Abstract

This paper reports the current state of condition assessment flat roofing and its impact on assessing the durability of flat roofs in the UK. The paper is intended to provide information to support the development of approaches to assessing the durability of flat roofing. This included the development of expert system and to this end the paper report work undertaken by or in close co-operation with the BRE upon diagnosis and condition assessment expert systems.

Keywords: flat roofing, condition assessment, expert systems.

1 Introduction

The typical design life of a building in the UK is considered to be 60 years. Recent experience has shown that the durability of flat roofs is not that long and the roof will need to be replaced at least once during the building life span. In effect the 60 years life is a notional lifetime attributed for insurance purposes and buildings do last longer than 60 years. The waterproof membrane of a flat roof will need replacing at some stage during the service life of the building due to the durability of the membrane affected mainly by natural weathering. In the U.K. there is a substantial amount of information in the BFRC/CIRIA guide on “Design and Good Practice”. It recognizes that the relatively recent inclusion of thermal insulation together with changes in building methods has led to the premature failure of a number of flat roof membranes. The reason for these failures can be due to design, materials or their interaction and installation. A failure of the roof membrane can be a combination of these factors resulting in sometimes a unique failure exceptional to one particular
roof, this can make assessing the durability at the design stage very difficult. There are however a number of faults which do occur frequently and can be recognized so that appropriate guidance can be given to avoid them in the future. Recognizing these faults and their symptoms is a part of the information given by a condition survey of the roof. Being able to assess the importance and impact of these faults is an important step in developing an approach to predict the durability of flat roofing.

The next section of this paper details the current state of the art in terms of flat roofing and the assessment of flat roofing in the UK. It is strongly felt that this information will be a critical factor in developing a successful approach to assessing and predicting flat roof durability.

1. Materials used in the UK for flat roofing membranes

The majority of flat roofs in the UK have membranes made from bituminous materials. The use of plastic or rubber sheets for flat roof waterproofing has increased in recent years.

1.1 Bitumen roofing felts

In the UK it is common for a bituminous membrane to be built-up in a number of layers. The roofing felt is supplied as a reinforcement or carrier that has been impregnated and coated with bitumen as part of a manufacturing process. The surface is coated with fine sand to prevent sticking in the roll. It is common for capsheets to be coated with mineral flakes or granules. The reinforcement or carrier can be organic fibre, asbestos, mineral (including glass) or polyester. Although asbestos carriers are no longer manufactured in the UK it is still possible to find roofs which have this type of covering. The most common way of forming a built-up membrane is by fusing the layers together using hot molten bitumen.

Although the bitumen can be polymer modified a built-up membrane which has polyester reinforcements is referred to as “high performance” regardless of the type of bitumen used. Built-up membranes made from high performance felts have been used successfully in the UK and have a service life of at least 20 years.

1.1.2 Mastic asphalt

Mastic asphalt is a bituminous material that has fillers such as limestone added to it together with fine aggregates to form a hot liquid applied membrane which can be used for roofs, floors or roads. In the UK mastic asphalt has been widely used for the waterproof membrane on concrete decks. Mastic asphalt is laid over a separating membrane to isolate it from movements in the substrate. There are examples of mastic asphalt roofs about 70 years old. The introduction of thermal insulation into roof designs and the widespread use of lightweight decks has shown that traditional mastic asphalts do not tolerate movement especially at the edges of the roof. Modern asphalt is modified with suitable polymers to enhance its performance.

1.2 General condition survey of a flat roof

This section deals with a general condition survey developed at the Building Research Establishment to be included in a Good Repair Guide (BRE Good Repair Guide 16). It shows how much information is required just to interpret a simple
external inspection. There is insufficient space here to show what factors influence the next important decision to replace or refurbish based on the condition survey.

Before embarking on any work on a flat roof it is essential to carry out a careful and detailed assessment of its condition. There is no point in carrying out repairs to the waterproofing membrane if there are serious problems in the roof structure. It is also wasteful to replace an otherwise sound roof when a repair would have been adequate.

1.2.1 History of the roof

The first thing to do is to find out about the roof's history. The information needed is:

- How old is the covering
- Has the covering been repaired before
- For how long has the roof been defective
- If the roof is leaking, does it leak during or immediately after rainfall? or a few days later?
- Does water pond on the roof?
- What is the room below used for? (Flat roofs above kitchens, bathrooms or utility rooms are more vulnerable to condensation problems than those above living rooms or garages.)
- Are there plans for change of use? is the roof used as a balcony or terrace? or are there plans to use it as such.

1.2.2 Visual inspection

The next step is to make a thorough visual inspection, both outside and inside the building. Before getting up on the roof make sure it is safe to do so. If the roof is sagging between joists do not walk on it. If possible carry out an inspection immediately after rainfall so that you can see any ponding or leaks and watch the speed of drainage.

1.2.3 Inspection check list

Table 1 below is a check list for an external inspection together with an interpretation of what the findings mean. This is general advice and is based on many years of inspecting flat roofs.

1.2.4 Other considerations

The BRE Good Repair Guide also has a check list for looking at the edges of the roof where faults often occur at edge details. Detailed information is given on faults in membranes, checking for condensation, problems with parapet walls, thermal insulation and fire performance.
Table 1: Typical inspection check list

<table>
<thead>
<tr>
<th>What to look for in the general flat area of a roof</th>
<th>Cause or Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are there any signs of previous repairs, and are they all in the same place?</td>
<td>This indicates that the original repair has been done poorly. Carry out proper new repair. Several patches mean a general problem. If the roof has dried out then overlay with a new covering. Otherwise, consider replacement.</td>
</tr>
<tr>
<td>Has the membrane been punctured? eg by cable clips.</td>
<td>If yes, a localised patch repair is needed. If there is a line of holes then it may be better to overlay with a strip of high performance felt.</td>
</tr>
<tr>
<td>Is there flowing, rippling, cracking or crazing?</td>
<td>This tends to indicate old age, particularly of mastic asphalt.</td>
</tr>
<tr>
<td>Are there splits holes or ruckles?</td>
<td>A hole may be caused by damage. Localised patch repair will be sufficient if cause can be established. Ruckles and splits are associated with substrate movement.</td>
</tr>
<tr>
<td>Are there blisters?</td>
<td>The likely cause is entrapped water or condensation. If blisters are small, inspect regularly. If they grow then further investigation of a condensation problem is needed.</td>
</tr>
<tr>
<td>Have the lap joints pulled or lifted?</td>
<td>This can be a problem with older membranes. In severe cases remove the old covering and replace with high performance felt checking other roof components. Filling with sealant is a short term solution and is rarely effective.</td>
</tr>
<tr>
<td>Has the roof been surfaced with chippings, solar-reflective paint or a factory-applied mineral surface(bitumen felts only)? Is the surface damaged or absent.</td>
<td>Solar reflective paints need maintenance about every 5 years. The wrong types on mastic asphalt can induce surface cracking. Chippings may be blown away by the wind if they are not secured in a surface dressing. In this case, the old ones should be removed and a new dressing compound and chippings applied.</td>
</tr>
<tr>
<td>Is there ponding of surface water?</td>
<td>Ponding can be tolerated by high performance felts and mastic asphalt. Combined with other symptoms it can indicate major problems.</td>
</tr>
<tr>
<td>• Is there excessive deflection, springiness or sponginess in the roof.</td>
<td>Deflection or sagging may affect the flow of water off the roof resulting in ponding and additional loading on the structure. It may be caused by: incorrectly designed structural components, or degradation of components.</td>
</tr>
<tr>
<td>• Is there flooding in gutters or above roof outlets.</td>
<td>This indicates a drainage problem. If flooding extends up to flashing level water can enter the building.</td>
</tr>
</tbody>
</table>

1.3 Repair, refurbish or replace

The decision to repair or replace the waterproof membrane is not an easy one to make despite having carried out a detailed assessment of the roof. Cost is always an important consideration but there does come a point when patching an old roof frequently is less cost effective than replacement with a new roof, especially considering the internal damage a severe leak may cause. A table has been developed in the Good Repair Guide which gives further guidance on the decision to repair or replace taking into account age of the roof. It is also apparent that a roof may exhibit more than one symptom and that the whole table should be studied before making a decision.

1.4 Comments on roof survey

The checklist stated above is just a part of that required for a full and comprehensive roof survey. The results of the condition survey lead to many situations and the BRE Good Repair Guide is only general in nature. To cope with the
situation that many roofs are unique would require the development of a much larger set of rules and causes which in paper form would be impractical to develop.

2 Introduction to the use of advanced information technology in support of flat roof condition assessment

The earlier parts of this paper have explained the current state of the art in flat roofing assessment. The BRE Good Repair Guide recognises that observations made at different intervals during the life of a roof covering will lead to different repair proposals. The current view is that a general estimate of service life is 20 years. More information of a specific nature is required to predict service life which in turn means that a much larger set of rules are needed. Other means than note pad and paper are required to gather and interpret this information for a wide range of systems. This part of the paper therefore explains the advances in the use of information technology in support of flat roofing assessment, using as an example a system called ROOF which was developed to aid the diagnosis of flat roofing defects.

A number of technologies collectively known as expert systems have been explored by the BRE. Expert systems are an information technology technique that falls within the IT area known as Artificial Intelligence (AI). Formally AI is the use of techniques developed by the AI community with the aim of making computers reason like human beings. The use of expert systems within the building industry does not have this aim, but is focused on the application of AI techniques to aid the development of computing systems to aid engineering tasks. The use of the term expert system is a misnomer for the role of such computing systems. Expert systems are not experts in a field of knowledge, at best the level of intelligence displayed could possibly be described as "a steady plodder". Expert systems do not generally invent new appreciation of knowledge or understanding of a new problem, but are very good at applying knowledge it already has, without omitting or overlooking some part of the knowledge or task related to the problem being examined. The authors prefer the term "Advisory" or "Assistant" for such systems rather than "Expert".

One significant advantage that the BRE sees deriving from the extensive use of expert systems is the formalisation of the data collected from site visits and examinations. A significant problem for the general assessment of building stock (for diagnosis, condition assessment or service life prediction) is the lack of data. What data that has been collected is extremely variable from one assessment to another assessment. This makes any formal (e.g. statistical) analysis of detailed aspects of the buildings behaviour difficult. To overcome this difficulty the data collection will need to be standardised, this can be best achieved by using an expert system to guide the data collection.

The work on ROOF is only one of several expert systems [Allwood et al 1986; Goodier and Matthews 1996; Dutton, and Maun 1996] that have been developed by or in close co-operation with the BRE. ROOF is a large rule based expert system that can diagnose over 270 defects affecting flat roofs. This diagnosis is undertaken using a rule base of over 1000 rules.
2.1 Background to the development of a roofing diagnosis system

There are numerous reasons why it is advantageous to develop such a computer system to assist the diagnosis of defects in flat roofing, these include:

1. Retention of expert knowledge. The development of an individual into an expert upon a subject is a very expensive task, and is generally achieved over a long period of time. When the individual is lost to the organisation (typically through retirement) the individuals knowledge is also lost to the organisation. A system incorporating some of the individuals knowledge is an effective way of mitigating some of this loss.

2. De-skilling of the task. As mentioned above experts are very expensive, if information about a defective roof can be collected by a less skilled individual supported by an expert system this can be extremely beneficial to the organisation.

3. Ensuring rigorous data collection. Regardless of the quality of the individual undertaking an assessment, important information, data and observations can be easily overlooked. Expert systems can help to avoid this by guiding the information collection. However, importantly, this guidance is targeted and refined and does not suffer from the restrictions of a checklist.

4. Support for design and specification. The ROOF system was designed not only to support diagnosis, that is determining the cause of a roof defect but to also support condition assessment and design checking.

A number of programming techniques were considered, these included:

1. Traditional Procedural Programming. Traditional programming such as 'C' or HTML/Java (web pages) has a number of advantages, such as, a fixed path from start to finish and an inexpensive development environment. However encoding interactive knowledge within such systems is extremely difficult and requires a clear understanding of the knowledge paths and often leads to considerable duplication.

2. Case Based Systems. Case Based Reasoning systems are an expert system technique where example problem cases (with known solutions) are identified as being close or similar to the problem (case) being considered. However the use of this technique for diagnosis (and other tasks) in buildings is restricted due to the lack of readily available and formatted example cases.

3. Rule Based Systems. Rule based systems are another expert system technique. This technique encodes the knowledge (e.g. the knowledge about roof diagnosis) in the form of IF <condition> THEN <conclusion> rules. The set of rules encoding the knowledge is known as a Rule Base. This rule base is searched using a software tool known as an inferencing engine to find the solution(s) to problems. This was the expert system technology adopted for ROOF.

It was envisaged that the ROOF system could be used at several points in the life cycle of a roof, these include:
1. The primary role of ROOF was to aid the on site diagnosis of defect of a flat roof. This can be used to aid the estimation of service life. When the cause (and hence seriousness) of the defect is correctly identified with a significant degree of confidence then the decision about repair or replacement can be undertaken with an improved degree of confidence.

2. As a tool to check condition. It is obvious that the knowledge used by an expert to diagnose a defect in a roof has a lot in common with the knowledge used to check a roof condition and likely service life. The use of the knowledge collected and encoded for diagnosis in ROOF for condition assessment was examined in some detail (Allwood and Goodier 1995c).

3. As a tool to check designs. The checking of a design is very similar to condition assessment except that the roof only exists on paper.

2.2 The development of the ROOF system

The next few sections of this paper detail the development stages for the ROOF system. This careful staged development is arguably more important for expert systems than for traditional programming. The stages here are similar to those followed for the development of other expert systems at the BRE (Goodier and Matthews 1996) and form a useful guide to follow when developing similar systems either for diagnosis, condition assessment or service life prediction. The descriptions of the stages presented here are brief, more detail can be found in other publications (Allwood and Goodier 1995a, 1995b). The stages in the development of the roof systems were:

1. The development of a specification.
2. Producing a list of goals for the system to identify.
3. Collecting the knowledge used to establish the goals.
4. Encoding the knowledge.
5. Testing the system.

2.2.1 Developing the specification

The development of the specification for ROOF had to consider a number of factors, these included:

1. The target user of the system. What level of expertise would the user have, this could vary from an experience roof inspector that was using the system as a supportive tool to a individual with no technical experience (the caretaker). The target user for ROOF was set as a building professional but with no experience of roofing.
2. The hardware system. The system was designed to run on a laptop computer. It is easily capable of running on a compact laptop such as a Toshiba Libretto.
3. The operating system. At the time of the initial development of ROOF MS Windows was not an established environment for technical computing. However it was decided to develop ROOF in this environment, this proved to be a fortuitous choice.
4. The development system. A detailed examination of the expert system shells (the
software systems used to develop and run rule-based systems) was undertaken to establish the best shell.

5. The degree of help to be given. The help to be included in an expert system has to be balanced between the competing requirements of clarity and completeness.

2.2.2 Producing a list of goals for the system to identify

A Goal is the expert system terminology for the fundamental cause of a defect that can affect a roof. When undertaking a survey it is one or more of these goals that the system is attempting to identify. It is the identification of these goals that is the first technical stage in the development of any rule-based system. In the building industry the identification of these goals is not trivial. Many experts do not find it easy to list goals as they represent the end result of their thinking whereas a consultation will start with symptoms. This requires that the system developers develop techniques to aid the identification of the goals [Allwood and Goodier 1995b]. The development of the goal list for ROOF was no exception to this. The goal identification exercise established 276 fundamental causes of defects that could be found on a flat roof.

2.2.3 Collecting the knowledge to identify goals

Once the set of goals have been established the main work in the development of the expert system can be undertaken, that is, the collection of the knowledge to identify and establish the goals. This process is known as knowledge elicitation. Knowledge that is used to establish goals can be collected from several sources, such as; published literature, example cases of defective roofs and directly from experts. All of these were used in the development of ROOF, but the most significant was the knowledge collected directly from experts. The knowledge was collected from the experts in a series of interviews. The interviews had a range of formats, such as informal discussions about roof diagnosis, review of example investigations, to, structured interviews to collect specific knowledge. The knowledge elicitation for ROOF was aided by the recognition of structure within the knowledge [Allwood and Goodier 1993, 1995b]. If structure can be found, this allows the elicitation tasks to be broken down, the knowledge elicitation is then considerably eased and the accuracy significantly improved.

2.2.4 Encoding the knowledge

One of the significant advantages of rule based expert system is that encoding the knowledge (if it has been collected in a structured manner) is relatively easy, though still not a trivial task. Figure 1 shows an example rule from the ROOF system. Figure 1 shows the benefit of establishing a structure to the knowledge that can be reflected in the encoded rules. Each set of rules that can be used to establish the cause of a defect has two halves. One half establishes that the symptoms on the roof are such that the cause of the defect can occur. The second half checks that the symptoms confirming the cause of the defect exists. The encoding of the knowledge was further aided by recognising the existence of meta knowledge (knowledge about knowledge) and how this influenced the system (Allwood and Goodier 1993). In rule
based systems knowledge is not only encoded in the rules, but also exists in the questions and help screens, this is the case with ROOF.

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if situation allows cause c3.5
and symptoms indicate cause c3.5
then causes include c3.5 built up roofing
improperly spanning expansion joint

if type of membrane is built-up roofing
and built-up membrane had base of low grade
and roof deck includes movement joint
and membrane does not include movement detail
then situation allows cause c3.5

if presence of splits is yes
and orientation of splits include in-line with movement joint
and location of splits include at movement joint
or offset slightly from movement joint
then symptoms indicate cause c3.5
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Fig. 1: Example rules from the ROOF system

2.2.5 Checking the system

Checking expert systems is not an easy task, primarily because the route to a conclusion is not fixed. ROOF was checked in several ways. One advantage of rule based systems is that the individual rules are English like and can be read by an expert. This was undertaken for ROOF. The system was taken on a number of site visits and tested against roofs with defects where the cause of the defects were known, and its' performance checked. ROOF was further tested using a technique known as blind testing. Here the data from a number of case studies were entered into the system and presented to experts. The solution found by both the systems and the experts were anonymously presented to an adjudicating expert. This enabled the systems' performance to be compared to an expert. The system performed very well in these tests.

2.3 Future expert systems development at the BRE

The BRE remains heavily involved in the development of expert systems for diagnosis, monitoring and specification. These systems can be expected to contribute to service life prediction. Two areas are currently underway. The first is the development of a real time expert system to aid structural monitoring, this follows on from earlier work [Goodier and Matthews 1996]. The second is the development of an expert system to aid flat roof specification. Real time expert systems to aid structural monitoring perform several functions such as improving the presentation of information, advanced sensor validation and applying engineering knowledge to check the structure. In many situations monitoring is the first stage in condition assessment, an important part of service life prediction. Benefits from the improved performance of monitoring can be expected to cascade down. The second system to aid flat roof specification will be based on standards, manufacturer's data and
published performance figures to make design less laborious and more accessible.

3 References


