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Review

Machine learning for durability and service-life assessment of reinforced concrete structures: Recent advances and future directions

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ABSTRACT

Accurate service-life prediction of structures is vital for taking appropriate measures in a time- and cost-effective manner. However, the conventional prediction models rely on simplified assumptions, leading to inaccurate estimations. The paper reviews the capability of machine learning in addressing the limitations of classical prediction models. This is due to its ability to capture the complex physical and chemical process of the deterioration mechanism. The paper also presents previous researches that proposed the applicability of machine learning in assisting durability assessment of reinforced concrete structures. The advantages of employing machine learning for durability and service-life assessment of reinforced concrete structures are also discussed in detail. The growing trend of collecting more and more in-service data using wireless sensors facilitates the use of machine learning for durability and service-life assessment. The paper concludes by recommending the future directions based on examination of recent advances and current practices in this specific area.

Contents

1. Introduction

The durability and service life of the reinforced concrete (RC) structures are one of the foremost problems faced by the construction industry for the past few decades. Degradation of RC structures induced by corrosion causes severe problem all over the globe [1–8]. It has been reported that corrosion associated maintenance and repair of RC structures cost multibillion USD per annum. Repairing of corrosion-induced damage in Western Europe alone costs 5 billion EUR annually [9]. Surprisingly, for corrosion related damage and control, some developed countries spend nearly 3.5% of their gross national product (GNP) [10].

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In another perspective, continued corrosion of reinforcement bar (rebar) is also the most prevalent form of deterioration in repaired RC structures, which accounts for 37% of the failure modes [11–13]. This leads to costly and time consuming repairs of repairs.

Clear understanding of the concrete performance is critical in order to estimate the durability and the service life of a structure. Most of the time, performance of concrete is assessed under the influence of single deterioration mechanism. However, in reality, several complex degradation mechanisms affecting the performance of concrete can act simultaneously or consequently [14,15]. The effect of the synergic degradation mechanisms is more faster and severe than the effect of any single action participating in the deterioration process [16–18]. Measuring the influence of the combined degradation mechanisms in laboratory and translating the results to an actual structure is impracticable. Moreover, concrete performance investigation either in laboratory or in field often tends to be time consuming and costly (directly and indirectly) [19]. For instance, conventional in-service inspection and maintenance programs of highway structures cause traffic delay which accounts for between 15%–40% of the construction costs [20]. Hence, cost-effective reliable prognosis of the concrete performance while in service, from economy and safety perspective, is prerequisites of life-cycle management of RC structures.

The implementation of durability monitoring systems in RC structures could allow identifying deterioration at an early stage. The accessibility of short- and long-term data with spatial and temporal resolution from the monitoring system is a critical underlying necessity for better durability assessment of RC structures. Data collected from the monitoring system have to be analysed efficiently in order to use them for estimation of the remaining service life of a structure. Indeed, data on their own are pointless unless either knowledge or an inference is extracted out from them. Machine learning can be implemented to analyse the monitored complex data and it can deliver more accurate results that can guide better decisions even in real-time without human intervention, e.g., fault diagnosis [21], and tsunami early warning system [22]. Machine learning techniques have been used extensively for a broad range of applications and its employment in civil engineering is not new. Currently, machine learning technique has a broad application prospects in the field of civil engineering to solve complex practical problems.

The objectives of this paper are threefold: (i) to present the current practice on durability assessment focusing on penetration of aggressive substances into concrete causing corrosion of rebar; (ii) to discuss the role of machine learning techniques in improving the accuracy of durability and service-life assessments; and (iii) to give an insight on the future direction of durability monitoring and service-life prediction of RC structures.

The structure of the paper is as follows. In Section 2, the conditions causing corrosion of rebar in RC structures are presented. The conventional models which are used to evaluate the durability and the remaining service life of RC structure along with their limitations are also discussed in the same section. The fundamental knowledge on machine learning is provided in Section 3. In Section 4, the application of machine learning techniques, in two specific areas, in the field of civil engineering is discussed. In Section 5, the current practices of machine learning techniques in durability and service-life assessment as well as durability monitoring systems are presented. The future direction of durability monitoring and service-life prediction approach is also explained in the same section. Finally, conclusion is presented in Section 6.

2. Durability and service life of RC structures

Corrosion of rebar in concrete is typically triggered by ingression of either carbon dioxide (CO_2) or chloride ions (Cl^-) into the concrete pores. Naturally, concrete is alkaline with a pore solution pH of 12–13 that passivizes embedded rebar. The passivation of rebar is deteriorated by the occurrence of Cl^- or by the carbonation of concrete [23–25]. Carbonation is a physicochemical phenomenon induced naturally by the ingression of CO_2 into the concrete pores from the surrounding environment and reacts with hydrated cement [26,27]. Both carbonation- and chloride-induced corrosion of rebar may diminish its cross-sectional area, degrade its elongation ability and cause serious cracks to the concrete, which in turn reduces the load-bearing capacity of the structure considerably. Cracked concrete could offer more ready access to moisture and aggressive gases and ions such as oxygen (O_2), CO_2 and Cl^- leading to aggravated rebar corrosion and degradation of concrete. Consequently, the serviceability, strength, safety and service life of concrete structures will be diminished [6–8,28]. Although chloride-induced corrosion of rebar is normally more harmful and costly to repair, carbonation-induced corrosion of rebar may attack a broader area of RC structures at a bigger scale. It is estimated that about two-thirds of the total concrete structures are exposed to favourable environmental situations for carbonation-induced corrosion [29,30].

The deterioration process of RC structure caused by corrosion can be divided into two phases: initiation and propagation. In case of carbonation-induced corrosion, the corrosion initiation phase corresponds to the diffusion of CO_2 gas into concrete while the rebar remains passivated. In chloride-induced corrosion, the corrosion initiation phase corresponds to the process of Cl^- penetrating into concrete. The propagation period covers the time from the onset of rebar corrosion to structural failure. This period is relatively short compared with corrosion initiation stage. Due to these, the duration of the initial stage has been regularly used to specify the durability and service life of RC structures [31,32]. The conceptual model of rebar corrosion process illustrating the initiation and propagation phases is shown in Fig. 1.

2.1. Deterioration models

Deterioration models are crucial for accurately predicting the performance of concrete and thus to make effective decision regarding maintenance and rehabilitation of RC structures. In the past three decades, considerable attempts have been made to develop durability models for RC structures exposed to environmental conditions that favour for carbonation- and chloride-induced corrosion. Accordingly, various models and input parameters have been established. The complexity level of the developed models vary from simple analytical models assuming uniaxial diffusion into concrete, to more sophisticated numerical models which considers the physical, chemical, and electrochemical processes of gas and ion transport [33–36]. Some of the applied analytical models and the related value of input parameters have been incorrect, incomplete, and/or unsuitable for the prevailing conditions. Due to these facts, the prediction results differ substantially even for the same concrete matrix exposed in identical conditions [37]. Though the complex scientific models provide reasonably accurate predictions, they lack user friendliness and demand highly skilled professional making them suitable only for research, but not for practical design applications. In practice, empirical deterioration models in the form of simple analytical equations on the basis of Fick's second law of diffusion are commonly adopted to model penetration of CO_2 and Cl^- into concrete.

2.1.1. Carbonation model

Concrete carbonation has been recognized as one of the major cause of early deterioration, serviceability loss and safety of RC structures. It is an essential index of durability. The classic carbonation depth prediction model deduced from Fick's second law of diffusion is shown in Eq. (1) [26,38–41]. This model obeys the square root law and can be applied to foresee the depassivation time by extrapolating the carbonation depth measured at a certain time to the future.

$$x_c(t) = k\sqrt{t}, \tag{1}$$

where $x_c(t)$ is carbonation depth at the time t in [mm], k is carbonation coefficient [mm/year$^{0.5}$] which is equivalent to $\sqrt{\frac{2.D_{CO_2}(C_1-C_2)}{a}}$, D_{CO_2} is