Assessing Cracking Characteristics of Concrete Structures by Distributed Optical Fiber and Non-Linear Finite Element Modelling

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ASSESSING CRACKING CHARACTERISTICS OF CONCRETE STRUCTURES BY DISTRIBUTED OPTICAL FIBER AND NON-LINEAR FINITE ELEMENT MODELLING

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ABSTRACT

This work shows how the experimental strain data obtained with an OBR (Optical Backscattered Reflectometer) measuring system can be used to locate cracking before being visually observable and also to estimate the crack width for different levels of load. The method is checked in a test up to failure carried out on a reinforced concrete slab, where the deployement of other standard sensors allowed to validate the results from the OBR system. The results are also compared with those coming from a 2D non-linear finite element model, showing also a good agreement.

KEYWORDS : *Distributed Optical Fiber Sensor, Non-linear FEM,Cracking detection.*

INTRODUCTION

Optical fiber is a transmission medium usually employed in data networks. A very glass thin wire (125 µm of diameter that is to say, as about the thickness of a hair) transfers data, through their lights pulses transmitted. Bundle light is completely confined and is propagated inside the fiber with an angle reflection above the critical limit angle of reflection, according to Snell's law.
Optical fibers are widely used in telecommunications, due to the ability to send a large amount of data over a long distance with similar speeds to radio or cable. They are the main transmission medium in telecommunications due to their insensitivity to of electromagnetic interference.
Nowadays, the continuous or regular measurement and analyses of key structural and environmental parameters under operating conditions, for the purpose of warning impending abnormal states or accidents at an early stage so as to avoid casualties as well as provide maintenance and rehabilitation advice, is one of the most important issues in Structural Health Monitoring (SHM).
The deployment of fiber optic sensors for structural health monitoring has been used for the past 30 years. Over these years, the technique has been developed to obtain measurements with accuracy similar to the standard strain gages and extensometers. The current state of the art offers three types of fiber optic sensors for structural health monitoring: Local fiber optic sensors (interferometric FOSs local sensors), quasi-distributed sensors (Fiber Bragg grating (FBG) sensor), and distributed fiber optic sensors such as the optical time domain reflectometry (OTDR) or the Brillouin scattering.
Several experiences have demonstrated the feasibility of using the Distributed Optical Fiber System OBR (Optical Backscattered Reflectometer) in the structural health monitoring of existing concrete structures [1,2,3] . This SHM technique has shown very effective in the detection and localization of initiating cracking in the concrete, either because of the increasing applied external loads or because of environmental actions as temperature and wind. Also, the distributed strain data has been used to calculate the deflection in selected points of the structure [1]. However, the continuous (in space) monitoring of the strain along the optical fiber, including the crossing of a crack provides additional information that can be used in further SHM applications. In the present paper, it is described how these data can be used to obtain crack width. This information is of paramount

importance concerning durability and long term performance of concrete structures. To this end, strategies for the computational simulation of reinforced concrete structures are proposed and then checked using the results of a test carried out in a reinforced concrete slab.

OPTICAL BACKSCATTERED REFLECTOMETER (OBR): DESCRIPTION AND BACKGROUND

Distributed optical fiber sensors are based on the intensity modulation of light travelling inside an optical fiber bonded to a deformable surface. The characteristics of the light are well known and they are modified as a function of the temperature and strain of the fiber. These changes are monitored in the back-scattered light and they are finally translated to strain and temperature changes in the surface [4]. In the back-scattered light process, 3 components or spectral bandwidths can be seen, named as Raman, Brillouin and Rayleigh scattering. Their analysis has derived on the 3 known methods of sensoring by distributed optical fiber. In the figure 1 are shown those bands and it can be also seen the low intensity of the Raman and Brillouin spectral bands as compared to the Rayleigh one.

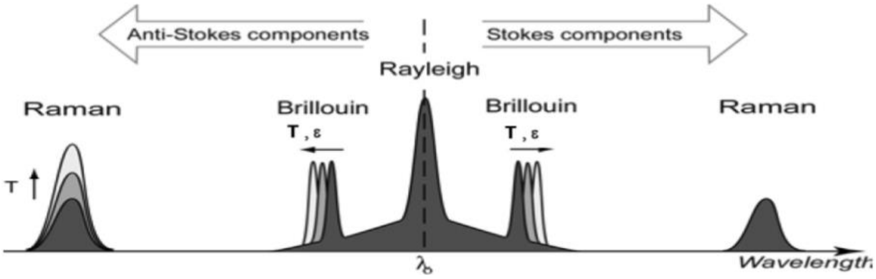

Fig 1. Wavelengths of the backscattered radiation

This fact derives on the different fields of application. The systems based on the Raman scattering are only used for temperature monitoring. The Brillouin based systems can measure temperature changes and strain, but it is extremely difficult to get good accuracy and resolution. The maximum spatial resolution is in the order of 1 meter. Therefore, these systems are used to monitor in very long distances, up to some kilometers. However, they are very limited in the detection of local phenomena as cracking in a material.

Recently, the Rayleigh scattering has been applied to the measurement of strain and temperature with a spatial resolution around millimeters [4]. The main issue is the use of the so-called Optical Backscattered Reflectometry (OBR). OBR is based on a frequency-domain technique, optical frequency-domain reflectometry (OFDR) that uses a tunable laser and an interferometer to probe reflections. Frequency domain techniques are usually used to analyse systems on the component-or module-level when very high resolution (microns) analysis of the reflections in a system is required. Optical backscatter differs from other frequency-domain techniques in that is sensitive enough to measure levels of Rayleigh backscatter in standard single mode fiber. The OBR uses swept wavelength interferometry (SWI) to measure the Rayleigh backscatter as a function of length in an optical fiber with high spatial resolution (at a strain and temperature resolution as fine as 1 microstrain and 0.1 °C). An external stimulus (like a strain or temperature change) causes temporal and spectral shifts in the local Rayleigh backscatter pattern. These temporal and spectral shifts can be measured and scaled to give a distributed temperature or strain measurement [5].

CONCRETE SLAB TEST

The OBR measuring system was deployed in a concrete slab of an experimental campaign conducted in the Structural Technology Laboratory of Technical University of Catalonia (UPC-

BARCELONATECH) [5,6]. Dimensions of the reinforced concrete slab were 5.6 m span length, 1.60 m width and 0.285 m thickness. The slab was simply supported at both ends and the loading was applied using an actuator of 1 MN capacity in the mid-span of the slab. The slab was monitored with OBR sensors at the top and bottom surfaces, exactly in the four stretches as show in Fig. 2. The slab was also monitored in the reinforcing steel bars with dynamic strain gauges. Deflection was measured at the center and ends of the slab using linear displacement transducers (LVDT). Joint opening at the middle of the slab was measured from their initiation using magnetic transducer “Temposonics” as seen in figure 2 (right).

Figure 2: Load arrangement and location of optical fiber and joint opening sensors

Strain Distribution

During the test, the strain distribution along the slab was mesured by the OBR system. Two measured results in the third stretch at different load levels (50 kN and 110 kN) are shown in the Fig 3. The measurements are in good agreement with the analysis, and apparent strain distribution peaks appear at 50 kN, around the middle of the span. The location of the peaks corresponds quite well to the crack location visually observed. Based on these data and other experimental results coming from the standard monitoring by strain-gages and LVDT, three non-linear finite element models of the slab were proposed and calibrated.

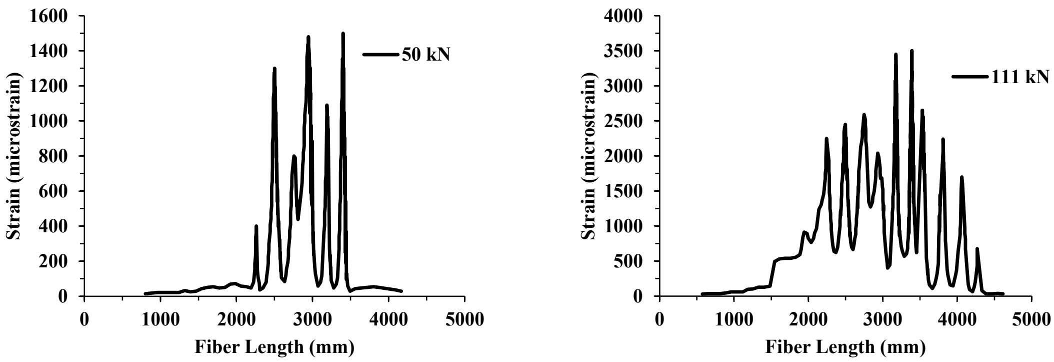

Figure 3: Strain along the fiber length (third stretch bottom side) for 50 kN and 110 kN

NON-LINEAR FINITE ELEMENT MODEL

The cracked behaviour of reinforced concrete structures may be modelled by discrete or smeared crack models. In the first case, the element remains always continuous and without damage. The cracks are modelled by displacement discontinuities between elements. In this way, the cracks can only develop through the element boundaries and to obtain the direction of crack propagation, the FEM mesh has to be progressivelly adapted or interface elements have to be used. The analysis with these models becomes very cumbersome and therefore are used to follow the propagation of singular cracks, but are not normally used to model a global crack pattern.

The smeared crack models are defined by : a failure criteria (constant or linear), a transfer across the crack (total, constant or variable) and a law to smooth the material behaviour (brittle, linear, exponential. The cracked material is worked out as continuous and the discontinuity of the displacement field due to cracking is extended over the whole element. Therefore, these models are a non-discrete global approximation to a process that is esentially discrete. However, they derive acceptable results in practical applications [7,8]. This approach is useful because does not impose any cracking direction. These models can be fixed or with rotation. In the first case, the cracking direction is the same during the all computational process (bending cracks). In the second case, they allow the co-rotation of the principal strain axes (shear-bending cracks) [8].

The concrete slab is modelled with 2D plain stress elements, with a total of 821 nodes and 239 square elements with 9 Gauss points. The reinforcing bars are modelled by elements with perimeter and sectional area identical to the real re-bars. The upper and bottom reinforcements consists of 7 bars each, with 16 and 20 mm diameter respectivelly. The concrete cover is 30 mm. (see figure 4) The steel yield strength is 550 MPa. The concrete properties are those obtained in the tests [5]. The compressive strength is f_c=51.31 MPa, and the tensile strength f_t=4.00 MPa. The elasticity modulus is 33,147 MPa.

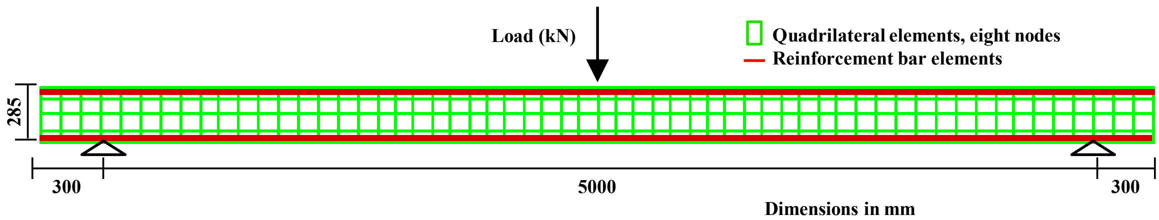

Figure 4. Mesh of Finite Element Model

The DIANA software [9] is used to model the test with 3 different scenarios : brittle behaviour of concrete (figure 5 left) with rotating cracks (FEM1) or fixed cracks (FEM2), and tensile strength with exponential decrease (figure 5 center) (FEM3). In all cases the stress-strain law in compression is according to Spanish Code [10] adjusted by a multilinear law (figure 5 right).

Results: model calibration

In table 1 are presented the measured deflections in the mid-span section and those coming from the 3 models. The models FEM1 and FEM2 give very accurate results. The results are grafically displayed in figure 6. Figure 7 shows the results obtained in each load step by the 3 models. It is clearly visible the change of stiffness at the level of 50 kN for FEM1 and FEM2, which corresponds to the appearance of the first cracks. In FEM3 cracking appears at around 100 kN, despite the deflection at failure becomes more similar to the other 2 models.

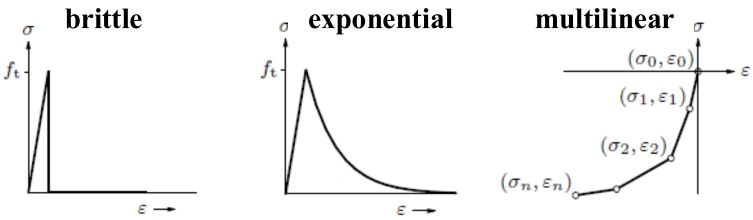

Figure 5: Tension and compression behaviour of concrete for FEM models

Table 1: Deflections at mid-span

Load (kN)	Experimental Deflection (mm)	FEM 1 Deflection (mm)	FEM 2 Deflection (mm)	FEM 3 Deflection (mm)
20	0.498	0.584	0.584	0.584
60	3.833	3.53	3.53	1.752
100	10.166	11.38	10.5	5.548
140	16.543	18.10	16.7	14.01
180	22.324	25.11	22.6	21.31
204-220	29.227	29.3	29.3	29.3

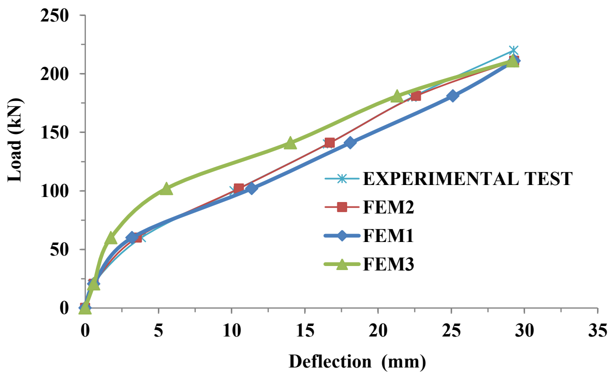

Figure 6: Experimental and FEM deflections

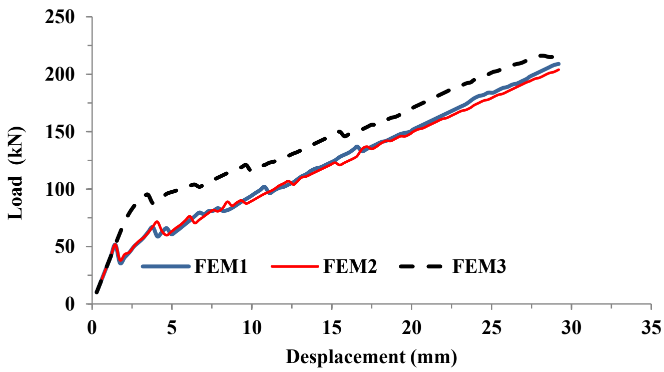

Figure 7: FEM max deflections in the middle of the slab

Crack pattern, location and width

In tables 2 and 3 are shown the strains measured by the OBR systems and those predicted by the FEM models at those points where cracking appeared (peaks) for load levels of 50 and 110 kN.

Table 2. Micro strains 50 kN

Peaks (mm)	με OBR	με FEM1	με FEM2
1953	0	0	0
2258	400	594	997
2456	1300	741	1134
2758	800	570	997
2932	1480	567	1223
2991	0	0	0
3185	1090	699	997
3382	1500	587	1223
3525	0	0	0
3795	0	0	0
4066	0	0	0
4270	0	0	0

Table 3. Micro strains 110 kN

Peaks (mm)	με OBR	με FEM1	με FEM2
1953	800	2950	1814
2258	2250	3002	1910
2456	2450	2963	1385
2758	2590	2279	2086
2932	2040	2324	2091
2991	1550	1201	2962
3185	3450	2326	2126
3382	3500	802	2369
3525	2650	966	2962
3795	2240	2129	2022
4066	1700	1295	2031
4270	675	700	---

From tables 2 and 3 we can conclude that the best approximation to the real strains is obtained with model FEM2 (crack pattern without rotation), as expected for a test zone mainly in bending. In figure 8 we can see the comparison between the experimental crack pattern and the one obtained with FEM2 for a load level of 110 kN at mid-span. In figure 9, the experimental and theoretical (FEM2) strain law are compared for two levels of load, showing a good fit. The theoretical values are obtained linking the points of cracking strain at the Gauss points of interpolation and taking into account the dimension of the corresponding finite element. The location of these points in the model are the closest to the peaks of strain identified in the test. The OBR system detected an early cracking at low level of load around 50 kN. The crack width could be experimentally obtained by the standard instrumentation but only in the points where the sensors were deployed (mid-span).

These values are shown in table 4 for different load levels and compared with the values obtained with the OBR system and the theoretical models FEM1 and FEM2. Again FEM2 provides the most accurate results.

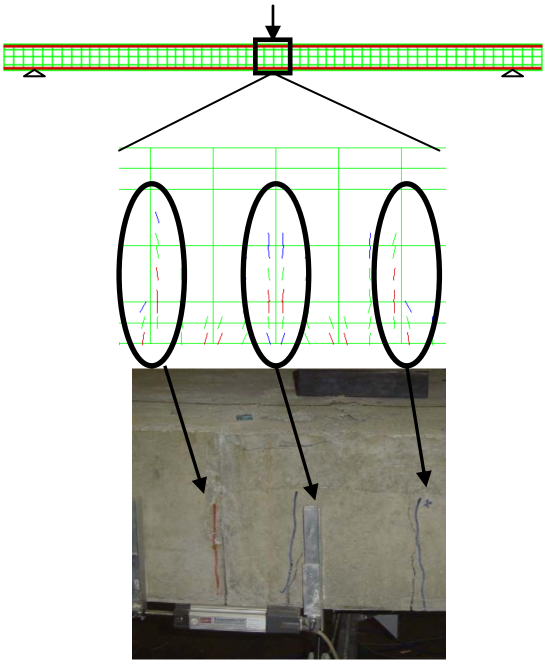

Figure 8. Comparison of experimental and theoretical crack patterns at mid-span

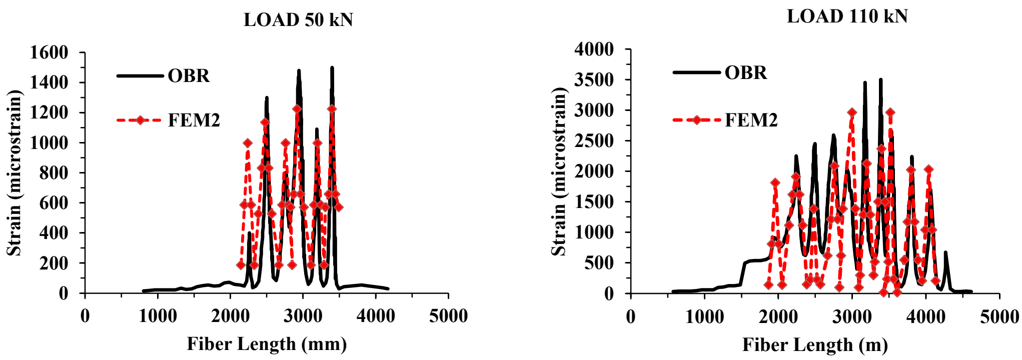

Figure 9. Comparison of experimental and theoretical strain along span

CONCLUSIONS

The experimental data obtained in the test allowed to calibrate a non-linear model for the concrete slab. Once calibrated, the model can be used to predict cracking location and width in different parts of the specimen. The OBR system deployed allowed to predict the formation of the initial cracking, the location of the cracks and also their width based on the continuous monitoring of strain along the optical fiber. The obtained results compare very well with the available experimental values obtained from the rest of the sensors as well as with the visual inspection and the values predicted by the non-linear finite element models. This validates the use of OBR sensoring system as a method for SHM of concrete structures.

Table 4. Crack width at mid-span

Load (kN)	Crack Width Transducer (mm)	Crack Witdth OBR (mm)	Crack Width FEM1 (mm)	Crack Width FEM2 (mm)
20	0.023	---	----	----
50	0.079	0.06	0.049	0.052
60	0.094	---	0.0705	0.106
70	0.116	0.11	0.132	0.138
100	0.130	---	0.174	0.152
111	0.157	0.19	0.202	0.206
140	0.284	---	0.245	0.259
180	0.420	---	0.482	0.409
220	0.594	---	0.552	0.533

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