Quantitative Strain Measurement with Distributed Fiber Optic Systems: Qualification of a Sensing Cable Bonded to the Surface of a Concrete Structure

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QUANTITATIVE STRAIN MEASUREMENTS WITH DISTRIBUTED FIBER OPTIC SYSTEMS: QUALIFICATION OF A SENSING CABLE BONDED TO THE SURFACE OF A CONCRETE STRUCTURE

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ABSTRACT

Distributed Fiber Optic Systems (DOFS) are an emerging and innovative technology that allows long-range and continuous strain/temperature monitoring with a high resolution. However, strain profiles measured in the optical fiber may differ from actual strain in the structure, due to the shear transfer through the intermediate material layers between the optical fiber and the host material (i.e., in the protective coating of the sensing cable and in the adhesive). Therefore, fiber optic sensors need to be qualified in order to provide accurate quantitative strain measurements.

This study presents a methodology for the qualification of a DOFS. It is proposed to establish a numerical modeling of the system, in which the mechanical parameters are calibrated from experiments. A specific surface-mounted sensing cable connected to an Optical Frequency Reflectometry Domain (OFDR) interrogator is considered as case study. We found that (i) tensile and pull-out tests are able to provide full information about materials and interfaces of our modeling; (ii) the calibrated model allows us to compute strain profiles along the optical fiber, (iii) which proved to be consistent with strain profiles measured on a cracked concrete beam during a 4-points bending test.

KEYWORDS: *Truly distributed fiber optic sensors, surface-mounted sensors, strain monitoring, crack detection, civil engineering structures*

1 INTRODUCTION

1.1 Context

Structural Health Monitoring (SHM) is an active field of research that aims at assessing the structural behavior and performance of civil infrastructures through the monitoring of key-parameters at various time scales. SHM can provide effective indexes to predict the residual lifespan of the instrumented structure and can help practitioners and infrastructures owners to optimize repair operations and reduce maintenance costs.

Reinforced Concrete (RC) structures are usually monitored with either short-gauge sensors like Vibrating Wire Gauges (VWG) or long-gauge sensors like Linear Variable Differential Transducers (LVDT). More recently, fiber optic sensors have proven to be a promising alternative to traditional sensors [1]. They are light, small, insensitive to electromagnetic waves, and they do not corrode. Thanks to the low attenuation of light propagating into the fiber, they can perform measurements over tens of kilometers. Finally, as the fiber is both the transmission medium and the transducer, a high degree of multiplexing is possible and installation cost of cable wires is reduced.

1.2 Mechanical transfer function (MTF) of DOFS

Distributed fiber optic sensors consist of an interrogation unit paired with a standard optical fiber. Measurement is based on the analysis of a backscattered light signal that allows continuous monitoring of strain and temperature along the fiber with a user-tunable spatial resolution. Various technologies are available, but the present study focuses on the use of Optical Frequency Domain Reflectometry (OFDR) for Rayleigh scattering. OFDR interrogation provides strain measurements with a centimeter scale spatial resolution, but the distance range is limited to a hundred meters.
Optical fibers are either surface-mounted or embedded into civil engineering structures [2]. For the monitoring of RC structures, fibers are usually fastened to steel reinforcing bars before pouring of the concrete. Hence, such embedded sensors are only intended for instrumenting new structures, unlike surface-mounted fibers which can be installed at the surface of any existing structure.

To protect the fiber from hazardous installation processes and environmental conditions, it is inserted in a cable with one or more protective layers. Cable geometries and designs are versatile and can be rather complex. Several fibers are often packaged together into a cable. For their attachment to the surface of a structure, sensing cables can be mechanically anchored or stuck with a suitable adhesive.

From a mechanical point of view, strain of the structure surface is transferred to the optical fiber through the protective and adhesive layers, which mainly deforms under shear stress. Thanks to this shear mechanism, the stress level is lower in the fiber than in the structure, so that the fiber is protected against high stress concentrations arising from cracks. But, since the strain measured in the fiber optic sensors can be different from the actual strain in the structure, measurements in the fiber are not directly quantitative.

In the case of a linear stress transfer (through interfaces and materials), the relationship between the actual strain of the structure and the strain measured in the fiber can be written as follows:

$$\varepsilon_{FO}(x) = (MTF \otimes \varepsilon_S)(x) \tag{1}$$

where x is the position along the fiber, ε_{FO} the strain in the optical fiber and ε_S the strain at the surface of the structure (both in $m.m^{-1}$), while $\otimes$ is the convolution operator. The MTF is called the Mechanical Transfer Function. According to the previous equation, the MTF is equal to the strain profile along the fiber when the strain of the structure is a Dirac delta function, i.e., an infinitely narrow crack:

$$\varepsilon_{FO,\delta}(x) = (MTF \otimes \delta)(x) = MTF(x) \tag{2}$$

In other words, the MTF is the impulse response of the system formed by the fiber optic sensor (FOS) bonded to the structure. For cracks with a finite opening ω, small enough with respect to the system dimensions, Equation (2) leads to:

$$\varepsilon_{FO,\omega}(x) = \omega \cdot MTF(x) \tag{3}$$

This MTF is of paramount importance to obtain accurate measurements and to evaluate crack openings. Therefore, several analytical studies based on Volkersen's theory [3] were undertaken by different authors to build a model for a FOS hosted by a concrete structure subjected to various boundary conditions. For instance, Ansari and Libo [4] have studied an optical fiber with a protective coating embedded into a concrete substrate; D. Li et al. [5] examined the behavior of a multi-layered axisymmetric cable. W.Y. Li et al. [6] investigated the case of a surface-mounted fiber with a bonding layer only while Her and Huang [7] added a protective coating. Finally, Feng et al. [8] developed an axisymmetric model for a FOS bridging a crack in the concrete substrate, which was also subjected to a constant deformation. They considered both the presence of protective and adhesive layers. These studies are all based on the following assumptions: all the materials present linear elastic behaviors, a perfect bond is assumed at all interfaces, shear and transverse deformations of both the fiber and the concrete adherent are neglected, while a pure shear deformation is considered for the intermediate layers. In the present study, the same assumptions are made, which will be then validated by the experimental tests.

From the results in [8], the theoretical MTF under the stated assumptions can be deduced:

$$MTF(x) = \frac{k}{2} e^{-k|x|} \tag{4}$$

with

$$k^2 = \frac{2}{E_f r_f^2 \left(\frac{1}{G_c} \ln\left({r_c}/{r_f}\right) + \frac{1}{G_a} \ln\left({r_a}/{r_c}\right)\right)} \tag{5}$$

where the subscripts f, c and a respectively represent the quantities related to the fiber core, coating and adhesive. E_f is the Young's modulus of the silica fiber, G_c and G_a are the shear modulii, and r_f, r_c, r_a the radii. k is called the shear-lag parameter and depends on the mechanical properties of the considered system (cable and host structure). It is thus a distinctive feature of this system. k is also inversely proportional to the effective bond length of the system L_τ:

$$\int_{-L_\tau}^{L_\tau} MTF(x)\,\mathrm{d}x = 0.97 \int_{-\infty}^{+\infty} MTF(x)\,\mathrm{d}x \quad \Leftrightarrow \quad L_\tau = -\frac{\ln(0.03)}{k} \tag{6}$$

L_τ corresponds to the shortest interfacial length necessary to transfer 97% of the applied load [9].

Actually, cables may not be axisymmetric and materials/interfaces may exhibit more complex behaviors. Thus, it is often necessary to go through a numerical modeling of the system in order to determine the stress transfer mechanism. However, this implies that all mechanical properties of the cable constituents and all interface laws are known, but this is rarely the case in practice.

A general methodology for determining the MTF of any cable was introduced in a previous work and applied to a specific embedded cable [10]. In the present study, tensile and pull-out tests were carried out to assess relevant properties of the materials and interfaces, and subsequently, to determine domains of linear elastic behavior and perfect bonding. A Finite Element (FE) modeling was then used to interpret experimental results. Then, a global FE model of the cable hosted by the structure was built, whose parameters were identified by fitting experimental results. Finally, the global model was used to establish the strain profile along the optical fiber induced by a surface crack opening, thus leading to the numerical determination of the cable's MTF.

In a previous study, such methodology has proven to be efficient for an embedded cable [11]. The present paper aims at demonstrating its effectiveness when applied to a surface-mounted cable. In the following, the methodology is carried out step by step, and results are then compared to experimental evidences collected during a 4-points bending test in a last section.

2 DETERMINATION OF THE MTF

2.1 Presentation of the cable

The FutureNeuro™ cable developed by Neubrex Co. [12], and manufactured by Fujikura Ltd., consists of two single-mode optical fibers inserted in a foamed adhesive tape designed to be stuck to the surface of a RC structure, and coated with a protective layer (Figure 1.A). Thus there is no need for an additional binding agent. The two fibers, made of silica glass, are protected by a primary coating with an outer diameter of 250 µm and are assembled together within a polymer matrix. The whole set is called the cable core (Figure 1.B). Total cable width and thickness are about 8 mm and 0.6 mm, respectively. This cable is intended for strain sensing of a host surface only. It works nominally over temperature range from -20°C to 60°C and can be stuck to various substrates, but the present study is concerned with concrete structures only.

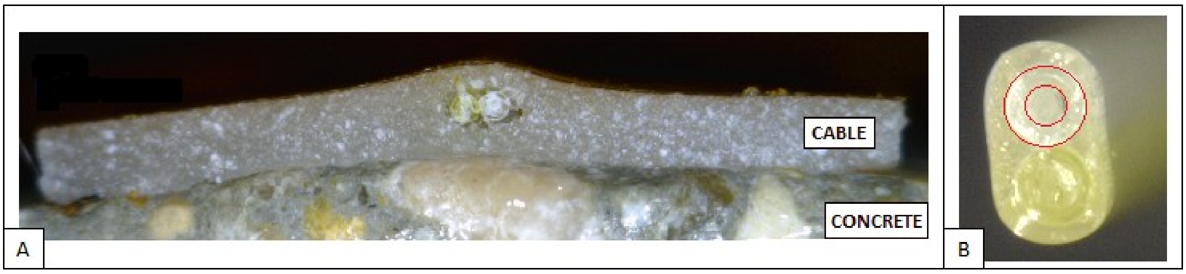

Figure 1: A – View of the cross-section of the cable stuck to the concrete surface. B – Zoom of the cable core, where two fibers and their primary coatings are assembled into a polymer matrix

2.2 Mechanical testing

Mechanical tests aim at providing all relevant mechanical properties that will be used in the global FE model of the cable stuck to the concrete structure.

2.2.1 Experimental devices

Mechanical tests were carried-out with an Instron 5960 universal testing machine of loading capacity 50 kN. For the present experimental campaign, the apparatus was equipped with a 100 N load cell and suitable grip devices. Tensile load was transmitted to samples attached to upper and lower grips. All tests were performed with a 1 mm/min displacement rate of the upper crosshead.

An Advanced Video Extensometer (AVE) was used for accurate displacement and strain measurements. It consists of a high-resolution digital camera and real-time image processing software, which tracks the distance between two markers drawn at the surface of the specimens.

The Rayleigh interrogator was the Optical Backscatter Reflectometer OBR-4600 commercialized by Luna Technologies. It makes it possible to measure strain profiles along the fiber with a maximum resolution of 1 µm/m and 0.1°C. A wavelength sweep from 1545.87 nm to 1588.63 nm was used. The tunable spatial resolution was set at 1 cm, for measurements over a 70 m-long range.

Tests were performed at a controlled room temperature of 20°C $\pm$ 1°C. The experimental setup is shown in Figure 2.

2.2.2 Tensile tests

Tensile tests were performed on samples of optical fiber with primary coating after they were stripped out of the cable. To avoid squeezing or damaging of the fiber inside the grips, each extremity of the sample was first stuck with superglue (ethyl cyanoacrylate glue with approximate Young's modulus after curing of 1 GPa [13]) to a metallic holder, which was then itself clamped in the grip (Figure 2.B and C). Data were collected by a computer that displayed real-time load-strain curves, as shown in Figure 3.A. The Young's modulus of the silica fiber E_f was calculated from the average slope of the linear curves, and was found equal to 77 GPa. A typical OBR strain profiles is reported in Figure 3.B. It exhibits exponential shapes on its two sides accounting for the stress transfer between the fiber and the holder through shear strain of intermediate layers, and are in agreement with the abovementioned analytical models. The shear-lag parameter of the corresponding system (optical fiber and coating perfectly stuck to the holder) depends on the shear modulus of the coating G_c and on the Young's modulus of the silica fiber E_f. Therefore we can calculate G_c = 0.46 MPa.

A failure of the primary coating around the silica fiber systematically occurred near the holder for all tested specimens, as shown in Figure 2.C. Such a failure is more likely caused by test conditions (flexure due to misalignment of the holders, damage of the primary coating caused by the holder or micro-damages of the coating during stripping and sample preparation), and do not correspond to an inherent failure of the material which is expected at a higher load level.

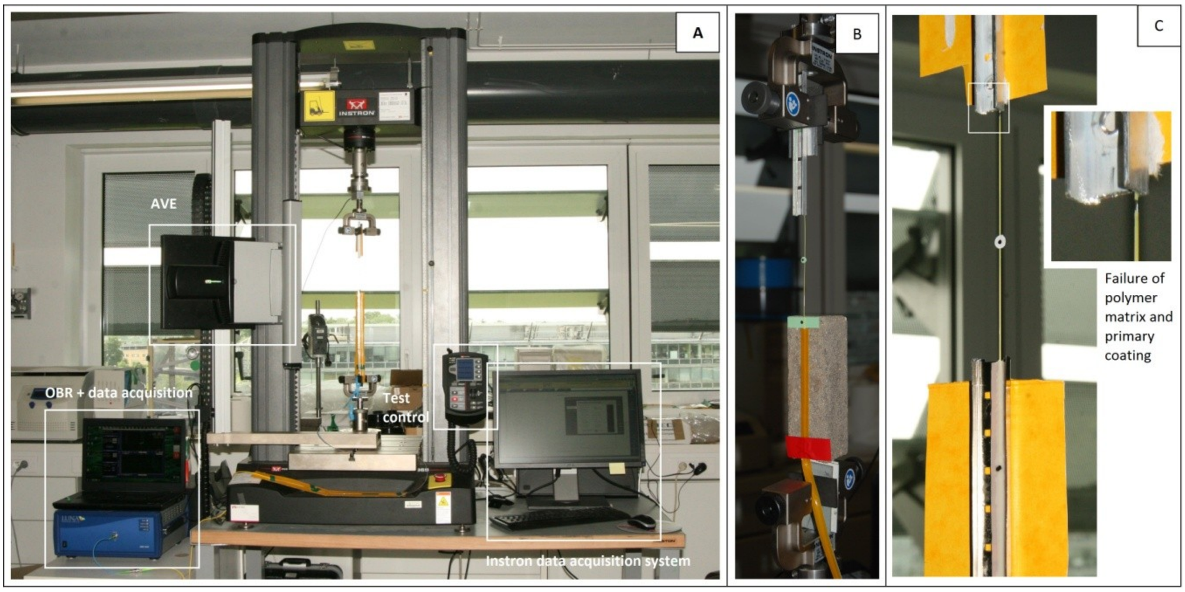

Figure 2: A – Experimental setup. B – A sample for the adhesive-concrete pull-out test. C – Failure of the polymer matrix and primary coating during a core-adhesive pull-out test

2.2.3 Pull-out tests

Pull-out tests are commonly used to evaluate the interface behavior between two materials of a bonded assembly [14]. In our case, both core-adhesive (Figure 2.C) and adhesive-concrete (Figure 2.B) interfaces were tested. The boundaries of the elastic domain were determined from the load-strain curves: the damage threshold was identified by a change of slope at the end of the linear domain. Again, failure of the tested specimens was consistently due to polymeric matrix and primary coating breaking at the exit point of the holder. Two shear-lag parameters could be calculated from the exponential parts of the OBR strain profiles (Figure 3.B).

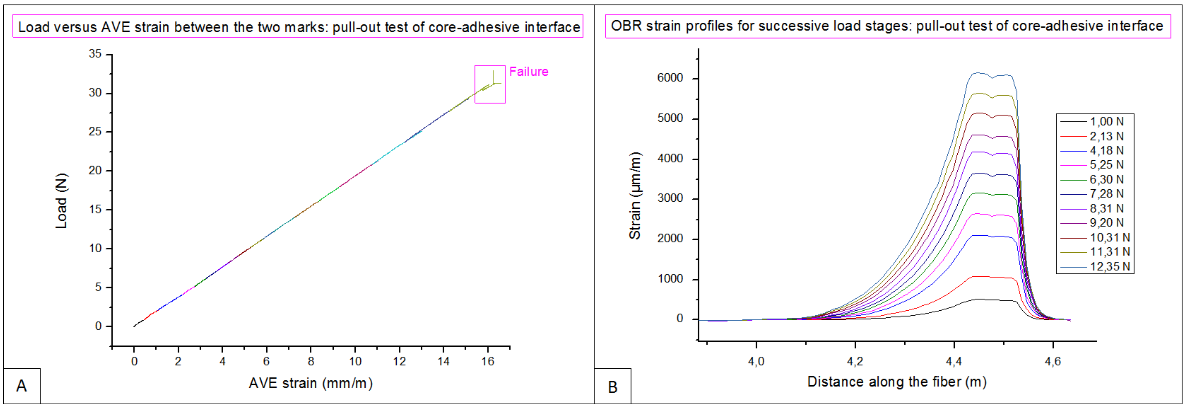

Figure 3: A – AVE load-strain curve for a core-adhesive pull-out test. B – Corresponding OBR strain profiles.

They depend on the shear modulii of a material equivalent to the primary coating–polymeric matrix assembly G_{eq} and of the adhesive G_a. Together with a FE modeling of the experiments, these shear lag parameters enabled us to calculate G_{eq} = 0.97 MPa and G_a = 60 kPa. Moreover, a comparison between the FE modeling (assuming a perfect bond for all interfaces) and test results showed a fair agreement, suggesting that interfaces are really perfectly bonded. This endorsed the working assumptions.

2.3 Global FE model and computation of the MTF

Thanks to the previous mechanical tests, a global 3D FE model of the cable stuck to the surface of a concrete prism could be calibrated. Numerical modeling was implemented using the commercial software COMSOL Multiphysics® with the structural mechanics module.

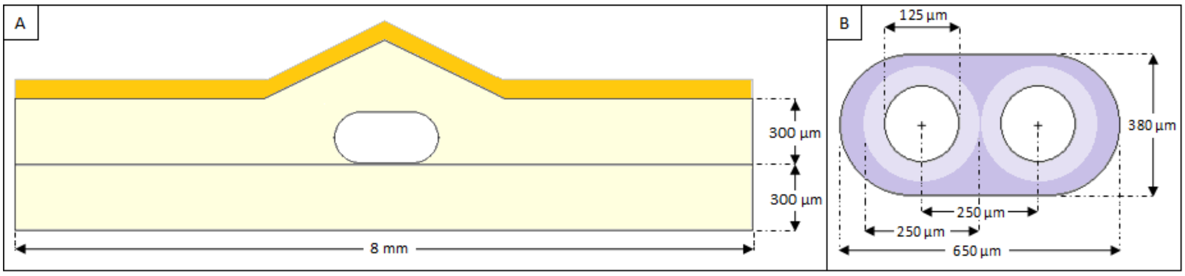

Figure 4: Simplified geometry of the model: A – Total section of the cable. B – Zoom of the core structure.

The model was based on a simplified geometry of the sensing cable, whose section is depicted in Figure 4. Symmetries of the cable made it possible to divide by four the volume to be meshed, but not to reduce the representative structure to a 2D modeling. Tetrahedral elements were used to build the mesh, and a high density of elements was considered inside and around the optical fiber. To avoid singularities in the mesh pattern, an homogeneous equivalent material accounting for both the polymeric matrix and the primary coating had to be considered. A 2D-section of the mesh pattern is shown in Figure 5. The Poisson ratios ν of the materials were arbitrary fixed, and the Young's modulii were chosen in accordance with the previous experimental results. Perfect bond were considered for all interfaces, i.e. the stiffness was set at a very high value (10^{14} Pa.m^{-1}). In these conditions, linear and elastic equations of mechanics ruled the behavior of the structure.

In order to compute a strain profile in the fiber which is (in first approximation) proportional to the MTF, boundary conditions were chosen to simulate the opening of a crack in the concrete medium, in agreement with Equation (3). In practice, a pre-existing crack is inserted in the middle of the concrete prism, which is consequently separated into two blocks that are moved away from each other through an imposed displacement.

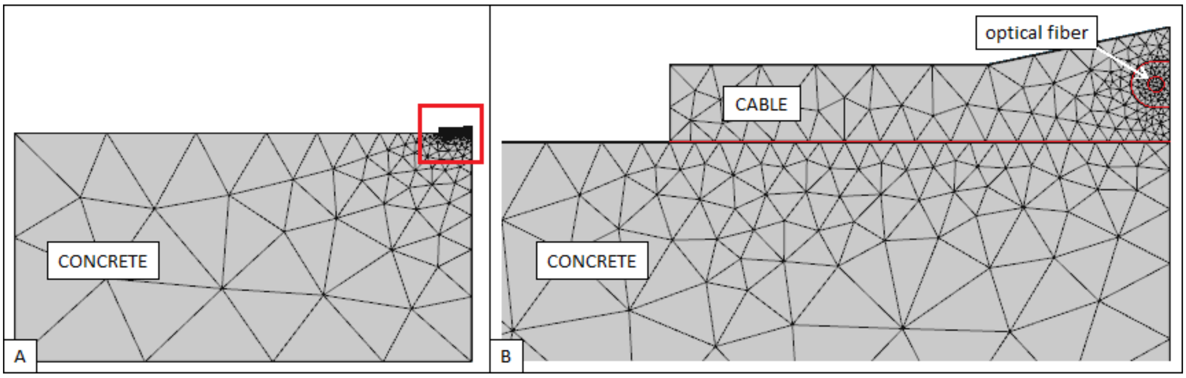

Figure 5: 2D-section of the 3D mesh used for FE computing: A – total section; B – zoom in the sensing cable

The resulting strain profile shown in Figure 6.B exhibits an exponential shape, and as a consequence, so does the MTF. The predictions of analytical models and Equation (4) are thus verified, which means that our real system and the theoretical simplified models behave in a close manner. The shear-lag parameter of the MTF was identified by fitting the profile with Equation (4), providing a value of k = 12 m^{-1}. Therefore the effective bond length was: $L_\tau = 29$ cm ± 3 cm

The uncertainty value of the transfer length was calculated by evaluating experimental uncertainties and propagating them through Equation (5).

As pointed out before, the observed failure modes were not due to material failure, but rather to experimental testing conditions. With the help of numerical modeling, it is possible to convert the average failure load into a stress threshold: the study is valid, i.e. elastic and linear assumptions are verified, until the shear stress in the polymer matrix/primary coating set reaches a value of 0.2 MPa, or equivalently until the crack reaches a width of 3 mm. However, this is a conservative limit and the domain of validity of the sensing cable is probably much broader.

In order to validate the previous methodology for the determination of the cable FTM, a confrontation with experimental evidences is needed.

3 EXPERIMENTAL VALIDATION OF THE METHODOLOGY

In this section, numerical results are compared with experimental data collected from a 4-points bending test conducted on a plain concrete beam equipped with the sensing cable. The experimental setup is shown Figure 6.A. Following the application of the bending load, a single failure was initiated on the tensile face and at the center of the beam, where LVDT sensors were also placed. As this crack propagated through the beam, the strain profile measured by the sensing chain (the cable paired with an OBR) was once again proportional to the MTF. According to Equation (3), the MTF could be found by dividing the strain profile by the crack opening value. This crack opening displacement corresponds to the area under the strain profile, since the MTF is normalized. Figure 6.B displays both the above modeled MTF and the experimentally determined MTF experimental. The two curves are remarkably similar. Besides, the experimental effective bond length can be calculated by fitting the experimental profile using Equation (4): a value L_τ = 25 cm was found while the modeled value was L_τ = 29 cm, suggesting a good agreement among the two methods.

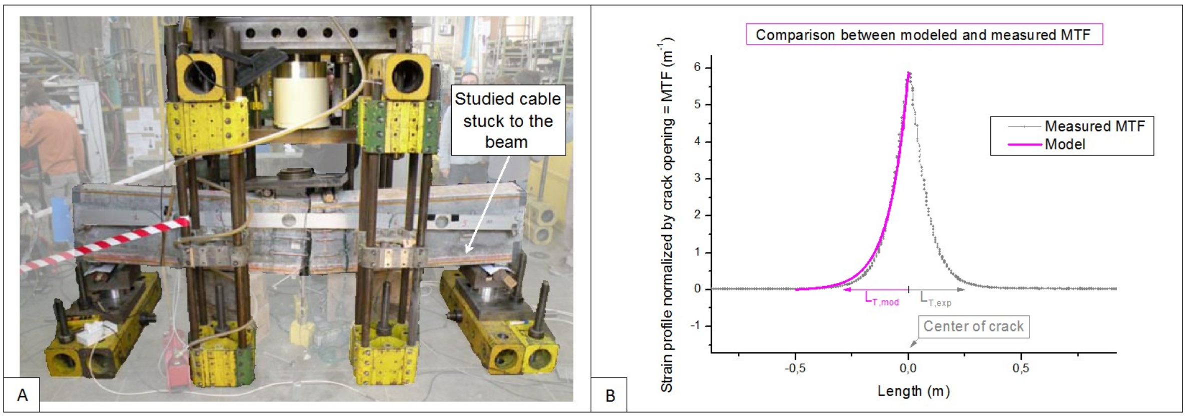

Figure 6: A – 4-points bending test on a plain concrete beam with a single crack formed in the central part.
B – Comparison between computed and measured MTFs, showing a good agreement

4 CONCLUSION

A fiber optic cable paired with a Rayleigh OFDR interrogation unit makes it possible to perform continuous strain monitoring with a centimeter scale spatial resolution for the SHM of very large infrastructures. A generic methodology was introduced in order to determine the relationship between the strain profile measured along the optical fiber and the actual strain of the monitored structure. Such a methodology is based on mechanical testing and modeling and has proved to be fully efficient for a specific surface-mounted cable. In addition, those results were consistent with experimental data obtained from a four-point bending test conducted on a plain concrete beam with a single crack.

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