Fracture Mechanics of Concrete Structures
Proceedings FRAMCOS-3
AEDIFICATIO Publishers, D-79104 Freiburg, Germany

A NOVEL DISTRIBUTED CRACK SENSOR FOR CONCRETE STRUCTURES

C. K. Y. Leung
Department of Civil and Structural Engineering, Hong Kong University of Science & Technology, Clear Water Bay, Kowloon, Hong Kong
N. Elvin, N. Olson,
Department of Civil and Environmental Engineering,
Massachusetts Institute of Technology, Cambridge, MA02139, U.S.A.
T. F. Morse and Y.-F. He
Laboratory for Lightwave Technology. Division of Engineering,
Brown University, Providence, RI 02912

Abstract
Concrete structures degrade through the formation and propagation of cracks. The severity of cracking in a concrete structure is therefore a good indicator of its 'health'. At the present, the assessment of cracking condition in concrete structures is carried out by manual inspection, which is inefficient, unreliable and costly. The objective of the present investigation is to develop a novel optical fiber sensor for the detection of cracks and the subsequent monitoring of their openings. Comparing with conventional approaches, the novel sensor possesses two major advantages: (i) no a-priori knowledge of crack location is required, (ii) a small number of fibers can be employed to detect and monitor a large number of cracks. In this paper, the sensing concept is described and preliminary experimental results are presented to demonstrate its feasibility. A theoretical model is also developed to provide guidelines for the optimization of sensor performance. Model predictions are in good qualitative agreement with experimental results.
Key Words: Crack Monitoring, Fiber Optic Sensor, Concrete Structures

1 Introduction

Concrete structures degrade through the formation and propagation of cracks. Crack openings beyond 0.2 to 0.4 mm (depending on environmental exposure) may lead to durability problems associated with steel reinforcement corrosion. Large openings beyond 1 to 2 mm, which may be caused by natural hazards, is a sign of severe damage and requires immediate closing of a facility. The detection and monitoring of cracks is hence an effective means to assess the 'health' of a concrete structure. At the present, cracking in concrete structures is assessed by manual inspection, which is inefficient, unreliable and costly. The development of a better approach is highly desirable.

Due to material inhomogeneities, the exact locations of cracks in a concrete structure cannot be predicted (although crack directions can often be accurately obtained from analysis). Conventional 'point' sensors, which measure strain at a local point, can easily miss the crack. With integrated sensors, which measure displacement between two points separated by a relatively large distance, it is not possible to distinguish between the harmless case of many fine cracks and the undesirable situation of one widely open crack. To overcome the limitations of existing crack sensors, we are developing a novel fiber optics based 'distributed' sensor which can (i) detect the formation of cracks without requiring a-priori knowledge of exact crack locations, (ii) carry out continuous monitoring once the crack is formed, and (iii) detect and monitor a large number of cracks with a very small number of fibers.

In this paper, the novel sensing concept is first introduced. Experimental results are then presented to demonstrate the feasibility of the approach. To provide guidelines for sensor optimization, a theoretical model combining mechanics and electromagnetic analysis is developed. Typical theoretical results will be presented and compared to preliminary experimental measurements.

2. The Novel Crack Sensing Concept

The principle of the sensor is illustrated in Fig.1, which shows a 'zig-zag' sensor at the bottom of a bridge deck. The backscattered power is measured as a function of time (with Optical Time Domain Reflectometry or OTDR). Before the formation of cracks, the backscattered signal vs time follows a relatively smooth curve (the upper line in Fig.1b). The loss in signal power with time is due to the increasing loss with distance traveled (which is directly proportional to the traveling time). In the straight portions of the fiber, the loss is due to absorption and scattering

(Allard, 1990). In the curved portion (where the fiber turns in direction), bending loss may occur depending on the radius of curvature. A simple physical explanation for the bending loss is as follows. The optic fiber is made up of a core surrounded by a cladding with a lower refractive index. For a straight fiber, a light ray launched into the core at a low angle to its axis will undergo total internal reflection at the core/cladding interface and will always stay guided in the core. However, when the fiber is bent, the increase in curvature may reduce the incident angle at the core/cladding interface to a value below the critical angle (Ansari et al, 1993). Some light energy will then move into the cladding and get dissipated.

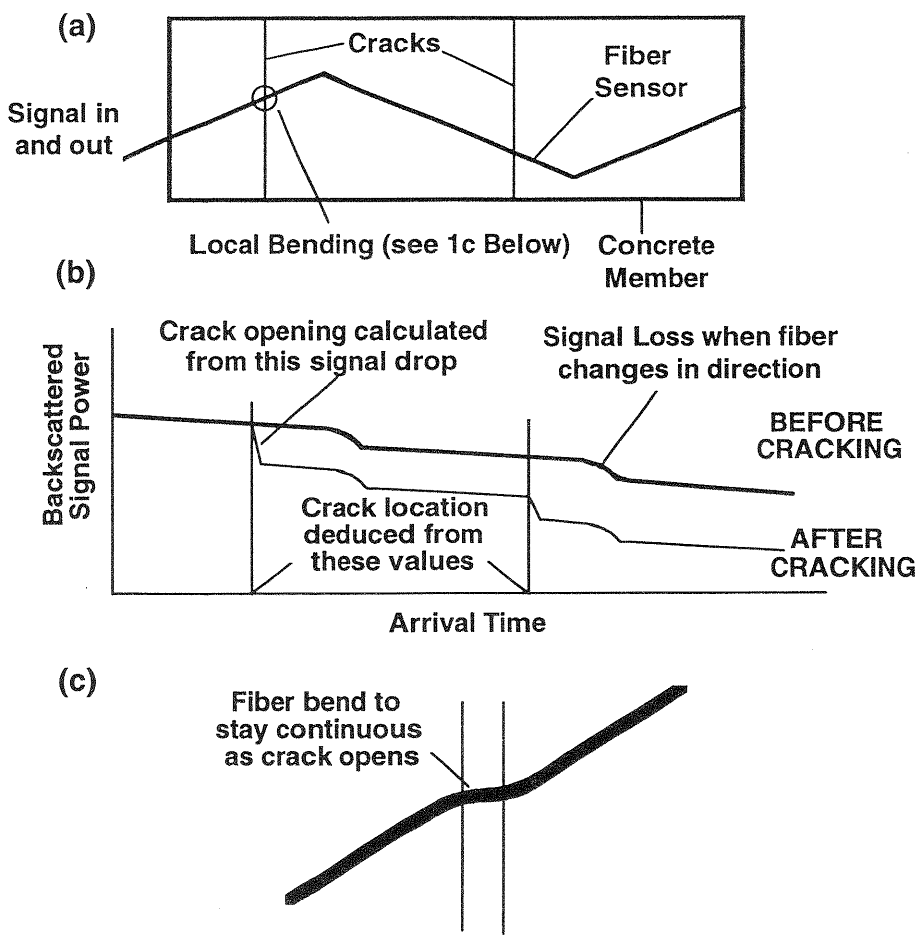

Fig. 1. The novel crack sensing concept

When a crack opens in the structure, a fiber intersecting the crack at an angle other than 90° has to bend to stay continuous (Fig.1c). The sudden bending of an optical fiber at the crack results in a sharp drop in the optical signal (lower line, Fig.1b). From the time values on the OTDR record corresponding to the sharp signal drops, the location of each crack in the structure can be deduced. Also, from the magnitude of the drop, the crack opening can be obtained if a calibration relation is available. The theoretical development of such a calibration curve will be discussed in the a later section. Note that the signal loss at the fiber turning point is shown for a general case. If the sensor geometry is designed to have a small curvature at the turning point, the loss will be negligible.

The proposed technique does not require prior knowledge of the crack locations, which is a significant advancement over existing crack monitoring techniques. This is made possible by a very special property of the optical fiber: any point along the fiber possesses sensing capability. Moreover, since the fiber can act as both the sensor and its communication link, a single fiber can be employed to detect and monitor a number of cracks. For the sensor to work, however, crack directions need to be known. An ideal application of the sensor is in the monitoring of flexural cracks in bridges, which may form at arbitrary locations along the deck, but essentially perpendicular to the spanning direction. To sense cracks effectively, several sensors should be employed. With a single fiber, if a crack intersects the 'zig-zag' fiber at a location where the fiber direction is changing, results will be difficult to interpret. The crack therefore needs to be picked up by another fiber with its turning point at other sections. For new constructions, the sensor can be cast in the structure. For existing structures, the fiber needs to be first incorporated into a polymeric sheet which will then be glued to the structure surface. If surface cracks are our major concern, the use of a 'sensing sheet' is preferable to an embedded optical fiber. This is because (i) the sensing sheet can be prefabricated under controlled conditions to ensure consistency, and (ii) the polymer can protect the glass fiber against alkali attack.

3 Preliminary Experimental Results

An experiment to demonstrate the feasibility of the novel sensing concept is illustrated in Figure 2. A sensing sheet is first made by embedding an optical fiber into a thin polymeric sheet (usually polyester or epoxy) (Fig.2a). To ensure that the fiber is free to slide and bend, releasing oil is put onto the fiber surface. After the sensing sheet is cured, it is removed from the mold and glued (with epoxy) to the bottom of a concrete beam (Fig.2b). A pair of notches are cut on the two sides of the beam so the

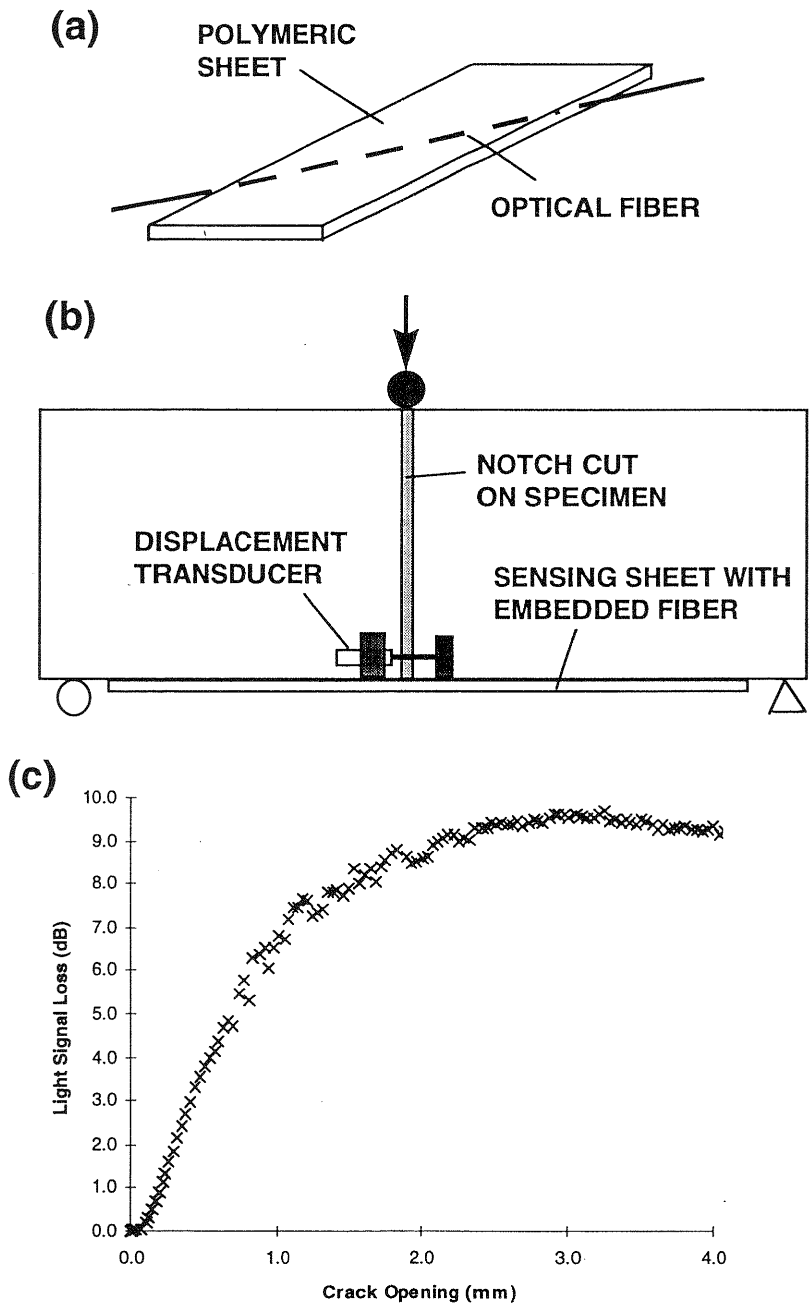

Fig. 2 Experimental Set-up and Preliminary Results

crack location is known. (Note: the polymeric sheet is not as wide as the beam so the notches do not reach the sheet). A displacement transducer is placed over the notch to monitor its opening. Loading is then applied to crack the beam and the signal loss is measured simultaneously with crack opening. The result (Fig.2c) shows that the sensor can be made sensitive to very small crack openings below 0.1 mm. At large openings, the loss will approach an asymptotic value, which represents the maximum possible loss at a particular crack. Note that the monitoring of multiple cracks along the fiber relies on the measurement of backscattered power. Since the backscattered signal is only a small fraction of the forward power, it is weak in intensity and limited in dynamic range. In order to monitor a large number of cracks with a single fiber, the maximum loss per crack needs to be controlled. Since reducing the maximum loss at a crack may also compromise the fiber sensitivity (reflected by the loss vs opening at the initial part), the design of an effective sensor involves the optimization of signal loss vs crack opening. Since the signal loss depends on many parameters including (i) the fiber size and inclination to the crack, (ii) the mechanical properties of fiber, matrix and the fiber coating, (iii) the optical properties of the fiber core and cladding, and (iv) the fiber coating thickness, sensor optimization through empirical testing is not practical. To provide guidelines for sensor design, a theoretical model is therefore developed.

4 Theoretical modeling of signal loss vs crack opening

The modeling of signal loss vs crack opening consists of two separate parts: (i) mechanical analysis to obtain the curvature variation along the fiber as the crack opens, (ii) electromagnetic wave analysis to calculate the loss of light energy in a deformed wave-guide. The modeling procedure is briefly described below.

4.1 Micromechanical Modeling of Fiber Bending

Crack opening leads to bending of the optical fiber (Fig.1c). Due to anti-symmetry, there is an inflection point in the middle of the crack. In the analysis, the fiber is first cut at the inflection point to produce two parallel but separate segments. A displacement is then applied to each of the cut ends to bring them back together. The deformation along the fiber corresponding to the applied displacement is obtained through a 3-D finite element analysis. 8-node solid elements are employed to model the fiber, the matrix as well as the polymeric coating around the fiber. The boundary of the matrix is placed at 5 fiber diameters from the fiber center. We find this distance sufficient to simulate a matrix of infinite extent.

With the finite element analysis, fiber displacement is only obtained at a given number of points. To obtain an accurate estimate of the curvature, which governs the signal loss, a reliable interpolation technique is required. It has been shown (Leung and Li, 1992) that a fiber in a cementitious matrix can be modeled as a beam on an elastic foundation, with foundation stiffness increasing with distance from the crack face. Here, we assume the foundation stiffness to be a linear function of distance from the crack face ($k = \beta^4 x$, where β is a constant to be obtained). A fourth order differential equation can then be set up and solved numerically. In reality, the stiffness will reach a constant value rather than increasing continuously. However, since the foundation reaction decreases rapidly with distance from the crack face, the assumptions of a continuously increasing stiffness and one with stiffness reaching a plateau give no noticeable difference in the results. By varying β, a best fit to the finite element result can be obtained. From the best fit curve, the curvature along the fiber is deduced for the calculation of signal loss.

4.2 Modeling of Signal Loss in a Curved Optical Fiber

Bending loss along an optical fiber with arbitrary curvature is obtained with two different techniques for small and large crack openings. For small crack opening, the beam propagating method (Feit and Fleck, 1978) is employed. For a time harmonic Electric field (E field), one can separate the time variable from the wave equation to obtain the Helmholtz equation in space variables. Instead of solving the Helmholtz equation in curvilinear coordinates, the curved fiber is first transformed into an equivalent straight fiber with a modified refractive index profile (Heiblum and Harris, 1975). A numerical solution of the Helmholtz equation is then obtained through the spectral decomposition technique. As the initial condition, the E field corresponding to that in a straight fiber is imposed at a point far away from the crack (where no loss has yet occurred). The E field is decomposed into its spectral components (in the space variables) through the use of discrete Fourier Transform. Each spectral component is then propagated separately and recombined by carrying out inverse Fourier Transform. With the availability of Fast Fourier Transform algorithms, spectral decomposition allows a much more efficient solution scheme than the more direct finite difference methods. The analysis is carried out along the fiber until it becomes straight again at the other side of the crack. The ratio of power at the input and output sections allows the calculation of dB loss as a result of fiber bending.

When crack opening is large, curvature change occurs over a larger portion of the fiber. The beam propagation method described above is no longer accurate, as the cumulating of error becomes significant. An alternative approach, which is more approximate in nature, is adopted.

This method, based on the work of Marcatili and Miller (1969), has been used by Minford et al (1982) and Mustieles et al (1993) for the calculation of signal loss in wave-guides. Once the curvature distribution R(s) over a length of fiber (L) is known, the loss is calculated from:

$$\text{Loss (dB)} = \frac{10}{\ln 10}\int_L \frac{C_1}{\sqrt{R(s)}}\exp[-C_2 R(s)]ds \qquad (1)$$

In eqn (1), C_1 and C_2 are constants depending on the optical properties of the fiber and the wavelength of light. To obtain these constants, we first consider a short length of fiber with a constant radius of curvature. Using the beam propagation method, the loss per unit length is calculated for a given wavelength and a particular set of optical properties. By repeating the computation for different curvature values, simulated values of signal loss vs curvature are obtained. By fitting eqn (1) to the simulated values, the constants C_1 and C_2 can be determined.

4.3 Results from the theoretical simulation

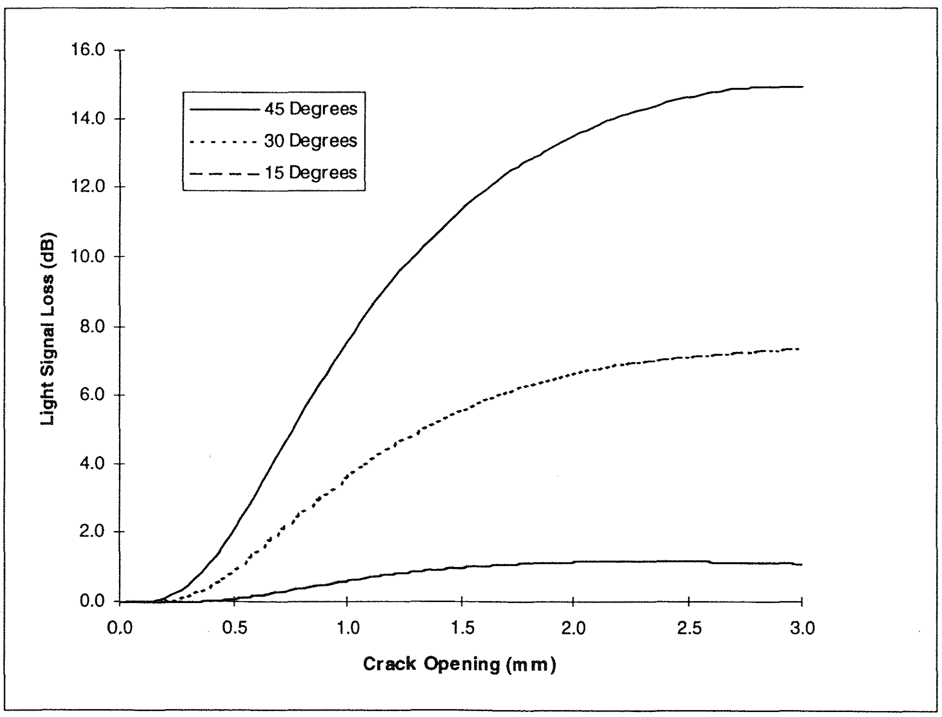

Fig. 4 Typical theoretical results of signal loss vs crack opening

Fig.3 shows typical curves of signal loss vs crack opening obtained with the theoretical model described above. Results are obtained for a specific set of fiber and matrix properties, at three different fiber inclination angles. In these cases, the beam propagation results at small crack openings happen to be almost identical to those computed with eqn (1). Therefore, only the results from eqn (1) are shown. Comparison of Fig.3 and Fig.2c reveals excellent qualitative agreement between theoretical and experimental results. Both plots show negligible loss at small crack openings. Only when the crack opening goes beyond a certain value would the signal loss start to rapidly increase. This is a desirable feature as very small cracks, which are harmless to the structure, will not give 'false alarms' to the user.

The theoretical results shows that when the fiber inclination changes from 15 to 45 degrees, the sensitivity is improved. At the same time, the maximum loss (i.e. the plateau value) also increases. This trend confirms our earlier claims that an optimal sensor design is required to achieve the best compromise between sensitivity and maximum loss (which governs the number of cracks that can be detected by a single fiber).

The preliminary experimental and theoretical work has clearly illustrated the feasibility of the novel sensing technique. Currently, additional experiments are under way to provide data for the quantitative verification of theoretical predictions. Once the theoretical model is fully verified, it can be applied to the design of optimal sensors for given performance requirements.

5 Conclusions

This paper focuses on the development of a novel optical fiber sensor for the detection and monitoring of cracks in concrete structures. Compared to conventional methods, the advantages of the technique include (i) no a-priori knowledge of crack locations is required (although crack direction need to be known), (ii) a small number of fibers can be used to detect and monitor a large number of cracks. Preliminary experimental results showed that the novel sensor can detect very small crack openings below 0.1mm. In order to design a sensor with (i) high sensitivity at small crack opening, and (ii) the capability to monitor a large number of cracks, a theoretical model is developed to provide guidelines for sensor optimization. Preliminary comparison of model prediction with experimental measurements shows very good qualitative agreement.

6 Acknowledgements

This project has been funded by the INEEL (Idaho National Engineering and Environmental Laboratory) University Research Consortium. The INEEL is managed by Lockheed Martin Idaho technologies Company for the U.S. Department of Energy, Idaho Operations Office, under Contract No. DE-AC07-94ID13223.

7 References

Ansari, F. and Navalurkar, R.K. (1993) Kinematics of Crack Formation in Cementitious Composites by Fiber Optics. **ASCE J. Eng. Mech.**, 119(5), 1048-1061.

Allard, F.C. (1990). **Fiber Optics Handbook for Engineers and Scientists**, McGraw Hill.

Feit, M.D. and Fleck, J.A., Jr. (1978) Light Propagation in Graded-Index Fibers. **Appl. Optics**, 17(24), 3990-3998.

Heiblum, M. and Harris, J.H. (1975) Analysis of Curved Optical Waveguides by Conformal Transformation. **IEEE J. of Quantum Electronics**, QE-11(2), 75-83.

Leung, C.K.Y. & Li, V.C. (1992) Effects of Fiber Inclination on Crack Bridging Stresses in Brittle Matrix Composites. **J. Mech. Phys. Solids**, 40(6), 1333-1362.

Marcatili, E.A.J. and Miller, S.E. (1969) Improved Relations Describing Directional Control in Electromagnetic Wave Guidance. **Bell Systems Technological Journal**, 48, 2161-2188.

Minford, W.J., Korotky, S.K. and Alferness, R.C. (1982) Low Loss Ti:$LiNbO_3$ Waveguide Bends at λ=1.3μm. **IEEE Journal of Quantum Electronics,** QE-18(10), 1802-1806.

Mustieles, F.J., Ballesteros, E. and Baquero, P. (1993) Theoretical S-Bend Profile for Optimization of Optical Waveguide Radiation Losses. **IEEE Photonics Technology Letters**, 5(5), 551-553.