ACHIEVING THE PERFECT FLAT ROOF

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Flat or low-slope roofs have recently acquired a bad image as a result of premature failures. But, flat roofs are essential to the needs of today's building programs. Therefore, substantial investments have been made worldwide in research and development work aimed at identifying and eliminating past problems.

That work has tended to concentrate on materials, products and systems for waterproofing; less attention has been paid to fundamental design of the flat roof as an element and even less to user requirements and service conditions. This paper seeks to place past performance of flat roofs in context with that of other elements of building. It suggests that membrane failure is less significant than has been thought and describes a methodical approach to flat roof design which is gaining increased acceptance.

KEYWORDS

Design brief, flat roof design, membrane performance, whole-life costs.

INTRODUCTION

The roof is one of the primary elements of building. The flat roof is an essential form of construction which enables us to meet the needs of modern society in a wide variety of buildings.

The design of low-slope roofs (those having a slope of five degrees (1:12) or less*) requires the use of an impervious waterproof covering. The designer may choose between profiled metal sheets with a capacity to span across intermittent supports, and waterproof coverings laid on a fully supported substrate. The latter group includes sheet metals (such as lead, zinc and copper), liquid-applied coatings (such as asphalt), and flexible sheet materials based on oil-derived products which can be grouped as bitumen, thermoplastics and thermosets.

When, in the 1960s, researchers began to notice an increase in premature failure of flat roofs ("failure" being defined as "not performing to the required level for a reasonable time") the initial reaction was to focus attention on the waterproofing materials—in those days primarily bitumen felt and asphalt.

Publication of their preliminary results[1] lead manufacturers to develop improved stronger membrane materials (with varying success), and to introduce new thermoplastic and thermoset products. These were often offered with exaggerated claims of long-term performance, but with little regard to the availability of suitably trained labor for their application. Many manufacturers saw a solution in offering waterproofing "systems" embracing the basic sheet materials, seaming/jointing products and equipment including a range of accessories for attaching the membrane and for forming details. The system approach is particularly prevalent with the newer materials. It does not always address the design of the whole roof and therefore falls into the trap of offering standardized solutions to unknown problems.

Those involved in the development and marketing of waterproof membrane materials have tended to assume that all roofing problems can be cured by improving membrane specifications.

However, it must be recognized at present there is no generally accepted classification of those materials. Furthermore, there is no general agreement on what constitutes the significant service conditions under which waterproof membranes are required to perform. Under those circumstances, standardized methods of testing materials,[2,3] even if they can be achieved, lack credibility.

Building research necessarily involves investigation into premature failure of constructions and materials. Finding out what went wrong and why has been referred to as "building pathology;" it offers a wealth of data and ample opportunity to learn from past mistakes. Perhaps it is inevitable that different lines of investigation have tended to reach different conclusions.

Continuing appraisal, over a number of years, of all types of building failures—including roof failures—has lead to the conclusion that the underlying causes are usually more complex than originally thought; leaking roofs are seldom due, primarily, to membrane failure. Failure of a roof to perform as expected over a reasonable length of time is more likely to be attributable to inadequacies of use, of design, of workmanship or a combination of those factors.

It follows, therefore, that the systems of waterproofing may be expensively over-engineered, while the flat roof as a whole remains liable to premature failure for reasons which have not been fully appreciated.

Those involved in research which is not "material-specific" are tending towards a broad consensus on the significant factors which determine the potential performance of flat roofs. An initial assessment indicates they may be grouped as:

- Client/User Factors.
- Climatic Factors.
- Workmanship Factors.

CLIENT/USER FACTORS

Initial capital investment, the way a building is used, and the degree of care and maintenance it receives are directly determined by the building owner/user. Only he can determine how long his investment is expected to last, and how and when it will be refurbished or renewed. The building owner/user alone controls the quality of the original build-

**The British Standard definition based on 10 degree (2:12) slope or less has recently been called into doubt and may well be changed to match the five degree definition more widely accepted by other standards bodies.*

ing envelope and the service conditions under which it must perform.

The activities and processes within the building have a direct influence on the building fabric.

High temperatures with high humidity levels are unavoidable in swimming pools, breweries, paper mills and many other industrial buildings. They lead to greatly increased risk of damage from interstitial condensation. Exhaust fumes from cooking or manufacturing processes often contain contaminants (such as fats and acids) which can cause local deterioration of the membrane.

In common with all other elements of building, roofs require regular inspection, care and maintenance to ensure optimum performance. All too often flat roofs are neglected until problems arise.

Successful flat roofing requires:

- Initial capital investment must be adequate for the required life to renewal.
- Conditions of use must not exceed those in the original brief.
- An appropriate level of care and maintenance must be applied.

CLIMATIC FACTORS

Geographic location of the project determines what conditions of climate a building must cope with during its lifetime; those conditions can be identified as:

- Temperature—Maximum/minimum, seasonal variation, degree of solar radiation.
- Wind—Frequency, direction, strength.
- Precipitation—Frequency, type-rain/hail/snow, quantity-annual/peak rate.
- Vapor drive—Severity/direction.
- Seismic shock—Frequency/severity.
- Lightning—Frequency.

Climatic factors must be regarded as the natural hazards common to all elements of building in a given location. Their values, and hence their significance to the designer, vary from region to region; some, notably wind, can vary widely within one location. Climatic factors can also change over time as can be seen with the present changes to the ozone layer and their effect upon world climate. Each factor must be evaluated for each roofing project and the total roof design must be developed for those specific conditions.

Geographic location can also have a direct influence on selection of the most appropriate roofing system.

If the project site is remote, or access for equipment (such as cranes) is limited, it will not be feasible to hoist large rolls of single-ply material onto the roof.

WORKMANSHIP FACTORS

All waterproofing materials depend upon site labor for their initial application and for their subsequent care and maintenance. Successful application in refurbishment[4] and repair, as well as in new work, requires:

- Weather conditions are such that site seaming and fixing the membrane can be carried out effectively.
- The correct materials are available to allow installation of the complete roofing system.
- Comprehensive instructions are given on all aspects of the installation including work methods and sequence.
- The labor force is properly equipped, trained and instructed in the particular roofing system.
  - It cannot be assumed that a roofer experienced in one material can transfer to a different material without training.
  - Plastics, rubbers and bitumens all require particular workmanship skills. If trained labor is not available, use a different material.
- The work is formally inspected and commissioned on completion.

DESIGN SOLUTIONS

The designer must take into account all the factors described (as well as local legislation on such matters as energy conservation, fire, appearance, etc.) and engineer a solution which meets the client/user brief within budget constraints.

If the designer is not familiar with a product, he should take pains to study it carefully before specifying it for the first time. It is always worthwhile to seek advice from others who have used the material, to visit job sites to see it being installed and then to tackle a small project first to obtain experience.

It is possible the client will be unwilling or unable to fund the appropriate solution, in which case he can be shown the options for alternative solutions with different capital costs and a different expectation of life to renewal.

Such costing exercises to assess the life cycle cost of a particular design solution are commonly applied to many building services, fittings and finishes. If costing exercises are to be applied to roofing, realistic data is needed on performance characteristics of different membrane materials, data which most manufacturers are unable or reluctant to provide.

Such reluctance is understandable in the absence of agreement on service conditions for their materials. It is in this context that the work of RILEM/CIB Joint Committee on Membrane Roofing Systems should be viewed. This work is directed in part at reaching the international agreement and codification of rooftop conditions as a basis for systematic design; the information, together with that provided by current methods of material testing already referred to, should form a sound basis for impartial assessment and selection of suitable waterproofing systems.

The author's research has highlighted certain key factors which have a fundamental influence on long-term performance of a flat roof. They are significant enough to outweigh substantial differences between membrane materials.

Directly related to the climatic factors already noted, they can be identified as:

- Structure.
- Wind.
- Thermal.
- Condensation.
- Drainage.
- Protection.
- Penetrations.

STRUCTURE

Construction of the roof structure should be sufficiently robust to provide adequate support for the roof slab/deck and its covering without undue deflection or flexing. Movement in building constructions is unavoidable; it stems from deflection under load, changes of moisture content and of temperature, settlement, and the effects of wind. It may occur only once or recur at greater or lesser intervals, it may be slow or rapid, it is seldom—if ever—uniform and it is frequently multidirectional. Waterproof membranes (other than in specialized applications such as tension or air-support structures) require full and continuous support.

The nature of that support—heavy as with concrete or light as with thermal insulation—has a direct and important influence on the optimum method of attaching the waterproof covering (and any insulation) to the roof.

When anticipated movement in the structure requires the provision of structural movement joints, those joints must be extended through the entire roof construction including the covering.

Many substrates are made up of panels (plywood, particleboard, wood wool, thermal insulation boards) in which dimensional changes result in significant variation of joint gap size.

Stresses which cause movement in the substrate should be isolated from the waterproof layer; to adhere a thin membrane to a moving substrate is to court disaster. Joint taping, partial bonding, loose lay and mechanical attachment all allow differential movement between the substrate and waterproofing, and so reduce the risk of membrane failure.

WIND

Wind creates powerful forces tending to tear off roof coverings. Those forces must be resisted by the combined dead weight of the coverings and the means of attaching them to the roof. National building codes commonly contain requirements to ensure safety under wind loads which can be assessed from local climatological data. The UK code[5] contains a method of calculating pull-off forces on a flat roof which enables the designer to assess accurately the appropriate means of attachment.

Unfortunately, while manufacturers of fasteners are able to provide test evidence of individual fastener performance, there is still much to learn about optimizing mechanical attachment to different supports, about bitumen adhesion, and about the effects of wind scour on ballast.[6]

THERMAL

Building provides a controlled environment for daily activities. We establish the temperature and relative humidity which best suit those activities, and the building envelope is expected to cope with the differences between inside and outside conditions. National energy policies, and market forces, ensure the provision of thermal insulation as part of that building envelope to conserve valuable energy.

An exposed waterproof covering is subject to a wide range of temperatures; variations of 80°C have been recorded. While a high density substrate will provide a thermal sink and so relieve some of these stresses, a low density substrate (such as thermal insulation) will concentrate them into the waterproof covering. Different layers of the roof construction react at different rates to temperature changes leading to differential stress between the layers.

While Bonafont[7] and others have shown how bitumen reacts to such conditions, thermal stress has been the cause of countless membrane failures in the past.

International standardized methods of test allow us to assess the performance of sheet materials under conditions of thermal cycling. The designer must be alert to the effects of dimensional change in the membrane on mechanical fixings and edge details. Reduction in membrane dimension due to aging or drop in temperature will induce stress on the membrane and on the fixings.

CONDENSATION

Many buildings contain large quantities of water vapor as part of their everyday function (swimming pools, bakeries, laundries and kitchens are obvious examples). The vapor in a heated interior creates a pressure differential between inside and outside atmospheres, i.e., across the building envelope.

Waterproof coverings on flat roofs are, by their very nature, highly resistant to the passage of water vapor; most are for all practical purposes vaporproof as well as waterproof. By placing such a membrane on the outside of the average (heated) building, the natural tendency for moisture to migrate from inside to outside is inhibited and so creates a potentially damaging "fail unsafe" condition.

National codes in Britain[8,9] and other countries have long recognized this problem and include calculation methods to enable the designer to assess condensation risk together with recommendations on how to avoid damage to the roof fabric.

Field investigations have frequently shown excessive condensation as the cause of reported leaks and have revealed substantial damage to water-sensitive insulation, fasteners and decking.

DRAINAGE

The frequency, type and quantity of precipitation are determined by geographic location. All the water that falls on a flat roof must eventually drain off as the surface is totally impervious.

During peak rainfall the roof may act as a temporary reservoir, but standing water (ponding) should be avoided. Ponding is unsightly, encourages the accumulation of silt and hence plant growth, may overload the structure and, in the event of failure of the membrane, greatly increases the consequent damage.

Drainage of a notionally flat roof requires surface slopes sufficient to ensure water run off. A fall of 1:100 (1/8 in. per foot) may be sufficient for a smooth surface but 1:40 (5/16 in. per foot) may be needed for a ballasted roof. Allowance must be made for deflection of the structure, for inaccuracy in building and for surface irregularities, all of which can reduce a theoretical slope to zero, or worse still a backfall.

Drainage falls must discharge water to gutters or outlets sized and located so as to take the water safely to drains. The safest discharge is achieved by extending the roof over and beyond the wall (this has the great merit of protecting the wall from the worst effects of the weather). However, internal outlets and downpipes are unavoidable on larger roofs and in extremely cold climates they may be preferred because of the problems caused by icing of external gutter systems.

The designer should determine, from climatological data, the frequency and duration of maximum rainfall so that drainage provisions can be sized and located to suit.

In the United Kingdom, the BS6367[10] gives comprehensive guidance on the necessary calculation methods.

PROTECTION

Flat roofs have many positive attributes, they can provide usable surfaces which have a significant economic value. Usable means accessible, and the roof must be designed to suit the intended use by providing appropriate access, security and roof surface protection.

This paper identifies four categories of use:

- Non-access roof.
- Foot access roof.
- Vehicle access roof.
- Roof garden.

Non-access roofs need no permanent fixed access provision and perimeter guard rails are not essential. The only surface protection required is UV and ozone resistance, and the ability to withstand annual care and maintenance inspections.

Foot access roofs are those where regular access is required to service fans, tanks, chillers and similar equipment mounted on the roof, and those intended for recreational use as a balcony or terrace. Here it is essential to provide perimeter security, and access should be by permanent fixed ladders or stairs. The membrane must be protected against foot traffic and against risk of mechanical damage from dropped tools, and from point loads (from the legs of tables and chairs, etc.).

Vehicle access roofs and roof gardens each present special problems for the designer. Such roofs will obviously be designed to suit the size and number of vehicles and people involved with access and with perimeter barriers. Subsoil drainage from gardens and drainage from ramps and decks must withstand silt, road salts, oil and chemicals which can damage the waterproof layer. Protection is essential in the form of an overlay or wearing surface.

The merit of protecting the waterproof covering against thermal stress has already been noted (such protection may be combined with protection against mechanical damage and wear). A protection layer will involve additional dead weight which may well contribute to protection against wind blow off.

It has been found that any type of waterproof covering can be expected to give extended service if covered by a protection layer. The protection should be appropriate to the roof use category and should extend to all upstands and vertical work. Reflective paint does not provide an adequate protection layer, but metal foil and mineral surfaced cap sheets to built-up felt roofing, stone aggregate on felt and asphalt, ballasted insulation in inverted warm roofs (protected membrane roofs), gravel and pavers in ballasted loose-laid systems have all been found to work well in practice.

PENETRATIONS

Any penetration of a waterproof covering is a potential leak. Penetrations are, however, required for many purposes including rainwater outlets, roof lights, chimneys, vents and the fixing of guard rails, lightning conductor tapes, etc.

Each penetration should be the subject of special detailing which assumes temporary standing water of some 75mm depth and takes account of possible differential movement.

Asphalt and other liquid-applied coatings may be readily and easily formed to complex shapes.

Sheet materials, however, are essentially two-dimensional; their detailing should always be considered in three dimensions in order to appreciate the complexity of cutting and sealing the waterproof layer.

Many flat roofs, condemned in their entirety as failures, have in fact been failures of detail work at penetrations.

CONCLUSION

The approach to flat roof design outlined in this paper is of great benefit in selecting and specifying waterproof coverings for different conditions. It is greatly assisted by the use of various computer-based design aids including software to calculate wind uplift, thermal performance, condensation risk, drainage requirements and whole-life costings.[11]

The classification of waterproofing systems by the FIT index[12] has been studied. It is described in another paper in the *Proceedings* and can be used to correlate the performance of a particular material to the requirements of the user.

By addressing the key factors described in this paper, the designer can achieve a perfect flat roof: "perfect" being defined as one which provides predictable performance over a predicted time at predicted whole-life cost.

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