SOME OBSERVATIONS ON THE BEHAVIOUR OF BUILT-UP ROOFING MEMBRANES OVER EXPANDED POLYSTYRENE IN THE U.K.

J. R. Carver
John Laing Research & Development Limited, Boreham Wood, Hertfordshire, England

ABSTRACT

Investigation of built-up membrane failures of systems with expanded polystyrene insulation produced no physical evidence that the expanded polystyrene insulation was responsible for splitting or ridging of the failed membranes. This conclusion contradicts a widely prevailing view, held especially in North America, that movement of polystyrene insulation causes membrane splitting. An analysis of membrane splitting and ridging in a number of failed BUR membranes in the British Isles indicates that their defects were caused by stresses generated within the membrane.

1. INTRODUCTION

Expanded polystyrene insulation in beadboard and extruded form has been widely used in flat roofs in the U.K as a convenient and economical means of providing a high standard of thermal insulation. A typical build-up consists of insulation boards 25-50 mm thick, bonded to a substrate of plywood, softwood boarding, or troughed metal deck, with or without a vapour barrier, and a membrane consisting of three layers of bituminous felt partially or fully bonded to the surface of the polystytrene. A typical method of partial bonding consists of narrow ribbons of hot poured bitumen applied to a granule-coated base layer. A method of full bonding using a base sheet coated with low melt bitumen has also been used to overcome the heat sensitivity of polystyrene.

The use of polystyrene insulation was approved in the British Standard Code of Practice for Built-up Felt (CP.144.1968) and roofs of the kind described were used in many types of buildings during the late 1960's and early 1970's. Problems of leakage associated with splitting of the membrane occurred. The present recommendation by the Felt Roofing Contractors Advisory Board is that expanded polystyrene should only be used if it is pre-felted and overlaid with fibre insulation board.

Investigations by others postulated that movement of the polystyrene insulation was the chief factor in splitting. Calculations were produced[1] to show that cyclic movements of the insulation could initiate splits in the lowest layer of the membrane immediately over joints in the insulation. Test methods involving cyclic movement of the substrate were claimed to produce realistic splits in membrane samples[2]. Much of the literature on the subject of splitting related to experience in countries other than the U.K., notably North America[3-9], where there are significant differences in climate.

To obtain more objective evidence of membrane defects in the U.K., in particular where extruded polystyrene insulation had been used, a series of investigations of reported membrane failures was carried out during 1976. These involved a variety of buildings sited in different parts of the country and mostly completed between 1967 and 1973. To keep the size of the problem in perspective, the proportion of roofs where serious problems have occurred is estimated at about 3%. All the roofs were of lightweight construction with metal or timber decks. Observed defects in membranes included splitting, ridging, impact damage, blistering and wind uplift, several roofs having more than one of these defects.

2. CASE STUDIES

The following case studies, grouped according to the type of membrane used, cover observations considered to have a particular bearing on the problem of splitting and ridging of membranes.

2.1. Fully Bonded Membranes with Mainly Organic Fibre Reinforcement.

2.1.1. Three flat roofed terraced houses were built in 1967 using a proprietary timber framed system with plywood deck laid to falls. The build-up consisted of 25 mm extruded polystyrene bonded to the deck with fully bonded glass fibre based first layer and two layers of organic fibre based bituminous felt with mineralised surface finish. Leaks were reported in the roof of one dwelling and it was understood that these had been traced to a long split in the middle of the roof and short splits near the perimeter. This part of the roof had been resurfaced before our inspection was made.

Several long splits about 2 mm wide were found to be confined to the top layer of felt at overlaps, indicating shrinkage across individual widths of felt and slippage between the top and second layer. A piece of the membrane was removed and the split was found not to be coincident with joints in the polystyrene insulation.

2.1.2. The roof of a community centre completed in 1973 consisted of a plywood deck laid to falls with bituminous felt vapour barrier and 25 mm extruded polystyrene insulation, fully bonded. The membrane consisted of a first layer of asbestos based felt, fully bonded to the insulation and two layers of organic fibre based felt, with reflective chippings. Leaks occurred in less than a year and these had been traced to numerous short splits close to the central gutter. The splits were aligned with the runs of felt and in most but not all cases coincided with joints in the insulation. The gutter and splits had been re-felted and treated with aluminum reflective paint in the Spring of 1976. The roof was inspected in June, 1976, when further splits were found. In two cases these proved to be confined to to the top layer of felt (see Fig. 1; although they were over joints in the insulation. Three short splits were found near the gutter in another part of the roof. Examination of the membrane revealed that only two layers of felt had been laid in this area.

The association of all splits with the central gutter was considered significant, although there was no obvious structural cause. The membrane in other parts of the roof appeared to be in good condition.

2.1.3. The roof of a Fire Station was completed in 1973. Owing to contractual problems, the Eastern half of this small roof which contained several large rooflights and a tank house, was insulated with 25 mm extruded polystyrene nailed to the timber deck, while the Western half, completed a few months later, contained no fixtures and was insulated with fibreboard.

Leaks occurred in the Eastern half within a year of completion, although the Western half remained sound. Several splits adjacent to rooflights were repaired in June, 1976. During the inspection which took place in August, 1976, a short split was found at the edge of a repair, between a rooflight and the perimeter upstand. This split was aligned in the machine direction of the felt and was over a joint in the insulation. Two other similar splits were examined; in one of these a nail was found in a joint between insulation boards in such a way as to suggest that any movement of the insulation had been negligible. Examination of membrane samples taken from the Eastern half of the roof showed that only two layers had been applied, although a three layer membrane had been specified.

It was evident that at least one split had formed within a few weeks during unusually dry and warm weather. The association of all splits with narrow sections created by rooflights and the contrasting behaviour of two different build-ups on one roof appeared to be significant.

2.1.4. The roof of a single story hospital ward block was completed in 1973, and leaks occurred within a year. The unsloped softwood boarded deck had 25 mm extruded polystyrene insulation bonded to a loose laid vapour barrier. The original membrane consisted of a first layer of asbestos based felt with two layers of organic fibre based felt fully bonded to the insulation and with mineralised surface. Use of organic felt was reportedly not in accordance with the specification, and a further layer of asbestos based felt had been added in 1975. The membrane subsequently failed again with extensive blistering and leakage.

Several long splits in the remedial felt were found to be coincident with splits in the original membrane which was saturated and rotten, and with continuous joints in the insulation. Blistering had occurred immediately under the remedial felt.

It was evident that a considerable amount of moisture had been trapped within the original membrane when the remedial felt was laid. Some of this moisture had been driven off by solar heating, resulting in blistering and further shrinkage of the original membrane at existing splits. Lack of restraint between the roof build-up and the deck may have contributed to the observed splitting.

2.1.5. A large steel decked factory roof was completed in 1971. 25 mm thick extruded polystyrene insulation was bonded directly to the deck laid to falls and the fully bonded membrane consisted of an underlayer of glass fibre based felt, and two layers of organic fibre based felt with applied mineral chippings. Leaks had occurred mostly in the Northern half of the roof and these were traced to numerous long and short splits in the membrane which were aligned with the machine direction of the felt. Examination of several splits showed that they were situated over continuous joints in the insulation. The splits occurred in groups but there was no apparent relationship with the structure. Examination of a typical split showed that it was developing in the upper layer of the membrane. Numerous small voids were found under the upper layers and the felt was saturated and rotten. A section of the membrane was examined and it was found that the lowest layer of the felt was still intact under the split.

Fissures in the surface caused by alligatoring (see Fig. 2) of the bituminous dressing were noted in the areas affected by splits indicating a possible route for moisture penetration of the membrane.

2.1.6. A large metal decked roof of a cold store was completed in 1971, and included up to 180 mm thickness of extruded polystyrene. The fully bonded membrane consisted of an asbestos felt first layer, and two layers of organic fibre based felt with reflective chippings. The owner became concerned when numerous ridges developed in the membrane, although no leaks were reported in connection with these features. The ridges occurred in both directions, and were typically spaced at two or three board widths, and were mostly situated slightly to one side of joints in the insulation.

Fragments of polystyrene were found adhering to the underside of a T shaped ridge. These fragments were separated by dark bands which suggested that movement between the membrane and insulation had been intermittent. The membrane was in sound condition and unusually thick and heavy.

2.2. **Fully Bonded Membranes with Inorganic Fibre Reinforcement.**

2.2.1. A sports pavillion completed in 1970 was built in prefabricated timber construction with plywood deck laid without falls. The roof build-up consisted of 25 mm extruded polystyrene fully bonded to the deck and two layers of asbestos based bituminous felt, fully bonded to the insulation. The surface of the membrane was treated with a bitumen compound and surfaced with 10 mm of loose chippings. Leaks occurred after three years and were traced to isolated short splits. Attempts to repair these had not been effective and several leaks were found when the roof was inspected. One of these was traced to a short split between the tank house structure and the perimeter. The split was over a joint in the insulation and there was evidence of attempted repairs with a bitumen compound. The location of this isolated split at a change in roof section was considered to be significant.

Some whitish markings were noted on the surface of the membrane in another part of the roof. These were found to coincide with joints in the insulation. Close examination revealed that the markings were caused by silt which had been deposited in slight depressions in the bitumen mop-coat. The membrane was found to be in good condition over these joints.

2.2.2. A large, metal-decked warehouse roof was completed in 1974. Insulation consisted of 25 mm extruded polystyrene laid diagonally and spot bonded directly to the deck. The membrane consisted of three layers of glass fibre based felt fully bonded to the insulation. The Northern half of the roof where most of the leaks had occurred contained numerous large rooflights. Leaks were reported within a year of completion and numerous repairs were noted especially around the rooflights.

A short split parallel with an overlap in the felt was examined and an impact fracture was found in the surface of the insulation directly over a trough in the metal deck. In another similar case the insulation had been completely fractured. Further evidence of impact damage was found in other parts of the roof. None of the splits coincided with joints in the insulation.

A few isolated ridges running across the machine direction of the felt were found near the Eastern perimeter. These features were not associated with joints in the insulation, and were indicative of membrane expansion and relative movement between the membrane and insulation.

2.2.3. A large factory roof completed in 1973, consisted of a metal troughed deck laid to falls with bituminous felt vapour barrier and both 25 and 50 mm extruded polystyrene, some of which was laid diagonally. The membrane consisted of three layers of glass fibre based felt fully bonded to the insulation. Leaks occurred within a year of completion but location was difficult due to the layer of chippings bonded to the surface.

Numerous splits were found in all cases parallel with the machine direction of the felt. In one case a split which was coincident with a joint in the insulation and had been patched earlier in the Summer of 1976 was found to have extended. Some evidence of impact damage was also noted. Laboratory examination of a number of samples indicated a tendency for splits to occur at overlaps within the membrane.

No splits were found in the area where insulation had been laid diagonally, but an isolated ridge was examined in this area near the Western perimeter. The ridge was transverse to the machine direction of the felt and the underside was characterised by smooth polished bitumen with no evidence of previous contact with the insulation (see Fig. 3). Thickening of bitumen between the layers of felt was noted on both sides of the ridge.

2.2.4. A large factory roof completed in 1969, consisted of a troughed metal deck laid to falls with bituminous felt vapour barrier and 25 mm extruded polystyrene, fully bonded. The membrane consisted of three layers of fully bonded glass fibre based felt with a dark mineralised finish. No significant splits or leakages were reported, but there were numerous shallow ridges across the runs of felt. There was concern that these might be an indication of premature failure. On examination most but not all of the ridges were found to be associated with continuous joints in the insulation. The ridges were mostly to one side of the joints and in some cases a slight change of level in the insulation due to uneven laying was noted. The surface of the membrane under ridges was typically polished bitumen with no evidence of previous contact with the insulation. In a few cases the bond between the membrane and the insulation appeared to have been disturbed for about 300 mm on both sides of the ridge.

A pattern of dark lines was observed on some parts of the surface of the membrane. These proved to be coincident with joints in the insulation and microscopic examination showed that the edges of slate granules in the dark regions were relatively smooth indicating reduced frost action at thermal bridges. There was no evidence that these markings were associated with deterioration of the membrane.

2.3. **Partially Bonded Membranes with Inorganic Fibre Reinforcement.**

2.3.1. A detached two-story house was built in 1971, the deck consisting of chipboard laid without falls, with bituminous felt vapour barrier and 50mm extruded polystyrene fully bonded. The three-layer, glass-fibre bitumen felt membrane was partially bonded with ribbons of hot bitumen, the first layer having granules on the under surface. There were several rooflights and other fixtures on this small roof.

It is understood that leaks at the perimeter of the roof reported during the first year, had been traced to splits at the perimeter upstand, which had been repaired. Further leaks occurred during 1975 and were traced to two long splits in the middle of the roof. Temporary repairs were made and the roof was examined in May, 1976.

The splits in the center of the roof which had originally been reported as being almost invisible, had widened to 2 mm. One of the splits was curved and both were aligned in the machine direction of the felt and were approximately coincident with a change of section of the roof. The contact area between membrane and insulation was estimated at 2-3%. It was noted that an oily condensate was trapped under the remedial felt.

2.3.2. A 15° pitch metal decked roof over a warehouse was completed in 1970. 25 mm extruded polystyrene insulation was fully bonded to a bituminous felt vapour barrier which was bonded to the deck. The two layer membrane was partially bonded by the ribbon method and consisted of a base layer of glass fibre felt with granular surface and a top layer of glass fibre felt with mineralised finish. The felt was laid in the direction of the slope and contact area between the membrane and insulation was estimated at 5%.

Numerous patches were noted running in the machine direction of the felt. An opening was made in the longest patch which revealed a bow shaped split (see Fig. 4) running across the middle of an insulation board, between joints in adjacent boards. A split in another part of the roof was found in a repaired patch which had been laid a few months previously.

3. DISCUSSION

It is evident from the case studies that different patterns of splitting and ridging behaviour observed in the membranes are the result of complex interactions of the factors such as membrane type, bond conditions throughout the build-up, location of fixtures, layout of insulation boards, moisture and temperature effects on membranes, aging characteristics of bitumen, etc. In no case has any physical evidence been found to support the view that movement of polystyrene insulation is responsible for splitting or ridging of membranes.

While some observations conform with findings described in the literature, e.g., tendency for splits to occur over joints in the insulation and in the machine direction of the felt, others differ significantly, e.g., splits occurring in the upper surface of membranes and partially bonded membranes. Reports in the literature of splitting coincident with major ridges, and splits occurring mainly in sub-zero temperatures, are not confirmed by our observations, which indicate that at least in the U.K splits and ridges are separate phenomena, and that a significant proportion of splits occurs in hot weather.

In the following discussion an attempt is made to identify the relevant factors and to provide an explanation of splitting and ridging of membranes which conforms with the evidence from the case studies. It is not within the scope of this paper to quantify these factors which in many cases would depend on further research and testing.

Most of the observed defects can be accounted for by postulating that movement of the membrane occurs as a result of internally generated stresses within the membrane. Evidence that fully bonded membranes are capable of independent movement as a result of internally generated stresses can most readily be seen in the formation of ridges. For example a ridge 50 mm wide and 10 mm high will be produced by horizontal movement of the membrane of approximately 5 mm. Ridges transverse to the machine direction of the felt were found where extruded polystyrene insulation was laid diagonally and could not have generated movement of the membrane in the direction observed.

Although the majority of ridges tends to form at discontinuities in the bond in the transverse direction (typically at joints in the insulation) it cannot be assumed that these ridges are caused by movement of the insulation. The observed spacing of ridges at two or three board widths is probably a function of the stiffness of the membrane. There is no evidence that individual insulation boards bonded to the substrate can combine to produce cumulative movement. Isolated ridges near the perimeter cannot be accounted for by excessive movement of individual insulation boards.

The movement necessary to produce ridges in a fully bonded membrane in relation to the substrate involves the distortion and internal shearing of the bonding bitumen. The ability of bitumen to flow, especially at elevated temperatures, tends to conceal physical evidence of this movement although some local modification of the bond pattern has been noted. (2.2.4).

Internally generated movements of the membrane are unlikely to be confined to expansion in the machine direction, although this type of movement is likely to be more evident as a result of larger dimensional changes due to the stiffening effect of fibre reinforcement preferentailly oriented in the machine direction, together with the additional stiffness provided by overlaps. Expansion movements within the membrane also occur across the runs of felt where the reduced stiffening effect of reinforcing fibres and absence of overlaps results in more localised relief of stresses. Slight buckling of the membrane can often be observed close to overlaps or over joints between insulation boards. (See Figs. 1 and 2.)

Movements due to moisture changes in bituminous felts based on organic, i.e., vegetable fibre, reinforcement are well documented. Since moisture movement is most likely to occur as a result of penetration of the outer surface, shrinkage will tend to occur in the upper layers of the membrane initially. Splits of this type have been observed in several cases. However, the location of surface splits over joints in the insulation creates a paradox in that it is difficult to envisage a mechanism whereby movement of the insulation can by-pass the lower layers of felt, and cause a split in the upper layer. An alternative explanation is that shrinkage stresses are set up in the membrane as a whole, as a result of contraction of the surface layer, and the resultant stresses tend to concentrate at discontinuities, typically, joints in the insulation. It is suggested that stress concentrations encourage the formation of micro-cracks resulting in increased moisture penetration and frost action in the stressed areas, and local weakening of the membrane.

It is also possible that the surface characterisitcs of different types of insulation board will provide different degrees of resistance to movement of the membrane. The coarse texture of fibre insulation board may be capable of absorbing local shrinkage movements in the membrane before they can build up to damaging levels. Lack of adequate bonding of the total build-up to the deck in the case of fully bonded membranes will enable large scale movements of the membrane to occur.

For partially bonded membranes, the ability of the bonding bitumen to transmit any forces that may result from movement of the insulation will be influenced by the contact area available and temperature of the bitumen. The occurrence of splits during the summer of 1976 in a partially bonded membrane where the contact area was estimated at 5% is significant in that the conditions for splits induced by movement of the insulation were least favourable, while the opportunity for shrinkage of the membrane was at its maximum. This membrane was well drained and consisted of glass fibre based felt, so that shrinkage was not caused by moisture movement. On the other hand shrinkage caused by loss of volatile constituents and other forms of aging of the bitumen in a comparatively thin and weak membrane could explain the observed splitting.

The effects of aging of bitumen, i.e., shrinkage and embrittlement caused by loss of volatiles and oxidation etc., are seen in a dramatic form in the phenomenon of alligatoring which affects bitumen dressing compounds exposed to the weather (see Fig. 2). The shrinkage of coating bitumens though less severe would tend to be cumulative due to the continuity provided by reinforcing fibres. This type of composite behaviour although complex and imperfectly understood could, it is suggested, account for the observed splitting in those cases where moisture movement and drying shrinkage are not involved, as well as being an additional factor in the rapid degradation of some organic fibre based membranes.

Evidence that tensile stresses are fairly uniformly distributed throughout membrane is provided by frequent observations of splits at weak sections created by the shape of the roof and location of features such as rooflights and tank housings. There is no reason why insulation boards situated near fixtures should exhibit more movement than similar boards elsewhere, whereas the behaviour of the membrane is consistent with that of other two-dimensional elements (e.g., masonry walls with window openings) subject to internally generated shrinkage stresses.

Further evidence that tensile stresses develop within the membrane can be seen in membrane behaviour which differs according to the direction in which polystyrene insulation boards are laid. Where continuous joints in the insulation are aligned with the machine direction of the felt splits tend to be elongated and wide. When the boards are laid in opposite directions splits over the joints are usually short. In cases where insulation is laid diagonally, however, no evidence has been found of splits occurring over joints although the basic properties of the insulation remain unaltered. These observations suggest that the insulation provides different degrees of restraint to membrane movement depending on the direction in which the boards are laid.

The difference in tensile strength of membranes in the machine and transverse direction is well documented and the absence of splits across the width of felt can be accounted for by the superior strength of the membrane in this direction. For movement of polystyrene insulation to cause splitting in one direction but not the other, it follows that its properties must fall within a critical zone but there is no evidence that the properties of polystyrene insulation are critical in this respect.

If movements generated within the membrane are, as our observations indicate, the cause of splitting and ridging the exact mechanism has still to be quantitatively explained both in terms of theoretical calculation and reproducible test results. Tests producing splits in membrane samples by mechanical movement of the substrate appear to be based on the assumption that substrate movement is the cause of splitting. Environmental tests would be a more appropriate method of producing splits as a result of stress build-up within the membrane, but so far as is known splitting failure has not been demonstrated by tests of this type.

An alternative approach would be to test different aspects of the problem in isolation, e.g., (a) the forces needed to produce movement of membranes over different substrates at different temperatures and under different bond conditions, and (b) the measurement of forces generated within membranes as a result of ageing and weathering processes and the effect of stress concentrations on the durability of membranes.

FIGURE 1 - SPLIT IN UPPER SURFACE OF MEMBRANE AND OVER JOINT IN INSULATION (NOT SHOWN). NOTE SLIGHT RIDGE (CASE STUDY 2.1.2)

FIGURE 2 - ALLIGATORING OF BITUMINOUS SURFACE DRESSING, WITH SPLIT IN UPPER SURFACE OF MEMBRANE OVER JOINT IN INSULATION (NOT SHOWN). NOTE SLIGHT RIDGE (CASE STUDY 2.1.5)

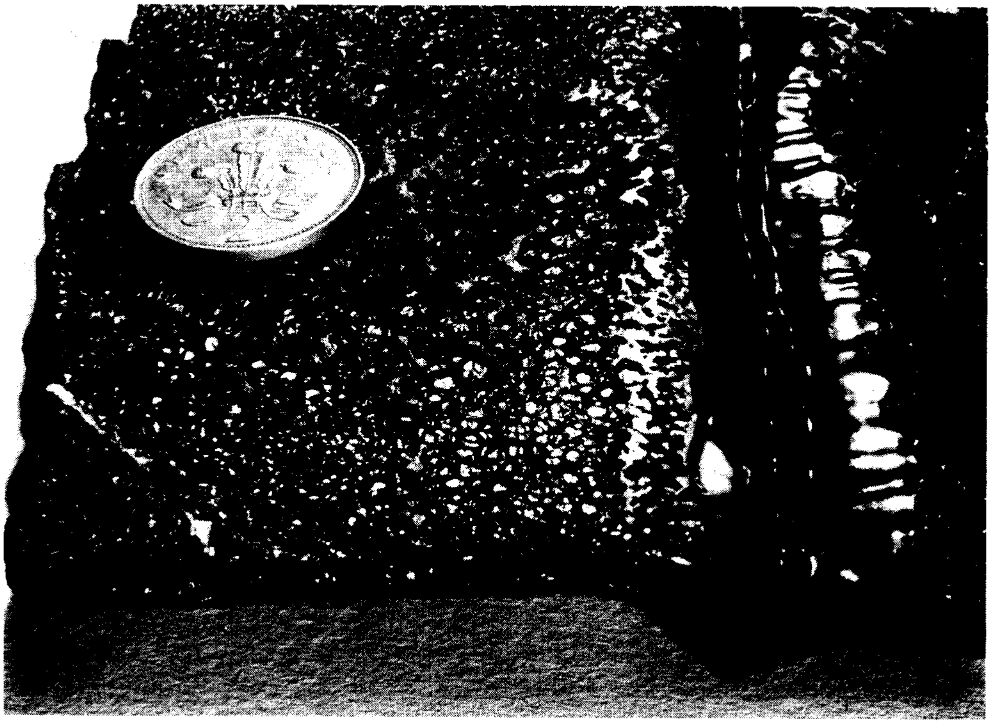

FIGURE 3 – RIDGE ACROSS RUNS OF FELT NEAR PERIMETER OF ROOF. NOTE DIAGONAL JOINT IN INSULATION AT BOTTOM LEFT CORNER AND THICKENING OF BITUMEN. (CASE STUDY 2.2.3)

FIGURE 4 – CURVED SPLIT, PARTIALLY ALIGNED WITH JOINT IN INSULATION. NOTE ABSENCE OF BONDING BITUMEN. (CASE STUDY 2.3.2)