Service Life Prediction for Buildings Exposed to Severe Weather

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Abstract

This paper presents a specific case study for estimating the service life of public buildings in the harsh weather of Kuwait using the factor method. Estimating the service life helps enhance the sustainability of these buildings and controls some economic aspects. The case in consideration was applied to the data collected for a project to assess the structural behavior of twenty-six buildings that belong to Kuwait University. The assessed buildings were located in two regions. The first region is 100 – 400m from the coast and the second region is about 5 km away from the coast. The buildings were assessed by visual inspection, material testing, and structural analysis. The findings of these investigations guided the working team to assign the values of the different factors used in the prediction process. The factors were predicted in a probabilistic approach to consider the inherent variability in the construction components and the surrounding effects. The results of the service life prediction provide a perspective for the expected life span of buildings in similar conditions.

Keywords: factor method; service life; prediction; assessment; severe weather

1. Introduction

Many trials have been carried out to predict the service life of buildings. Most of these trials have focused on corrosion and carbonization as the prime reasons for the deterioration of concrete buildings (Liu; 1996, McGee *et al.*; 2000, 2002). The Factor Method considers many parameters in predicting the service life of a building or its components. The method stresses that a building's durability is a function of its components and the environment affecting these components. The International Organization for Standardization adopted the factor method in its ISO 15686 publications as a comprehensive tool for service life prediction. This method is based upon collecting data related to the behavior of the constituting materials, construction process, the environment inside and outside, and the facility's use and maintenance processes. This study uses the factor method to predict the service life of public buildings in severe weather according to an extensive material and structural investigation of those buildings (ISO 15686-1; 2000, ISO 15686-2; 2001, Athena Institute; 2006).

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2. Objectives

A thirty-year plan for the buildings and facilities of the Kuwait University was prepared. The plan included the determination of whether the existing buildings can be exploited within the plan's time period and which buildings may be restored to pursue their functioning.

The buildings have been exposed to severe weather in which the temperature ranges from 0^{o} C to 50^{o} C over the year with humidity ranging from 0 to 100%. The variability of temperature and humidity along with salinity of the air has left the buildings in a critical situation that needs investigation. The assigned project included material and structural assessment of twenty-six buildings. The project targeted defining which buildings would need rehabilitation or replacement to complete the long-term plan.

This paper is concerned only with the prediction of the overall service life of the buildings as categorized in two groups according to their location with respect to the coast. Details of the materials testing, structural analysis, and proposed rehabilitation for each building are not considered in the scope of this manuscript.

3. Methodology

The assessment of a building usually starts with collecting data about that building. Unfortunately, there was no available documentation for the buildings in consideration, which were 30-40 years old. The available historical data was based upon verbal discussions with stakeholders who previously worked in the university. A mandatory survey of the buildings

Table 1. Summary of Experimental Results

Test	Group I (Coastal region)		Group II (Near Coast region)	
	Mean	Standard Deviation	Mean	Standard Deviation
Compressive strength (MPa)	23.1	4.6	27.9	3.9
Chloride content (% of cement)	0.44	0.108	0.31	0.067
Carbonation depth (mm)	8.1	2.27	6.8	1.26
Concrete resistivity (Ωcm)	13810	1980	24420	3830
Half-cell potential (V)	-0.261	0.046	-0.164	0.032
pH	9.3	1.73	12.1	1.95

Fig.1. Sample from Assessed Buildings

was done to prepare "as-is" drawings at the very beginning of the project. This phase was followed by preparing structural drawings for the building, showing the location and dimensions of the structural elements as concluded from the investigative survey. An analysis of structural behavior and integrity was carried out to obtain the expected stresses in the different elements in the building.

The expected service life of the buildings is predicted based upon the factor method, including the effect of the structure's components and the surrounding environment on the durability of the building. The buildings were categorized into two groups. Group I included fifteen buildings within a few hundred meters from the coast, which are 35-45 years old. Group II included eleven buildings which are about 5 km from the coast and are 25-35 years old. The life estimate is based primarily on the field and lab tests, the effects of severe environmental conditions in the region, and the expected maintenance and operation. The estimate of maintenance and operational factors are based upon the previous experience of the interviewed personnel in the university, similar experiences in public buildings, and the quality assurance procedures proposed by the university.

4. Investigation Process

The investigation process for each building was begun by doing a survey of the building and preparing "as-is" drawings. Simple architectural drawings were prepared to illustrate the spaces of the building and their utilization. The anticipated concrete dimensions and the expected reinforcement were allocated in the structural drawings for the building. Numerous cores were taken from different elements of the building to construct a perspective for the structural elements and their concrete dimensions and the contained reinforcing steel.

The second stage included visual inspection of the building to record any clear deterioration in the structure or the serviceability of the building. The target of this process was to document any settlement, expansion, deformation, dusting, cracking, peeling, scaling, spalling, discoloring, efflorescence, exposed reinforcement, or any other indicator of deterioration. This process was required to provide more details about the locations with anticipated problems. The extracted concrete cores were used to perform the required testing. Table 1. provides a conclusive summary for the collected data, and is categorized into two groups.

5. Analysis of Experimental Results

The results of the experimental investigation illustrated moderate deterioration due to severe exposure of the coastal buildings. A lower level of deterioration was obtained by the results of investigating the offshore buildings. The structural analysis of the buildings pointed only to one building with structural integrity problem. Some other buildings showed structural issues due to the deterioration of the composing material.

Most of the existing models considered that one of the major symptoms for service life termination is the increase of the chloride content at reinforcement location to a critical limit that accelerates the corrosion process. This time period is commonly predicted by the simple Fick's Second Law as follows (Liu; 1996):

$$C_x = C_s(t) - [C(t) - C_i] erf(\frac{x}{2\sqrt{D\,t}}) \qquad (1)$$

where;

C_x = chloride concentration at depth x;
C_s = chloride concentration at surface;
C_i = initial chloride concentration;
D = diffusion coefficient;
x = depth;
t = time; and
erf = error function.

Fig.2. shows the upper and lower limits of the expected chloride content over a period of 70 years starting from the assumed construction date.

Carbonation of concrete is the second most important cause of corrosion. The higher the CO_2 content on the surface of concrete, the higher the rate of carbonation inside the structural element. This relationship can be simplified by using the following parabolic equation (McGee *et al.*; 2000):

$$X_c = A_c \cdot t^{1/2} \qquad (2)$$

where;

X_c = the carbonation depth;
A_c = a constant;
t = time.

Fig.3. presents the extrapolation of the upper and lower limits of carbonation depth in concrete elements for both regions. The same trend is observed with respect to concrete resistivity where the resistance greater than 20,000 Ωcm indicates low corrosion activity (McGee *et al.*; 2002).

6. Factor Method

The factor method is adopted by ISO 15686 to predict the service life of a building and/or its components. The method is based on considering interaction between the material of the building and the environment inside and outside the building. A reference service life must be assumed for the building. This is defined by ISO specification as "service life that a building or parts of a building would expect to have in a certain set of in-use conditions". The reference service life is modified by some factors that consider the effect of specific in-use parameters that primarily control the service life of the building. The prediction of the service life is calculated using the following equation:

ESLB = RSLB x Factor A x Factor B x Factor C x Factor D x Factor E x Factor F x Factor G (3)

where;

ESLB = estimated service life of the building,
RSLB = reference service life of the building,
Factor A = quality of components,
Factor B = design level,
Factor C = work execution level,
Factor D = indoor environment,
Factor E = outdoor environment,
Factor F = in-use conditions, and
Factor G = maintenance level.

The evaluation process of the modification factors is based primarily on the collected data for the material and structural performance of the buildings and supported by the experience of the performing team besides the available and collected information concerning the history, performance, and exposure of the building. In the project under consideration, the historical information, material characteristics, mechanical analysis and exposure conditions were investigated to the extent that allows a reliable decision. The quantitative values of the low, most-likely, and high values of the modification factors

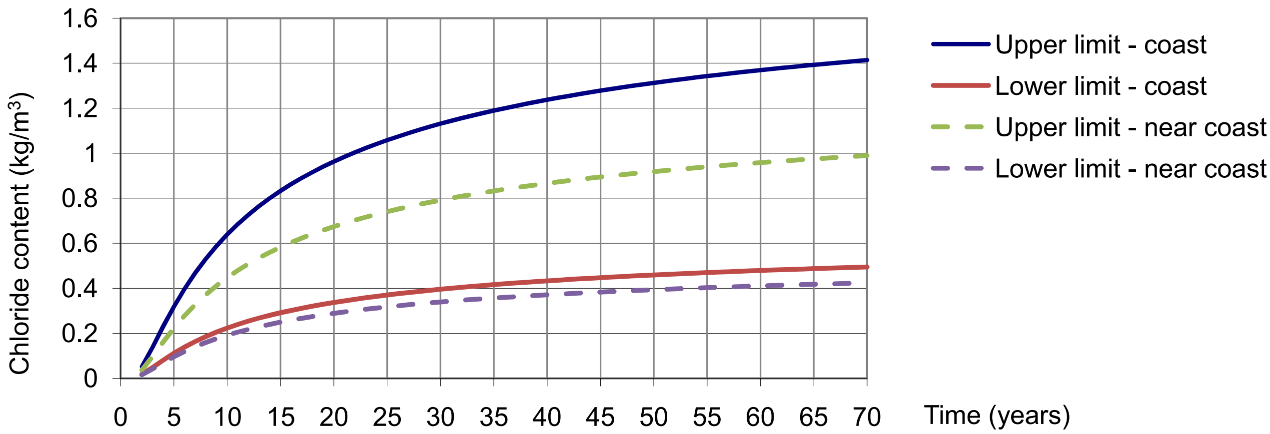

Fig.2. Variability of Internal Chloride Content

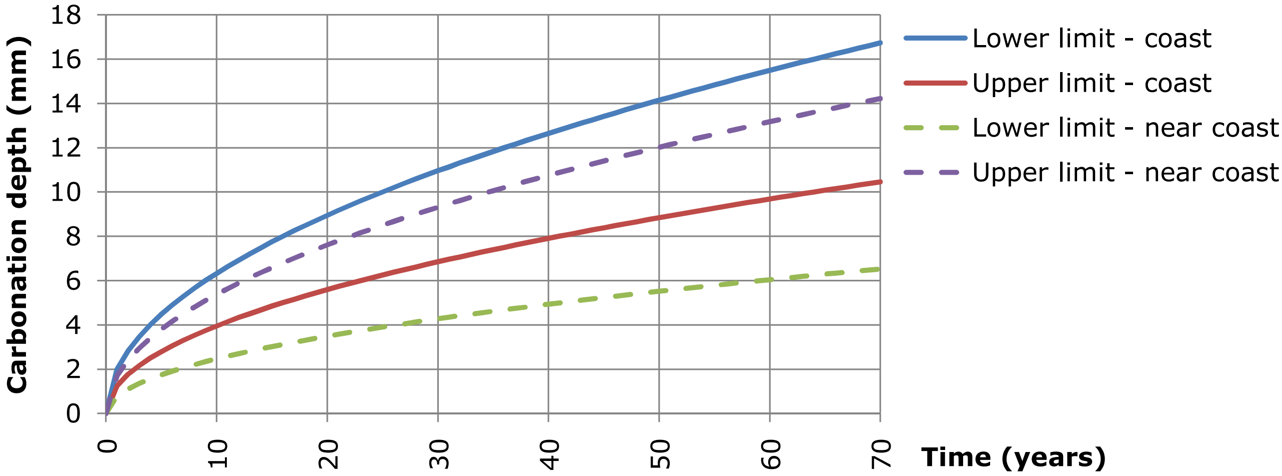

Fig.3. Effect of Time on the Carbonation Depth

Table 2. Qualitative Description of Modification Parameters

Factor	Coastal region	Near coast region
A. Quality of components	Elements deteriorated due to severe exposure to fluctuating temperature and humidity. Some buildings need rehabilitation	Low humidity fluctuation but high temperature exposure
B. Design level	N/A	N/A
C. Work execution	No signs of distress due to execution defects	Only one building has problems of integrity due to being built in several stages with different designers and constructors
D. Indoor environment	No signs of indoor exposure	No signs of indoor exposure
E. Outdoor environment	Increase of pollution due to the adjacent harbor and increase of vehicle's exhaust	Increase in exhaust
F. Usage condition	No expected change in usage	No expected change in usage
G. Maintenance	Below average commitment for maintenance is expected	Below average commitment for maintenance is expected

Table 3. Quantitative Classification of Modification Parameters

Factor	Coastal region			Near coast region		
	Low	Most likely	High	Low	Most likely	High
RSLB	30	30	30	30	30	30
Factor A	0.40	0.70	0.90	0.70	0.85	1.00
Factor B	1.00	1.00	1.00	1.00	1.00	1.00
Factor C	0.90	1.00	1.10	1.00	1.10	1.00
Factor D	0.90	1.00	1.05	0.90	1.00	1.05
Factor E	0.50	0.70	0.90	0.80	0.95	1.00
Factor F	0.90	1.00	1.05	0.90	1.00	1.05
Factor G	0.80	0.90	1.00	0.80	0.90	1.00
Overall Factor		0.44			0.73	

were deduced from discussions with the engineers of the performing agencies including the test-performing agency and the engineering agency.

The uncertainty in the prediction process is incorporated in statistical form. Instead of using deterministic value for each factor, three values in the form of low value, most likely value, and high value are introduced. Probabilistic approaches have been proposed by many researchers for the prediction of the service life of buildings (ISO 15686-8; 2004, Marteinsson; 2005, Hans; 2005). The most likely value corresponds to the traditional deterministic value and to be realized, is expected to have a 50% confidence level. The low and high values represent the tails of the probability distribution of the prediction life. It is proposed that these values deviate from the most likely value by twice the standard deviation value of the distribution. This statistical configuration means that the low and high values have a probability confidence level of being realized of 5% and 95%.

Table 2. presents a simple configuration for the basic conclusions inferred from the data collection and testing processes. In addition, Table 3. presents the quantitative values worked out from the collected information and the subsequent discussions. The later table includes the low, most likely, and high values for each modification factor. Hovde (2005) presented a sample to evaluate the modification factors, which was

a good guide for the work in this study.

7. Predicting Service Life

The last step in predicting the service life distribution for the considered buildings and similar buildings in similar environments is to apply Equation (3). Equation (4) is used to predict the mean value of each factor based on the proposed three values and hence sum these means to get the assembled mean for all factors (Moser, 20004):

$$Mean = \frac{Low + 2.95\ Most\ Likely + High}{4.95} \quad (4)$$

Also, Equation (5) is used to predict the standard deviation of the factors. The sum of the variances (V) is calculated to get the standard deviation of the predicted service life of the building (Moser, 2004):

$$\sigma = \frac{High - Low}{4.6} \quad (5)$$

$$V = \sigma^2 \quad (6)$$

The reference service life of the building (RSLB) was considered to be 30 years as proposed by the authorities. Despite the fact that the common life for public buildings is 50 years, the authorities requested lowering this reference based on local experiences with similar buildings in the same severe conditions.

The final result shows that the buildings in the coastal region have a 95% probability of surviving 3 years or more and a 5% chance of surviving 23 years or more with a mean of 13 years. On the other hand, the buildings in the near coastal region have a 95% probability of surviving 15 years or more and a 5% chance of surviving 29 years or more with a mean of 22 years. The standard deviation of the buildings is 5.3 years and 3.3 years for the buildings in the coastal and near coastal regions, respectively. The coastal buildings encounter higher uncertainty because of the severe exposure; hence, there is a higher variance in expectations.

8. Conclusion

The presented study confirms the following conclusions:

- Service life needs to be predicted in a stochastic form to consider the uncertainty and variability in the building and the surrounding conditions.
- Buildings in the coastal zone experience higher uncertainty than other buildings in near coastal zones.
- More conservative design, maintenance, and operation processes are recommended for the buildings in the coastal zone.
- The numerical results in this study could be used as a guide for the service life prediction of buildings in similar conditions.

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