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Long-term performance of prestressed concrete bridges

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Abstract
This article provides an overview regarding the SHM and assessment of prestressed concrete bridges is performed, mainly focussing on the identification of performance indicators (PI) associated with the long-term performance. The critical aspects related to the monitoring plan as well as the structural assessment based on updated structural models are outlined, being the latter considered as the bottom line of any further considerations. Although the definition of PI devoted to the long-term behaviour of prestressed concrete bridges is not straightforward, two definitions of PI are suggested by taking into account the two main components of the bridge: (i) bearing and expansion joints and (ii) the prestressed concrete structure. Finally, two examples - Lezíria Bridge and Miguel Torga Bridge - are presented in order to illustrate the benefit in using SHM in the assessment of the long-term performance due to creep and shrinkage effects. It is showed that a reduction in the associated uncertainty is achieved and consequently, costs associated with bridge management can be potentially optimized.

Keywords: Bridges, concrete, prestressing, performance indicators, long-term performance

1. INTRODUCTION

The long-term performance of prestressed concrete bridges depends on several factors. Time-dependent phenomena such as creep and shrinkage of concrete, relaxation of steel and environmental conditions influence how the structure deflects over time. In general, the structural effects associated with these time-dependent phenomena are: (i) increase of deformations, (ii) losses of prestress and (ii) redistribution of stresses. The increase of deformations can be, in some cases, significant and therefore, it must be taken into account in the design of bearings and expansion joints. On the other hand, the redistribution of stresses is particularly important for evolving structural systems, such as segmental bridges. Hence, these time-dependent phenomena have to be properly quantified in order to ensure the safety, serviceability and durability of the bridge.
For the particular case of creep and shrinkage, the majority of the codes offer models to be used for structural design (rather than for assessment). Even so, the development of these phenomena is subjected to a high degree of uncertainty either due to the variability of the input parameters or limitations associated with the models. In order to take into account that uncertainty, the Eurocode 2 (EC2) [1] proposes a safety factor for long-term extrapolation of time-dependent deformations that can go up to 1.20. Therefore, this uncertainty is important in the analysis of the time-dependent behaviour of the structure. Several studies have shown that uncertainty associated with creep and shrinkage modelling might lead to an underestimation of

the predicted deflections [2]. Indeed, this can lead to loss of serviceability and durability, which in turn can lead to operating restrictions with possible repairing/retrofitting.
In this context, it is critical to define PI, supported on data collected by SHM systems to reduce the uncertainty associated with the aforementioned time-dependent phenomena, that are able to identify in advance potential malfunctions of the bridge and reduce potential costs.

2. LONG-TERM OBSERVATION AND ASSESSMENT OF PRESTRESSED CONCRETE BRIDGES

Nowadays, it is possible to monitor highly instrumented structures continuously and remotely, with a high degree of automation. Present SHM solutions are versatile enough to allow for surveillance tasks to be realized remotely with sound cost-effectiveness [3]. This is performed by measuring a set of physical or chemical parameters with appropriate sensors, which allow the permanent knowledge of critical parameters through a compatible acquisition and communication system, allowing automatic and remote storage in a database, often accessible through the Internet. In general, and for the long-term observation of the structure behaviour, continuous measurement at low frequencies (e.g. hourly measurements) is adopted to capture the trends that are mainly dominated by creep and shrinkage of concrete, relaxation of steel and environmental effects.

2.1 Monitoring the long-term behaviour

The observation of the long-term behaviour of prestressed concrete bridges is based on the measurement of a set of parameters with the aim of getting a good understanding on how the structure deflects over time. Typically, this is performed by monitoring deflections of mid span sections, horizontal displacements at bearings/joints, rotations of supporting sections and strains in critical spots. For this, the parameters usually monitored can be clustered in three main categories: (i) *structural measurements*, i.e. measurements collected directly from the structure by means of embedded/external sensors able to measure physical parameters in critical zones of the structure; (ii) *specimen measurements*, i.e. strain and temperature measurements collected over time from concrete specimens made with the same concrete of the structure and (iii) *environmental measurements*, i.e. measurements on temperature and relative humidity conditions.
As aforementioned, the long-term behaviour of prestressed concrete bridges is highly dependent on creep, shrinkage and environmental factors. Due to this fact, it might be insufficient to use only *structural measurements* to understand the long-term behaviour of the bridge. Hence, and in addition to the *structural measurements*, *specimen measurements* are used to quantify the deformations that are due to creep and shrinkage, whereas the *environmental measurements* are used to quantify the deformations that are due to the variations of temperature and relative humidity.
Table 1 summarizes the parameters that are usually considered in the long-term observation of the structural behaviour of prestressed concrete bridges. In addition, some of the typical SHM technologies employed in the measurement of these parameters are also mentioned.
For the specific case of the *structural measurements* (Table 1), it is also necessary to identify where it is intended to measure them along the bridge length. For this, it is important to keep in mind that the objective here is to capture, as best as possible, the long-term deflection of the bridge. Therefore, the sensors need to be located where it is expected that they will record the maximum expected amplitude, among all the possible locations.

Category	Parameter	SHM technology (sensors)
structural measurements	Vertical displacement	LVDTs, LDV, GNSS, Hydrostatic levelling system
	Bearing/Joint displacement	LVDTs, jointmeters
	Tower top displacement	GNSS
	Rotation	Inclinometers
	Strain	Electric strain-gauges, vibrating wire strain-gauges, FBG strain gauge
	Support reaction	Load cells
specimen measurements	Creep	Strain gauges
	Shrinkage	Strain gauges
environmental measurements	Temperature	Thermistor, Thermocouple, RTD, FBG
	Relative Humidity	Hygrometer

Table 1: Typical parameters monitored in the long-term observation of prestressed concrete bridges.

In this context, a priori knowledge about the structure behaviour is important in order to be able to identify the critical sections that are aimed to be monitored with suitable sensors. The most reliable method to identify those sections is by means of structural models. Nonetheless, the identification of those critical sections is quite straightforward for the particular case of prestressed concrete bridges subjected to dead loads and time-dependent effects (i.e. creep, shrinkage and environmental effects). For instance, the maximum vertical displacement is expected to occur (i) at the mid spans for inner spans and (ii) approximately at 1/3 of the span length for outer spans.
Figure 1 and Figure 2 shows, as an illustration, a typical instrumentation plan devoted to the long-term observation of the structural behaviour of prestressed concrete bridges [4].

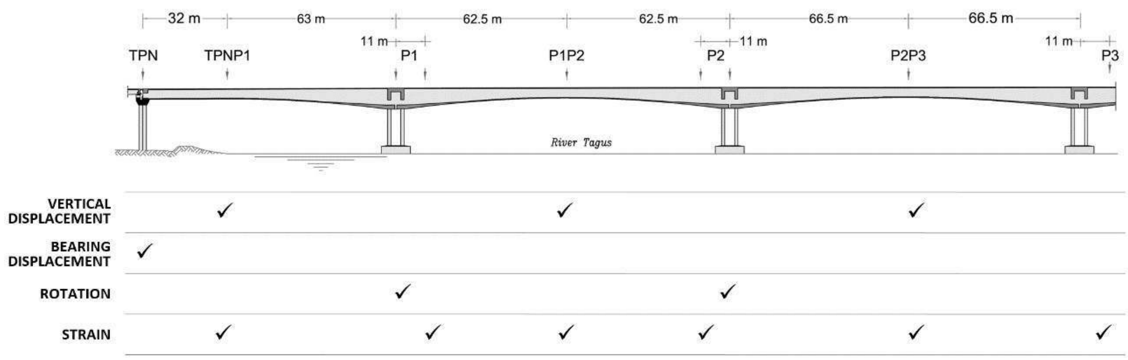

Figure 1: Long-term monitoring system - measurements location.

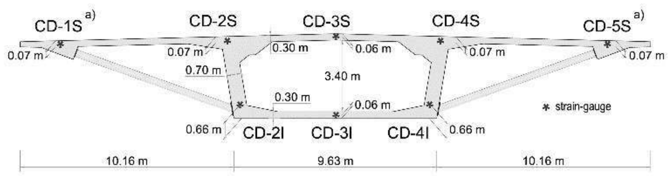

Figure 2: Long-term monitoring system – strain gauges location.

2.2 Assessment of the long-term behaviour

Structural models (e.g. FE models) are normally developed to obtain predictions, (reference values), which in turn are used to assess if the collected measurements are within the expected range of magnitude. Nevertheless, the reliability of those predictions is dependent on the assumptions that are made in the development of the structural models. As aforementioned, uncertainty is inevitable in the assessment of the long-term performance of prestressed concrete bridges. Hence, it is important to collect, as much as possible, real information related to the monitored bridge with the aim of reducing the associated uncertainty. Models that consider real information from the bridge are called *updated structural models*.

This real information might be grouped in four main categories: (i) *material characterization*, mainly the mechanical properties of the employed concrete, including the evolution over time of those properties (i.e. compressive strength, modulus of elasticity, hardening, creep and shrinkage), and the passive and prestressing steel (i.e. modulus of elasticity, tensile strength and relaxation); (ii) *environmental conditions*, mainly the temperature and relative humidity conditions of the bridge; (iii) *loading*, mainly dead loads, weight of scaffolding systems and the prestressing applied on the bridge during construction and (iv) *time-history*, mainly a detailed identification of the main critical phases of the bridge construction (i.e. concrete pouring and prestressing) and any other events related to possible repairing/strengthening actions on the bridge.

3. PERFORMANCE INDICATORS FOR THE LONG-TERM ASSESSMENT

PI may be expressed as an abstraction of superior level related to a bridge characteristic, which enables to identify the condition or performance of a bridge. However, the definition and quantification of PI associated with the long-term performance of prestressed concrete bridges is not a straightforward procedure.

Commonly, the assessment of the long-term performance of prestressed concrete bridges is done based on periodical inspections. However, it has been shown that the use of SHM technologies allows an important improvement in the assessment, based on the measurement of selected *structural parameters* (Table 1) and its comparison with values predicted by structural models (reference values).

Although these structural parameters are easily quantified by means of SHM technologies (Table 1), the utilisation of them as PI is not practical because the admissible range for those parameters is dependent on the characteristics of the structure (e.g. the admissible range for the vertical displacement depends on the span length of the bridge). For this reason, it is more convenient expressing a PI as a dimensionless index (e.g. as a relation between a measured value and a reference value).

In this context, the bridge is seen as a composition of two main components for the definition of PI: (i) bearing and expansion joints (PI type 1) and (ii) the prestressed concrete structure (PI type 2).

3.1 PI type 1 - Bearings and expansion joints

From a structural point of view, the magnitude associated with the *structural parameters* are restricted to a range of admissible values, which depends on the structure itself. For example, the bearing or joint displacement is ultimately restricted by the maximum range of the bearing or joint device (i.e. physically, it cannot go further without severe consequences). Hence, reference values, e.g. maximum range of a bearing/joint device, might be used to define the PI associated with these parameters. A simple ratio between what is being measured – the displacement – and the reference value – the maximum range of the device – is proposed as presented in Eq. (1). From this expression, values near of 5 (the maximum value for this PI) indicates a potential damage scenario.

$$PI_1 = \frac{displacement}{maximum\ range} \times 5 \quad PI \in [0,5] \tag{1}$$

These longitudinal displacements depends on two main effects: (i) the time-dependent behaviour of concrete and (ii) temperature variation. Quantification of each effect on the displacement is easily obtained [6]. Although the admissible range has to be with respect to the total displacement, this quantification is useful for a better comprehension of the structure behaviour.
For the particular case of bearing displacements, despite the possibility of a high number of bearing devices in a long-span bridge, the critical ones can be easily identified after an analysis of the time dependent behaviour of the structure. Consequently, the displacements from these can be selected for PI.

3.2 PI type 2 - Prestressed concrete structure

Regarding the prestressed concrete structure, the stress level installed on the bridge is suggested to be used, as presented in Eq. (2). The concrete stress, ε_c, should be calculated based on the structural models of the bridge by taking into account all available information related to the bridge (according to section 2.2). In other words, the concrete stress is indirectly obtained based on the *updated structural model* that is able to best match the measurements collected from the SHM system (e.g. displacements, rotations, strains). On the other hand, the characteristic compressive strength, f_{ck}, and the characteristic tensile strength, f_{ctk}, are used as reference values for the quantification of f_c in Eq. (2). Moreover, a more restrictive scenario can be established by limiting the concrete stress up to $0.45 \cdot f_{ck}$, according to EC2, in order to avoid non-linear creep and the associated potential reduction of durability. Similar to Eq. (1), values near of 5 for Eq. (2) (the maximum value for this PI) indicates a potential damage scenario.

$$PI_2 = \frac{\sigma_c}{f_c} \times 5 \quad PI \in [0,5] \ and\ f_c = \begin{cases} f_{ctk} & if\ \sigma_c > 0\ (tension) \\ 0.45 \cdot f_{ck} & if\ \sigma_c < 0\ (compression) \end{cases} \tag{2}$$

It is also worthy of note that for the prestressed concrete structure there are several parameters that can be related to the definition of a PI, such as, vertical displacement, rotation or strain. Nevertheless, priori knowledge about the range of values expected for these parameters is required. For this case, reference values set by the bridge designer is proposed to be adopted mainly for the most significant parameters. Hence, the definition of the PI according to Eq. (1) is suitable.

4. VALUE OF SHM FROM IN-SITU CHARACTERIZATION OF CREEP AND SHRINKAGE

4.1 Uncertainty associated with creep and shrinkage

Among all the phenomena affecting the performance of prestressed concrete bridges, it has been observed that, as far as the long-term behaviour is concerned, creep and shrinkage effects are perhaps the ones with highest uncertainty. Several studies show that long-term predictions differ significantly from the observed response, mainly due to the models that are used to quantify creep and shrinkage effects [2, 4, 6-10].

Although the majority of shrinkage and creep models are relative recent and comprehensive, there are systematic deviations and a lack of consensus in their utilisation. For example, Goel et al. [11] showed, based on the RILEM database, that none of the models for shrinkage and creep is able to offer reliable predictions at the specimen level. This is mainly due to the fact that the majority of these models are mainly thought for design purposes rather than for assessment. Indeed, some engineers prefer models that are able to predict creep and shrinkage deformations from as few parameters as possible [12]. Although this might be more convenient, it is not realistic [2].

In this context, i.e. taking into account the limitations of the available models, the best approach to reduce uncertainty associated with creep and shrinkage effects is through long-term observation supported on SHM systems. The potential benefit of this approach, from the bridge management perspective, can be assessed according to Eq. (3) [13]. If the parameter V (Value of SHM) is positive, this means that the bridge owner/operator benefits in employing SHM systems (i.e. overall, the operational costs decrease).

$$V = B_1 - B_0 \ , \ \begin{cases} B_0 = Life\ cycle\ benefit\ without\ SHM \\ B_1 = Life\ cycle\ benefit\ utilizing\ SHM \end{cases} \qquad (3)$$

In order to illustrate the potential benefit in using SHM in the quantification of creep and shrinkage effects, monitoring data collected in two modern bridges in Portugal – Lezíria Bridge and Miguel Torga Bridge – are herein presented as case studies.

4.2 Lezíria Bridge

The permanent SHM system of the Lezíria Bridge [14] is a comprehensive case study available in the literature. The monitoring data from this bridge allowed to better understand the long-term behaviour of segmental bridges based on a combination of several factors, including (i) the bridge's scale, (ii) the monitoring data collected since the beginning of construction, (iii) the comprehensive scanning of real data related to materials, geometry, and loading, and (iv) the FE modelling approach based on a full model of the bridge, including a detailed time-step analysis from the beginning of construction. A comprehensive description of the employed numerical models and the obtained results can be found elsewhere [4].

For the purpose of discussing the potential value of SHM in the long-term performance of prestressed concrete bridges, Figure 3 shows *specimen measurements* (Table 1) related to creep and shrinkage properties of the concrete used on the bridge. In addition, predictions based on the EC2 models (related to B_0 in Eq. (3)) and predictions adjusted to the creep and shrinkage measurements (related to B_1 in Eq. (3)) are overlapped. Based on the results (Figure 3), it is possible to conclude that EC2 models do not predict accurately the creep and shrinkage properties of the employed concrete and consequently, a benefit is obtained when using SHM to measure these phenomena in order to better understand their real evolution over time.

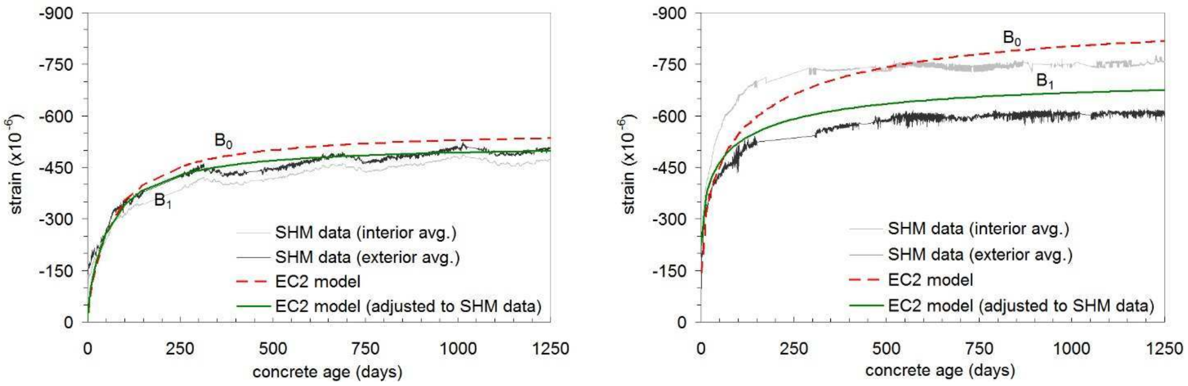

Figure 3: Specimen level – measurements vs. model for shrinkage (left) and creep (right).

Now, at the structural level, and considering the previous information as an input in the structural model (related to B_0 and B_1), Figure 4 shows the results obtained from the *updated structural model* regarding one of the bearing displacements of the bridge. It is quite straightforward to conclude that there is a clear benefit in utilizing SHM because based on this information (from Figure 3) the predictions for the bearing displacement is more in agreement with what is being measured (green line against dashed red line in Figure 4). Hence, it is also possible to conclude that the PI value associated with the performance of the bearing (Eq. (1)) is less severe and consequently, potential maintenance/repair costs related to the good performance of this device might be saved in a medium/long-term basis.

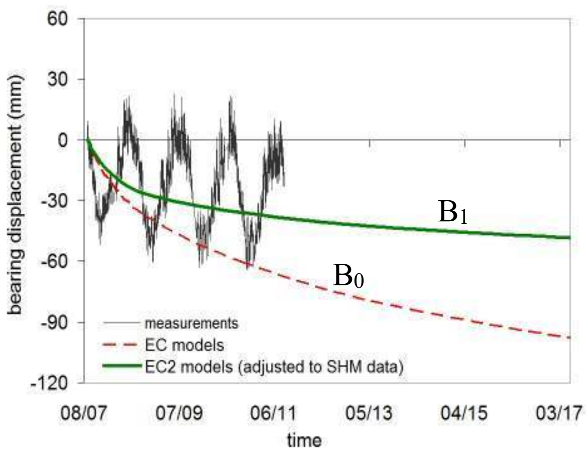

Figure 4: Structural level – measurements vs. model for the bearing displacement.

4.2 Miguel Torga Bridge

Miguel Torga Bridge is 900m long with a main span of 180m. The bridge girder is a single-cell curved box-girder of variable inertia. A SHM monitoring system was installed during the bridge construction and data has being collected since then.

Particular attention was given to the in-situ assessment of the time-dependent properties of the employed concrete. For this purpose, 47 shrinkage specimens and 15 creep specimens were cast and placed either on the deck or inside the box-girder [8].

As in the previous case, Figure 5 presents the strains measured in some of the shrinkage specimens and creep coefficients derived from measurements collected from creep specimens. In addition, predictions based on the EC2 models and adjusted to the creep and shrinkage measurements are also plotted. In this case, shrinkage is overestimated by the prediction obtained from EC2 model, whereas creep is underestimated.

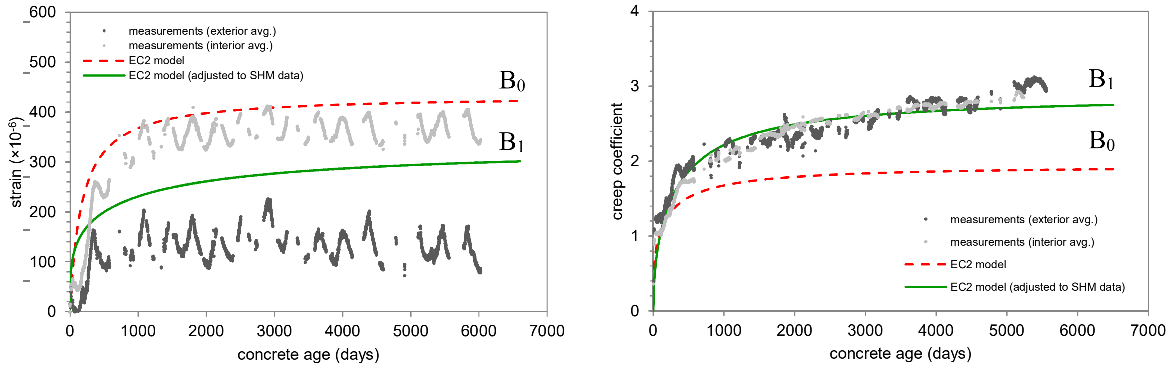

Figure 5: Specimen level – measurements vs. model for shrinkage (left) and creep (right).

Taking these measurements/predictions as an input in the structural model, the assessment of the structural behaviour was performed and compared to the *structural measurements* (in this case, strains). Figure 6 shows the evolution of strains at the mid-span section of the main span. Both predictions (either EC2 models or EC2 models adjusted to SHM data) and measurements collected by the vibrating-wire strain gauges installed on the structure are plotted. In addition, the results are grouped in two charts, on the left the deformations for the top slab, whereas the deformations for the bottom slab are presented on the right.
The benefit in utilizing SHM is once again demonstrated. Indeed, the predictions for the concrete strains are more in agreement with what is being measured when SHM data is used to update the structural model (green line against dashed red line in Figure 6). Moreover, it is also possible to conclude that the PI value associated with the performance of the bridge (Eq. (2)) might be more severe than what was being expected because higher deformations (stresses) are taking place.

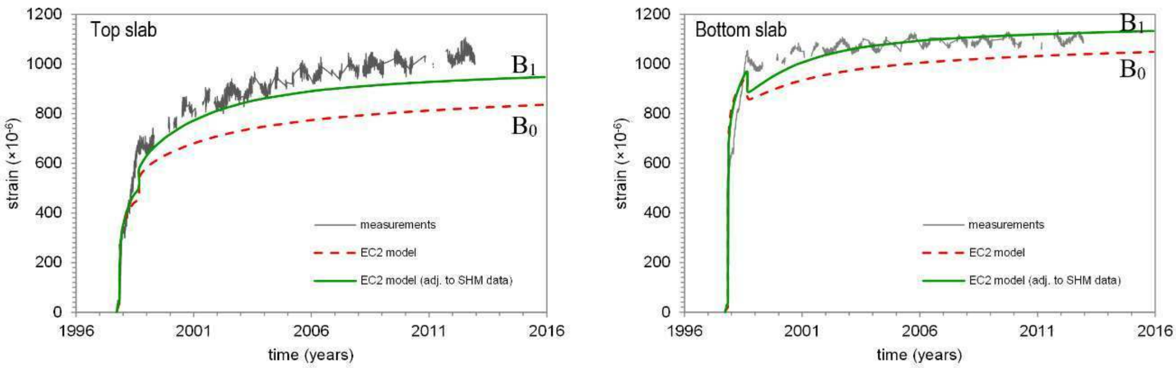

Figure 6: Structural level – measurements vs. model for the strains at mid-span.

5. CONCLUSIONS

The long-term performance of prestressed concrete bridges is highly dependent on creep and shrinkage effects. On the other hand, the available creep and shrinkage models are not suitable for bridge assessment, in general. Hence, this means that the best approach to characterize creep and shrinkage phenomena is by means of SHM systems.

In order to assess the long-term performance, the definition of PI depends on: (i) the component that is being analysed, (ii) the parameters that are measured with the support of SHM systems employed in the bridge and (iii) the existence of *updated structural models*. In addition, the two main components of the bridge are considered in the formulation of PI: (i) bearings and joint devices and (ii) prestressed concrete structure. The reason for this is mainly due to the fact that the performance of one of these components might not necessarily depend on the other one.

Finally, the two case studies presented in this article show that comprehensive monitoring systems installed on the bridge since the construction and the existence of *updated structural models* are crucial for a better/accurate long-term assessment. With this, a reduction in the uncertainty associated with the long-term performance of the structure is achieved and consequently, potential maintenance or repair costs might be optimised from the perspective of the bridge owner/operator.

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