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Effects of the axial force eccentricity on the time-variant structural reliability of aging r.c. cross-sections subjected to chloride-induced corrosion

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ABSTRACT

Reinforced concrete structures are generally affected by degradation phenomena, which may include changes in strength and stiffness beyond the baseline conditions which are assumed in structural design. Some of these aging effects may cause component or system strengths to degrade over time, particularly when the concrete is exposed to an aggressive environment which may increase the risk of structural failure. For r.c. structures, due to the uncertainties in material and geometrical properties, in the magnitude and distribution of the loads, in the physical parameters which define the deterioration process, the structural safety should realistically be considered time-variant. In this context, this paper implements a computational probabilistic approach to predict the time-evolution of the mechanical and geometrical properties of a r.c. structural element (i.e., bridge pier) subjected to corrosion-induced deterioration as a consequence of the diffusive attack of chlorides in order to evaluate its service life. Adopting appropriate degradation models of the material properties, concrete and reinforcing steel, as well as assuming appropriate probability density functions related to mechanical and deterioration parameters, the proposed sectional approach is based on Monte Carlo simulations in order to evaluate time-variant axial force-bending moment resistance domains, with the aim to estimate the time-variant reliability index β for different axial force eccentricity values. Finally, an application of the proposed methodology to estimate the expected lifetime of a deteriorating r.c. bridge pier is described and discussed.

1. Introduction

The design of reinforced concrete structures is usually aimed at ensuring the performance requirements considering the structural system intact and without taking explicitly into account the progressive deterioration of system properties over time. Concrete structures in service are generally affected by aging, which may include changes in strength and stiffness assumed in structural design. Some of these deterioration effects may cause the degradation of the component or system strengths over time, particularly when the concrete is exposed to an aggressive environment which may increase the risk of structural failure. The ability to evaluate safety of aging concrete structures is a key aspect of solutions to problems associated with decaying infrastructure [1]. For r.c. structures, the structural performance should be considered time-variant because of the material deterioration which worsens the mechanical properties by decreasing the capacity to withstand the applied loads [2]. Therefore, in order to ensure an adequate level of structural performance during the whole service life of a structure, the structural model should also be able to account for the structural deterioration [1,3,4].

Within this issue, many works [5–8] have been focused on the modelling aspects of diffusion, corrosion and damaging process as well as on the service life prediction and life-cycle cost analysis (LCCA). Among the several studies and models developed over the years, Life-365 [9,10] is a computer-based model, developed by the American Concrete Institute (ACI), useful to evaluate the service life and life-cycle cost analysis of r.c. structures. Okasha and Frangopol [11] presented a computational methodology for the life cycle prediction and service life estimation of bridges using advanced modelling tools and employing incremental nonlinear FEA. Cheung et al. [12] developed a 2-D FE coupled model to evaluate the chloride penetration process in varying environment to predict the corrosion initiation time. Orcesi and Frangopol [13] implemented a model using the lifetime functions to evaluate a probability of survival of bridge components. Strauss et al. [14]

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introduced a reliability assessment of r.c. structures and demonstrated real existing bridge structures by adopting the reliability index through advanced life cycle computer simulation based on nonlinear finite element analysis. Proposal based on the electrical resistivity has been made by Andrade and Andrea [15] to calculate both the initiation and propagation periods, as well as for predicting concrete aging related to durability. Biondini et al. [16–19] proposed a general approach to the limit analysis of plane framed structures as well as to the probabilistic prediction of the lifetime of r.c. frames with respect to structural collapse. In particular, the structural system has been considered to be exposed to an aggressive environment and the effects of the structural damaging process have been described by the corresponding evolution in time of the axial force-bending moment resistance domains by modelling both mechanical behaviour and aging process of structural elements through a cellular approach and defining appropriate damage indices. Moreover, they also presented a formulation of a three-dimensional r.c. deteriorating beam finite element for nonlinear analysis of concrete structures under corrosion [20] and investigated at a cross-sectional level the time evolution of the uncertainty effects associated with the different parameters defining the probabilistic structural performance of two existing cable-stayed bridges in Italy subjected to deterioration process by means of time-dependent sensitivity factors based on a regression of the simulation results [21]. Celarec et al. [22] presented a simplified methodology for seismic performance evaluation with consideration of performance degradation over time, based on an extension of the SAC/FEMA probabilistic framework for estimating mean annual frequencies of limit state exceedance. As for the performance-based durability engineering (PBDE) issue and decision-oriented approach, a modular framework for assessing the economic, environmental and social impacts of structural durability has been proposed by [23] and applied to a concrete structure expected to undergo climate-change-accelerated chloride-induced reinforcement corrosion by developing a convolution integral. In particular, the framework links a series of conditionally independent analysis stages: exposure analysis, deterioration analysis (to predict the evolution of detectable damage measures, such as the presence of cracking, over time), repair analysis and impact analysis. Regarding the scientific studies dealing with LCCA of aging systems [24–26], Akiyama et al. [27] established a methodology for the probabilistic hazard assessment associated with airborne chloride and proposed the criterion for designing r.c. structures that satisfy a target reliability level. In particular, the procedure to integrate the hazard associated with airborne chloride into life-cycle seismic reliability estimation of r.c. bridge piers is provided in [28]. Alipour et al. [29] developed an integrated computational methodology to simulate the chloride intrusion and to estimate the corrosion initiation time in order to evaluate the global structural degradation due to the corrosion mechanisms. This way, the extent of capacity loss is calculated using the moment-curvature and nonlinear static (pushover) analysis and results are utilized to evaluate the LCC of bridges as well as different inspection and maintenance strategies are considered to minimize the total LCC. Sanchez-Silva et al. [30] proposed a stochastic model aimed at characterising the structural condition at a given time of structures that deteriorate as a consequence of the combined action of progressive degradation (e.g., corrosion, fatigue) and sudden events (e.g., earthquakes) in order to estimate the structural reliability and establish the possible intervention policies.

In this context, it is noteworthy that, due to the uncertainties in material and geometrical properties, in the magnitude and distribution of the loads, in the physical and mechanical parameters which define the deterioration process, the time-variant structural safety can realistically be assured in a proper way in probabilistic terms through Monte Carlo simulations [16,19] in order to evaluate the time-variant probability of failure, as well as the expected structural lifetime associated with a prescribed reliability level.

Within the time-variant reliability assessment of r.c. structures exposed to an aggressive environment, this paper implements a reliability-based approach to predict the time-evolution of the mechanical and geometrical properties of a statically determinate r.c. structural system (i.e., bridge pier) subjected to corrosion-induced deterioration in order to evaluate its service life or, complementarily, residual service life. Following the same approach proposed in some of the abovementioned studies, including [16–18,20,28,29], also in this work, through Monte Carlo simulation the behaviour and resistance capacity of the most stressed structural cross sections are analyzed over time considering all the effects due to the chloride-induced deterioration process. Differently, this study provides the reliability assessment by investigating how the material deterioration influences the section mechanical response in probabilistic terms considering different eccentricity values of the axial force. In particular, the structural response of r.c. systems is investigated by modelling the mechanical behaviour through a fiber-approach and considering, within the sectional analysis, all the effects of the deterioration process due to the chloride-induced reinforcement corrosion [18–20,31–35] by adopting some of the several models proposed in literature. Assuming appropriate probability density functions related to mechanical and deterioration parameters, the proposed approach is based on developing Monte Carlo simulations in order to define axial force-bending moment resistance domains at different time instants. With the aim to estimate the time-variant reliability of the structural element through the reliability index β [36,37] for different axial force eccentricities, appropriate values of both coefficients of variation (COV) of the probability density functions (PDFs) related to actions and of the design reliability index β_d are assumed at the initial time instant in order to derive the axial force-bending moment actions from the axial force-bending moment resistance. This way, for each eccentricity value, the probability density function related to axial force-bending moment resistance is considered time-variant whereas the probability density function related to axial force-bending moment actions is assumed time-invariant. It follows that, assuming a target reliability index β_{target}, it is possible to evaluate the service life, or residual service life, of the r.c. element subjected to chloride-induced corrosion for different values of the axial force eccentricity, COV of the probability density functions related to actions and of the design reliability index β_d. An application of the proposed prediction model to estimate the lifetime of a deteriorating r.c. bridge pier is discussed as example useful to describe the details of the proposed approach.

2. Structural reliability and service life: the reliability index β

The service life of a r.c. structure can be defined as the time period T during which a structure will fulfill the required performance. In probabilistic terms, the service life (lifetime) of a r.c. structure is defined as the time period T during which the probability of failure P_f, or else the reliability index β, does not exceed a threshold P_f^*, respectively is not smaller than β^*, [38–40]:

$$T = \min\{(t - t_0)|P_f \leqslant P_f^*\} = \min\{(t - t_0)|\beta \geqslant \beta^*\} \tag{1}$$

where t_0 is the initial time (end of construction of the structural element) and t is a generic time instant ($t > t_0$). The relation between P_f and β [40] is shown in Table 1. According to Eurocode 0 [40], three different reliability classes are specified, RC3, RC2, RC1, respectively related to three consequences classes CC3, CC2 and CC1, characterised by minimum reliability indices, or rather, maximum failure probabilities. Table 2 shows the minimum reliability indices β related to Ultimate Limit States for the three reliability classes considering a reference period of 1 year as provided by Eurocode 0 [40].