Damage Assessment in a Reinforced Concrete Structure under Quasi-Static Shear Loading Using OFDR-based Fibre-Optic Distributed Strain Monitoring

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ABSTRACT

EDF and CEA have established an experimental program to improve knowledge of the behavior of wall-slab junctions under both out-of-plane bending and in-plane shear. The program involved reduced-scale mock-ups made of reinforced concrete (RC) that are representative of the structural elements of nuclear plant buildings. In parallel to vast experimental campaigns, numerical models of the junction under study are derived and calibrated in order to improve the computation of building responses under seismic excitations. The analysis of damaging process of these structures is reproduced by nonlinear numerical simulations, realized within the Finite Element framework CAST3M developed at CEA (www-cast3m.cea.fr/) and code Aster (https://code-aster.org), which account for steel plasticity and concrete damage, including crack propagation based on loading conditions and history.

Of all the distributed techniques applicable to the Structural Health Monitoring (SHM) of RC structures, Optical Frequency-Domain Reflectometry (OFDR) is well suited because of its high spatial resolution. The OFDR principle relies on swept-wavelength homodyne interferometry. Light from a tunable laser source is split and sent through sensing and reference fibers, both being arms of an interferometer. The backscattered light recombines at an optical detector and an interferogram is recorded as the laser frequency is tuned. The spectral-domain signal is then Fourier-Transformed to yield the backscattering profile along the fiber. Finally, the fiber is segmented into successive centimeter-long gage lengths and a cross-correlation procedure provides the strain profile with respect to a reference state.

We implemented the OBR4600 OFDR device from Luna Innovations. The OBR 4600 is a single channel device that provides static distributed strain monitoring over a range of 70 m, with an accuracy in strain of ±5 µm/m, a spatial resolution (gage length) of about 5 mm, and a readout time of typically 10 seconds.

On the last mock-up of the experimental program, the jacks applied quasi-static displacements ranging from 0.69 mm to 11.49 mm, yielding progressive structural damage and eventually reaching concrete crack and steel plasticity. Strain profiles and natural frequencies were determined and compared to the modeling. Distributed Fiber Optic Sensing (DFOS) results provide access to continuous strain distributions along the instrumented rebars, localize deficiencies and local deformations around rebar crossings and also the emergence of concrete degradations in the joint. The OFDR technique enables highly reliable *in-situ* SHM of damage mechanisms within concrete structures, providing effective data for model verification and validation used in safety-related structures assessment.

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INTRODUCTION

In collaboration with EDF, CEA has implemented an experimental program aimed at improving the understanding of the behavior of a representative reinforced concrete structural element, the shear wall-floor slab junction (JVP2), commonly used in nuclear power plant (NPP) buildings. The objectives of this campaign are to better understand the behavior of shear wall-floor connections in seismic conditions and to provide a validation basis for numerical simulations used in engineering studies. In addition, a more precise instrumentation is needed to determine the local behavior of structures in order to optimize equipment sizing in accordance with seismic resistance standards [1]. EDF is thus seeking to assess the vulnerability of civil engineering structures used in French NPPs facilities and to provide the French Nuclear Authority (ASN) with reliability guarantees in the event of a potential seismic event, using a combined approach of simulation and experimentation [2].

To meet these needs, CEA Paris-Saclay owns an outstanding testing platform in Europe: the TAMARIS seismic testing platform. EDF's goal was to create 1/4-scale models to evaluate their behavior during calibrated seismic tests, combining simulation techniques (CAST3M, Code_Aster) and progressive damage analysis. These models are equipped with conventional instrumentation (displacement sensors, accelerometers, strain gauges and imaging) and their testing protocols were defined in collaboration with CEA (DES/DM2S).

As part of this study, EDF and CEA DES decided to reinforce the instrumentation of the reinforcing bars (rebars) of the tested specimen by implementing optical fibre sensing (OFS) in addition to the conventional solutions mentioned above. Fibre optic measurements offer several significant advantages for SHM applications [3]. First, they allow for *in situ* measurement of the relative elongation of the rebars that make up the reinforced concrete. This feature provides a better understanding of the evolution of damage, knowing that when the concrete fractures, most of the load is taken up by the rebars. In addition, this technology allows for much greater measurement capacity (typically several hundred points distributed over the entire length of each rebar), thus providing distributed measurement. This allows for more precise and comprehensive analysis of the tested structure [4].

CEA LIST has selected the OFDR (Optical Frequency-Domain Reflectometry) metrology technique [5], which allows for low frequency measurement of strain profiles along the optical fibre attached to the rebar.

MOCK UP DESIGN

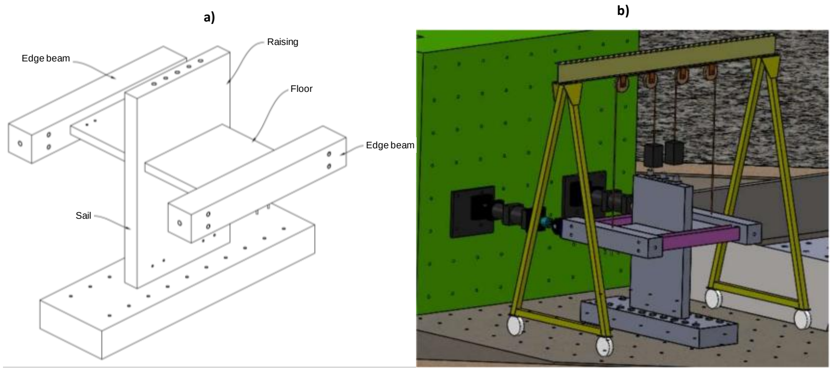

Figure 1 : **a)** Geometry of the model incorporating six rebars equipped with fibre optic measurement lines, **b)** Model in test configuration on the reinforced floor, with jacks anchored to the reaction wall.

The mock-up is composed of a vertical wall, two floors, a riser, two edge beams at floor ends and a base, anchored on the strong floor (Figure. 1.a). Rebars are placed according to Figure. 2. Six rebars were instrumented with optical fibers. Two rebars were placed along the longitudinal axis and the four others were placed transversally. Two hydraulic jacks were anchored on the reaction wall and placed in parallel along edge beams (Figure. 1.b). They were monitored under push-pull action and imposed a symmetric transversal loading at floor level (servo-controlled in order to avoid structure twist). Finally, additional instrumentation (displacement sensors, accelerometers, strain gauges and Digital Image Correlation (DIC)) was carried out onto the structure.

SENSOR INSTALLATION

The nomenclature of the six instrumented rebars includes optical switch channel number, rebar diameter and length, its position related to the jack (Front, Rear) and the floor (Up, Down), and the distance from either the axis, edge of the floor (See Figure. 2).

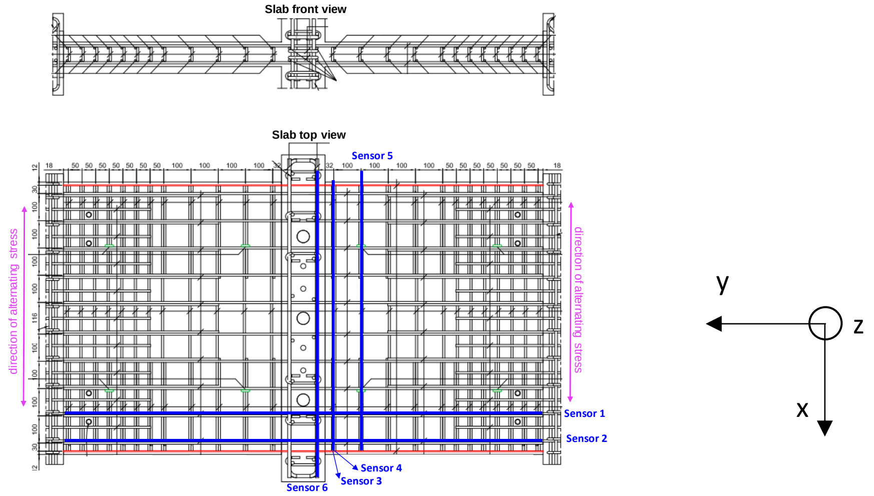

Figure 2 : (top): Drawing of the location of the optical fibres in the mock-up floor and (bottom) Top view of the instrumented floor before closing the formwork.

Figure 3 : a) Mounting of an instrumented rebar onto the reinforcement grid (steel wire set tight with an Archimedes screw tool) b) View of a half-part of the mock-up and laser level.

We assessed an implementation protocol of optical fibers within rebars that involves rebar-to-fiber strain transfer qualification, machining and mechanical protection (compatible with concrete elaboration) [1]. In our study, a 0.3-mm deep V-groove is machined onto the surface of each rebar. The optical fiber is bonded inside the groove using a two-component adhesive. The optical fiber outputs are protected by a 2.3-mm diameter metal-ringed cable, held in a groove at each end of the bar, and extended by a second sheath (7 mm diameter) that emerges from the concrete (Figure. 3). We spliced each fiber end to an E2000 PC/APC pigtail compatible with the instrumentation.

QUASI-STATIC SHEAR LOADING EXPERIMENTS

Monitoring of strain profiles along rebars using the OFDR technique

The Optical Backscatter Reflectometer OBR 4600 from Luna Inc. (www.lunainc.com) was used with an optical switch. The OBR 4600 exhibits a dynamic range of 70 dB and a measurement range of 70 m in standard mode [6]. The strain resolution and uncertainty are typically ± 1 µm/m and ±5 µm/m respectively. The average measurement time is 10 seconds, including laser tuning and Fourier processing, thereby restricting its use to quasi-static experiments. In our case, we investigated distributed strain profiles as an indicator of permanent damage over steel rebars.

The OBR4600 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). In our case, it was tuned over the range [1588.18 nm - 1610.42 nm]. 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 $\Delta\varepsilon$ (strain change with respect to a reference strain).

Quasi-static shear loading test protocol

OFDR measurements were carried out at a rate of one run each day, in the morning, in the same environmental conditions (the temperature was stable during all the test campaign). Reference measurements were made on the first day and used throughout the entire campaign. The recorded strains are therefore cumulative. Each run is composed of three low-speed push-pull saw-tooth type cycles in the y-direction to damage the specimen by applying stress along the axis of maximum rigidity (Figure. 4a). A run is defined by the maximum displacement value and its speed (m/s). During the first cycle, the maximum and minimum loading stresses are maintained for a few minutes to allow for the non-automated sequential acquisition of the six sensors by the OBR4600 (See Figure. 4a). Twenty-eight run tests were performed on the model for progressive jack control displacement from 0.68 mm up to 11.49 mm.

Each run N is followed by a frequency test noted N+1, aiming to record the natural frequencies (NF) of the model in order to characterize its damage. A frequency test consists in applying a complex excitation of constant amplitude over a wide frequency band (several hundred Hertz). More specifically, two statistically independent commands are specified to the actuator controller to apply a white-noise type excitation along the y-axis combined with a secondary (uncorrelated) torsion excitation along the z-axis. The accelerograms recorded during the frequency tests are processed using a modal identification algorithm based on subspace detection [7].

Frequency Analysis

The figure below (Figure. 4b) shows the evolution of natural frequencies during the course of the test, as reliable damage indicator. Three regimes can be distinguished:

- A linear elastic regime for jack displacements in the range [0.69 - 4.3 mm],
- A second non-linear regime in the range [4.3 - 8.3 mm], exhibiting a clear change in slope,
- A significant drop for the last four displacements that can be attributed to a non-linear and non-elastic regime.

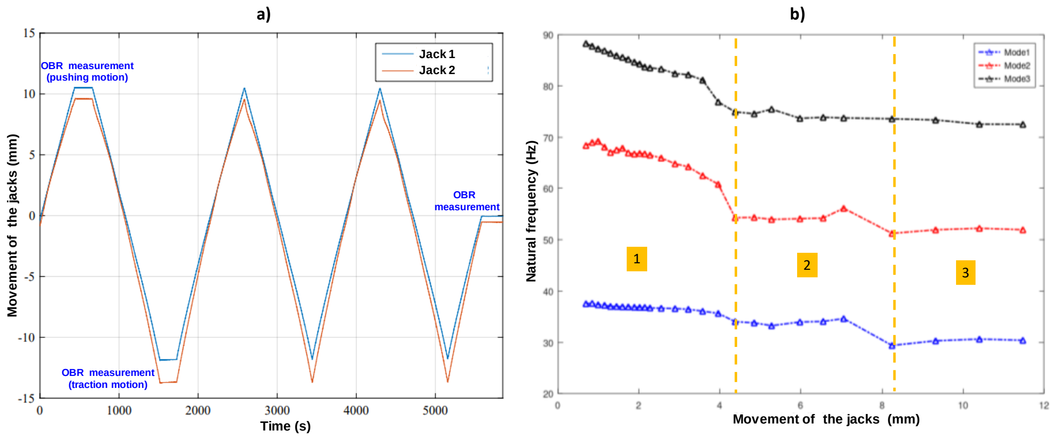

Figure 4: **a)** Example of a measurement cycle (data from actuator controller), and **b)** Evolution of natural frequencies of the dominant modes (along y-axis) with respect to run test number, showing three regimes.

Experimental OFDR results

Figure 5.a shows the evolution of the strain profiles along rebars #1 and #4 during the tests. In light of NF data, three regimes can be distinguished:

i. **A linear elastic regime** in the range [0.67 mm-1.67 mm].
Maximum strain starts from 200 µm/m up to 900 µm/m, probably due to the intertwining of the steel bars. Additionally, a mirror effect is observed for the compression stress profile, but with a minimum strain (~ -450 µm/m) that is about half the maximum one. At this stage, no crack nor damage are observed in the structure.

ii. **The nonlinear elastic regime** in the range [2 mm-4.38 mm].
This regime corresponds to a loss of structure stiffness due to progressive damage and cracks in concrete. The maximum strain range from 1200 µm/m to 2000 µm/m (proportional to the displacement of the actuators). The minimum strain remains constant at -1000 µm/m, which is half the maximum strain. Higher strain amplitudes are associated with superficial cracks and progressive loss of stiffness.

iii. **A nonlinear non-elastic regime** in the range [8.25 mm-11.49 mm].
This last regime is characterized by a dramatic increase in maximum strain, reaching up to 3500 µm/m. Also visible are signal oscillations, indicating structural damage. It should be noted that for large displacements (d > 8.25 mm), superficial cracks can propagate deep into the structure.

Figure. 5.b shows the evolution of the strain profile over the 980-mm long rebar #4. In the first regime, the maximum strain in both push and pull loading configurations does not exceed

100 µm/m. In the second regime, the maximum strain is 350 µm/m and we note a significant strain difference for both push and pull configurations. Finally, in the third regime, a non-linear/non-elastic regime is observed, with no compressive strain. The maximum strain is stable (between 800 µm/m and 1000 µm/m) regardless of the configuration.

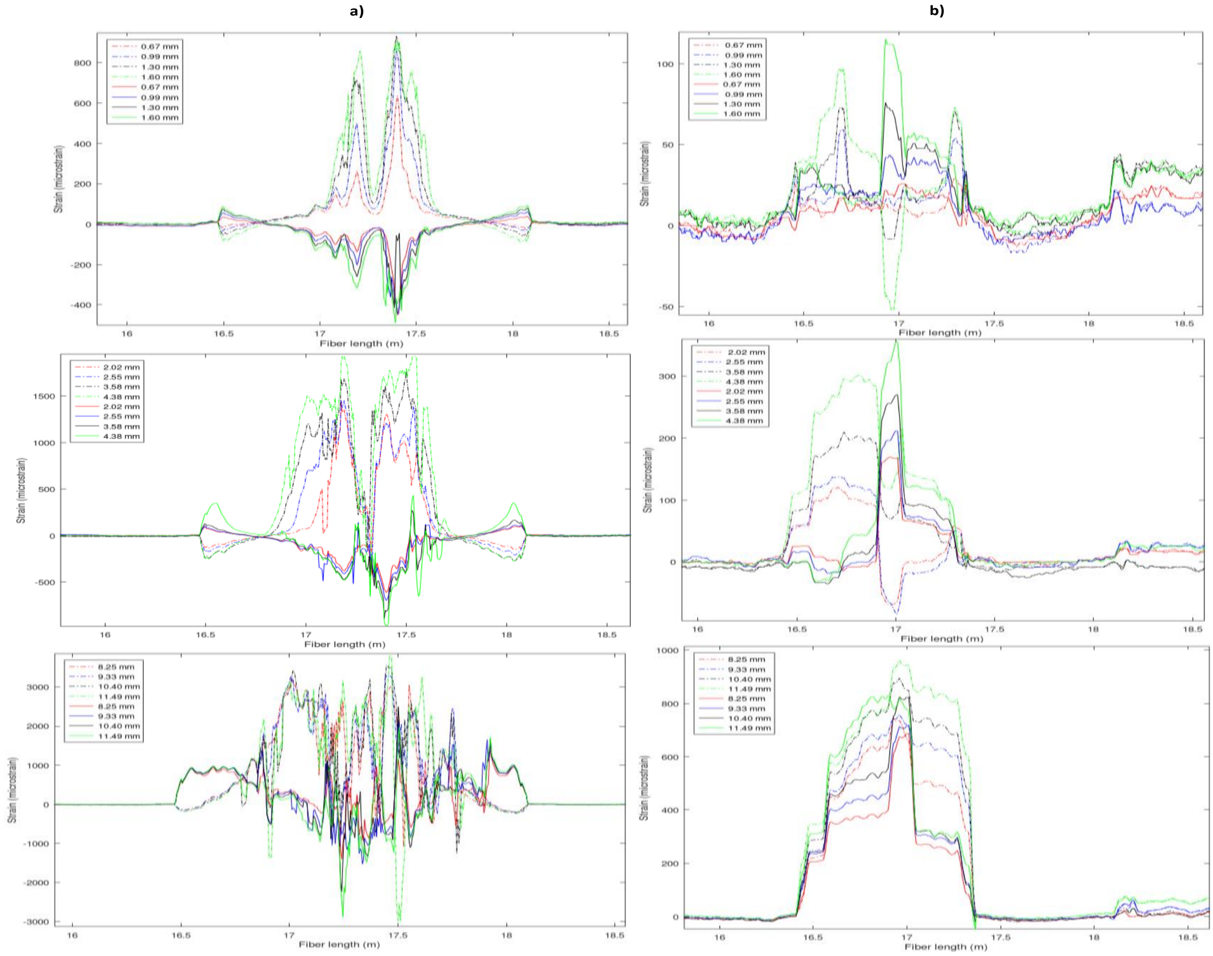

Figure 5 : Evolution of strain profiles for different displacements recorded on rebar #1 a) (along x-axis, perpendicular to loading stress), and rebar #4 b) (along y-axis, parallel to loading stress). **Top**) linear elastic regime, **middle**) nonlinear elastic regime and **bottom)** nonlinear, non-elastic regime. Strain profiles in continuous and dashed lines are under push and pull loading configurations respectively.

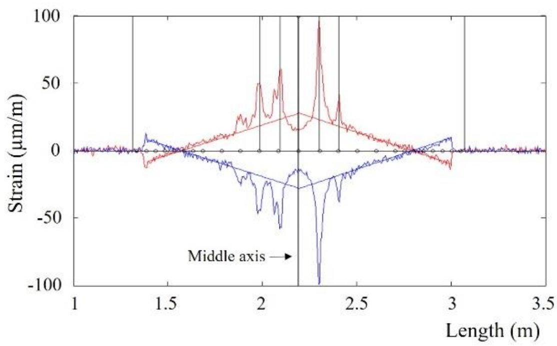

Figure 6 *:* Strain profiles for rebar #1 (Run 51: ± 0.69 mm) and linear approximation, with rebar locations.

Furthermore, we performed an analytical calculation for the bending strain distribution along the floor under concentrated load, in the elastic regime (Figure. 6). The longitudinal strain follows the moment diagram and is linearly dependent with distance to middle axis. Over the strain baseline, strain peaks are also visible and are due to rebars crossing. These peaks are correlated to cracking trigger in concrete and plastic strain generation in the reinforcement at the concrete crack crossing.

CONCLUSIONS

As part of an EDF-CEA experimental program, a 1/4-scale mock-up of a wall slab junction (JVP2) was designed, equipped with conventional instruments (accelerometers, electrical strain gauges, DIC) and optical fiber sensors (OFS). 6 rebars were instrumented with optical fibres and inserted into the mock-up before concrete pouring. The mock-up was finally tested under quasi-static shear loading by hydraulic jacks on the Tamaris platform (CEA-Saclay, France).

OFS provide complementary *in-situ* measurements of local and distributed strain in order to improve modelling accuracy. We implemented the OBR4600 OFDR device (Luna Innovations) in conjunction with an optical switch. Strain profiles were recorded sequentially along the six rebars during loading stabilization.

Quasi-static movement test sequences were applied to the mock-up, producing progressive structural damage and eventually reaching concrete crack and steel plasticity. As a relevant damage indicator, the measurement of natural frequencies of the longitudinal bending mode allowed us to distinguish three different regimes: i) a linear elastic regime, ii) a second non-linear regime, and iii) a non-linear and non-elastic regime. These three regimes are observed on distributed permanent strain profiles as well. All these experimental data are used as input data for numerical modelling. The OFDR technique applied to OFS rebars proves to be a useful investigation method for SHM of reinforced concrete structures, in order to evaluate seismic degradation mechanisms. *In-situ* distributed strain data allows to reduce experimental variance and improve modelling accuracy.

REFERENCES

1. Magne S. *et al.*, "*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," l2th Intemational Workshop on Structural Health Monitoring (IWSHM), Stanford (USA), September 10-12, 2019.
2. Hervé-Secourgeon E. *et al.* "Towards a model for wall-slab junctions in nuclear reinforced concrete structures: first steps," in *TINCE Conference*, Paris-Saclay, France, August 29-31, 2018.
3. Zhang, W., Gao, J., Shi, B., Cui, H., Zhu, Health. H. 2006. "Monitoring of Rehabilitated Concrete Bridges Using Distributed Optical Fiber Sensing," *Comput.-Aided Civ. Infrastruct. Eng.* 21, 411–424.
4. Woods, J., Lau, D., Bao, X., Li W. 2015. "Use of a Novel Distributed Fiber Optic Strain Measurement System in the Seismic Retrofit of RC Shear Walls," in *6th Int. Conference on Advances in Experimental Structure Engineering*, Univ. of Illinois, Urbana-Champaign (USA).
5. Eickhoff W., Ulrich, R. 1981. "Optical frequency-domain reflectometry in single-mode fibers," *Appl. Phys. Lett.*, 39 (9), pp. 693–695.
6. Luna Technologies Inc. "OBR 4600 Optical Backscatter Reflectometer," Roanoke, VA, USA, 2019.
7. Charbonnel, P.-E. 2021. "Fuzzy-driven strategy for fully automated modal analysis: Application to the SMART2013 shaking-table test campaign," *Mech. Syst. Signal Process 152*, 107388**.**