NRC Publications Archive Archives des publications du CNRC

Towards standardization of service life prediction of roofing membranes

Lounis, Z.; Lacasse, M. A.; Vanier, D. J.; Kyle, B. R.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

Publisher's version / Version de l'éditeur:

ASTM Special Technical Publication, 1349, pp. 3-18, 1999

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=0a6d1dab-e94a-45ca-915a-f93c0243fce2>
<https://publications-cnrc.canada.ca/fra/voir/objet/?id=0a6d1dab-e94a-45ca-915a-f93c0243fce2>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

Towards standardization of service life prediction of roofing membranes

NRCC-42034

Lounis, Z.; Lacasse, M.A.; Vanier, D.J.; Kyle, B.R.

A version of this document is published in / Une version de ce document se trouve dans:
Roofing Research and Standard Development: Fourth Volume, ASTM STP 1349, 1999,
pp. 3-18

The material in this document is covered by the provisions of the Copyright Act, by Canadian laws, policies, regulations and international agreements. Such provisions serve to identify the information source and, in specific instances, to prohibit reproduction of materials without written permission. For more information visit <http://laws.justice.gc.ca/en/showtdm/cs/C-42>

Les renseignements dans ce document sont protégés par la Loi sur le droit d'auteur, par les lois, les politiques et les règlements du Canada et des accords internationaux. Ces dispositions permettent d'identifier la source de l'information et, dans certains cas, d'interdire la copie de documents sans permission écrite. Pour obtenir de plus amples renseignements : <http://lois.justice.gc.ca/fr/showtdm/cs/C-42>

National Research
Council Canada

Conseil national
de recherches Canada

Canada

Zoubir Lounis¹, Michael A. Lacasse¹, Dana J. Vanier¹, and Brian R. Kyle²

TOWARDS STANDARDIZATION OF SERVICE LIFE PREDICTION OF ROOFING MEMBRANES

REFERENCE: Lounis, Z., Lacasse, M.A., Vanier, D.J., and Kyle, B.R., “Towards Standardization of Service Life Prediction of Roofing Membranes,” *Roofing Research and Standards Development: 4th. Volume, ASTM STP 1349*, T. J. Wallace and W.J. Rossiter, Jr., Eds., American Society for Testing and Materials, 1998.

ABSTRACT: A service life prediction approach for roofing membranes and systems is proposed based on a probabilistic modeling of the time-dependent performance. The membrane performance is modeled using a discrete Markov chain that evaluates the change of performance over time as a result of deterioration or repair. The transition probability matrix will be developed using in-field performance data collected during consecutive inspections for each roofing system, membrane type, age group, exposure conditions, and maintenance level. The use of in-field performance data captures the interaction and synergism of the various degradation factors, in addition to the impact of other roofing components, uncertainty and variability of material properties, environmental conditions, and quality of workmanship and maintenance. The service life is determined considering both the technical and economical performances, in addition to the risk of failure; this constitutes the first step towards the standardization of the service life prediction of roofing membranes and systems.

KEYWORDS: service life prediction, standards, roofing membrane, performance, deterioration, stochastic model, risk of failure, life-cycle cost.

RÉSUMÉ : Cet article présente une approche concernant la prévision de la durée de vie des membranes et systèmes de couverture, basée sur une modélisation probabiliste de la performance en fonction du temps. La performance des membranes est modélisée au moyen d’une chaîne de Markov discrète qui permet de déterminer la modification de cette performance suite à une détérioration ou une réparation. Ce modèle stochastique sera mis au point à l’aide de données sur la performance in situ, recueillies au cours d’inspections de couvertures, tout en tenant compte du type de système de couverture, du type de membrane, du groupe d’âge, des conditions d’exposition et du niveau d’entretien. L’utilisation de données sur la performance in situ permet de comprendre l’interaction

¹ NSERC Research fellow, associate research officer, and senior research officer, respectively, National Research Council Canada, Ottawa.

² Senior engineer, Public Works Government Services Canada, Ottawa.

qui existe entre les éléments constitutifs de la couverture ainsi que le synergisme des divers facteurs de dégradation. Le modèle probabiliste prend en compte l'incertitude et la variation des caractéristiques d'un matériau, les facteurs de dégradation ainsi que la qualité de l'exécution et de la maintenance. La durée de vie est déterminée en fonction des performances techniques et économiques ainsi que du risque de dégradation; cette procédure constitue le premier pas vers la normalisation de la prévision de la durée de vie des membranes et des systèmes de couverture.

MOTS CLÉS : prévision de la durée de vie, normes, membrane de couverture, performance, détérioration, modèle stochastique, risque de dégradation, coût du cycle de vie.

The extensive deterioration and early failures of roofing systems are the consequences of inadequate design, materials, workmanship and/or maintenance, in addition to aggressive environmental degradation factors. This deterioration has resulted in shortened service lives of roofs and increased costs of repair, relocation, and disposal. The current design and construction practice, based on minimizing initial costs, and the lack of standards, or inadequacies in standards [1], have contributed to this problem, and have inhibited any competition based on life cycle costs. In existing standards, no explicit requirement regarding the service life of roofing systems is given, in addition to a lack of specifications regarding required maintenance and repair over the roofing service life. The need for the development of standardized approaches to service life prediction of building materials and components has been recognized in the literature for decades [2-7]. The main reasons for this lack of standards for service life prediction and maintenance planning, include: (i) Complexity of the deterioration problem and lack of understanding of the degradation mechanisms affecting various roofing systems and materials; and (ii) Lack of reliable quantitative approaches to durability design and service life prediction, despite the fact that thousands of research papers related to material and component durability have been published over the past two decades [7]. Moreover, the adoption of such standards is hampered by the liability concerns raised by the specification of a design or target service life.

The standard ISO/DIS 7896-1990: "*Performance Standards in Building-Presentation of Performance of Roofs Made from Components from the Same Source*," identifies the main performance requirements for roofing membranes as water tightness, energy conservation and durability. The major degradation factors are temperature, solar radiation, water, and wind, compounded by inadequate design, poor workmanship and lack of maintenance. The actual performance of roofing membranes is time-dependent and presents considerable uncertainty and variability due to the time-dependence and randomness of degradation factors, materials properties, workmanship, and maintenance. In this paper, a stochastic model of the performance of roofing membranes is proposed using a discrete Markov chain. This Markov chain can model both the deterioration and repair processes, and forecast the future performance of roofing membranes and systems throughout their entire service lives. The development of this model requires in-service performance data collected during successive inspections of the roof.

In ASTM E 632-82: “*Standard Practice for Developing Accelerated Test to Aid Prediction of the Service Life of Building Components and Materials*,” the service life of a building component or material is defined as “*The period of time after installation during which all properties exceed the minimum acceptable values when routinely maintained.*” The definition of minimum acceptable value of performance is not a straightforward task, and may be subjective and arbitrary. In this paper, the service life is determined based on the predicted time-dependent technical performance profile, economical performance (costs of maintenance and repair), and risk of roofing membrane failure (costs of disruption, relocation, and damage for contents under the roof due to water leakage).

The objectives of this paper are: (i) stochastic modeling of roofing membrane performance; and (ii) development of a performance and risk based service life prediction method. This constitutes the first phase towards the development of service life prediction and maintenance standards. The emphasis of the paper is on conventional built-up roofing (BUR) membranes, and water tightness function. The paper reviews the performance of roofing membranes and existing methodologies for service life prediction, describes the proposed stochastic model, and discusses its implementation towards the development of standards for service life prediction and maintenance technique.

Performance of Roofing Membranes

The performance requirements of roofing systems may be categorized as [8]: (i) water tightness; (ii) heat transfer control; (iii) condensation control; (iv) load accommodation; and (v) maintainability. Low slope roofs are separated into two configurations depending upon the relative positions of the membrane and the insulation. Conventional roofing systems place the insulation below the membrane, while the protected membrane roofing (PMR) systems shield the membrane from environmental effects by placing it under the insulation. Bituminous built-up roofing membrane (BUR) has been the standard for low-slope roofs for over 100 years. However, its share has dropped considerably, owing to the introduction of new systems, including single-ply elastomers, weldable thermoplastics, and modified bitumens [9].

The BUR membrane is a composite material that consists of bitumen and felts, usually shielded from solar radiation with a mineral aggregate surfacing. Given its excellent resistance to water penetration and extremely low water absorptivity, bitumen is the main waterproofing agent, with asphalt being the predominantly used bitumen (as opposed to coal tar pitch). The roles of the felts are the stabilization and reinforcement of the bitumen by providing about 90% of its tensile strength [9]. The trend in the roofing construction is towards the use of glass felts instead of organic felts [10]. Organic and asbestos felts are roughly twice as strong in the longitudinal direction than in transverse direction, while the glass fiber felts are quasi-isotropic [9]. An increase in the number of felt plies results in an increase of the tensile strength and service life of the membrane. The roofing industry has traditionally assigned 5 years’ anticipated service life to each felt ply [9]. In an industry-wide survey, it was found that the service life of built-up membranes increased with the number of plies, and that no membrane type had more than 50% probability of lasting more than 20 years [11].

Degradation Factors and Failure Modes of BUR Membranes

As mentioned earlier, the major degradation factors that affect the performance of BUR membranes are temperature, solar radiation, water, and wind [8], in addition to poor workmanship and lack of maintenance, as illustrated in Fig. 1. A further examination of potential degradation factors [12] considered the impact of roof traffic, environmental pollution, as well as flashing and location stabilizer failure. The exposure of roofing membranes to one or more of these degradation factors induces a sequence of degradation mechanisms, which are physical and/or chemical changes that lead to detrimental changes in one or more properties of the membrane materials (bitumen and/or felts). These physical/chemical changes, in turn, induce distresses or anomalies, that may ultimately lead to the physical failure of the membrane and the loss of its water-tightness function, with the resulting consequences of failure as shown in Fig.1.

The main properties of roofing membranes include tensile properties at different temperatures, load at break, elongation at break, and energy to break [8]. The physical changes induced by weathering include a decrease in the tear strength, elongation, and mass, and an increase in tensile strength, and moisture content [8]. The assessment of the chemical changes that affect asphalt is made possible through the use of chromatographic separation of the asphalt fractions [8,10]. The increase in tensile strength and decrease in elongation are induced by a loss from the molecular weight saturates fraction and the increase in high molecular weight asphaltenes fraction [8]. A built-up roofing membrane may be modeled as a visco-elastic (Boltzmann-type) material, which is brittle and elastic at subfreezing temperatures, plastic and semi-fluid at moderate and hot temperatures [9,13]. Cold weather membrane contraction has no counterpart hot-weather expansion, except in minor thermal ridging of the flexible membrane. Therefore, an aging membrane tends to experience cumulative shrinkage [9].

FIG. 1-- *Degradation factors and failure modes of BUR membranes*

Splitting is the most significant failure mode causing immediate loss of water tightness. It often occurs over the insulation joints where the membrane is subjected to the greatest amount of stress [9,13]. Furthermore, given the brittle nature of the membrane at low temperatures (limited breaking strain), thermal contraction is another cause of splitting. Other distresses or anomalies include blisters, ridges and slippage, with a recognition of flashing failure leading to approximately 20% of roofing problems [9].

Blistering over large sections of a roof may significantly shorten the membrane service life by increasing the likelihood of photochemical oxidation of exposed bitumen. Their occurrence also increases the chance of puncture by roof traffic, however if these blisters are small and few in number, they can be considered anomalies. Ridging generally reflects the placement pattern of insulation boards on the roof and is usually a result of moisture absorption, and subsequent expansion, in the roofing (organic) felts.

Performance Assessment

Mathey and Cullen [14] were first to establish the key performance criteria for built-up roofing membranes. Twenty performance attributes were identified as having a significant influence on the overall performance of the roofing assembly under in-service conditions. Of these attributes, ten were selected (e.g. tensile strength, thermal expansion and contraction, flexural strength, tensile and flexural fatigue strength) to develop a preliminary performance format, which for each attribute included a statement of requirement, criterion test methods and commentary regarding test deficiencies. These proposed criteria were based on unweathered laboratory-tested membranes that have not been validated through comparison to in-service performance. The proposed performance criteria are too stringent, because in-service roof membranes that do not satisfy the proposed criteria were performing effectively [8]. The energy to break was advocated by Cash and Bailey [8] as a more realistic indicator of membrane performance in service. The French “FIT” discrete performance rating system classifies roofs using discrete indexes in increasing levels of fatigue resistance (F) indentation resistance (I), and temperature resistance (T) [15]. An analytical model predicting the strains and stresses in roofing membranes induced by substrate movement was developed by Pommersheim et al. [13]. A criterion for failure indicating either rupture of the felt or disbonding of the bitumen was established [13].

However, the trend in recent years for the use of single ply membranes has shifted the emphasis on developing improved performance criteria for these new membrane types instead of further development of criteria for conventional BUR assemblies.

Methodologies for Service Life Prediction

As mentioned earlier, despite the extensive research on durability of building materials and components, no reliable quantitative approach to service life prediction has gained wide acceptance. In the early seventies, the ASTM subcommittee E06.22, was established to address the need for the evaluation of the durability performance of innovative building components. In 1978, this subcommittee issued the ASTM E632 standard, which was approved in 1982, and re-approved in 1988. Similarly, the ISO/WD 15686-1997 “*Buildings-Service Life Planning-Part 2: Service Life Prediction Methods*” contains a generic procedure for service life prediction of building components. In addition to the above standards procedures, three guides for durability of buildings and components have been developed, namely the British BS 7543-1992: “*Guide to Durability of Building Elements, Products and Components*”; Japanese AIJ-1993 : “*Principle Guide for Service Life Planning of Buildings*”; and Canadian CSA S478-1995: “*Guidelines on Durability in Buildings*”. The BS 7543 and CSA S-478 standards

address qualitatively the requirement of durability of structural and building envelope elements, while the AIJ guide proposes an empirical “factorial” approach. In the following sections, a brief summary of the existing approaches to service life prediction is given, including a presentation of the methodology, advantages and shortcomings.

Generic Methods

Of the various generic approaches to service life prediction reviewed by Sjöström [3], two of these have been formally adopted either as a standard (ASTM E632-88) or technical recommendation [16]. Both these methods, primarily developed by the NIST [2], outline essentially the same process with additional details given in the RILEM technical recommendation. The major parts of this method include: (i) Performance characterization of material or component in relation to established performance criteria, and requirements and the type and range of degradation factors; (ii) Development of rationale for both short and long-term aging tests based on knowledge of the key performance indicators, degradation mechanisms and degradation factors; (iii) Evaluation of aging test rationale and failures modes using accelerated aging tests; and (iv) Comparison of predictive tests and long-term in-situ tests based on deterioration type and rate of degradation.

These generic methods do not provide a detailed description of the manner in which accelerated or in-service performance testing should be carried out, as a result there are limited applications in the literature [17,18]. Methodologies for developing tests to aid in service life prediction of roofing membranes have been adopted by the RILEM technical committee [16].

Accelerated Aging Tests

The accelerated aging tests, advocated by the ASTM E-632, are carried out by imposing higher than normal stress levels on components on order to increase the rate of degradation such that the component will fail within a relatively short period of time in relation to its expected service life. The performance and failure-time data derived from these tests are analyzed by fitting a degradation model to the data to estimate the relationship between performance, age and stress level.

Instances where the use of these techniques have provided some insight into the long-term durability of roofing systems include, for example, studies by Nelson [20]. Nelson showed that for built-up membranes, the time to failure in a creep rupture test was approximately the same as the time to failure from cyclic fatigue tests, in addition, the governing factor was the magnitude and duration of the applied load, and not the number of cycles. Hence it appears that cyclic fatigue is not the most significant degradation mechanism for these types of roofs but rather resistance to tensile stress over prolonged periods of time. Cash and Bailey [19] found that the widely accepted heat aging procedure was not adequate in predicting the change in properties measured in the field. This is further confirmed in an extensive testing of BUR membranes [21], where it was found that heating at 65°C, even for 28 days, was not a suitable method for predicting the property changes expected to occur in service.

Although accelerated testing can be useful in ranking different materials, it has many shortcomings, which include: (i) Difficulty to simulate the degradation mechanisms

of the various materials and their interaction; (ii) Difficulty to reproduce the stochastic nature of the degradation factors affecting the roof performance; and (iii) Difficulty to correlate accelerated laboratory test results to the actual in-service results.

Empirical and Heuristic Approaches

The Japanese AIJ guide has fostered the notion that an empirical approach to service life prediction is both achievable and available. It suggests that the service life of building components can be estimated based on the assumption that a standard life of a component can be adjusted through the use of factors that account for the use, location and workmanship. Current work within the CIB W80 task group focusing on evaluating this method suggests that there is considerable work required before “factorial methods” could prove to be, credible, consistent and reliable [22]. Despite its practicality, this approach has many shortcomings, which include: (i) It is not performance based and as such no identification of adopted minimum performance requirement; (ii) Arbitrary choices of standard lives and adjusting factors; and (iii) Deterministic approach, despite the large uncertainty and variability of the service life. It appears then, that this method is neither readily available, nor is it likely to be attainable in the near future.

In addition to the above factorial approach, an empirical or heuristic service life prediction method is proposed in “Roofer”, as part of an engineered management system (EMS) for bituminous built-up roofs [23]. A family of performance deterioration curves above and below the so-called “normal deterioration curve” are proposed. This normal curve is defined as that for which the roof service life is 20 years, assuming a perfect initial condition rating. The service life of a roof is defined as the time for which the roof condition index (RCI) reaches the value 33, specified as the minimum performance requirement. The roofer system is a practical tool that holds promise for a simplified quantitative approach to service life prediction. However, there are some limitations with the system regarding the definition of minimum performance requirement, service life of roofing membrane (vs. roof system), validation of the decay curves, and their dependence on the relevant explanatory variables.

Economic Performance-based Approach

After the prediction of the technical performance and corresponding service life of a roofing membrane or a roofing system, it is necessary to assess its economical performance through the assessment of its life-cycle cost. Life cycle cost (LCC) analysis is a method of assessing the economic performance of a project or project alternatives over a designated study period, and encompasses all relevant costs including the costs of designing, purchasing/leasing, constructing/installing, operating, maintaining, repairing, replacing, and disposing of a particular building or system. Such assessment is critical for optimal decision-making regarding maintaining, repairing or replacing the roofing membrane or system. The ASTM E 917-94: “*Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems*,” addresses in detail the issue of economic performance of buildings. LCC analysis is especially suitable for assessing the potential economic advantages of scenarios with differing initial capital costs and projected future costs (i.e., operations, maintenance, repair and replacement). This approach can also accommodate differing options such as tax benefits, discount rates, inflation, study

periods, and timings of cash flows. The LCC in present-value terms (PVLCC) is computed as follows:

$$PVLCC = \sum_{t=0}^N C_t / (1+i)^t \quad (1)$$

where C_t = sum of all relevant costs occurring in year t ; N = length of study period, years, and i = discount rate. In general, the assessment of the economic performance of different roofing membranes (or systems), or different maintenance strategies may yield optimal solutions that are considerably different from those based on technical performance. Although not explicitly stated, the economical performance criterion may be the governing factor in defining the service life of roofing membranes, referred to as or “economic life,” which may be determined as the time at which repair costs become excessive. The definition of this economic life may be very subjective with large bias and variability. LCC analysis is not proposed as a “better system” than technical evaluation, but rather as an additional tool for predicting service life.

Reliability-based Approach

The potential application of probabilistic methods to service life prediction has been identified by Masters [24]. Within the accelerated life testing methodology, described earlier, both deterministic and probabilistic approaches have been used for service life prediction [17, 18]. More recent work [12, 25] has proposed using complete life data and statistically derived limit states functions to describe likelihood of roof system and component failure. These procedures rely upon the determination of acceptable levels of risk based upon the consequences of failure relative to building usage, occupancy and significance.

Stochastic Performance Model and Risk-based Service Life Prediction

In this paper, a more comprehensive approach to service life prediction is proposed by considering the following three criteria: (i) technical performance; (ii) economic performance; and (iii) risk of failure. The risk-based approach to service life prediction requires the consideration of the risk of membrane and roof failure, in addition to the life-cycle cost. The risk of failure will be evaluated through an assessment of the probability of failure and the consequences of failure, which include the costs of disruption, relocation, energy, and damage to contents under the roof. The probability of failure is determined from the assessment of the technical performance. The actual performance of roofing membranes is time-dependent and presents considerable uncertainty and variability, therefore, it should be modeled as a stochastic process. The proposed model enables the forecast of future performance of roofing membranes and systems throughout their entire service lives. A reliable performance prediction model is essential for the durability evaluation of different membrane materials in the initial design stage and for the planning of effective roofing maintenance management strategies for both new and existing roofs.

As mentioned earlier, the membrane performance deterioration is the result of the environmental degradation factors (temperature, solar radiation, water, wind), poor

materials and workmanship and inadequate maintenance. Furthermore, the membrane performance is also dependent on the performance of the flashing, insulation, and deck. The combination of two or more of these degradation factors will result in complex degradation mechanisms with cumulative damage effects. These irreversible damages accumulate until the membrane reaches a threshold performance level that defines failure or loss of water tightness capability, and the time at which it failed defines the technical service life.

Implementation of Markovian Models

In this paper, the membrane performance is represented by discrete condition ratings, that are obtained by mapping the assessed condition onto a 1-7 rating scale, in which 1 and 7 correspond to the “failed” and “excellent” conditions, respectively, as shown in Table 1. Discrete condition ratings have been extensively used in the condition assessment of various infrastructure systems including bridges, pavements, dams, and roofs [23, 27, 28]. The condition of the roofing membrane is estimated from in-field inspection by measuring the extent and severity of the damage. This inspection includes identification of all distresses, measurement of their sizes and identification of severity levels, in a procedure similar to that used in “Roofer ”[23]. The total damage is determined by combining the various distresses considering their consequences on the membrane performance. In Table 1, a description of the condition of the membrane corresponding to the different ratings, in addition to the associated damage, is given.

TABLE 1-- *Condition rating of BUR roofing membranes*

Condition rating	Condition description	Damage (%)
7	Excellent : No noticeable distresses/anomalies.	0-10
6	Very Good: Minor anomalies (e.g. small blisters)	11-25
5	Good: Presence of some distresses (ridges).	26-40
4	Fair: Moderate deterioration; Water tightness is still adequate.	41-55
3	Poor: Major deterioration; Potential loss of water tightness	56-70
2	Very Poor: Extensive deterioration; Localized water leakage	71-85
1	Failed: Extensive water leakage.	>85

The Markov chain is a stochastic process whose state space is finite or countable, that may be described by the state vector $\{S(t_j) = k, k = 1, 2, \dots, 7\}$, such that the probability of a future state of the membrane, $S(t_{n+1})$, at time t_{n+1} is governed solely by its present state $S(t_n)$ at time t_n and not its entire history, i.e.:

$$P[S(t_{n+1}) = s_j \mid S(0) = s_0, S(t_1) = s_1, \dots, S(t_n) = s_i] = P[S(t_{n+1}) = s_j \mid S(t_n) = s_i] = p_{ij} \quad (2)$$

The transition probability p_{ij} represents the likelihood that the condition of the membrane will change from state i at time t_n to state j at time t_{n+1} . Equation (2) indicates that the conditional probability distribution of any future state $S(t_{n+1})$ is independent of the previous states, $S(t=0)$, $S(t_1)$, ..., $S(t_{n-1})$, and depends only on the present state $S(t_n)$. This assumption represents the first-order type of stochastic process correlation underlying the Markovian process [26]. The states 7, 5, ..., and 2 are called transient states, whereas state 1 is called an absorbing state, which is a state that cannot be vacated, once entered if no repair is made. The Markovian modeling of the performance requires

only limited data on the condition of the roofing membrane at two or more points in time, in order to derive the probabilities of transition from one state to other states having lower condition ratings. Each drop in the condition rating of the roofing membrane may be the result of a different mechanistic deterioration process.

The performance of roofing membranes is dependent upon several explanatory variables, including age, environmental conditions, material type, and quality assurance. In order to validate the adopted Markov chain model, it is necessary to develop transition probability matrices for roofing membranes and systems according to their classification with regard to the above explanatory variables. A stationary stochastic process may be assumed which implies the time-invariance of the transition probability matrix. The deterioration of a roofing membrane of a given class can be modeled using the following transition probability matrix :

$$\mathbf{P} = \begin{bmatrix} p_{77} & p_{76} & p_{75} & p_{74} & p_{73} & p_{72} & p_{71} \\ 0 & p_{66} & p_{65} & p_{64} & p_{63} & p_{62} & p_{61} \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \dots & p_{22} & p_{21} \\ 0 & 0 & 0 & 0 & \dots & \dots & 1 \end{bmatrix} \quad (3)$$

in which p_{ij} is the probability of transition from state i to state j in one step or transition time. This transition time is generally taken as one year, however, other time intervals can be chosen depending on the time between consecutive inspections. If the probability of a roofing membrane decaying by more than one state in one transition period (e.g. 1 year) is assumed negligible, the above transition probability matrix is greatly simplified. This simplification, in turn, yields the modeling of the deterioration process by the Markov chain shown in Figure 2, for a roofing membrane with seven condition states, as defined in Table 1, assuming no repair at this stage. Once, the one-step transition probability matrix is generated, the future performance of the roofing membrane can be predicted using the n -step transition matrix as follows:

$$\mathbf{P}\{S(t_n)\} = \mathbf{P}\{S(0)\}\mathbf{P}^n \quad (4)$$

in which $\mathbf{P}\{S(t_n)\}$ = state probability matrix at time t_n after n transitions; $\mathbf{P}\{S(0)\}$ = initial state probability matrix; and $\mathbf{P}$ is the transition probability matrix.

FIG. 2-- Markov chain modeling of roofing performance deterioration

The probabilistic prediction of the performance using Eq. (4) is illustrated in Fig.3, which indicates the evolution with time of the probability mass function of the roofing membrane performance. In general, at the start of the membrane service life, the probability mass is close to condition rating 7, however, after aging and deterioration , this probability mass shifts from states having high condition ratings to those with lower condition ratings. Ultimately, if no repairs are made, all the probability mass accumulates

in the absorbing state having the minimum condition rating 1. The mean performance curve and the corresponding mean service life (t_L) are also shown in Fig.3.

The transition probability matrix is determined from the historical performance data collected during inspections. It is derived as the solution that minimizes the difference between the condition ratings assessed from in-field inspection data and those predicted using the Markov chain model. The underlying assumption of the first-order Markov chain model referred to as the “*Markovian property*” refers to the dependence of the rate of deterioration on the current stress and cumulative damage only, and not on the entire stress history. The validity of this property will be checked through statistical inference testing. This prediction model can be further improved using the Bayesian updating technique if additional performance data become available.

Data Collection

The development of this Markovian model will be based on performance data of roofing components and systems collected throughout Canada using “Roofer” as a data acquisition system. A representative sample of roof sections, grouped according to age, material type, geographical location, and operating conditions, will be inspected at two, three or more points in time. These condition rating data will be used to generate the transition probability matrices needed to develop the performance profile of roofing membranes and systems according to their classification with regard to the above explanatory variables.

FIG. 3-- Markov chain prediction of roofing membrane deterioration

Advantages of Markovian Models

- Requires limited in-service performance data from two, or more consecutive inspections and makes beneficial use of existing historical performance data;
- Model is flexible and can easily be updated if additional performance data become available;

- Simple and practical stochastic model to forecast future performance, rate of performance degradation and service life;
- Uses in-service performance data, which takes into account : (i) interaction of degradation factors; (ii) impact of performance of other roofing components (flashing, insulation, and deck) on membrane performance; (iii) uncertainty and variability of weathering factors, degradation mechanisms, quality of workmanship and maintenance;
- Since, it is performance-based, it yields practical and effective maintenance management system (different from lifetime model, which predicts only the service life, i.e. the time for replacement)
- Overcomes the shortcomings of accelerated life testing and empirical factorial approaches discussed earlier.
- Using this approach, it is possible to assess the correlation between each change in condition rating to the corresponding change in the membrane properties (tensile strength, elongation, energy to break, etc.), in order to determine the governing degradation factors and performance criteria.

Standardization of Service Life Prediction

Need for Service Life Standardization

The standardization of the prediction of the service life of building components and systems is critical for the design and maintenance of durable and cost-effective building components and systems. In fact, the lack of a standardized approach has contributed in part to the current extensive deterioration of buildings and building components, including roofing systems.

As mentioned in the previous sections, attempts at the standardization of service life prediction have been made in the last two decades, including the accelerated life testing and empirical factorial methods. However, given the qualitative nature of the proposed methodologies and the lack of practical and reliable prediction methods, these methods have not gained wide acceptance.

This paper recommends the Markov chain model as a quantitative method to service life prediction of roofing membranes, to be used in conjunction with life cycle cost analysis. Furthermore, it is recommended that performance-based evaluation of building materials and components be adopted. For without a definition of minimum performance requirements, it is impossible to establish (i) design criteria to establish the service life of roofing systems; and (ii) maintenance procedures to ensure adequate reliability of roofs, and avoidance of premature failure.

Minimum Performance: Technical, Economical, and Risk-Based Service Life

The service life prediction approach should be performance-based, in order to forecast the performance of the component or system over time and assess the maintenance and repair needs, with the objective of minimizing the life-cycle cost. Both ASTM E632 and ISO-7896 standards address some aspects of performance requirements of buildings or building parts. However, there are few performance-based

standards available to assist practitioners. ASTM E632 hints at performance requirements; however, it skirts the issue with definitions such as “*the expected in-service performance requirements and criteria define the minimum acceptable levels of performance....*” The standard ISO/DIS 7896 provides good general guidelines regarding the requirement for quantitative performance testing for roofing systems. For example, the identified functional requirements or “roles” of roofing membrane include: resistance to humidity, energy conservation, and durability. The degradation factors or “agents” include wind and static atmospheric pressure, rain, freezing, and acidity of air and rain. The related “performance requirements” include tightness with respect to rainwater, melted snow and powder snow; propensity to interstitial condensation; thermal comfort and energy conservation; ease of maintenance, and durability requirements. Examples of required test methods for rainwater tightness include “absence of penetration of rainwater which would otherwise give rise to the presence of dripping water or moisture stains on the ceiling, or cause damage to the roof or other parts of the building. In conjunction with such performance-based tests, a consistent framework and terminology for the performance concept in building, which identifies the function, performance requirement, and occupancies is also required [29]. Unfortunately, the standard falls short, even in its own admission, in providing all the testing procedures required for roofing membranes. Many of the tests required to evaluate such performance do not exist and “will be the subject of future international standards”. However, it is still believed that performance-based standards are essential for service life prediction.

A performance-based approach requires the definition of minimum performance requirements, which when attained would indicate the end of technical service life. However, the life-cycle cost or risk of failure may dictate that the adopted minimum technical performance requirements and corresponding technical service life are not adequate. Shorter lives minimizing the life cycle cost or the risk of failure are defined as “economical life” and “risk-based service life”, respectively. However, practicality dictates that the final decision regarding the service life is the responsibility of the asset manager, who is the final arbitrator and must choose which of the available calculations best suits the situation. For example, all calculations could indicate the end or potential end of the service life and could point at early replacement of a roofing membrane. However, projected cash flows may not permit an immediate replacement. Or, technical and risk-based service life calculations could suggest another decade of adequate performance and reliability; however, the long-term operations and energy costs may suggest immediate replacement of inefficient materials.

Towards Standardization of Service Life Prediction of Roofing Membranes

This paper is the first step of an extensive research endeavor related to service life prediction of roofing membranes and systems. The paper describes an alternative quantitative methodology to predict the service life of roofing membranes, using a stochastic modeling of the performance through the use of a Markov chain. This technique has extremely good potential, at both the project and facility network level, to assist asset managers evaluate their portfolio. In addition, it is strongly suggested to use performance-based standards to establish minimum performance requirements. However, considerable work, as it relates to roofing membranes specifically, is still

required in the area of standardization and testing methods before comprehensive service life prediction methodologies are used extensively by practitioners, namely:

- Adoption of a comprehensive framework for the performance concept in building, as outlined in ISO 6240-1984 “Performance Standards in Buildings- Contents and Presentation” and ISO 6241-1992 “Performance Standards in Building – Principles for their Preparation and Factors to be Considered”;
- Classification of buildings (type, consequences of roof failure) and roofing systems; similar to the work initiated by ASTM Subcommittee E06.25 on Whole Buildings and Facilities;
- Adoption of an elemental framework of building components such as recommended in ASTM E1557-96 “Building Elements and Related Site Work-UNIFORMAT II” to insure consistency of data collection and to assist life cycle cost analysis;
- Classification of environments or exposure conditions as per ISO standards;
- Classification of quality assurance and maintenance levels according to guidelines established in the ISO 9000 “Total Quality” series to insure consistency of inspections, maintenance, repair and rehabilitation strategies;
- Standardization of inspection procedures to determine roofing membrane condition ratings using in-service performance data. This standardization must be founded on accepted frameworks discussed earlier;

Some of these points relating to roofing membrane service life prediction will be addressed in the course of future research for the National Research Council Canada’s Building Envelope Life Cycle Asset Management (BELCAM) project [30].

Conclusions

In this paper, a stochastic modeling of the performance of roofing membranes is proposed using a seven state Markov chain. It is a probabilistic cumulative damage model which forecasts the future condition of roofing membranes, taking into account the uncertainty and variability of the material properties, installation, impact of other roofing components, environmental degradation factors, maintenance and repair. The development of this model requires a limited amount of in-service performance data collected during roofing inspections. This model allows further updating if additional performance data become available. The use of in-service performance data to develop this stochastic model overcomes the difficulties associated with accelerated life testing and empirical factorial approaches. Transition probability matrices will be derived for each roofing system type, membrane material type, age category, environmental conditions, and maintenance level. This approach is proposed as the first step towards the standardization of service life prediction of roofing membranes and systems. The service life is determined considering both technical and economical performances, in addition to the risk of failure. The need for developing standards for service life prediction of roofing membranes and roofing systems stems from the necessity to design durable buildings with cost-effective operation and maintenance planning.

References

- [1] Cullen, W.C., "Problems Prompt a Quest for High Quality Standards," *Roofing Research and Standard Development*, 3rd Volume, ASTM STP 1224, Wallace/Rossiter, eds., pp.3-14.
- [2] Masters, L.W., "Service Life Prediction: The Barriers and Opportunities," *Proceedings of 9th CIB Congress*, National Swedish Institute for Building, Gävle, Sweden, 1983, pp. 9-20.
- [3] Sjöström, C., "Overview of Methodologies of Prediction of Service Life," In *NATO Advanced Research Workshop on Problems in Service Life Prediction of Building and Construction Materials*, Masters, L.W., ed., Martinus Nijhoff Publishers, Dordrecht, The Netherlands, 1985, pp. 3-20.
- [4] Masters, L.W., "Service Life Prediction: A State-of-the-Art," *Durability of Building Materials and Components* 5, 1987, pp. 1-9.
- [5] Masters, L.W., and Brandt, E., "Systematic Methodology for Service Life Prediction of Building Materials and Components," *Materials and Structures*, 1989, Vol. 22, pp. 385-392.
- [6] Frohnsdorff, G.J. and Martin, J.W., "Towards Prediction of Building Service Life-The Standards Imperative," *Durability of Building Materials and Components* 7, 1996, pp. 1417-1428.
- [7] Lounis, Z., Lacasse, M.A., Siemes, A.J.M., and Moser, K., "Further Steps Towards a Quantitative Approach to Durability Design," *CIB World Congress*, Gävle, Sweden, 1998, pp.1-10 (to be published).
- [8] Cash, C.G., and Bailey, D.M., "Predictive Service Life Tests for Roofing Membranes: Phase 1," *USACERL Interim Report FM-94/03*, 1993.
- [9] Griffin, C.W., and Fricklas, R., *The Manual of Low-Slope Roof Systems*, Third Edition, McGraw-Hill, New York, 1996.
- [10] Antrim, R., Johnson, C., Kirn, W., Platek, W., and Sabo, K., "The Effects of Acrylic Maintenance Coatings on Reducing Weathering Deterioration of Asphaltic Roofing Materials," *Roofing Research and Standard Development*, 3rd Volume, ASTM STP 1224, Wallace/Rossiter, eds., 1994, pp.101-115.
- [11] Cash, C.G. , "Durability of Bituminous Built-Up Roofing Membranes," *Durability of Building Materials and Components*, American Society for Testing and Materials STP 691, Sereda, P.J., and Litvan, G.G., eds., 1980, pp. 741-754.
- [12] Marcellus, R.W., and B.R. Kyle, "Theoretical Limit State Functions for Low Slope Roof Systems", *Canadian Society for Civil Engineering*, Sherbrooke, Canada, 1997, pp.27-30.
- [13] Pommersheim, J.M., Mathey, R.G., and Clifton, J.R., "Mechanical Performance Model for Roofing Membranes," *ASCE Journal of Structural Engineering*, Vol. 109, No. 6, 1983, pp. 1431-1449.
- [14] Mathey, R.G., and Cullen, W.C., "Preliminary Performance Criteria for Bituminous Membrane Roofing," *NBS Building Science Series* 55, 1974.

- [15] Chaize, A., and Fabvier, B., "FIT Classifications for Roofing Systems," *Proc. 3rd International Symposium on Roofing Technology*, 1991, pp. 356-360.
- [16] RILEM committee 75-SLR/CIB W83, "Performance Testing of Roofing Membrane Materials," *Intl. J. of Roofing Technol.*, Vol.2, 1990, pp.20-26.
- [17] Aköz, F., and Akman, M.S., "Service Life Estimation for Multi-ply Flat Roof Membranes," *Durability of Building Materials and Components 5*, 1990.
- [18] Rossiter, W.J., Martin, J.W., Lechner, J.A., Embree, E., and Seiler, J.F., "Effect of Adhesive Thickness and Surface Cleanness on Creep-Rupture Performance of Ethylene-Propylene-Diene Terpolymer (EPDM) Peel and Lap-Shear Joints," *Roofing Research and Standard Development, 3rd Volume, ASTM STP 1224*, Wallace/Rossiter, eds., 1994, pp.123-138.
- [19] Cash, C.G., and Bailey, D.M., "Predictive Service Life Tests for Roofing Membranes: Phase 2," *Durability of Building Materials and Components 7*, 1996, pp. 1023-1034.
- [20] Nelson, P.E., "Fatigue Behavior of Asphaltic Roofing Membranes," *Durability of Building Materials and Components 2*, 1981, pp. 463.
- [21] Stenman, H.K., Mech, M.N, Paroli, R.M., and Lei, W., "Maximum Tensile Load and Elongation Properties of Heated Built-Up Roofing Membranes at Selected Cold Temperatures," *Roofing Research and Standard Development, 3rd Volume, ASTM STP 1224*, Wallace/Rossiter, eds., 1994, pp.78-86.
- [22] Hovde, P.J., "Evaluation of the Factor Method to Estimate the Service Life of Building Components," *Proceedings of Symposium on Materials and Technology for Sustainable Construction*, Sweden, 1998 (to be published).
- [23] Bailey, D.M., Brotherson, D.E., Tobiasson, W., and Knehans, A., *ROOFER: An Engineered Management System (EMS) for Bituminous Built-Up Roofs*, USACERL Technical report M-90/04.
- [24] Masters, L.W., "A Reliability-Based Approach to Service Life Prediction," *Proc. Int. Symp. on Mathematical Modeling of Roofing Systems*, Oak Ridge, 1988.
- [25] Kyle, B.R. and Kalingar, P., Service Life prediction of Roofing Systems by Reliability based Analysis", *Proceedings 4th International Symposium on Roofing Technology*, Gaithersburg, MD, 1997, pp. 17-19.
- [26] Bogdanoff, J.L., and Kozin, F., *Probabilistic Models of Cumulative Damage*, J Wiley & Sons, New York, 1985.
- [27] Butt, A.A., Shahin, M.Y., Feighan, K.J., and Carpenter, S.H., "Pavement Performance Prediction Model Using the Markov Process," *Transportation Research Record 1123*, Transportation Research Board, Washington, D.C., 1987, pp. 12-19.
- [28] Saito, M. (ed.), *Infrastructure Condition Assessment- Art, Science, Practice, Proceedings Conference of American Society of Civil Engineers*, Boston, 1997.
- [29] Vanier, D.J., Lacasse, M.A., and Parsons, A., "Modeling of User Requirements Using Product Modeling," *3rd International Symposium on Applications of the Performance Concept in Building*, Tel-Aviv, Israel, 1996, Vol.2, (6), pp.73-82.

- [30] Vanier, D.J. and Lacasse, M.A., “BELCAM Project: Service Life, Durability and Asset Management Research,” *Durability of Building Materials and Components* 7, 1996, Vol. 2, pp. 848-856.