Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability – Casas, Frangopol & Turmo (eds)

Contributions to IM-SAFE project based on the experience gained about numerical model updating of in-service bridges using multidisciplinary research

Óscar Bouzas, Brais Barros, Borja Conde, Manuel Cabaleiro, Ana Sánchez-Rodríguez & Belén Riveiro

Centro de Investigación en Tecnologías, Energía y Procesos Industriales (CINTECX) Applied Geotechnologies Group (GeoTECH) – Universidad de Vigo, Vigo, Spain

ABSTRACT: Bridges are especially vulnerable assets: a large part of the European bridge stock is reaching the end of its design service life and at the same time bridges are frequently subjected to corrosive and abrasive environments that accelerates damage. Numerical models have been demonstrated to serve as powerful tools to predict the current degree of damage and safety based on the actual condition of the structure. However, accurate numerical model development is still a challenge. Among other reasons, model input uncertainties can cause large differences between the numerical model predictions and the actual measured response from the structure. These discrepancies can be reduced significantly when proper model updating techniques are adopted. These techniques require acquiring various data representing the actual response of the structure, accurate geometric description and revision of assembly of the components, updated properties of materials, etc. LASTING project proposed the integration of various surveying and NDT techniques to build accurate numerical models of in-service bridges, which are later combined with vibration-based methods and probabilistic approaches to calibrate the numerical model produced. This paper presents several experiences in different ageing bridges in Spain where extensive experimental campaigns were carried out. Detailed descriptions about geometric data acquisition using LiDAR systems, ultrasounds, among other NDT techniques, combined with Operational Modal Analysis for the dynamic analysis of the structure are presented. The experiences gained with this project are now transferred to IM-SAFE project, so it will be discussed how this multidisciplinary research can contribute to reach safer bridges.

1 INTRODUCTION

Transportation infrastructures are one of the key indicators of the socioeconomic development of a country. Moreover, the well-being of the citizens is directly influenced by the quality and quantity of the transportation infrastructures. In this context, when speaking of transportation infrastructure quality, we refer to their preservation and maintenance state in terms of an efficient usage with utmost security. Indeed, safety is one of the main concerns of the structural design, hence regulations have been developed by experts and public administrations which are focused to design and build structures with the maximum safety level. However, there is no country with regulations or standards for the structural evaluation of in-service infrastructures, hence ignoring the deterioration and the structural modifications that may arise during the life cycle of the infrastructures, as well as the changing conditions since they are designed and built.

Accordingly, the European Commission (EC) is aware of the increasing number of extreme events, mainly natural (where climate change plays an important role) but also man-made (accidents, negligence, vandalism, or terrorism), so it has started to promote concrete actions to improve the resilience of transportation infrastructures to these events. Therefore, it is important to take into consideration new meteorological conditions, loading –and usage- conditions, as well as changes on the behavior of the population in order to evaluate whether or not the infrastructures are operating in safety conditions. These issues have been raised by the EC in the transportation program from the infrastructure sector. This way universities, private companies, transport operators and public administrations can develop and validate new methods, tools and strategies to design and build safer infrastructures. However, the infrastructure network in Europe is huge, being of special relevance the bridges that sustain the railway network, most of them built in the XIX century, and still in operation. It is also worth mentioning the large number of concrete structures in the terrestrial transportation network, which, although not as old as the bridges, are under deterioration processes (which are typically not quantified) and whose reliability and re-estimation of

DOI: 10.1201/9781003322641-295

service life are essential. The number and the geographical dispersion of these structures makes necessary to develop tools for the monitoring and evaluating structures on a large scale, as well as to prioritize detailed studies on those structures whose risk is bigger. The aforementioned actions of the EC propose the usage of new tools based on satellite and terrestrial remote sensing to monitor the evolution of these infrastructures, obtaining data that can feed new decision making systems based on predictive models.

The structural evaluation of in-service bridges has not been regulated yet, so different non-invasive auscultation methods and advanced computational models that have in account the current state of the structures in operation have emerged in the universities.

This paper presents several experiences in different ageing bridges in Spain where extensive experimental campaigns were carried out. Detailed descriptions about geometric data acquisition using LiDAR systems, ultrasounds, among other NDT techniques, combined with Operational Modal Analysis for the dynamic analysis of the structure are presented. The experiences gained with this project are now transferred to IM-SAFE project, so it will be discussed how this multidisciplinary research can contribute to reach safer bridges.

2 METHODOLOGY

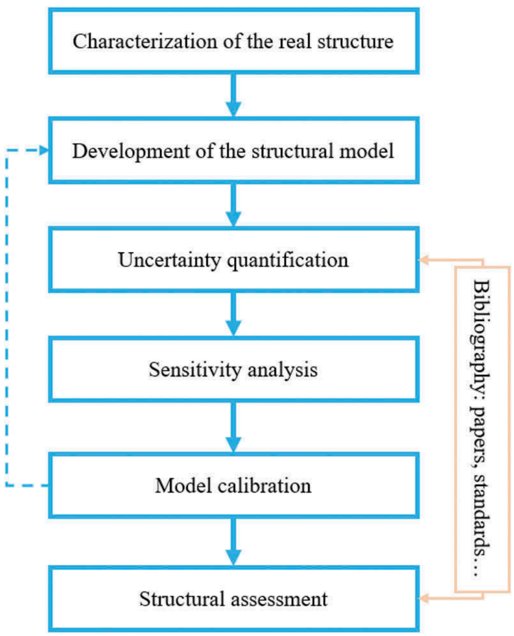

Figure 1. Overall methodology implemented.

The main goal of the LASTING project was the development of new methods for large scale and accurate inspection, which allowed the updating of advance structural models of critical vulnerable structures, such as bridges, for its assessment and reliability index calculation. In order to achieve this goal, several strategies were followed, which have been summarized in the general methodology presented below:

2.1 *Characterization of the real structure*

During this step, the required data for posterior stages is acquired. Most bridges have a non-intrusion requirement because their use or their heritage value. Hence, only non-destructive testing techniques can be used. In this methodology, geometrical, mechanical and dynamical information must be extracted. Geometrical data is obtained using the Terrestrial Laser Scanner (TLS) (Sánchez-Aparicio 2019) and taking in-situ measurements with a precision gauge for complementing the scanning information. On the other hand, the mechanical and physical properties of the constituent material of the bridge can be acquired by ultrasonic tests (Krautkrämer 1990), due to the relationship between the velocity of the propagation of longitudinal waves through a structural element and the Young's modulus of its material, which is shown in Equation 1.

$$E = \rho \cdot C_l^2 \cdot (1 + \mu) \cdot \frac{1 - 2 \cdot \mu}{1 - \mu} \tag{1}$$

Where E, ρ and μ are referred to the Young's modulus, density and Poisson's ratio of the material respectively and C_l is the velocity of propagation of the longitudinal waves through an element.

Subsequently, the mechanical behavior of the real structure must be measured to perform the model updating. Some authors carried out static analysis and measured the displacements of the structure (Matos 2019). Nevertheless, it is preferred to obtain the global mechanical response, so, in this methodology, the modal properties (natural frequencies and mode shapes) are measured instead by performing an Operational Modal Analysis (OMA). In this analysis, several uniaxial accelerometers are placed in some previously defined locations to measure the short-term accelerations of the construction in the vertical and transversal directions. Besides, the OMA is based on the ambient vibration tests, so it does not need any external excitation for acquiring the dynamical response. Finally, a visual inspection is carried out to identify, locate and write down the damage presented in the bridge that can modify its behavior.

2.2 *Development of the structural model*

The experimental data obtained during the characterization and some theoretical information extracted from the bibliography are used as a basis to develop a 3D Finite Element (FE) model of the studied bridge. This leads to an accurate representation that consider the three-dimensional effects that the structure suffers in real life. Nevertheless, the Finite Element Method (FEM) generates a computationally demanding structural model. Thus, in order to reduce these demands, the structural models generated in the LASTING project, were modelled using beam and surface elements. On the other hand, the experimental information can also be used to create physical models of the studied bridges. These models are a completely real representation of the bridge, their elements, their boundary conditions, etc. Nevertheless, they cannot be used for the structural analysis that are going to be carried out herein due to their complexness and their high computational requirements. In addition, all the desired data and both, the structural and physical models, can be introduced in a HBIM model to create a detailed database of the construction, which will be useful for monitoring purposes.

2.3 *Uncertainty quantification*

Before the model calibration, the definition of coherent deviations of the selected model parameters is required. These deviations can be defined using the available bibliography like current standards or researches of other authors. During this step, two definitions of the uncertainty can be established. On the one hand, these deviations can be defined as linear distributions that are delimited by an upper and lower bounds. On the other hand, they can be described as some probability density function (PDF), which statistical moments are acquired from the sources of information commented before.

2.4 *Sensitivity analysis*

The model updating and the probabilistic assessment of structures are iterative processes, which requires a lot of computational costs and leads to very time-consuming calculations. If an acceleration of them is required, a sensitivity analysis must be carried out. This analysis studies the influence of each parameter in all the desired responses and ranked them. Hence, the user can select again the parameters which are going to be more relevant during the following calculations, establishing the non-influential ones as constants in the structural model. There are several ways for performing the sensitivity analysis. In the LASTING project, different manual and automatic sensitivity analysis techniques were performed.

2.5 *Model calibration*

The accuracy of the structural model developed during the step 2 has to be verified in order to have a representative model of the real bridge. If the numerical response does not match with the real one, a model calibration must be performed. The model calibration is an iterative process that variate the parameters of the structural model for calculating its mechanical responses and compare them with the experimental ones. Hence, the parameters will change, according to the definition of their uncertainties, until their optimal values are found. These values correspond to those that minimize an objective function previously defined. In the LASTING project, this function considers the natural frequencies (using the frequency error between responses), the mode shapes (using the MAC value, that compares the numerical and experimental displacements of certain points) or both responses. It must be noted that the iterative process can comprehend the development of the structural model, the uncertainty quantification and sensitivity analysis steps too if better results are required. Once again, there are several approaches to perform this procedure.

2.6 *Structural assessment*

The structural health of a real construction can be assessed if a representative structural model of it is gotten. The current standards distinguish deterministic evaluations, which use the theory of partial factors, and probabilistic assessments, which consider the uncertainty definition of each parameter in the structural model. Concerning the probabilistic evaluations, it is possible to calculate the reliability index and the probability of failure of a structure performing probabilistic calculations. These indicators measure the probability of a bridge to not be safe in a specific condition. In addition, during this step is also possible to calculate any desired response of the structure such as the maximum Von Mises stress or the deflection in an element of the bridge.

3 CASE STUDIES

During the LASTING project, several variations of the methodology outlined before were applied in different real bridges located in Galicia, northwest of Spain.

3.1 *Stayed footbridge of Valadares*

The stayed footbridge located in Valadares was built in 1999 to allow the students to cross from their school to the village of Valadares, making the journey safer. This footbridge consists of three different spans that gives the construction a U-shape. The two end spans increase the height of the deck to allow the connection of the two sides of the bridge by means of a middle span above the main road. The concrete deck of the footbridge lays on a longitudinal steel tube and a C-shaped beam which are connected by several tapered T-beams. Furthermore, the whole structure is suspended by twenty prestressed cables that connect it to two steel pillars. Concerning to the supports, the footbridge has several fixed ones. The ends of the bridge and the three circular tubes on each of them are connected directly to the ground.

A visual inspection was performed to identify and locate the damage presented in the bridge. Nevertheless, some local corrosion and cracks can be observed in some structural elements. Besides, there were some spots with vegetation on the steel, which tend to absorb moisture and can lead to more degradation in them.

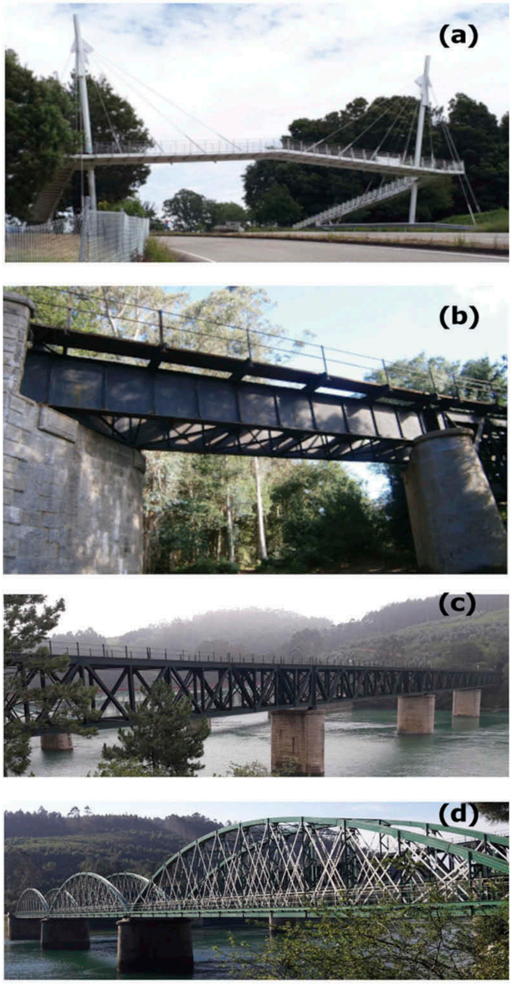

Figure 2. Bridges where the methodology was implemented: a) Valadares; b) Vilagarcía; c) Vicedo; d) O Barqueiro.

3.2 *Truss bridge of Vilagarcía*

The truss bridge of Vilagarcía is a single-span riveted steel truss bridge built in 1899 to allow the crossing of the train over the Umia river. In the bridge, the two chords connect its upper and lower sides, which, in turn, are transversally connected by transverse beams. In addition, these beams are transversally and vertically joined by cross-bracings that increase the stiffness of the construction. Furthermore, in the upper side of the bridge, two stringers were installed in order to place the railway track on them.

During the visual inspection, the isostatic behavior of the structure was verified by looking at its supports. In additon, it must be noted that there were no standard beams, all the cross-sections were made up of different combinations of steel plates and angle beams instead. On the other hand, the structure had several damages due to corrosion, especially in the connections between structural elements, where the moisture and the concentration of saltpeter is higher.

3.3 *Railway bridge of Vicedo*

The railway bridge of Vicedo was built in 1966 to allow the crossing of the train between the municipalities of O Vicedo and O Mañón, which are separated by the Sor river. Nowadays, the bridge is still in use, with two trains per day. The structure is a four-span riveted steel truss bridge. Each span is divided in twelve cells that have four chords, two transverse beams and trusses, four vertical beams, two cross bracings and two diagonal beams. Two stringers were installed on the bridge to place the railways on. Besides, all the spans have an isostatic behavior and rest on masonry piers. The beams are conformed by different combinations of steel plates and angle beams.

The bridge is located on an estuary, a placement with a lot of saltpeter in the ambient that damage the structure. Due to this fact, the bridge had to be retrofitted in 2017. During this maintenance works, several structural elements such as some chords, vertical beams and rivets had been repaired or substituted. These changes were verified during the visual inspection. Furthermore, the bridge was painted so it was not possible to identify several damages in it.

3.4 *O Barqueiro Bridge*

O Barqueiro Bridge is a three-isostatic-span riveted steel tied-arch bridge built in 1901 to cross the Sor river and allow the passage of people and goods between the municipalities of O Vicedo and O Mañón. In 1980, it was closed due to the high damage it presented. Nevertheless, in 2006 it was rehabilitated and pedestrianized. The bridge has two arches that has their arch ribs and tie beams connected by several vertical hangers, which, in turn, are longitudinally connected by rectangular cross bracings. In addition, the arch ribs are linked between them by transversal beams and circular-shaped cross bracings. On the other hand, the wooden deck of the bridge lays on stringers and transverse deck beams. Once again, the cross-sections of all the structural elements are combinations of steel angle beams and plates.

During the visual inspection it was observed that the bridge has several damages such as global superficial corrosion. Nevertheless, in some spots such as the tie beams, the stringers, the transverse beams and the connections between the tie beams, vertical hangers and transverse beams were severely corroded. These spots are more prone to accumulate water, moisture and saltpeter coming from the estuary behind the bridge. It was also observed that the replaced structural elements during the rehabilitation works were connected to the structure using bolts or welding them to it, instead of the original rivets. In fact, the welded elements suffered much more corrosion that any other beam in the bridge.

4 RESULTS AND DISCUSSION

4.1 *Characterization of the real structure and development of the structural model*

In the characterization enough measurements have to be taken in order to correctly capture the possible uncertainty of the parameters of the bridge. Hence, in all the case studies up to one hundred measurements of the cross-section dimensions were taken, so as estimations of the Young's modulus were done. Concerning the terrestrial laser scanner, several scanning positions under and on the bridges had to be defined to correctly capture their dimensions. Subsequently, these captured point clouds were postprocessed to generate an accurate and reliable final point cloud. Afterwards, depending on the dimensions of the structure, its accessibility and its structural configuration, different OMA setups were defined. In fact, it was not possible to perform an ambient analysis in the railway bridge of Vicedo due to the presence of the train. The modal properties extracted from the OMA were written down for its use in the model calibration.

Table 1. Mesh parameters of the structural models.

Case study	Elements	Nodes
Valadares	4476	8720
Vilagarcía	34909	31545
Vicedo	2860	5465
O Barqueiro	23311	65538

All the experimentally captured information was considered during the development of the different structural and physical models. The physical models are three-dimensional accurate representations of the real structure using solid elements, these models are not suitable for calculations due to its high computational requirements. Nevertheless, they can be used to storage useful information and to include them in a HBIM model of each bridge. On the other hand, the structural models were created using beam, cable and shells elements for representing the structural elements of the bridges, and interfaces, springs or end releases to simulate the mechanical response of some spots such as supports and connections. The mesh parameters of each of the developed structural models can be seen in Table 1.

4.2 *Uncertainty quantification and model updating*

Previous to the model updating, the definition of the upper and lower bounds had to be carried out. On the one hand, these bounds can be delimited by probability density functions, whose parameters can be acquired from some standards, papers or books (JCSS 2001, Li 2020). The bounds can be described as confidence intervals that comprehends almost all the possible values of the distribution (e.g. the confidence interval of 99.7%) or using some theorems such as the three-sigma one. On the other hand, the bounds can be calculated by performing analytical simulations to the structural models or by calculating their values using some standards like the ISO 9223 and ISO 9224 about the corrosion of a steel element through the years.

Afterwards, a modal analysis of the original structural model is performed to verify if a model calibration is required, in all the case studies this verification was done. The simplest model calibration technique is the manual updating. This is a process where the values of the parameters are iteratively changed until the objective function is minimized. The minimization depends on the number of iterations, the engineering judgment and the defined bounds. It is not recommendable for calibrations where too many parameters must be considered. This technique was carried out in the case studies of the stayed footbridge of Valadares and the truss bridge of Vilagarcía.

Due to the huge number of parameters in the Vilagarcía bridge a manual sensitivity analysis was performed. In this, the values of the parameters were changed one per iteration to study their influence in the numerical natural frequencies. It was found that the mechanical properties, the transversal stiffness of the supports and the thicknesses of the main chords and the cross bracings had a considerable influence in the desired response, while the remaining parameters could have their value fixed during the calibration. Subsequently, the manual model calibration was carried out, which consisted of varying the values of the parameters to minimize the objective function showed below:

$$\pi = \sum_{i=1}^{n} \frac{f_{i,num}^2 - f_{i,exp}^2}{f_{i,exp}^2} \tag{2}$$

Where $f_{i,num}$ and $f_{i,exp}$ are the numerical and experimental frequencies of the mode n.

On the other hand, the mode shapes were checked visually. A total of 15 and 16 iterations must be done in the footbridge and the truss bridge respectively to achieve a correct calibration of their structural models. The results of these model calibrations are shown in Table 2.

In O Barqueiro Bridge three different automatic calibration techniques were performed. All of them considering both modal properties, the natural frequencies and the mode shapes. The initial modal analysis results show a good match between mode shapes but a difference of 60 % in some frequencies. Hence, it was verified that the structural model must be calibrated for achieving a good structural assessment. The initial considered parameters were the mechanical properties of the steel, the thicknesses of the structural elements and the stiffnesses of the classified connections and the supports. The first model updating technique tried to minimize the computational time and costs of the calibration without losing accuracy in the results. Firstly, a sensitivity analysis based on the Spearman correlation coefficients was carried out (Costa 2016), which measure the linear correlation between a parameter and a response. This analysis pointed out the Young's modulus, two thicknesses, the stiffnesses of the low-damage connections and the transversal stiffnesses of the supports as the influential parameters in the structural model. To minimize the computational requirements a Douglas-Reid surrogate model (Zorda 2014) was generated and introduced in a genetic algorithm (Bautista-De Castro 2018) to minimize the objective function shown in the Equation 2. Furthermore, the MAC values were calculated.

selected but a different sensitivity analysis was performed. In this technique the Sobol' Indices were calculated, which measure how the inputs in a model and their combinations influence the desired outputs. Nevertheless, calculating these indices demands huge computational power, thus a surrogate model based on the Gaussian process-based response surface (GASP) was created (Sacks 1989). The Young's modulus, the thickness of the vertical hangers, the stiffness of the low-damage connections and the stiffnesses of all the supports were identified as influential parameters. Subsequently, the optimization algorithm was run to minimize the objective function showed in Equation 3.

$$\pi = \frac{1}{2}\left[W_f \cdot \sum_{i=1}^{n}\left(\frac{f_{i,num}^2 - f_{i,exp}^2}{f_{i,exp}^2}\right) + W_{MAC} \cdot \sum_{i=1}^{m}(1 - MAC_i)^2\right] \tag{3}$$

Where W_f and W_{MAC} correspond to the weight factors of the frequency errors and MAC values. In this case study they had a value of 0.75 and 0.25 respectively.

In Table 3, it can be seen how this second technique is able to have much better results due to the accuracy of the surrogate model, the optimization algorithm and the consideration of the MAC values in the objective function. Nevertheless, the used algorithms require much higher computational times.

Finally, in O Barqueiro Bridge a stochastic model calibration based on the Bayesian optimization was carried out, following the framework proposed in (Bayarri 2002). This technique can determine the probability density functions of the selected parameters, allowing the quantification of their uncertainty, using the experimental data measured during the characterization of the real structure, thus the uncertainty quantification step was not necessary. Nevertheless, this technique also demands high computational costs, so a GASP surrogate model had to be created to reduce them.

Table 2. Results of model calibrations in Valadares and Vilagarcía bridges.

	Valadares			Vilagarcía		
Modes	Real (Hz)	Model (Hz)	Error (%)	Real (Hz)	Model (Hz)	Error (%)
1	2.21	2.18	1.37	12.81	13.30	3.83
2	2.86	3.05	6.54	19.31	19.59	1.43
3	4.01	4.01	0.18	22.63	23.09	2.06
4	4.84	4.51	6.70	26.06	27.31	4.80
5	8.41	8.03	4.61	35.06	35.68	1.75

The results in Table 3 shown how the objective function was correctly minimized. However, it can be observed that the MAC values could be improved.

The second deterministic calibration technique was based on a local optimization algorithm, the Trust Reflective Algorithm, which is solved by the Gauss-Newton method. The same initial parameters were

As it can be seen in Table 4, this technique is also able to minimize the objective function and provide a well-calibrated structural model.

Table 3. Results of model calibrations in O Barqueiro Bridge.

	Deterministic 1			Deterministic 2	
Modal property	Real (Hz)	Model (Hz)	Error (%)	Model (Hz)	Error (%)
Freq 1	1.05	1.00	4.52	1.05	0.08
Freq 2	2.74	2.81	3.85	2.71	0.27
Freq 3	6.19	6.43	3.84	6.19	0.06
Freq 4	7.31	7.38	0.31	7.29	0.91
MAC 1	1.00	0.88	12.00	0.99	1.00
MAC 2	1.00	0.88	12.00	0.93	7.00
MAC 3	1.00	0.95	5.00	0.99	1.00
MAC 4	1.00	0.95	5.00	0.99	1.00

Table 4. Results of model calibrations in O Barqueiro Bridge using the stochastic approach.

	Stochastic		
Modal property	Real (Hz)	Model (Hz)	Error (%)
Freq 1	1.05	1.08	2.26
Freq 2	2.74	2.73	0.50
Freq 3	6.19	6.24	0.74
Freq 4	7.31	7.34	0.29
MAC 1	1.00	1.00	0.00
MAC 2	1.00	0.94	6.00
MAC 3	1.00	0.99	1.00
MAC 4	1.00	0.99	1.00

4.3 *Structural assessment*

The assessment of a structure is a task that must follow the indications of the current standards (EN 1990, EN 1993-1-1). The same structure can be evaluated using different approaches depending on the limit state that need to be assessed. For example, an ultimate limit state is a function that compares the resistance and the load condition of a case study.

$$g(X) = R - S \tag{4}$$

Where *g(X)* denotes the limit state function of a structure that has X random variables and R and S are its resistance and the effect of the loads respectively. The limit state can be evaluated in a deterministic or a probabilistic way.

In deterministic structural evaluation the limit state is assessed according to the theory of partial factors, which tried to emulate the most unfavourable condition of the construction. During this project, deterministic structural assessments could not be performed because the lack of information related to wind, water and snow loads. Nevertheless, in the stayed footbridge of Valadares, the loads demanded by the current standard (EN 1991-2) were applied and several calculations were performed to check if the Von Mises stress of the bridge and its cables surpasses the values established in the standards (EN 1991-2, EN 12385-10).

In probabilistic structural evaluation (also called reliability analysis) the probability of failure p_f of a structure is calculated. This probability of failure has a direct relationship with the limit state definition. For example, concerning the ultimate limit state, the probability of failure can be calculated according to Equation 5.

$$p_f = P(g(X) \leq 0) = P(R \leq S) \tag{5}$$

Besides, the probability of failure can be expressed as a reliability index β, which indicates the reliability level of the studied structure.

$$\beta = -\phi^{-1}(p_f) \tag{6}$$

Where $\Phi(\cdot)$ denotes the standard normal cumulative distribution.

In the railway bridge of Vicedo a reliability analysis was purposed. Firstly, a probabilistic evaluation of the railway bridge of Vicedo was performed. Every reliability analysis begins with the definition of the probability density functions of the selected parameters, whose parameters can be extracted from the bibliography (JCSS, Moreira 2017). Subsequently, a deterministic analysis was performed in order to identify the most unfavourable section. Therefore, the loads demanded by the standard EN 1991-2 were placed in ten positions all along the bridge. For each load position, the maximum Von Mises stress of the structural model was calculated and compared. Finally, two reliability analysis, according to the classification of its parameters (Bouzas 2021), were carried out using the Directional Sampling reliability method (Dynardo 2020).

The results can be consulted in Table 5, Group 1 and Group 2 refer to the two classifications of parameters. However, it must be noted that this results are not suitable for a correct assessment because the structural model was not calibrated so there are no evidences that it correctly represents the real structure behaviour.

On the other hand, in O Barqueiro Bridge a reliability analysis based on a calibrated structural model was purposed. The calibrated parameter values (obtained from the Douglas-Reid and genetic algorithm deterministic model updating) and their probability distributions were updated using the Bayesian inference to consider the experimental data captured during the characterization of the bridge too. Afterwards, the loads demanded by the standard EN 1991-2 were positioned in 20 different positions for identifying the most unfavourable section. In each position the ultimate load factor was calculated using non-linear deterministic analyses to identify the most unfavourable section of the bridge. In this reliability analysis, two different limit states were evaluated, a serviceability limit state referred to the existence of local damage defined in Equation 7 and an ultimate limit state referred to the collapse of the structure, which is defined in Equation 4.

$$\sigma_{VMmax} \leq f_y \tag{7}$$

In both evaluations, the Directional Sampling reliability method was used for obtaining the probability of failure and the reliability index of the structure.

Table 5. Updated probability of failure and Reliability index for Vicedo and O Barqueiro bridge.

	Vicedo		O Barqueiro	
Result	Group 1	Group 2	SLS	ULS
p_f	6.26E-11	2.98E-07	4.00E-02	2.00E-02
β	6.43	5.00	1.80	1.99

The reliability indexes shown before must be compared with the target reliability indexes established by the standards (EN 1990, ISO 2394, ISO 13822, JCSS 2001) to evaluate the health of the structure. In O Barqueiro Bridge, the structure surpasses the demands regarding the studied serviceability limit state but not the ones related to the ultimate limit state, so it can be concluded that the structure is not safe for the load condition applied.

5 CONCLUSIONS

In this paper, the experiences obtained during the LASTING project has been summarized. Several real bridges located in Galicia, northwest of Spain, have been used as case studies for developing and testing a methodology focused on the calibration of complex structural modes and their use for the assessment of their structural condition.

Non-destructive testing techniques enable the acquisition of important information of the structure such as structural configuration, physical and mechanical properties of the constituent material, dimensions of the cross-sections and its real overall mechanical response, which can be used as a deep database for model development and calibration or structural assessment.

The model calibration allows the updating of a structural model using the theoretical and experimental available information, verifying that the calibrated structural model presents the same behavior as the real construction. On the other hand, structural assessments based on reliability analysis has proved an improvement in the quality and accuracy of evaluations due to the consideration of the possible deviations presented in the parameters of a structure.

The techniques outlined herein leads to the acquisition of reliable and accurate information that can be used as a basis for an optimal decision-making related to the inspection and maintenance actions of real structures such as historical bridges.

ACKNOWLEDGEMENTS

This project has received funding from the Spanish Ministry of Science, Innovation and Universities through Project Ref. RTI2018-095893-B-C21. This work has been partially supported by the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No. 958171.This work has been partially supported by the Spanish Ministry of Science, Innovation and Universities through the grant PRE2019-087331.

REFERENCES

Bautista-De Castro, Álvaro; Sánchez-Aparicio, Luis Javier; Ramos, Luís F.; Sena-Cruz, José; González-Aguilera, Diego. Integrating geomatic approaches, Operational Modal Analysis, advanced numerical and updating methods to evaluate the current safety conditions of the historical Bôco Bridge. *Construction and Building Materials*. 158 (2018): 961–984.

Bayarri, M.j.; Berger, J.O.; Higdon, D.; Kennedy, M.C.; Kottas, A.; Paulo, R.; Sacks, J; Cafeo J.A.; Cavendish, J.; Lin, C.H.; Tu, J. A framework for validation of computer models. *National Institute of Statistical Sciences*. 2002.

Bouzas, Óscar; Conde, Borja; Cabaleiro, Manuel; Barros, Brais; Riveiro, Belén; Riego, Nicolás. Reliability-based structural assessment of a historical steel railway bridge. *IABSE Congress Ghent 2021, Structural Engineering for Future Societal Needs, Congress Proceedings*. (2021): 1839–1846

Costa, C.; Ribeiro, D.; Jorge, P.; Silva, R.; Arêde, A.; Calçada, R. Calibration of the numerical model of a stone masonry railway bridge based on experimentally identified modal parameters. *Engineering Structures*. 123 (2016): 354–371.

Dynardo GmbH, Weimar. 2020. *Methods for multi-disciplinary optimization and robustness analysis*.

European Committee for Standardization. 2004. *Steel wire ropes – Safety – Part 10: Spiral ropes for general structural applications*. (EN 12385-10). Brussels.

European Committee for Standardization. 2019. *Eurocode 0: Basis of structural design*. (EN 1990). Brussels.

European Committee for Standardization. 2019. *Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges*. (EN 1991-2). Brussels.

European Committee for Standardization. 2013. *Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings*. (EN 1993-1-1). Brussels.

International Organization for Standardization. 2010. *Bases for design of structures – Assessment of existing structures*. (ISO 13822). Switzerland.

International Organization for Standardization. 2012. *Corrosion of metals and alloys - Corrosivity of atmospheres - Classification, determination and estimation*. (ISO 9223). Switzerland.

International Organization for Standardization. 2012. *Corrosion of metals and alloys - Corrosivity of atmospheres - Guiding values for the corrosivity categories*. (ISO 9224). Switzerland.

International Organization for Standardization. 2015. *General principles on reliability for structures*. (ISO 2394). Switzerland.

Joint Committee on Structural Safety. 2001. *Probabilistic model code. Part 2: load models*.

Joint Committee on Structural Safety. 2001. *Probabilistic model code. Part 3: material properties*.

Krautkrämer, Josef; Krautkrämer, Herbert. 1990. *Ultrasonic Testing of Materials*. Berlin. Springer-Verlag Berling Heidelberg GmbH.

Li, Huihui; Li, Lifeng; Zhou, Guojie; Xu, Liang. Effects of various modeling uncertainty parameters on the seismic response and seismic fragility estimates of the aging highway bridges. *Bulletin of Earthquake Engineering*. 18 (2020): 6337–6373.

Matos, José C.; Moreira, Vicente N.; Valente, Isabel B.; Cruz, Paulo J.S.; Neves, Luís C.; Galvão, Neryvaldo. Probabilistic-based assessment of existing steel-concrete composite bridges - Application to Sousa River Bridge. *Engineering Structures*. 181 (2019): 95–110.

Moreira, Vicente N.; Matos, José C.; Oliveira, Daniel V. Probabilistic-based assessment of a masonry arch bridge considering inferential procedures. *Engineering Structures*. 134 (2017): 61–73.

Sacks, Jerome; Welch, William J.; Mitchell, Toby J.; Wynn, Henry P. Design and analysis of computer experiments. *Statistical Science*. 4 (1989): 409–423.

Sánchez-Aparicio, Luis Javier; Bautista-De Castro, Álvaro; Conde, Borja; Carrasco, Pedro; Ramos, Luís F. Non-destructive means and methods for structural diagnosis of masonry arch bridges. *Automation in Construction*. 104 (2019): 360–382.

Zorda, Tobia; Briseghella, Bruno; Liu, Tao. Finite element model updating of a tied-arch bridge using Douglas-Reid method and Rosenbrock optimization algorithm. *Journal of Traffic and Transportation Engineering*. 1 (4) (2014): 280–292.