Concrete bridge monitoring through spatially distributed fibre optic sensing

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Abstract

Understanding the behaviour of existing concrete bridges is difficult due to the complex structural systems, the evolution of material properties, and sometimes undocumented construction processes. Collecting monitoring information has been a useful tool to update knowledge on structural behaviour. Recent breakthroughs in the development of fibre optic sensing allow for continuous strain monitoring throughout the bridge length, leading to a spatially distributed monitoring system. This paper presents the application of this technology for the structural identification of local (i.e., cracks) and global (i.e., load distribution between girders) bridge behaviour on a full-scale prestressed concrete bridge from 1958 in Switzerland.

1 Introduction

Many countries are experiencing deteriorating bridge networks, while traffic demand is increasing. Due to large constraints on the infrastructure management budget, as well as potential impacts on users, it is crucial to determine structural safety accurately to optimize infrastructure management.

One key issue is that engineering uses structural assessment methods developed for new designs that are not adapted for existing structures [1]. Another challenge is the subjectivity and inaccuracy of visual inspection [2]. To improve decisions regarding bridge safety, researchers have developed data-informed methodologies, aiming either at detecting damage [3] or improving knowledge of the behavior of the existing structure [4]. For instance, structural-performance monitoring frameworks aim to leverage field-measurement information to reveal untapped reserves of load-bearing capacities in existing structures [5].

The choice of the appropriate monitoring systems is nonetheless crucial to reveal a reserve of capacity [6]. Strain measurements have been a popular monitoring technique since the 1950s due to the cheap and robust strain gauge devices [7]. More recently, fiber optic sensors (FOS) have allowed for distributed strain monitoring over long distances with high spatial resolution [8] despite higher data monitoring costs. Recently, a breakthrough in sensor development has enabled low-gage pitch up to 1 mm [9], allowing for crack detection through local strain spikes (Fig. 1).

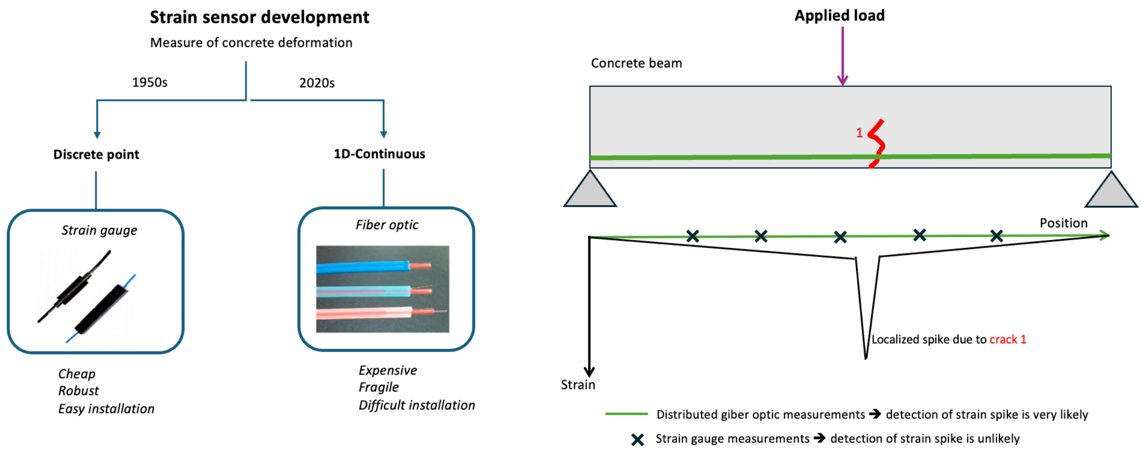

Fig. 1 Distributed fiber optic sensors vs conventional strain gauge for concrete-structure monitoring.

Distributed fiber optic sensors (DFOS) enable the collection of novel information on structural behavior, leading to a new understanding of concrete structural performance [10]. For instance, these spatially-distributed strain datasets, allow for accurate crack detection in concrete elements [11]. A new framework has been recently introduced to leverage DFOS datasets during static load tests for global structural behavior understanding, such as the evaluation of the load distribution between girders, the boundary conditions and the extrapolation of the bridge deflection accurately [12].

This paper presents an overview of the potential of DFOS for concrete bridge monitoring. Through DFOS datasets acquired during static load testing on a full-scale prestressed concrete bridge, local and global behavior of the concrete structure can be understood. This information gain is compared to conventional strain gauge measurements as well as information provided by the finite-element model. This study demonstrates the large potential of the recent DFOS monitoring technique to provide a comprehensive information gain on structural behavior, allowing for the accurate evaluation of structural capacity.

2 Structural performance monitoring with distributed fiber optic sensors

2.1 Bridge presentation

The Ferpècle Bridge is located in Les Haudères (Switzerland). The structure has a single span of about 35 meters. The structure is made of two prestressed concrete girders with a height of 1.5 meters. The bridge was built in 1958, and the deck was widened from 5.3 to 7.9 meters in 2023 using ultra-high-performance fiber-reinforced cementitious composite (UHPFRC). The UHPFRC intervention involves clamping the boundary conditions between the superstructure and the abutments, leading to a change of static scheme [13]. This unique intervention enables a drastic increase in structural performance (rigidity, bending capacity, shear capacity) as well as an improvement of the bridge durability thanks to the low permeability of the UHPFRC.

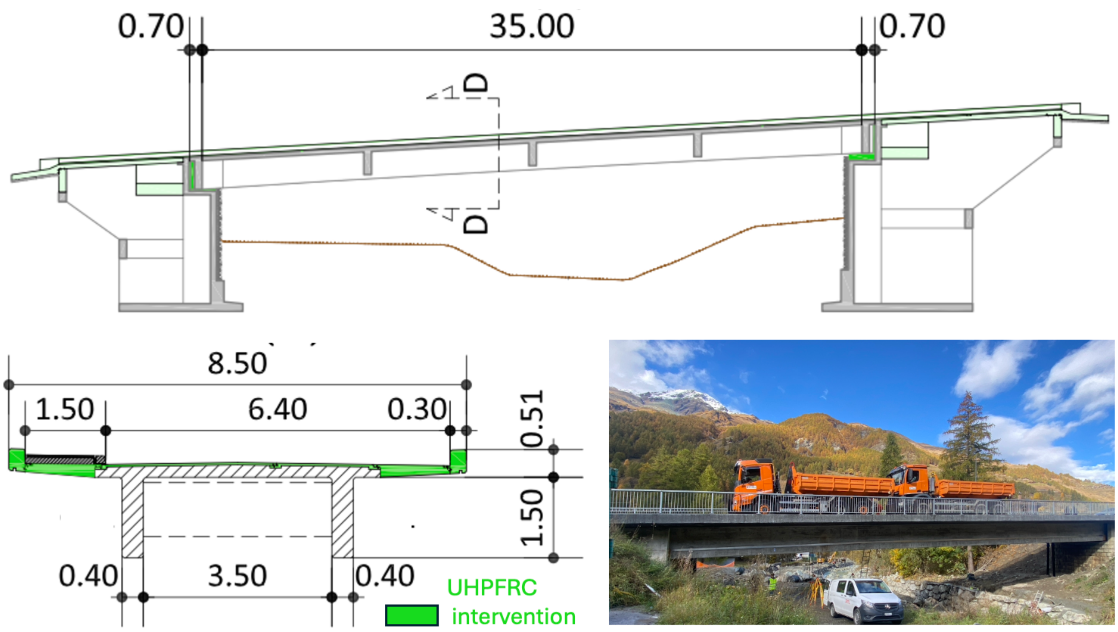

Fig. 2 Ferpècle bridge presentation. Top: Elevation. Bottom left: Cross section; Bottom right: Static load testing on the bridge.

2.2 Distributed fiber optic monitoring campaign

The intervention was realized in 2023, and the scaffolding for the widening was used to install DFOS throughout the span on both girders. The external web of each concrete girder was grooved in a notch of 6mm deep. The cables were then glued to the concrete surface, and a steel plate was placed to protect the fiber optics (SMARTEC-DiTeSt SMARTProfile Sensor [14]) to protect them from environmental ingress. The upstream girder is referred to as Channel 1 (CH1), while the downstream girder as Channel 2 (CH2). The interrogator is a LUNA data acquisition system (ODiSI 6100 [15]), which records strain measurements at a resolution of 2.6 millimeters. It means that approximately 12000 data points per girder at a rate up to 5 Hz.

5 static load tests, involving either one or two trucks of 26.5 tons were made in 2023. DFOS strain datasets thus involve the difference in strain created by the trucks on the bridge. 6 LVDT sensors were also installed to validate deflection predictions based on DFOS datasets acquired during the load tests. A typical strain dataset obtained during static load testing is shown in Fig. 2. It is possible to see the global girder behaviour, such as the fixed-static scheme (strain values are negative near supports and positive at midspan). Moreover, local strain spikes are observed that potentially correspond to concrete cracking. It demonstrates the versatility of the strain datasets acquired by DFOS sensors for bridge monitoring.

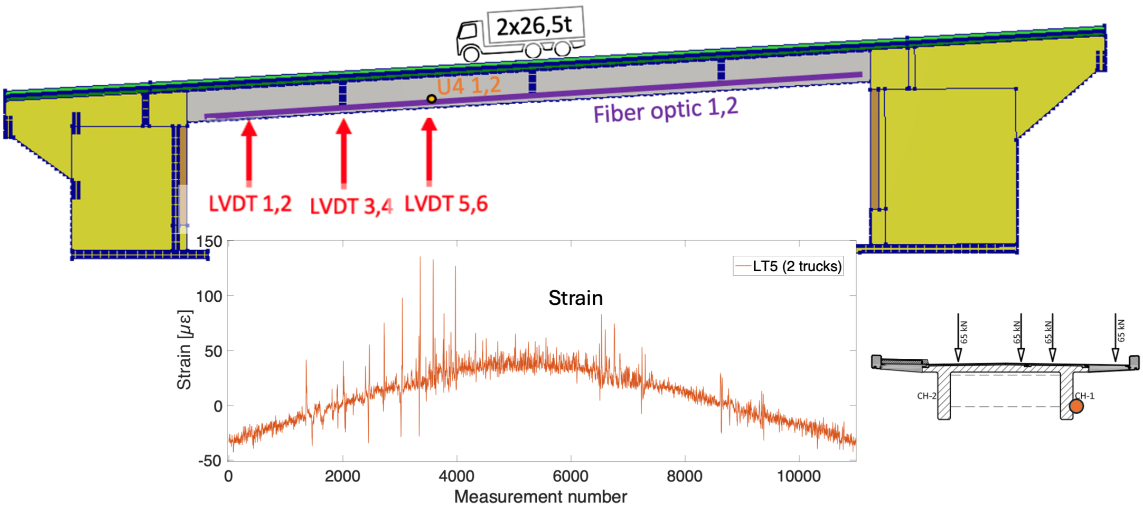

Fig. 2 Distributed fiber optic datasets collected during static load tests.

2.3 DFOS data interpretation

The strain measurements by the DFOS during load test 3 (LT3) are shown in Fig. 3. This load test involves two trucks placed on the same line, aiming at creating an asymmetric loading that maximizes the loads on the left girder (CH2).

Strain data show that CH2 has larger deformation. Moreover, the influence of cross beams is clearly shown at quarter-span and midspan locations. At these locations, the strain profile exhibits a local reduction of the deformation due to the local increase in rigidity. Such local effects are happening only over about 2-3 meters and they are usually not visible with strain gauge datasets unless a very dense sensor network is used.

If only a few strain gauges are used, such as midspan on each girder, the measurements will fall exactly in these strain local effects. In such situations, the engineers may thus underestimate the maximum strain on the structure as they may believe that these are the maximum strain values, although they occur not exactly at midspan.

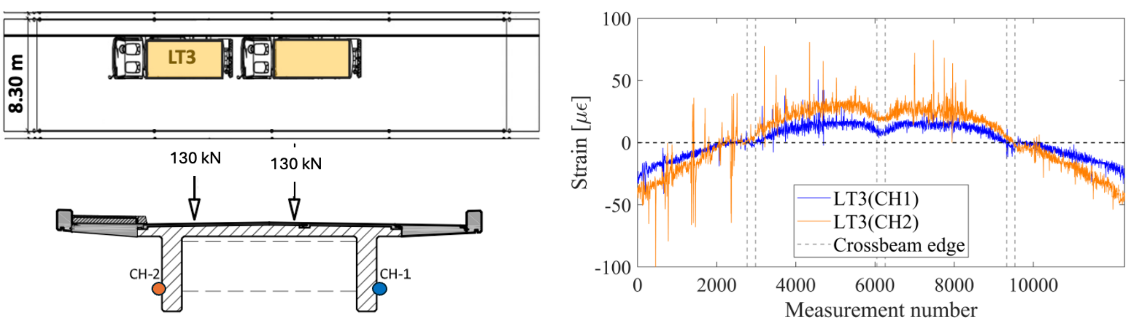

Fig. 3 DFOS data during LT3. left: Load test 3 (LT3) with truck position. Right: Strain profile acquired by DFOS channel 1 (CH-1) and Channel 2 (CH-2).

One expected information extracted from sensor data for structural performance monitoring (SPM) is the load distribution between girders. This information is crucial to evaluate the bending moments and shear in each girder accurately. Five monitoring scenarios are analyzed, each employing different values for calculating load distribution coefficients based on sensor data:

- Scenario 1 relies on strain data obtained from the DFOS. The ratio between CH1 and CH2 measurements
- Scenario 2 applies values derived from equilibrium equations based on classical beam theory (De Saint Venant) as would be done during bridge examination without monitoring data.
- Scenario 3 uses the discrete strain measurements at midspan as would do a discrete strain gauge at that location.
- Scenario 4 incorporates both mid-span and quarter-span strain data.
- Scenario 5 combines both mid-span and near-support measurements.

Results on load-distribution coefficients for all data-collection scenarios are shown in Fig. 4 (left), as well as the measured strain ratio by the DFOS. Values for scenarios 3 to 5 significantly differ from Scenarios 1 and 2 as they involve strain measurements that are affected by local effects. These scenarios lead to incorrect evaluations of maximum bending moments (Fig 4, right), either on the safe or unsafe side. Nonetheless, this discrepancy was particularly important for LT3, which is the load test the most influenced by these local effects. For more symmetrical load tests, “strain gauge” data (Scenarios 3-5) allows for relatively accurate evaluations of the load-distribution coefficient.

When comparing Scenario 1 and Scenario 2, the maximum bending moments are reduced by 7% in CH2, showing that DFOS datasets reveal that the load distribution between girders is more evenly distributed than using conservative design assumptions.

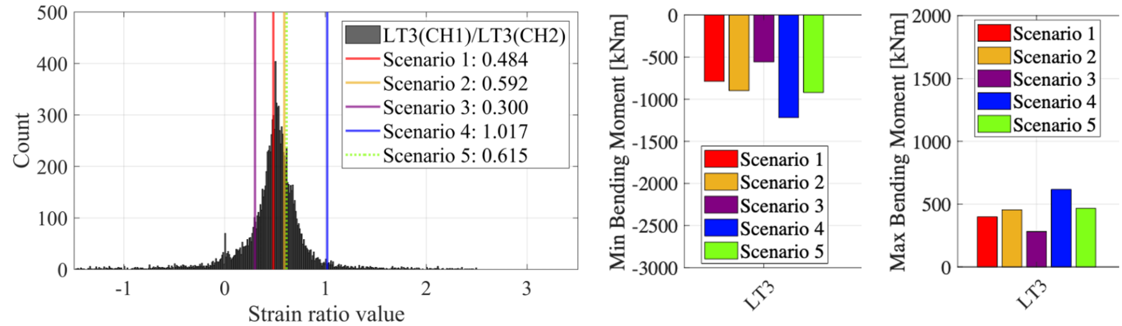

Fig. 4 Interpretation of DFOS data. left: Strain ratio between girders. Right: Extrapolation of bending moment at midspan and support.

It is possible to extrapolate the bridge deflection from DFOS datasets through the double integration of the strain profile, following the methodology presented in [12]. This extrapolation requires information gained on the load distribution between girders and boundary conditions as well as additional information such as structural rigidity. As this later parameter cannot be directly extracted from the DFOS datasets, a range of plausible values has been chosen for the structural rigidity. This range allows for estimating the envelope of bridge deflection. The best fit (defined across the five load tests) has been estimated by calibrating the rigidity with LVDT measurements. The mean discrepancy between best-fit predictions and LVDT measurements is 0.1 mm. The bridge deflection predictions based on DFOS can precisely match true measurements but require calibrating the rigidity.

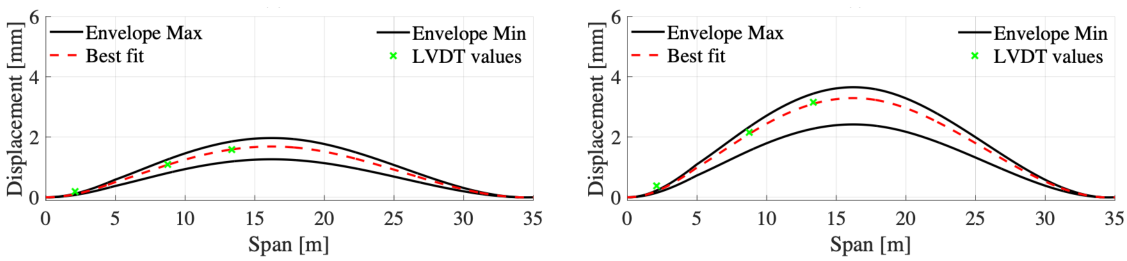

Fig. 5 Extrapolation of bridge deflection. Left: CH-1, Right: CH-2.

3 Numerical model prediction

In this section, the information gained by the DFOS is compared to strain gauge sensors and with the information provided by the numerical model. The 3D finite-element model (FEM) has been built in DIANA and all structural elements (passive reinforcement bars, prestressing bars, UHPFRC layer, curbs,…) have been modelled for both the superstructure and the abutments (Fig 6). For concrete and reinforcement steel, constitutive laws following FIB 2010 Model Code have been taken. The UHPFRC constitutive model has been created based on the Swiss standards for UHPFRC [16]. The mesh size is set to 50 cm for concrete elements and 5 cm for the UHPFFRC layer. Load tests have been precisely modelled to obtain the most accurate strain predictions possible. The model has shown closed agreement (discrepancy smaller than 5%) with LVDT and acceleration datasets collected during the load testing, and its rigidity calibrated [13].

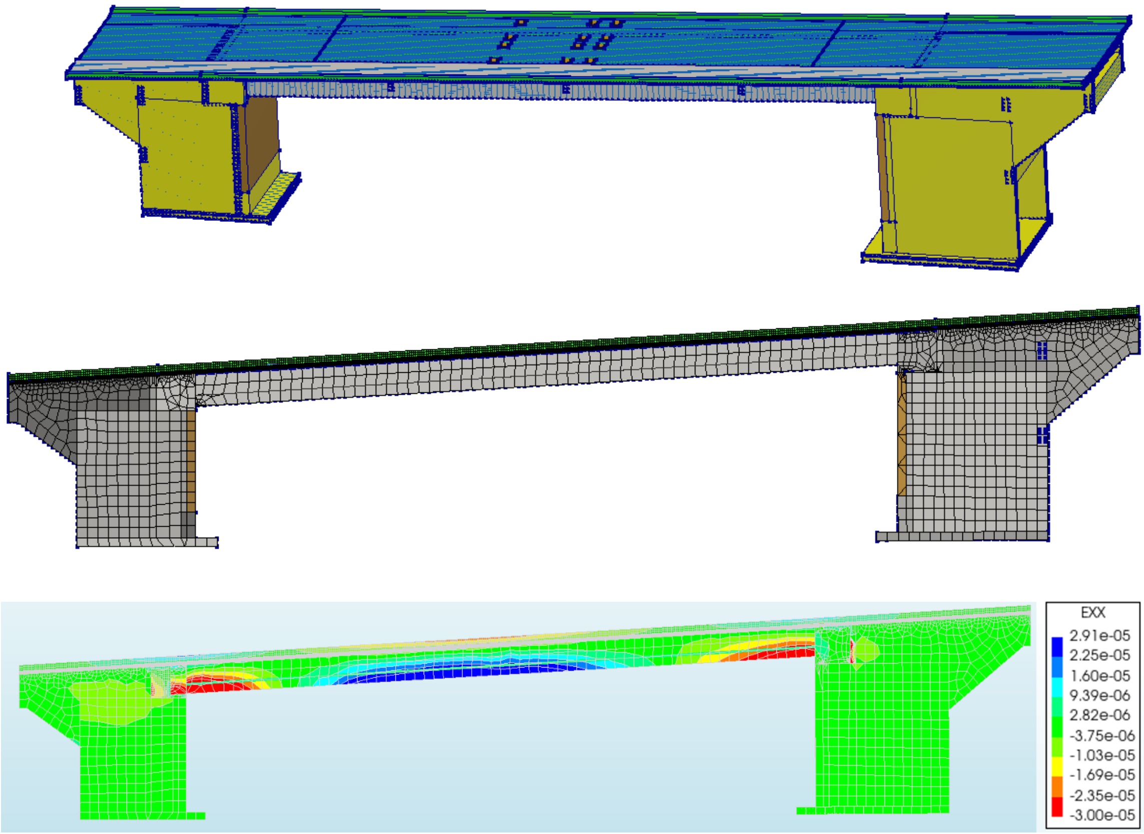

Fig. 6 Numerical modelling of Ferpècle bridge.

The FEM strain predictions are compared with the DFOS for both girders (Fig. 7). Globally, the predictions closely fit with the DFOS measurement data. Nonetheless, predictions at midspan and quarter spans, where the strain fields are affected by the secondary beams, do not exhibit the pattern observed in DFOS data. This result shows that the FEM model is not able to clearly replicate this local pattern behaviour. It is likely that a smaller mesh size may help improve the FEM strain predictions. Nonetheless, it will require a larger computational time, which may not be feasible in practice.

The FEM predictions are relatively accurate for the global strain profile (Fig. 7). Nonetheless, the strain ratio, calculated as scenario 1, provides a value of 0.75. This value is relatively far from DFOS results (Fig. 4), showing that the FEM is not able to replicate accurate load distribution between girders accurately. The strain predictions near the supports closely match DFOS datasets, meaning it could replicate actual boundary conditions (here fixed-fixed).

It is worth mentioning that the FEM provided accurate predictions for both strain profile, load distributions and deflection measurements for LT5, which involve the two trucks at midspan. In the preliminary study, it was demonstrated that the FEM predictions have less than 5 % of discrepancies between DFOS measurements and predictions [13]. It shows that the FEM predictions depend on the load tests. Due to the principle of superposition in LT5, the effect of the transverse beams is less significant, as shown in [12].

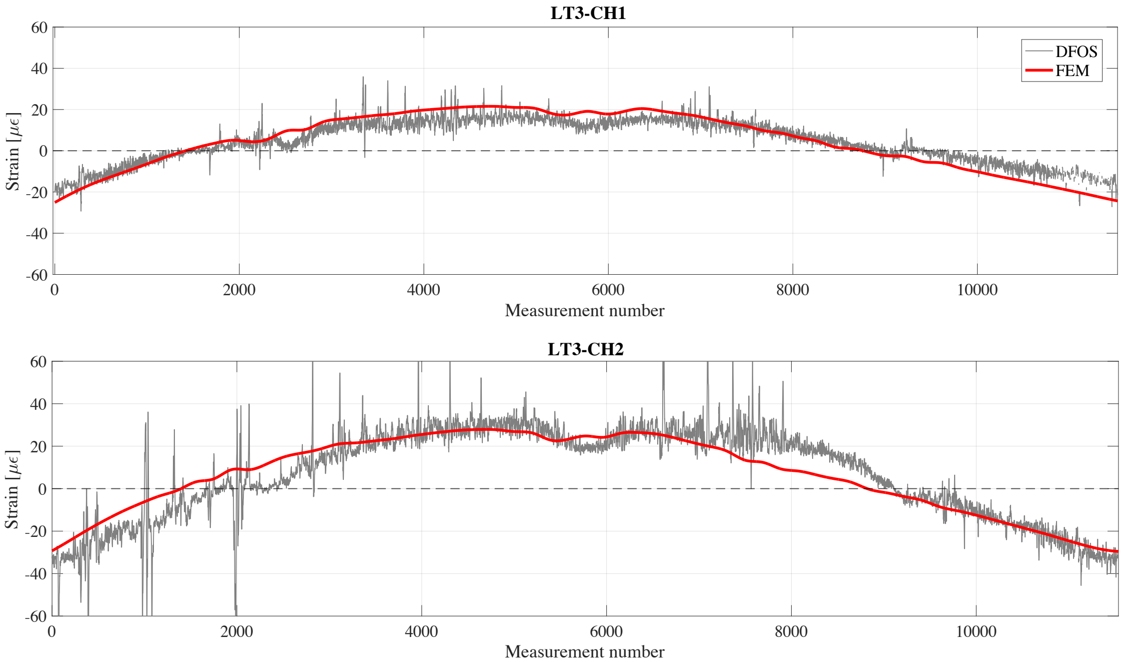

Fig. 7 Comparison of DFOS and numerical model predictions for CH-1 and CH-2 in LT3.

4 Comparison of information gain

The information gain from DFOS datasets is compared to conventional methodologies, either with strain gauges or numerical modelling. Table 1 summarizes the main findings in terms of global bridge behavior understanding. DFOS provides a comprehensive information gain. It also shows the limitations of conventional strain gauges and FEM. The DFOS information gain is sufficient to accurately evaluate the structural safety verifications without requiring numerical modelling. Nonetheless, these two approaches are complementary and should be combined. The future work consists of leveraging both DFOS and FEM to evaluate the structural capacity of the bridge accurately.

DFOS information gain is associated with significantly higher costs, mostly due to the implementation and interrogator price (fiber optics themselves are relatively cheap). This additional information may not be justified by the additional expenses, and a value-of-information framework [6] should be evaluated.

Table 1 Comparison of the potential of the DFOS dataset for concrete bridge examination

Bridge behavior	DFOS	Strain sensors	Numerical model	Comments
Local rigidity increase	YES	X	≈	DFOS reveals local rigidity changes due to secondary elements that are difficult to accurately obtain without high fidelity FEM
Crack detection	YES	X	X	Cracks, within DFOS locations, are detected straightforwardly which cannot be obtained with conventional solutions
Transverse load distribution	YES	≈	≈	The load distribution is accurately defined with DFOS data as with an numerical model. Strain gauge needs dense sensor networks
Boundary conditions	YES	≈	YES	The boundary conditions are accurately defined with DFOS as with a FEM. Strain gauge needs dense networks for such identification
Bending moment diagrams	YES	≈	≈	The bending moment are accurately defined with DFOS data as with a high-fidelity FEM. Strain gauge needs dense sensor networks
Displacement estimations	YES	X	≈	The bending moment are accurately defined with DFOS data as with a high-fidelity FEM. Strain gauges cannot give deflection estimations without previous identifications.

5 Conclusion

This study demonstrates that distributed fiber optic sensors provide a comprehensive information gain on concrete bridge behavior. This sensing technology supports engineers in their existing structure examination by providing additional knowledge on the local (cracks, secondary beam effects) and global (boundary conditions, bending diagrams, displacement estimations) behavior. This information allows for a more accurate evaluation of structural verifications at both serviceability and ultimate limit states, improving bridge safety assessment and leading to more sustainable infrastructure management.

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