SERVICE LIFE PREDICTION OF ROOF SYSTEMS BY RELIABILITY-BASED ANALYSIS

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The development and application of a reliability-based system for the service life prediction and management of maintenance and repair procedures of low-slope roof systems are described in this paper. By using statistical databases and probability theory, this system is capable of establishing levels of reliability in satisfying various governing conditions (also known as limit states) as determined by performance requirements or financial considerations. By using the reliability as a measure of performance requirements, inspection, preventive maintenance, repair, and major rehabilitation decisions can be made based on economic analysis over the life cycle of a roof. Therefore, this system will assist in making rational management decisions on a scientific basis. The paper details the data collection procedures and demonstrates the possible applications of this method in managing roofing component performance. Following similar procedures, reliability-based life cycle management systems can be continuously modified to reflect changes in roofing technologies and component performances.

KEYWORDS

Life cycle, maintenance management, reliability-based analysis, service life.

INTRODUCTION

The roofing industry has witnessed tremendous changes during the past three decades. Never before have contractors and designers had such a large variety of materials, systems, and assemblies to choose from when designing a roofing project. Brought about by advances in material sciences, computer-assisted engineering and design, and years of research in materials and systems behavior, a plethora of products and roofing options are now available.

Along with the huge increase in product and system diversity has come an increase in the complexity of roofing construction. Different materials require different application techniques and detailing. Roofs behave dynamically, responding to a wide array of loads and stresses during their service lives. The relation of the roof to other building envelope components and how they are connected is critical to the overall performance of both the roof and the building itself.

Roofing professionals are accustomed to speaking of roofs in terms of life spans that approximate twenty years, and they are also aware of numerous examples of roofs that have ceased to perform, or to remain watertight, well before that time. This is often referred to as premature failure. Under closer scrutiny, it is usually revealed that these "failures" are rooted in an inappropriate initial design, improper installation materials or application, misunderstanding of the roof's particular requirements, or a disregard for the need to provide routine and regular maintenance. The efforts to obtain optimal roof performance do not end once it has been constructed. Planned and regular maintenance are essential to ensure that any roof will provide satisfactory performance for its full expected life.

Roofs are expected to fulfill various functions for considerable periods, under extremely harsh and often uncontrollable conditions. Roof failure, or less than expected level of service, can result in serious adverse consequences to building value, operational costs, and occupant comfort. A roof cannot be switched off like a production machine while repairs are made. They are required to provide near-continuous protection from moisture and vapor, ultraviolet exposure, cyclic thermal loads, cold, noise, wind, and fire. The ability to accurately evaluate performance during a roof's life cycle and to manage and alter future roof performance would be very useful.

Given the importance of the roof as a component of any building, the implementation of a program designed to maintain the roof to an acceptable level of service is essential. A thorough examination of the relative efficiency of repair and replacement and the long- and short-term return on investment is crucial to the decision making process. An ongoing refinement in the prediction of roof system service lives would be helpful in preparing and managing investment plans. The relative effects of repair and maintenance options would also be used as a guide for annual operations and maintenance allocations.

This paper describes the philosophy, basic development, data collection, and potential applications of an analysis package intended to predict service life and to assist in the management of maintenance and repair procedures for low-slope roof systems. This undertaking was to develop a tool to rationally estimate the performance of roof systems and, thereby, permit scientifically based assessments of the most appropriate, likely, and cost-effective maintenance, repair, and major rehabilitation schedules.

PERFORMANCE RELIABILITY THEORY

The challenge is to identify the degree, quantity, and appropriate timing of corrective and remedial action. Because of the complexity of the degradation mechanisms and the many variables involved, reliance upon traditional methods of prediction has proven ineffective and imprecise. As a result, building owners and asset managers are not equipped with the necessary tools to make optimal and efficient resource allocation with regard to their roofing assets.

The resource allocation and planning process must consider the impact of any repair and maintenance options upon future roofing performance. This is a very complex and indeterministic process.

Traditionally, the design of most building components has been approached in a deterministic manner; relevant parameters usually consist of selected factors of safety multiplied by expected service loads. Since service loads are rarely known with certainty, they should actually be treated as random variables. The reliance upon fixed or arbitrary values for pertinent variables cannot adequately consider the natural variation of the physical parameters, and such techniques should not be used to assess roof performance.

Because the factors associated with both the design and maintenance of roof systems are inherently random, they are best suited to assessment using statistical analysis techniques. These analytical tools have traditionally formed the basis of reliability theory and have more recently provided the framework for the study of civil-engineering-related reliability problems. Techniques or methods that evaluate the probability that certain conditions will be satisfied are generally referred to as being "reliability-based."

Some fundamental terminology related to these techniques and, in particular, to its use with the work described in this paper, is presented below.

- *Limit state functions* are the mathematical expressions of the performance requirements.
- *Governing parameters* are the physical and chemical properties that are used to mathematically define the limit state function(s).
- *Probability density function* (PDF or probability distribution) is the frequency function, $f(x)$, describing the likelihood that a particular variable will take a specific value, x.
- *Reliability* is the probability that a function will be fulfilled (equal to the probability of survival, p_s, ranges from value of 1 when fully satisfactory to 0 when unable to satisfy functional requirements).
- *Component reliability* is the probability that the component will provide its defined function.
- *System reliability* is the probability that the system of components will fulfill its function.

History of Reliability Theory

In the past, reliability theory has most often been identified with the military, aerospace, and electronic fields. The importance of reliability theory in the area of civil engineering has been increasingly realized over the past number of years. The real beginning of structural reliability as a topic for academic research may be traced back to Freudenthal.[1] In the past decade, reliability in civil engineering applications has received heightened attention and concern about the optimal performance and safety of structures.

Although reliability theory has become an accepted approach to design in many fields, its history of application to asset and maintainability management is much shorter. Researchers have investigated using reliability theory toward the repair, maintenance, and management of important structures including nuclear power stations. [2,3,4,5] Recognition of the potential application to roofing service life prediction came relatively early.[6,7] The analysis of time-dependent changes in system reliability has been considered only in the recent past.[8] These techniques are now being widely used for maintenance management[9,10] and in various construction domains.[11]

Methodology

The performance of any particular component, subsystem, or system of an asset is dependent upon numerous variables. Only in rare instances would the values of any of these variables or their interactions be known categorically. In most instances, the values and nature of these variables are in accordance with specific distribution functions. The exact distributions are evasive; the records of performance from various sources are used to indicate tendencies in observed conditions that reflect physical conditions.

Using figures and distributions generated from the physical data, the reliability-based framework calculates the probability of exceeding designated acceptable limits. The limits:

- may be functions that define physical or chemical performance
- may be condition or serviceability indices
- may reflect user requirements of the system being investigated

They define the performance requirements for a component or an entire roof system. In order to meet ongoing operational requirements, it must be possible to calculate the likelihood of exceeding any (or all) limiting conditions at any point in the life span.

Reliability is considered to be the probability that these limits will not be exceeded and is defined as the probability of survival , p_s, which is related to the probability of failure, p_f by:

$$R = p_s = 1 - p_f \qquad [1]$$

The performance of a component in relation to a certain limiting condition can be described as a function of a set of basic parameters (X_i, i = 1,...,n). For example, the deformation of a component, d, can be expressed as a function of the load effects, material properties, and geometric parameters:

$$d = d\,(X_1, X_2, \ldots, X_n) \qquad [2]$$

Assuming that the maximum allowable deformation for a certain serviceability condition is d_0 the boundary between failure and survival can, in this case, be described by $d = d_0$ or:

$$d - d_0 = 0 \qquad [3]$$

Failure occurs if $(d - d_0) > 0$ while the system is safe for $(d - d_0) < 0$. Substituting Equation 2 into Equation 3, one can write:

$$f(X_1, X_2, \ldots, X_n) = 0 \qquad [4]$$

in which d_0 was incorporated in the function f, such that failure occurs if $f > 0$ and no failure occurs if $f < 0$. The function

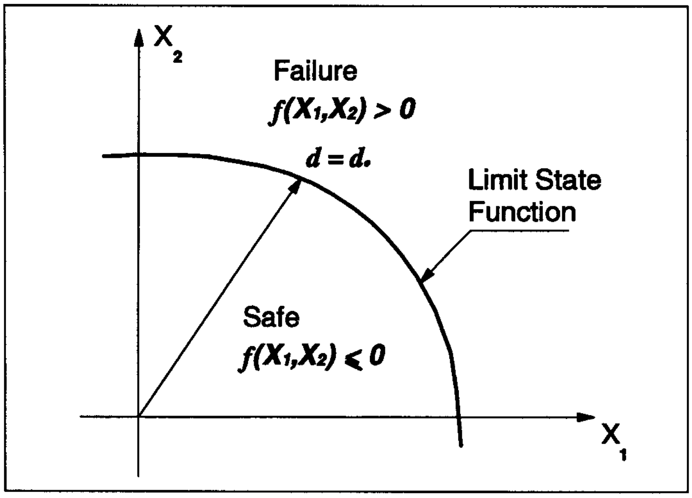

Figure 1. Illustration of reliability problem in two-dimensional space. Note: In this illustration, the limit state depends only on two basic parameters, x and y_2.

f is called the limit state function, and it separates the failure region ($f > 0$) and the safe region ($f \leq 0$).

This concept is illustrated in Figure 1, where the problem is simplified by assuming that the limit state depends only on two basic parameters, $f(X_1, X_2)$. The concept is equally applicable, although more difficult to solve, in an n-dimensional space.[12, 13] If one envisions a perpendicular axis to the (X_1, X_2) plane on which a joint probability density function is defined, the probability of failure is represented by the volume under the density function and over the failure region.

The previous discussion concentrates on the reliability of providing a single functionality; only one limit state function being tested. Methods are available to obtain reliability estimates (or bounds) for systems requiring that several functional conditions be met.

The reliability-based maintenance and management concept and the predictive techniques described within this paper attempt to put this theory into practice.

The predicted service life is defined as the age when reliability falls below a permissible level of risk. The risk acceptance level (RAL) may vary with each type of roof system being examined, the building usage and occupancy, and historic significance, as well as the limit state function(s) being evaluated. The acceptable risk is directly determined by economic and life-safety concerns, as well as the significance that society places on the installation. In fact, all facilities are capable of having limitless physical service lives. The same, however, cannot be said of their economic lives.

As part of the BELCAM project, a National Research Council Canada (NRCC)/Public Works and Government Services Canada (PWGSC) joint initiative, work is currently underway to provide guidance on appropriate levels of risk and expected roof service life. Reliability assessment and risk analysis are viewed as the keystone enabling technology for execution of that project.[14]

The methodology must be capable of reflecting changes in physical and chemical conditions through adequate consideration of repair, inspection, and maintenance information. Output from the analysis will be available to modify the output of, or input to, performance prediction databases. By scrutinizing the condition of any given roof, the merits of various construction and maintenance options may be determined on an economic, as well as a scientific, basis. Because the intent of the analysis is to examine the performance indicators at any time during the roof's life, it is crucial to the methodology that information gathered be useful for ongoing supervision of operations and maintenance on an annual basis. Reassessment of the service lives and economic factors affecting any given facility must be conducted frequently enough to provide an accurate reflection of the asset performance and to allow for modification of the operations and maintenance practices if (and as) deemed necessary.

GOVERNING CONDITIONS AND DETERIORATION

The primary design concerns for most roofs are the provision of strength, thermal performance, watertightness or resistance, and the fulfillment of given serviceability criteria. In most instances, the initial requirements will be adequately addressed by following standard design procedures. The variations in load, material properties, construction practice, and mechanical resistance are incorporated in recognized design practices. However, the physical and chemical changes that occur during the life of roofing components and the impact upon performance are usually not considered at the design stage. Similarly, serviceability aspects are considered as factors of the conditions existing at the time of design and construction.

The rate of degradation of the initial conditions and the nature of those changes drastically affect the long-term performance and functional life of a roof. Therefore, by evaluating the progression of deterioration in any given element, it is possible to assess that component's capability to provide the initial design function at any time during the service life.

Time-dependent limit state functions, considered to be representative of the conditions most likely to govern performance of low-slope roofs, have been identified for use within this framework and were presented at recent technical conference.[15]

Changes in roof performance are directly related to the initial design and the degradation mechanism(s) taking place, as well as the intensity, frequency, and fluctuations of applied loads. The effect of the deterioration will have varying significance, depending upon initial design and construction conditions, as well as the functional requirements under consideration.

FRAMEWORK FOR RELIABILITY-BASED ANALYSIS

In keeping with the methodology described previously, relevant data from the initial design, as well as inspection and maintenance records, is used to assign probability density functions (PDFs) to each of variables identified in the limit state functions. From these PDFs, the analysis program designates values for each of the parameters and calculates the reliability using either Monte Carlo Simulation or Second Order Reliability methods.[16] Results are presented in both graphical or textual report format, as well as being electronically retained for calibration purposes.

The technique relies upon the definition of limit state functions to describe the performance. As the knowledge of these items changes, so may the models used by the computer program. The reliability-based framework provides the capability to input, edit, record, and test limit state functions without requiring computer programming knowledge. By continually updating the statistical databases on inspection and maintenance, the distributions assigned will be reflective of historical tendencies, as well as current conditions, thereby providing a more realistic basis for prediction.

Performance Databases

In order to make sound decisions relative to various design options, repair and replacement scenarios, or return on investment, it is crucial that adequate and suitable data exists.

Through regular systematic collection of field performance data and use of the data within the methodology, it is believed that the confidence in the distributions being chosen and, hence, in the methodology itself will steadily increase. Output from the analysis will, similarly, be available to modify the output of, or input to, the performance database.

During the past two decades, considerable effort has been made to develop databases and analytical tools to assess design considerations and to predict the physical and financial performance of roofing. Not all of the efforts appear to have borne fruit, possibly being good ideas slightly before their time.[17, 18] Other studies examined what the roofing industry chose to report as "wrong" with its performance.[19, 20] This approach severely limited the usefulness and quality of the information by entering an extreme "failures only" bias into the databases. More detailed and standardized tools to estimate the costs of standard operating practices of building construction and the associated life cycle costs were developed.[21, 22, 23] In the past ten years, very significant progress has been made toward the standardized assessment of roofing condition and also in attempts to predict remaining service life.[24, 25, 26]

Although it is recognized that material selections, detailing, system design, and selected maintenance options influence both the annual operating cost and its service life, it is difficult to accurately determine the significance of these factors. By regularly and consistently collecting data that reflect performance, the knowledge of the costs associated with owning and maintaining various roofs, as well as of the effect of the maintenance procedures upon their service lives, will be continually improved.

The ability to manage annual operations and maintenance activities will be greatly increased once the desired service life of an asset has been determined and translated into annual operations budgets. The relative impacts of various operations and maintenance scenarios on asset performance will become more evident as the experience/knowledge base grows. The costs associated with various levels of maintenance may then be used to manage the roofs in a fiscally prudent manner so as to optimize financial performance.

Preliminary Data Collection

In 1993, Public Works and Government Services Canada (PWGSC) commissioned a review of existing literature pertaining to roof failure mechanisms, as well as an evaluation of ongoing scientific studies on roof performance. The objective of this effort was to formulate limit state functions to be used for service life prediction. In addition, a plan for PWGSC's database collection and input needs was to be made. Data from as many available sources as possible was to be used to establish a preliminary roof performance database.

Relatively early in this project, it became clear that although considerable research had been done to quantify and understand deterioration processes in many specific areas of roof performance, very little had been done to correlate the laboratory testing results to field exposure conditions and service life. Similarly, it was found that although large roofing databases existed, they contained very little substantive information on service life or life cycle and maintenance management issues. Much of the information available from the existing databases was of the "snapshot" variety; rarely was their reference to a roof's age or inspection and maintenance history.

Having had mixed results with external data sources, the study turned its attentions toward PWGSC's internal records, expecting to find readily extractable and usable performance data. Some of the required data was available but was kept in numerous locations and in varying states, ranging from paper files to very rudimentary spreadsheets. There was inconsistency in the thoroughness of roof histories and incomplete inspection and cost information. Despite these problems, this collection exercise yielded usable data on 122 roofs; information included geographic location, roof type, insulation type and thickness, presence of vapor barrier (retarder), installation date, and replacement dates. In addition, data on 36 roofs at a Canadian Armed Forces base was included in this first round of data collection. In total, 158 datapoints, birth-to-death statistics, were used to create this preliminary database for roof service life prediction.

Very basic statistical information on service lives was able to be extracted from this dataset. The data was perceived to have many gaps, little information on most single-ply membrane roofs and a large sample of coal-tar roofs. A better understanding of roofing durability issues and service life could be obtained only if as much data as possible on in-service roofs was included (i.e., those that had not failed). There was, however, significant illustration of the effects that some building and material science issues may have had upon roofing service life, particularly the decline in coal-tar usage, the introduction of vapor barriers (retarders), and thicker insulations to reduce energy consumption.

Scrutiny of the database revealed that the information for the Canadian Armed Forces' roofs indicated marginally shorter service lives (across all membrane and roof types) than for those of the general population. Current interpretation of this anomaly is that the use of standard operating procedures and roof replacement based on baseline budget allocations rather than inspection and condition reports had biased the dataset and reduced the projected service life.

Restructuring Data Input and Collection

In consideration of the recommendations of the previously noted study, the PWGSC roofing database was redesigned to permit chronological tracking of all activities that occur for any given roof. Replacement, repair, routine maintenance, and inspection can all be traced from a single database. The first 80 data fields are designed to allow for current and future assessments of problem roofing practices, material defects, and identification of practices (design or installation) that should be improved.

Additional data was added to the existing set by examining PWGSC's internal asset management reports, as well as gaining further leads by cross referencing contracts for roofing projects to building asset identifiers—a slow and tedious process. With the inclusion of the additional roofing data and the removal of the data on military roofs mentioned previously, PWGSC now has data for more than 200 roofs.

Attempts are currently underway to adopt the enhanced database structure as the information repository on roof systems for PWGSC. If this system is fully adopted, basic design and geographic data will be required for each "new" roof that is installed. Updates will be required as any modification is made to a given roof, and periodic verifications will be used to substantiate the data. In attempts to improve data quality, as well as heighten awareness of roofing condition problems, PWGSC is considering the standardization of its roofing inspection and data gathering procedures (most probably along the lines of ROOFER,[24, 25, 26] but in less detail).

Based upon past levels of roofing activity, it is reasonable to expect that data for 100 to 200 roofs will be added to the database annually. PWGSC's involvement with the data gathering component of the BELCAM project[14] and its ever-beneficial relationship with the Canadian Roofing Contractors' Association are expected to provide even greater sources of data to the system.

APPLICATIONS

Because the limit states used to describe performance are time-dependent functions,[15] the examination of any of these limit states, or systems that they may define, permits re-evaluation of roof performance at any time within the life cycle of a roof.

The system developed by PWGSC permits users to define, record, and modify limit state functions without computer programming, as well as allowing the rapid evaluation of the significance of the functions and parametric sensitivity analysis. Specific-purpose limit state functions can be developed and tested using this capability.

The user can specify the complexity of functional interactions needed to model the roof system being evaluated. Limit states can be examined as independent functions or in systems defined by the user to reflect the particular configuration under consideration. Systems, graphically depicted in Figure 2, can be defined as a number of functions combined in parallel or in series. In series systems, if one component fails, so does the system. All components of a parallel system must fail for system failure to occur. More complex systems may be modeled by combining parallel and series subsystems.

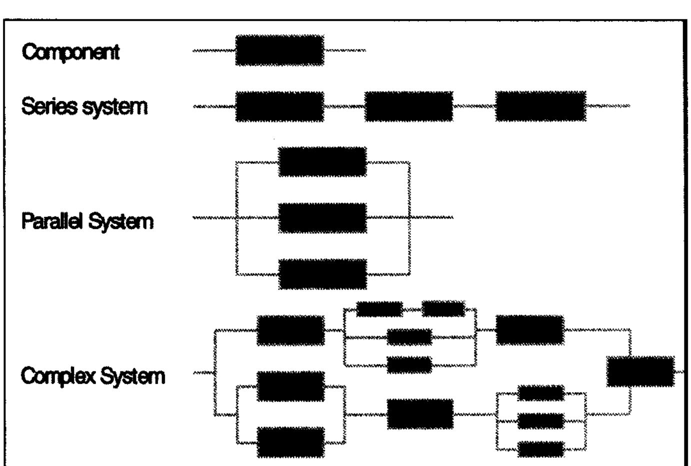

Figure 2. System definitions.

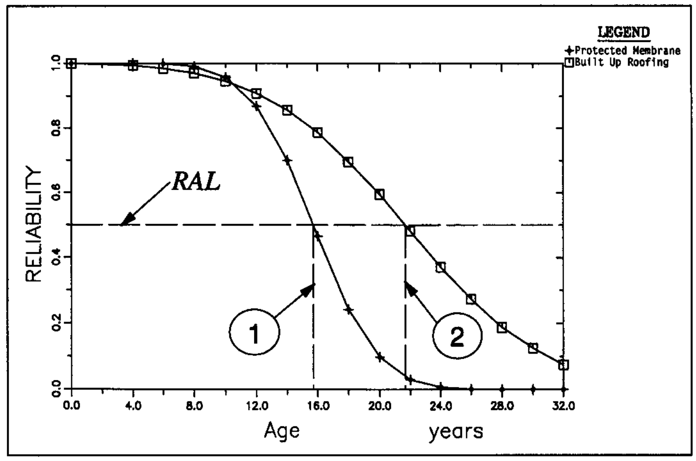

Figure 3. Comparison of historical performance of basic design options.

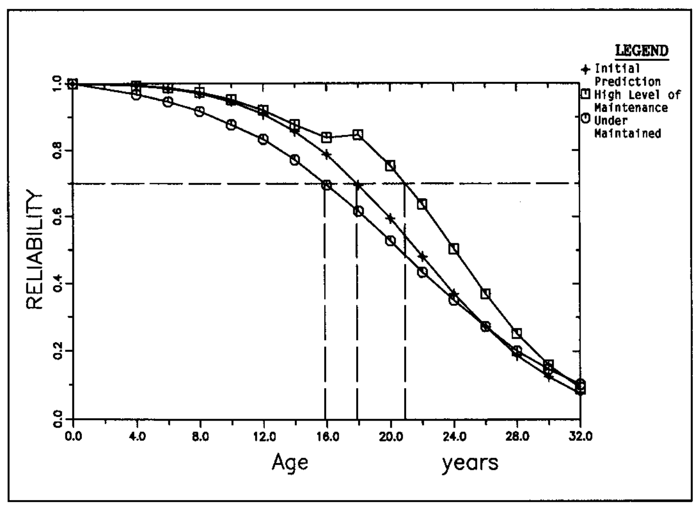

Figure 4. Effect of maintenance practices on service life.

Assessing Service Life and Performance Comparison

As discussed previously, the service life is defined as the age of the roof when the performance of the particular system being modeled fails to provide performance to an acceptable level of reliability [defined as the risk acceptance level (RAL)]. In Figures 3 to 6, the RAL is indicated by the horizontal dashed line. The intersections of that line with the performance prediction curves mark the ages when the reliabilities of performance are considered to be inadequate (illustrated with the vertical dashed lines, 1 and 2 in Figure 3).

Similar predictive techniques have been very successfully applied for condition assessment and the prediction of remaining service life of parking garage structures[27] and to the maintenance and management of bridge decks.[28]

Various designs may be evaluated to determine their potential impacts upon the service lives. Figure 3 presents the performance expectations for two basic design options, as extracted from the historical database. Option 1 is a standard four-ply asphalt and aggregate built-up roof, and Option 2 is a four-ply asphalt protected membrane roof configuration. The service life expectations (corresponding to an acceptable reliability level of 50 percent) are approximately 22 years and 16 years, respectively.

Because these curves are based upon past performance,

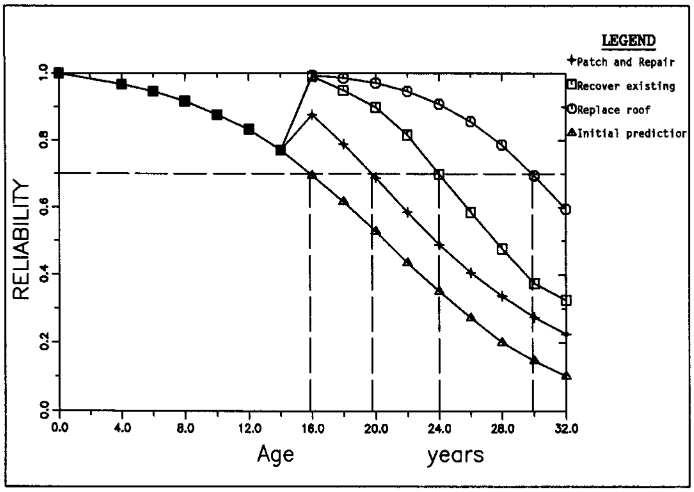

Figure 5. Comparison of rehabilitation options.

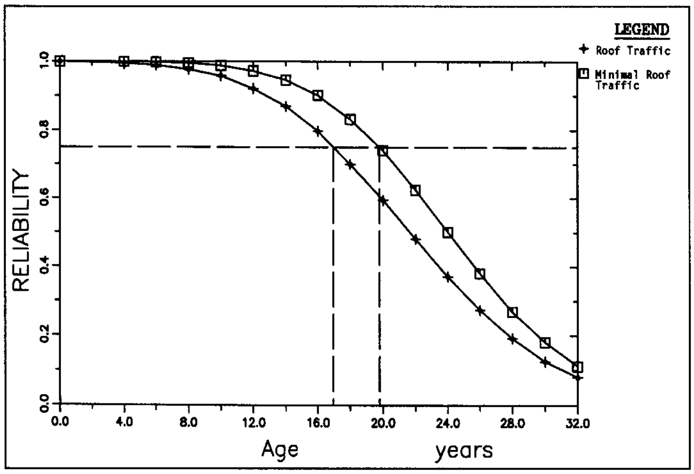

***Figure 6.** Effect of roof traffic on service life.*

they reflect historical design practice, material properties, and construction methods. The now-abandoned practice of adhering the insulation to the upper felts in the protected membrane system (leading to failure upon excessive insulation movement) is considered to be the main reason for the difference between the curves of Figure 3. For any maintenance or repair activities on older existing roofs, consideration of all relevant legacy practices must be complete. If, however, the comparison is between options on more recently placed roofs, care should be taken to minimize the influence of recognized design or construction errors upon the service life prediction. Presently, there is not adequate detailed information in the PWGSC database on protected membrane roofs to permit the exclusion of the effects of the previously noted design/construction flaws from the performance prediction.

In assessing the economic merits of construction or repair alternatives, the total costs and initial capital, as well as operations and maintenance requirements, must be considered.

Because this system permits prediction of remaining service life at any time during the life cycle, various economic aspects of roof system performance may be continually evaluated. Existing practice only permits analysis of these factors either prior to the service life (speculative) or at conclusion of the life cycle (historical value only).

Operational Decision Making Tool

The consequences of potential action or inaction relative to operational and maintenance procedures may also be monitored with this system. Figure 4 depicts the example of two roofs, extracted from the PWGSC database, of comparable configurations (BUR four-ply organic felts, asphalt, and aggregate) and on buildings of similar consequence located in the same city. They contain general office space, and each houses significant records and archival information. The acceptable level of risk for these building is, therefore, fairly low; reliability of performance should be relatively high. With these considerations in mind, the RAL has been arbitrarily set at a reliability level of .70.

The only appreciable historical difference between these two roofs was the frequency of periodic inspection (i.e., post-application) and maintenance. By evaluating the service lives and results presented in Figure 4, relative to inspection findings and maintenance actions, the benefits associated with maintenance become evident. The central curve, represented by +s, indicates the predicted performance of the roofs—an acceptable reliability for approximately 18 years. The actual roof performances, as reflected by inspection information, yielded service lives of approximately 21 years for the well-maintained roof and 16 years for the poorly preserved covering. These observed performance curves are, inpart, due to the particular environmental loads upon the roofs. It is very reasonable to expect vastly differing performance from one geographic or climatic region to another.

Numerous options may be available to restore the performance of the poorly maintained roof (i.e., that with a service life of 16 years, indicated with os in Figure 4), including the removal and patching of the damaged areas, re-covering the existing system, or the complete roof replacement.

Each of these options may be assessed in terms of prolonged life and economic factors. Figure 5 illustrates the predicted performance, based upon the PWGSC database, for each of these options: extending the service life to 20 years, 24 years, or 30 years, respectively, from the original service life of 16 years.

If the roof is completely replaced, there are additional roof management decisions that may be implemented to further extend its life. Figure 6 depicts the potential benefits, a prolongation of approximately three years, to be realized by minimizing roof traffic.

The illustration represents the projected performance curves, based upon the PWGSC database, for a new roof. If heavy roof traffic is permitted, the assembly has an expected life of 17 years, and without roof traffic, it yields a predicted service life of 20 years.

CONCLUSIONS

Reliability theory can be efficiently applied to the maintenance, repair, and management of roof systems. Levels of reliability in satisfying various limit states can be established based on performance requirements or economic considerations. This approach provides the necessary flexibility to owners or designers in meeting their specific performance requirements and financial constraints.

By using reliability as a measure of performance, decisions concerning periodic inspection, preventive maintenance, repair, and reroofing can be made based on economic analysis throughout the asset life cycle. Therefore, the methodology presented in this paper has great potential for various types of applications in design, maintenance, and management of new and existing roofs (i.e., assessing service life; performance life cycle analysis; evaluating impact of operations and maintenance practices; analyzing maintenance, repair and renovation alternatives; as well as the optimization of material and system selection, detail design, and operation and maintenance schedules).

Various levels of complexity of limit state functions can be readily incorporated into the reliability-based framework. Specific needs and levels of accuracy of the life cycle predictions can be achieved by using different limit state functions.

This methodology may be used as the basis for development of reliability-based systems for a broad range of building and architectural components.

RECOMMENDATIONS

Research to understand, explain, and model roofing deterioration mechanisms must continue. More linkage must be made between laboratory testing and the in-service (time-dependent) deterioration of roof components and systems.

Adequate, consistent roofing data and data management are essential to the integrity of the limit state functions and to the potential mainstreaming of this approach. The use of these techniques for initial design assessment will be possible only if the effects of identified (and rectified/abandoned) design or construction problems are substantiated with significantly more roof performance data.

Considerable effort should be spent to standardize procedures to assess acceptable levels of risk, dependent upon building or client space usage and the consequences of roof failure.

Although the inspection procedures are very well-suited to a framework similar to that used by ROOFER,[24, 25, 26] service life determinations should employ the reliability-based assessment as much as the existing databases permit. In all likelihood, a hybrid approach of using condition indices and reliability-based predictions will result. Validation of deterioration models, limit state functions, and inspection and maintenance information should include evaluations and comparisons of changes in roofing condition indices, as determined by ROOFER, relative to the performance curves predicted using reliability-based methods.

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