THE INTERCONNECTED PHYSICS OF ROOF COMPONENTS

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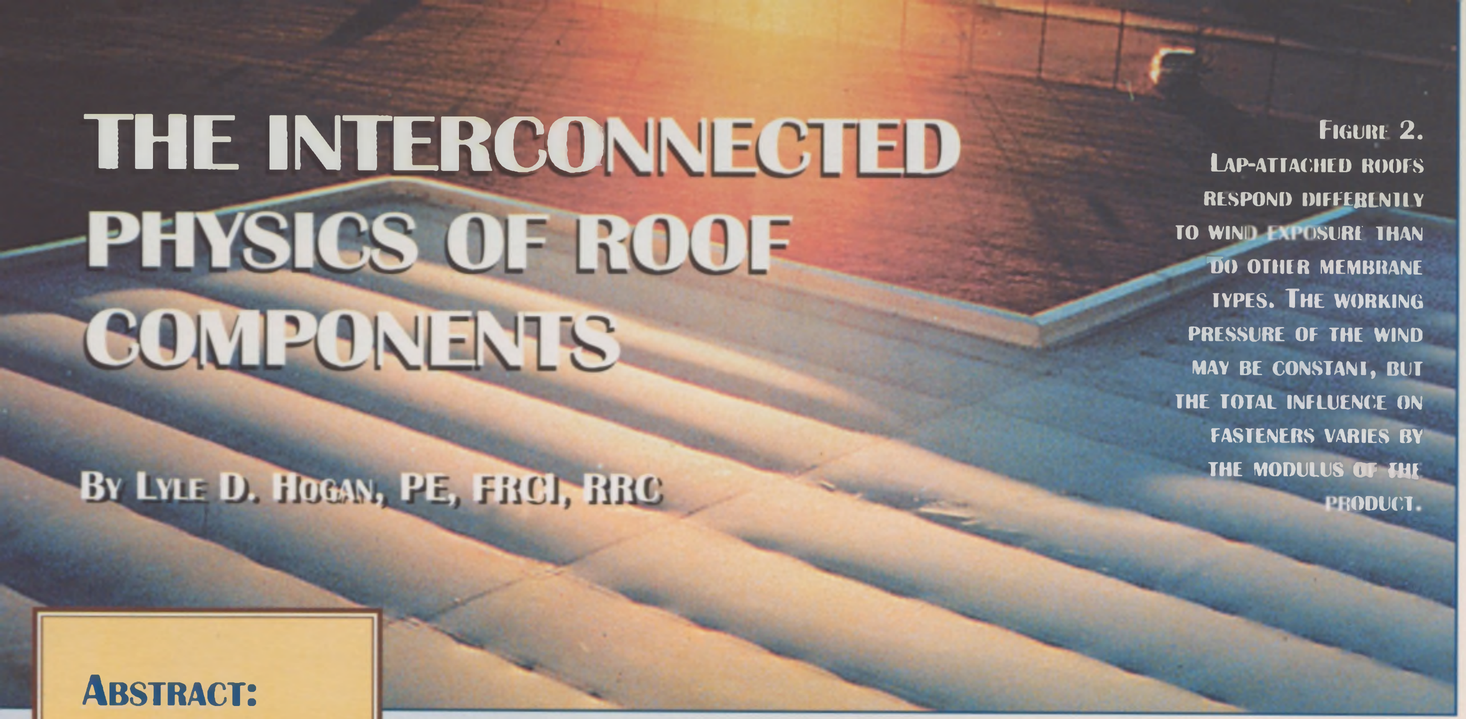

Figure 2. Lap-attached roofs respond differently to wind exposure than do other membrane types. The working pressure of the wind may be constant, but the total influence on fasteners varies by the modulus of the product.

Abstract:

Roof construction is founded in physics. As disturbing as that may be, the concept is encountered daily. Behavior of roof assemblies (including the various substrate types) is somewhat predictable when examined in the backdrop of physics.

A related notion, mechanics of solids, proceeds upon inescapable constants such as gravity and mass (at least regarding construction on this planet). This treatise is not intended as a comprehensive discussion of the physical sciences. Instead, the concepts offered are meant to illustrate the relationships between and among roof assembly components. Examples of other building construction components are used as analogies.

Inertia

The bulk or mass of roof components can be understood by inertia. Consider the difficulty in accelerating or bringing to a halt an element of a roof deck. An earthquake is a type of natural event which can induce acceleration. Plywood decks on wood structures behave radically different from a cast-in-place concrete deck during such exposure. The shock energy will be transmitted and reflected through these media at a rate governed by density of the materials used and the fixity of connections (among other variables).

Similarly, a vertical load may create identical deflections in plywood and steel decks. This would suggest that they are equally capable substrates for a given project. Yet, abrupt vertical loading may induce far different instantaneous deflection with attendant susceptibility for irreversible deformation and membrane rupture. Inertia is the phenomena responsible for this difference in behavior.

Inertia can be witnessed by analyzing the various corrugations of steel roof decks. Span tables confirm that for any gauge of deck, load capabilities differ, varying only with the fluting configuration (i.e. shape, profile, spacing, and opening).

A related aspect is thermal inertia. This is the tendency of some decks to serve as a thermal sink better than others, responding slowly to top side temperature changes. A concrete deck slightly less than five inches thick will have five times greater thermal inertia than some other lightweight substrates examined (Beech & Saunders, 1985). Separate research by Kunzel and Petersson confirmed that underside temperatures (of heavy concrete decks; see *Figure 1*) changed little with wide changes in the external environment. Roof coverings should be appropriately matched to perform in the setting of several parameters. Deck inertia is important among them.

Thermal storage capacity should be considered in surfacings as well. Gravel surfacing has the capacity to act as a thermal "flywheel." Removal of the surfacing and replacement with a mineral-surfaced cap sheet will generate a new behavior of the substrate (Duchene, 1985).

Modulus

Young's Modulus of Elasticity (E) is the slope of a graph plotting deformation against the ten-

Figure 1. Concrete decks have high thermal inertia. When compared to other substrates, rooftop temperature changes are transmitted slowly into the building.

sile load per unit area. This works well for examining solid materials; however, some roof materials do not behave as pure solids through a reasonably expected service temperature range. That is, the value for E would vary greatly with changes in temperature. A modulus of elasticity is therefore not meaningful for these materials, but a load-strain relationship nonetheless exists (albeit quite temperature sensitive). Bitumen is an example of a material having engineering properties which range according to temperature. This is the basis for studying the rheological properties of materials.

Anyone having drilled, punched, or sheared stainless steel is well aware of its hardness in comparison with other metals. For this reason, many suppose that stainless steel is stronger than the same thickness of carbon steel. Its tensile strength is well in excess of that for carbon steel (85,000 psi compared to 60,000 psi). Yet the modulus for the stainless is 28,000 ksi compared to 29,500 ksi for carbon steel (Eshbach & Souders, 1974). Carbon steel, then, has a greater slope for load-strain relationships, deforming less for a stated load. This difference can be viewed in span tables contrasting stainless with carbon steel roof deck sheets. The concept is better appreciated if the surface hardness of stainless is neglected for the moment.

One-ply membranes also behave according to modulus values. For instance, wind-induced oscillation (flutter) imparts energy to the fasteners. Other factors being constant, the higher modulus membranes transmit this energy more effectively than lower-modulus, more flexible products (i.e. EPDM). A highly-reinforced, lap-attached, sheet membrane would apply much different loads to the fastening devices during wind events than would a thick, bituminous, adhered membrane (*Figure 2*). Yet, the working pressure of the prevailing wind is the same. The varying modulus values of the two products hold part of the explanation.

Membrane modulus values also played a part of deck span tables as various products were implemented. Designers were told, for instance, to size structural elements so as to limit vertical deflections to l/180, l/240, etc. This was in an effort to avoid rupturing of a high modulus bituminous membrane (built-up roof), the hands-down system of choice for decades. This author is unaware of any current polymeric membrane product incapable of withstanding vertical deflections of the substrate well in excess of the figures above. Many such products have had performance problems, but the resilient nature (low modulus) of the coverings is largely immune to damage from deck deflection.

MOMENT

A force times its measured distance from some point of influence is considered the moment value acting about that point. Comparatively hard or brittle materials are well capable of transmitting moment. Further, rigid materials "attract" moment. Consider two types of pitch pocket filler surrounding an iron penetration (*Figure 3*). Movement of the iron is transmitted through the material. Rigid fillers (like cementitious grout) impart more separation stress to the sides of the pitch pocket form than more resilient polymeric products.

FIGURE 3. RIGID FILLER IN A PITCH POCKET ATTRACTS AND TRANSMITS MOMENT BETTER THAN A RESILIENT PRODUCT. SUSCEPTIBILITY FOR SPLITTING AND SEPARATION THEN BECOMES APPARENT.

Steel deck sheets may be installed spanning across three, four, or more bar joists. That arrangement is intended to transmit moment induced (by loads in one area) across the supports into other regions. Multiple single spans may work apart at the sheet endlaps. Distribution of the moment is appealing management of an influence that might split a comparatively rigid membrane.

SHEAR DIAPHRAGM

A structure having only horizontal and vertical members would be unstable, even when fastened appropriately to adjacent members. Lateral loads imparted (by wind and earthquake acceleration) induce horizontal shear in the structure. As a result, a diaphragm is needed in the horizontal plane.

In the absence of a diaphragm, horizontal shear can aggravate connections and result in twisting or torsional behavior within the structure. Resistance is provided in several locations in a structure by using a diaphragm and/or diagonal bracing (*Figure 4*). Bracing (bridging) may be found between and among wood joists and steel purlins. This, however, is to control potential rotation of the members and should not be confused with shear diaphragm elements.

FIGURE 4. A STRUCTURAL SYSTEM HAVING ONLY VERTICAL AND HORIZONTAL MEMBERS MUST BE STIFFENED AGAINST HORIZONTAL LOADS. SHOWN HERE IS ORDINARY DIAGONAL BRACING USING STEEL SECTIONS.

A plywood roof deck is an excellent shear diaphragm when anchored properly into framing members. This is also the reason plywood is used at corners of framed wood walls, substituting for other types of sheathing found elsewhere in the same construction (*Figure 5*).

FIGURE 5.
PLYWOOD IS USED AT CORNERS OF FRAMED WOOD WALLS, SUBSTITUTING FOR ORDINARY SHEATHING USED ELSEWHERE. THE PLYWOOD IMPARTS HORIZONTAL SHEAR RESISTANCE TO THE FRAMING.

A structural metal roof, by definition, has no deck or substrate. Modern standing seam coverings are carried on a system of concealed clips which accommodate thermal movement (*Figure 6*). This appealing divorcement of the roof covering from the framing elements, however, renders standing seam assemblies incapable of serving as a shear diaphragm. Such resistance must be gained elsewhere in that type of structure such as with the diagonal elements described above. Note that even conventional steel decks do not develop full diaphragm capability until side lap stitching screws are in place (*Figure 7*).

FIGURE 6.
STRUCTURAL METAL ROOFS ARE CARRIED ON A SYSTEM OF CONCEALED CLIPS, ALLOWING LONGITUDINAL MOVEMENT OF THE PANS. BEING, THEREFORE, SEPARATED FROM THE STRUCTURE, THE ASSEMBLY IS INCAPABLE OF SERVING AS A SHEAR DIAPHRAGM.

FIGURE 7.
CONVENTIONAL STEEL DECKS DO NOT DEVELOP FULL DIAPHRAGM CAPABILITY UNTIL SIDE LAP STITCHING SCREWS ARE IN PLACE.

FLUID DYNAMICS

Those things that flow can be examined in a study of fluid dynamics. A substance does not have to be in "liquid" form to be a fluid. For roofing analysis, wind is the fluid of interest. Wind tunnels all whistle the same tune, and the influence on construction surfaces can be modeled reliably. Bernoulli's Energy Equation is the form used to express working pressure as a function of fluid velocity. Modified appropriately for the density of air, the influence is generally in the form:

$$P = 1/2\ \rho(v)^2$$

where: P = the pressure of the wind acting on the surface
ρ = the density of air
v = the wind speed

Simplified, the pressure acting on a surface varies as the square of the wind velocity. This is pivotal in understanding why roofs come off (even though most should not). Try holding your hand from the window of an automobile moving at both 40 k/hr and 80 k/hr. The velocity has doubled, but the difference in pressure experienced has increased exponentially. Such an example ratifies the velocity pressure curve, a parabolic function because the formula is a second degree equation (*Figure 8*).

Roof design for wind resistance embodies a shape factor analysis. That is, we convert the pressure acting normal to a wall surface to an influence over the top of a structure. Such converting incorporates a 50% escalation of the working pressure for design purposes (1.5 times the wall surface pressure). Other escalations and factors are applied later.

COEFFICIENTS OF THERMAL MOVEMENT

The movement of various construction materials as a function of temperature is well known. A coefficient of thermal expansion has been determined for virtually everything used in roof construction. Joining certain materials occasionally results in mismatch, particularly where long-term waterproofing is required. Sheet metal accessories integrated into membrane products is a classic case where this union is crucial.

Consider light-gage (0.032 inch) aluminum and how it compares with bulk (0.125 inch) aluminum of the same length. Note that the coefficient of thermal expansion is unrelated to the thickness of the material (Hogan, 1993). That is, the amount of movement has nothing to do with the gage of the material. The difference in performance is the amount of shear force exerted on the fasteners used to secure the accessories.

The force acting on the fasteners (of bulk thickness metals) may be substantial, potentially shearing the attachment devices and/or elongating fastener holes. The force actually at work is identical to the force required to stretch it by the same amount (Beiser, 1991). Because of this, the thicker bulk metals are divorced from a membrane while light gage metals may be functionally restrained by frequent fastening.

Summary Remarks

Nonperformance of various roof types may be explained when the properties of one component are not well matched to others in the composite. The interaction of the components has been explored by several researchers. Van Wagoner (1989) has examined the membrane and insulation combination. The deck and structure have played a pivotal role in the observations of this writer. I will not attempt to improve on Griffin (1982) who postulated:

"The characteristic problems of roof system designs are a combination of incompatible materials rather than isolated failures of single components. Two or more components may satisfy their individual material requirements to perfection and yet, in combination, fail disastrously."

Successful integration of the multiple components is crucial to achieving the optimum roof service life. A better understanding of physics will lead the way to improved system performance.

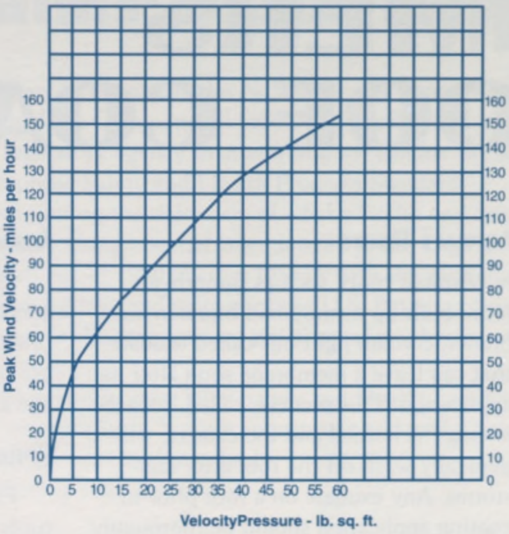

Figure 8. The velocity pressure curve is parabolic because it is the plot of a second degree equation. The pressure varies as the square of velocity.

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