

Estimation of the Remaining Service Life of Reinforced Concrete Structures Exposed to Corrosion Using a System-Based Performance Approach: A Cooling Tower Case Study

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ABSTRACT

Estimating the remaining service life of reinforced concrete structures exposed to corrosion requires an approach that captures global structural behavior while avoiding the computational burden of conventional reliability methods. This study proposes a system performance-based analytical-practical framework for service life prediction. First, the current condition of the structure is assessed through field tests, including determination of concrete and reinforcing steel strength, reinforcement corrosion rate, chloride ion penetration depth, and concrete cover thickness. A validated empirical model is then employed to predict corrosion progression and the time-dependent degradation of mechanical and geometric properties of structural members. An updated numerical model of the structure is developed, and a system performance index is defined based on the overstrength factor under gravity loading. Service life is estimated by tracking the degradation of this index and identifying the time at which it drops below the performance threshold. Application to an industrial cooling tower showed that the overstrength factor decreased from 1.08 at 40 years to 0.89 at 60 years, with functional end of life occurring at 47 years; thus, the remaining life at assessment was 7 years. A strengthening scenario demonstrated that targeted retrofit of critical members can significantly extend service life. The method is computationally efficient and supports rehabilitation decision-making.

KEYWORDS

Estimating remaining service life, corrosion, cooling tower, condition assessment, reinforced concrete structure.

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1. Introduction

Following the construction of critical infrastructure, optimal maintenance management is essential to mitigate localized damage and gradual structural degradation throughout the life cycle, as improper oversight can lead to premature failure and excessive repair costs. Consequently, accurately estimating a structure's remaining service life is vital for determining effective maintenance strategies and end-of-life decisions, while simultaneously serving as a fundamental requirement for economic feasibility analysis, asset valuation, and the implementation of Physical Asset Management (PAM) systems in industry [1]. Two general approaches for estimating the service life of structures, data-driven and model-driven, are identified in technical literature. Data-driven methods are limited to structures with comprehensive historical data, such as bridges. Model-driven approaches, including element-based (potentially unrealistic for overall structure failure) and system-based (focused on overall performance), exist [2]. However, the use of complex analytical models for corrosion and reliability analyses in model-driven estimations is computationally intensive, time-consuming, and costly, thereby challenging their practical application. This study presents a practical analytical framework for estimating the remaining service life of reinforced concrete structures exposed to corrosion using a system performance-based approach. Unlike conventional element-based methods, the proposed methodology evaluates the overall structural performance and considers the interaction between structural members under progressive deterioration. The framework integrates condition assessment, corrosion modeling, nonlinear structural analysis, and performance evaluation to estimate the functional end of life of existing reinforced concrete structures. The efficiency of this method is evaluated through a case study on an industrial cooling tower, and its effectiveness in life estimation and optimal maintenance planning is confirmed.

2. Methodology

This paper defines the functional lifespan of a structure as the period until its performance reaches a threshold, regardless of physical failure. It employs a system-based performance approach for reinforced concrete structures, analytically assessing overall system performance degradation to determine lifespan. The method involves four main stages, as shown in "Figure 1", and introduces a practical, computationally efficient index to represent system performance, making it suitable for engineering applications.

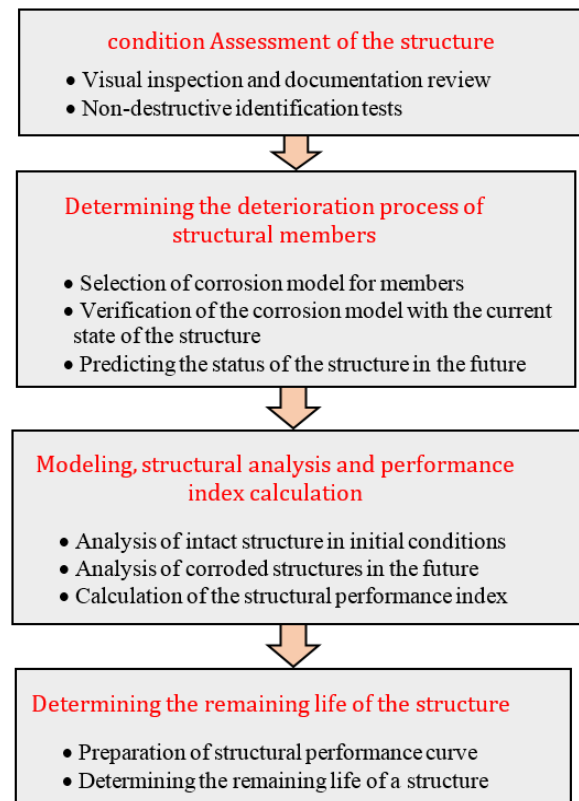


Figure 1. Flowchart of the process of estimating the remaining life of structures with a system performance-based approach

In the final stage, in order to estimate the lifetime of the structure, a structural performance curve is prepared, which is obtained by plotting the calculated values of the performance index over time, and the end of the structure's life is determined from the intersection of the performance loss curve with the acceptable threshold value of the performance index.

3. Results and Discussion

A reinforced concrete industrial cooling tower with approximately 40 years of service life was selected as a case study ("Figure 2"). The structure operates under aggressive environmental conditions, including cyclic wetting and drying, chloride exposure, and elevated humidity, which accelerate reinforcement corrosion and structural deterioration. The assessment process included visual inspections, review of technical documents, destructive and non-destructive testing, chloride penetration measurements, reinforcement sampling, concrete compressive strength testing, and temperature measurements at different elevations of the structure. The results of field investigations indicated that the most severe deterioration occurred at the upper levels of the cooling tower beneath the steel diffusers. Significant chloride penetration, concrete cover deterioration,

reinforcement corrosion, and cracking were observed in these regions.



Figure 2. General view of the studied cooling tower

Concrete compressive strengths ranged from approximately 25 to 42 MPa, depending on structural location, while measured reinforcement corrosion confirmed a substantial reduction in steel cross-sectional area in heavily exposed members. Chloride concentration tests revealed that in nearly 68% of the investigated sections, chloride content exceeded allowable limits, particularly in upper structural levels. To predict future deterioration, a corrosion model based on Fick's second law of chloride diffusion and empirical corrosion propagation equations was employed [3]. The model was calibrated with field data, and corrosion predictions showed acceptable agreement with observations, validating its use for deterioration modeling. Corrosion progression was then estimated for future structural ages of 45, 50, and 60 years. Structural performance was evaluated using nonlinear static analyses performed in SAP2000 [4]. A system-level performance index based on the structural overstrength factor was introduced as a practical indicator of structural safety. The index represents the ratio between the structural load capacity at the acceptable performance threshold and the code-prescribed design load level [5]. The intact structure at the time of construction exhibited an overstrength factor of 1.45, indicating adequate reserve capacity. However, progressive corrosion caused a gradual reduction in the strength and stiffness of structural members, particularly in roof beams where severe chloride exposure existed. Analyses of corroded structural models showed that the overstrength factor decreased gradually to 0.89 at age 60 years. Plastic hinge formation patterns demonstrated increasing concentration of flexural and shear failures in upper-level beams as corrosion intensified. Based on the developed structural performance curve ("Figure 3"), the functional end of life of the cooling tower was estimated at approximately 47 years after construction. Therefore, considering the current structural age of 40 years, the remaining service life of the structure was estimated to be nearly 7 years under normal operational loading

conditions. The study also demonstrated that targeted strengthening and rehabilitation strategies could effectively extend the remaining service life of the structure (from 7 years to over 20 years) by improving the structural performance curve.

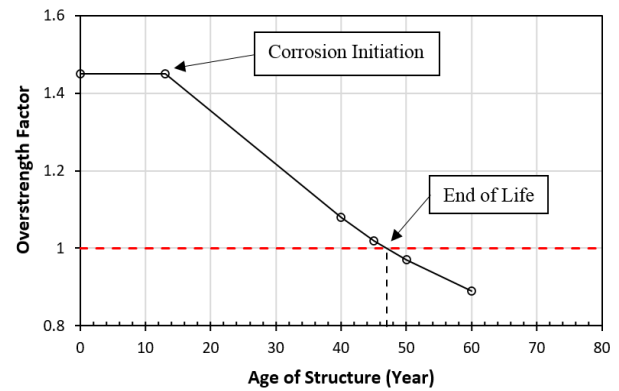


Figure 3. Performance curve of the studied structure

4. Conclusions

This research presented a practical analytical framework for estimating the remaining service life of corrosion-affected reinforced concrete structures based on system-level structural performance evaluation. The proposed methodology was validated through a case study of an industrial cooling tower. The proposed framework provides a computationally efficient and practically applicable tool for remaining life assessment of deteriorating reinforced concrete structures. By combining field assessment with system-level structural analysis, the methodology offers a realistic basis for maintenance planning, rehabilitation prioritization, and lifecycle management of industrial infrastructure subjected to corrosion-induced deterioration.

5. References

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