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# Understanding Corrosion in Restored Concrete Zones through Sensor Data Analysis

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## Abstract.

Despite reinforced concrete bridges being highly durable, they remain susceptible to natural ageing and disasters, potentially impairing their performance over time. This drives an increase in maintenance, rehabilitation, and repair expenditure, accounting for half of the construction sector spending in developed nations. Structural and durability monitoring becomes crucial to establish long-term maintenance schedules and ensure safety throughout their lifespan. Typically, maintenance schemes rely on sensor systems that periodically or continuously collect information, utilizing various sensors such as electrical, optical, chemical, and sound sensors. Sensor reliability is subject to environmental factors, its own durability and potential power outages, which can temporarily or permanently interrupt data acquisition making difficult or even impossible damage detection. This study focuses on analyzing the evolution of concrete electrical resistivity over time in five repaired concrete zones instrumented with durability sensors to estimating corrosion progression. Based on a compiled and filled database by the authors, this research utilizes degradation models and correlation indices to estimate concrete cover deterioration. Leveraging over fourteen years of sensor data from a reinforced concrete structure, the study focuses on comprehending concrete resistivity evolution in repaired zones to gain insights into the loss of protective concrete cover characteristics to reinforcement corrosion. The study deliberates its findings and extends recommendations for applying this approach to other sensor analysis, enabling a more profound understanding of concrete structure health and longevity.

**Keywords:** Structural health monitoring, Concrete Resistivity Sensors, Corrosion, Degradation models.

## 1 Introduction

Ensuring the longevity and reliability of reinforced concrete bridges stands as a paramount concern amidst the persisting vulnerabilities to natural disasters. Despite their

inherent durability, these critical infrastructures confront ongoing challenges that impact their performance over time, necessitating substantial expenditure, accounting for nearly half of the construction sector's spending in developed nations [1], [2]. To address these issues, structural and durability health monitoring emerges as a pivotal strategy, essential for establishing comprehensive maintenance schedules and safeguarding their sustained safety throughout their lifespan.

Typically reliant on sensor systems, these monitoring approaches engage diverse sensors, encompassing electrical, chemical, optical, and sound sensors, to gather essential structural information periodically or continuously. However, the reliability of such sensors faces susceptibility to environmental influences, durability constraints, and potential power disruptions, posing risks of temporary or permanent interruptions in data acquisition.

Degradation models serve as pivotal tools in unraveling structural decay and forecasting the long-term performance of assets, crucial for crafting effective maintenance schedules amidst diverse environmental and societal influences. These models, spanning mechanistic, probabilistic, statistical, and metaheuristic approaches, offer distinct perspectives on structural deterioration. Mechanistic models, seen in works by Villain et al. [3] and Nguyen et al. [4], meticulously establish links between influential variables and degradation outcomes, utilizing complex simulations to understand phenomena like chloride penetration into concrete. In contrast, probabilistic models, as evidenced by studies from Kwon et al. [5], and Bastidas-Arteaga et al. [6], deal with inherent variability, considering stochastic elements impacting corrosion and structural fatigue. Markov Chain (MC) models, a standout in statistical approaches, discretize degradation states to probabilistically estimate transitions, showcased in methodologies by Bastidas-Arteaga and Schoefs [7] and Zhang et al. [8], integrating inspection data and chloride penetration models. While each model category offers unique insights, mechanistic models demand high costs, probabilistic models navigate complexity, statistical models lack resistance quantification, and metaheuristic models, notably Artificial Neural Networks (ANNs), show promise but rely heavily on available data and opaque decision processes.

This study undertakes a comprehensive analysis of five repaired concrete zones, delving into the longitudinal evolution of concrete electrical resistivity over time and scrutinizing reinforcement corrosion progression. By using a recently processed database, which includes a new methodology for imputing missing data in an SHM system [9], this research aims to estimate concrete deterioration employing degradation models. Spanning over fourteen years of sensor data from a reinforced concrete structure, this study meticulously scrutinizes the evolution of concrete resistivity within repaired zones, offering profound insights into corrosion progression. The paper is structured as follows: Section 2 outlines the methodology employed; Section 3 presents the application's information. Section 4 describes the results and discussion, and finally, the research conclusions are presented in Section 5.

## 2 Methodology

This chapter presents the methodology employed to assess corrosion in a repaired reinforced concrete structure by monitoring electrical resistance as a key indicator. Specialized sensors were installed in the structure, enabling continuous measurement of resistivity over time. Utilizing these resistivity data, stochastic degradation models based on Markov chains were proposed to predict the evolution of corrosion in the structure. This chapter details the significance of electrical resistance in concrete and the application of Markov degradation models.

### 2.1 Electric resistance as an indicator of durability

Estimating the deterioration of a structure due to corrosion can be achieved through the utilization of various indicators linked to the durability of materials against the phenomenon of reinforcement steel corrosion. Concrete resistivity, among other parameters, like corrosion potential, emerges as a pivotal parameter in the durability assessment of reinforced concrete structures. Due to the simplicity of the measure, it is used in degradation models and as it gauges the electrical resistance of concrete. Making it, a crucial marker for the presence of cracks and chloride ions that may trigger the initiation of steel reinforcement corrosion within the structure [10].

Nevertheless, resistivity sensors might be influenced by the concrete's degree of saturation and temperature. A higher degree of concrete saturation substantially lowers the determined electrical resistivity [11], [12]. Regarding the temperature's influence, an increase in temperature augments ion mobility and consequently reduces concrete resistivity [12], [13]. Hence, the analysis of electrical resistivity measurements in concrete should be conducted with special care because of environmental variations but also because they are affected by temporary or permanent interruptions in data acquisition particularly detrimental to information analysis.

### 2.2 Stochastic degradation model

There are many models for calculating the deterioration of reinforced concrete over time. The calculation of deterioration can be proposed through empirical or physical models. Generally, models that consider resistivity focus on calculating the initiation period and in very few cases the corrosion propagation period. Models such as those of Andrade and D'Andrea [14] or EHE-08 [15], are robust models that make use of resistivity together with other variables such as the resistivity of concrete saturated in water and cured for 28 days or the corrosion rate. These models can be difficult to implement especially in older structures where resistivity is taken from recently added sensors and little complementary information has been collected.

On the other hand, statistical models rely on analyzing a repository of established failure knowledge or historical records to predict future deteriorations. They find common application in assessing the extended performance of structures such as bridges and operate through deterministic or stochastic methodologies [16].

The Markov Chain (MC) models describe a system's evolution through defined states within a transition period. These models dictate that the probability of the future state relies solely on the present state, excluding dependence on past states [17]. Within a transition period, the system holds a probability of moving from one state to another, symbolized by transition probabilities  $P_{ij}$  from state  $S_i$  to future state  $S_j$  [18]. The transition probability of each state is calculated using historic information data using

$$P_{i,j} = \frac{S_{i,j}}{S_i} \quad (1)$$

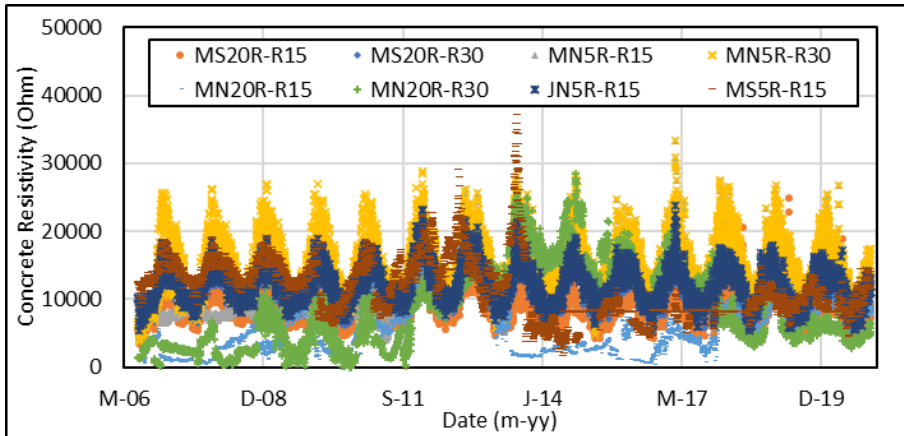
These probabilities construct a transition probability matrix (See eq. 2), with  $P_{ij}$  denoting the likelihood of transition between states  $i$  and  $j$ . Such algorithms offer insight into structural degradation as an ongoing, natural process, crucial for understanding deterioration trends without external intervention [19], [20].

$$P_{i,j} = \begin{bmatrix} P_{1,1} & P_{1,2} & \dots & P_{1,m} \\ P_{2,1} & P_{2,2} & \dots & P_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ P_{m,1} & P_{m,2} & \dots & P_{m,m} \end{bmatrix} \quad (2)$$

Once this probability matrix representing structural degradation is established, it enables the prediction of bridge performance over a specified period. Subsequently, using the initial database, degradation curves are modeled to span the lifespan of these structures, typically extended up to a period of 100 years.

### 3 Application description

A database of eight resistivity sensors installed in a repaired concrete area of reinforced concrete bridge located in Portugal near the sea. This database was previously populated by a study conducted by the authors to have a complete database of 14 consecutive years [9]. The concrete resistivity was measured using two-graphite electrode sensors with a daily measurement of the bridge, as shown in Figure 1.



**Fig. 1.** Concrete resistivity sensors installed in the structure. Adapted from [9].

## 4 Results and discussion

For the development of MC, it is necessary to establish sensor condition states. Table 1 presents the levels set for this analysis. The initial condition state represents a high risk of corrosion, the following two states represent a moderate risk of corrosion, and the remaining states signify a passive condition.

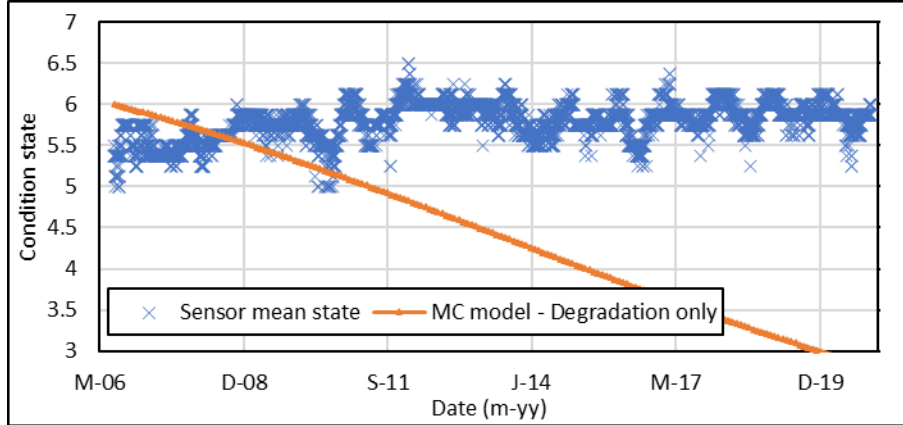
**Table 1.** Condition states establish for the MC model.

Condition state	Resistivity
1	<100
2	100-500
3	500-1000
4	1000-3000
5	3000-6000
6	6000-20000
7	>20000

In civil engineering the MC models have primarily been applied to bridge deterioration based on visual inspections [19]. Simple MC models consider deterioration as a degenerative system; therefore, structures in the future can only remain in the current state or deteriorate. Using this basis, the probability transition matrix for repaired concrete of the analyzed structure is calculated (See eq. 3). From this matrix, the degradation curve is established for a structure with an initial sensor condition of 5 and compared with the daily average of the sensors (See Figure 2).

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.06 & 0.94 & 0 & 0 & 0 & 0 & 0 \\ 0.01 & 0.03 & 0.96 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.01 & 0.99 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.02 & 0.98 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.01 & 0.99 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.30 & 0.70 \end{bmatrix} \quad (3)$$

With this model, it is estimated that sensors will begin detecting a high risk of corrosion after 30 years of measurements. However, significant differences are observed when considering only the degradation of the environment detected by the sensors, rendering the model unreliable.



**Fig. 2.** MC model considering deterioration only.

As mentioned earlier, sensors are influenced by external factors, primarily temperature and humidity. Thus, high temperature and low humidity can lead to decreased water content in concrete, improving sensor measurements and altering the periods of corrosion initiation or propagation. Therefore, a second transition probability matrix is calculated to account for the deterioration and improvement of sensor readings over time (See Eq. 4).

$$P = \begin{bmatrix} 0,39 & 0,17 & 0,06 & 0,39 & 0 & 0 & 0 \\ 0,05 & 0,76 & 0,09 & 0,07 & 0,03 & 0 & 0 \\ 0,01 & 0,02 & 0,86 & 0,11 & 0 & 0 & 0 \\ 0 & 0 & 0,01 & 0,78 & 0,21 & 0 & 0 \\ 0 & 0 & 0 & 0,02 & 0,75 & 0,23 & 0 \\ 0 & 0 & 0 & 0 & 0,01 & 0,98 & 0,01 \\ 0 & 0 & 0 & 0 & 0 & 0,30 & 0,70 \end{bmatrix} \quad (4)$$

Figure 3 displays the outcomes of sensor data prediction, starting with an initial state of 5. It can be observed that the system converges closer to the daily average of the sensors. Nonetheless, a stationary distribution is evident in the model with a value of 5.96. Consequently, in the long term, the variance outside this value is minimal, and no deterioration will be observed using this model.

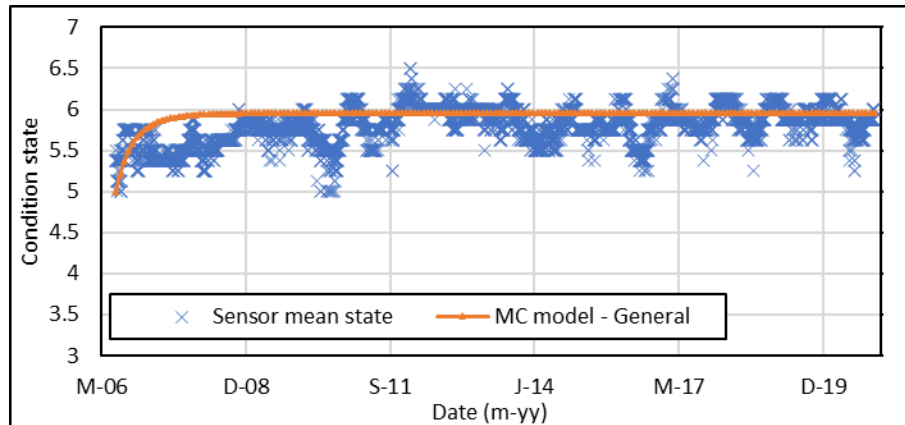


Fig. 3. MC model considering deterioration and improving of the sensors.

## 5 Conclusions

The present paper explores two stochastic Markov Chain models to calculate concrete degradation over time. An eight-sensor database from a repaired concrete area on a bridge in Portugal is utilized to demonstrate the practical application of these models in predicting degradation and structural lifespan.

The single deterioration Markov Chain (MC) model fails to accurately represent the data evolution. The comprehensive MC model, accounting for both deterioration and improvement, yields a stationary distribution, resulting in a singular value over time, thereby complicating the estimation of future degradation in this specific case. Consequently, both analyzed MC models are deemed invalid for predicting the future deterioration of concrete based on the examined sensors.

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