Assessment of reinforced concrete structures' performance under environment aggressiveness for durability monitoring

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ABSTRACT: An increasing number of systems and non-destructive techniques are being developed to evaluate the durability of reinforced concrete (RC) structures through parameters such as its pH or chloride contents. However, the determination of these parameters is not enough to estimate the remaining lifespan of existing structures, since corrosion and carbonation rates depend on different threshold values that may vary with temperature, type of cement or environmental conditions (i.e. dry-wet cycles) of the structure, among others. Therefore, in order to calibrate a durability-oriented monitoring system, it then becomes necessary to analyse the performance of the structure and not only the evolution of the external environmental aggressiveness. This paper focuses on the assessment of the evolution of RC bridges in relation to their performance under environment aggressiveness through the analysis of one Spanish Bridge Management System (BMS) database. A methodology to evaluate the available information of a representative group of bridges is described, which provides a sound basis to choose representative bridges to be monitored and, therefore, to adjust prediction degradation models.

1   INTRODUCTION

The aim of any Management System of any group of structures must be to provide all possible information about the assets which make up the system. By doing so, the administrator, a private company or a public administration, is able to organise hierarchically the assets according to their condition or importance, as well as its needs of maintenance or reparation. This enables the administrator to make decisions which may prioritise investments from both the technical and the economic point of view.

Whereas the monitoring of the mechanical deterioration and damage of structures has been technically solved in recent years, the durability monitoring of the deterioration of structures due to physical, chemical or biological processes is currently in a less developed stage. For instance, corrosion and carbonation rates depend on different threshold values that may differ significantly from the standard values proposed for design purposes of new constructions. These thresholds vary with temperature, type of cement or environmental conditions (i.e. dry-wet cycles) of the structure, among others. Therefore, durability prediction models and monitoring systems must also include the evolution of the performance of the structure subjected to the aggressive action of various agents.

In order to evaluate the evolution of the changing behaviour of an existing structure under aggressive environments, it is necessary to study all the information gathered from inspections, reparations, etc. of existing structures nearby. Thus, by identifying similar behavioural patterns and comparing them with the environment aggressiveness, location, type of cement, etc. of the

structures associated to each pattern, it is possible to establish correlations between different data sources. Therefore, in order to calibrate a durability-oriented monitoring system, it then becomes necessary to analyse the performance of the structure and not only the evolution of the external environmental aggressiveness. Only by combining such two approaches it is possible to design efficient durability monitoring smart systems of structures. In other words, it shall be possible to gather adequate information to make sound decisions on the management of the asset with regards to when and how to intervene within the context of a Management System.

In this work, a methodology for the analysis of the information gathered in Bridge Management Systems (BMS) has been designed with the objective of providing a sound basis to choose representative bridges to be monitored and, therefore, to adjust prediction degradation models.

As an example, one Spanish BMS has been studied according to the proposed methodology to demonstrate how to obtain behavioural patterns and relevant conclusions regarding the performance of the reinforced concrete (RC) bridges which constitute the Management System. It is possible to define a durability-oriented monitoring system for the analysed group of RC bridges by means of the obtained information.

2   ASSESSMENT METHODOLOGY

2.1   General overview

BMSs may include different information depending on the type of the structures which make up the Management System, their age, the attention to detail paid by inspectors and engineers in charge of their maintenance, the economic resources spent in the system, and many other factors. Consequently, not all BMSs include the same data, which is one of the main problems to solve when designing a durability-oriented monitoring system of a group of structures.

As explained before, the deterioration of any RC structure due to durability issues depends on many properties and characteristics of each structure itself. This, added to the fact that each Management System has different information records, makes it impossible to establish a methodology based on the evaluation of specific parameters related to the RC structures and their materials properties, since that information is not always available in many cases.

For this reason, the proposed methodology is not based on the analysis of a determined set of durability factors, but on the analysis of the Management System as a whole. Thus, it is possible to determine different behavioural patterns under environmental aggressiveness associated to different groups of RC structures, although the specific technical characteristics of the structures which are part of the groups are unknown. Once the behavioural pattern of each group of structures has been determined, it is possible to design a durability monitoring system for these structures.

2.2   Analysed Bridge Management System

A Spanish BMS has been analysed to show the proposed methodology for the assessment of RC bridges' performance under environment aggressiveness for durability monitoring.

The analysed BMS includes all road bridges (1704 in total) located in an inland province of Northern Spain, divided into 7 different conservation areas. Within the scope of this paper, the conservation area with the larger amount of bridges has been studied, which is composed of 298 bridges. The analysed conservation area is at an average elevation of 450 m.a.s.l., and it has an average temperature of 12.5ºC, an average precipitation of 786 mm, 126.3 raining days and 38.8 freezing days (values calculated with all available data until 2018 included).

Based on any BMS, a numerical quantification of field inspections can be obtained. Some examples are the AASHTOWare Bridge Management software, formerly Pontis, the reliability-based life-cycle Management System proposed by Frangopol et al. (2000), or the proposals of Chiaramonte and Gattulli (2005), Helmerich et al. (2008) and Roelfstra et al. (2014).

The studied BMS is based on the system known as *Bridge*, of the company 4EMME, and it provides a numerical quantification of each inspection carried out in the bridges included in the Management System which is defined as follows. A damage index (DI) is calculated as the weighted sum of all damages detected in a field inspection, where G stands for the weight (importance) of the damage, K_1 stands for its extension and K_2 stands for its intensity, for the number of elements i to n affected by each damage j to m:

$$DI = \sum_{i=1}^{m} \sum_{j=1}^{n} (G \cdot K_1 \cdot K_2) \tag{1}$$

It must be noted that it is beyond the scope of this paper to discuss the adequacy of the weight, importance and extension factors of the damages considered by the analysed BMS.

Only RC bridges are analysed in this paper, but not all damages included in the BMS and associated to concrete elements are related to durability deterioration. In order to carry out the assessment of RC bridges' performance under environmental aggressiveness described in this paper, only damages listed in the following table have been considered to calculate the durability Damage Index according to equation (1). According to Ceccotti et al. (2011), coefficients K_1 and K_2 are thought to adopt only one of the discrete listed values.

Table 1. Durability damages considered in the analysis

Damage	Weight (G)	Extension (K_1)	Intensity (K_2)
Passive humidity patches	1	0.0-0.2-0.5-1.0	0.0-1.0
Active humidity patches	4	0.0-0.2-0.5-1.0	0.0-1.0
Leaching and local damages	2	0.0-0.2-0.5-1.0	0.0-1.0
Reinforcement cover loosening	2	0.0-0.2-0.5-1.0	0.0-1.0
Reinforcement corrosion	5	0.0-0.2-0.5-1.0	0.0-0.2-0.5-1.0
Crazing cracking	1	0.0-0.2-0.5-1.0	0.0-1.0
Horizontal cracking	2	0.0-0.2-0.5-1.0	0.0-0.2-0.5-1.0
Vertical cracking	2	0.0-0.2-0.5-1.0	0.0-0.2-0.5-1.0
Oblique cracking	5	0.0-0.2-0.5-1.0	0.0-0.2-0.5-1.0
Longitudinal cracking	2	0.0-0.2-0.5-1.0	0.0-0.2-0.5-1.0
Transverse cracking	5	0.0-0.2-0.5-1.0	0.0-0.2-0.5-1.0
Outer reinforcement corrosion	3	0.0-0.2-0.5-1.0	0.0-0.2-0.5-1.0
Badly executed previous reparations	1	0.0-1.0	0.0-1.0
Prestressed reinforcement cover loosening	5	0.0-0.2-0.5-1.0	0.0-0.2-0.5-1.0
Humidity patches (prestressed reinforcement)	2	0.0-0.2-0.5-1.0	0.0-1.0
Corroded/non-covered reinf. in extreme faces	2	0.0-0.2-0.5-1.0	0.0-0.2-0.5-1.0

As mentioned above, 298 bridges are part of the analysed conservation area, but only RC bridges have been included within the scope of this paper. Neither RC elements of non-RC bridges nor repaired RC bridges were considered since their behaviour is prone to be different from the original one. Only inspection records of bridges with an age not larger than 30 years have been analysed since available results of inspections carried out in older bridges were limited as considerable number of them corresponds to RC elements located in non-RC bridges.

Given that inspections are subject to human error, once the data of the non-repaired RC bridge inspections were selected and their durability Damage Index calculated according to equation (1), inspections whose durability Damage Index could be considered atypical were rejected in order to avoid rather aberrant results. The Chauvenet's criterion was applied in order to reject inspections with out-of-order results. According to this criterion, an acceptation probability band of data centred on the mean value of a normal distribution is established. It is described by the following formula, where $\bar{x}$ stands for the sample mean value, s_x stands for the sample standard deviation and x stands for the value of the suspected outlier:

$$\bar{x} \pm \frac{|x - \bar{x}|}{s_x} \tag{2}$$

After applying the Chauvenet's criterion, 347 inspections of non-repaired RC bridges remained satisfactory to carry out the data analysis.

2.3   Data analysis

To evaluate the performance under environment aggressiveness associated to each one of the 347 inspections of non-repaired RC bridges, a Durability Performance Index (DPI) was defined:

$$\mathrm{DPI} = 1 - \frac{\mathrm{DI}}{\mathrm{DI_{max}}} \tag{3}$$

Since each BMS could have its own numerical damage evaluation system, it is necessary to define a relative universal index which could be used to evaluate the performance of each structure under environment aggressiveness independent of the damage evaluation adopted by each Management System. Therefore, the Durability Performance Index has been defined according to formula (3), where for the analysed BMS *DI* stands for the Damage Index of each inspection (calculated according to equation (1) for the damages listed in Table 1), and *DI_{max}* stands for the maximum historical DI value of all inspections registered in the Management System, once the atypical values were dismissed.

Since the DI defined in the analysed BMS does not have a defined maximum value and the results of different inspections are not comparable as not always the same damages are detected in all inspections, the DPI is calculated for each inspection, and its value is between 0 and 1, what makes possible the analysis of the results of all inspections as a whole.

The value of the DPI will be equal to 1 in the ideal situation of no durability damage identified in the inspection, and equal to 0 in the extreme situation of complete durability damage identified in the inspection. Logically, those extreme values of 0 and 1 are not likely to be obtained in any real case. It is to be kept in mind that the DPI analysed in this paper is exclusively related to durability. Thus, leakage of water, rust spots, typical cracking pattern induced by rust or corrosion evidences, as well as concrete degradation due to sulphate attack, scaling due to de-icing agents, etc. are examples of symptoms associated to durability. As it may be derived, degradation of durability conditions is globally considered throughout this DPI, not making use in this approach of rather conventional models to predict carbonation depth or chloride contents. The DPI relative approach makes it possible to consider different types of

damage together with the same durability index, what is in line with the Miyamoto's (1990) model.

The evolution of the DPI in time is fitted by the following expression proposed by Miyamoto (1990), in which the parameters *a* and *b* define the deterioration curve:

$$\text{DPI (t)} = b - a \cdot t^4 \tag{4}$$

The previous expression is based on a large inspection campaign of bridges built in the 60s in Japan, which was carried out at the end of the 90s. In that expression, the parameter *b* stands for the initial DPI value, which is usually taken equal to 1.

$$\text{DPI (t)} = \text{DPI}_0 - a \cdot t^4 \tag{5}$$

The time *t* is referred to the time of the inspection, in years after the construction of the bridge.

It is to be noticed that the assumption of equation (4) as a general evolution law of the DPI is independent of the studied region or its environmental conditions, since parameters *a* and *b* may be derived after proper fitting. Even exponent 4 could be derived similarly.

Miyamoto's model is an empirical model with a physical sense which is based on a data field and is easy to apply to different structural elements. Tena et al. (2018) compared the advantages and drawbacks of the most relevant ageing models and concluded that Miyamoto's model usually achieves the most accurate results.

As a matter of fact, the model of the ageing process proposed by Miyamoto has been widely used in different countries other than Japan, and there are experiences of its applicability not only in reinforced concrete bridges, but also in steel or masonry bridges. For instance, the reference curve for the ageing process of the Greek bridge management system is accurately approximated by the IRIS model, which is based on Miyamoto expression (4).

Based on the DPI values of inspections, the durability damage deterioration most probable curve of each RC bridge typology can be obtained, and their confidence bands estimated for a defined significance *α*. Deterioration curves of slab bridges and beam bridges of the analysed conservation area are calculated in this paper (Figures 1 and 2).

In order to determine the initial value of the Durability Performance Index, *DPI₀*, and the value of the parameter *a* of the deterioration curves, a change of variables is needed:

$$z = t^4 \rightarrow \text{DPI}\left(\sqrt[4]{z}\right) = \text{DPI}_0 - a \cdot z \tag{6}$$

Since there are different DPI values for each time of inspection, *t*, the mean DPI value should be considered for each time of inspection, *t*. Given that expression (6) defines the equation of a straight line, regression coefficient *a* and initial value *DPI₀* can be easily obtained.

In the following table, the values of these parameters, as well as the value of the Pearson correlation coefficient, are shown for the RC slab bridges and RC beam bridges typologies.

Table 2. Parameters of the durability deterioration curves

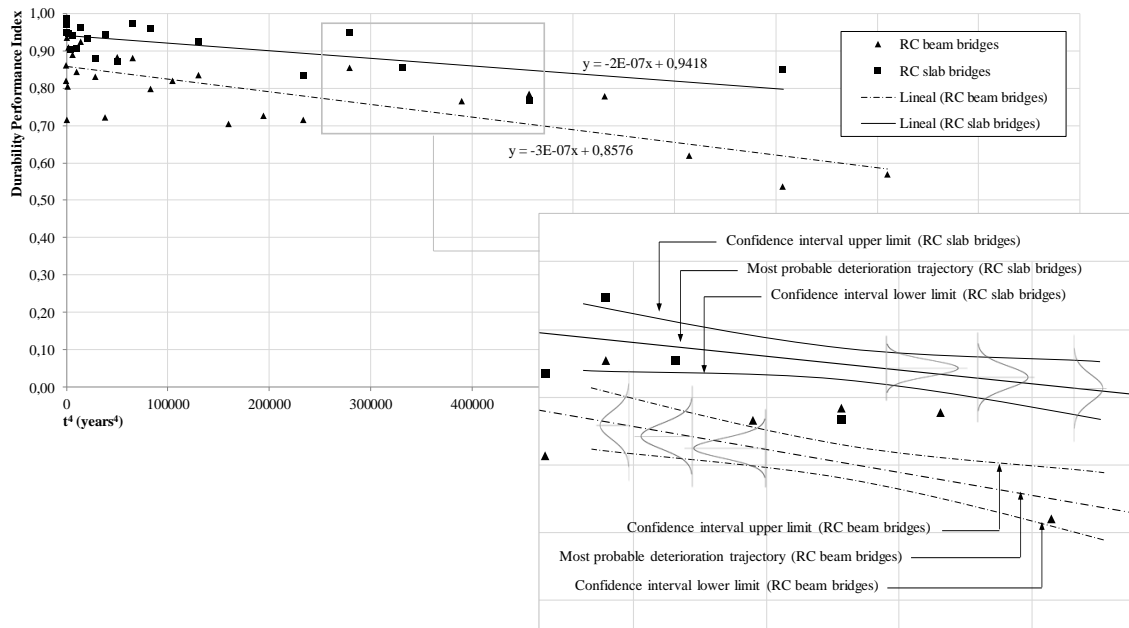| RC bridge typology	a	DPI_0	R (Pearson)
Beam bridges	$3.3722 \cdot 10^{-7}$	0.8576	0.76
Slab bridges	$2.0364 \cdot 10^{-7}$	0.9418	0.67

Figure 1. Most probable linear regression of inspections DPI values after the change of variable (6)

According to these results, it is concluded that the most probable deterioration of the performance of the RC beam bridges located in the studied conservation area under environment aggressiveness is defined by the expression:

$$DPI\,(t) = 0.8576 - \left(3.3722 \cdot 10^{-7}\right) \cdot t^4 \tag{7}$$

Likewise, the most probable deterioration of the performance of the RC slab bridges located in the studied conservation area under environment aggressiveness is defined by the expression:

$$DPI\,(t) = 0.9418 - \left(2.0364 \cdot 10^{-7}\right) \cdot t^4 \tag{8}$$

3   CONCLUSIONS AND OUTLOOK

According to the outlined methodology, it is possible to determine the most probable deterioration evolution of the performance of different typologies of RC bridges under certain environment aggressiveness (Figure 2).

Any durability monitoring smart system should be able to predict the deterioration of all bridges included in the Management System, and not only those which have been instrumented. Once the most probable deterioration pattern (curve) of each RC bridge typology has been obtained (Figure 2), it is necessary to identify those bridges whose behaviour is closer to the most probable of each typology by identifying those bridges whose DPI results from the different inspections carried out in those bridges are closer to the curve which define the most probable deterioration evolution of the bridge typology in question. Thus, if representative bridges of each typology are selected properly, results provided by a durability monitoring system installed in these bridges will be representative of the behaviour of the whole typology of bridges.

A durability monitoring smart system must be able to apply interpretation and decision automatic criteria by itself, based on the data provided by the different sensors and devices installed in the selected representative bridges of the BMS.
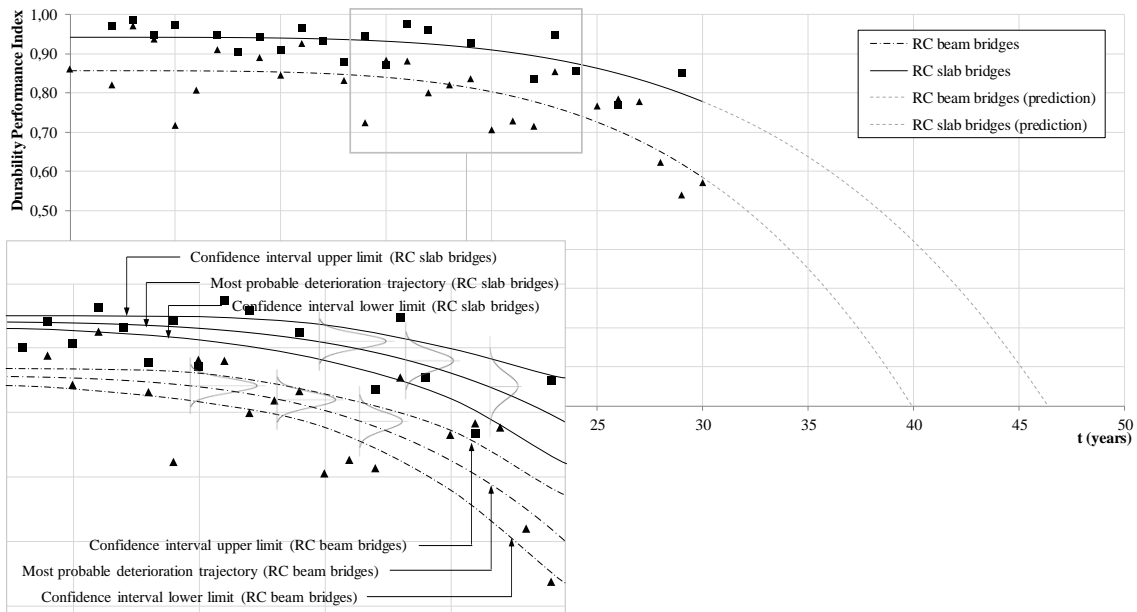
Figure 2. Durability deterioration most probable curves of RC beam and slab bridges under the analysed environment aggressiveness

Acceptance thresholds can be established so that the monitoring smart system provides a schedule of the needed works to be carried out in the RC bridges of the BMS according to the remaining time until the stablished thresholds are reached. Let us suppose that a certain RC bridge has an age equal to t_a. In Figure 3, a durability damage threshold DT has been stablished as an example. In this case, after applying the designed methodology, the durability monitoring smart system is able to predict the remaining lifespan of the bridge associated to such DT and the remaining time until the durability damage threshold is reached depending on the typology of the analysed RC bridge.

Once the most probable durability deterioration curves of each RC bridge typology have been obtained, the durability monitoring smart system is also able to prioritise inspections, maintenance and reparation works according to the age of each bridge.
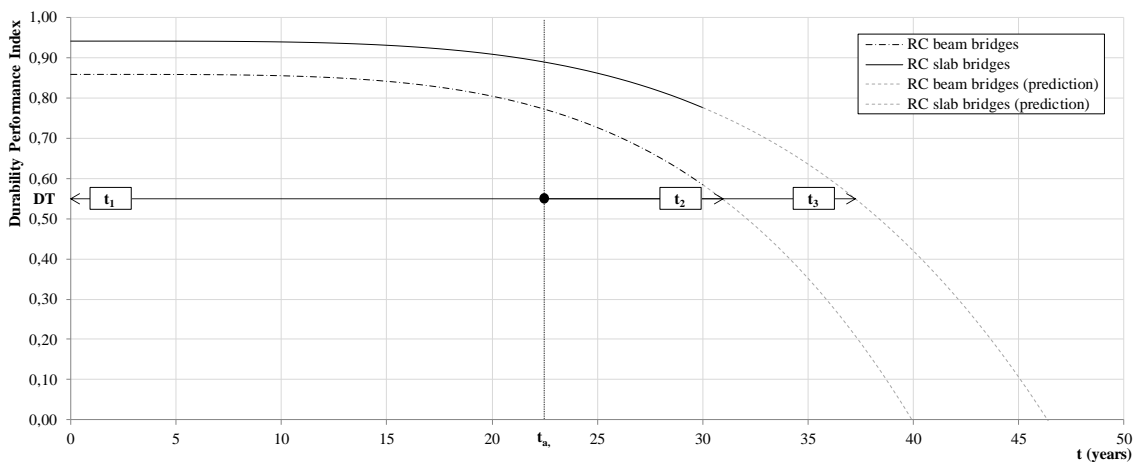

Figure 3. Applications of the durability deterioration curves for durability monitoring

Most implemented BMSs are used to schedule the above-mentioned works depending on the age of the structure, using the time t_1 shown in Figure 3 as a reference for the planification. However, the time t_1 does not provide information about the remaining life of the structure and all typologies are analysed with the same criteria. A better approach would be to use the deterioration curves to estimate, depending on the RC bridge typology, the remaining time until the stablished damage threshold DT is reached. With this approach, it is possible to use the time t_2, t_3, etc. as a reference for the planification of inspections and maintenance works depending on the bridge typologies, so as to identify which bridges are closer to the damage threshold or at the end of their lifespan. With this information, a proper inspection, maintenance and reparation strategy can be designed from an optimal technical and economical point of view.

This method also enables owners to enhance the frequency of principal inspections and, once optimised, to provide sound basis to choose the moment of special inspections. This is essential to define, at least, refurbishment interventions oriented to change the degradation rate or, in other words, to enlarge the remaining life-span.

The deterioration curves which may be obtained according to the explained methodology can also be useful to choose the optimum RC typology of new bridges built under the analysed environment aggressiveness conditions. If the typology with slower durability deterioration (which implies a higher lifespan) is chosen for new RC bridges, their lifespan will be the highest and their maintenance costs the lowest possible .

In this paper, an analysis of typologies has been carried out. However, the same methodology could be applied to bridge elements (decks, piers, abutments, etc.) instead of typologies. Besides, curves shown in Figures 2 and 3 are only applicable to non-repaired bridges. Since the deterioration evolution of repaired bridges may differ significantly from the behaviour of non-repaired bridges, an equivalent analysis of repaired bridges could be performed.

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