Determining the structural properties of concrete bridges through the combination of static and dynamic load testing

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Abstract. Examining structural safety requires assumptions regarding several properties of the bridge structure, such as the material properties, boundary conditions, and self-weight. The traditional approach is to assume conservative values for each bridge property, following the conventional new-design philosophy. Nonetheless, this approach leads to conservative evaluations of bridge capacity and may lead to the inaccurate conclusion that the structure is deficient. Over-conservative in structural safety assessments has large negative environmental and economic impacts on global infrastructure management. Another approach is to conduct multiple tests and monitoring activities on the structural system to determine the values of these bridge properties more accurately. This paper presents a methodology to determine several parameters, including the structural stiffness, the boundary conditions, and the self-weight of concrete bridges based on data from static and dynamic load testing. The methodology is used on a prestressed concrete bridge in Switzerland. This bridge from 1958 has a single span of 35 meters and has been significantly strengthened and widened in 2023. By accurately identifying the self-weight, this study shows the potential of bridge monitoring for a more sustainable and economic infrastructure management.
Keywords: Bridge load testing, Structural identification, Existing bridges, Structural health monitoring; Fiber optic sensor.

1. Introduction

Most bridges in many countries like Switzerland have been built after the Second World War and are approaching, according to today's understanding, their theoretical end of service duration. Replacing all these structures will have significant environmental and economic impacts [1], so it is necessary to accurately assess their structural capacity to prioritize infrastructure maintenance[2]. In practice, civil-infrastructure management is mostly based on subjective visual inspection [3]; novel data-informed frameworks are needed for accurate structural performance evaluation.

Significant research efforts have been made to develop structural health monitoring systems that detect and quantify damage on structures [4]. Nonetheless, these methods mostly detect local loss of rigidity in the structure (for instance, due to concrete cracking), but it does not mean that structural integrity (mostly governed by steel reinforcement) is affected [5].

Another approach is to use sensor data on bridges to re-evaluate the structural properties [6]. Methodologies involve detecting structural rigidity and boundary conditions through load testing [7], identifying long-term prestressed losses [8], or identifying live load levels on the bridge through bridge weigh-in-motion [9], or a combination of these methods [10]. These methods have allowed to uncover significant reserve capacity in numerous case studies [11].

Nonetheless, one aspect that has often been neglected in updating bridge properties, is the potential of updating the bridge self-weight. For concrete bridges, it is common that the self-weight represents around 70% of the total loads on the structure. The precise identification of the bridge weight enables the reduction of the safety factor on the bridge self-weight. However, precisely identifying the bridge self-weight can be challenging as this structural property can only be identified through inverse analyses from dynamic excitation. Moreover, this inverse analysis is also affected by other bridge parameters, such as the structural rigidity and boundary conditions that are typically also imprecisely defined.

In this study, a methodology to precisely identify the self-weight is proposed. This methodology combines both static and dynamic load testing, as well as multiple sensing technologies (accelerometers, deflection sensors, and fiber optics), to obtain precise self-weight estimation on the bridge. This new information allows the discovery of untapped reserve capacity in the structure, especially for ultimate limit states.

2. Methodology to identify bridge self-weight

The methodology to identify the bridge self-weight is shown in **Fig. 1** through the combination of static and dynamic load testing. First, the structural model is generated. Three-dimensional finite-element models are recommended to improve the precision of structural-behavior predictions. Non-structural elements should also be included in the analysis as they influence the structural stiffness under service conditions. Parameters that have the largest influence on structural behavior (boundary conditions, concrete elastic modulus, …) are selected. Uncertainties from remaining parameters are estimated (such as secondary parameters, model simplification, mesh size).

Then, static and dynamic load tests are performed on the structure. The boundary conditions are first updated through the deformation shape. This deformation shape can be measured through linearly-continuous monitoring systems, such as fiber optics. Another option is to perform local measurements at supports. Next, the stiffness of the structure is obtained through model calibration using static measurements (such as deflection, deformation, inclination) and previously achieved boundary-condition identifications. Finally, the self-weight is identified through model calibration using dynamic properties, like the natural frequency, of the bridge given the previously identified values of bridge stiffness and boundary condition.

As it is impossible to estimate precisely the boundary-condition and rigidity values due to remaining uncertainties and measurement errors, it is crucial to account for the propagation of uncertainties through the identification process. These uncertainties lead to the definition of the updated safety factor for the bridge self-weight.

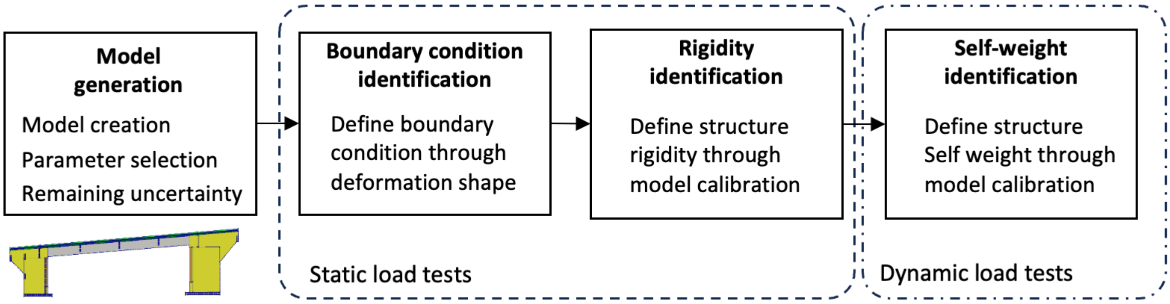

Fig. 1. Methodology to identify bridge self-weight combining static and dynamic load testing.

3. Case study

3.1 Bridge presentation

The Ferpècle Bridge is a prestressed reinforced concrete structure with a double-girder cross-section located in the Swiss Alps at an altitude of 1450 meters. The bridge was built in 1958 and needed to be widened in 2023. The initial static system is a simply-supported beam with a 34.5-meter span, resting on abutments with side walls approximately 7 meters high (**Fig. 2**). With a beam height of 1.75 meters, the slenderness of 1/20 is audacious for a simply-supported beam structure.

An intervention has been performed with UHFPFRC in 2023 to widen the deck from 5.3 to 7.9 meters. The intervention consisted of a cantilevered UHPFRC full slab with a variable thickness. Moreover, the abutments have been clamped to the superstructure, modifying the static system and achieving a monolithic half-frame structure. The initial bending-moment deficit at mid span is thus redistributed to the supports, where the new layer of UHPFRC (70 mm with (ϕ22 @100 mm)) is used to create the necessary bending resistance.

With regard to material characterization, a C45/55 concrete grade (updated from the C30/37 defined at the construction stage) has been selected for the existing bridge concrete. The tensile strength of the reinforcing steel was accepted at $f_{sd} = 300\ MPa$. For prestressed bars, an ultimate strength of $f_{pd} = 730\ MPa$ was assumed.

Load levels are defined in the Swiss standards for existing structures SIA 269 [12]. Action effects due to the loads are presented in characteristic values in **Table 1**. The self-weight of the bridge creates the largest bending moment on the structure. Thus, reducing the self-weight safety factor has a large impact on structural safety evaluations.

Table 1. Action effects of loads.

Load	Bending moment (characteristic value) [kNm]	Relative part (%)
Self-weight	14500	60
Live loads (distributed)	5900	25
Life loads (concentrated)	3600	15

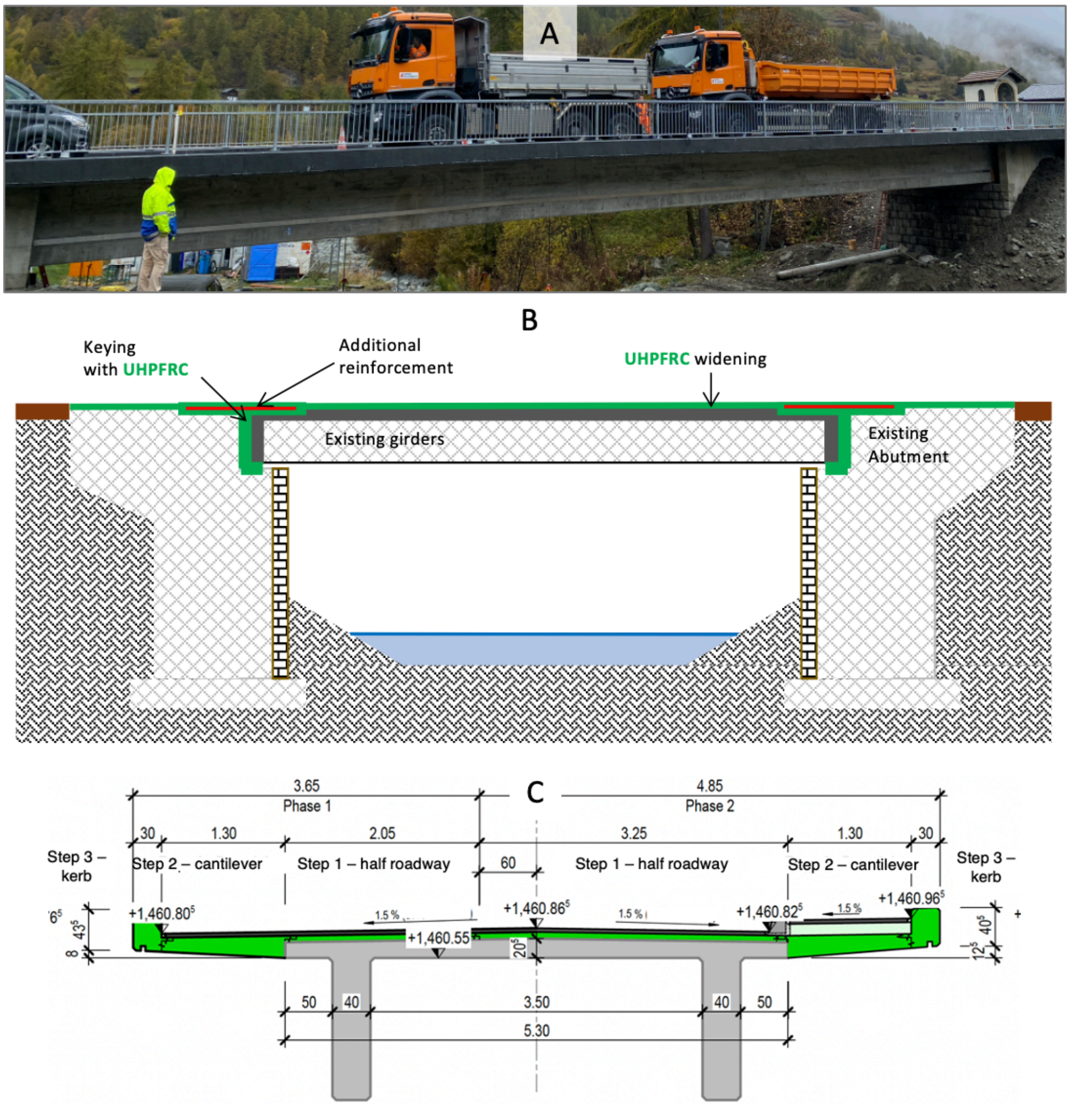

Fig. 2 Presentation of the bridge. A) Photograph of the bridge during load test; B) Longitudinal view of the intervention; C) Cross-section of the intervention.

To validate the structural intervention, a numerical model of the structure has been built using the DIANA software (**Fig. 3**). The model involves shell elements, and all reinforcement bars and prestressed tendons have been explicitly included. To increase the accuracy of the model prediction, non-structural elements (pedestrian ways, curbs) have been added to the model. Moreover, the abutments have also been modelled to accurately replicate the complex structural system. The tensile strain-hardening behaviour of the UHPFRC has also been precisely modelled. Precise constitutive laws of concrete and steel properties are considered. The structural safety is assessed through non-linear analyses to account for stress redistribution in the structure. Predictions of structural behaviour during load tests are made through linear analysis, as materials are expected to remain in the elastic domain under the test loads.

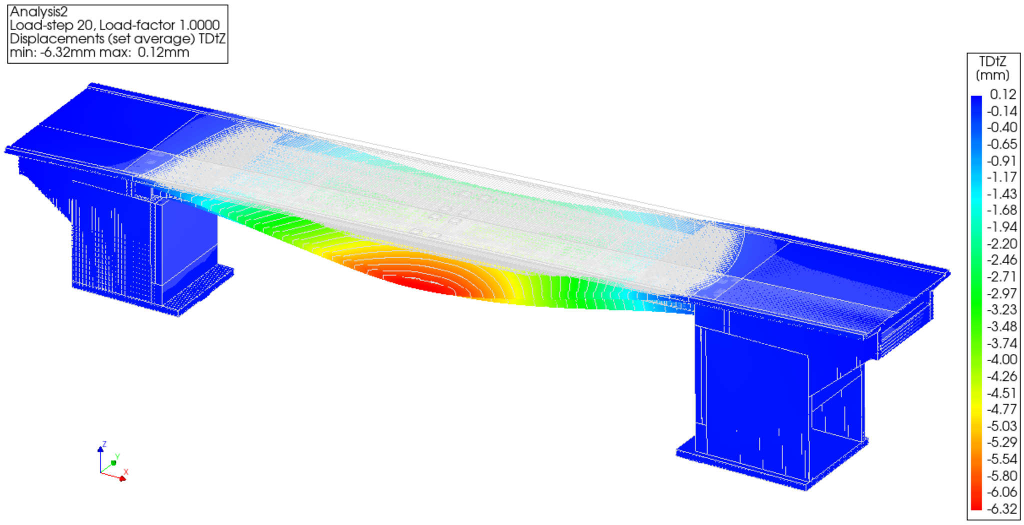

Fig. 3. 3D finite-element model of the structure built with shell elements in DIANA software, and model predictions during static load tests. The deformed model is due to the load case of ..??..

3.2 Monitoring campaign

Static and dynamic load tests were performed on the 31st of October 2023. Static load tests consisted of two trucks of 26 tons placed at multiple locations, while the dynamic load tests involved exciting the bridge with a moving truck. In this study, only the most unfavourable static load test, which consisted of placing the two trucks next to each other at midspan, is considered.

The monitoring system involves 6 LVDT sensors, two continuous fiber optics running throughout the entire bridge span (approximately 12'000 measurement points for each fiber), and 9 accelerometers. The sensor locations and load test configuration are shown in **Fig. 4**. It is important to note that the monitoring campaign occurred prior to casting the asphalt layer.

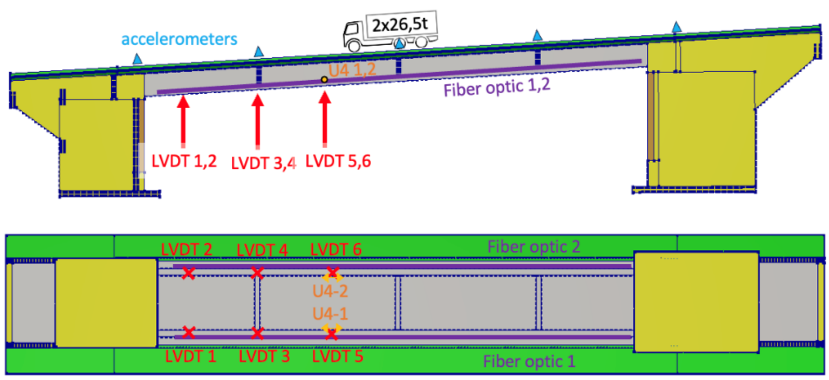

Fig. 4. Sensor network installed on the bridge.

3.3 Updating boundary conditions using fiber optic measurements

The first step of the methodology involves the identification of the boundary conditions based on distributed monitoring. In this study, the fiber-optic measurements are used to define whether the clamping of the boundary conditions during the intervention led to a fixed beam during service conditions as designed.

A strain analyses of theoretical fixed and simply supported beams under the static loads (2x3 axles for a total of 53 tons placed at midspan of the bridge) are made without accounting for the beam rigidity (**Fig. 5**). These theoretical deformations are compared to the fiber-optic measurements throughout the beam length as well as finite-element model prediction.

The fiber-optic measurements demonstrate that the bridge behaves like a fixed beam during the static load tests. Fixed boundary conditions are thus considered in subsequent analysis. Moreover, the comparison between field measurements and finite-element model predictions shows an uncertainty of 6 % at midspan. This uncertainty will be considered when defining the safety factor of the updated self-weight.

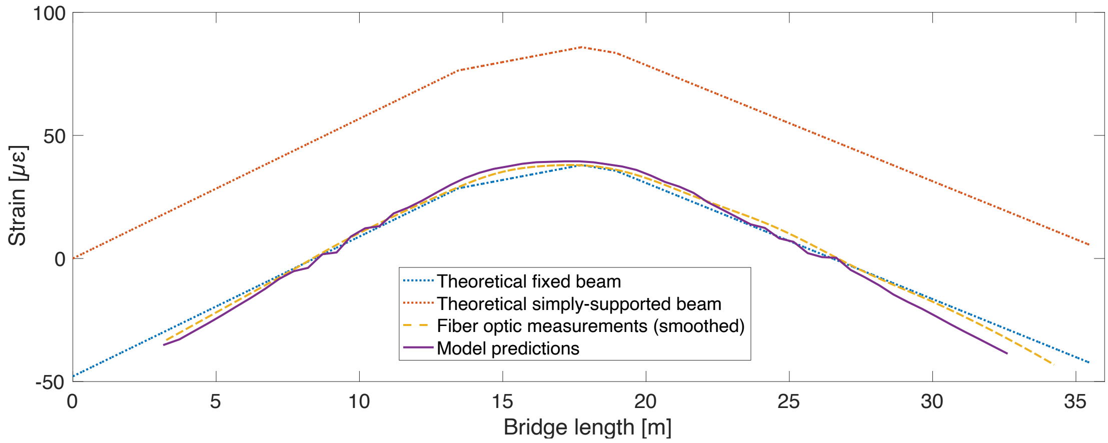

Fig. 5. Identification of boundary condition using fiber optic measurements

3.4 Updating rigidity through static load testing

The first step consists of updating the boundary condition and rigidity properties of the bridge based on the static measurements. Based on a sensitivity analysis, two main parameters have been shown to influence the deflection and strain predictions of the numerical model: the elastic modulus of prestressed concrete and the elastic modulus of UHFPRC. The connection between the bridge superstructure and the abutment is assumed to be perfectly monolithic. The remaining parameters, such as the elastic modulus of the concrete for pedestrian sidewalks, is estimated to impact predictions by less than 1%. The mesh size has also been reduced within the limits of computational efficiency to minimize its impact on the model prediction (estimated to affect the predictions by less than 1%).

After model calibration based on LVDT sensor measurements, the elastic modulus of concrete is estimated to be 40 GPa, while the UHPFRC elastic modulus is equal to 45 GPa. The discrepancies between predictions and measurements range from 1.5 to 9.2 %, with an average value of 5.0 % (**Table 2**).

Table 2. LVDT measurements and calibrated model predictions.

	LVDT 1	**LVDT 2**	**LVDT 3**	**LVDT 4**	**LVDT 5**	**LVDT 6**
Unit	mm	mm	mm	mm	mm	mm
Measurements	0.365	0.228	2.28	1.37	3.44	2.06
Predictions	0.34	0.24	2.07	1.35	3.37	2.17
Difference [%]	6.85	-5.26	9.21	1.46	2.03	-5.34

3.5 Updating bridge self-weight

Once the bridge stiffness and boundary conditions are updated, the equivalent density of the concrete can be updated. The range of the equivalent density is taken to be relatively large (between 2000 and 2900 kg/m^3) to implicitly account for potential differences in element sizes (such as thickness of the deck, girder width). For this analysis, it is assumed that the UHPFRC density ρ_U is equal to 2600 kg/m^3.

The dynamic tests consisted in using a truck (26,5 tons) running over the bridge as well as ambient vibration monitoring. Predictions and natural-frequency measurements based on the dynamic tests show a discrepancy between typical concrete density (2300 to 2500 kg/m^3) within the 5-% threshold ranges around the measured value. This result demonstrates that the equivalent density of concrete is close to the expected value. The discrepancy between measured and predicted values for ρ_c equal to 2400 is about 3.3 %. Moreover, an analysis including conventional safety factors (i.e., 1.2 for existing concrete and 1.35 for new UHPFRC) for concrete and UHPFRC shows that the natural frequency would be about 20 % lower, which is not plausible given the monitoring results.

The safety factor on the bridge self-weight is now evaluated by combining the three monitoring discrepancies using the Euclidian distance, Equation (1). The obtained value is then multiplied by a factor $\gamma_{g,2}$ equal to 1.05 (Equation 2) to account for uncertainty in the calculation between self-weight action and action effects in structural-analysis model [13]. The γ_g obtained is equal to $\gamma_g = 1.14$. This value is then taken to update structural verifications.

$$\gamma_{g,1} = \left(1 + \sqrt{\textstyle\sum_i^3 r_i^2}\right) \quad (1)$$

$$\gamma_g = \gamma_{g,1} * \gamma_{g,2} \quad (2)$$

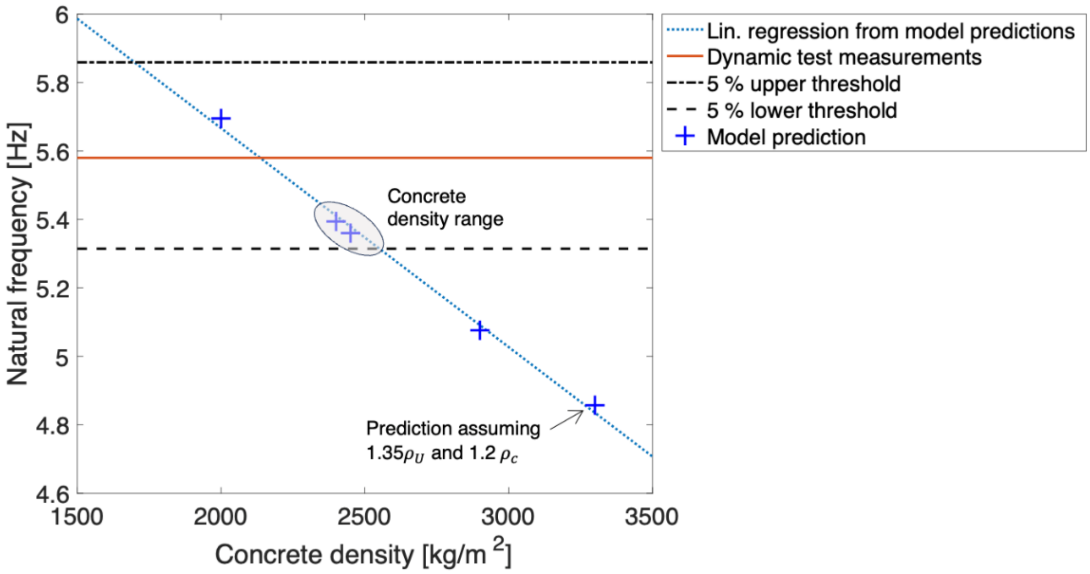

Fig. 6. Comparison of model predictions and natural-frequency measurements.

3.6 Impacts on structural verifications

Structural safety is evaluated based on the concept of the degree of compliance n [14] using design values of both structural resistance R_d and action effects E_d (Equation 3). The structural safety is evaluated based on the two most critical verifications at ultimate limit states: the bending moment at support and the shear on the girders. The impact of the model updating on the degrees of compliance with structural verifications is shown in **Table 3**. For both structural verifications, the increase in the degree of compliance is significant, especially for the bending verifications. This result demonstrates the potential of the proposed methodology to discover untap reserve of capacity in concrete bridges.

$$n = Capacity/Demand = \frac{R_d}{E_d} \quad (3)$$

Table 3. Structural safety evaluation prior to and after self-weight model updating.

	Bending moment	**Shear**
Prior self-weight updating	1.02	1.29
After model updating	1.14	1.35
Difference [%]	+11.7	+ 3.9

4. Conclusions

This study emphasises the importance of the self-weight in the examination of concrete bridges. Action effects due to the bridge structure self-weight are usually significantly larger than the ones of live loads. Updating the load factor and the self-weight is thus a promising solution to unlock an untapped reserve of capacities for ultimate limit states. A 3-step procedure is proposed that combines information from fiber-optic sensors, static and dynamic load tests to update bridge self-weight as well as the associated load factors. The methodology has been applied to the Ferpècle Bridge in Switzerland, which has been strengthened in 2023. Thanks to the proposed methodology, an additional 11,7 % of reserve capacity in bending is revealed, which could be significant in upcoming examinations of the bridge, for instance, if live loads increase in the future. The proposed methodology supports engineers and bridge owners for more sustainable management of existing concrete bridges.

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