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# **In Situ Distributed Strain Monitoring of a Small-Scale Reinforced Concrete Structure Using Combined FBG/OFDR Fiber Optics Sensing for Assessment of Its Seismic Degradation Mechanisms**

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## **ABSTRACT**

An experimental program has been defined by EDF (French electric utility) and CEA with the aim to improve the knowledge of the wall-slab junctions' behavior, by means of reduced-scale mock-ups made of reinforced concrete (RC), representative of Nuclear Power Plant (NPP) building structural elements. As part of the Tamaris platform (CEA), the "Azalée" shaking table provides 3D excitation. A wall-slab 1/4-scaled mock-up was designed, constructed, equipped with both Optical Fiber Sensors (OFS) and conventional instrumentation (accelerometers, displacement & strain gauges, Digital Image Correlation (DIC)) and vibration-tested.

OFS provide *in-situ* local or distributed strain measurements, complementary to other methods. Gathering *in situ* distributed strain data is thus of considerable interest since it helps reducing experimental variance and eventually improving modeling accuracy. Fiber Bragg Grating (FBG) and Optical Frequency-Domain Reflectometry (OFDR) sensing techniques are well suited to Structural Health Monitoring (SHM) of RC structures during seismic evaluations.

As a proof-of-concept, sensing rebars were embedded within the wall-slab mock-up. Artificial ground motion test sequences were applied producing cyclic bending. Wavelength/frequency data were recorded by FBG/OFDR units during several runs with accelerations growing up from 0.18 g up to 2 g. Dynamic strain, natural frequencies, and both local (Bragg) and distributed (OFDR) permanent strains were then compared to both modeling and complementary data. OFS sensing reveals itself as a helpful investigation method for Structural Health Monitoring (SHM) of RC structures, in order to assess for seismic degradation mechanisms. To the authors' knowledge, this experiment is a world first involving both *in situ* FBG and OFDR measurements simultaneously in this context.

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## INTRODUCTION

An experimental program has been defined by EDF and CEA with the aim to improve the knowledge of the wall-slab junctions' behavior, by means of reduced-scale mock-ups made of reinforced concrete (RC), representative of NPP building structural elements. In parallel, research is underway in order to propose a constitutive model of the junctions, to represent their contribution in terms of stiffness and strength and to compute the building response under seismic excitations, *e.g.* [1]. The analysis of the degradation behavior of these structures requires dedicated nonlinear numerical simulation softwares (*e.g.* CAST3M code of CEA) accounting for steel plasticity and concrete damage (crack propagation depending upon loading conditions and history).

A wall-slab 1/4-scaled mock-up was designed, constructed and equipped with both OFS and conventional instrumentation (accelerometers, displacement & strain gauges, DIC). Finally, the instrumented mock-up was vibration-tested onto the "Azalée" shaking table, one of the three shaking tables available on the Tamaris platform (CEA) dedicated to seismic evaluations of equipments and structures.

OFS provide a complementary *in-situ* local or distributed strain measurement compared to other methods. Apart from strain gauges, most of them are restricted to surface analysis. Gathering distributed strain data within the structure is thus of considerable interest since it helps reducing experimental variance (on account of the larger number of measurement points) and eventually improving modeling accuracy. Among all OFS applicable to the monitoring of RC structures [3], Fiber Bragg Grating (FBG) and Optical Frequency-Domain Reflectometry (OFDR) sensing techniques are well suited to Structural Health Monitoring (SHM) of RC structures during seismic evaluations. So far, few seismic experiments have involved OFS in view of qualifying damage assessment of RC structures [4-5]. To the authors' knowledge, this experiment is a world first involving both *in situ* FBG and OFDR measurements in this context. FBG sensing provides both static and dynamic local strain analysis while OFDR sensing technique monitors distributed permanent strain.

## MOCK UP DESIGN

The fig. 1 describes the wall-slab 1/4-scaled mock-up under test. The slab was 3-m long and wall and slab thicknesses were 16 cm and 9 cm respectively.

Two sensing rebars were placed along the slab direction, perpendicular to the wall, along X-axis. A first rebar was placed at a distance of 125 mm from the edge while the second one was placed at a distance of 625 mm.



Figure 1. Front (left) and top (right) views of the mock-up mounted onto the "Azalée" shaking table (CEA/DEN)

## MANUFACTURING OF SENSING REINFORCING BARS (REBARS)

Ribbed steel rebars were 2.74-meter long and their diameter was 6 mm. The elastic limit of steel is  $\sim 500$  MPa (*i.e.*  $\sim 0.25\%$  in strain). The fibers were laid inside a groove machined along the rebar length (0.3-mm deep). Finally, larger grooves were machined at each extremity to accommodate steel-armored fiber cables. Each sensing rebar was equipped with seven FBGs, epoxy-bonded at high temperature ( $80^{\circ}\text{C}$ ). Since maximum strain was expected at wall-slab junction, it was decided to cut the fiber in two equal parts, interrogated at both extremities (Fig. 3). FBGs were placed near rebar crossings, of locations indicated on Fig. 2. Three FBGs were photowritten on fiber #1 and #3 while four FBGs were photowritten of fibers #2 and #4.

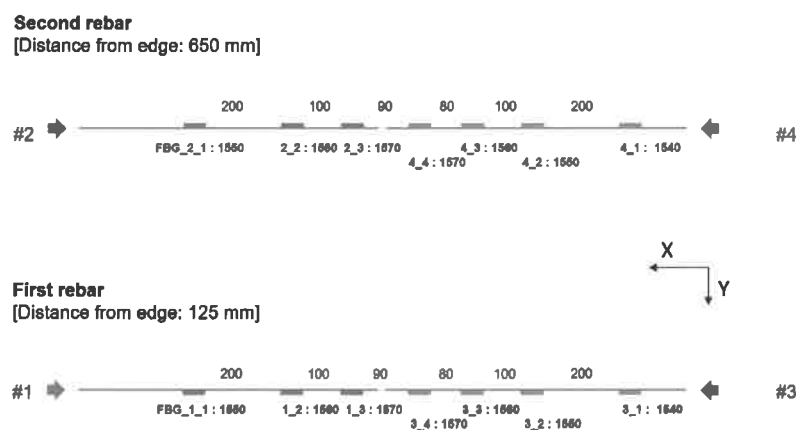


Figure 2. Location of FBGs along the sensing rebars (FBG 4\_4 and FBG 3\_4 were placed at middle part of the slab, on neutral axis).



Figure 3. View of the sensing rebars (equipped with OFS), before embedment within the mock-up.

## MOCK-UP INSTALLATION

Sensing rebars were fixed within the steel reinforcement, along with the other rebars (Fig. 4). Concrete was then poured and vibrated in order to remove excess air. Care was taken not to shock the sensing rebars during the vibration process. The thickness of concrete layer over each rebar was 15 mm. Then, the mock-up was taken up and fixed onto the "Azalée" shaking table, after a 28-day cure (Fig. 1).

The slabs were loaded (1900 kg) to ensure a better consistency with similitude laws and shaking table dynamics capability. The total mass of the specimen was about 4600 kg. In order to account for structural loading, prestressing struds put the wall under compression (up to 3 MPa).

Finally, the mock-up structure was equipped with conventional sensors: accelerometers and displacement gauges were bonded onto the structure surface, and electrical strain gauges were bonded onto steel rebars as well. Finally, DIC was performed by recording images of a speckled front part. 2D displacement data are then derivated in the space domain in order to retrieve 2D strain patterns.



Figure 4. View of the fiber sensing rebars, installed within the mock-up prior to pouring of concrete (FBGs are identified by white markers).

## VIBRATION EXPERIMENTS

### Material and methods

The OFDR device was tuned over the range [1588.18 nm - 1610.42 nm] while the spectral range for FBG interrogation was [1540 nm - 1575 nm]. Both sensing techniques were applied on the same fiber strands. FBG data provide local dynamic strains during excitation and local permanent strains. OFDR data provide distributed permanent strain measurement along fiber length.

Bragg sensing: Bragg wavelengths were monitored during vibration tests with the help of a SI-255 sensing unit (Micron Optics Inc., [www.micronoptics.com](http://www.micronoptics.com)). This device includes a laser tuned in the range [1500 nm – 1580 nm] at a maximum rate of 5 kHz. Data were recorded at a sampling rate of 500 Hz (average = 10). The SI-255 device exhibits a dynamic range of 60 dB and may accommodate up to 8 channels in parallel. Wavelength data are NIST-traceable. The #136 low-threshold (LT) detection algorithm was chosen. The strain sensitivity of FBG was 1.21 pm/microstrain.

OFDR sensing: Strain distribution along the fiber strands were monitored before and after each endurance test using the OFDR technique [6]. The Optical Backscatter Reflectometer OBR 4600 from Luna Inc. was used ([www.lunainc.com](http://www.lunainc.com)). This device incorporates a Continuous-Wave (CW) highly-coherent tunable laser diode. The greater the spectral range, the better the spatial resolution of Rayleigh backscatter distribution (e.g. 40 micrometers for a tuning range of 21 nm). The OBR 4600 exhibits a dynamic range of 70 dB and a measurement range of 70 m in standard mode. For a gauge length of 1 cm, the number of data points used for cross-correlating Rayleigh distributions with the starting one is approximately 250. The correlation provides a frequency shift linked to strain by the relation:  $\Delta\nu$  (GHz) = -0.151  $\epsilon$  (microstrain).

Strain and temperature sensitivities are the same as for FBG sensing. The strain resolution is typically of  $\pm 1$  microstrain. Finally, the response time of the OBR 4600 device is about 10 seconds including laser tuning and Fourier processing, thereby restricting its use to quasi-static experiments, *i.e.* in our case: investigating permanent distributed strain as an indicator of permanent damage over steel rebars.

## Vibration test protocol

Among the three vibrating tables available on the Tamaris platform, “Azalée” is the largest 6-degree-of-freedom (6-DOF) shaking table facility in Europe, operating since 1991 at CEA-Saclay, France [2]. “Azalée” is a plate (6 x 6 m<sup>2</sup>, 25 tons) moved by eight hydraulic actuators of 100-ton force each and 250-mm displacement range each (Fig. 5a), providing 3D excitation (combined vertical and horizontal movements). Its operating area (displacement vs frequency) depends of actuator design and structure mass. The frequency range is typically [0.5 - 50 Hz] and accelerations may exceed 1.8 g. Comparatively, peak accelerations of up to 0.8 g were recorded during the Kobe seism (Japan) in 1995. Reference acceleration spectra are sent to the actuators and realized ones are recorded from accelerometers.

Artificial ground motion test sequences (Fig. 5b) were applied producing cyclic bending in both wall and slabs (horizontal (X): 100 %, vertical (Z): 66 %). Each vibration test lasts about 15 s. Nine vibrations experiments were performed under increasing (measured) accelerations: 0.18 g, 0.35 g, 0.53 g, 0.7 g, 0.89 g, 1.23 g, 1.33 g, 1.6 g and 2 g. Day-to-day temperature variations were recorded in the Tamaris hall in order to compensate for temperature-induced shift of permanent strain. The temperature remained stable within  $\pm 1^\circ\text{C}$  during the experiment.

Before and after each test, a low-acceleration frequency scanning is performed so as to record natural frequencies and to assess for seismic-induced damage.

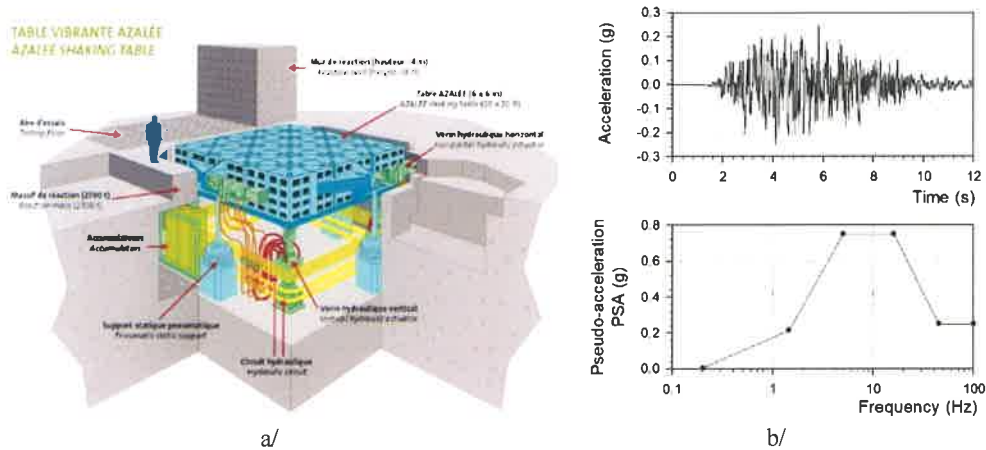


Figure 5. a/ Artist's view of the "Azalée" shaking table (CEA-Saclay),  
b/ Reference temporal signal used for the test (X-direction) and associated target spectrum.

FBG data were recorded during each test while OFDR data were recorded after frequency scanning. Local dynamic strain signals are shown on Fig. 6, zeroed several seconds before the test.

On Fig. 7-right, cumulative strain are indicated for line #1 with respect to reference wavelength.

Fig. 7-left shows consistency between strain data obtained with both electrical strain gauges and FBGs although FBG 4\_3 exhibits a signal higher by a factor of 1.4 probably due to strain gradients within the slab.

## Experimental results obtained with OFS

Under low acceleration value (0.18 g), the structure behaves elastically and no permanent strains are observed. For higher accelerations, the dynamic strain pattern is no longer symmetric due to propagation of cracks (Fig. 6). The crack pattern in the wall-slab junction area is then fixed and major cumulative strains occur in existing cracks.

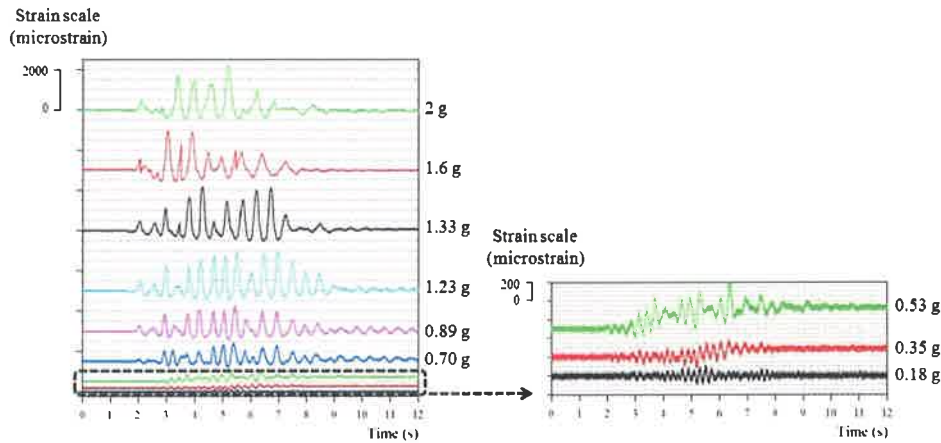


Figure 6. Evolution of strain of FBG 1-1 during successive vibration tests. The dynamic strain signals are shifted upwards for clarity.

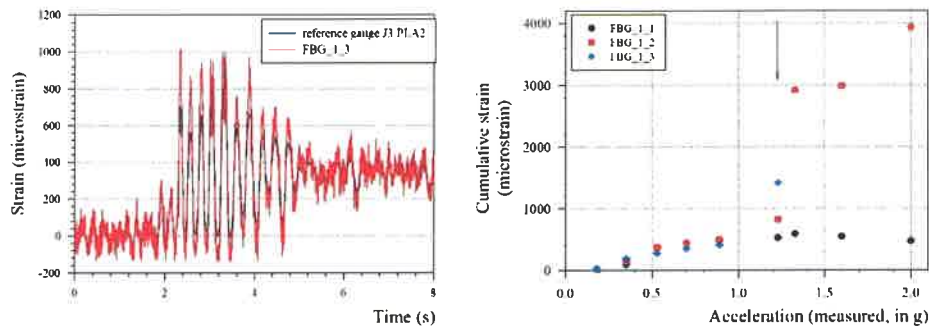


Figure 7. Comparison of strain data obtained during the test at 0.35 g with the electrical gauge (J3 PLA2) close to FBG 4\_3 (left) and evolution of cumulative strain after successive vibration tests as a pertinent indicator of the permanent cumulative damage (right).

The natural frequency of the mock-up structure according to the longitudinal bending mode (along X-axis) drops down as it loses rigidity, due to progressive concrete cracking and other factors. As an example, Fig. 8 (left) shows the Fast-Fourier Transform (FFT) of strain signals recorded from FBG 1\_1 (Fig. 6), giving an indication of the evolution of natural frequencies for this mode. The natural frequency of the X-axis bending mode starts at around 4.8 Hz (pristine structure) and drops down to below 1 Hz at the end of the experiment, witnessing for dramatic loss of stiffness (Fig. 8 (right)). Such a frequency shift cannot be explained by concrete cracking alone, and the boundary conditions at mock-up base (ball-joints and pivots) are certainly involved as well. Nevertheless, in a standard structure, the shift in natural frequency could be



considered a fully pertinent damage indicator. It is worthwhile noticing that its evolution closely follows that of cumulative strain. Finally, the distributed permanent strain measurements yielded from OFDR data are depicted on Fig. 9 and compared to FBG strain data (only results up to 1.23 g are shown for clarity).

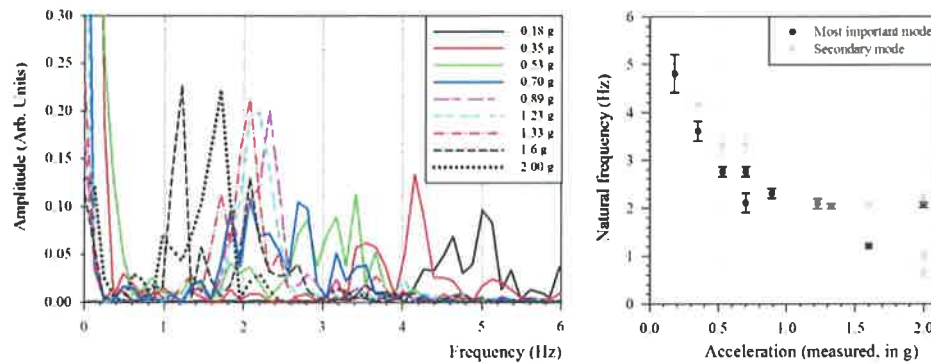


Figure 8. Vibration spectra obtained by FFT of the strain signals from FBG 1\_1 (left) and evolution of natural frequencies of the longitudinal bending mode (right) during successive vibration tests as another pertinent indicator of the permanent cumulative damage.

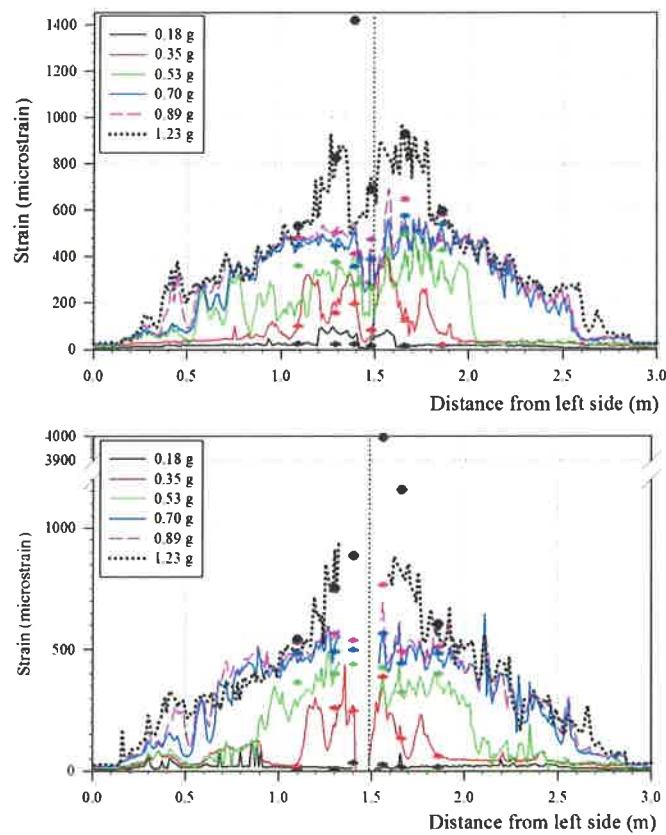


Figure 9. Evolution of permanent strain inferred from OFDR data (lines) and FBG strain data (dots). Top: lines #1 and #3, bottom: lines #2 and #4. Origin taken at left side of the slab, according to Fig. 3.



Strain data are symmetric with respect to wall axis and exhibit triangular-like distributions, indicative of the bending moment for a homogeneous slab. Strain fluctuations are reproducible; they are due to rebar crossings and crack openings. In highly damaged high-strain-gradient zones (*e.g.* wall), OFDR strain data are missing and only FBG data are available, showing higher robustness. No fiber breakage was observed below 1.33 g. FBGs were not proof-tested subsequently to photowriting so that a large range of breaking strains was observed (from 0.22 % up to 0.7 %).

## CONCLUSIONS

In the context of an experimental program EDF-CEA, a wall-slab ¼-scaled mock-up was designed, equipped with conventional instrumentation (accelerometers, electrical strain gauges, DIC) and OFS and finally vibration-tested onto the "Azalée" shaking table of the Tamaris platform (CEA-Saclay, France).

OFS provide complementary *in-situ* local and distributed strain measurements with the aim to improve modeling accuracy. FBG and OFDR sensing techniques were both implemented within the mock-up along with conventional instrumentation. As a proof-of-concept, OFS were directly epoxy-bonded onto two steel rebars, oriented perpendicularly to wall plane within the structure before concrete pouring.

Artificial ground motion test sequences were applied producing cyclic bending in both wall and slabs. Wavelength/frequency data were recorded by both instruments during several runs with accelerations growing up from 0.18 g up to 2 g. Dynamic strain signals and natural frequencies of the longitudinal bending mode were recorded, confirming that natural frequency shift is a pertinent damage indicator. Both local (Bragg) and distributed (OFDR) permanent strains were compared and used as input data for numerical modeling. Bragg sensing turned out to be more robust than OFDR sensing particularly in highly damaged high-strain gradient zones.

OFS sensing reveals itself as a helpful investigation method for SHM of RC structures, in order to assess for seismic degradation mechanisms. *In situ* distributed strain data helps reducing experimental variance and improving modeling accuracy.

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