Development of an Automatic Algorithm to Analyze the Cracks Evolution in a Reinforced Concrete Structure from Strain Measurements Performed by an Optical Backscatter Reflectometer

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Abstract. Structural Health Monitoring (SHM) is a key procedure in infrastructure lifecycle management, since it enables a real-time diagnosis of the state of damage of the structure. As a complement to conventional sensors, Distributed Optical Fiber Sensors (DOFS) have gradually played a prominent role in SHM for the last decade. DOFS are composed of an optoelectronic device paired with an optical fiber in a cable. DOFS can provide strain profiles over several kilometers with few micro-strains accuracy. Several optoelectronic devices exist based on the analysis of backscattered light in the silica of the optical fiber. An Optical Backscatter Reflectometer (OBR) performs strain measurements with a centimeter spatial resolution. Embedding a sensing cable in a concrete structure developing cracks led to the appearance of peaks on strain profile provided by the OBR. These strain peaks measured in the optical fiber can be explained by the shear deformation of the protective coating of the cable. The relation between the strain in the optical fiber and the actual one in the embedding medium is called the Mechanical Transfer Function (MTF) of the cable. Knowing the cable's MTF, strain profiles and especially strain peaks could be analyzed by a deconvolution algorithm, so as to automatically detect, localize and determine the evolution of cracking in the concrete structure. The developed algorithm was applied on OBR measurements performed in a reinforced concrete beam, equipped with a sensing cable, and submitted to a 4 points bending loading. For an end-user point of view, this kind of algorithm really completes DOFS devices, so as to get an efficient tool for SHM.

1. Introduction

Durability of civil infrastructures is a crucial issue that can have major economical, social and environmental impacts. Infrastructure owners must face difficult challenges, such as optimization of maintenance and extension of service life. To ensure safety of these structures and to prioritize maintenance effort, there is a need to monitor the structural condition over time. In this context, Structural Health Monitoring (SHM) is considered as a key procedure, because it enables a real-time diagnosis of the state of wear/damage of an

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infrastructure. To be efficient, SHM must provide relevant information regarding the integrity of large civil structures such as bridges, dams, dykes, and nuclear power plants. Conventionally, structural monitoring involves the measurement of strain, displacement, rotation and/or acceleration at various points along the structure.

Historically, Reinforce Concrete (RC) structures are monitored with short-gauge sensors like Vibrating Wire Gauges (VWG) [1] providing local information, and long-gauge sensors like invar wires associated with Linear Variable Differential Transducer (LVDT) providing global information [2].

As a complement tool to traditional sensors, fiber optic sensing systems are an attractive tool for SHM. Over these years, the technique has been developed in order to obtain measures with accuracy similar to the standard strain gauges and extensometers. Optical fibers consist in light waveguides made of silica glass, commonly used in the telecommunication industry. Several advantages characterize them: they are light, small (outer diameter around 125 µm) and insensitive to electromagnetic fields. Paired with an optoelectronic device, these sensing systems enable to record strain profiles and/or temperature along kilometers of fibers embedded into a host structure.

Different interrogation units are available, whose operating principles are based on the analysis of the backscattered light in silica. The collected signal corresponds to the continuous record of scattering phenomena as a function of the position along the fiber. As shown in Figure 1, if a laser pulse with a wavelength of λ_0 is launched inside silica optical fiber, light is partially backscattered. The resulting signal is spectrally decomposed into three distinct peaks corresponding to three outstanding phenomena.

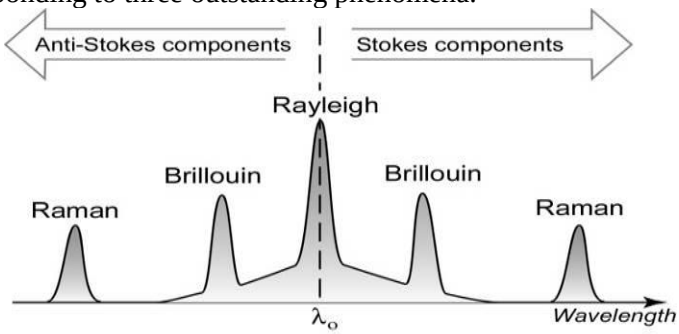


Figure 1: Backscattering spectrum of a monochromatic wave within an optical fiber.

Rayleigh scattering is due to fluctuations of silica density and composition, Raman to thermal molecular vibration and Brillouin to photons – phonons interactions. Analysis of the backscattered light provides two information: temperature and strain. This is due to the fact that the Raman effect is temperature sensitive, while the Brillouin and Rayleigh effects are both temperature and strain sensitive.

Measures of profiles along the fiber can be obtained by two main interrogation methods: Optical Time Domain Reflectometry (OTDR) and Optical Frequency Domain Reflectometry (OFDR). With regard to OTDR, commonly used with Brillouin interrogator, a laser pulse is used and the location is calculated considering the time of flight measurement. It is simply an optical pulse-echo technique. Regarding the OFDR, used with Rayleigh interrogator, a swept frequency pulse is used to interact with the optical fiber. Fundamentals and operating principles of Rayleigh and Brillouin systems are fully detailed in [3] and [4]. In practice, an OFDR Rayleigh system operates by first measuring and storing the Rayleigh scatter signature of the fiber at an initial state. Then, the scatter profile is measured at a later time, whilst strain or a temperature perturbation is applied to the fiber. Data sets are broken into intervals along the fiber and Fourier transformed into the optical frequency domain. To determine the spectral shift between the reference and perturbed scans, a cross correlation is performed for each fiber interval. Any change in strain or temperature manifests as a shift in the correlation peak. A distributed measurement is

formed by compiling the spectral shifts for each interval along the fiber. The relation between the spectral shift and the change in strain and temperature is given by Eq. (1).

$$\Delta\nu_{FO} = C\varepsilon_{FO}.\varepsilon_{FO} + C_{TFO}.\Delta T_{FO} \qquad (1)$$

where $\Delta\nu_{FO}$ is the Rayleigh spectral shift, ε_{FO} the fiber strain, ΔT_{FO} the fiber temperature change, $C\varepsilon_{FO}$ and C_{TFO} are calibration constants. For a standard single-mode fiber of type G652, at 1550nm, typical values of these constants are respectively around −0.15GHz/με and −1.25GHz/°C. Rayleigh OFDR systems offer a high resolution (in the cm range), but the maximum distance is limited to 100m [3] for a strain sensitivity of 1μm/m.
Several feasibility studies in SHM [5], [6], [7] tested Rayleigh OFDR systems and establish that it can be easily used to detect and localize cracks into several structures. This paper focuses on reinforced concrete structures. Embedding optical fiber cable into a reinforced concrete structure led to appearance of peaks on measured strain profile. Those peaks can be explained by the shear deformation of the protective coating of the cable [8].
The purpose of this article is to propose an algorithm allowing the tracking of cracks evolution. First step is to understand influences of each components of the measurements system, then a model is proposed to estimate measured signal in a beam which presented cracks. An algorithm is described to decompose signal into cracks signature and is applied on a reinforced concrete beam submitted to a four-point bending test.

2. Influence of Cable's Coating

2.1. Definition of MTF

An optical fiber and its primary coating are too fragile to be directly used in industrial applications. Usually, the optical fiber sensors are composed by several fibers wrapped by a protective coating. This cable is characterized by outer diameters of few mm. The coating protects the optical fiber against mechanical/chemical aggressions. As a consequence, due to shear deformation of the cable's coating, strain measurement in the optical fiber may differ from that in the host structure [8]. For this reason, a methodology was developed to determine the relationship between strain fields in the optical fiber and in the host materials. This relationship is called mechanical transfer function (MTF) of the cable in the host structure [7].
Taking a strain profile measured by an interrogator (ε_{meas}), [9] proposes a relation between measured strain profile and the longitudinal strain profile into host structures (ε_{HS}), involving the cable's mechanical transfer function (MTF_{cable}):

$$\varepsilon_{meas}(x) = \varepsilon_{HS}(x) \otimes MTF_{cable}(x) \otimes \Pi_{interrogator}(x), \qquad (2)$$

where x is the curvilinear abscissa; $\Pi_{\text{interrogator}}$ is a rectangular function with a width value corresponding to the spatial resolution of the interrogator. If spatial resolution is greater than the Full Width at Half Maximum (FWHM) of the MTF, then the influence of interrogator will predominate over that of the MTF. On the contrary, for the same FWHM, if the spatial resolution is smaller than FWHM, the MTF will have a major influence on the determination of strain profile in the host material. In our case, the Rayleigh interrogator has a centimeter spatial resolution, implying that the MTF will have a major influence on determination of the strain profile.

Once MTF_{cable} identified for a defined fiber optic cable, it permits us to estimate the strain profile into the host material. We suppose this transfer function constant over time and we admit a constant temperature.

2.2. Cracks Signature and Detection

Into reinforced concrete structures, cracks signatures can be easily modeled as strain peaks [5], [7]. To a first approximation, in Strength Materials Modeling (SMM), a crack located at the position is modeled by a Dirac shifted to this position [9]. The influence of cable coating is represented by MTF, therefore a crack signature is modeled by the convolution of a Dirac and the MTF. If several cracks exists, the measured strain profile by the Rayleigh OFDR could be modeled by:

$$\tilde{\varepsilon}(x) = \sum_{i=1}^{Npk} MTF_{cable}(x) \otimes (A(i)\delta(x - X(i))), \quad (3)$$

where A and X are vectors represented respectively amplitudes and positions of cracks into the reinforced concrete structure and N_{pk} is the number of cracks in the structure.
If distances between several cracks positions are inferior to the FWHM of the MTF, then the measured strain profile presents peaks and subpeaks.
An algorithm allowing to find positions and amplitudes of cracks into the structure and their evolution is presented thereafter.

3. Algorithm for Tracking Cracks Evolution in Reinforced Concrete Structures

The purpose of the algorithm is to obtain the vectors containing the positions X and the amplitudes A of cracks for different solicitations (loads). The algorithm detects strain peaks by finding local maxima into the strain profiles $\varepsilon^{N}_{meas}(x)$ measured by the Rayleigh OFDR system for the N^{th} solicitation. The vectors containing the amplitudes and positions of the cracks for the N^{th} solicitation are denoted A^N, X^N.
Some thresholds are imposed by the measurement system and physical arguments: A_{thres} is the amplitude threshold used to identify a strain peak as a crack, which depends on strain measurement accuracy; X_{thres} is the minimal distance which distinguishes two different cracks. It depends on the load applied on the reinforced concrete structures and the spatial resolution of the measurement system. When the elements of amplitudes and positions vectors are superior of these thresholds, it signifies that cracks have appeared between two solicitations.
The total number of cracks detected for the N^{th} solicitation is denoted $N_{pk}{}^{N}$. If the numbers of peaks in step N is inferior or equal to that in step N-1, then the second step consists in optimizing the amplitudes vector A^N to estimate the strain profile $\tilde{\varepsilon}^{N}(x)$ using Eq. (3). In order to do this, the algorithm minimizes a cost function *CF* defined as the distance between the estimated model and the measured signal:

$$CF = \left\| \tilde{\varepsilon}^{N}(x) - \varepsilon^{N}_{meas}(x) \right\| = \sum_{i=1}^{M} \left(\tilde{\varepsilon}^{N}(x_i) - \varepsilon^{N}_{meas}(x_i) \right)^2, \quad (4)$$

where M represent the number of available samples x_i. If the numbers of peaks in step N is superior to that in step N-1, it means that at least one peak has been detected. The vectors

A^N, X^N are updated with the amplitude(s) and position(s) of the new peak(s), while the number of peaks is incremented.
Detection of sub peaks is possible thanks to the comparison between the measured and estimated strain profiles. If some peaks have not been detected so far, then they will appear in the subtraction. A novel couple of vectors (A_{sub}, X_{sub}) is found thanks to local maxima detection and if the amplitudes of the peaks correspond to the same criteria as above it means that new peaks are detected. The vectors (A^N,X^N) are updated with the amplitudes and positions of these new peaks, while the number of peaks is incremented.
This iteration is repeated until no more peaks or subpeaks are detected. The flowchart of this algorithm is shown in Fig. 2.

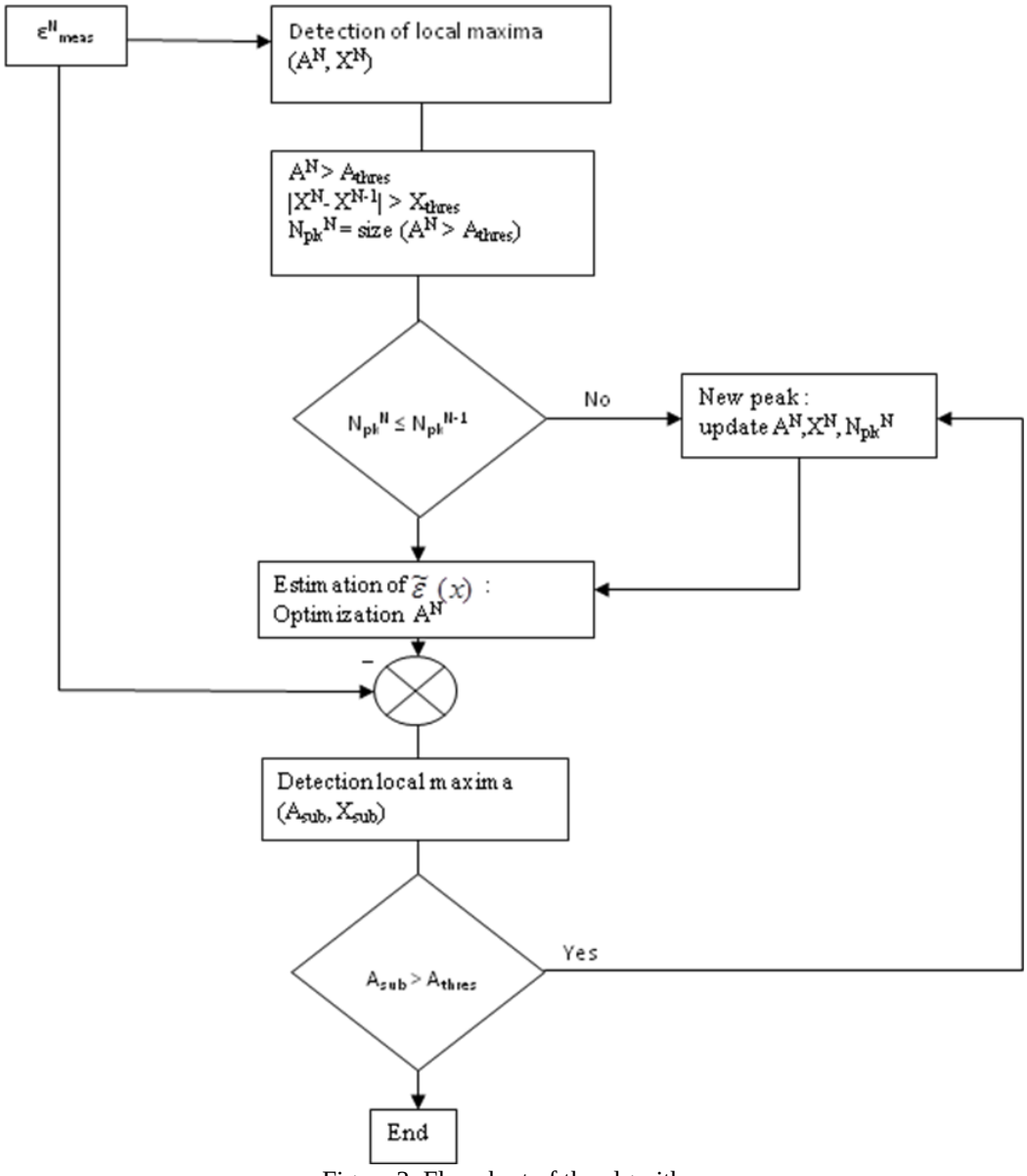


Figure 2: Flowchart of the algorithm

4. Application for a Four-Bending Test on a Reinforced Concrete Beam

A reinforced-concrete beam has been submitting to a four-point bending test for different load levels from 7 kN to 100 kN. Results of loading are presented in [7] and can be summarized: a zone of compression and a one of tension. The beam has been instrumented

by a DOFS composed by a Rayleigh interrogator, a particular optical fiber sensing cable and conventional vibrating wire gauges. Further details of the instrumentation and the experiment can be found in [7]. The interrogator performed strain measurement for each loading level with a spatial resolution of 1cm. The commercial sensing cable is presented in [9] and its MTF has been fitted by an exponential function shown in Figure 3:

$$MTF_{cable}(x) = A.e^{-B.|x|}, \qquad (5)$$

where B=20m^{-1}, A = 10µm/m.

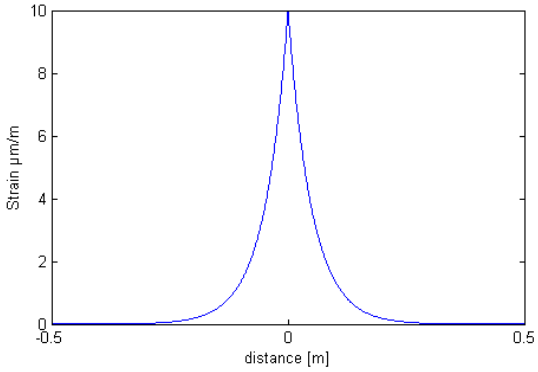
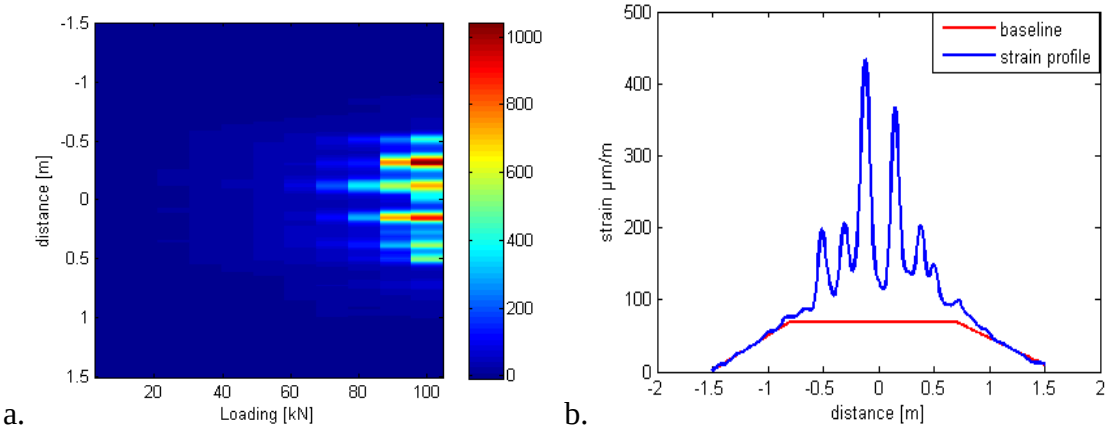


Figure 3: Mechanical Transfer Function of a commercial cable [6]

The FWHM is about 8cm. We verify that MTF as a major influence on strain measurement. The matrix of the measured strain profiles for different solicitations is shown in Figure 4.



a. b.

Figure 4: a. Evolution of strain cracks signature in µm/m depending on the load applied on the reinforced concrete beam (scale in µm/m). b. Measured strain profile for applied load of 70kN and trapezoidal baseline.

As regards to Figure 4a, measured strain profile presents strain peaks but also a baseline due to elastic behaviour of the reinforced concrete. A trapezoidal approximation of baseline was validated by SMM in [9]. Testing our algorithm on those measurements needs thus a preprocessing step: optimize the trapeze parameters and subtract the baseline contribution from signal. Then cracks signature remains in the strain profile but this operation will interfere on amplitudes of cracks detected.

In order to increase spatial resolution for the accurate crack position identification, oversampling is next applied on signals. The new spatial resolution is of 0.005m.

5. Results and discussion

The thresholds are related to strain measurement parameters and physical phenomena. For this application, the distance between two cracks should be superior to 2cm. A compromise

between early cracks detection and accuracy of their positions has to be found. We have set the minimal amplitude to 30µm/m. If we chose a smaller value, cracks are detected earlier but their position accuracy is worth.
With these thresholds, the proposed algorithm was applied on the matrix of the measured strain profiles after the preprocessing. The obtained results are shown in Fig. 5.

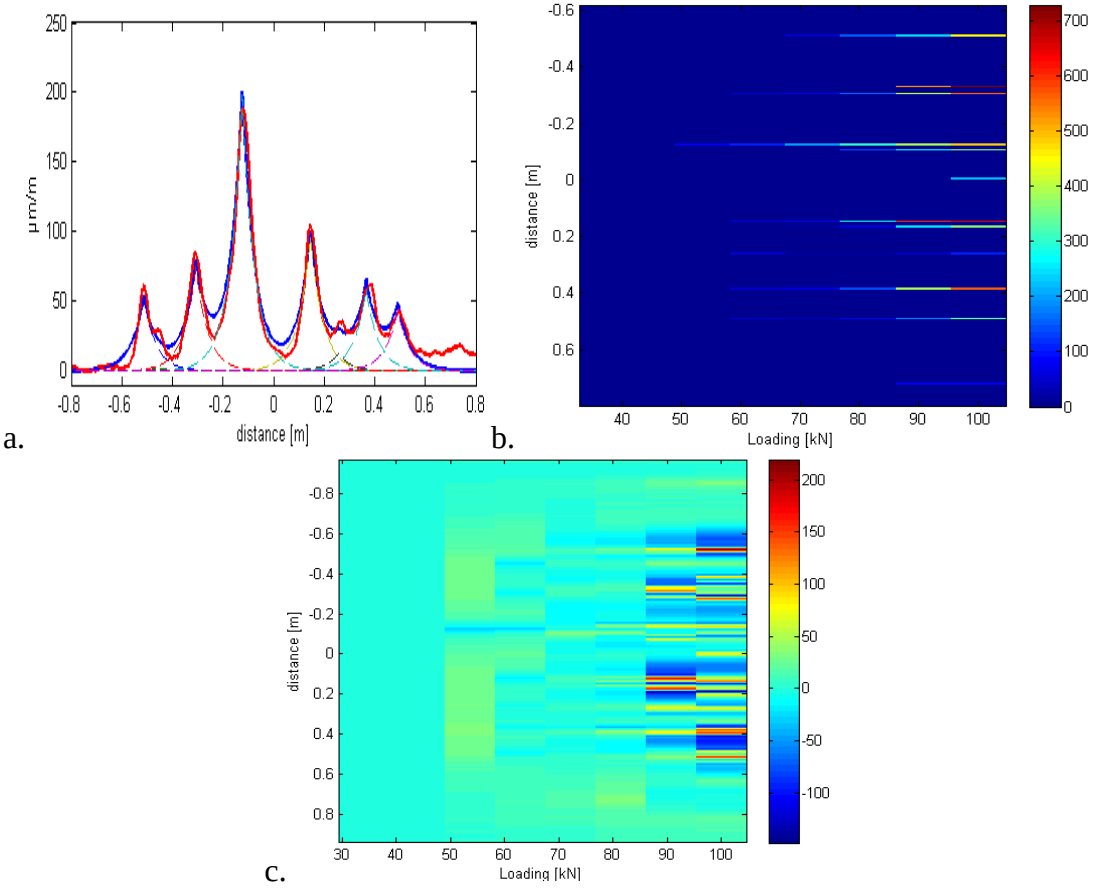


Figure 5 : a. Strain profile (red line) for load level of 70kN, reconstructed signal (blue line) and crack signatures (dotted lines) for a 0.005m spatial resolution. b. Map of crack locations and evolution function of load levels and distance for a 0.005m spatial resolution. c. Errors between reconstructed signal and measured signal for a 0.005m spatial resolution.

As regards to Figure 5a, the algorithm decomposes the signal (the strain profile measured for a particular solicitation) into cracks signatures. Detection, localization and evolution of cracks are summarized in a map shown in Figure 5b. The algorithm detects the first crack when the load is 50kN. Exceeding the elastic limit, a first crack appears at a position of -0.12m to the center of the beam. Positions uncertainty is +/- 0.005m, which is the spatial resolution after interpolation.
As we can see in Figure 5b, crack amplitudes and areas increase with the level of the load. Unfortunately, there were no traditional crackmeters installed at the surface of the beam, so as to make quantitative comparisons. Further experiments need to be carried out for the qualification process.
As regards to Figure 5c, the errors between reconstructed and measured signals are limited between 200µm/m and -150µm/m. This is due to the fact that the algorithm minimizes those errors finding new peaks, but the peak parameters do not respect defined criteria to be considered as crack signatures. We can reduce these errors by choosing a smaller threshold for the amplitude, however the accuracy of the position of the peaks will not be so good.

6. Conclusion

DOFS have gradually played an important role in SHM for the last decade. In term of accuracy, they equal conventional sensors. Several feasibility studies use Rayleigh OFDR to test its industrial interest. Applications on industrial domains show that Rayleigh OFDR enables to detect and localize cracks in reinforced concrete structures, earlier than visual inspection. Cracks strain signature is convolution of a Dirac modeling a crack with the MTF which characterizes the cable coating influence on the measurement. Position and amplitude of Dirac permit to find location and to quantify cracks. This article proposes an algorithm to detect and localize cracks automatically and analyze their evolution into a reinforced concrete structures. It establishes a precise map of cracks with the evolution of their amplitudes. It has been tested on a reinforced concrete beam load by a four-bending press. Results of position of cracks are in adequation with visual inspections. Unfortunately, no traditional crack meters were installed in surface, so as to make quantitative comparisons. Further work will be carried out to find a relation between amplitudes or peak areas and crack openings.

References

[1] Lamour V, Haouas A, Dubois J-P, Poisson R. Long term monitoring of large massive concrete structures: cumulative effects of thermal gradients. Non-destructive testing in civil engineering, Nantes, France; 2009.

[2] Courtois A, Henault J-M, Simon A, Beck Y-L, Salin J. La surveillance en exploitation des enceintes de confinement et des aéroréfrigérants à tirage naturel du parc nucléaire d'EDF. Revue Générale Nucléaire, 2 : 49–59. 2011 [in French]

[3] Hartog A. Distributed Fiber-Optic Sensors: Principles and applications. Optical Fiber sensor Technology, edited by KTV Grattan and BT Meggit, 2000; 251-301.

[4] Bao X, Dhiliwayo J, Heron N, Webb D J, Jackson D. A. Experimental and Theorical Studies on a Distributed Temperature Sensor Based on Brillouin Scattering. Journal of Ligthwave Technology, Vol. 13, No. 7 1340-1348, 1995.

[5] S. Villalba, J.R. Casas, Application of optical fiber distributed sensing to health monitoring of concrete structures, Mech. Syst. Signal Process. (2012), doi:10.1016/j.ymssp.2012.01.027

[6] Guemes A, Fernandez-Lopez A, Soller B; Optical Fiber Distributed Sensing – Physical Principles and Applications. Structural Health Monitoring. 2010.

[7] Henault J.-M., Quiertant M., Delepine-Lesoille S., Salin J., Moreau G., Taillade F., Benzarti K., Quantitative strain measurement and crack detection in RC structures using a truly distributed fiber optic sensing system, Construction and Building Materials, Available online 22 June 2012, ISSN 0950-0618, 10.1016

[8] Ansari F, Libo Y. Mechanics of bond and interface shear transfer in optical fiber sensors, Journal of Engineering Mechanics 124: 385-394. 1998.

[9] Henault J.M, Salin J, Moreau G, Quiertant M, Taillade F, Benzarti K, Delepine-Lesoille S. Analysis of strain transfer mechanism between a truly distributed optical fiber sensor and the surrounding medium. ICCRRR 2012.