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# Monitoring for durability and structural performance of highway bridges

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The ageing and deterioration of highway bridges can have very serious consequences in terms of reduced safety, serviceability and functionality. Many bridges built in the 1960's and 1970's are considered deficient by today's standards. The widespread deterioration and some recent failures have highlighted the importance of developing and implementing effective inspection strategies, including structural health monitoring systems, which can identify structural problems before they become critical and endanger public safety. Continuous monitoring is becoming necessary due to ageing of bridges, increased traffic loads, changing environmental conditions, and reduced capacities, especially for medium and long-span bridges given the severe consequences of failure. The implementation of monitoring programs can assist in optimizing the in-depth inspection, maintenance, rehabilitation, and replacement of bridge structures. The continuous and simultaneous measurements at critical discrete points of a bridge system will allow the assessment of its performance with respect to different limit states, including safety and serviceability. Prediction models, updated from such monitoring data, can optimize intervention strategies as to how and when to repair or rehabilitate thus extending service life and reducing life-cycle costs.

The objectives of this paper are: (i) to present an approach for the efficient use of structural health monitoring into the durability and structural reliability assessment process; (ii) to highlight the applicability of the approach to short, medium and long-span bridges; and (iii) to demonstrate the effective use of field monitoring data for the calibration and updating of service life prediction models. A case study on a medium-span concrete highway bridge is also presented and used to illustrate the approach.

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# Monitoring for durability and structural performance of highway bridges

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ABSTRACT: The widespread deterioration and some recent failures of highway bridges have highlighted the importance of developing and implementing effective inspection strategies, including structural health monitoring, which can identify structural problems before they become critical and endanger public safety. Continuous monitoring is becoming necessary due to ageing of bridges, increased traffic loads, changing environmental conditions, and reduced capacities, especially for medium and long-span bridges given the severe consequences of failure. The implementation of monitoring programs can assist in optimizing the in-depth inspection, maintenance, rehabilitation and replacement of bridge structures. The continuous measurements at critical discrete points of a bridge system will allow the assessment of performance with respect to different limit states, including safety and serviceability. Prediction models, updated from such monitoring data, can optimize intervention strategies as to how and when to repair or rehabilitate, thus extending service life and reducing life-cycle costs.

## 1 INTRODUCTION

A large number of bridges were built during the post-war construction booms of the 1950's, 1960's and 1970's. Many of them are considered deficient in terms of structural capacity and functionality, as a result of ageing, increased traffic loads, deterioration, and more stringent bridge design codes. The widespread deterioration and some recent bridge collapses have highlighted the importance of developing and implementing effective structural health monitoring strategies, which can identify structural problems before they become critical and endanger public safety. Continuous monitoring is becoming necessary due to ageing of highway bridges, increased traffic loads, and changing environmental conditions that affect their structural performance. The implementation of monitoring strategies can help optimize in-depth inspection, maintenance, repair, rehabilitation and replacement of bridges. The continuous and simultaneous measurements at critical discrete points of a deteriorating bridge system can allow the assessment of its performance with respect to different limit states, including safety and serviceability. Moreover, deterioration prediction models can be calibrated from such monitoring data, which can optimize intervention strategies as to how and when to repair or rehabilitate, thus extending the service life of highway bridges. The majority of Canada's bridges are short and medium-span bridges that exhibit serious deterioration induced by corrosion due to the use of de-icing salts and compounded by increased traffic loads. On the other hand, long-span bridges are more sensitive to reductions in the flexural and torsional stiffness induced by corrosion damage and overload in the superstructure, and basically, their performance is usually controlled by serviceability limit states. The vibration amplitude of the deck due to traffic or wind becomes more serious with the deterioration and there could be a significant change of the vibration modes, resulting in serious reduction of the bridge fatigue resistance. Hence, the dynamic parameters of long-span bridges are of great influence on the monitoring strategy.

The objectives of this paper are: (i) to present an approach for the efficient use of structural health monitoring in the durability and structural reliability assessment process; (ii) to highlight the applicability of the approach to short, medium and long-span bridges; and (iii) to demonstrate the effective use of field data for the calibration and updating of service life prediction models. A case study on a medium-span concrete highway bridge is presented and used to illustrate the approach.

## 2 FIELD MONITORING STRATEGY AND BENEFITS

In Canada, investments in bridges have been under the levels required to hold their average age constant. According to Statistics Canada, their average age rose from 21.3 years in 1985 to 24.5 years in 2007 with a mean service life of 43.3 years, suggesting that Canada's bridges have passed 57% of their useful life on average (Gagnon et al. 2008). In the U.S., nearly 25% of highway bridges are either structurally deficient or functionally obsolete, according to the FHWA NBIS database (Dec. 2007). A FHWA report on corrosion protection of concrete bridges estimated that the total cost to eliminate the backlog of deficient concrete bridges in the U.S. ranged between $78 billion and $112 billion, depending on the time required to carry out the task (Virmani and Clemena 1998). The prohibitive costs required to upgrade highway bridges require the development of decision support tools for bridge owners and engineers. Such tools will enable them to assess the condition of their structures, predict future performance and allocate the limited funds to better manage maintenance work and achieve adequate reliability and minimum life cycle costs. Causes of bridge failure may include: inadequate design of materials and structural systems, heavy traffic loads, inadequate inspection and maintenance, lack of effective management systems, and inadequate funding. The consequences include: increased risk of fatalities, reduced service level, increased maintenance and user costs, and larger environmental impact.

Structural health monitoring (SHM), either with embedded sensors or by actual field testing, is an evolving technology that allows monitoring the condition of existing or new civil engineering structures. Implementation of SHM as an essential part of structural design will be key to the development of the next generation of long-life smart bridges. Intelligent sensing systems may be composed of four main elements: (i) sensors and actuators collecting data and taking action in an environment of interest; (ii) a network for the transmission of data and control signals; (iii) systems for data management and visualization; and (iv) specific analysis and decision making applications. Figure 1 illustrates the concept of SHM for a bridge structure.

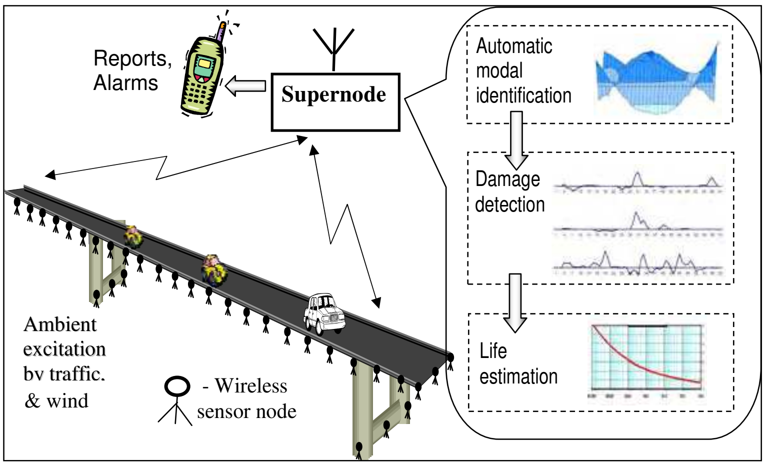


Figure 1: Concept of structural health monitoring of bridge structures.
(Source: http://www.intelligent-systems.info/wisan/SMT2004/Sazonov-SMT2004.htm)

The selection of the required types and number of sensors located at discrete and critical points in a given bridge relies on the type of bridge and the experience of the engineer and his/her knowledge of the physical, chemical and mechanical processes, and on the budget allocated for SHM. In a larger context, monitoring data can be considered similar to quality assurance and acceptance sampling, since it is not realistically feasible to monitor all performance indicators in all sections of an entire bridge (Frangopol et al. 2008). In-depth information on the design of SHM systems and specific bridge applications can be found elsewhere (Mufti 2001). Structural health monitoring can benefit owners and users of bridge structures in four different areas described below.

### 2.1 *Ensuring public safety*

SHM can enable bridge owners to monitor the performance of their structures from a central site via Internet, thereby reducing the number of site visits for visual inspections and destructive- and/or non-destructive testing. Therefore, SHM can provide key information on structural performance (e.g. excessive girder deformations, column buckling, foundation settlement) and for durability assessment (e.g. concrete cracking, reinforcement corrosion, freeze-thaw damage), allowing timely decisions on corrective measures before problems become critical and endanger public safety. Bridges are safety-critical systems, which should be monitored to ensure that the likelihood of failure of critical load bearing elements is kept very low, especially for bridges in urban areas, long-span bridges, or non-redundant systems, for which failure can have catastrophic consequences.

### 2.2 *Development and adoption of new construction technologies*

SHM can provide a structured approach to assessing the performance of emerging technologies applied in demonstration projects, whether they are conducted on old structures or new construction. Research on bridges involves the use of sensors and data logging systems for continuous monitoring of selected performance parameters (Tennyson et al. 2001; Cusson et al. 2006). Sensors can provide detailed knowledge of: (i) the conditions under which the structure is being evaluated, including: applied loads, imposed displacements, and ambient environment; and (ii) selected performance parameters, which could give insights about the performance of a newly-developed concrete and steel technologies used in the structure, or the changes in the behaviour of the structure as a result of strengthening or repair.

### 2.3 *Development and calibration of prediction models*

The vital information acquired by SHM can foster a better understanding of damage initiation and damage accumulation in bridge structures and calibration of service life prediction models. The continuous updating of service life predictions with monitored field data can have a strong influence on intervention planning. More details will be given in the next section.

### 2.4 *Update of loading data for the design of bridges*

Another benefit of SHM is to help assess the live loads and environmental loads on bridge structures and identify any major variations from the values that are assumed in bridge design codes. This is becoming an important issue given the growing concerns with climate change and its potential impact on the safety and serviceability of bridge structures due to increases in wind loads, flooding, thermal gradients, freeze-thaw cycles, de-icing salt use, etc.

### 2.5 Applicability of the approach to medium and long-span bridges

Since the core idea of the approach is the continuous comparison of the monitored values of key structural, durability and environmental parameters at critical sections of the bridge with some specified threshold values, as well as with the predictions from service life performance models, then no change in the core philosophy is needed for the approach to be applicable to medium and long-span bridges. However, the range of monitored structural and environmental parameters needs to be expanded to comprehensively assess the special characteristics of these bridges. In addition to corrosion parameters, the environmental parameters would include: wind intensity, duration, vibration and distribution on the bridge deck; interaction between vortex shedding vibrations and traffic vibration; and deck vibration due to wind excitation of other bridge elements. The structural parameters would include: stiffness distribution along the deck; fatigue cracks at critical joints; effect of reinforcement corrosion on ductility and deformation patterns; and dynamic performance and vibration modes in relation to the excitation.

## 3 CASE STUDY

The purpose of this section is to illustrate the benefits of SHM in improving the reliability of service life predictions and, more specifically, to point out that some of the input data, which are commonly used in service life prediction models, can be somewhat different from reality, as some parameters can vary widely in time and space and can also be highly uncertain.

### 3.1 Description of bridge and experimental program

In 1996, the Ministry of Transportation of Québec undertook the rehabilitation of the Vachon bridge, which is a major highway bridge in Laval (near Montreal) Canada. Part of the rehabilitation consisted of rebuilding the severely corroded barrier walls, of which ten 35-m long spans were selected for the application and evaluation of corrosion inhibiting systems. The wall reinforcement consisted of 15-mm diameter bars as illustrated in Figure 2. The concrete had a water-cement ratio (w/c) of 0.36 (selected to obtain low permeability), a cement content of 450 kg/m$^3$, and an average 28-day strength of 45 MPa. On-site surveys of the barrier wall were performed annually from 1997 to 2006, including measurements of corrosion potential and corrosion rate in the barrier wall, of which the concrete cover was 75 mm. For early detection of corrosion, sets of rebar ladders were embedded during construction. The ladder bars had concrete cover thicknesses of 13 mm, 25 mm, 38 mm, and 50 mm (Fig. 2), allowing additional corrosion measurements to be taken. More details can be found in Cusson et al. (2008).

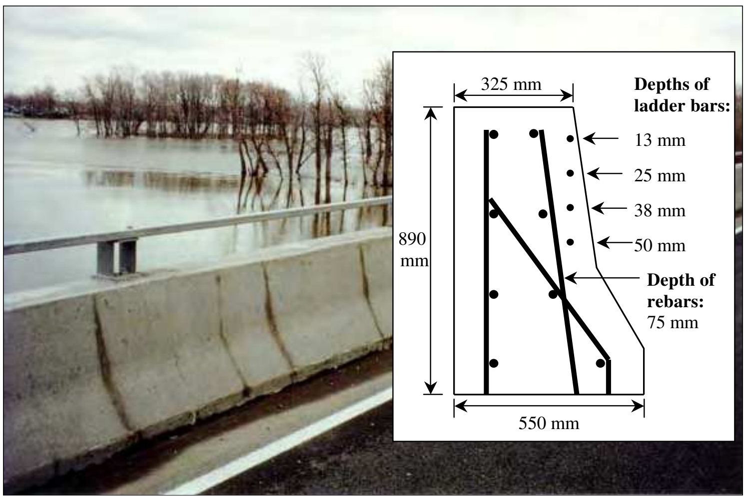


Figure 2: Cross-section of reconstructed barrier wall (Vachon Bridge, Laval, Canada).

### *3.2 Analysis of selected field test data*

#### 3.2.1 Measurement and prediction of chloride ingress into concrete

Concrete cores were taken from the bridge barrier walls after 1, 2, 4, 5, 8 and 10 years of exposure to de-icing salts in order to test several parameters, including chloride concentration. Of the 10 spans of barrier wall under study, three of them had identical concrete formulations and concrete surface conditions (referred to as Spans 12, 19 and 21 in Cusson et al. 2008).

Figure 3 presents the average total chloride contents measured in concrete after 10 years of exposure to de-icing salts. The best-fit curve was obtained by linear regression analysis of the measured data and Crank's solution to Fick's $2^{nd}$ law of diffusion (Crank 1975, Tuuti 1993):

$$C(x,t) = C_S\left(1 - erf\left(0.5\ x / \sqrt{D_C\ t}\right)\right) \quad (1)$$

where $C(x,t)$ is the chloride concentration at depth $x$ after time $t$; $C_s$ is the apparent surface chloride concentration; $erf$ is the error function, and $D_c$ is the apparent chloride diffusion coefficient. From the field data, an average apparent surface chloride content of 20.7 kg/m$^3$ and an average apparent chloride diffusion coefficient of 0.93 cm$^2$/year were obtained. In reality, the highest near-surface chloride content was measured to be at least 16.8 kg/m$^3$ in the barrier wall (Figure 3), which is already quite higher than the maximum value of 8.9 kg/m$^3$ suggested by Weyers (1998) for geographical regions with severe levels of exposure to de-icing salts. Note that these guidelines were developed in the US and may not apply to regions like Canada or other northern countries, where more de-icing salts are used for longer winter periods. Similarly, the apparent chloride diffusion coefficient measured for the concrete barrier wall was found to be much larger than those obtained from the literature on similar concrete structures. For example, Figure 3 shows the predicted chloride profile using Equation 1 with a mean $C_s$ = 7.4 kg/m$^3$ suggested by Meyers (1998) for severe exposure conditions, and $D_c$ = 0.21 cm$^2$/year measured by Dhir et al. (1990) on a concrete very similar to that used in this case study. It can be seen that the chloride profile is largely underestimated after only ten years of salt exposure. These discrepancies can be explained by the large fluctuations of many factors influencing chloride ingress into concrete, including concrete mixture formulation, hydration and curing characteristics, temperature and humidity conditions, and surface chloride concentrations. It can be concluded that determining the chloride profile for a given concrete structure using carefully-selected literature values, even from apparently-similar concretes, can result in inaccurate estimations, thus resulting in poor predictions of the remaining service life of the structure.

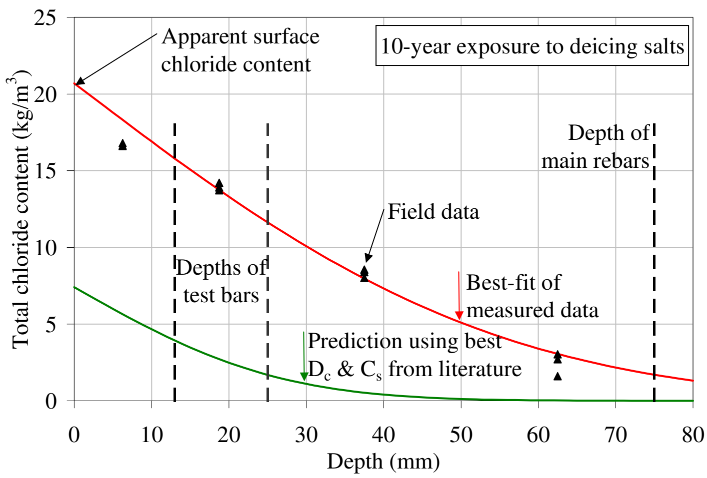


Figure 3: Measured and predicted profiles of total chloride content after 10 years.

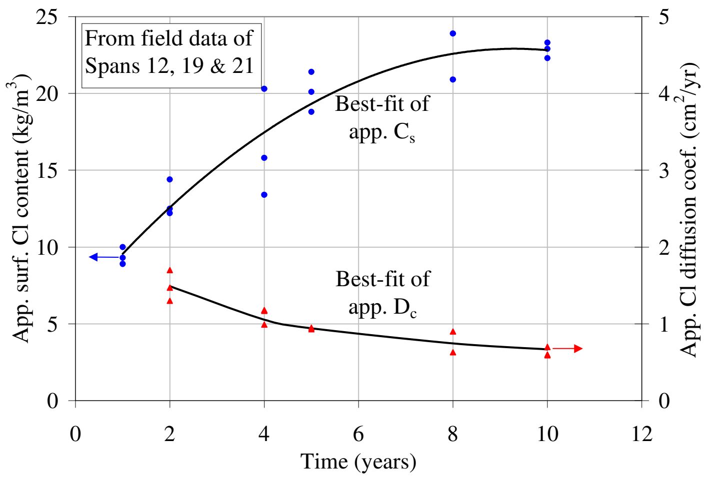


Figure 4: Measured apparent surface chloride contents and apparent chloride diffusion coefficients over 10 years.

Figure 4 presents the measured apparent surface chloride concentration over time, where it is shown that it increased significantly over time and reached a maximum value of 23 kg/m$^3$ after 9 years. Figure 4 also presents the apparent chloride diffusion coefficient over time, where it is observed to decrease by a factor of 2 from Year 2 to Year 10. This could be explained in part by the continuing cement hydration and corresponding reduction in concrete porosity. Knowing that most chloride diffusion prediction models use constant values of $C_s$ and $D_c$, the above observations suggest that simplified models may give inaccurate predictions if input values of $C_s$ and $D_c$ are not updated with field monitoring data.

### 3.2.2 Prediction of corrosion initiation and concrete spalling

In order to predict the time of corrosion initiation ($t_i$), Eq. 1 was rearranged by setting $C(x,t)$ equal to a chloride threshold value ($C_{th}$), at which steel corrosion can initiate, and $x$ equal to the effective cover depth ($d_c$). Assuming an elastic behaviour for concrete in tension, stresses generated by corrosion products were estimated using the thick-wall cylinder model (Bažant 1979, Lounis and Daigle 2008), which calculates the increase in rebar diameter $\Delta d$ for each stage of corrosion-induced damage. The corrosion propagation times ($t_p$), corresponding to the onset of internal cracking, surface cracking, and delamination/spalling were found as follows:

$$t_p = \frac{\pi\, d\, \Delta d}{2\, S\, j_r \left[ 1/\rho_r - \alpha/\rho_s \right]} \tag{2}$$

where $d$ is the rebar diameter; $S$ is the rebar spacing; $j_r$ is the rust production rate per unit area; $\rho_r$ is the density of corrosion products (3600 kg/m$^3$ for $Fe(OH)_3$); $\rho_s$ is the density of steel (7860 kg/m$^3$); and $\alpha$ is the molecular weight ratio of metal iron to the corrosion product (0.52). The total time to reach a given corrosion-induced damage level is then found as the sum of the corrosion initiation time ($t_i$) and the individual corrosion propagation times ($t_p$) up to that level.

Figure 5 presents a sensitivity analysis of the times to initiate corrosion and concrete spalling, depending on several factors: (i) cover thickness; (ii) chloride threshold; and (iii) corrosion rate. At the 75 mm depth (location of main rebars), the prediction indicates a time to corrosion initiation between 6 and 10 years based on threshold values suggested by ACI (2001) and CEB (1992). However, no significant corrosion was observed on sections of reinforcing bars cut from the barrier wall after 10 years (Cusson and Qian 2007).

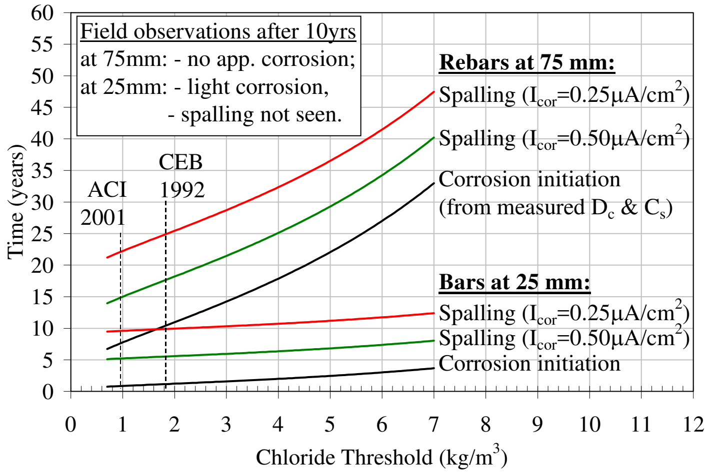


Figure 5: Sensitivity analysis of time to rebar corrosion and time to concrete spalling.

Combined with the observation that the concrete surfaces over the 25-mm deep bars were still free of defects after 10 years (Cusson and Qian 2007), it seems that chloride threshold values larger than 2 kg/m$^3$ would be more appropriate in this case than the ACI and CEB values. In fact, the literature shows a strong disagreement amongst researchers on the range of values to use for the chloride threshold of conventional reinforcing steel in concrete (Alonso et al. 2000, Lounis and Daigle 2008). At a depth of 75 mm, the models predicted concrete spalling after 15 to 17 years of exposure, based on the commonly used corrosion rate of 0.50 µm/cm$^2$ and on the ACI and CEB chloride threshold values. Again, this event appears to be quite unlikely in this case. In fact, the average corrosion rates measured in the bridge barrier walls (near cracks) were 0.25 µm/cm$^2$ for the 75-mm deep reinforcement (and 0.30 µm/cm$^2$ for the 25-mm deep test bars). With this field data, and assuming a chloride threshold larger than 2 kg/m$^3$, the models predict the onset of spalling after at least 25 years for the 75-mm deep bars, which appears to be a more appropriate prediction.

## 4 DISCUSSION

The above case study showed that some of the input data that are commonly used in service life prediction models (e.g. surface chloride content, chloride diffusion coefficient, chloride threshold and corrosion rate) could be very different from actual field values, because these parameters vary widely in time and location and are highly uncertain. Although the case study is on bridge barrier walls, the lessons learned also apply to other parts of a bridge as long as they show a bare concrete surface exposed to similar levels of chlorides, like a bare concrete deck.

In order to deal with the high variability and uncertainty of input data, two approaches could be used in combination. As mentioned before, structure health monitoring is one approach that can continuously provide valuable information on several key parameters simultaneously. For example, corrosion rates are usually ‘manually’ measured during the summer time for convenience, resulting in higher than yearly-average rates. This could result in overly conservative predictions of service life. On the other hand, remote monitoring of the corrosion rate with embedded instrumentation on a daily basis could provide a meaningful value of the yearly average, which can still be expected to increase as reinforcement corrosion and concrete deterioration develop over the years. The second approach is the use of probabilistic models accounting for this variability using average values and coefficient of variations of key parameters as well as their stochastic correlation in time and space (Lounis and Daigle 2008). Such models are more robust than deterministic models, and can be calibrated with SHM data.

## 5 SUMMARY AND CONCLUSIONS

The deterioration of highway bridges can have serious consequences in terms of safety and serviceability. Structural health monitoring (SHM), either with embedded sensors or actual field testing, is an evolving technology that allows monitoring the health of existing or new bridges. SHM can benefit the owners and users of bridge structures by ensuring public safety, assessing structural integrity, and optimizing bridge inspection and maintenance. SHM can help assess the performance of new construction/rehabilitation technologies, the development and calibration of service life prediction models, and the updating of loading data for use in the design of bridges. The approach can be used in short, medium and long-span bridges, by expanding the range of monitored parameters to comprehensively assess the features of these bridges. It was shown in a case study that some of the input data, commonly used in service life prediction models, could be very different from reality, because these parameters vary widely in time and location and are highly uncertain. It was also shown that service life predictions could be improved significantly by updating the models with field monitoring data. Future research and field projects are needed to develop and demonstrate integrated strategies that combine (i) cost-effective structural health monitoring, including the identification of critical areas and key parameters to monitor in a bridge system, and the effective management and interpretation of SHM data, and (ii) service life modeling, including the use of more realistic input data and model updating techniques.

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