Construction Management & Economics

ISSN: 0144-6193 (Print) 1466-433X (Online) Journal homepage: https://www.tandfonline.com/loi/rcme20

Deterioration patterns of building cladding components for maintenance management

I. M. Shohet , M. Puterman & E. Gilboa

To cite this article: I. M. Shohet , M. Puterman & E. Gilboa (2002) Deterioration patterns of building cladding components for maintenance management, Construction Management & Economics, 20:4, 305-314, DOI: 10.1080/01446190210125563

To link to this article: https://doi.org/10.1080/01446190210125563

Published online: 21 Oct 2010.

Construction Management and Economics (2002) **20**, 305–314

Deterioration patterns of building cladding components for maintenance management

I. M. SHOHET*, M. PUTERMAN and E. GILBOA

Department of Civil Engineering and National Building Research Institute, Technion – Israel Institute of Technology, Haifa 32000, Israel

Received 18 September 2000; accepted 17 January 2002

Increasing demands are made on maintenance programmes to provide tools that will support maintenance planning. Among of the most important parameters affecting the efficiency of maintenance management are the precision and the reliability of the predicted service life (PSL) of building components. The main objective of this study was to develop a methodology for the establishment of databases listing deterioration patterns of building components based upon their actual condition. The methodology consists of four steps: (1) identification of failure patterns, (2) determination of the component performance (CP), (3) determination of the life expectancy of deterioration path (LEDP) and (4) evaluation of the predicted service life (PSL). The proposed methodology can be used for planning of maintenance activities, for evaluation of economic implications caused by intensive decay and for maintenance management.

Keywords: Maintenance management, deterioration, predicted service life, exterior cladding, performance

Introduction

There is a growing awareness worldwide of the importance of the maintenance of constructed facilities (Bourke and Davies, 1997; Cash, 1997, 1999; Horner *et al.*, 1997; Cane *et al.*, 1998; Van-Winden and Dekker, 1998; Underwood and Alshawi, 1999). This trend is due to the growing complexity of buildings, the increasing proportion of systems in them, higher levels of service, and the higher portion of maintenance costs in the life cycle costs of buildings. It is strengthened in the light of the limited budget commonly allocated for growing stocks of buildings. These place ever-higher demands on the life expectancy models predicting the deterioration paths of building components.

Increasing demands are made on maintenance programmes to provide tools that will support maintenance plans. These tools should provide quantitative means for the prediction of the service life of building components at different levels of performance. The maintenance strategies used by organizations differ from those preferred by owners of a large stock of facilities. Hotels and hospitals, for example, demand that most of the building components and systems in their utility perform at the highest level. Preventive maintenance is the preferred policy for components such as medical gas systems, and air conditioning systems. Replacement of components may be found efficient in these conditions due to the significant saving of labour, which is the principal expense of maintenance. Owners of residential buildings, on the other hand, may be satisfied with holding their facility at an 'acceptable' level of service, in order to minimize the costs of maintenance and keep to a failure-free performance. These different demands call for a flexible tool that will make possible an effective evaluation of the service life of building components based upon their actual condition and subject to different desired performance level.

The goals of the methodology were: (1) characterization of deterioration patterns of different failure mechanisms, and (2) development of a systematic, quantitative, and user-friendly procedure to evaluate the service life of building components based upon their actual condition at a given time. The approach must be sustained by indicative criteria in order to allow routine use of the method.

*Author for correspondence. e-mail: ishohet@tx.technion.ac.il

Construction Management and Economics
ISSN 0144–6193 print/ISSN 1466-433X online © 2002 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/01446190210125563

Models and methodologies for predicting the deterioration of building components

This section reviews selected projection methods for the evaluation of the service life of building components. These methods may be classified into four categories: (i) factorial, (ii) experimental, (iii) empirical and (iv) statistical.

Factorial methods are based on a review of factors of degradation and the determination of life expectancy based on multipliers limiting service life (e.g. quality multiplier). Experimental methods make use of *in situ* tests or laboratory accelerated degradation tests to evaluate the effect of a specific agent of deterioration (e.g. poor quality of materials). Empirical methods are supported by a field survey of factors of degradation followed by the systematic determination of the life cycle expectancy based upon ranking systems. The statistical method is sustained by the statistical analysis of mechanisms of deterioration integrated with mathematical models.

The AIJ method

In 1979 the Architectural Institute of Japan initiated research and development on the subject (AIJ, 1993). The resulting methodology falls under the category of factorial methods and is summed up in the expression:

$$Y = Y_s \times A \times B \times C \times D \times E \times F \quad (1)$$

Where Y is the predicted service life, Y_s is the standard service life, A is the quality of the materials used, B is the quality of the design, C is the quality of implementation, D is the level of maintenance, E is the environmental conditions, and F is the general condition of the building. This methodology provides a simplified means for determining the life cycle expectancy; however, it suffers from two significant drawbacks. First, it does not refer to the escalation or deceleration of the deterioration mechanism over time. Second, the predicted service life refers to the applied attributes of the component and ignores the supplied performance level of the element. The latter is a principal parameter that determines maintenance decisions and activities.

The RILEM methodology

An integrated and comprehensive methodology based upon existing methods was suggested in Masters and Brandt (1987). This method, which combines the experimental approach with a diagnostic investigation, consists of five phases.

(1) Definition: user's requirements and functional needs
(2) Preparation: comprising the identification of degradation mechanisms, sources of deterioration, and major indicators of premature degradation
(3) Pre-testing: planning of accelerated deterioration tests
(4) Testing: accelerated and continuous deterioration testing
(5) Interpretation and discussion: reduction of service life

This approach requires users of the method to possess a wide knowledge and understanding of deterioration mechanisms. Thus it is adequate for major case studies but is too cumbersome for implementation in routine maintenance activities.

Laboratory tests

This approach is demonstrated in Searls and Thomasen (1991) and Henriksen (1995). It was proved to be suitable for cases in which the effect of a single source of deterioration is investigated. A similar approach is realized in accelerated deterioration testing, in which a single phenomenon is isolated and tested under intensive conditions.

Physical and visual ranking of the performance of building claddings

This method, implemented in Shohet and Laufer (1996), is based upon a systematic evaluation of the physical and the visual degradation of building cladding systems and uses a survey of multiplicity of buildings of different ages that are exposed to both aggressive environmental and intensive service conditions. The rating system is composed of five points: from 1, severe failure, to 5, high performance. This methodology considers the consequences (physical as well as visual) of environmental conditions on the service life of building claddings.

In Hermans (1995) the concept of the interdependence between the performance of a building's component and the level of service of the entire facility was treated with emphasis on the efficient performance management of facilities.

Markov chains

This approach elucidates the probability of the performance of roofing systems using a discrete stochastic process that relies on the time variance and the randomness of the performance referred to. The setting of transitional probability matrices sustains the methodology. The aim is the development of an effective risk-based roofing maintenance management that minimizes the lifecycle costs of roofing systems, comprising the costs of maintenance and of repair (Vanier *et al.* 1996; Lounis *et al.* 1998). Nevertheless, this approach is adjustable only for components under standard deterioration paths (with no apparent cause of failure). The method cannot be implemented for the prediction of service life in failure conditions.

The review of prominent methodologies bears the development of a performance-based service life prediction tool for monitoring building components. Such a methodology may be useful for systematic decisions regarding replacements of building components and affecting the scope of maintenance activities.

Preliminary field survey

A preliminary in-depth field survey was carried out at the start of the development. This stage focused on two objectives: (a) a survey of the methods of implementation and (b) a review and survey of the abundant mechanisms of premature deterioration in exterior cladding systems. The preliminary survey encompassed five types of cladding: 1, concrete cladding; 2, cementitious stucco cladding; 3, synthetic stucco cladding; 4, ceramic mosaics; and 5, stone cladding.

The survey included 150 samples out of which it defined 30 typical failures. The failures were classified according to categories of cladding as shown in Table 1 for cementitious stucco. This table is used as a preliminary tool to identify the mechanisms of failure, and later to evaluate the performance level of the cladding.

The field survey produced the following conclusions.

- There are 30 major typical mechanisms of deterioration, which lead to wear and tear due to premature degradation of exterior claddings. The failures mechanisms were later categorized under six groups as discussed in the next section.
- 80% of these failures appear, with different levels of severity, within the first year after construction. These figures were deduced from the data gathered in the field survey.
- 90% of the failures become visible in the first two years after construction.

Figures 1 and 2 show a typical deterioration path of exterior cementitious stucco which, in this case, was caused by the lack of a drip-edge at the coping of the building (this failure is classified under poor design). The independent variable is time (in years), and the dependent variable expresses the performance level of the component on a scale between 0 and 100, where 100 represents complete performance and 0 represents severe failure. Figure 1 depicts the deterioration with the aid of indicative descriptions of deterioration. The linear graph in Figure 2 is the result of a regression analysis of 21 samples of stucco rendering that were identified with the same mechanism of failure, with no adverse condition such as corrosive environment, intensive use, etc. The regression line shows that the plaster performance deteriorates to the level of 40% after 19 years. This performance level is characterized by severe aesthetic and physical failure. Further details about the scale are presented later. The area between the two dashed lines (in Figures 2 and 3) represents the prediction interval at the $(1 - \alpha)$ level ($\alpha = 0.05$) of significance. It was established through the data gathered in

Table 1 Example of a checklist of agents of deterioration in cementitious stucco

Failure index	Type of failure	Possible deterioration agent
1	Degradation, peel off, crumbling	Porous rendering in marine environment
2	Change of colour and peeling	High absorption of water
3	Leaking of corrosion-tinted water from metallic fittings	Corrosion
4	Graffiti	Intensive use, poor maintenance
5	Cracking and local peeling	Corrosion and swelling of the reinforcement bars
6	Appearance of moisture and leaks in the vicinity of the top of the building (coping)	Faulty coping or lack of this component
7	Broken edges of columns, beams, etc.	Lack of protection on columns (poor design)
8	Spots of moisture and absorption of water	Sloping planes of porous materials
9	Degradation of stucco, crumbling and peeling off	Erosion due to wind
10	Horizontal or vertical cracking	Lack of expansion joints
11	Moisture spots, and stains around in-wall drainpipes	Cracks in or rupture in drainpipes
12	Development of micro-organisms and cyanobacteria near edges of the building	Lack of drip edge and coping, development of moisture on the cladding
13	Horizontal and vertical cracking	Sinking of cantilever
14	Diagonal cracking	Differential sinking of foundations

Table 2 Description of the physical scale

Physical rate	Description of features
1 [20]	A significant portion of the cladding had peeled off. There are developed cracks more than 5 mm wide in the cladding.
2 [40]	Cracks more than 1 mm wide and in more than 5% of the cladding area.
3 [60]	Cracks 0.5 mm wide and up to 5% of the total cladding area. In mosaic cladding there is falling of up to 3%.
4 [80]	Capillary cracks in a portion of the cladding. In mosaic or ceramic tiles there is an initial development of micro-organisms on the cladding, or falling-off of single elements.
5 [100]	Cladding is complete and undamaged. There is no falling-off in mosaic and stone claddings. There might be capillary cracks.

Table 3 Description of the visual scale

Visual rate	Description of features
1 [20%]	Significant portion of cladding surfaces is not complete. There are developed cracks on cladding surfaces.
2 [40%]	As in 1, but the damage is local. Micro-organisms have developed over a third or more of the cladding
3 [60]	Cladding surface is not uniform, a significant portion of the surface is characterized by lapses in uniformity because of physical damage or discolouring.
4 [80]	Cladding surface is not uniform (because of minor cracks, falling-off of tiles, or micro-organisms). There are significant distinctions in cladding colour.
5 [100]	The cladding is complete and undamaged (no visible cracks). There is no falling-off in mosaic and stone claddings. There are no colour distinctions. Cladding surface is uniform.

the field survey, and their statistical analysis, which assumes a normal distribution of the population in each failure. This region is used to assess the validity of the observations and the statistical validity of the entire analysis of the predicted service life.

Review of failures

A review of the causes of failure identified the six most frequent sources of premature deterioration in exterior cladding systems under study (Shohet *et al.*, 1999a,b).

(1) Faulty design (e.g. lack of design details, such as expansion joints)

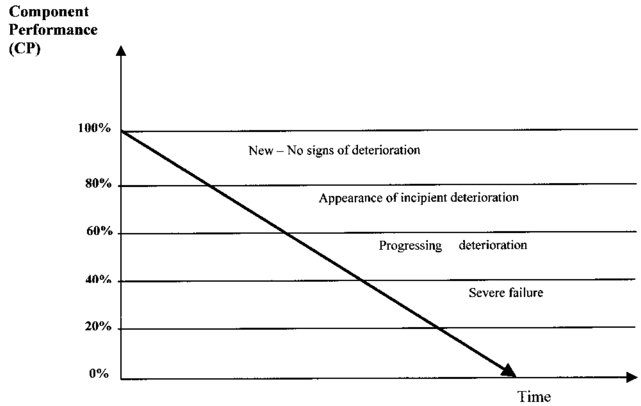

Figure 1 Example of deterioration pattern of exterior cementitious stucco

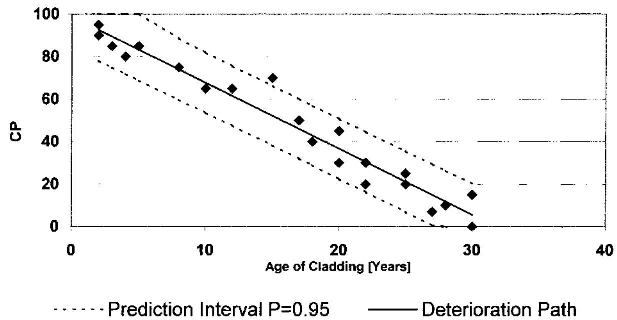

Figure 2 Lack of drip-edge in cementitious stucco, linear pattern, LEDP = 19 years

(2) Poor quality of application (e.g. poor or lack of bond due to poor implementation)
(3) Poor quality of materials (e.g. porous stucco, poor quality of stone)
(4) Adverse climatic or atmospheric conditions (air pollution, sea-shore environment, and intensive UV)
(5) Poor maintenance
(6) Intensive use (e.g. in school or military buildings, above standard occupancy)

The major causes of premature deterioration identified in the field survey were summarized as the basis for a systematic review of failures. Table 1 offers an example of such a review for cementitious stucco. The causes of deterioration were first classified according to symptomatic criteria such as cracking, peeling off, and decay. This classification is later visualized in files of descriptive photographs to assist the user in the verification of the features. Each component's performance is defined as the relative level of service, on a scale between 0 and 100. These rating grades are used for the evaluation of various components in the building. The methodology may be used to evaluate the condition of the entire building in a comprehensive building evaluation survey.

Deterioration patterns over time

Characterization of patterns of deterioration is perceived in this methodology as the principal means for predicting the service life of components. The patterns are presented in graphs in which the independent variable is time and the dependent variable is the CP (component performance), reflecting the change in the performance level over time. The graphs are supported by a two-stage analysis: (i) trends in the deterioration patterns identified in the field survey, and (ii) analysis of mechanisms of deterioration, based on the identification of deterioration patterns that had been clearly detected.

The field survey from which the curves were deduced included over 150 samples in three categories of cladding: cementitious cladding, synthetic cladding, and ceramic mosaic cladding. For each category, the survey was focused on three typical failures. The data were gathered with the aid of a form filled out with the parameters of the building and the cladding (Appendix and Tables 2 and 3). The age of the claddings that were rehabilitated or renovated referred to the recent renewal time. Each pattern of deterioration was characterized by a major single source of failure. The sources of deterioration in cementitious stucco were found to be: (a) porous stucco in a marine environment, where the latter is defined as within 200 m or less from the coastline (Israel Standards Institute, 1999), (b) air-pollution, defined as up to 1 km from a major source of pollution, and (c) lack of design details, e.g. lack of expansion joints.

Two patterns of deterioration were defined following the findings of the field survey.

1. Linear pattern, which is typical in situations where a permanent deterioration agent exerts a continuous and consistent impact on the cladding. This pattern is manifested in the effect of erosion by wind and in the decay caused by intensive UV radiation or micro-organisms.
2. Concave-shape (exponential) pattern, which characterizes such physical or chemical phenomena as concrete shrinkage (which can cause the failure of the entire system of exterior cladding or lead to deterioration due to chlorides), or porous cementitious stucco in a marine environment (Figure 3). The deterioration pattern is sustained by a regression line with $R^2 = 0.85$, and the prediction interval is at statistical significance of $p = 0.95$.

The methodology presented hereafter uses the curves to identify the actual condition point of exterior cladding, and the deduced predicted service life.

Methodology

The methodology combines the factorial method with the systematic ranking of performance levels of cladding components. Nevertheless, the method treats the component's supplied performance rather than the supplied attributes. This combination takes advantage of the factorial method's benefits (it is practical and timesaving), and the systematic rating of performance levels (uniform performance criterion). In contrast to other methods reviewed in the literature survey, the proposed method is sustained by evaluation of the actual performance level of the component, rather than using an identical predicted paradigm of deterioration. The method requires thus a systematic evaluation of the performance level integrated with deterioration patterns of identified failures. It provides a tool that may support actual performance monitoring and lifecycle control of building cladding components.

Due to the scope of the subject, the methodology was implemented on three types of exterior cladding: 1, stucco; 2, ceramic claddings and 3, stone claddings. The following sections review the 3 stages of implementation of the methodology.

Determination of component performance (CP)

This step is taken with the aid of visualizing photo-tables and systematic ranking scales of the performance of the component on a scale from 0 to 100% (Figure 1, Tables 2 and 3). One hundred percent represents no defects or any sign of failure, 80% shows incipient deterioration, 60% points to escalating deterioration and below 60% indicates severe failure. This scale was found to be a consistent tool for ranking performance levels with different users. The CP describes the impact of several factors (e.g. quality of materials, intensive use) on the service conditions and on the durability of the component. However, in the ranking process the focus of the observation is on the symptomatic effects of deterioration.

Determination of the typical path of deterioration

The establishment of paths of deterioration provides a means for evaluating the presumptive service life for a specific deterioration mechanism (like corrosion of reinforcement bars). This concept is shown in Figure 4. Provided that the age of the component and the CP (the one evaluated in the preceding stage) are known, the user determines the actual condition point (ACP) for the specific deterioration mechanism. The user may examine the statistical probability of the evaluation by the 95% prediction interval (Figures 2 and 3). The path of deterioration thought by the user to be the typical one is deduced through extrapolation from the

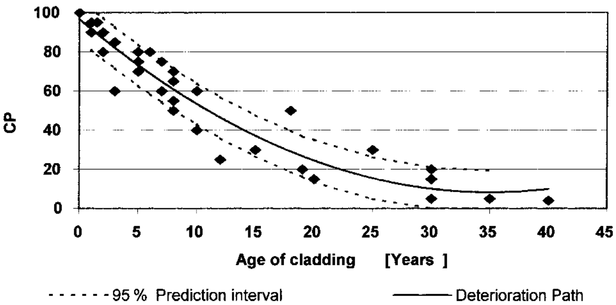

Figure 3 Deterioration pattern and 95% prediction interval for cementitious stucco in a marine environment, concave pattern

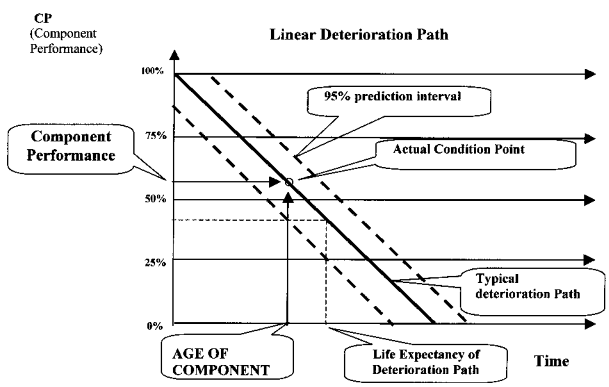

Figure 4 Determination of a typical path of deterioration

curve between the ACP and performance level 40 parallel to the trend in the deterioration pattern of the failure. It is then possible to evaluate the predicted service life (PSL) if the actual deterioration path is followed. That path then represents the life expectancy in the situation in which the specific agent is the only one affecting the component. The user must repeat this procedure for each deterioration mechanism identified in the review of failures.

Determination of the predicted service life (PSL)

The model for determining the predicted service life is sustained by the factorial method; however, it combines the evaluation of the actual performance level of a cladding component expressed as the CP (component performance). The predicted service life is calculated using the expression

$$\mathrm{PSL} = \mathrm{SLE} \times \mathrm{LELC}_i \tag{2}$$

where SLE is the standard life expectancy and LELC_i is the life expectancy limiting coefficient for the failures identified.

The standard life expectancy (SLE) represents the normal lifecycle of cladding systems along a normal deterioration path, in which no exterior adverse conditions and no defects, such as inferior quality of materials, faulty design, or poor implementation, are visible. These conditions represent standard service conditions. The standard service lives for the materials studied in this work are (Shohet, 1995):

Cementitious stucco: 25 years
Ceramic claddings: 35 years
Stone claddings: 40 years

The LELC is calculated in order to quantify the effect of a specific deterioration path on the predicted service life of the component. It uses the SLE (standard life expectancy), the IC (influence coefficient), and the LEDP (life expectancy of deterioration path) through the expression

$$\mathrm{LELC} = 1 - \frac{\mathrm{SLE} - \mathrm{LEDP}}{\mathrm{SLE}} \times \mathrm{IC} \tag{3}$$

where LELC is the life expectancy limiting coefficient for the deterioration mechanism; LEDP is the life expectancy of the deterioration path, for the specific mechanism; and IC is the influence coefficient for the specific deterioration factor. One can see that LELC decreases as IC and LEDP increase, and vice versa. The influence coefficients were determined with the data gathered in the review of failures in the field survey. The LELC is highly sensitive to the influence coefficient.

Determination of the influence coefficient (IC) for a deterioration path

The influence coefficient for a specific deterioration path expresses the partial effect of a specific deterioration agent in a comprehensive failure of the cladding system. The value of this coefficient varies between 0 for degradation agents that do not affect the predicted service life (for example the effect of UV on stone), and 1 for agents that strongly impact the PSL (e.g. corrosion of porous cementitious stucco in a marine environment, and peel off of ceramic tiles due to lack of expansion joints in ceramic mosaics). The corrosion of reinforcement bars, for example, is given an IC of 0.6, while the deterioration caused by exterior mechanical damage to edges of ceramic tiles, referred to as a local deterioration agent, is given an IC of 0.25.

Representative example

The implementation of this method follows four steps, parallel to the stages of the methodology.

Step 1: Identify and define failures based on the list of the deterioration agents

Step 2: Determine the component performance (CP) for each deterioration mechanism with the aid of the performance rating scales (Tables 2 and 3)

Step 3: Determinate the life expectancy limiting coefficient ($LELC_n$) for any deterioration mechanism (defined in step 1)

Step 4: Evaluate the predicted service life (PSL) using the LELC and expression 3.

General data and identification of deterioration mechanisms

The structure under examination is a six-storey building with cementitious stucco. The building is 20 years old, and the exterior cladding was renovated nine years before the survey. Two degradation mechanisms were found. There was decay of the stucco due to its poor quality (porous rendering in a marine environment), with a component performance level of 50. This performance rate reflects cracks 0.5 mm wide and peel-off of cladding to the extent of 5% of the entire cladding area. Also there was deterioration of stucco due to lack of a drip-edge, with a component performance level of 60, reflecting development of micro-organisms and change of colour near the top edges of the cladding surface.

The life expectancy of the deterioration path for the first failure is 13 years, a value that is deduced from the intersection of the deterioration curve from the ACP along the deterioration path, with the performance level of 40% (Figure 5). In a similar manner, the life expectancy of deterioration path for the second mechanism is 15.5 years (Figure 6). The life expectancies of the two deterioration paths are used in the next stage to determine the predicted service life of the cladding under failure conditions.

Determination of the PSL

The predicted service life is deduced by first determining the life expectancy limiting coefficient (LELC) for the deterioration mechanisms identified in the previous step. This is followed by the determination of the PSL. The influence coefficient (IC) for the first deterioration mechanism is 1, reflecting the comprehensive effect of this failure over the entire cladding surface and structure. The IC for the second mechanism of deterioration is 0.25, reflecting the local effect of this mechanism on the edges of the cladding surface.

The LELCs for the failures were calculated using the LEDPs for the failures and the coefficients for the deterioration mechanisms: $LELC_1 = 0.52$ and $LELC_2 = 0.91$. Then the PSL was calculated with these coefficients using expression 2:

$$PSL = 25 \times 0.52 \times 0.91 = 11.6 \text{ years}$$

View of the 20 years old building – coated with rehabilitated eight years cementitious stucco in sea-shore environment

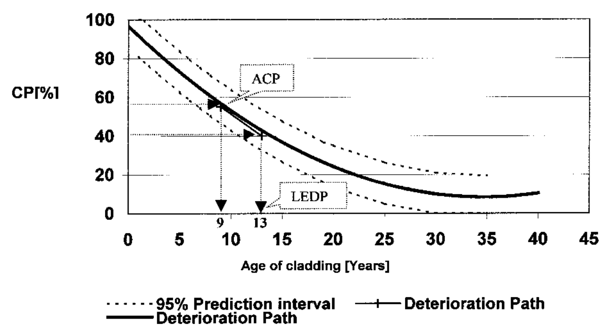

Figure 5 Determination of the LEDP for the deterioration of porous stucco in a marine environment, representative example

The stucco cladding's predicted remaining service life is less than three years. The statistical significance of these results is sustained by the validity of the deterioration patterns of the two observations. In this case $p = 0.95$ for both observations. It can be evaluated that the statistical validity of the entire analysis is at a level of $p = 0.90$, with regard to the population of field survey claddings.

Concluding remarks

The proposed methodology can be a useful and practical tool for three typical purposes in maintenance planning and also for the evaluation of the economic

View of the failure in cementitious stucco of the 9 years old cladding

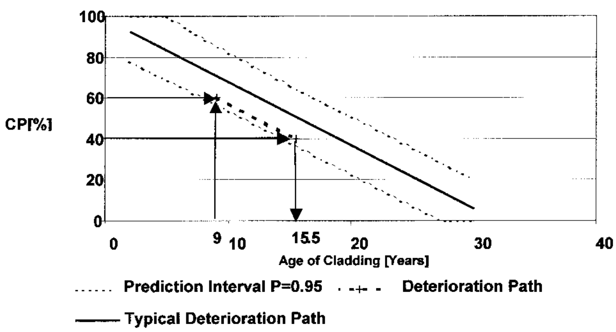

Figure 6 Determination of the LEDP from lack of drip-edge in cementitious stucco, representative example

implications of rehabilitation or different repair solutions. It may be applied in the following ways.

(1) Planning of maintenance activities: the methodology can be used as a decision tool to prioritize different activities of maintenance based upon the actual condition point of the component and the probability of failure. For components that are found to be on a similar service level (CP), the one with a steep deterioration pattern will be given higher priority compared with building components with moderate deterioration paths.
(2) Evaluation of costs of rehabilitation or different repair solutions with respect to the existing cladding with identified deterioration pattern.
(3) For economic evaluation of intensive decay and degradation due to poor implementation, poor quality of materials, or lack of details. Frequently this scenario appears in cases of dispute between owner and contractor. The methodology presented here can be used to systematically assess the economic implications of intensive deterioration. The deterioration pattern can be expressed in terms of life cycle costs as a means of assessing the costs of failure.

The proposed approach may support facility maintenance managers in the precise scheduling of maintenance works. That precision may allow the cautious delay of repair work based on the model prediction, and may save costs due to the extension of the service life and the delay in the allocation of financial resources for maintenance activities.

Summary

The methodology presented in this paper was developed as a basic instrument for predicting the service life of building components in failure conditions for maintenance purposes. The method is based on examination of the actual condition of the component in question, and its symptomatic analysis. This tool may be practical and simple to use in the establishment of an effective maintenance policy.

The advantages of the method may be summarized as follows.

(1) Uniformity of criteria for evaluating the performance level and for identifying deterioration mechanisms. Systematic tables sustain the method for the determination of the CP and the LEDP. These data form a systematic frame for estimating the predicted service life (PSL).
(2) Symptomatic characterization of deterioration mechanisms. The methodology does not require detailed information or knowledge concerning the quality of the workmanship, the suitability of materials, or the impact of adverse environmental conditions. The symptoms of deterioration, the actual condition point (performance), and the age of the component sustain the analysis.

Nevertheless, the methodology suffers from two drawbacks. (a) The factors that determine the final output of the procedure are the influence coefficients, derived on the basis of the experience and evaluation of the developers of the methodology. These factors may be different in different diverse climatic or atmospheric conditions, and must be adapted to prevailing conditions. (b) The method requires a large investment in terms of time for the establishment of the databases of deterioration patterns.

Acknowledgement

We should like to express our gratitude to the Israel Ministry of Construction and Housing for its support of the research that led to this paper.

References

AIJ (1993) *Principal Guide for Service Life Planning of Buildings*, English Edn, Architectural Institute of Japan, Tokyo, Japan.

Bourke, K., and Davies, H. (1997) *Factors Affecting the Service Life Predictions of Buildings: A Discussion Paper*, Laboratory Report, Building Research Establishment, Garston, UK.

Cane, D., Morrison, A., and Ireland, C. J. (1998) Maintenance and service costs of commercial building ground-source heat pump systems. *ASHRAE Transactions*, **104**(2), 699–706.

Cash, C.G. (1997) The relative durability of low-slope roofing. In *Proceedings of the Fourth International Symposium on Roofing Technology*, 17–19 September, Rosemont, IL.

Cash, C.G. (1999) Comparative testing and rating of thirteen thermoplastic single ply roofing membranes. In Lacasse, M. and D. Vanier, D. (eds), *Proceedings of the Eighth International Conference on Durability of Building Materials and Components, 8DBMC*, pp. 1083–92.

Henriksen, F. (1995) Reactions of gases on calcareous stones under dry conditions in field and laboratory studies. *Water Air and Soil Pollution*, **85**, 2707–12.

Hermans, M. (1995) *Deterioration characteristics of building components: a data collecting model to support performance management*. PhD thesis, Eindhoven University of Technology.

Horner, R.M.W., El-Haram, M.A. and Munns, A.K. (1997) Building maintenance strategy: a new management approach. *Journal of Quality in Maintenance Engineering*, **3**(4), 273–80.

Israel Standards Institute (1999) Israel Standard 1920–Part 1, *Plaster: General requirements and test methods for mortar for plaster*.

Lounis, Z., Vanier, D.J., and Lacasse, M.A. (1998) A discrete stochastic model for performance prediction of roofing systems. In *Proceedings of CIB World Building Congress on Sustainable Construction*, pp. 315–24.

Masters, L.W., and Brandt, E. (1987) *Prediction of Service Life of Building Materials and Components*, CIB W80/RILEM 71-PSL, Final Report.

Searls C.L. and Thomasen S.E. (1991) Repair of the terracotta facade of Atlanta City Hall. In *Proceedings of the Second International Conference on Structural Repair and Maintenance of Historical Buildings*, pp. 247–57.

Shohet, I.M. (1995) *Comparison of Methods for Exterior Claddings*, Research Report, National Building Research Institute, Technion–Israel Institute of Technology (in Hebrew).

Shohet, I.M., and Laufer, A. (1996) Exterior cladding methods: a techno-economical comparison. *Journal of Construction Engineering and Management ASCE*, **122**(3), 242–7.

Shohet, I.M., Rosenfeld, Y., Puterman, M., and Gilboa, E. (1999a) *Characterization of Deterioration Patterns of Building Components for Maintenance Management*, Research Report, National Building Research Institute, Technion–Israel Institute of Technology (in Hebrew).

Shohet, I.M., Rosenfeld, Y., Puterman, M., and Gilboa, E. (1999b) Deterioration patterns for maintenance management: a methodological approach. In Lacasse, M. and Vanier, D. (eds), *Proceedings of the Eighth International Conference on Durability of Building Materials and Components, 8DBMC*, pp. 1666–78.

Underwood, J. and Alshawi, M. (1999) Towards an integrated application for forecasting building element maintenance. *International Journal of Computer Integrated Design and Construction*, **1**(1), 39–48.

Vanier, D.J. and Lacasse, M.A. (1996) BELCAM project: service life, durability and asset management research. *Durability of Building Materials and Components*, 7(2), 848–56.

Van Winden, C. and Dekker, R. (1998) Rationalization of building maintenance by Markov decision models: a pilot case study. *Journal of The Operational Research Society*, **49**, 928–35.

Appendix: Deterioration patterns field survey

1.1.1.1. Form #____

Date of Visit : _________

Address of Building: _________

Designation of Building:

1 – Residential 2 – Office 3 – Public 4 – Other (please specify) ___________

Height of the building: _______

Distance of Building from the coast line: ________

Vicinity of the building to air-polluting sources: Power plant ______

Heavy industry ______

Main road ______

Age of the building:______

Type of cladding: 1. Cementitious stucco; 2. Synthetic stucco; 3. Ceramic mosaic;

Rehabilitation of the exterior claddings in the past – Yes/No

If yes, When these activities were undertaken? _______

Objectives or causes of rehabilitation _________

<u>For Ceramic mosaics</u>:

Details of joints: Width ________ ; Fillers in joints: Acrylic, Cementitious, Other, please specify __________

Symptoms of failures in joints:

1. Cracks and crumbling of fillers
2. Peel off of tiles
3. Development of micro-organisms