards 2 × 4 ft. in size—1 inch perlite
**All boards 3 × 4 ft. in size—perlite/urethane foam composites, C = 10

TABLE 1
Ultimate load summary.

	Contact Area	Quantity of Asphalt
Light Mopping	0—2 ft. ^{2}	0—7.5 lb./100 ft. ^{2}
Medium Mopping	2—4 ft. ^{2}	7.5—15.0 lb./100 ft. ^{2}
Heavy Mopping	4—5.7 ft. ^{2}	15.0—21.4 lb./100 ft. ^{2}

TABLE 2

Asphalt Type	Test Temperature 73°F	Test Temperature 20°F
ASTM D312-78 Type II	4.5 in.-lb.	0.8 in.-lb.
ASTM D312-78 Type III (Hard)	1.2 in.-lb.	0.2 in.-lb.

TABLE 3
Total strain energy from split beam test.

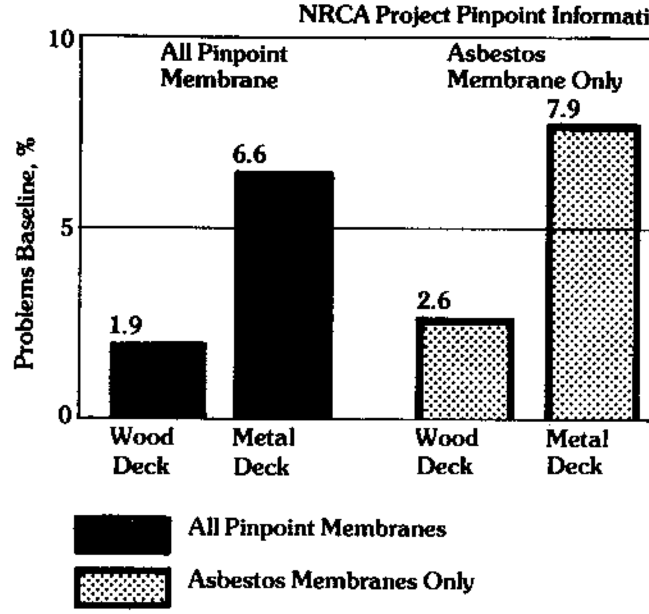

FIGURE 1
Deck type affects roof splits.

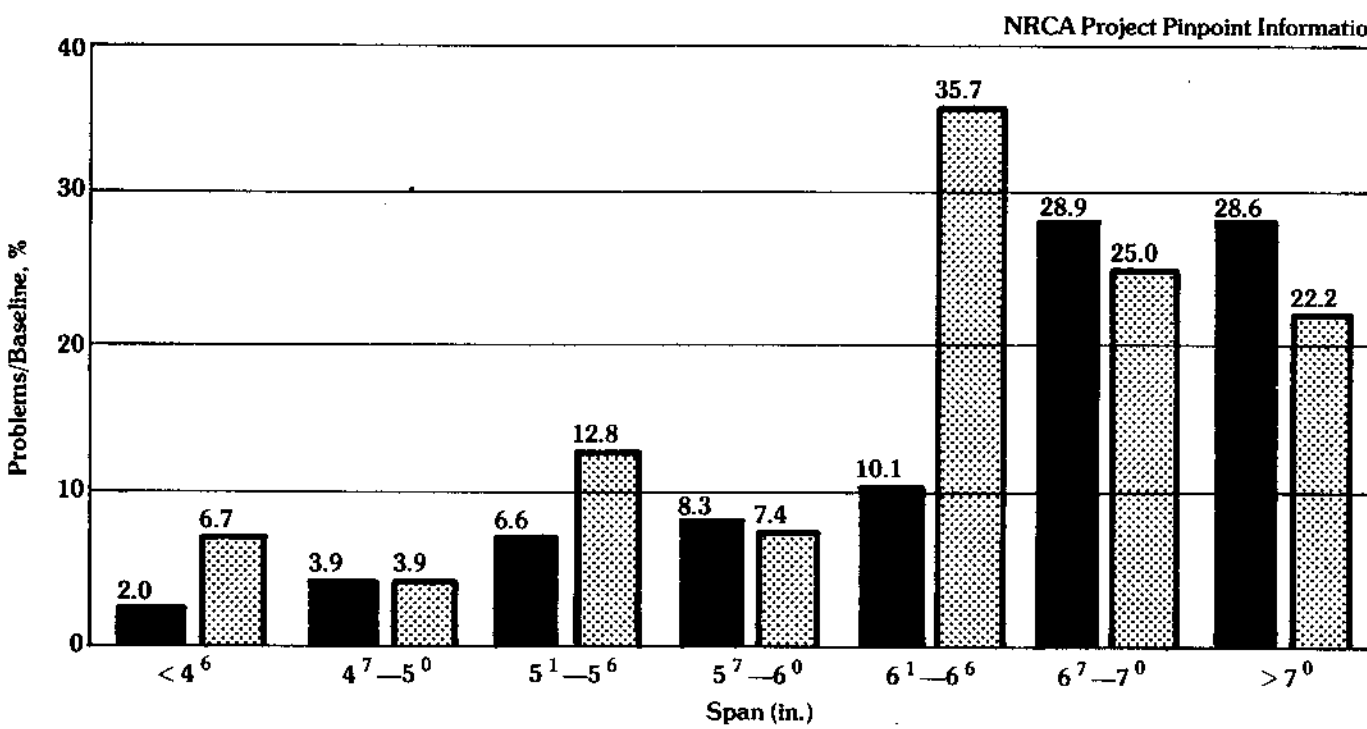

FIGURE 2
Metal deck span has major effect on roof splits.

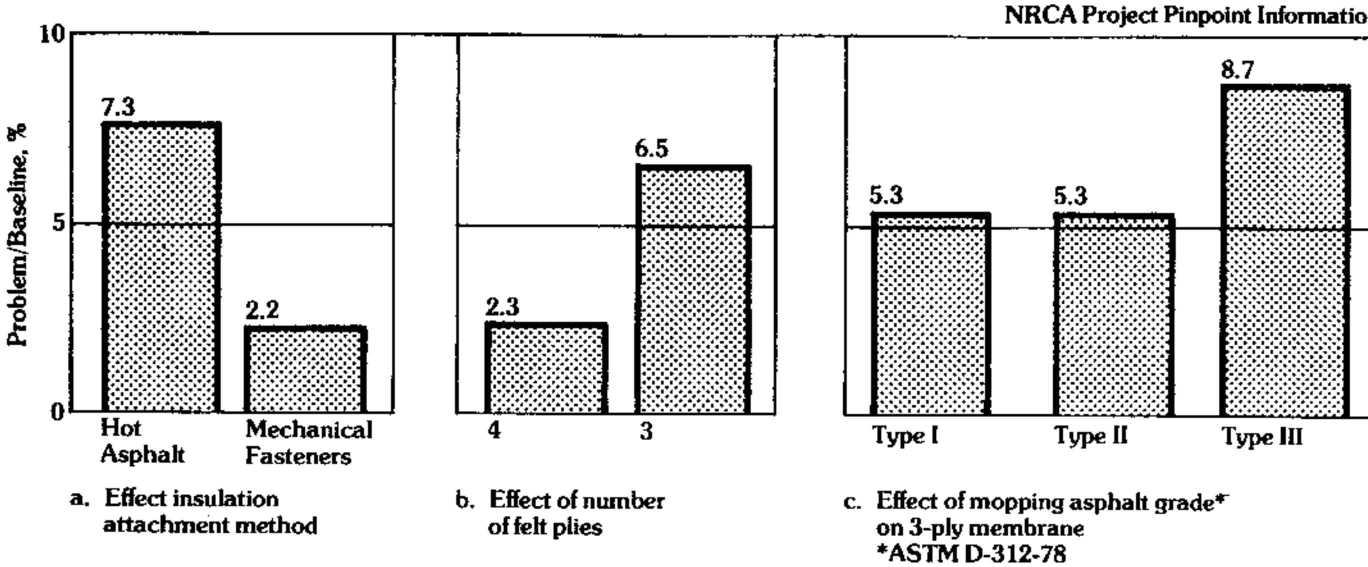

FIGURE 3
Influences on asbestos membrane splits.

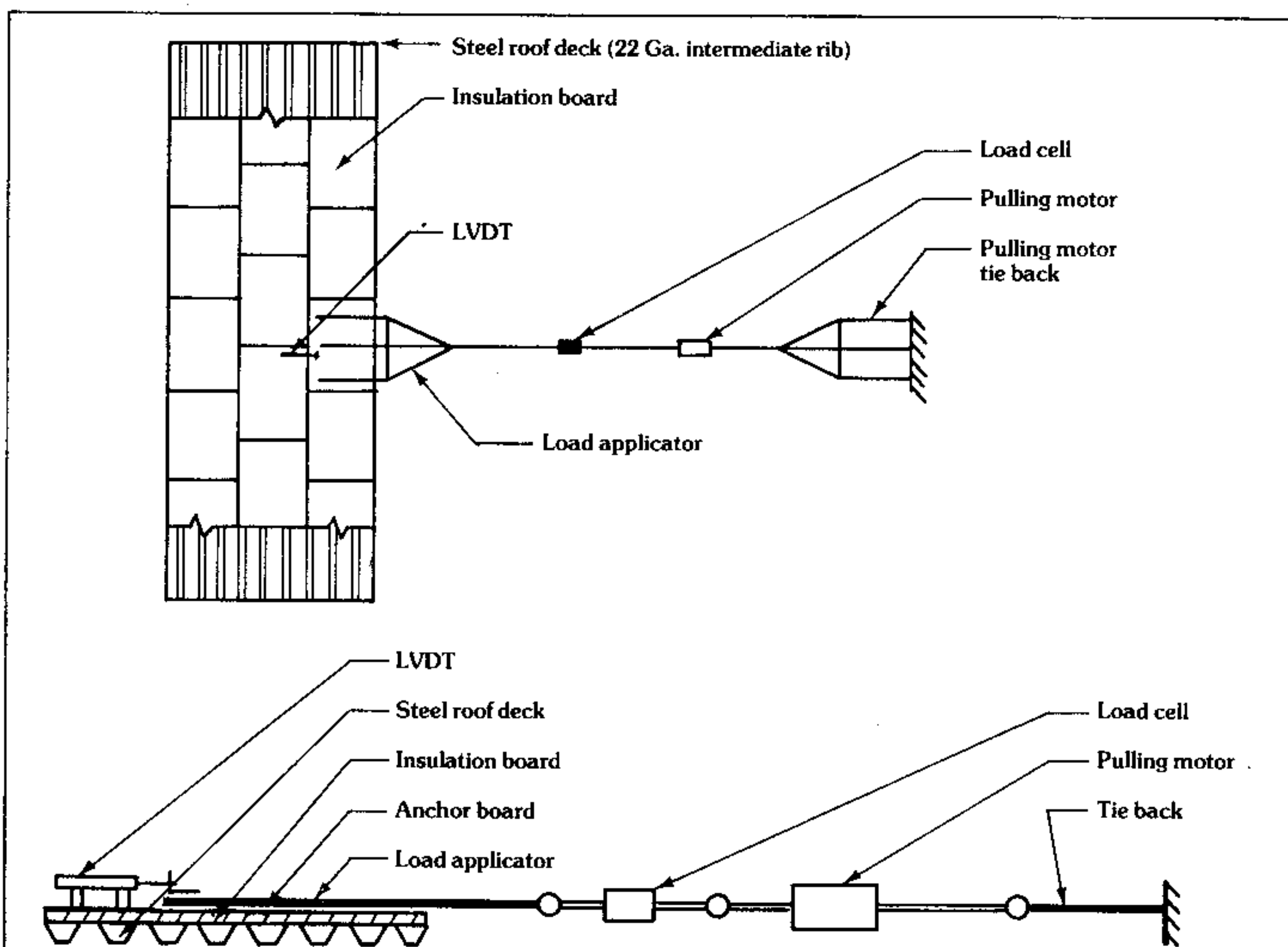

FIGURE 4
Horizontal shear test apparatus.

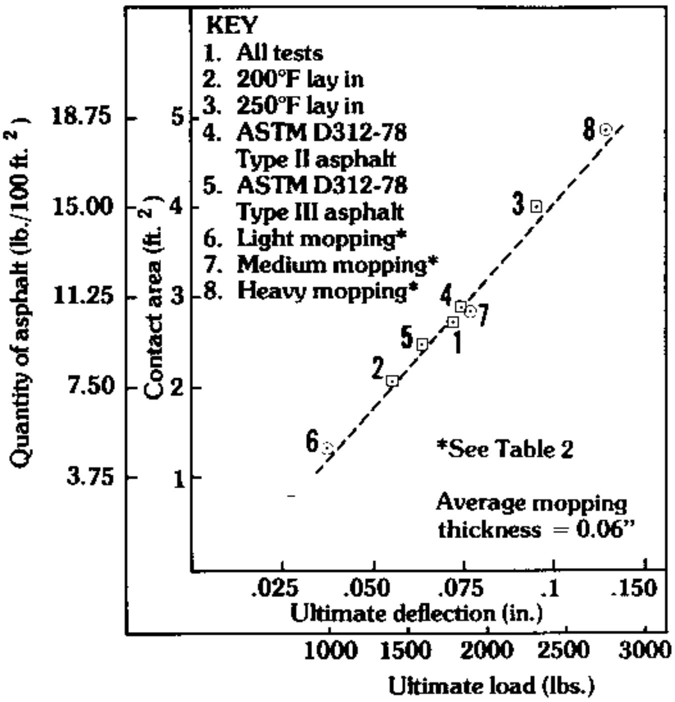

FIGURE 5
Load-deflection versus quality of asphalt for 1" perlite insulation board attached to 22 ga. deck from horizontal shear test.

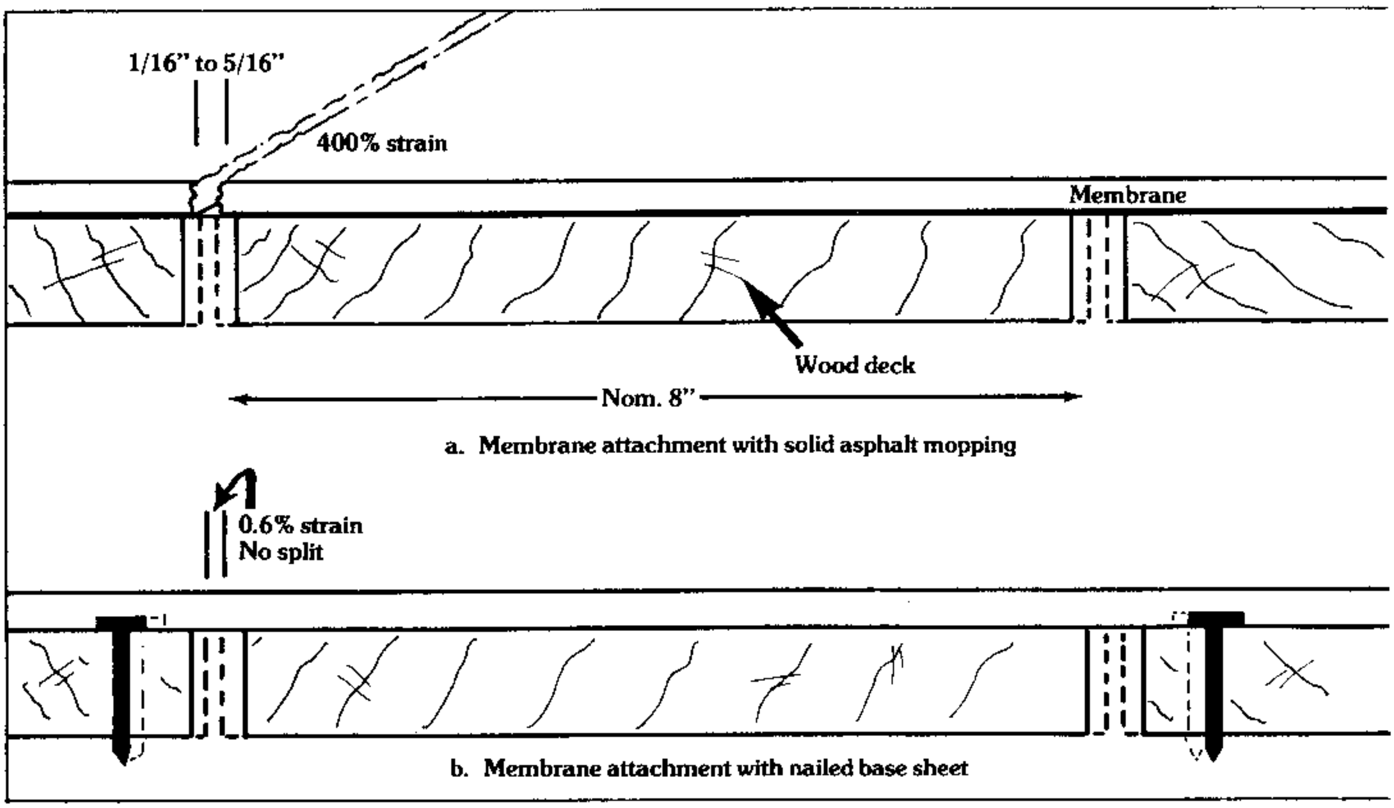

FIGURE 6
Strain concentration in roofing membrane.
Uninsulated wood deck (3% shrinkage).

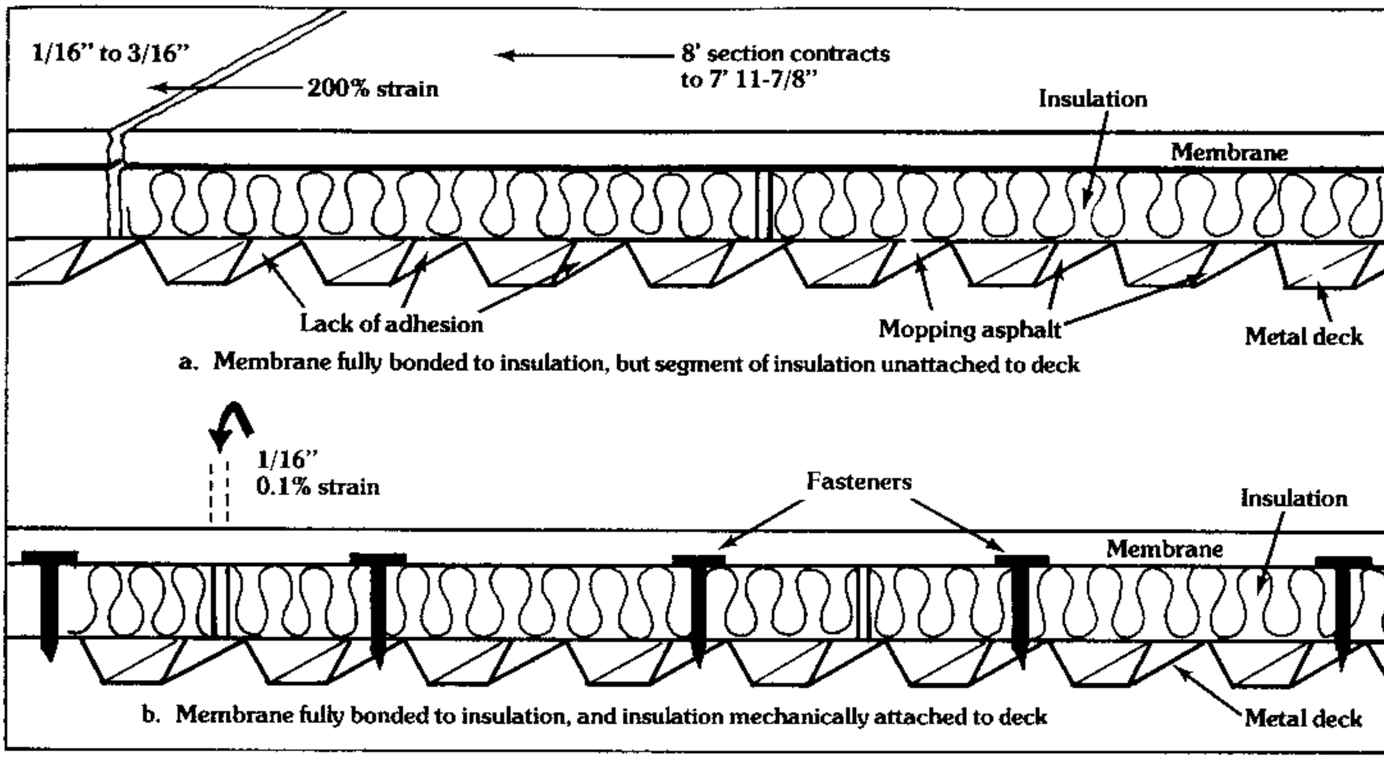

FIGURE 7
Strain accumulation in roofing membrane (30°F temperature drop). Insulated metal deck.