Getting the Roof Right the First Time

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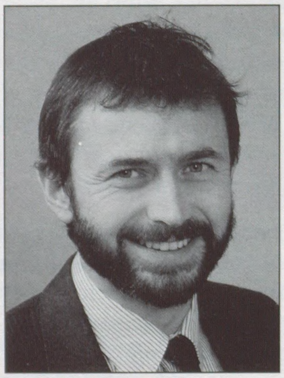
Abstract

This paper summarizes practitioner research and offers constructive feedback from investigations on a wide variety of roof types. Two common mistakes are the inadequacy of the roof design and the widespread use of constructions which could be described as "infirm" with narrow margins of error.

Understanding the real in-service behavior of a roof system is complex and follows from an appreciation of the relationships among four disciplines: waterproofing, structure, heat and vapor control, and material science. For special situations such as roofing above humid interiors or in exposed locations, this whole system approach is even more necessary, demanding that designers have a good working knowledge of all four disciplines. Reliable and concise design guides are sought.

Responsibility for the various elements of the design work has become divided and confused, especially in the highly competitive 'design and build' form of contracts popular in the United Kingdom (U.K.).



Keith Roberts

Introduction

Roof systems that fail to perform are expensive in environmental terms. Initially, there is a waste of time and resources allocated to drying out water leakage or condensation, and often requiring the making good of decorative finishes. Over a longer period of time, the life span of the roofs is reduced such that materials need to be replaced more frequently. Ineffective thermal insulation increases the energy demand of a building.

Unsatisfactory roofs are also expensive in financial terms. One national study looking at corrosion of metal roofs estimated that the cost of premature roof failures in the U.K. alone is in the order of 40 million pounds ($61 million) per year. That translates into a high cost for individual companies, both in terms of senior management time and soured client relationships. Thankfully, the majority of new roofs do meet with the satisfaction of their building owners. It is the occasional few that leak, collapse, or blow away; all too often these are major buildings of national significance. Why is this?

Background

Rollinson Glanville Consultants has, since 1975, investigated more than 500 roofs of most forms of construction throughout the U.K. and Ireland. Its client base is broad and includes building owners, their professional advisers, major contractors, roofing contractors, and manufacturers of roofing systems. Consequently, the firm is independent and unbiased and this paper is offered as a fair and balanced view.

Looking back through our records of roofs inspected during the normal course of our work, the distribution of roof types and the need for the inspection is summarized in Figure 1. Approximately one third of our work is litigious. The size of the roofs varies considerably. At one extreme, we have investigated a domestic garage roof of 40 square metres (430 sq. ft.) — at the other end of

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Roof Type	Purpose of Inspection						
	Defective Roofs						
	Wind Damage	Leakage	Condensation	Durability	Preventative Maintenance	New Build	Total
Membrane	10	28	-	3	16	5	62
Sheet & Tile	5	37	16	31	11	7	107

Figure 1. Summary of individual roofs inspected between 1991 and 1994.

the scale, a large industrial warehouse of 86,000 square metres (925,000 sq. ft.). Remarkably, there was a similar number of leaks in both roofs!

Principle Causes of Roof Failure

In the past, the basic underlying causes of a building defect have been categorized into one of three divisions: design, workmanship, or materials.

In our experience, most problems stem from a combination of the three in different proportions. When liability is at stake, it is the balance of these proportions that is of keen interest to the various parties. Reaching a settlement on what these proportions should be can become extremely complex and take months or years to resolve. Formally presenting the issues in court is so time consuming and costly that commercial settlements are usually agreed upon before reaching a full trial.

Reviewing the 169 buildings we have investigated and reported on over the past four years, one of the greatest common weaknesses has been the inadequacy of the roof design. All too often, we have found that design tasks were simply not carried out. Explanations for this have included a lack of adequate design time, common misunderstandings of design principles, inaccurate technical guides, and ambiguous manufacturer literature. Above all, the most common cause is probably confusion and misunderstanding among the parties concerning who is actually responsible for the roof design. Improvements to these areas of weakness will be discussed later in this paper.

The importance of appropriate standards of workmanship can never be underestimated. The constant need to encourage tradesmen to work with care and diligence in using their gas torch, bitumen ladle, or hot air gun (often working in exposed places and in difficult weather conditions) is a constant challenge to the waterproofing industry. The competitive world of subcontract labor provides a strong disincentive to invest in training and to do the job properly.

Thirdly, we turn to the materials division, which again is strongly motivated by the need to be competitive in a crowded market. Our investigations indicate that some generic types of roof assemblies tend to fail more often than others.

Infirm Roofing

The term 'robust technologies' has been used to describe those building methods which have proved to be stable and reliable. They are well understood by designers and contractors alike and are detailed in textbooks and manufacturers' literature. They are relatively insensitive to errors of design, manufacture, assembly, or use. These building methods have upper and lower bounds to their performance, beyond which the technology is no longer robust. Hence, the opposite term 'infirm technologies' can be used to describe building methods which are sensitive to errors of design, manufacture, assembly, or use.

The feedback from our roof investigations suggests that many constructions which were once considered to be robust are becoming infirm. We can examine this process by considering a detailed example from British practice: the sheet metal roof commonly used on industrial buildings.

The original robust method involved a single skin of overlapping sheets laid to a slope exceeding 15 degrees, as for tiles. Since the slope was free draining, even in windy conditions, there was no need to seal the end laps. This gave the additional benefit of allowing natural ventilation to the underside of the weathering sheet and reducing the risk of condensation.

In recent years there has been a trend to lower the slope of the roof, apparently to reduce the overall height and volume of wide buildings. To maintain the waterproofing properties of the metal roof cladding system laid at a pitch of less than 15 degrees, a fully sealed system is required. This places a heavy reliance on the narrow band of sealant sandwiched within the end and side laps, which must be continuous and fully adhered to both the upper and lower surfaces. In practice it is found that these sealant tapes are difficult to lay successfully in exposed rooftop locations and they do not fully adhere to cold and damp surfaces. A secondary problem is that the laps are no longer ventilated, so that there is an increased risk of condensation forming on the underside of the sheeting.

Our roof inspections have found that it is common for small amounts of rainwater to pass through partly sealed laps on low-pitched metal-clad roofs. This problem is particularly apparent on single skin roofs with a weak side lap profile, or on double skin roofs where the internal liner sheet has been perforated for acoustic reasons. Additionally, the condensation problems seem to be worsening because this type of roof construction is now regularly used above heated buildings with high internal vapor pressures.

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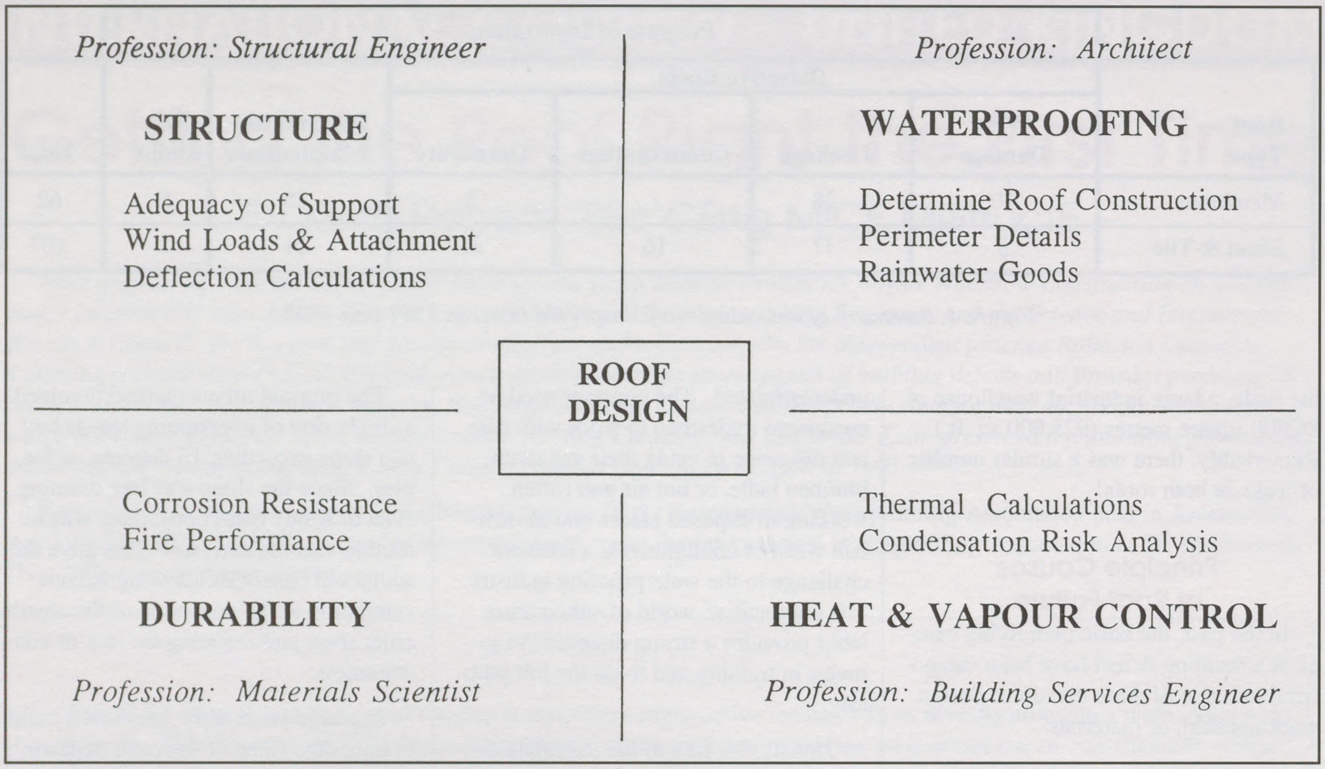

Figure 2: Four Discipline Model

The above is one example of a well established robust method becoming infirm. Other roof systems which have become less robust and more sensitive to errors include:

1. Mastic asphalt laid directly over insulation. In recent years, this has been specified in greater thicknesses. The reduced heat sink effect from the mass of the building is resulting in greater thermal movements in the asphalt on warm summer days and is causing detrimental secondary effects on lightweight pedestrian tiles and surface finishes.

2. Thermoplastic roof lights on low pitched metal roofs, assembled in two skins to reduce heat loss during the winter months. In the summer the top skin becomes hotter, tends to sag more, and induces greater differential movement at the perimeter supports.

3. Fully supported metal roofs, above heated buildings. The introduction of insulation, combined with higher internal vapor pressures, has resulted in a greater condensation risk in the plywood substrate, leading to reverse side corrosion in anaerobic conditions on lead, zinc, and aluminum roofs. Effective ventilation within the roof construction has become essential.

These and other established methods of forming roofs have evolved and become infirm. New and innovative techniques which have not performed satisfactorily could equally be described as infirm. There is a need for those involved in the waterproofing industry to learn from recent experiences using an effective feedback system. This will enable them to develop more robust technologies like, for example, self supported metal roof systems with concealed attachments.

Understanding the Performance of a Roof

To understand how a roof is performing, one has to look at the whole system and consider how it behaves within its own local climate through the four seasons. But what are the specific tasks involved in a holistic roof design, and which profession is the best qualified to undertake them?

A popular method to assist in understanding a problem is to develop a theoretical model, and the "Four Discipline Model" shown in Figure 2 is offered for discussion. The model recognizes that the techniques and skills needed for the design of a roof are drawn from at least four different disciplines: architecture, structural engineering, building services engineering, and material science. Some would argue that fire engineering is a separate discipline on its own, while others may claim that a civil engineer is well qualified to cope with the majority of tasks. It is important to recognize that designing a roof demands a multi-disciplined approach and a good working knowledge of all four disciplines. All too often the training of construction professionals has become isolated into discrete divisions.

For many traditional roof constructions, a rigorous design approach may not be appropriate. However, for special situations such as the humid environments above a swimming pool or in a textile factory, or in exposed locations with high wind suction loading, the need for the multi-disciplined approach is essential. The model is also helpful for retrospective investigations of roof con-

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structions which are failing to perform.

One other useful lesson we can draw from the model is that each of the four disciplines interrelate with one another. For example, consider a flat roof above a textile factory. The roof slope is low, requiring a membrane (waterproofing). The internal air temperature and relative humidity are high, requiring thermal insulation and a vapor control layer (heat and vapor control). Around the perimeter of the roof the wind suction loading will be greater than the bond strength of the weakest link in the roof build up, requiring mechanical fixings (structure). The screws puncture the membrane which tears under cyclic wind action, resulting in warm moist air meeting cold external surfaces and condensing (heat and vapor control). The water is trapped within the roof, resulting in the steel fasteners rusting and ultimately breaking (durability). Under stormy weather conditions there are high wind suction loads, resulting in the membrane becoming detached (structure). The loose waterproofing layer tears at the roof edge, resulting in water ingress (waterproofing).

Case Study: Deal Leisure Pool

In January of 1992, we were commissioned by the owners of Deal Leisure Pool in Kent to investigate the causes of water dripping from the ceiling of the insulated metal roof construction. Figure 3 shows a cross section through the building. On opening up the roof, it was found that the vapor control layer (vcl) was not lapped properly and was discontinuous, allowing condensation to form (heat and vapor control). Along the top edge of the large roof light, the gutter had not been laid to a fall and the seals were poor (waterproofing). Many of the fixing screws were missing, presenting a high risk of wind blow-off since the exposed site is within 500 meters of the sea front (structure).

Even with a good standard of workmanship, it would have been easy to puncture the polyethylene vcl, and when considered with the ineffective natural ventilation below the outer metal roof cladding, one could reasonably describe the construction as infirm.

We were subsequently commissioned to design a new roof and to provide advice to the site team. A PVC single-ply membrane was chosen for the weathering skin, with its low vapor resistance allowing any water vapor that passes through the vcl to migrate out of the roof over a period of time. Figure 4 (next page) shows the new roof construction.

There were two distinguishing features. Firstly, to reduce vapor loss through the vcl at the fixing penetrations, the flanges of the top hat batten were clamped to the deck using a sealed rivet. Secondly, to improve the external appearance of the grey colored PVC membrane (which is clearly visible from ground level and expected to show dirt stains with time) a batten roll rib detail was developed using PVC coated metal. This has the effect of introducing a surface feature to the roof to take one's eye away from the plane of the membrane, while at the same time acting as the mechanical anchorage point.

The roof was successfully completed in the spring of 1993, and two years later the building owner has reported no more roof leaks. In addition, the energy demand for the building has fallen, confirming that the old roof was thermally ineffective.

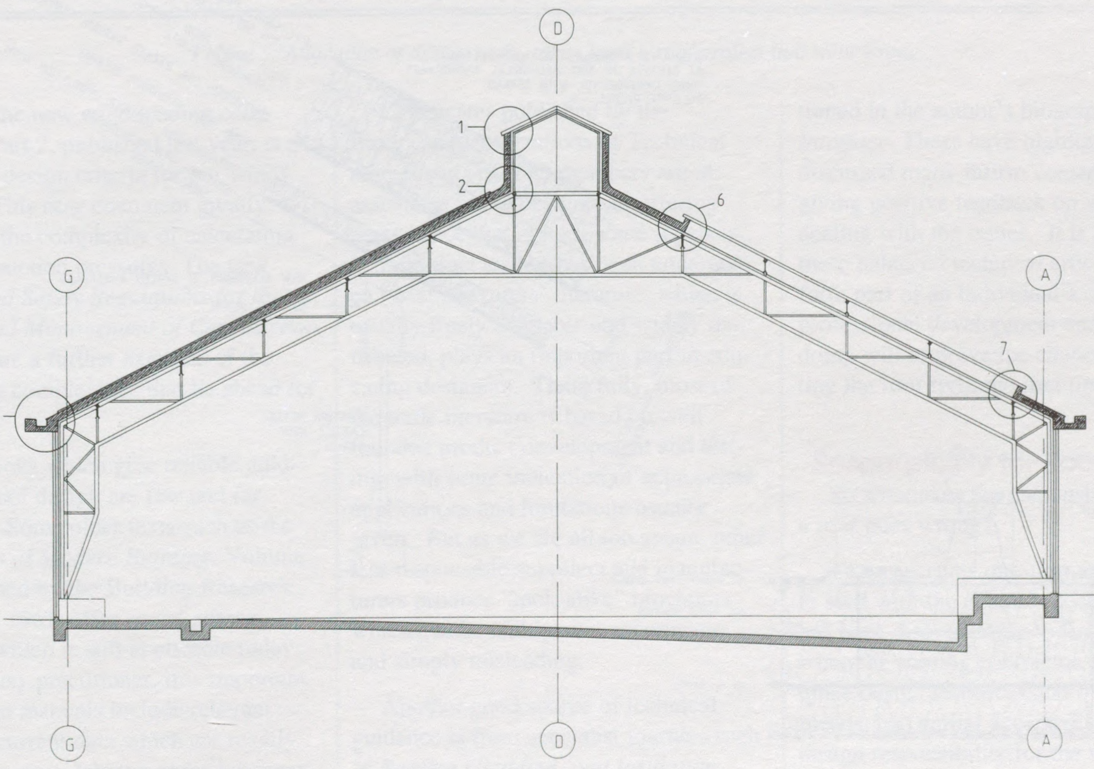

Figure 3: Typical cross section 'A' through Deal Leisure Pool.

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The Roof Designer

So, who actually designs the roof? Textbooks and product literature routinely refer to the "Roof Designer" as if there is an individual charged with this responsibility. But is there such a person?

The case study was a little unusual in that one person carried out the initial investigation and then went on to design the new roof construction. In the U.K., there are a few specialist designers, although the design of a single roof is usually divided among a wide number of parties. Figure 5 gives an example of how the individual design tasks were undertaken by different parties for one particular roof project (not the case study), which happened to go wrong: an important element of the waterproofing system simply wasn't designed.

The valley gutters leaked. The inadequate design of the rainwater goods is a typical result of the fragmented nature of the industry where there is often poor coordination between, in this case, the manufacturers of the down pipes, outlets, internal gutters, and roofing system, coupled with the inadequate overall design supervision. If we were asked what single task should be done to reduce the incidence of water ingress from roofs, it would be that one person should design the complete rainwater goods system, starting from where the raindrop falls on the roof to the point of discharge into the underground drains. This person would check that the components are properly positioned and adequately sized, and that they actually fit together.

Over the past ten years we have seen the growth in the U.K. of manufacturer, importer, and specifier organizations. These have been responsible for specifying and supplying materials for a large number of flat roofs throughout the country. This is a good example of a single party taking control of the roof design. To achieve this, the designers preparing the specifications need to be experienced and properly trained to follow the prescribed set of options and standard details in a considered quality procedure.

For the one-off job where the design and construction team are selected just for that project, the demands on the roof designer can be great. Where there is a lack of experience within the team, heavy reliance is placed on the published technical guidance.

Published Design Guidance

From our investigations, we have often found that, when advising on liability, one of the key issues becomes the published design guidance. What should a competent person have known?

The most important documents are the mandatory standards and national regulations, with the expectation that those undertaking the elements of the design have a working knowledge of the relevant codes. With the forthcoming release of large numbers of European standards, this will not be an easy task. Many general practitioners have found it difficult enough to keep up with changes in national standards. For example, in

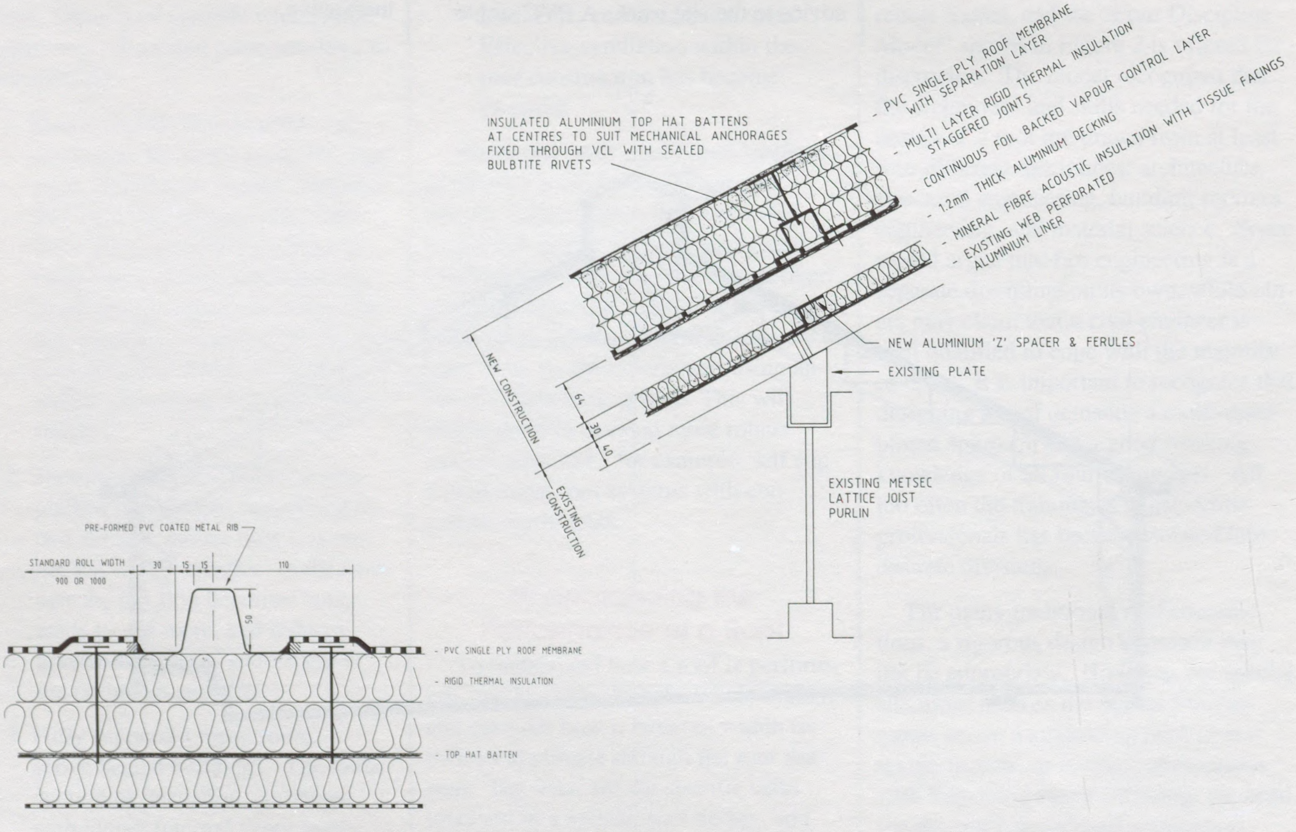

Figure 4: Details of new roof construction.

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Party	Design Task
Architect	- Determines roof plan and slopes - Specifies finished appearance - Co-ordinates interface details
Structural Engineer	- Determines support positions - Checks attachment strength under wind loading
Quantity & Cost Consultant	- Gives financial budget
Decking Manufacturer	- Develops and tests his component
Fastener Manufacturer	- Develops and tests his component
Membrane Manufacturer	- Develops and tests his component
Insulation Manufacturer	- Calculates thermal properties, condensation risk analysis - Develops and tests his component
Waterproofing Manufacturer	- Develops and tests his component
Main Contractor	- Programmes work - Dictates direction of work
Roofing Contractor	- Co-ordinates roof assembly - Proposes method of work
Mechanical & Electrical Contractor	- Positions the holes for pipes and air extracts
Question: Who designed the roof?	

Figure 5: Allocation of design tasks, taken from a roof project that went wrong.

the U.K. the new wind loading code BS6399 Part 2, published last year, is a dominant design criteria for our windy islands. This new document greatly increases the complexity of calculating the wind suction pressures. The new *Health and Safety Regulations for the Design and Management of Construction Projects* are a further example of the increasing complexities that lie ahead for designers.

Textbooks which give reliable guidance on roof design are few and far between. Some older texts such as the *Principles of Modern Building*, Volume II, published by the Building Research Station in 1961, offer sound advice, much of which is still applicable today. For the busy practitioner, it is important that design manuals include relevant tables of current data which are readily accessible, since lengthy prose tends not to be read.

Certificates published by the European Organizations of Technical Agreement (EOTA) members are of assistance to the designer in offering reassurance that at least some independent product testing has been undertaken. Manufacturers' literature, which is usually freely available and widely distributed, plays an important part in educating designers. Thankfully, most of the trade literature is based on well founded product development and testing, with some indication of appropriate applications and limitations usually given. But as we are all too aware, other less responsible suppliers and manufacturers produce "look-alike" brochures which can be ambiguous, incomplete, and simply misleading.

Another good source of technical guidance is from specialist journals such as *Roofing Cladding, and Insulation* (publisher of "Technical Notes" mentioned in the author's biography) and *Interface*. These have highlighted and discussed many infirm constructions, giving positive feedback on ways of dealing with the issues. It is hoped that these balanced technical articles will form part of an individual's continuing professional development and in so doing will improve the chances of getting the roof right the first time.

Responsibility for Roof Design

So who takes the responsibility when a roof goes wrong?

To answer this question, it's helpful to start with the contract documents. It has been disconcerting to find occasions when the roofing contractor, with inadequate design resources and of limited means, had earlier accepted an onerous design responsibility for the whole roof system, presumably at a time when he

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was keen to win the contract. His failure to understand his liabilities and to seek design guidance at an early stage has been an important contributory factor to a number of roof failures.

Within the U.K. over the past ten years there has been a significant growth in the number of "design and build" contracts for the construction of all types of buildings. In principle, the contractor gives a price to the promoter for building the project based on an outline specification, and the contractor then commissions an architect and engineer to do the detailed design. It has been our recent experience that this form of contract places great demands on the contractor's design coordinator, especially for complex roof constructions. When there is a large number of specialist subcontract packages with complex interfaces, the design responsibilities can easily become confused, particularly when there are strong incentives to cut costs wherever possible.

One technique which could assist the design coordinator or the roofing contractor would be to adopt a design audit system. This could take the form of a schedule of design tasks and be divided into the four disciplines to ensure that all of the tasks have been included. In the light of experiences with some quality assurance systems which have degenerated into a paper chase, leaving the roof to be built unsupervised, one is cautious to recommend yet another checklist. It would, however, be a positive action with the objective of ensuring that the whole roof is properly designed.

Recommendations

1. Greater respect should be given to the design of a roof and, in particular, the rainwater goods system, with appropriate resources allocated to the task and the adoption of a design audit promoted.
2. It should be recognized that some roof systems can be described as "infirm" and are sensitive to errors at all stages of the construction sequence.
3. Feedback should be passed from the construction and maintenance teams to designers and manufacturers. This would improve the common understanding of the real performance of roofs, encouraging manufacturers and promoters of infirm assemblies to develop more robust construct-ions.
4. There is a need to clarify and improve the understanding of design responsibilities, especially on "design and build" contracts.

Conclusion

This paper has brought together the thoughts and observations from a multi-disciplined team of engineers and architects that has inspected a wide variety of roofs throughout the U.K.. It is hoped that by allocating greater resources to the design of roof constructions, the number of roof systems that fail to perform will be reduced. Thus by "getting the roof right the first time", there will be both financial and environmental advantages to be gained by all.

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This is the first of regular articles devoted to international roofing. All RCI members and nonmembers outside the U.S. are encouraged to submit technical papers and articles. *Interface* will also consider certain reprints from other publications and proceedings and welcomes all suggestions. Please contact Lyle Hogan at (910) 768-7185 or call RCI Headquarters and ask for Jeanette.

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