DETERIORATION PATTERNS FOR MAINTENANCE MANAGEMENT – A METHODOLOGICAL APPROACH

Deterioration patterns for maintenance management

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Abstract

Increasing demands are made on maintenance programs to provide versatile tools that will support maintenance strategies at different levels of service. One of the most important parameters affecting the efficiency of maintenance programs is the precision and reliability of the predicted service life of building components. The main objective of this study is to develop a methodology for the establishment of databases listing deterioration patterns of building and systems components based upon their actual condition monitored in-situ. The methodology integrates diagnostic tools into an analytical model and is sustained by a comprehensive field survey. The methodology was implemented at this stage on three types of exterior cladding systems: (1) stucco claddings; (2) ceramic tiles or mosaics; and (3) stone claddings. A preliminary field survey reviewed some 30 mechanisms of failures that may stem from: (a) Faulty design; (b) Poor quality of implementation; (c) Poor quality of materials; (d) Adverse climatic conditions (intensive UV or chlorides); (e) Adverse atmospheric conditions caused by air pollution; (f) Poor maintenance; (g) Intensive use. The methodology incorporates 3 steps: Identification of failures patterns, Determination of the actual condition point, and evaluation of the predicted service life.

Keywords: maintenance management, deterioration, service life, failure analysis, diagnosis, exterior claddings.

1 Introduction

There is a growing awareness world-wide of the importance of the maintenance of constructed facilities. This trend is an indication of the growing complexity of buildings, the increasing portion of systems in them, and the higher levels of service that are demanded by different types of owners - institutions, private owners, etc.

These raise ever-higher requirements of the life-expectancy models predicting the deterioration paths of various building components with a view to improving the effectiveness of the implementation of maintenance plans.

1.1 Rationale

Increasing demands are made on maintenance programs to provide versatile tools that will support maintenance strategies at different levels of service. The maintenance strategies used by Organizations differ from those preferred by owners of large stock facilities, the latter often requiring other levels of performance. Hotels and hospitals, for example, require that most the components in their utility facilities perform at the highest level and stipulate that they be replaced as soon as start to deteriorate. Owners of office buildings, on the other hand, may be satisfied with holding the facility at an “acceptable” level of service, in order to minimize the costs.

1.2 Objectives

The main objective of this study is to develop a methodology for the establishment of databases listing deterioration patterns of building and systems components. Such a methodology would enable the maintenance staffs to evaluate the life cycle of building components based upon their actual condition monitored in-situ. The goals may be defined as follows:

- Characterisation of deterioration patterns of different degradation mechanisms;
- Development of a systematic, practical procedure to determine the Service Life of building components based on their actual condition at a given time.

Due to the scope of the subject, the methodology was implemented at this stage on three types of exterior claddings: (1) Stucco, (2)ceramic claddings, (3) stone claddings.

1.3 Stages of development

The development process consisted of 5 sequential phases, as follows:

1. Field Survey;
2. Classification of deterioration mechanisms and typical failures;
3. Analysis of patterns of premature deterioration and failures;
4. Mathematical representation of deterioration mechanisms;
5. Development of a systematical model for determining the Predicted Service Life (PSL).

2 Background and review

The preliminary survey of existing methods revealed two main terms in the domain of Service Life Prediction: Failure, performance of building components, and methodologies to characterize the pattern of deterioration mechanisms.

2.1 Failures

Failure is defined as a condition in which a component does not meet the performance requirement of its designated use. This definition includes a wide range of sophisticated features such as minor visual faults in the component, and more severe serviceability problems such as excessive deformations, premature deterioration of materials, leaking roofs and facades, etc. (Feld & Carper, 1997).

There are two classical approaches to the characterization of failures:

- The "symptomatic" approach – This concept focuses on the results of the failure and the effects of the failure on the building in terms of cracking, peeling off, leakage etc. This approach does not involve an in-depth analysis of the failures.
- The "circumstantial" approach – This concept focuses on the failure itself and the mechanisms of degradation, the history of the building, and the major faults that led directly or indirectly to premature degradation.

The methodology here presented uses both approaches in the treatment of Predicted Service Life (PSL) of building components. The knowledge base of this methodology is sustained by an analysis of the numerous degradation mechanisms that were identified in the field survey, while the symptomatic approach is used to supply the user of the methodology with the classification of mechanisms of premature deterioration.

2.2 Models and methodologies for predicting the deterioration of building components

This section reviews some projecting methods for the evaluation of the service life of building components. These methods may be classified into *factorial*, *experimental*, and *empirical*, methods. The first category is based on a review of degradation factors and the determination of life expectancy based on multipliers. The second category makes use of in-situ tests or laboratory-accelerated degradation tests to evaluate the effect of a specific agent of deterioration. The third category is supported by a field survey of degradation factors followed by the systematic determination of the Life Cycle based upon ranking systems.

2.2.1 The AIJ method

In 1979 the Architectural Institute of Japan initiated research and development in the domain (Architectural Institute of Japan 1993). The methodology proposed by that institution falls under the factorial methods and is summed up in the following expression:

$$\mathbf{Y} = Ys * A * B * C * D * E * F \qquad \textbf{(1)}$$

where: Y – the predicted service life
Ys – the standard Service
A – the quality of the materials used
B – the quality of the design
C – the quality of implementation
D – Level of maintenance
E – Environmental conditions
F – General condition of the building

The deficiencies of this approach are:

- It requires in-depth studies of design, material, and implementation factors;
- It does not refer to the escalation or deceleration of deterioration over time.
- It does not define a systematic ranking of the service level.

2.2.2 The RILEM methodology

An integrative and comprehensive methodology based upon existing methods was suggested in (Masters, 1987). This method combines the experimental approach with diagnostic investigation. It consists of 5 phases:

1. Definition of user's requirements and of functional needs;
2. Preparation - Including 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 – Prediction of Service life.

This approach combines experimental with diagnostic tools, and thus requires a wide knowledge and understanding of deterioration mechanisms.

2.2.3 Laboratory tests

This approach is demonstrated in (Searls &Thomasen, 1991; and Henriksen, 1995). It was proved to be adequate for cases in which the effect of a specific agent of deterioration is investigated. A similar approach is realized in accelerated deterioration testing. Its major disadvantage is the time and the financial resources required. It is thus cumbersome for use in maintenance management.

2.2.4 Physical and visual ranking of components performance

This method, implemented in (Shohet & Laufer, 1996), is based on a systematic evaluation of the physical and the visual degradation of building systems and uses a survey of multiple buildings of different ages and subjected to environmental conditions. The ranking system is composed of 5 levels, 1- representing total failure and 5 – high-performance components. This methodology emphasized the strong impact of environmental conditions on the life cycle of building components.

In (Hermans, 1995) the concept of the dependency between the Building components performance and the entire facility's level of service was treated with emphasis on the performance management of facilities.

The methodology described in the present paper synthesizes the factorial method with the systematic ranking of cladding components. This synthesis makes use of the advantage of the factorial methods (time saving), while employing a systematic ranking of performance levels.

3 Methodology

The development comprised 5 stages, which built an empirical basis and later a mathematical basis for the method:

1. Comprehensive field survey;
2. Systematic review of failures;
3. Characterization of 4 types of deterioration patterns;
4. Development of tables for identifying agents of deterioration and their effect on the life cycle of the component;
5. Integration of the paths of deterioration into the predicted life cycle through Life Cycle Limiting Coefficients.

3.1 Field survey

A preliminary in-depth field-survey was carried out at the beginning of this work. This tool aimed at the following objectives: (a) Survey of the methods of implementation; (b) Review and survey of the abundant mechanisms of premature deterioration in exterior cladding systems.

The field survey produced with the following conclusions:

- There exist some 30 major typical mechanisms of deterioration, which lead to failure due to premature degradation.
- 80% of these failures, of different levels of severity, appear within the first year after construction.
- 90% of the failures become visible not later than two years after construction.

Based upon these findings, the methodology aims at predicting the Life Cycle Expectancy of exterior claddings on the strength of an in-depth review of the faults, defects, and failures in exterior cladding components. Figure 1 shows a typical deterioration path of exterior cementitious stucco which in this case was caused by the lack of drip-edge at the top of a residential building. Figure 2 illustrates the concept of deterioration patterns evolved in this work (demonstrated in this particular case by a linear pattern). The main area (coloured dark grey) represents 80% of the population (of this deterioration mechanism) – exhibiting the standard pattern. The wider section represents a range under which we assume 90% of the population to fall.

A review of the causes of failure identified seven of the most frequent sources of premature deterioration in exterior cladding systems under study:
(1) Faulty design; (2) Poor quality of implementation; (3) Poor quality of materials; (4) Adverse climatic or atmospheric conditions (air pollution or intensive UV); (5) Adverse atmospheric conditions caused by air pollution; (6) Poor maintenance; (7) Intensive use.

3.2 Review of failures

The major agents of premature deterioration identified from the field survey were summarised as the basis for a systematic review of failures. Table 1 offers an example of such a review for cemetitious stucco. The agents of deterioration were first classified on the basis of symptomatic criteria such as cracking, peeling off, and decay. This classification was later amplified with files of descriptive photographs to assist the user in the verification of the features. These tables were then used as a basis for the establishment of a photo-ranking system for the determination of the Components Performance in Failure Condition (CPFC), as seen in Figure 3.

3.3 Determination of component performance in failure conditions (CPFC)

The next stage of development is the establishment of checklists for characterising the performance level of a component. This step is taken with the aid of photo-tables that visualise the condition of the component based on a scale of 0-100%. (Figures 1 and 3). 100% represents perfect condition with no deficiencies, 75 % represents the beginning of deterioration, 50% represents escalating developing deterioration and below 25% represents a condition of severe failure. This scale is used as a consistent tool for ranking the performance levels with numerous users. The CPFC expresses the impact of several factors on the service condition, and the durability of the component. However, in the ranking process we are not interested in the mechanisms but in the symptoms of deterioration. This makes the methodology friendly for multiple users who may not be experts in the in-depth analysis of the deterioration mechanisms. The tools used in the methodology contain tables for 30 mechanisms in 3 categories of exterior claddings (stucco, ceramics, and natural stone).

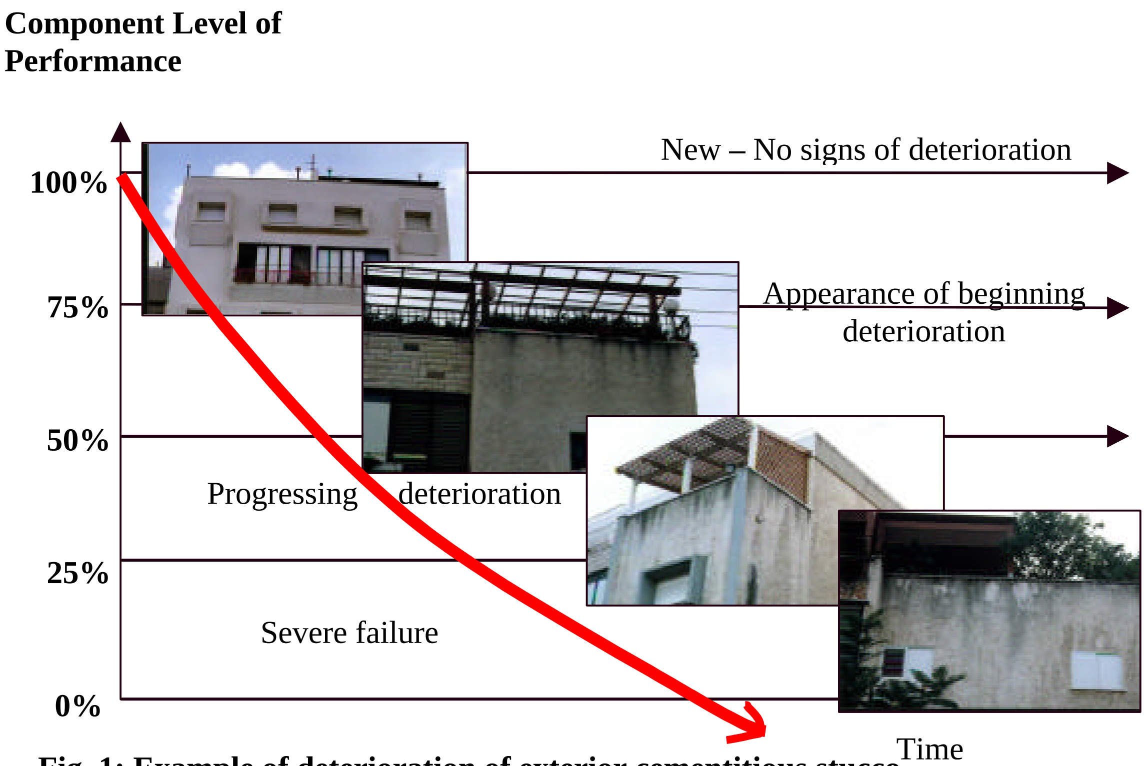

Fig. 1: Example of deterioration of exterior cementitious stucco

3.4 Deterioration patterns over time

The characterisation of deterioration patterns is perceived in this methodology as the focal tool for predicting the service life of components. The deterioration patterns are presented in graphs in which the independent variable is time, the dependent variable is the CPFC expressing the change in the level of service over time. The graphs (Figure 3) are sustained by a 2-stage analysis:

- Trends of deterioration patterns identified in the field survey. Analysis of mechanisms of deterioration, based on the identification of deterioration agents that were clearly detected.

Table 1: Example of checklist of deterioration agents in cementitious cladding

Failure Number	Type of failure	Deterioration agent
1	Change of colour and peeling off	Moisture due to irrigation
2	Leaking of corrosion from metallic fittings	
3	Graffiti	
4	Cracking and local peeling off	Corrosion and swelling of the reinforcement bars
5	Appearance of moisture and leaks in the vicinity of the top of the building (coping)	Faulty coping or lack of this component
6	Broken edges of columns, beams etc	Lack of protection on beams
7	Spots of moisture and absorption of water	sloping planes with porous materials
8	Degradation of stucco, crumbling and peeling off	Erosion due to wind
9	Horizontal or vertical cracking	Lack of expansion joints
11	Moisture spots, and stains around in-wall drainpipes	Cracks or disruptions in drainpipes
12	Development of Micro- organisms and cyanobacteria near edges of the building	Lack of drip edge and coping and development of moisture on the cladding
13	Horizontal and vertical cracking	Sinking of cantilever
14	Diagonal cracking	Differential sinking of foundations

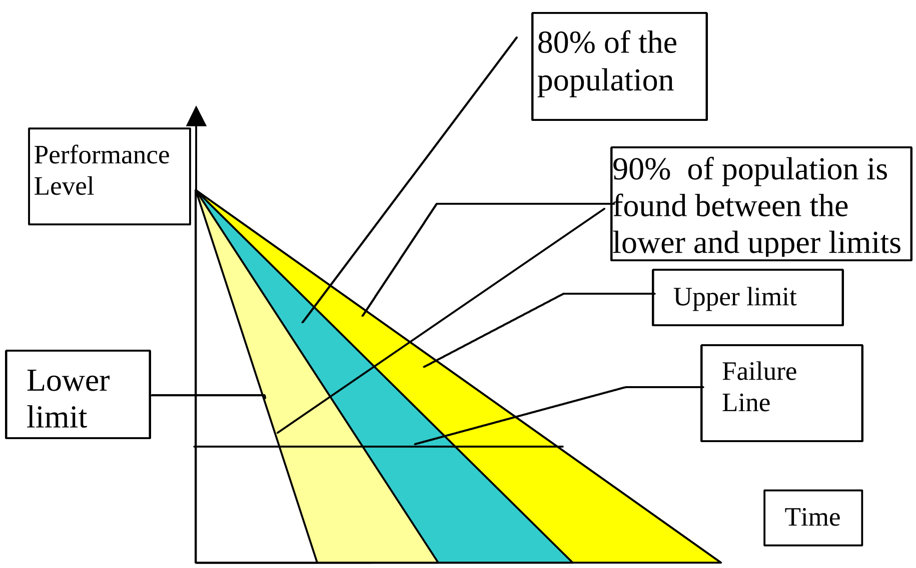

Fig. 2: Schematic paradigm of deterioration pattern – linear deterioration pattern

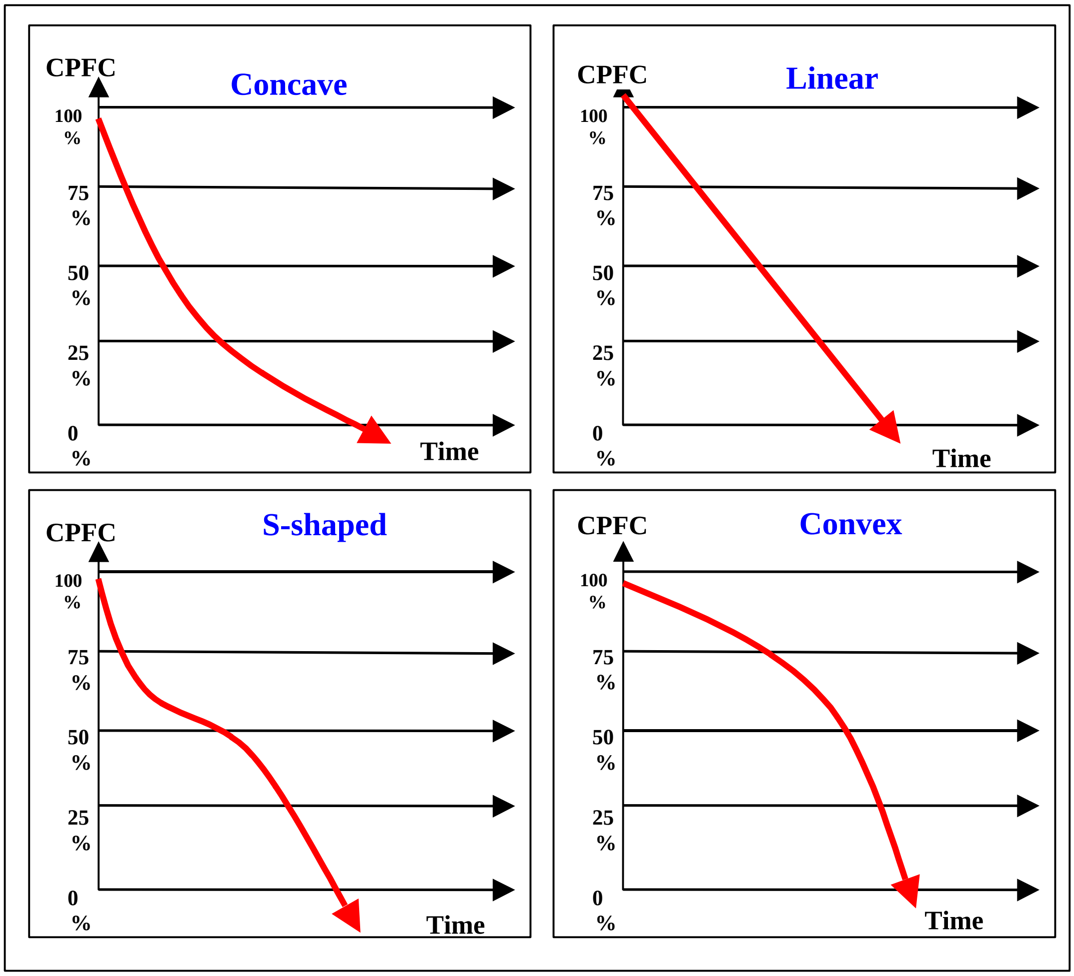

Fig. 3: Four typical patterns of deterioration paths

Four patterns of deterioration were defined (Figure 3):

1. Linear pattern – This pattern 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, the decay caused by intensive UV radiation (on synthetic stucco), etc.
2. "Convex-Shaped" pattern – characterises physical or chemical phenomena, such as concrete shrinkage, that cause physical failure of the entire system of exterior cladding.
3. "Concave-shaped" pattern – represents the action of chemical and physical agents on claddings such as stucco and natural stone. Such impact appears in cases of microorganism or Cyanobacteria development on cementitious stucco and on natural stone. The difference between the cases is the pace of decay – fast in stucco, slower in stone.
4. S-shaped pattern – represents a deterioration mechanism that changes its intensity over time. The pattern appears when certain building details, such as coping or drip edge, are lacking, a situation that makes a visual impact shortly after the end of construction. Then the major mechanism becomes the physical reaction, which takes longer to affect the strength of materials. When that process ripens,

the deterioration accelerates, and its impact becomes visible. This pattern was characterized in the case of a drip edge lacking at the top of buildings.

3.5 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 (such as corrosion of reinforcement bars etc.). This stage is visualized in Figure 4. Provided that the age of the component and the CPFC (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 check his evaluation by using the 90% range between the upper and the lower deterioration paths as defined previously (in Fig. 2). This step makes use of a form that helps the user to identify the *specific* deterioration pattern on the basic deterioration graph that had previously been identified. The deterioration patterns were derived from the ACP (Actual Condition Points) that had been gathered in the field survey. The deterioration path (thought to be the typical one) is extracted by the user through extrapolation from the curve between the starting point (Age 0, CPFC=100), and the Actual Condition Point (ACP). Following this step, it is possible to evaluate the Service Life for the Deterioration Path can be evaluated. This parameter 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 Stage 2 (3.2).

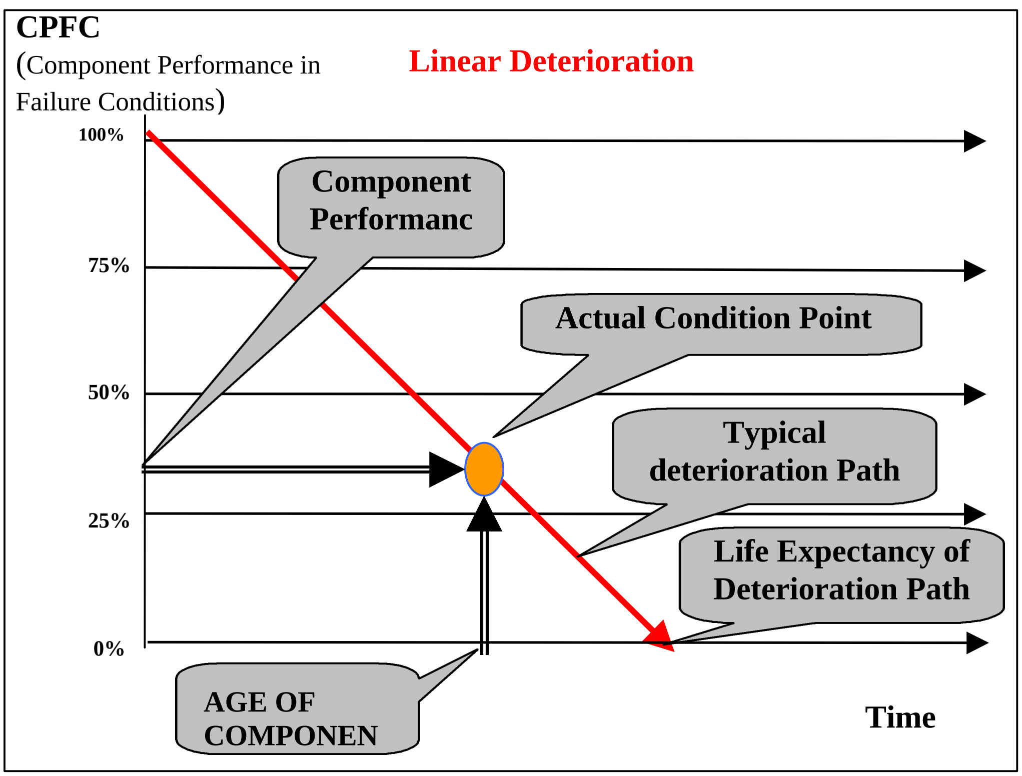

Fig. 4: Determining the typical path of deterioration

3.6 Determination of the predicted service life (PSL)

The model for calculating the Predicted Service Life is sustained by the factorial method combined with the evaluation of the CPFC (Component Performance in Failure Condition).

3.6.1 Evaluation of the standard life expectancy (SLE)

The parameter expressing the Life Expectancy of cladding systems, known as the Standard Life Expectancy, is based on findings of previous studies. It expresses the service life of the component along a normal aging path, in which there are no exterior adverse conditions, and no defects, such as inferior quality of materials, faulty design, or poor implementation are visible. These conditions represent ideal normal service conditions. The Standard Service life for the materials studied in this work include:

1. Cementitious stucco: 20 years;
2. Ceramic claddings: 25 years
3. Stone cladding: 40 years.

3.6.2 Determination of the influence coefficient (IC) for deterioration paths

The Influence Coefficient for a specific deterioration path expresses the partial effect of a specific deterioration agent in the comprehensive failure of the cladding system. The value of this coefficient ranges 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 (corrosion of porous cementitious stucco in a marine environment). For example, the corrosion of reinforcement bars 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 IC=0.25.

3.6.3 Determination of the Life Expectancy Limiting Coefficient (LELC)

The LELC is now calculated in order to quantify the effect of the specific deterioration path on the Predicted Service Life of the component. The LELC is based on the SLE, the IC, and the LEDP through the following expression:

$$LELCn = 1 - \frac{SLE - LEDPn}{SLE} * ICn \qquad \textbf{(2)}$$

Where,

LELCn – The Life Expectancy Limiting Coefficient for the n^{th} deterioration mechanism;

SLE – the Standard Life Expectancy;

LEDPn – the Life Expectancy of the Deterioration Path, for the specific mechanism;

ICn – the Influence Coefficient for the specific deterioration factor;

It is seen that LELC decreases as IC and LEDP increase, and vice-versa. The Influence coefficients were determined with the data collected in the review of failures in the field survey. It is clear that the LELC is strongly sensitive to the Influence Coefficient. This point stresses the sensitivity of the model to the relative effect of more than one deterioration mechanism acting simultaneously on the component.

3.6.4 Determination of the predicted service life (PSL)

The Predicted Service life in actual conditions is finally determined by multiplication of SLE by LELC for any deterioration mechanism detected in the first stage. Equation (3) describes the determination of PSL:

$$PSL = SLE * LELC_1 * LELC_2 * ...... * LELC_n \quad \textbf{(3)}$$

Where,
SLE – the Standard Life Expectancy
$LELC_n$ – the Life Expectancy Limiting Coefficient

The mathematical model is based on the factorial method and is sustained by the Performance Level which is determined using the CPFC.

4 Demonstrative example

The implementation of this method follows 5 steps:

- Step 1: Verification of the age of the building;
- Step 2: Identification of the types of deterioration mechanisms, using the appropriate Checklist of Failures;
- Step 3: Determination of the Component's Performance in Failure Conditions (CPFC) for each deterioration mechanism;
- Step 4: Determination of the Life Expectancy Limiting Coefficient ($LELC_n$) for any deterioration mechanism (defined in Step 2);
- Step 5: Calculation of the Predicted Service Life (PSL) using the LELC for each failure.

The method was tested on several cases of premature deterioration. The following example, which deals with natural stone cladding, was selected for the purpose of demonstration.

4.1 General data and deterioration mechanisms

The structure is a 7-story building with natural stone cladding. The degradation mechanisms found were:

- Deterioration of the stone caused by its poor quality (High absorption combined with low rigidity)
- Deterioration of the stone caused by the unprotected steel in a "corrosive" environment

Based upon this and using the photo-checklist-tables for the determination of the CPFC, it was found that the CPFC was 50% for the first, and 65% for the second, deterioration mechanism.

4.2 Determination of the PSL

The Predicted Service Life is now calculated by determining the Life Expectancy Limiting Coefficient for the deterioration mechanisms identified in Step 2. The LEDP for the deterioration mechanisms (found to be Nos. 12 and 10), and the LELC were calculated to be 0.65 and 0.85, with Influence Coefficients of 0.5 and 0.3 respectively.

The PSL, as derived from pertaining to these Coefficients was calculated using expression (3) and found to be 22.1.

5 Conclusion

The method presented in this paper was developed as a tool for the prediction of the service life of building components for maintenance purposes. The method is therefore based on an examination of the actual conditions affecting the component in question and a symptomatic analysis. This tool is 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 the performance level and for the detection of deterioration mechanisms. The method is sustained by systematic tables for the CPFC and the LEDP that form a consistent foundation for the estimate of the Service Life.
2. Symptomatic characterization of deterioration mechanisms. The methodology does not require detailed information or knowledge concerning the quality of workmanship, the quality of materials, or adverse environmental conditions.
3. User-friendliness. It is based on a simple 5-step procedure.

The disadvantages of the methodology are:

1. High sensitivity in the first year of the components – at age 2 years, a tolerance of 10% in the CPFC may result in an uncertainty of 50% in the evaluation of the Predicted Service Life.
2. The factors that impact the final output of the procedure are the Influence Coefficients, determined on the basis of a subjective evaluation by the developers of the methodology. These factors may be different in diverse climatic or atmospheric conditions.
3. The method requires a large investment in terms of time order to develop the database of deterioration patterns, IC_s, and the photo-table for the determination of deterioration mechanisms.

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