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Quantification of cracks in reinforced concrete structures using distributed fibre optic sensors

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Abstract

Even under normal service loads, reinforced concrete structures in the field of civil engineering are full of micro cracks. More than twenty years of development of distributed fibre optic sensing techniques in terms of accuracy and spatial resolution made them capable of not only monitoring strain and temperature changes, but also detecting and localizing cracks. In order to detect safety-related issues and better maintenance and to offer better maintenance and management strategies, continuous monitoring of the crack width is also paramount. The paper focuses on the application of a theoretical mechanical strain transfer model in concrete substrate. The experimental setup involved employment of the Optical Frequency Domain Reflectometry (OFDR) technique with high spatial resolution. Three-point bending tests were performed on 1m length reinforced concrete beams instrumented with embedded and surface attached fibre optics cables. Results showed that the Crack Opening Displacement (COD) in single and multiple neighboring micro cracks cases can be well estimated.

1. Introduction

The importance of civil infrastructures for growth of modern countries is now relatively well recognized. However, the excessive use of existing ones has led to their accelerated deterioration. Together with the widespread corrosion of steel rebar, overall aging and fatigue loads, the situation becomes worrying. Most of the local damage in a structure is revealed by cracks. Thus, monitoring cracks at the micro level is important to give assurances of a structure's strength and serviceability, reduce down time during structural repair and upgrade works. For a long period of time, visual inspection and some traditional Non Destructive Testing (NDT) techniques were commonly used to detect cracks. While these techniques are expensive and time consuming, Distributed Optical Fibre Sensors (DOFS) have emerged giving hope of achieving a more accurate, reliable and quasi real-time crack detection and characterisation. Measurement systems are composed of an interrogator and an optical fibre playing the role of a sensor. These fibres are small, resistant to corrosion and insensitive to external electromagnetic perturbations. As a result, these sensors are either embedded into new structures or bonded to the surface of those already existing. Concerning the interrogators, Brillouin or Rayleigh systems are available. The Rayleigh systems based on OFDR achieve higher spatial resolution (<1cm) than Brillouin systems who, on the other hand, can interrogate larger distances. It is important to underline that the strain measurement and

crack detection are related to the accuracy and spatial resolution of the interrogator and the mechanical and geometrical properties of the optical fibres used as sensors. The high spatial resolution of the Rayleigh interrogator permits to neglect its contribution so that the strain measured depends only on the mechanical properties of the optical cable.
Furthermore, since bare optical fibres are brittle, they are usually surrounded by protective layers. The influence of the mechanical properties of these different layers and the interface between them can be described by the Mechanical Transfer Function (MTF). Several mechanical models were proposed for embedded (1,2) and surface attached discrete sensors (3,4) and then extended to distributed sensors. In (5), the authors proposed a first approach to use DOFS strain measurements for crack quantification. The authors assumed that the creation of a crack produces a Gaussian strain variation until a certain limited state where debonding between optical fibres and coating layer occurs. On the other hand, authors in (6) assumed an exponential distribution and proposed a methodology for determining experimentally the Mechanical Transfer Function (MTF). A concrete beam instrumented with an embedded optical cable was tested and results showed a good agreement between the computed MTF and the measured one. Unfortunately, no crack meters were installed to validate the estimated crack openings. This methodology was later applied on a surface bonded cable (7) showing promising results. In (8), the authors proposed an analytical model where Crack Induced Strain (CIS) took a similar exponential distribution. An experimental test on a 15m long steel beam was performed. However, due to the use of a DOFS system with low spatial resolution (1m), the test was limited to better estimate crack's position. In (9), the authors simplified the model and a test on a 1m long aluminium plate was performed with a higher spatial resolution (20cm). Discrepancies between the estimated and the measured Crack Opening Displacements (COD) were attributed to an error in strain measurements performed by the Brillouin based DOFS system. A year later, the authors studied the dual crack case in order to predict the capability of the system in detecting and differentiating the neighbouring cracks (10). In (11), the same model was used to monitor cracks under dynamic loading.
Contrary to steel and aluminium, reinforced concrete structures can exhibit more complex behaviours due to heterogeneity of concrete. In order to use this model for the crack opening estimation in concrete substrate, a proper experimental setup with high spatial resolution has to be investigated. Hence, the aim of this paper is to study the analytical model proposed by Feng (8) with a special type of fibre optic cable embedded in and bonded to the surface of a reinforced concrete beam.

2. Strain transfer theory

In (8), the authors established a shear lag model based on the one proposed by Ansari et Libo (2). It describes the effect of deformation discontinuity due to the crack opening as an additional displacement at the level of the host material (Figure 1) and neglects any effect on the axial strain or debonding caused by the creation of the crack. Thus, the crack formation only generates a localized strain distribution. In addition, the fibre core and the different surrounding layers are supposed to have a linear elastic behaviour with a perfect bonding at all interfaces.

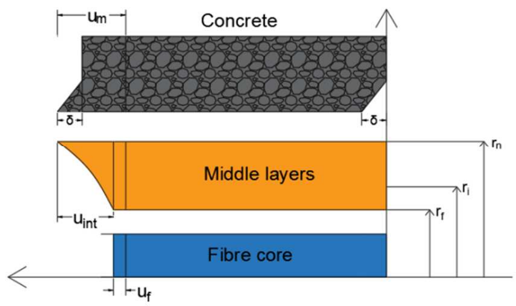


Figure 1. Stress distribution in host material, adhesive, coating and fibre core.

According to Feng's model, the strain in the host material and the fibre core are related by the following equation:

$$u_f''(x) - \beta^2 u_f = -\beta^2[\delta + \int_0^x \varepsilon_m(x)dx] \tag{1}$$

$$\text{With } \beta^2 = \frac{2}{E_f r_f^2 (\sum_{i=2}^{n} \frac{1}{G_i} ln\frac{r_i}{r_{i-1}} + \frac{1}{G_1} ln\frac{r_1}{r_f})} \tag{2}$$

δ, L and β are half of the COD, half of the bonding length and the shear lag parameter respectively. E_i, G_i and r_i represent in turn the Young modulus, shear modulus and the radius of the ith layer. u_f, ε_f and ε_m correspond to the displacement in the fibre, strain in the fibre and strain in the host material. Therefore, by choosing a linear strain variation in the host material $\varepsilon_m(x) = k*(|L-x|)$ and by adapting the following boundary conditions: $u_f(0)=0$ and $\varepsilon_f(L)=\varepsilon_f(-L)=\varepsilon_m$, the strain $\varepsilon_f(x)$ is given by:

$$\varepsilon_f(x) = +\beta\frac{(\delta - k/\beta^2)e^{2\beta L}}{1+e^{2\beta L}}e^{-\beta x} - \beta\frac{(\delta - k/\beta^2)}{1+e^{2\beta L}}e^{\beta x} + \varepsilon_m(x) \tag{3}$$

If $e^{2\beta L} >> \delta >> k/\beta^2$, the equation can be simplified to:

$$\varepsilon_f(x) = \delta\beta e^{-\beta x} + \varepsilon_m(x) \tag{4}$$

3. Experimental investigation

3.1 Test Preparation

A reinforced concrete beam was tested under three-point loading. Figure 2 shows the geometry of the beam and details of internal reinforcement and instrumentation by optical cables. One Linear Variable Differential Transducer (LVDT) sensor on each side served as a crack meter. One Strain Gage (SG) (on each side) was glued at distance of 7cm from the central crack location to monitor the strain variation in concrete during the test.

ODISI – B interrogator (manufactured by Luna) based on Optical Frequency Domain Reflectometry technique was used. This technique measures the strain with an accuracy of less than 10µm/m, with high spatial resolution of 5mm. Aiming to reduce the cost of DOFS systems for large structures monitoring, low cost type of fibre optic cable compared to other cables specially designed for measurement, was chosen. The cable contains six fibres wrapped around a central rod and embedded in a soft polymer matrix. One of the optical fibres was used for performing the measurements. Optical cables were either attached to rebar or bonded to the surface.

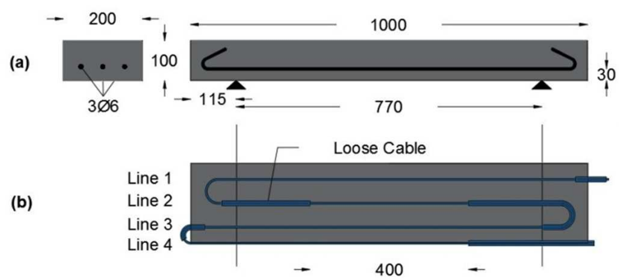


Figure 2 : (a) Shop drawing of tested beam and (b) instrumentation by optical cables.

3.2 Results and discussion

The MTF, mentioned in equation (4), was adapted to fit the measurement data using a least square fitting method. The variable coefficients are β and δ. Figure 3 compares the fitted model to the measurement data during the evolution of the first primary crack. The residuals appear randomly scattered around the zero line, indicating that the model describes well the measurement data. A significant variation of the strain at specific points over the length of the beam can be attributed to the heterogeneity of the concrete substrate. This variation complicates the fitting process at small crack openings. Furthermore, high levels of residuals that are situated less than 2cm away from the crack can be due to different phenomena like debonding at the cable/concrete interface or a plastic deformation in different interlayers due to the creation of the crack.

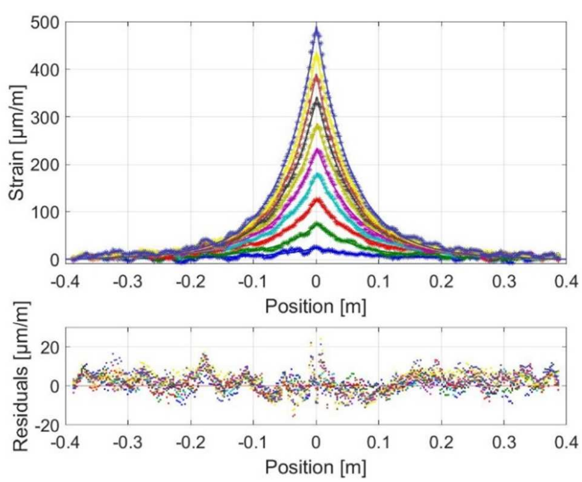


Figure 3. Fitted MTF near the first appearing micro crack compared to the measured one at different load levels.

3.2.1 Estimation of strain in host material

In previous works, the strain in the host material was considered either equal to zero due to energy release near the crack (9) or to the strain at the crack location just before its formation (6). In (7), the authors proposed to decompose the strain profiles measured by DFO and LVDT sensors into an elastic strain and a crack contribution. Thus, after several iterations, they estimated the strain distribution inside the concrete. Hence, it was important to study the effect of ε_m parameter on the fitting process and the estimation of β and δ.

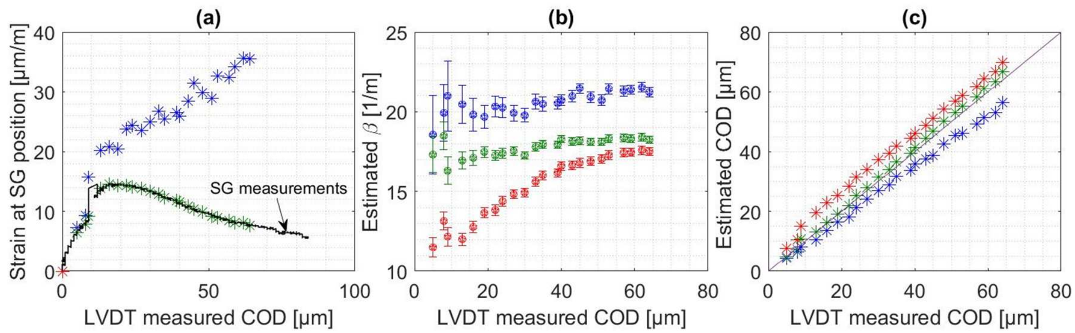


Figure 4: (a) Estimated and measured strain at the strain gage position. (b) Estimated β variation with respect to measured COD. (c) Comparison between the estimated and the measured COD. Case 1 (Blue), Case 2 (Red), Case 3 (Green).

Figure 4 compares the results of fitting the model to strain measurements extracted from line 4 in three different cases:

1. A linear distribution $\varepsilon_m(x) = k(t)*(|L-x|)$, consistent with the three-point loading test, is selected. k is added as a variable coefficient similar to δ and β during the fitting process (in blue).
2. ε_m is neglected when compared to the CIS. Thus, ε_m is equal to zero (in red).
3. The same triangular distribution as case 1 was adapted. However, k was updated using strain gage measurements (in green).

Figure 4 (a) shows the variation of ε_m at the strain gage position. After a crack formation, strain in concrete decreases until reaching a state where the rebar takes the full load. Thus, the increase in ε_m values computed in case 1 proves that the estimated ε_m values are incorrect. On the other hand, by observing Figure 4 (b), case 1 shows higher values of β compared to cases 2 and 3. Case 2 estimated an increase in β values, which tend to reach those computed in case 3 at higher COD. This could be explained by the decrease in ε_m and a relatively higher increase in CIS. As a result, ε_m can be neglected.

Finally, δ values estimated in case 3 show good agreement with LVDT measurements contrary to case 1 and 2 (Figure 4 (c)). These results show a high effect of ε_m on δ and β estimation for small COD.

3.2.2 One crack state

The estimated COD from four different sensing optical lines are shown in Figure 5 (a). When compared to measured COD values with LVDT sensors attached on the front and back side of the beam, estimated COD values from line 4 show a good agreement with front LVDT measurements fixed at the same location (Figure 6 (b)).

Higher strain values, observed during the test, led to a crack propagation from the front to the backside and, as a result, bigger COD was measured on the front side.

The same phenomenon can be observed from estimated COD values for embedded optical lines near the rebar. However, these values are higher than those measured on the surface of the beam. The reason of this discrepancy is related to an error in the positioning of LVDT sensors. Figure 6 (a) shows that LVDT sensors, fixed at the same level of line 4, are closer to the top of the beam than lines 1, 2 and 3.

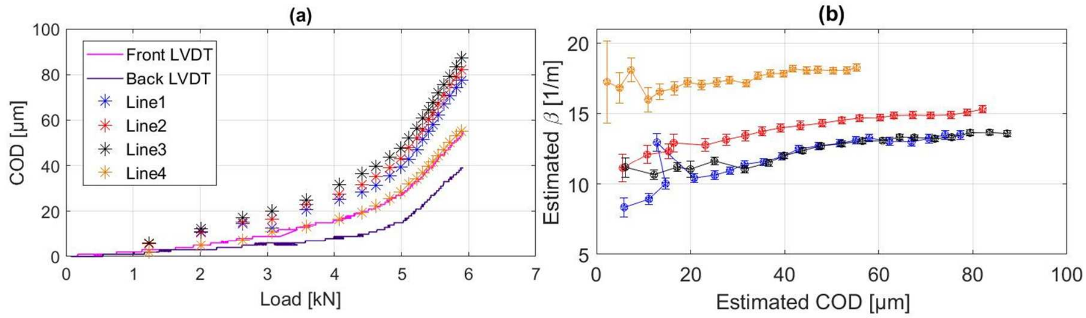


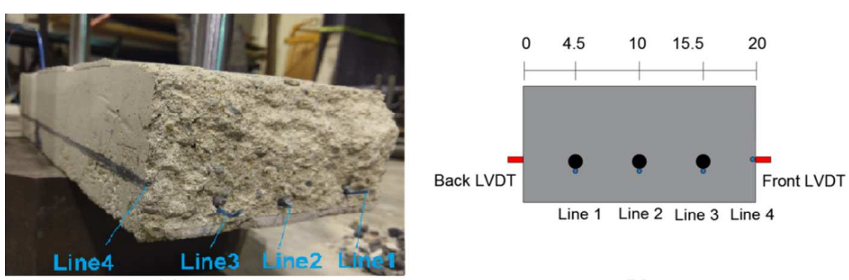
Figure 5 : (a) Comparison between the estimated and measured COD. (b) Estimated shear lag parameter with respect to the estimated COD for each line of optical fibre.

Likewise, estimated shear lag values are plotted in Figure 5 (b). The shear lag parameter increases with the COD until reaching a constant value of 18.2 m^{-1} for sensing line 4, 13.4 m^{-1} for line 1 and 3 and 15 m^{-1} for line 2. Based on the definition proposed by (12), the effective bonding length L_τ corresponds to the shortest interfacial length required to transfer 97% of the applied load. Thus, L_τ is defined by:

$$\int_{L_\tau}^{L_\tau} MTF(x)dx = 0.97 \int_{-\infty}^{+\infty} MTF(x)dx$$

$$L_\tau = -\frac{\ln(0.03)}{\beta} \quad (6)$$

The corresponding effective bonding lengths are 19.27 and 26.2cm. Thus, for line 2, the bonding length equal to 20cm (Figure 2), proved to be less than the effective one. Henceforth, this could be the reason behind a higher shear lag parameter values than line1 and 3.



(a) (b)

Figure 6: (a) View of the optical fibres after beam failure. (b) Shop drawing of LVDT and optical lines positions.

3.2.3 Multiple crack state

In reinforced concrete structures, civil engineers are usually facing a case where multiple micro cracks appear simultaneously. Hence, line 4 strain measurements near the central crack were monitored after the creation of multiple neighbouring cracks. The model involved two, three, four and five micro cracks cases with CODs of $2\delta_1$, $2\delta_2$, $2\delta_3$, $2\delta_4$, $2\delta_5$ spatially distributed along the optical cable at x_1, x_2, x_3, x_4 and x_5, respectively. The induced strain in the distributed sensor can be acquired from the superposition of the induced strain of each crack. Thus, the strain distribution can be expressed by:

$$\varepsilon_f(x) = \sum_{i=1}^{k} \delta_i \beta \exp[-\beta(x - x_i)] + \varepsilon_m \quad (7)$$

Eventually, and with the rising number of cracks, a compromise between early crack detection, accuracy in estimating their positions and CODs is important.
Another key factor is the distance between two cracks. For this reason, the Full Width to Half Maximum FWHM should be computed. Based on the MTF of the cable, FWHM can be calculated as follows:

$$FWHM = \frac{2\ln(2)}{\beta} \quad (8)$$

Therefore, FWHM is equal to 7.62 cm for β=18.2 m^{-1}. When the distance between two micro cracks is less than the FWHM, only one peak is formed from two neighbouring cracks and detecting the number and position of micro cracks becomes more complex. However, in this case study, the distance between the cracks was more than the FWHM and all five different cracks were easily detected.
The model fits well the measurement data. Figure 7 (c) shows the estimated COD ($2\delta_1$) for the central crack compared to LVDT measurements until 400 µm. No discrepancies is observed and an appropriate estimation is accomplished.

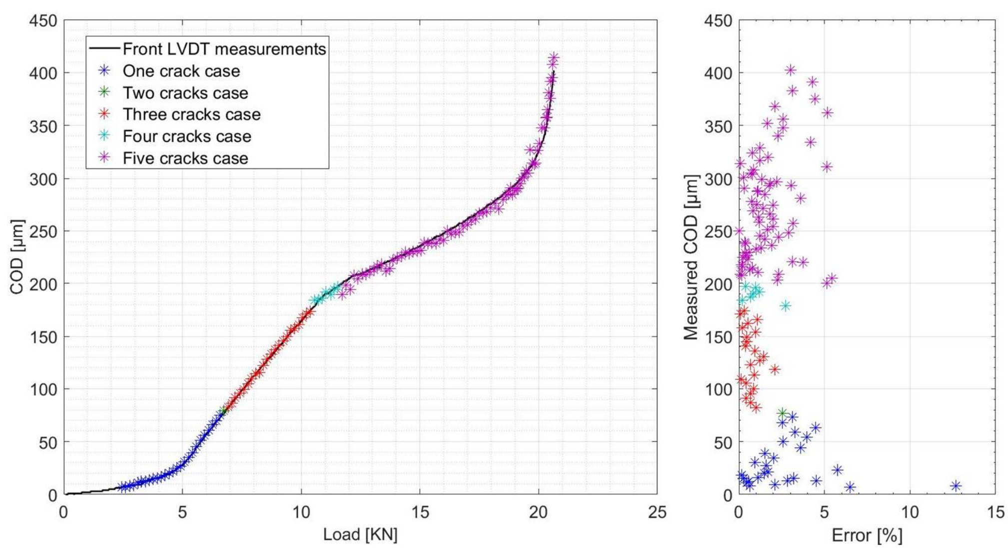


Figure 7 : (a) Monitored central crack COD in multi cracks in different cases. (b) Calculated error of estimated COD compared to the measured one.

The calculated absolute error reaches less than 6% starting from a 10µm crack opening (Figure 7 (b)). However, this error decreases to less than 2% in three and four cracks

cases. In fact, at small CIS levels (one crack case), repeatability errors of the interrogator (±5 µm/m) and strain variations caused by the heterogeneity of the concrete (±10µm/m) cannot be neglected and, consequently, affect the estimated COD values.
In addition, at high levels of CIS, the frequency of dropout points (or outliers) increases in the areas of rapid strain transitions near the crack zone. This strain change across a gage length is too big for the ODISI-B interrogator to measure the frequency shift, and therefore calculate the average strain. Consequently, the error in estimating the COD increases until a limit state (COD= 400µm) where the fitting process does not converge due to low number of data points.

4. Conclusion

In conclusion, an optical cable paired with a Rayleigh OFDR interrogator unit makes it possible to perform continuous strain monitoring with a centimetre scale spatial resolution. The application of a MTF for crack opening estimation was validated for concrete structures. The strain in concrete is an important parameter that should be well separated from the CIS in order to successfully estimate small CODs. Further work is needed to study the behaviour of the cable under higher CODs and to better understand the effect of the bonding length on the strain transfer. In addition, monitoring crack openings in multiple neighbouring cracks case was achieved. However, the work could be extended in order to monitor all several micro cracks.

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References

1. A. Nanni, C. C. Yang, K. Pan, J. S. Wang et R. R. Michael, "Fibre-optic sensors for concrete strain/stress measurement", ACI materials Journal 88, pp 257-264, 1991.
2. F. Ansari et Y. Libo, "Mechanics of bond and interface shear transfer in optical fibre sensors", Journal of engineering mechanics 124, pp 385-394, 1998.
3. S.-C. Her et C.-Y. Huang, "Effect of coating on the strain transfer of optical fibre sensors", Sensors 11, pp 6926-6941, 2011.
4. H.-t. Zhao, Q.-b. Wang, Y. Qiu, J.-a. Chen, Y.-y. Wang et Z.-m. Fan, "Strain transfer of surface-bonded fibre Bragg grating sensors for airship envelope structural health monitoring", Journal of Zhejiang University SCIENCE A 13, pp 538-545, 2012.
5. M. Imai et M. Feng, "Sensing optical fibre installation study for crack identification using a stimulated Brillouin-based strain sensor", Structural Health Monitoring, 2012.
6. J. M. Henault, J. Salin, G. Moreau, M. Quiertant, F. Taillade, K. Benzarti et S. Delepine-Lesoille, "Analysis of the strain transfer mechanism between a truly

distributed optical fibre sensor and the surrounding medium", International Conference on Concrete Repair, Rehabilitation and Retrofitting ICCRRR-3, 2012.

7. A. Billon, J.-M. Hénault, M. Quiertant, F. Taillade, A. Khadour, R.-P. Martin et K. H. Benzarti, "Qualification of a distributed optical fibre sensor bonded to the surface of a concrete structure: a methodology to obtain quantitative strain measurements", Smart Materials and Structures 24, 2015.
8. X. Feng, J. Zhou, C. Sun, X. Zhang et F. Ansari, "Theoretical and experimental investigations into crack detection with BOTDR-distributed fibre optic sensors", Journal of Engineering Mechanics 139, pp 1797-1807, 2013.
9. D. Meng, F. Ansari et X. Feng, "Detection and monitoring of surface micro-cracks by PPP-BOTDA", Applied Optics 54, pp 4972-4978, 2015.
10. D. Meng et F. Ansari, "Interference and differentiation of the neighboring surface microcracks in distributed sensing with PPP-BOTDA", Applied Optics 55, pp 9782-9790, 2016.
11. S. K. BABANAJAD et F. ANSARI, "Mechanistic Quantification of Microcracks from Dynamic Distributed Sensing of Strains.", Journal of Engineering Mechanics 143(8), 2017.
12. H. Yuan, "Improved theoretical solutions of FRP-to-concrete interfaces", Proceedings of the International Symposium on Bond Behaviour of FRP in Structures, BBFS, 2005.