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Model updating of in-service bridges using multidisciplinary research - case studies in Spain

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Abstract

This paper presents several experiences focused to create and update accurate numerical models of ageing bridges in Spain. The experimental campaigns included integration of various NDT technologies such as laser scanning, ultrasounds, etc., combined with vibration-based methods such as Operational Modal Analysis. From these multi-source data it was possible to create an accurate numerical model of each structure, which was lately subjected to a calibration using the actual dynamic response of the structure. Thus, the updated structural model presents the same behaviour as the real construction, offering a powerful tool to more accurately predict the safety level of the structure. On the other hand, structural assessments based on reliability analysis has been proved to improve the quality and accuracy of safety analysis due to the consideration of the possible deviations presented in the parameters of a structure. These works were compiled as case-studies in Spain within IM-SAFE project.

Keywords

Steel truss bridges, Numerical model updating, NDT characterization, Structural assessment

1 Introduction

The development of transport infrastructure is a significant and expensive investment for economically advanced EU countries, accounting for an average 1,1% of GDP in the 19 EU Member States [1], (representing 2,4% and 1,2% of GDP in US and China, respectively). The ageing in European infrastructures requires growing maintenance expenditures, as it can be extracted from the OECD dataset [2]. Bridges are challenging structures to design and built, that become one of the most vulnerable assets in the terrestrial transportation networks. Most of the transport bridge stock built after 1945 was projected with a design life of 50-100 years, being most of them operational today [3]. In large amount of them, the maintenance activities are already overdue (EC DG for Internal Market, 2019). In Europe there are more than 1.5 million bridges in operation with average age about 45 years, where some 1.500 railway bridges are to be strengthened and 4500 have to replaced [4]; in US more than 45000 have a deficient structural condition [4,5]; being the Chinese bridge stock the one with largest deficient structures with more than 80000 [4]. In the last years there has been a number of bridge failures and collapses that were attributed specifically to material degradation and lack of maintenance (continuous monitoring could avoid collapse in more than 42% of the US failures [6], and in more than 33% of the Chinese collapses [7]. The quality of the European bridge stock has been heavily questioned in national and international press in the second half of 2018, after the dramatic events of the Genova Bridge collapse in Italy on August 14 [8]. Bridge failures can cause significant human and economic losses (eg. in China there were more than 300 bridge collapses with 564 fatalities and 917 injuries in the period 2000-2014 [9]; in the US the FHWA reported 161 bridge failures in the period 2000-2008 causing more than 30 fatalities and 170 injuries [10], while invoking long-lasting disruptions in the transport networks and other indirect costs. Recurring extreme loading caused by natural and human-made events (also attributed to climate change) contributed to the faster deterioration of the structures [11].

Since the beginning of this century, structural health monitoring (SHM) became a trending discipline in structural engineering that has been rapidly adopted for most critical infrastructures. The construction of very long spam bridges and the upgrade of older bridges to support larger loads speeded up the incorporation of SHM sensors and systems [3]. However, most of the bridge stock in Europe is not equipped with monitoring systems since their construction. In fact, their condition monitoring is a much

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more complex task as very few of them are already integrated with continuous monitoring sensors due to the high cost, thus only ad-hoc solutions are typically adopted [3]. With the evolution of the technology and the digital era, many different approaches exist nowadays for the detection, parameterization and monitoring of many local damage indicators, even though, the extrapolation of those specific parameters to the global behaviour of the structure is still a challenging problem.

The SHM at global scale is connected to the analysis of the dynamic properties of the structure, by means of vibration monitoring, for which many different technologies have been proved to provide reliable information when different data analysis methods are applied.

Developing a Finite Element (FE) model for aging steel bridges is challenging and can result in discrepancies between predicted and actual responses of the structure. To address this, model updating techniques are normally used, often employing modal parameters extracted from output-only modal analysis. This operation helps to bridge the gap between the predicted response from a numerical model and actual responses of the structure.

This paper presents a global framework to perform the model updating of ageing bridges from the data captured by various non-destructive testing and monitoring systems. Extensive experimental campaigns were carried out in various ageing bridges in Spain that were used to validate the proposed methodology. The experimental campaigns included the geometric data acquisition using LiDAR systems, ultrasounds, among other NDT techniques, combined with Operational Modal Analysis for the dynamic analysis of the structure. The experiences gained through this research were transferred to IM-SAFE project [12], aiming to provide examples on how to reduce uncertainties of in-service structures and thus reaching safer bridges [13].

2 Model updating methodology

The proposed methodology for model updating comprises 5 steps, namely:

- Characterization of the structure trough experimental campaigns
- Creation of the structural model
- Uncertainty quantification
- Sensitivity analysis
- Model calibration and structural assessment

2.1 Experimental campaigns

A visual inspection is typically conducted in a first instance in order to identify what is the current condition of the structure and if visible damages are present and their location. This information is very relevant to plan the subsequent experimental campaigns, and to decide which equipment will be needed to collect the necessary data.

These equipment may include non-destructive testing techniques or remote measurements, which allows for the collection of experimental data while maintaining the structure's condition intact. These techniques include hand-made measurements, 3D modelling through terrestrial laser scanning, ultrasonic tests, and ambient vibration tests. Overall, these technologies allow the geometric reconstruction of the built structure, its mechanical properties, as well as the registration of the actual dynamic behaviour of the structure.

Terrestrial Laser Scanner (TLS) is used to gather geometrical data of the whole structure while in-situ measurements with a precision gauge supplement the scanning information in those elements whose size is not perceptible with the scanners resolution. Ultrasonic tests are normally used to obtain the mechanical and physical properties of the bridge's constituent material by measuring the velocity of longitudinal wave propagation, which is related to the Young's modulus of the material.

In order to update a model of a real structure, the mechanical behavior of the structure must be measured. Some authors propose to use static analysis and displacement measurement for the calibration of the numerical model. Our methodology proposed using Operational Modal Analysis (OMA) to obtain the modal properties (natural frequencies and mode shapes) and thus characterize the global mechanical response. OMA involves placing accelerometers at specific locations of the bridge in order to measure the accelerations in vertical and transverse directions; it relies on ambient vibration tests to acquire the dynamical response, which means it does not need external excitation. As mentioned above, at this stage is very important the visual inspection in order to locate and record any damage that may be altering the bridge's behavior.

2.2 Creation of the structural model

The experimental data obtained during the characterization was used as a basis to create the 3D geometric model of the bridges. This model is later enriched with other data extracted from bibliography so that the 3D Finite Element (FE) model could be developed. It is important to mention that the acquired data allows creating an accurate representation considering the 3D effects of the real structure. However this FE method has important drawbacks such as the high demand of computational resources to evaluate the accurate model created. In order to alleviate these computational demands, the bridges used to validate our methodology were modelled using beam and surface elements.

The acquired data about the bridge could also be used to define the physical models. Even though these physical models are not used for structural analysis due to its extreme complexity, they constitute a very relevant source of information to characterize the constitutive elements, boundary conditions, etc., and thus be integrated in further steps of the monitoring of the structure, eg. BIM models.

2.3 Uncertainty quantification

The definition of coherent deviations of the selected model parameters is required for the model updating. In our methodology these deviations were defined using the available bibliography such as current standards or the values proposed by other authors. Two definitions of the uncertainty can be established: i) these deviations can be defined as linear distributions delimited by an upper and lower bounds; alternatively, they can be described as some probability density function (PDF), which statistical moments are acquired from the aforementioned sources.

The bridges using to validate the methodology are steel truss bridges, thus for the material properties the JCSS standard [14] was adopted where the variability of the structural steel density is defined as a Gaussian distribution with a CoV of 1 %. The three-sigma rule of thumb was applied, so the bounds set were the values that delimit a confidence interval of 99.7 %. For the Young's modulus, the variability of as a log-normal distribution with a CoV of 5 % in accordance to other similar works. Similarly, based on the inverse cumulative distribution function, the selected bounds were the ones that define a confidence interval of 99.7 %.

2.4 Sensitivity analysis

The model updating of structures is based on iterative processes, which are processes with an extremely high computational cost so it typically leads to time-consuming calculations when using ordinary computers. Sensitivity analysis (SA) is typically adopted with the purpose of accelerating the calculations. This analysis studies the influence of each parameter in all the desired responses and ranked them in terms of relevance for the response. Once the influential parameters are identified and selected by the user, the non-influential ones are defined as constant values in the structural model. There exists various ways to perform the sensitivity analysis; in the current work, different manual and automatic sensitivity analysis techniques were adopted.

2.5 Model calibration and structural assessment

To ensure a structural model of a bridge accurately represents the real bridge, it is necessary to verify the model's precision. If the numerical response of the model does not match the actual response of the bridge, the model must be calibrated. Model calibration is an iterative process that adjusts the parameters of the structural model until its mechanical responses align with the experimental responses. The iterative process continues until the optimal values of the parameters are found, which minimize a predefined objective function. The objective function can consider natural frequencies, modal shapes, or both responses.

The iterative process of model calibration takes places once the previous steps of development of the structural model, quantification of uncertainties, and sensitivity analysis, are completed. During the calibration process, various approaches can be used to adjust the parameters of the model. For example, one approach is to minimize the difference between natural frequencies of the model and the experimental results. Another approach is to compare the modal shapes of the model with the experimental results using the MAC value, which quantifies the similarity between the two.

Obtaining a representative structural model of a bridge allows for the evaluation of the bridge's structural health. Current standards distinguish between deterministic and probabilistic evaluations. Deterministic evaluations use the theory of partial factors, while probabilistic evaluations consider the definition of uncertainty for each parameter in the structural model. Through probabilistic calculations, it is possible to compute the reliability index and the probability of failure of a bridge, which measures the probability of the bridge not being safe under a specific condition. During this stage, it is also possible to compute any desired response of the structure, such as the maximum von Mises stress or the deflection in a bridge element.

In summary, the precision of a structural model of a bridge should be verified and calibrated, if necessary, to ensure it accurately represents the real bridge. The calibration process can include iterative steps to adjust parameters and consider uncertainty to achieve optimal results. With a representative structural model, it is possible to evaluate the structural health of a bridge and compute any desired response of the structure.

3 Results

The aforementioned methodology was tested in various ageing bridges in the Northwest of Spain. Particularly, the current paper presents the results obtained in three steel truss bridges which are summarized below.

3.1 Real bridges under evaluation

3.1.1 Single-span bridge in Vilagarcía de Arousa.

The bridge is a riveted steel structure, 15.6 meters long and 5.8 meters wide, supported by two stone abutments. Steel plates and L-shaped profiles are used to create all beams, which are connected by rivets. The bridge has two girders, 1.57 meters high and 0.38 meters wide, connected by four transverse beams. The girders have 26 web stiffeners and 31 L-shaped bracings to provide lateral stiffness. A frame made up of two longitudinal beams and seven transverse beams is placed over the bridge to distribute loads.

Figure 1 Downstream elevation view of Vilagarcía bridge.

3.1.2 Four-span railway bridge in O Vicedo

The bridge is a four-span riveted steel truss structure with each span divided into twelve cells comprising of four chords, two transverse beams and trusses, four vertical beams, two cross bracings, and two diagonal beams. The bridge has an isostatic behaviour and rests on masonry piers, while two stringers support the railways. The beams are made up of various combinations of steel plates and angle beams. Due to its location on an estuary with high saltpetre levels, the bridge required retrofitting in 2017. The maintenance works included repairing or replacing several structural elements such as chords, vertical beams, and rivets, which were verified through visual inspection. The bridge was also painted, obscuring some of the damages.

Figure 2 Downstream elevation view of O Vicedo railway bridge.

3.1.3 Three-span bridge in O Barqueiro

The bridge has three isostatic spans, whose approximated dimensions are 48.10 meters in length, 6.4 meters in width, and featuring a steel arch that reaches 7.5 meters at its highest point. The deck is composed of 65 longitudinal and 14 transversal I-shaped beams, with the arch's top and bottom beams being horizontally deployed I-shaped beams. The deck is connected to the arch through 48 hangers comprising a T-shaped beam, while six transverse beams reinforce the arches on top. The bridge also features 44 diagonal steel plates reinforcing the arch-deck connection, 18 diagonal cables connecting the adjacent hangers on the bottom, and 10 diagonal cables connecting the five central hangers on top.

Figure 3 Upstream elevation view of O Barqueiro bridge.

3.2 Creation of structural models from the experimental data

Sufficient measurements must be taken during the characterization process to accurately capture any uncertainties regarding the bridge parameters. For the case studies presented in section 3.1, up to one hundred measurements of the cross-section dimensions were taken in each bridge and thus the Young's modulus was estimated. To accurately capture the dimensions of the bridges, laser scanning survey with multiple scanning positions under and on the structures were defined using a terrestrial laser scanner FARO Focus X330. These captured point clouds were then postprocessed in order to align them into a global point cloud of the entire bridgeto generate a reliable and accurate final geometric model.

Depending on the accessibility, dimensions, and structural configuration of each bridge, different OMA setups were defined. In some cases, it was not possible to perform an ambient analysis on the railway bridge of Vicedo due to the presence of the train. The modal properties extracted from the OMA were recorded for use in model calibration.

All the experimental information captured during the process was considered in the development of different structural and physical models. The physical models are accurate three-dimensional representations of the actual structure using solid elements, but are not suitable for calculations due to their high computational requirements. However, they can be used to store useful information and include them in a HBIM model of each bridge for further applications.

On the other hand, the structural models were created using beam, cable, and shell elements to represent the structural components of the bridges. Interfaces, springs, or end releases were used to simulate the mechanical response of certain spots such as supports and connections.

3.3 Model Updating

Before updating the model, it was necessary to define the upper and lower bounds for the variables to be updated. These bounds can be determined using probability density functions with parameters obtained from standards, papers or books such as [14]. The bounds can be represented as confidence intervals that encompass nearly all possible values of the distribution (e.g., a 99.7% confidence interval) or using theorems such as the three-sigma one. Alternatively, the bounds can be calculated by conducting analytical simulations or using standards like ISO 9223 [15]and ISO 9224 [16] for corrosion analysis.

A modal analysis of the original structural model was performed to verify if model calibration was necessary, which was confirmed in all case studies. The manual updating technique was used for calibration, which involves iteratively changing parameter values until the objective function is minimized. However, this technique is not recommended when many parameters need to be considered. The truss bridge of Vilagarcía was calibrated using this technique.

In the case of Vilagarcía bridge, a manual sensitivity analysis was performed due to the large number of parameters. Each parameter was changed iteratively to determine its influence on the numerical natural frequencies. It was discovered that mechanical properties, the transversal stiffness of the supports, and the thicknesses of the main chords and cross bracings had a significant influence on the desired response, while the remaining parameters could have their values fixed during calibration. After this analysis, the manual model calibration was carried out by varying parameter values to minimize the objective function that consisted in minimizing the differences between the numerical and experimental frequencies of every mode considered.

In the case of the mode shapes, these were evaluated by visual analysis. In the bridge of Vilagarcía, 16 iterations were needed to obtain a correct calibration. The results of the model updating of Vilagarcía Bridge are depicted in figure 4.

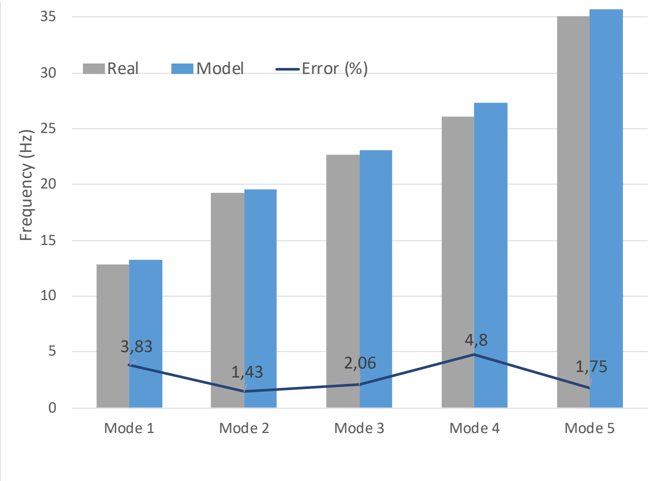

Figure 4 Results of calibration in the bridge of Vilagarcía

In the case of O Barqueiro Bridge, three automatic calibration techniques were employed. These calibrations were focused on the modal properties, this is, the natural frequencies and mode shapes. The initial modal analysis showed a good match between mode shapes but a significant difference in some frequencies (up to 60%), indicating the need for structural model calibration. The initial parameters considered for calibration were mechanical properties of the steel, thicknesses of structural elements, and stiffnesses of classified connections and supports.

The first model updating technique aimed to minimize computational time and costs while maintaining accuracy. A sensitivity analysis based on Spearman correlation coefficients was conducted to identify influential parameters such as Young's modulus, thicknesses, stiffnesses of low-damage connections, and transversal stiffnesses of supports. To reduce computational requirements, a Douglas-Reid surrogate model [17] was developed combined with a genetic algorithm to minimize the objective function that minimizes differences between numerical and experimental frequencies. Additionally, Modal Assurance Criterion (MAC) values were calculated.

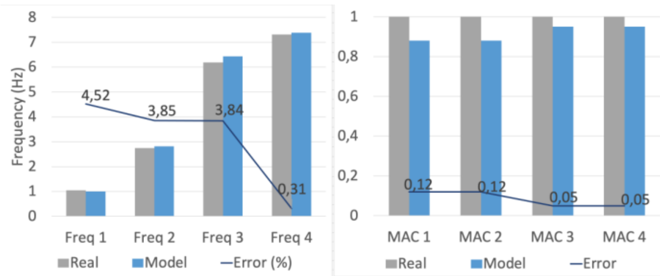

Figure 5 Results of calibration using the first deterministic approach in the bridge of O Barqueiro

According to the results of the calibration depicted in Figure 5, it can be seen that the objective function was correctly optimized. In the case of MAC values, the errors reach values of 12%, so there is space for improvement.

For the second deterministic calibration technique applied to the structural model, the Trust Reflective Algorithm was used and solved by the Gauss-Newton method. The same initial parameters were used as in the first technique, but a different sensitivity analysis was carried out using Sobol' Indices to determine the influence of inputs and their combinations on the desired outputs. However, the computation of these indices required a significant amount of computational power. As a result, a surrogate model based on the Gaussian process-based response surface was created. This analysis revealed that the Young's modulus, thickness of vertical hangers, stiffness of low-damage connections, and stiffnesses of all supports were the most influential parameters. Finally, an optimization algorithm was executed to minimize an objective function aimed at minimizing differences between numerical and experimental natural frequencies and MAC, using weight factors of 0.75 for the frequencies differences and the 0.25 for MAC differences.

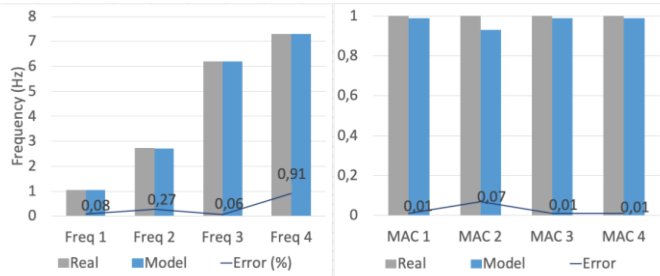

Figure 6 Results of calibration using the second deterministic approach in the bridge of O Barqueiro

The superiority of the second deterministic approach can be observed in Figure 6, as it yields much more accurate results, owing to the precision of the surrogate model, the optimization algorithm, and the inclusion of MAC values in the objective function. However, it should be noted that these algorithms entail significantly longer computational times.

3.4 Structural Assessment

The assessment of a structure must comply with the current standards [18], [19] and can be evaluated using different approaches depending on the limit state to be assessed. A limit state is a function that compares the resistance and load conditions of a case study, where g(X) represents the limit state function of a structure with X random variables and R and S are the resistance and effect of loads, respectively (Equation 1). The limit state can be evaluated deterministically or probabilistically.

$$g(X) = R - S \quad (1)$$

Deterministic structural evaluation assesses the limit state according to the theory of partial factors, which attempts to emulate the most unfavorable construction conditions. However, during this project, deterministic structural assessments could not be performed due to a lack of information related to wind, water, and snow loads.

Probabilistic structural evaluation (also known as reliability analysis) calculates the probability of failure (pf) of a structure, which has a direct relationship with the limit state definition.

$$p_f = P(g(X) \leq P(R - S \leq 0) = P(R \leq S) \quad (2)$$

The probability of failure can be also can be represented by the reliability index β:

$$\beta = -\Phi^{-1}(p_f) \qquad (3)$$

Being *Φ(·)* the standard normal cumulative distribution.

A reliability analysis was carried out on the Vicedo railway bridge, which involved a probabilistic evaluation to determine the probability density functions of selected parameters based on information from the bibliography [20], [14]. A deterministic analysis was then performed to identify the most vulnerable section of the bridge by calculating the maximum Von Mises stress for each of ten positions along the structure, based on loads specified in the standards [21]. Two reliability analyses were subsequently conducted using the Directional Sampling reliability method, and the results are presented in Table 1. However, it's important to note that the lack of calibration in the structural model means that the results may not accurately reflect the behavior of the bridge.

Table 1 Probability of failure and reliability indexes of O Vicedo bridge

O Vicedo	**Group 1**	**Group 2**
p_f	6.26E-11	2.98E-07
β	6.43	5.00

In the case of O Barqueiro bridge, a reliability analysis was proposed that utilized a calibrated structural model. The Bayesian inference method was used to update the calibrated parameter values and their probability distributions based on experimental data collected during the bridge's characterization. To identify the most vulnerable section, loads specified in the standard EN 1991-2 were placed in 20 different positions, and the ultimate load factor was calculated using non-linear deterministic analyses. The reliability analysis evaluated two different limit states, namely the serviceability limit state and the ultimate limit state, which were defined in Equations 4 and 5, respectively.

$$\sigma_{VMmax} \leq \frac{f_y}{y_{M,ser}} \qquad (4)$$

$$\frac{ULF}{2} \geq 1 \qquad (5)$$

The Directional Sampling reliability method was adopted to calculate the failure probability and the reliability index of the bridge, as presented in table 2.

Table 2 Probability of failure and reliability indexes of Braqueiro bridge

O Barqueiro	**SLS**	**ULS**
p_f	4.00E-02	2.00E-02
β	1.80	1.99

To assess the health of a structure, the reliability indexes obtained from the reliability analyses must be compared to the target reliability indexes specified by relevant standards (such as [18], [22], [14]). In the case of the O Barqueiro Bridge, the structure was found to exceed the demands of the studied serviceability limit state, but not those of the ultimate limit state. Therefore, it can be concluded that the structure is not safe under the applied load condition.

4 Conclusions

A framework for model updating of ageing in-service bridges has been developed and tested using real bridges located in Galicia, Spain. The methodology focuses on the calibration of complex structural modes and their use for assessing the structural condition of the bridges.

Non-destructive testing techniques are employed to obtain essential information about the structure, such as its structural configuration, physical and mechanical properties, cross-sectional dimensions, and overall mechanical response. This information is then used to develop and calibrate a structural model or to assess the structure.

The process of model calibration involves updating a structural model using both theoretical and experimental information and verifying that the calibrated model accurately represents the real structure. Additionally, reliability analysis-based structural assessments help to improve the quality and accuracy of evaluations by considering possible deviations in the structure's parameters.

By using the techniques outlined in this paper, reliable and accurate information can be obtained, which can be used as a basis for optimal decision-making regarding inspection and maintenance actions for real structures, including historical bridges.

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