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FUNDAMENTALS OF ROOF DESIGN

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A roof is constructed to protect a space from some aspects of the natural environment. At its simplest it is required to provide shelter from rain or shade from the sun. As the requirements of the space beneath it become more complex, however, so does the function of the roof. Its general functions are similar to those for exterior walls (CBD 48), with loads, allowance for traffic and rain penetration control the main differences.

Function of a Roof

Basically, a roof, in conjunction with exterior walls, must enclose space in such a way that environmental conditions can be regulated within acceptable limits. In this context environment must be regarded in the broadest sense to include not only temperature, air movement, humidity, precipitation and radiation, but also such factors as noise, fire, dust, odours, insects, plants, animals, and people. To accomplish this basic function the roof system must perform as a barrier or selective separator; it must prevent, limit or allow flows of mass and energy, depending upon the environmental differences and the degree of separation required.

Requirements of a Roof

A roof must be structurally sound, aesthetically pleasing, economical, durable, and provide the required degree of environmental separation. Requirements can be considered individually, but because there is a strong inter-relationship they must also be considered collectively.

The *Roof Structure* must be designed to support or withstand all loads that may be applied to it without risk of collapse or structural failure. It is the foundation upon which all other elements and materials of the roof are supported. Excessive structural movements that might impair the performance of any of these elements must not occur, and expansion joints through the entire roof system should be incorporated where major movements are anticipated.

Most roof structures, although structurally sound, do suffer movements that may cause failures in other elements of the roof system. These take the form of deflections (CBD 54) and differential movements arising from loads, shrinkage, creep, warpage, thermal variations, moisture changes and the form of the structure. Cracks, which may be of no structural significance, often play an important role in producing failures of the roof system by tearing bonded membranes or by permitting increased heat flow and air and vapour migration. Deflections also may induce sufficient stress in a membrane to cause its rupture. Near-flat roof surfaces, through deflection, may fail to drain and allow ponding of water, which can cause accelerated deterioration of the roof materials.

Deflections and differential movements in a roof structure should be anticipated and their magnitudes estimated. It is particularly important to recognize and provide for the long-term behaviour of materials under load, especially creep in concrete and wood, because total deflections can be several times the elastic deflection. Locations where minor cracks in the structure can be expected should be established and precautions taken to prevent the occurrence of undesirable conditions in other elements of the roof. If adequate allowance for movements cannot be made through the use of slip sheets, expansion joints, and increased slopes to drainage, the structure should be redesigned to reduce movements and deflections to an acceptable value.

Flat or near-flat roofs are frequently required to serve as traffic decks, promenades and roof gardens. Where such multi-use is to occur all loads must be duly considered in the structural design. With roof terraces it is common to find one section of the structure more heavily loaded than an adjacent area. In such a case it is of the utmost importance that the differences in total, long-term deflections between one member and another be considered. Roof terrace design will be the subject of a future Digest, but the fact that the waterproofing membrane is normally buried under expensive surfacing materials, making it relatively inaccessible for maintenance, demands that all precautions must be taken to prevent damaging it.

The *Aesthetic* values of a roof are the particular responsibility of the building designer and as such are outside the scope of this Digest. The preservation of the building's appearance, however, is dependent upon the technical performance of the total construction and is best achieved through compliance with good technical design. Aesthetic qualities of roofs can normally be varied through a wide range, but insistence upon technically undesirable features can result in unsatisfactory solutions.

The requirement for *Economy* is an overriding consideration that influences and is influenced by all the requirements of a roof. Maintenance costs are largely dependent upon technical design and must be considered in conjunction with initial cost; some initial savings may result in excessive maintenance or early obsolescence of a building. Through a knowledge of building science, however, economies can be made without degradation of the system or, at worst, with full cognizance of the problems to be expected and the maintenance required. As most buildings are constructed at considerable cost to meet a need, their components should be durable in order to obtain the best return on the investment.

Durability, more properly called "service life," is not an inherent property of any material; it is determined by the properties of the material and the environment in which it is required to serve. It is a rough measure of the time through which materials or combinations of materials continue to perform in a satisfactory manner. In complex constructions such as roofs, the performance of any one material influences the environment and the performance of all other materials in the system.

Service life is of such major importance that an understanding of all the factors affecting the durability of all components of the roof system is essential. The properties and behaviour of materials can be established by test and many materials have been discussed in past Digests. The environment in which any one must serve is determined by the environments being separated, the properties of all the materials in the system, their relative positions, and the behaviour of the roof structural system. By judicious selection and arrangement of materials the roof designer can greatly ease the requirements of the various elements and thus broaden his choice of materials and methods of construction to gain a durable system.

The *Separation Of Environments*, as the prime function of a roof, must receive particular attention, especially since the effects associated with performing this function normally determine the service life of the materials in the system. Exposure to the exterior environment may produce deterioration of a material, whereas heat, air and moisture flows affect the behaviour of all materials in the roof system.

Separation of Environments

As a selective separator of dissimilar environments a roof system is subjected to variations of almost all the environmental factors; the differences from one side to the other determine the duties of the roof and the properties it must possess. The environmental differences of greatest importance to the durability of a roof system relate to rain penetration, heat flow, vapour flow, air flow, radiation and fire, all of which involve actual or potential flows of mass or energy. The transfer of heat and radiation represents energy flow, whereas air and moisture movements represent mass flow. Flow takes place at a rate dependent upon the difference of potential and on the resistance offered by the medium, in this case all the materials interposed between the environments being separated. The potential is temperature for heat flow and pressure for air and vapour flow. The potential for liquid water flow may be kinetic energy, capillary suction, gravity and air, vapour or hydrostatic pressure. Water may also be induced to flow by thermal, electrical or chemical effects. In all cases flow is from the higher to lower potential, and the net result is a tendency to equalization of potentials.

Most materials offer resistance to flow, and gradients of potential occur across materials or constructions interposed between dissimilar environments. Previous Digests have discussed temperature (CBD 36) and vapour pressure gradients (CBD 57); the effects of thermal bridges (CBD 44); and the nature of air leakage (CBD 23). A knowledge of the gradients resulting from separation of environments permits a designer to determine the environment in which each material must serve.

Exposure to the Exterior

The effects of exposure to the exterior environment are dependent upon the material and the nature and degree of exposure. Absorption of solar radiation (CBD 52) can result in surface temperatures of over 200°F, producing expansion and accelerated deterioration of exposed materials. Radiation to a clear night sky may cause roof temperatures to drop below the ambient air temperature, with accompanying contraction and possible wetting by dew. The extreme temperature variations between night and day in a black roof material over insulation can exceed 140 F deg and the seasonal variation may be over 250 F deg. Atmospheric pollutants contacting roof materials, especially when combined with water, can accelerate deterioration. Traffic of any type on a roof may cause physical damage that will impair its performance. An obvious solution to some of these problems is to shade or protect materials that may be damaged with materials not so vulnerable to the rigours of the exposure (CBD 65).

A roof should be designed to shed water as readily as possible, because accelerated membrane deterioration occurs at the edges of shallow ponds. Ponds also provide a large volume of water to produce major damage if a leak does develop, and the expansion and contraction of ice may contribute to membrane failure. There are, however, situations where intentional ponding of the roof may be employed to minimize heat gain within the building or to shade the membrane from direct solar radiation. Such a roof must be specially designed and constructed, because the water depth is quite critical and the effects of a failure can be severe.

Rain Penetration Control

Rain penetration occurs when there is water on the roof surface, openings through which it can pass, and forces acting to move it inwards. If any one of these conditions is eliminated, it cannot occur. Obviously if the roof is never wet, rain penetration is not a problem. Similarly, if there are no openings, leakage cannot occur. It is also true, but not so widely recognized, that even with water on the roof and openings through which it can pass, rain penetration will not occur if all the forces acting to move it inwards are controlled (CBD 40).

Shingled and tiled roofs seldom leak despite the many openings through them because the forces acting to move water inward are controlled. Rain penetration due to kinetic energy is prevented by overlapping the shingles. Capillary suction acts only to draw and hold water into the capillary spaces between them. An air pressure drop through the roof acts to move water toward the interior, but it is resisted by the force of gravity acting to pull it outward, down the slope. Leakage of shingled roofs is prevented as long as the height through which the water must be raised is greater than the air pressure difference measured in inches of water column. Leakage through joints in some roof tile systems is prevented by the inclusion of a space, too large to produce capillary suction, which is open to the outside, with air leakage resistance provided inward of the cavity. In this situation there is no inward air pressure drop nor capillary suction at the wetted end of the potential leakage path. This approach can be employed at any line of potential leakage, but it must be remembered that all forces acting to move the water inward must be controlled. Shingled roofs that have sufficient overlap for their slope normally leak only after severe damage or when ice dams prevent the required drainage.

To prevent rain penetration through very low-sloped and flat roofs a completely continuous membrane, through which there are no holes to permit leakage, must be provided because the forces acting to move water inwards cannot be controlled. Not only is this perfection in water tightness difficult to achieve, it is more difficult to maintain over a reasonable service life without frequent maintenance. Because of the inaccessibility of most roofs this maintenance is seldom provided. Imperfections in workmanship, deterioration of materials and minor failures resulting from deflections or small differential movements in the structure can produce severe leakage through any membrane whose success is dependent upon perfection, especially when ponding is also permitted.

It is obvious from this discussion that roofs designed to function despite openings are less susceptible to failure as a result of accidental openings than systems where a perfect seal is required; and that greater deflections and differential movements in the structure can be tolerated without risk of leakage.

There are many products used to produce water-tight membranes; all may have individual design, installation and maintenance problems, but they can provide a reasonable service. These membranes will perform most satisfactorily when they are protected from the mechanisms that cause their deterioration. This may be accomplished by selecting the material best suited to the environment in which it must perform, or by modifying this environment. A knowledge of the environment, therefore, is essential for the selection of materials and roof design analysis.

Workmanship is always of considerable importance in producing successful roofs. It is of greatest importance in flat roofs. Design, however, is still the basis of success.

Conclusion

Most problems with roofs can be eliminated, or at least minimized, by compliance with the following principles for roof design:

1. Consider all requirements, both individually and collectively, and do not sacrifice one requirement for another without recognizing the consequences of such a decision.

2. Design the structure to keep movements and deflections to an economic minimum, and make allowances in the associated constructions for those that will inevitably occur.

3. Know the environment in which each material must serve and its effect upon the material.

4. Ease the duties imposed on each material by judicious selection and positioning in the assembly.

Through systematic, rational analysis the pertinent factors affecting the performance of roofs can be recognized and the probable performance of a total system determined. This capability makes it possible to discriminate between various systems for particular applications and, even more important, to develop improved designs.

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