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Life-cycle cost analysis of reinforced concrete structures in marine environments

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Abstract

Chloride-induced corrosion of carbon steel reinforcement is the main cause of deterioration of reinforced concrete (RC) structures in marine environments. One of the ways to protect RC structures from corrosion is to use corrosion-resistant stainless steel reinforcing bars. However, stainless steel is between six and nine times more expensive than carbon steel. Thus, its use can only be justified on a life-cycle cost basis. In the paper a time-variant probabilistic model was presented to predict expected costs of repair and replacement which was then used to calculate life-cycle costs for RC structures in marine environments under different exposure conditions. Results of the life-cycle cost analysis can be applied to select optimal strategies improving durability of RC structures in marine environments, including the use of stainless steel reinforcement.

Keywords: Chlorides; Corrosion; Deterioration; Life-cycle cost; Reliability; Reinforced concrete

1. Introduction

Reinforced concrete (RC) structures deteriorate with time if subject to an aggressive environment. As a result, as civil infrastructure is aging owners have to spend an increasing percentage of their budgets on rehabilitation (or replacement) of existing RC structures. Thus, there is obviously a strong financial incentive to extend the service life of existing structures, and to design new RC structures which will require less maintenance and repair over their lifetime.

Chloride-induced corrosion of reinforcing bars is the primary cause of deterioration of RC structures in onshore and offshore marine environments. Corrosion is initiated by chloride contamination, often in conjunction with inadequate cover or poor quality concrete. It then leads to

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cracking and spalling that indicates the need for an assessment of existing safety, repair or replacement of damaged structural elements, or the need for more frequent inspections. All these cases will require the allocation of additional financial resources.

To improve durability, reduce maintenance costs and extend service life special design requirements for RC structures built in marine environments are usually specified. These requirements include the use of high performance concrete (with low water/cement ratio), increased concrete cover (e.g., AS 3600 [1]), and the use of admixtures (i.e., corrosion inhibitors). These measures tend to increase the initial cost of structures, but do not completely eliminate the risk of corrosion because of poor detailing, variable construction quality, etc. while high-performance concrete is more susceptible to cracking.

An alternative approach is to use corrosion-resistant stainless steel reinforcing bars. These bars are about six to nine times more expensive than carbon steel reinforcing bars [2]. However, it has been suggested that expected reductions in maintenance and repair costs and the extension of service life can justify their use on a life-cycle cost basis (e.g., [2–5]). It is also worth noting that the cost of reinforcing steel is only a small fraction of overall initial construction costs, thus, the replacement of carbon steel reinforcement by stainless steel should result in a rather moderate increase in the overall initial costs (normally, less than 20% [5–7]). Moreover, stainless steel reinforcement can be used selectively by replacing carbon steel only in the most vulnerable areas (i.e., where cracking might occur, locations of reduced cover or other areas where direct access of chlorides, water and oxygen might have place) that should further reduce an increase in the overall initial cost.

The present paper will focus on a life-cycle cost analysis of RC structures in marine environments. A structural deterioration life-cycle probabilistic model is used to calculate probabilities of cracking and spalling for RC structures with carbon steel reinforcement in splash zones and coastal regions. The model includes the random variability of surface chloride concentration, chloride diffusion, threshold chloride concentration, corrosion rates, concrete material properties, element dimensions and environmental conditions. If excessive cracking and spalling are observed across a structure then this would constitute the end of service life if repairs were not conducted [8–10]. It is therefore assumed herein that the incidence of widespread cracking and spalling will result in repair in order to extend the service life of RC structures. Time-dependent probabilities of spalling are calculated for annual increments over the lifetime of the structure (100 years) and the probability that multiple repairs will be needed during the life of the structure is then calculated. Life-cycle costs considering initial construction cost, costs of improved durability and expected maintenance and repair costs can then be estimated.

For RC structures with stainless steel reinforcement it is assumed that the probability of corrosion is negligible, and subsequently expected costs of structural repairs necessitated by corrosion can be neglected (e.g., [4]). Thus, expected life-cycle costs of RC structures with stainless steel reinforcement can be assumed equal to their initial costs. This means that in order to make decision about the use of stainless steel reinforcement in a RC structure only results of life-cycle cost analysis of the structure with carbon steel reinforcement are needed.

2. Life-cycle cost analysis

If all attributes and consequences of a decision concerning a structure can be expressed in monetary terms then an optimal decision will be the one that minimises the life-cycle cost of the