Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Predicting the usefulness of monitoring information for structural evaluations of bridges

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ABSTRACT: With economic, environmental, and material resources becoming increasingly scarce, more sustainable solutions for the management of civil infrastructure are required. Accurately evaluating the structural capacity is primordial to avoid unnecessary replacement of existing bridges. The assessment of existing structures is currently made based on construction drawings, recorded information on the materials used, and visual inspection. The remaining uncertainties on the structural behavior are compensated by conservatism assumptions. Monitoring data collected through bridge load testing, structural performance monitoring, and non-destructive tests provide additional information on the structural behavior leading to decision regarding bridge safety and reducing considerably the costs and environmental impacts of management. Nonetheless, collecting this information is often costly as the sensor deployment and the data management are expensive. The monitoring costs may not always be justified by the benefits in terms of information gain. This paper proposes a methodology to evaluate the potential impact of monitoring activities on the evaluation of structural performance. A full-scale bridge in Switzerland is used to assess the usefulness of several monitoring techniques. Results show that the monitoring leads to more accurate evaluations of structural verifications, and each method provides complementary information.

1 INTRODUCTION

Civil structures are designed using conservative assumptions and simple design models. Existing structures have thus untapped reserve capacity, and monitoring the structural behavior can unlock this potential (Smith, 2016). A better knowledge of the behavior and properties of a complex structure through monitoring may be then leveraged to optimize structural rehabilitation, focus inspection, and extend service durations (Frangopol et al., 2008).

Monitoring of structural behavior can be separated into two activity subsets depending on the monitoring goal: the evaluation of the structural capacity at a given time, called structural performance monitoring (SPM) (Feng et al., 2004), and the evolution of the structural behavior over time, called structural health monitoring (SHM) (Farrar & Worden, 2010). These two uses of monitoring data have different implications for infrastructure management. SPM provides information for structural-capacity evaluations (Proverbio et al., 2018) and the structural behavior in its environment (i.e., traffic loading and environmental actions) (Sawicki & Brühwiler, 2022). SHM aims to detect current and future damage in structures (J. M. Brownjohn, 2007), improving their maintenance and safety assessments in the future (Orcesi & Frangopol, 2011). Despite the undeniable potential of structural monitoring, both SHM and SPM are still rarely put into practice by asset managers (Ye et al., 2022). Several reasons explain this reluctance: the lack of time, the lack of resources, and missing related courses in curricula (Große et al., 2019).

The assessment of existing structures is made based on construction drawings (if they are recorded), and visual inspection. The remaining missing information is compensated by conservative assumptions following new-design principles (Brühwiler et al., 2012). Several

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methods have been proposed to assess existing-structure performance (Ghosn et al., 2016a; Ghosn et al., 2016b). In Switzerland, structural safety is evaluated based on the indicator of the degree of compliance n calculated using Equation (1). A value of n exceeding 1.0 means that structural safety is ensured and that there is reserve capacity (Swiss Society of Engineers and Architects, 2011). This generic metric has the advantage that it can be applied to any structural verification for ultimate limit states (ULS), fatigue limit states (FLS), and service limit states (SLS). Analytical or numerical models are required to compute structural capacity and load effects. Typically, several structural verifications are made for each limit state.

$$n = Capacity/Demand \tag{1}$$

SPM aims to update the evaluations of the degrees of compliance using field measurements. Several monitoring techniques are possible for this task, such as non-destructive tests (NDT) (Helal et al., 2015), bridge load testing using static and/or dynamic excitations (Brownjohn et al., 2011), and continuous monitoring to measure the real bridge condition (i.e., through a bridge weight in motion process) (Lydon et al., 2016). Evaluation of structural behavior based on monitoring data may require an inverse analysis (Pasquier & Smith, 2016). Sensor data do not directly support the structural-property evaluation, meaning that the data interpretation is complex (Catbas et al., 2013). Conventional residual-minimization approaches have provided unsafe parameter estimates and population-based methodologies (i.e., Bayesian model updating, error-domain model-falsification) are recommended (Pai & Smith, 2022).

The choice of the monitoring system significantly influences the success of SPM (Ercan & Papadimitriou, 2021). Studies have developed strategies to predict the information gain of monitoring systems, for instance, based on information entropy (Bertola et al., 2017; Papadimitriou, 2004). Recently, efforts have been made to quantify the value of information by comparing maintenance intervention with and without including expected information gain (Bertola et al., 2020; Kamariotis et al., 2022). Nonetheless, the first choice of engineers is to select the appropriate monitoring techniques rather than sensor configuration. This paper proposes a methodology to evaluate the usefulness of several monitoring systems in terms of their potential influence on the degrees-of-compliance evaluations.

2 METHODOLOGY

In this section, the methodology to predict the benefit of monitoring data on the evaluation of bridge structural capacity. This methodology is shown in Figure 1 and involves four main phases.

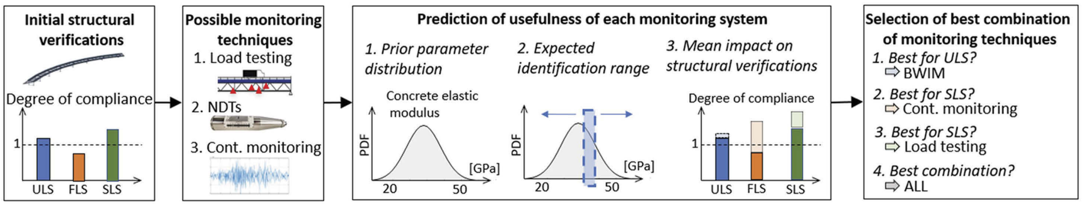

Figure 1. Methodology predicting the usefulness of monitoring techniques for structural-performance evaluation.

The first phase involves evaluating structural performance without monitoring information. After a visual inspection, the main structural characteristics (i.e., material properties) and load levels are estimated. These estimations are based on recorded information (such as structural drawings) and conservative bridge-parameter values on missing information.

Several structural verifications are made for serviceability, fatigue, and ultimate limit states. The results are expressed in terms of degrees of compliance (Equation 1). Typically, a finite-element model is built to improve the accuracy of structural verifications. At this stage, the first evaluation of bridge potential deficiencies is made, and potential uncertainties on the structural behavior are assessed.

The second stage involves defining the potential monitoring techniques that could be applied. Estimations of sensor types, the number of devices, and the duration of monitoring are made. Additionally, it must be evaluated which bridge parameters can be more precisely estimated using monitoring data from each technique.

The third stage involves assessing the usefulness of each monitoring technique independently and is performed using three steps. First, the prior distribution of each bridge parameter (i.e., material properties, boundary conditions, load levels) is estimated. Then, based on monitoring-technique accuracy, the expected identification range is defined. The identification range may sometimes be complex to estimate, especially when monitoring involves updating multiple parameters using inverse analysis. Nonetheless, studies on sensor placement have shown that it is possible to predict expected parameter ranges after monitoring (Bertola et al., 2017, 2020). As measurements are unpredictable, this step only involves defining possible ranges of parameter identification rather than a predicted value. For instance, bridge load testing will enable the identification of the bridge girder stiffness from which concrete elastic modulus with a precision range of 5 GPa, called the identification range. Let's assumed that the elastic modulus has an expected value defined between 20 and 50 GPa with a mean value of 35 GPa. Expected parameter values after monitoring are evaluated based on the most conservative value when centering the identification range on the mean value of the prior distribution. In the previous, the expected identification value is equal to 35 - 5/2 = 32.5 *GPa*. The third step is to reevaluate the degrees of compliance based on expected identification values for each monitoring technique. It may happen that the reevaluations of the degrees of compliance may not vary if the parameter is not influencing the structural verification. In this example, the elastic modulus will have influence on the SLS verifications but no impacts on the ULS verifications. Each method may provide information on a subset of bridge parameters, and the expected influence on structural verification can vary significantly.

The last step is selecting the appropriate combination of monitoring techniques that maximize the information gain for all limit states. As each monitoring technique provides different information, the best technique will often differ between structural verifications of limit states. A combination of monitoring techniques is thus often recommended to maximize the information gain. Another strategy would be to pick only monitoring techniques that may significantly influence structural verifications with a degree of compliance smaller than 1.0.

3 CASE STUDY

3.1 *Bridge presentation*

In this section, the methodology proposed in Section 2 is implemented on a full-scale case study in Switzerland. This eight-span viaduct was built in 1959 is an eight-span viaduct (Figure 2) and is one of the first steel-concrete composite bridges built in Switzerland. The superstructure involves a reinforced concrete (RC) slab fixed to two steel box girders. The spans vary between 12 and 25.6 m, and the bridge width is 12.7 m. The RC slab has a varying thickness between 0.17 and 0.24 m, while the two steel girders have a constant height of 1.30 m. The structure was subject to an intervention in 2002, where longitudinal stiffeners on the steel girders and bolts at the Gerber joints between the spans were added.

3.2 *Monitoring systems*

This bridge was monitored between 2016 and 2019. Strain gauges and thermocouples were installed to monitor traffic effects and temperature variations directly on rebars in both longitudinal and transverse directions with potential fatigue issues (see Section 3.3). These sensors were also used for bridge weight-in-motion and calibrated using load tests. Several static load tests were performed on the fourth span in 2016. The sensor network during these tests involved five LVDTs at mid-span, and five strain gauges both in the transverse and longitudinal directions near midspan were mounted (Bayane et al., 2021). Two non-destructive tests were performed: rebound hammer and sound-velocity measurements on the RC slab on the same span.

Figure 2. Composite steel-concrete bridge case study in Switzerland and the finite-element model.

3.3 *Prior evaluation of bridge capacity*

The bridge performance before monitoring was assessed following the rules given in Swiss standards for existing structures (Brühwiler et al., 2012), using construction and intervention drawings, and visual inspections. A numerical model was built using SCIA software, and the model involves 1D and 2D elements. The entire bridge is modeled (including bride piers) to improve the accuracy of the predictions at the monitored span (Figure 2). The bridge deck geometry has been modeled accurately, especially the complex shape of the RC slab. The size of the finite elements is set to 400 mm, except for the monitored span, where it is reduced to 100 mm to improve the quality of the predictions.

Several structural verifications have been made: 13 for ULS, 10 for FLS, and 2 for SLS. Of these 25 structural verifications, only two have degrees of compliance smaller than 1.0, and both involve FLS on longitudinal and transverse rebars in the RC deck (Figure 4).

3.4 *Expected information gain*

3.4.1 *Step 1 – Prior distribution and potential information gain*

In this section, the usefulness of information gain is made. First, the main bridge parameters that can be identified using the three monitoring techniques (bridge load testing, B-WIM, and continuous monitoring) are defined. These parameters involved: the deck stiffness (approximated as the elastic modulus of concrete), the rotational stiffness at the Gerber joints, the daily maximum stress differences in rebars due to traffic loading, the ULS load level (in terms of maximum axle force), and the concrete compressive strength. The prior distribution of each distribution is shown in Figure 3. Value ranges and distributions of these parameters are selected based on engineering judgment.

Figure 2 also qualitatively presents the potential information gain of each monitoring technique on these parameters. Rebound hammer and sound-velocity measurements provide information on the uncracked elastic modulus and compressive strength of concrete. Static load testing helps update concrete elastic moduli and the rotational stiffness at boundary conditions, but these estimates may not be precise enough to provide reliable safety verifications. The continuous monitoring provides accurate estimations of maximum stress differences necessary for fatigue safety verification, while B-WIM helps to define more accurate load models for ULS. These monitoring techniques thus provide complementary information.

3.4.2 *Step 2 – precision of monitoring output*

The second step involves estimating the precision of monitoring outputs. For each parameter that can be updated by a monitoring technique, an identification range is estimated (Table 1). For NDTs, these identification ranges mostly depend on the sensor precision and the number of tests performed. The continuous monitoring and B-WIM have precisely measured the traffic on the bridge for three years. Nonetheless, these techniques require estimating tails of distributions to

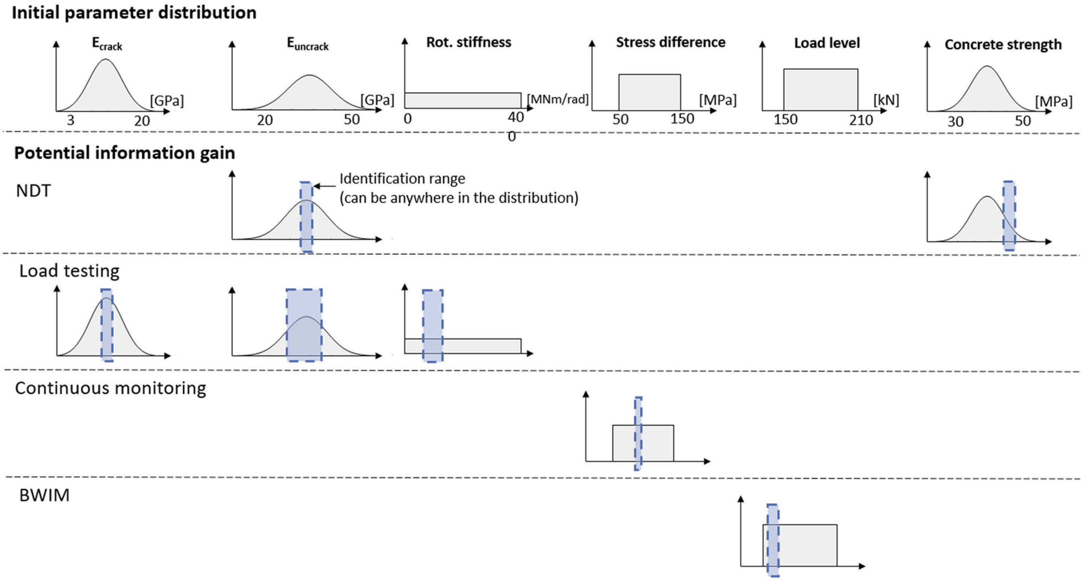

Figure 3. Prior bridge-parameter distributions and potential information gain of each monitoring technique on these parameter distributions.

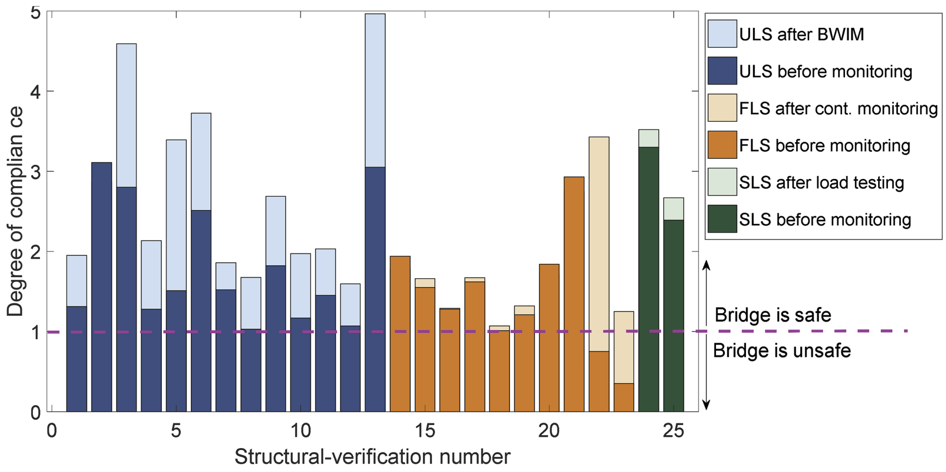

Figure 4. Degrees of compliance prior to and after monitoring for each structural verification.

define accurate evaluations of maximal stress differences and axle load levels which may have some extrapolation errors. Bridge load testing provides simultaneous information on three bridge parameters based on an inverse analysis. The precision of identification ranges is determined using the hierarchical algorithm based on the sensor configuration and performed load test. More information on this information gain can be found in (Bertola et al., 2022).

3.4.3 *Step 3 – Influence on degrees of compliance*

Based on the results in Steps 2 and 3, the expected values used for structural verification after monitoring are obtained. These values are calculated as the mean value in the prior distribution (Figure 1) minus half of the precision range (Table 1), and the results are shown in Table 2. Each monitoring technique helps increase a subset of bridge parameter values.

For each monitoring technique, the influence of expected monitoring outputs on the degrees of compliance is evaluated (Table 3). Except for the NDT (only updating and E_{ncr}), all monitoring techniques provide useful information for the bridge structural verifications. Nonetheless, only load testing provides useful information for SLS verifications, while FLS verifications are mostly influenced by continuous monitoring and ULS verifications by the BWIM data. When all techniques are combined, an average increase of degrees of compliance of 19 % over the 25 structural verifications is obtained, showing that monitoring can provide

Table 1. Estimates of value-range identification for each parameter and each monitoring technique.

Bridge parameter	Precision of identification range of monitoring technique			
	NDT	Load testing	Cont. Monitoring	B-WIM
Cracked RC section E_{cr} [GPa]	-	6	-	-
Uncracked RC section E_{ncr} [GPa]	5	15	-	-
Rot. Stiffness [MNm/rad]	-	100	-	-
Stress difference [MPa]	-	-	2	-
Load level [kN]	-	-	-	5
Concrete strength [MPa]	2	-	-	-

Table 2. Expected parameter values obtained after monitoring.

Bridge parameter	Mean expected values after monitoring			
	NDT	Load testing	Cont. Monitoring	BWIM
Cracked RC section E_{crack} [GPa]	6	10	6	6
Uncracked RC section E_{ncr} [GPa]	30	28	20	20
Rot. Stiffness [MNm/rad]	0	100	0	0
Stress difference in steel rebar [MPa]	150	150	73	150
Maximum axle load [kN]	210	210	180	210
Concrete compressive strength [MPa]	38	30	30	30

significant information for bridge performance evaluation. Nonetheless, in a value of information perspective (only measuring when it can change the safety assessment of the bridge), only the continuous monitoring is justified.

Table 3. Expected influence of monitoring information on structural-verification degrees of compliance.

Structural verification	Mean degrees of compliance before monitoring	Expected mean degrees of compliance after monitoring				
		NDT	Load testing	Cont. Monitoring	BWIM	Combined
SLS	2.84	2.91 (+3%)	3.23 (+14%)	2.84 (+0%)	2.84 (+0%)	3.23 (+14%)
FLS	1.45	1.45 (+0%)	1.45 (+0%)	1.76 (+21%)	1.45 (+0%)	1.76 (+21%)
ULS	1.82	1.88 (+2%)	1.82 (+0%)	1.82 (+0%)	2.12 (17%)	2.1 (+18%)
Combined	1.75	1.79 (+2%)	1.79 (+2%)	1.88 (+7%)	1.91 (+9%)	2.08 (+19%)

3.5 *Result validation*

In this Section, predictions in terms of monitoring usefulness are compared to observed information gain based on field measurements. Details of the data interpretation and evaluations of degrees of compliance after monitoring can be found in (Bertola et al., 2022).

In the previous section, it was concluded that each monitoring technique (except NDT) provides useful information, and their combination should improve degrees of compliance by a mean average of 19 %. The results of the information gain after monitoring are shown in Figure 4. On average, the monitoring data increases degrees of compliance by 36 %. As predictions were evaluated as mean values, both prediction and observed results can be evaluated as similar.

It is also worth looking at information-gain predictions in terms of the performance of each monitoring technique individually. For SLS verifications, it was predicted that the most useful technique is static load testing, and this result is validated by field measurement. The prediction for ULS verifications showed that only the B-WIM could provide significant information, and this result is also validated by field measurements. Continuous monitoring is the most useful monitoring technique for FLS verifications, and this prediction is verified using monitoring data. These results confirm that the proposed methodology can provide accurate estimations of the usefulness of monitoring techniques.

Thanks to monitoring data, the bridge safety is now verified as FLS verifications that had a degree of compliance smaller than one has updated values larger than 1.0. This result confirms that structural performance monitoring can lead to untap reserve capacity of bridges.

4 CONCLUSIONS

In this study, a methodology is provided to estimate the usefulness of serval monitoring techniques for bridge performance evaluations. This methodology supports engineers and bridge owners by selecting the optimal combination of monitoring techniques to maximize the information gain in terms of increasing the metric for structural-safety assessments. A bridge case study in Switzerland, where four monitoring techniques were performed, showed that most monitoring techniques provide useful and unique information. Additionally, the predictions in terms of expected information gain for each technique and their combinations are in agreement with results based on monitoring data. In the next step, this methodology will be extended for a comprehensive value-of-information framework to select the optimal combination of monitoring techniques.

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