Real-framework comparison of optical fiber distributed sensing techniques for Building Information Modeling

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Abstract – This work explores the application of Distributed Optical Fiber Sensing (DOFS) for structural health monitoring within the context of Building Information Modeling (BIM). The study addresses concerns about reliability and implementation of optical sensing techniques by providing, for the first time to the authors' knowledge, a technical validation of two DOFS technologies in a real framework. Strain measurements are carried out on a small reinforced concrete beam using Optical Frequency Domain Reflectometry (OFDR) and Brillouin Optical Frequency Domain Analysis (BOFDA). Both methods successfully detect induced strain, with OFDR demonstrating superior resolution (3 cm) and faster measurement times (under 30 s), but exhibiting noisy results and requiring post-processing filtering. On the other hand, BOFDA provides a 40 cm resolution and a 2-minute measurement time, but can measure over several km and has the potential for monitoring large infrastructures. A larger-scale experiment is then performed on a decommissioned bridge beam to simulate real infrastructure monitoring for BIM development. BOFDA provides consistent results and accurately predicts the location of failure during destructive testing. Although OFDR again shows higher resolution, its limited sensing range and installation constraints demonstrate that it is unsuitable for large structures. Ultimately, the study proves the potential of both DOFS techniques to replace extensive conventional sensor networks with single optical fibers, offering a unique benchmark for future applications in civil engineering. Ongoing data analysis promises further insights into sensor calibration and data interpretation.

Keywords: Optical Fiber Sensing; Brillouin Optical Frequency Analysis (BOFDA); Optical Frequency Domain Reflectometry (OFDR); Structural Health Monitoring (SHM); Building Information Modeling (BIM)

1. INTRODUCTION

Building Information Modeling (BIM) is a collaborative process to produce digital representations of the physical and functional characteristics of buildings and civil assets [1]. Among different data required by the BIM methodology, an important role is played by Structural Health Monitoring (SHM), that is, the collection of structural information such as strain and cracks development in the infrastructure that is being modeled. Fiber optics technologies have thoroughly penetrated SHM field thanks to their unique features: minimum invasiveness, remote interrogation (without the need of electric supply) and electromagnetic immunity [2]. Furthermore, extensive research effort is being carried out to use installed optical fiber links as coexisting data carriers and sensors [3], which could be beneficial for an efficient and low-cost SHM. Among different fiber technologies for SHM, Distributed Optical Fiber Sensing (DOFS) is an appealing choice, since a single fiber works as a dense array of sensors that can be embedded across the entire structure to provide real-time monitoring of physical parameters such as load, strain etc. DOFS of strain can be performed by two main techniques, i.e. Rayleigh and Brillouin scattering; these correspond to the measurement of two different scattering phenomena in the fiber, which behaves as an intrinsic sensor. In this work we compare the two measurement techniques in a real framework, i.e. on concrete beams embedding optical fibers. Rayleigh and Brillouin scattering are detected and processed by two instruments that implement Optical Frequency Domain Reflectometry (OFDR) and Brillouin Optical Frequency Domain Analysis (BOFDA) respectively.

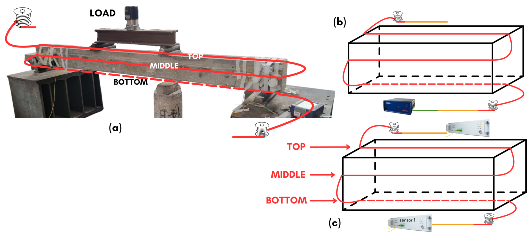

Fig. 1. Beam with embedded sensing fibers (a) and interrogation scheme for OFDR (b) and BOFDA (c).

2. EXPERIMENTAL ACTIVITY

Strain measurements were first performed on a custom made 3 m–long beam (Fig. 1 (a)), with a rectangular section of 20 x24 cm. Standard single mode fibers (SMF28) with a 250 μm jacket were embedded in grooves made on the top, bottom and side faces of the beam and secured by a chemical anchor. Therefore, the total sensing range was 9 m, while the access span (fiber length from the interrogator to the beam) was approximately 10 m. OFDR requires a single-ended fiber, as depicted in the schematic of Fig. 1(b), whereas BOFDA requires both ends of the sensing fiber to be connected to the instrument (Fig. 1(c)). The data were collected during a test in which the beam was subjected to load cycles within a pseudo-elastic regime, i.e. load was set to 2.5 , 5 and 10 kN. The strain information was calculated by applying standard strain coefficients retrieved from literature. The data collected from a load cycle (in this case cycle n.3 out of 5) are summarized in Fig. 2 and Fig. 3.

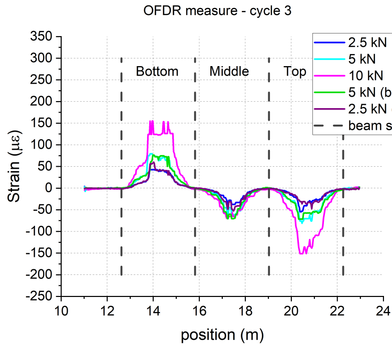

Fig. 2. OFDR strain measurement during load cycle 3.

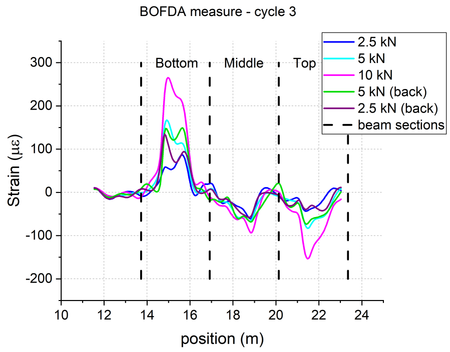

Fig. 3. BOFDA strain measurement during load cycle 3.

Both systems detect the induced strain and demonstrate the expected behavior (i.e. stretching at the bottom face and compression on the middle and top faces). OFDR offers superior resolution, down to $3\,\mathrm{cm}$ and measurement time below $30\,\mathrm{s}$, whereas BOFDA can measure the strain with a resolution of $40\,\mathrm{cm}$ and measurement time about $2\,\mathrm{min}$. The measurements are qualitatively in good agreement and provide a strain profile that resembles the one predicted by theory. However, there is a quantitative difference, in particular for a load of $10\,\mathrm{kN}$. This is ascribable to three main aspects: 1) the strain coefficients of both Rayleigh and Brillouin scattering are fiber-dependent and may vary, for the same fiber type, among different manufacturing batches, 2) the embedding process may further change the sensitivity of the sensing fiber, and, 3) the OFDR measurements are smoothed by a median filter to get rid of unreliable spikes that are due to the fact that the lab instrument used is sensitive to vibrations and environmental conditions. On the other hand, both graphs exhibit good reproducibility of the strain curves when the load is increased and then decreased (curves 2.5 and $5\,\mathrm{kN}$ well overlap those labeled "back"). This also corroborates that the beam is undergoing elastic regime. A similar measurement campaign was performed on a girder (Fig. 4, $16\,\mathrm{m}$–long, with a dovetail section of approximately $1\,\mathrm{m}^2$) recovered from a decommissioned road bridge [4], with the objective of providing data for the evaluation of residual structural performance and failure mechanisms. The girder was also equipped with conventional electric strain gauges, load cells and displacement transducers. The sensing fibers were embedded according to the schematic of Fig. 1 (b), (c) and the total sensing length, considering the

Fig. 4. Real framework testbed: $16\,\mathrm{m}$*-long beam from a decommissioned bridge. The bottom-right inset shows the cabling of electric sensors.*

fiber spans to access the test site, extended to $70\,\mathrm{m}$. The load tests were performed in three cycles with increasing loads: $50\,\mathrm{kN}$, $90\,\mathrm{kN}$ and up to destructive testing (occurred at $120\,\mathrm{kN}$). The BOFDA system showed consistent and repeatable results, demonstrating the capability to predict the breakage and providing a pinpoint of the location of failures. Once more, OFDR offered superior resolution, but its sensing range limited to $70\,\mathrm{m}$ and some constraints on the installation did not allow the collection of useful data. A glance at the test site (inset Fig. 4) proved the potential of both sensing systems, since a large sensing infrastructure made up of several cables that connect the electric sensors could be replaced with a single optical cable, working both as an intrinsic sensor and carrier of the sensing information. This experiment represents a unique benchmark for future employment of optical fiber sensing in civil applications. The data analysis is still ongoing and more reliable and useful results shall be obtained by ad-hoc calibration of the sensing fiber and quantitative comparison with the readings of the strain gauges and displacement sensors.

3. REFERENCES

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