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THE SYSTEMS APPROACH TO ROOF PERFORMANCE

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The proliferation of materials and complexity of roofing systems have confronted contractors and designers with mounting problems of evaluation and selection. A more scientific knowledge of roofing problems is thus imperative. Even if we use high-quality materials, without a clear picture of the interdependence among system components, we risk reduced durability or premature roof failure. We must closely examine the mechanical behavior of every system component, noting the impact of other components on this behavior.

Humidity from various sources inside the roof system poses another threat to durability. Contemporary materials often have low water absorptivity, which can affect the durability of the organic felts differently in different climates.

Thickened insulation, required because of the energy crisis, is still another modern problem, increasing temperature differentials among roof system components.

Designing a flat-roof sandwich (deck, insulation, membrane) system, you cannot design each component in isolation, without regard to the effect of other components on it, or its effect on other components. Good roof design must follow an overall or system behavioral model to satisfy its service requirements. yet we still lack a totally reliable system behavioral model giving us a comprehensive picture of the interdependent actions of each roof component and its effect on roof-system performance.

Several European research programs aim at creating roof system behavioral models. These programs aim at quantifying certain aspects of roof system design now relegated to guesswork, inspired by the ultimate goal of standardizing the performance criteria for both system components and the overall system.

Flat roof systems, with thermal insulation boards sandwiched between deck and membrane have become popular in Europe, mainly for industrial buildings, for the following reasons:

- Light weight, coupled with thermal-insulating quality
- Limitation of thermal movement in structural deck
- Ability to control internal condensation via a vapor retarder (difficult to achieve in previous systems that had insulating masses of lightweight concrete)
- Ease of coordinating application of the various roof system components
- Immediate protection of the structural supports against rain water
- Less water than normal is required in the construction process

Our most important current problem resulting from the interaction of roof system components concerns thermal behavior. Today's increased thermal-insulating standards can cause accelerated aging and higher thermal stresses in membranes. The demand for increased thermal insulation intensifies the problem of condensation within the roof assembly sandwich, largely because of the greater hazard of thermal "bridges".

An examination of several roof-failure case histories illustrates these principles and designers' ignorance of them.

Case 1

A roofing system is made up as follows:

- corrugated steel deck
- extruded polystyrene insulation boards adhered to deck
- polybutylene membrane glued to insulation boards with hot bitumen

A few weeks after the roof was completed, the membrane appeared split at insulation joints. Simple calculation of thermal movement would have warned the designer that these movements could not be absorbed by the elastomeric membrane. Placing isolating strips at the joints would have distributed these thermal stresses. The designer either ignored the interaction between the insulation and the membrane, or had too much faith in the quality of his materials.

Case 2

Another roof system was made up as follows:

- precast concrete deck panels
- polystyrene insulation boards adhered to the deck
- a loose layer of granulated cork
- three-ply, aggregate-surfaced membrane mopped to the cork layer

Four years after completion, the roof leaked through membrane splits parallel to the felt's machine direction. Unlike the Case 1 membrane, the Case 2 system's membrane had been laid isolated from the extruded polystyrene insulation boards by the cork. The membrane splitting was not continuous. And it was not limited to the joints between insulating boards.

As in Case 1, the failure again resulted from design errors – in this case, the omission of a vapor retarder, choice of felt materials, and failure to slope for positive drainage. The site location, at the foot of a mountain range, was subjected to extreme temperature differential (seasonally from –20°C to +40°C) and the production process inside the building created high relative humidity. A simple calculation of annual residual condensation inside the roof system would have shown the need for a vapor retarder.

Lacking the required vapor retarder, the roof system was invaded by strong currents of vapor which, localizing in the cellulosic reinforcement, led to rapid decay of the organic felts. A three-ply organic felt membrane may contain from 0.3 to 0.6 liters of air per square meter.

Ponded water, continually present on the unsloped, undrained roof surface, maintained a nearly perpetual supply of water at the roof surface.

Examination of the membrane revealed that the membrane was split only where it was corrugated, in the machine direction of the felts. Water absorbed by an organic felt expands the cellulosic fibers, which can expand the felt width by an average 1.5%. Such transverse expansion accounts for the corrugations.

Obviously, these corrugations were not caused by thermal movement, for they were located far away from the insulation board joints, where thermal movement would concentrate. Moreover, since the long dimension of the insulation boards parelleled the direction of the felt corrugations, the joints where major movements occurred lay at right angles to the corrugation.

Contraction stresses from winter temperatures well below freezing split the water-weakened felts at the tops of the corrugation ridges, since perimeter anchorage prevented the membrane from contracting in response to thermal stresses. Diagnosis: Omission of the needed vapor retarder plus selection of unsuitable felts weakened by upward migrating water vapor account for this roof failure.

Case 3

A school building's roof system comprised the following components:

- laterite-cement deck
- polystyrene insulation boards adhered with bitumen to the deck
- membrane made up of two prefabricated bituminous sheets with glass-felt reinforcement welded hot crosswise
- protective surfacing of concrete planks on side on sand

One year after construction, numerous leaks were discovered along the perimeter. Apart from the danger caused by the lack of a vapor retarder (required because of high interior humidity) and the lack of an effective runoff layer between the membrane and insulating substrate, the leaks resulted exclusively from a perimeter detail that did not provide for thermal movement in the membrane. The membrane, in fact, was completely drowned in the plastering along the perimeter shell.

Though a detail of this kind might be acceptable for an anchored bituminous membrane, running lengthwise, on a concrete deck, it is unacceptable for a membrane with full freedom of movement.

The perimeter detail was deficient, because it had a rigid angular connection concentrating thermal tensile stresses that ultimately exceeded the membrane's strength, as evidenced by a continuous split along the perimeter. An application error helped to ensure failure: only the upper felt had been turned up vertically; and it had been oriented with its weakest (transverse) direction resisting the imposed stress.

In this case, design errors were compounded by field application errors.

Case 4

The roof system was made up as follows:

- laterite-cement deck
- extruded polystyrene insulation boards adhered with hot bitumen to the deck
- three-ply bituminous membrane crossed with organic felts, grained on top, and laid semi-independently with a "base coat," heated with a flame from above.

Three years after completion, the roof had numerous leaks. Lesser leakage had occurred earlier at the perimeter, where the membrane had shrunk as much as 10 cm in a width of 25 cm.

This movement resulted in considerable perimeter splitting. Again as in Case 3, application errors promoted leaks, in this case at skylights. Rigid attachment of the membrane to the bases of the skylights prevented the above-mentioned shrinkage, thus resulting in tensile splitting of the membrane. Despite abundant bitumen on its surface, the deck surface was so irregular that it prevented good anchorage of the insulation. Lack of adherence between deck and insulating boards thus caused deformations and shearing stresses at insulation joints near the skylights, and these stresses started the splitting. Except for some between insulation boards near the small skylights, the joints appeared to be tight (when inspected during winter). This indicated that the membrane contraction had been greater than the insulation's contraction, and that the loose, inadequately anchored insulation boards had been pulled along by the membrane. In this pulling action, the fixed points constituted by the skylights produced stress concentrations, ultimately resulting in membrane splitting.

In this case, too, design errors were compounded by field errors responsible for the failure.

Case 5

This roof system comprised the following:

- precast concrete deck units
- extruded polystyrene boards anchored to deck
- single-ply prefabricated bituminous membrane, reinforced with polystyrene and surfaced with embossed aluminum sheet

Within a few months of completion, the roof had numerous leaks. Cause of failure was careless application. For single-ply roof membranes, the margin of permissible error is lower than for conventional multi-ply membranes. Single-ply membranes require a specially trained applicator. In this particular case, the siliconated paper laid to protect the gluing edge had only been partially removed before the membrane units had been soldered. The consequently weakened overlapped joints could not resist normal thermal stresses in the membrane: detachment between adjacent strips at the overlaps thus resulted from construction error.

Judged by these pathological case histories, many roof designers are ignorant of the complex behavior of flat roof systems, despite the wide-spread use made of the type of roof systems analyzed in this paper. Formulation of good theoretical models is vital to good design. Experience, a good enough guide for the past, cannot solve the proliferating problems accompanying the introduction of new materials and new combinations of materials. Uncritical dependence on experience is hazardous, a fact borne out by many case histories of roof failure.

A flat roof system presents a series of functional demands that promote use of a wide range of components. This diversity, in itself a complex problem, is aggravated by the introduction of new materials inadequately tested for their behavior in service and for their impact on the behavior of the overall roof system. These new materials have simplified application techniques - notably through single-ply membranes. These single-ply membranes, however, seriously reduce the margin of permissible error in comparison with the traditional multi-ply systems. They accordingly require more specialized workmen.

Yet despite the growing popularity of single-ply membranes in Europe, the necessary scientific recasting of the whole waterproofing problem has not been accomplished. Instead, roof technology simply evolves along lines that may increase failures and even ultimately prove uneconomical.

We have seen how widespread failures cannot be controlled except by proper choice of component materials. In my opinion, however, these problems are confronted only at the highest levels, both in design and application. In particular, in addition to the development now going on at levels of complex thermo-water-proofing, we need improvements in the structural deck, which is tending more and more to precast concrete structures. The designer of prefabricated building systems often ignores the necessary coordination with waterproofing, and thus often finds himself up against formidable detailing problems. Costly solutions are often required and that is the source of a large proportion of roof problems.

Another problem, aggravated also by fragmentation in the overall system, concerns recent modifications that promote condensation within the roof system. Vapor flow poses a greater problem in prefabricated systems because of the reduction in the fly-wheel effect characteristic of solid structural decks. Improved standards for thermal insulation and relative humidity heighten the probability of condensation because of the greater heterogenity of the thermal characteristics of the various system components and because of increased differences in surrounding vapor pressure.

Another design problem seldom considered in a prefabricated building system concerns required roof slope and drainage. Because of limited design loads imposed on the roof structure, it is often impossible to add screeds for sloped concrete fill. Inevitably, where unsloped surfaces pond water, the membrane eventually splits and admits water inside the building. Drippage occurs not only during the rainy period; it is prolonged until the water has been completely removed. Even prefabricated systems with carefully planned and constructed slopes often take no account of this slope in locating drains, or of the greater deck thickness required where the drains are located. Drains installed at too high an elevation promote ponding as readily as unsloped roofs.

Roof deck surface finish is also important. If it serves as substrate for board insulation, the deck surface must be smooth to permit good adhering. On the other hand, if it contains screeds for lightweight insulating concrete fill, the deck surface should be rough, to spread out shrinkage cracks and promote good bond to the support.

The regularity of the top support surface is just as important when a vapor retarder is specified, to avoid punctures or tears in the vapor retarder material. Joints between precast deck units pose a special problem.

Clearly, we need closer coordination between deck fabricators, on one hand, and roofing material manufacturers and roofers, on the other.

From this brief analysis of contemporary roofing problems clearly emerges the necessity of a complete change in the mode of overall operation - in design and application as well as research. We must expand our material-oriented approach to a more scientific systems approach, embracing the subtle complexities of total roof performance.