DETERIORATION OF REINFORCED CONCRETE STRUCTURES AND LIFE CYCLE ASSESSMENT

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Abstract

Since material degradation is inevitable in reinforced concrete structures it is important to assess how concrete structure deteriorate, i.e., determine the residual capacity and subsequent life cycles of the structure. The intention of this paper is to present an experimental program aiming to investigate strength and serviceability deterioration of concrete structures, exemplified by corrosion of reinforcing steel in concrete. Data produced from the experiment is used to develop deterioration models for concrete structures. With the deterioration models a life cycle assessment of concrete structures is possible. For this purpose, a method, for life cycle assessment, which is based on time-dependent reliability theory, is outlined.

1 INTRODUCTION

Reinforced concrete structures are one of the most widely used engineered structures and are frequently subjected to extreme natural hazards as well as material and structural deterioration. Of three major mechanisms that cause structural concrete deterioration (Warner, et al 1989), steel corrosion in concrete is the most severe form of deterioration with the capacity to threaten the structural safety and integrity. It is also the most difficult problem to deal with (Sagoe-Crentsil, 1990).

The corrosion induced premature structural deterioration is attributed to a combination of factors including area reduction and bond loss. This combined effect of steel corrosion on structural performance has not been fully investigated and an understanding of this effect can only be gained through experiment (Andrade 1995, Guirguis 1990, Yeomans, et al 1978). Assessment of the life cycle of corrosion-affected structures must be based on models of structural deterioration in terms of strength and serviceability limit states used in design. Such models can only be derived from realistic and accurate data. Field data tends to be of poor accuracy and has a high degree of variation. Laboratory data so far is obtained from tests that do not fully represent structures in-service (i.e. under loading) and hence it is not applicable to developing structural deterioration models. To carry out tests under both corrosion and loading an experimental facility capable of simulating the desired aggressive environment and maintaining the load during the corrosion process is necessary.

The intention of this paper is to present an experimental program aiming to investigate strength and serviceability deterioration of concrete structures, caused by corrosion of reinforcing steel in concrete. The thrust of the program is that service loading is applied to test specimens which at the same time are subjected to simulated marine environment in a large corrosive environmental chamber with salt spray facility. Data produced from the experiment is used to develop deterioration models for the structure. With the deterioration models a life cycle assessment of concrete structures is possible. A method, for life cycle assessment, which is based on time-dependent reliability theory, is outlined.

2 EXPERIMENT

2.1 Large Corrosive Environmental Chamber

The carry out the proposed tests a large corrosive environmental chamber is necessary. The chamber built at Monash University has the following functions:

Other features of the chamber include: (1) dimension of 4 by 8 meters; (2) fully computerised; (3) service loads can be applied; and (4) different environments can be simulated.

2.2 Details of Specimens
Test specimens, i.e., beams, are broken down as follows: 2 cement types - normal Portland cement and fly ash blended cement (3:7); 2 water/cement ratios - 0.45 and 0.6; 2 duplicates for statistical study; and 3 time periods - 3, 5 and 7 months duration respectively, which are time points to load the specimens to failure so that the residual capacity can be determined in a destructive manner. Additional specimens are used under natural condition to verify the data acquired under accelerated conditions. Typical details of the beam are as shown in Fig. 1.

![Figure 1](image_url)

**2.3 Test Method and Measurement**

The test rig is as shown in Fig. 2. The specimens are exposed in the chamber for acceleration. A typical cycle of wet and dry is as shown in Table 1. The salt solution used in spray contains 3.5% NaCl (by weight) to simulate Australian sea water. Service loads of 60% ultimate load are applied by lead ingots and kept constant during the test duration.

![Figure 2](image_url)

**Table 1 Typical week of acceleration**

<table>
<thead>
<tr>
<th>Day</th>
<th>Temperature</th>
<th>Relative humidity</th>
<th>Spray of NaCl solution</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>25°C</td>
<td>N.A.</td>
<td>2 hrs on, 1 hr off for 8 hrs</td>
<td>Wet</td>
</tr>
<tr>
<td>Tuesday</td>
<td>25°C</td>
<td>60%</td>
<td>Off</td>
<td>Natural</td>
</tr>
<tr>
<td>Wednesday</td>
<td>50°C</td>
<td>20%</td>
<td>Off</td>
<td>Dry</td>
</tr>
<tr>
<td>Thursday</td>
<td>25°C</td>
<td>N.A.</td>
<td>2 hrs on, 1 hr off for 8 hrs</td>
<td>Wet</td>
</tr>
<tr>
<td>Friday</td>
<td>25°C</td>
<td>60%</td>
<td>Off</td>
<td>Natural</td>
</tr>
<tr>
<td>Saturday</td>
<td>50°C</td>
<td>20%</td>
<td>Off</td>
<td>Dry</td>
</tr>
<tr>
<td>Sunday</td>
<td>50°C</td>
<td>60%</td>
<td>Off</td>
<td>Extra</td>
</tr>
</tbody>
</table>

The following parameters are investigated in the experiment: (1) Bond loss between concrete and reinforcing steel, which is determined by slips at the interface of concrete and steel and recorded with DeMag gauge; (2) Corrosion rate, which is determined by the cross section reduction of steel bars; (3) Ultimate strength, which is determined by external loads at cantilevered ends; (4) Deflection, which is measured at the cantilever ends; and (5) Cracks. Crack width, depth and patterns are also measured and monitored during the test.
3 DETERIORATION MODELS

Data generated from the test is then used to develop deterioration models for life cycle performance assessment of next Section. It may be noted that the data presented herein is more realistic in the view that the test represents the structures in service — this is the thrust of the paper. However, due to the length limit, it is not possible that all data produced the test can be presented in the paper. Instead, only data used to develop deterioration model for serviceability limit state, namely, bond slip and deflection are presented, which are as shown in Fig. 3 and 4. Deterioration models for the strength limit state will be presented at the conference.

Figure 3 Bar Slip with Time for 0.45 and 0.6 w/c Normal Cement Specimens

Figure 4 Deflections with time for both 0.45 and 0.6 w/c Normal Cement Specimens

As may be noted large variation exists in the data. This is not surprised due to the uncertain nature of the problem of steel corrosion. This again justifies the use of probabilistic approach in dealing with life cycle assessment of concrete structure where a large degree of certainty exists. From the data shown the following deterioration models can be developed. For bond slip, the mean function of bond slip can be expressed as:

\[ \mu_{\text{slip}} = 2 \times 10^{-5} t^2 - 0.0001t \]  
(1a)

and the standard deviation function can be expressed as

\[ \sigma_{\text{slip}} = 0.005t \]  
(1b)

for the 0.45 w/c ratio normal cement specimens. In the same way, the deterioration models for deflection can be derived which are summarised as follows:
With these models, the performance of the reinforced concrete structures over time can be assessed in terms of reliability as to be shown below. Therefore the development of these deterioration models are of significantly practical importance in terms of life cycle performance assessment and asset management.

4 LIFE CYCLE ASSESSMENT

In the context of time-dependent structural reliability theory, assessment of structural deterioration and life cycle performance is based on the probability of the violation of the limit state the structure was design against. At the time that the probability of deterioration failure is below an acceptable limit, a life cycle is formed at which maintenance is required or the service life of the structure is attained.

Let the performance of a reinforced concrete structure be represented by residual capacity, $X$. The original capacity, $X_0$, of a structural member is determined based on design codes (SA 1994). $X_0$ is a nominal value of the capacity, which is a random variable. Using the deterioration models developed in above Section, the serviceability capacity of the structure at time $t$, $X(t)$, can be expressed as

$$X(t) = \varphi(t)X_0$$

where $\varphi(t) \geq 1$ is known as deterioration function, taken from either equation (1) or (2). For the structural member to be serviceability it should satisfy the following limit state

$$X(t) \leq a$$

where $a$ is a threshold of the serviceability. In equation, $X(t)$ is a time-dependent random variable, i.e., a stochastic process.

For reliability problems involving stochastic processes, the structural reliability depends on the time that is expected to elapse before the first occurrence of the stochastic processes exceeding the limit sometime during the service life $[0, t_L]$ of the structure. Equivalently, the probability of the first occurrence of such an excursion is the probability of structural failure $p_f(t)$ during that time period. Under some assumptions (see, Melchers 1987), the so-called "first passage probability" can be determined from

$$p_f(t) = p_f(0) + \int_0^t v d\tau$$

where $p_f(0)$ is the probability that the structure fails at time $t = 0$. For structural deterioration problem $p_f(0)$ is obviously very small and may be assumed to be zero, which means that it is unlikely that a structure deteriorates as soon as it comes into use. The main difficulty in application of equation (5) to practical problems is the determination of the upcrossing rate $v(t)$, to which only few solutions exist.

When the stochastic process $X(t)$ is a scalar Gaussian process, the upcrossing rate can be evaluated directly by Rice formula (Rice, 1954) as

$$v = v^*_a = \int_{-\infty}^{\infty} (\tilde{x} - \dot{a})f_{x|\dot{x}}(a, \dot{x})d\tilde{x}$$

where $v^*_a$ is the upcrossing rate of the scalar process $X(t)$ relative to $a$, the threshold (limit state) to be crossed, $\dot{a}$ is the slope of $a$ with respect to time, $\tilde{x}(t)$ is the time derivative process of $X(t)$ and $f_{x|\dot{x}}(x, \dot{x})$ is the joint probability density function for $X$ and $\dot{x}$. A solution to equation (6) can be expressed analytically, when the threshold $a$ is not random as defined in equation (4), as (Li and Melchers 1993a)
where $v_{\text{corr}}$ stands for the upcrossing rate when the threshold is not random. In equation (7) $\Phi()$ and $\phi()$ are standard normal density and distribution functions respectively, $\mu$ and $\sigma$ denote the mean and standard deviation of $X$ and $\bar{x}$, represented by subscripts and 'I' denotes the conditional probability. For a given stochastic process, all the variables in equation (7) can be determined as shown in Li and Melchers (1993) and Li (1995).

Using the models developed from data of experiment life cycles of the structure can be determined in terms of the reliability as shown in Fig. 5, where the target reliability index $\beta_T = 3$ and the minimum (acceptable) reliability index $\beta_m = 2$. Detailed calculation cannot be presented in the paper due to length limit.

![Figure 5 Concept of life cycle performance (schematic)](image)

5 REFERENCES


Guirguis, S., (1990), Durable Concrete Structures, TN57, Cement & Concrete Association of Australia.


