DEVELOPMENT OF A FIBRE OPTIC CRACK SENSOR FOR CONCRETE STRUCTURES

Christopher K.Y. Leung[1], K.T. Wan[1], Yi Jiang[2]
[1] Department of Civil Engineering, The Hong Kong University of Science and Technology, Hong Kong SAR
[2]Department of Opto-Electronic Engineering, Beijing Institute of Technology, PRC

ABSTRACT

The condition of a concrete structure can be effectively assessed through the monitoring of cracks. Large cracks may be warning signs of severe degradation, while small cracks with openings from 0.2 to 0.4 mm may lead to durability problems associated with the penetration of water and other chemicals. Since the location of cracks in a concrete structure is not known in a-priori, conventional 'point' sensors (e.g., strain gauges) are not effective in the sensing of cracks. In this paper, we will describe recent findings on a fiber optic crack sensor that allows the detection and monitoring of multiple cracks without requiring prior knowledge of crack locations. The sensing principle will be discussed first, following by the theoretical derivation of signal loss vs. crack opening relation. The fabrication of a sensor suitable for both external bonding and internal installation in a concrete structure will be described. Representative experimental results will be shown to demonstrate the applicability of the sensor under both static and cyclic loading. Measured losses are found to be in good agreement with theoretical results. Based on the experimental and theoretical findings, the potential of the sensor for practical applications is demonstrated. .

1. INTRODUCTION

The degradation of concrete structures is a major infrastructure problem in many parts of the world. If deterioration can be detected at an early stage, timely maintenance can extend the lifetime of structures, and avoid severe degradation that may jeopardize public safety. Due to the low tensile strength of concrete, deterioration is always accompanied by the formation and propagation of cracks. The condition or "health" of a concrete structure is hence best assessed from its state of cracking. For example, if cracks in a concrete structure open by more than 0.2 to 0.4 mm under service loading, penetration of water and salt (from sea water or de-icers) will accelerate the steel corrosion. Once such cracks are detected, they should be sealed. Crack monitoring is also an effective means to assess structural condition after the occurrence of natural hazards. After a strong earthquake, if widely opened cracks (of several mm's) are detected at critical locations, the structure is likely to be severely damaged, and should be closed down for repair.

Due to material inhomogeneities, the exact locations of cracks in a concrete structure cannot be predicted. Conventional sensors are either point sensors (such as strain gauges and accelerometers) that only provide information at a single point of the structure, or integrated sensors (e.g, a LVDT with long gauge length) that measure displacement between two points separated by a relatively large distance.

To overcome the limitations of conventional sensors, Leung and co-workers [1,2] have developed a novel distributed crack sensor based on the optical fiber. Since the fiber can act as both the sensor and the communication link, it can theoretically detect any changes that take place along its length. If the optical fiber is coupled to a concrete structure in a proper way, a crack forming at any location along the fiber can be detected, and a single fiber is able to detect and monitor a number of cracks. In the following sections, the sensing principle is first explained. Then, recent theoretical and experimental investigations will be described to demonstrate the practical applicability of the sensing concept.

2. SENSING PRINCIPLE

The principle of the sensor is illustrated in Figure 1(a), which shows a 'zig-zag' optical fiber coupled to the concrete member. The backscattered power is measured as a function of time with Optical Time Domain Reflectometry (OTDR). Before the formation of cracks, the backscattered signal vs. time follows a relatively smooth curve (the upper line in Figure 1(b)). In the curved portion (where the fiber changes in direction), bending loss may occur depending on the radius of curvature. When a crack opens in the structure, a fiber intersecting the crack at an angle other than 90° has to bend to stay continuous (see inset of Figure 1(a)). The sudden bending of an optical fiber at the crack results in a sharp drop in the optical signal (lower line, Figure 1(b)). From the times corresponding to the sharp signal drops in the OTDR record, the location of each crack in the structure can be easily calculated as the light velocity in the optical fiber is known. From the magnitude of each drop, the crack opening can be determined.

The proposed technique does not require prior knowledge of the crack locations. However, crack directions need to be known. Further discussion of the sensing principle is found in Leung et al [1,2].

3. DERIVATION OF A THEORETICAL MODEL FOR POWER LOSS

The analysis of the optical power loss in the crack sensor involves two major steps. As the crack opens, the induced curvature along the fiber is first obtained through a mechanical analysis. An optical analysis is then performed to compute the optical power loss along the curved waveguide.

A model for the mechanical analysis is shown schematically in Figure 2. The dotted lines in Figure 2(a) show the part of the matrix that will be included in a three-dimensional finite element analysis. Figure 2(b) and (c) illustrate the loading and boundary conditions of the analysis. The crack opening is assumed to be made up of two parts, a displacement component u_1 parallel to the fiber as in Figure 2(b), and a perpendicular component u_2 that would bend the fiber into a curved configuration. The magnitude of the two components can be easily calculated from the actual opening of the crack (δ) and the angle between fiber and crack opening direction (θ) as:

$$u_1 = \delta\cos\theta \qquad (1)$$

$$u_2 = \delta\sin\theta \qquad (2)$$

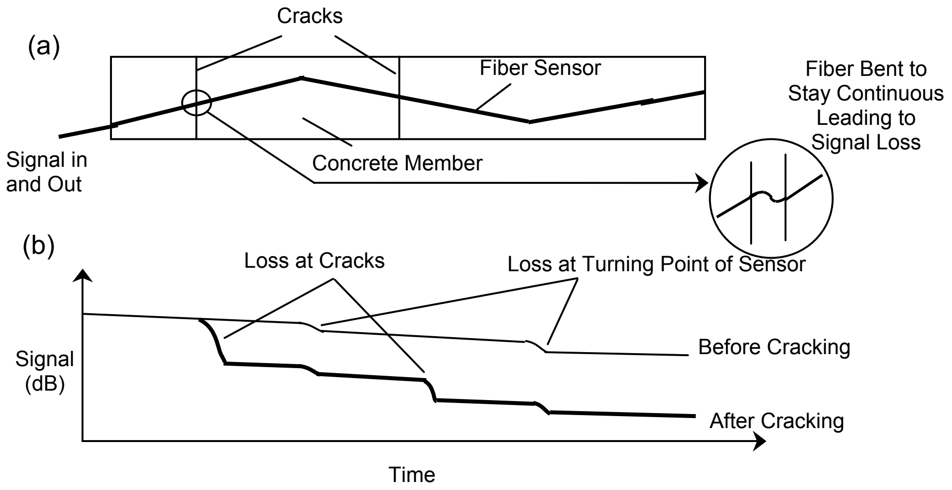

Figure 1. Concept of Distributed Sensing with the Novel Sensor

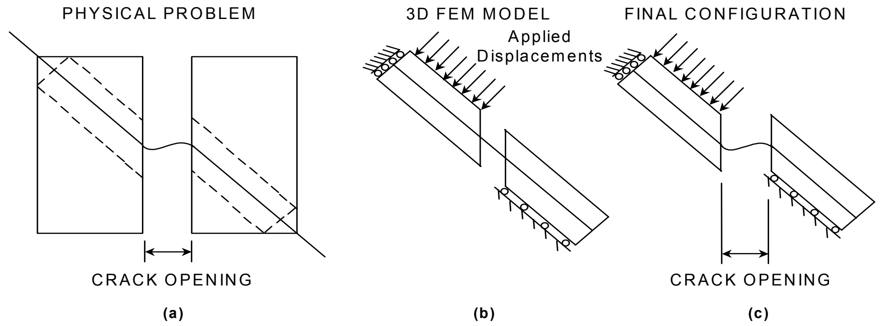

Figure 2. Schematic Illustration of the Mechanical Analysis

Based on the nodal displacements from the FEM output, the rotation of transverse planes along the fiber can be determined. By numerically computing the change in rotation angle with distance along the bent fiber axis, the curvature can be obtained.

In this investigation, we focus on the development of crack sensor with single mode fibers, for which Marcuse (Marcuse [3]) has derived an analytical expression relating the power loss per unit length to the fiber curvature, as well as other parameters that can be derived from the wavelength of light and the fiber optical properties. It suffices to say that once the curvature distribution along the fiber is known, integration can be performed with Marcuse's equation (for loss per unit length vs. curvature) to obtain the total loss along the bent fiber.

In Marcuse's derivation, the photoelastic effect is neglected, so the results are only theoretically correct for small curvature, when the bending stresses are small. In our case, the radius of curvature can be on the order of 1 mm, and high stresses are induced in the fiber. As pointed out by several investigators (Nagano [4], Valiente [5], Gauthier [6]), the photoelastic effect is essentially leading to a reduction in fiber curvature. To find the proper reduction factor, optical fibers are looped around cylindrical rods of different diameters. The measured loss (per unit length) is compared with theoretical prediction from Marcuse's model. The ratio of theoretical to experimental value gives the reduction factor. For different optical fibers, the reduction factor is different. In our work, based on experimental testing, the correction factors for two different types of optical fibers have been obtained.

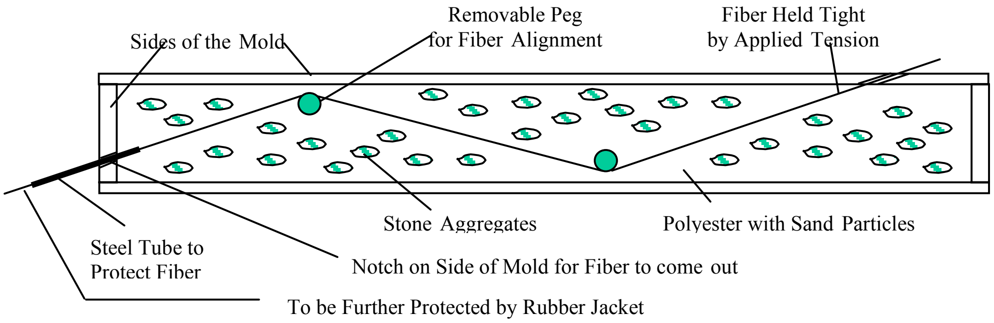

Figure 3. Illustration of the Fabrication a Sensor Sheet

4. SENSOR FABRICATION

The preparation of the optical fiber sensor is illustrated in Figure 3. With round pegs (which may be removed later) placed at proper locations inside a mould, the fiber is made to run in a pre-determined configuration. With the fiber held tight, polyester is poured slowly into the mold to form a sensor sheet about two millimeters in thickness. Before polyester is added, releasing oil is added on all sides of the mold and the pegs, to facilitate removal of the sheet after the polyester hardens. Releasing oil is also put on the surface of the optical fiber. By minimizing the bond between the fiber and the polyester, when a crack in the concrete structure induces cracking of the sensor sheet, the fiber will be able to slide and bend to introduce optical power loss. Before the polyester hardens, fine sand particles are also added. These particles will sink into the polyester and weaken the plate. Once a crack in the concrete member intersects with the sheet, the sheet will crack at once. For applications requiring an externally bonded plate (e.g., monitoring of flexural cracks at the bottom of a bridge deck), the preparation procedure described above is sufficient. For an internally embedded sensor, stone aggregates are also added to the polyester before it hardens (as shown in Figure 3). These aggregates, which protrude from the surface of the sensor sheet, will improve the bond when the sheet is embedded inside concrete. At the location where the fiber is coming out of the sheet, a small steel tube is placed around the fiber for protection and the end of the steel tube is further covered with soft rubber. This way, the breakage of fiber at the exit point can be prevented.

5. EXPERIMENTAL RESULTS WITH THE CRACK SENSOR

5.1 Crack Monitoring Under Monotonic Loading and Comparison with Theory

As an illustration of crack monitoring with the sensor sheet, a simple experiment involving the 4-point bending of a concrete beam is performed. The sensor sheet is embedded inside the concrete beam at a distance from the bottom surface. A pair of notches is cut on the two sides of the beam, so the crack location is known. A LVDT is placed across the notch at the same level of the sensor sheet along the depth of the beam. When loading is applied, the optical power loss is measured simultaneously with the crack opening. A number of tests have been performed using sensor sheets made with different types of optical fibers running at different angles to the longitudinal direction. In Figure 4, the results for sensors made with SMF28 fibers running at 30 and 45 degrees to the crack plane are shown. In the plots, the signal loss of the fiber was measured with an optical power meter, while the crack opening is obtained with the LVDT. Also shown in the figure are the predicted power loss vs. crack opening relations from the model described in the last section. Generally speaking, the agreement between experimental and theoretical results is very good.

Both the theoretical and experimental results indicate that the sensitivity of the sensor to crack opening increases with the fiber inclination angle to the crack plane. If the sensor is designed for the monitoring of one or two cracks, a higher inclination angle should be employed. However, with a higher angle, the asymptotic loss at large crack opening is also higher. When a sensor is designed for the distributed sensing of a large number of cracks, one should limit the asymptotic loss so the dynamic range of the OTDR system will not be used up when light has passed through a small number of cracks. For different applications, different signal loss vs. crack opening relations are desirable. Using the theoretical model, which has been verified with experimental data, simulation can be performed to identify the appropriate design parameters (such as fiber type, inclination angle, fiber coating) before actual sensors are made and tested to verify the performance. The amount of trial and error testing can hence be significantly reduced.

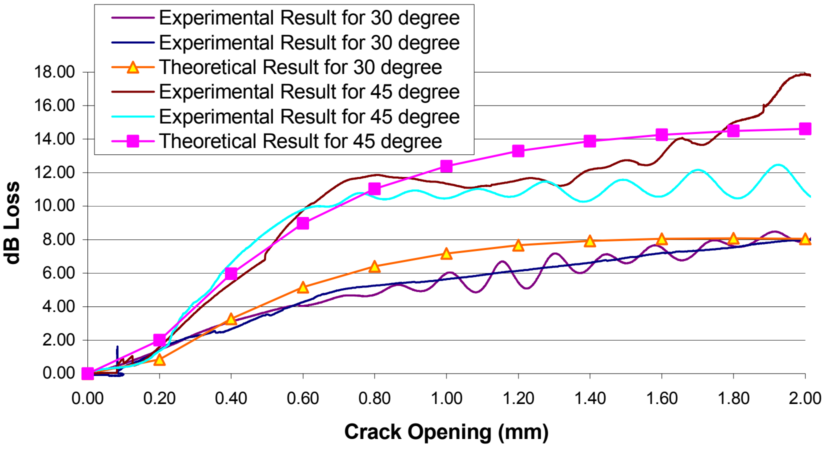

Figure 4. Experimental and Theoretical Results for Crack Sensors with Fiber at 30 and 45 degrees to the Crack Plane

5.2 Preliminary Work on Crack Monitoring Under Cyclic Loading

One of the potential applications of this optical crack sensor is to monitor structural damage under seismic loading. Thus, the dynamic behavior of the sensor has to be examined. Using a beam specimen with steel reinforcements, monotonic loading is first applied until the load vs. displacement curve approaches a plateau. Sinusoidal loading is then applied from 20% to 95% of the peak load until the beam fails. During the cyclic loading, the load history, changes in crack opening and optical power loss are measured, and typical variations are shown in Figure 5. The results are plotted in a way that the values on the y-axis represent the loading (in kN), the optical power loss (in dB) and crack opening (in mm). There is only one major flexural crack at the mid-span of the beam. The crack opening is reflected by increasing optical loss. The fiber breaks after 23 loading-unloading cycles. The crack opening propagates from 0.4mm at the beginning to 1.8mm when the fiber breaks. Since the sensor is installed at the level of a quarter of the height from the bottom, 1.8mm crack opening at that level indicates severe damage of the beam. So, practically, the fiber sensor can survive quite severe structural damage. Figure 6 shows that the loss at the crest (or peak point) of crack opening at each loading cycle can be predicted from the model. By continuous monitoring of the optical loss during an earthquake, the maximum crack opening can be obtained for assessing the degree of damage.

6. CONCLUSIONS

In this investigation, the principle of a fiber optic crack sensor is presented. Actual sensors have been fabricated and tested. A theoretical model for power loss vs. crack opening is also developed. For crack sensing under monotonic loading, the predictions from the theoretical model are found to be in good agreement with experimental results. With its validity verified, the theoretical model can be employed to provide design guidelines for the crack sensor. Preliminary experimental work also shows that the sensor is applicable to crack monitoring under cyclic loading. The measured

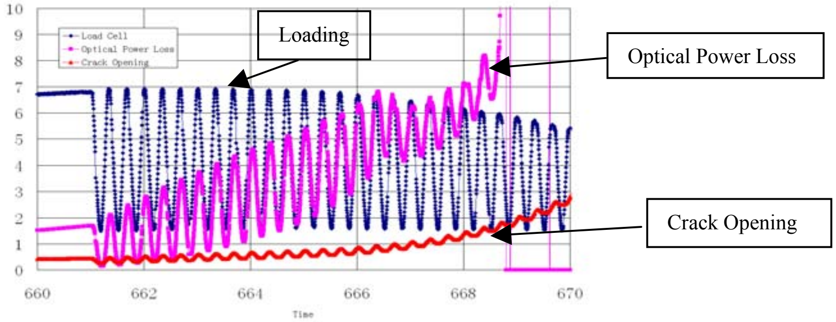

Figure 5. Variation of Optical Power Loss, Crack Opening and Loading with Time

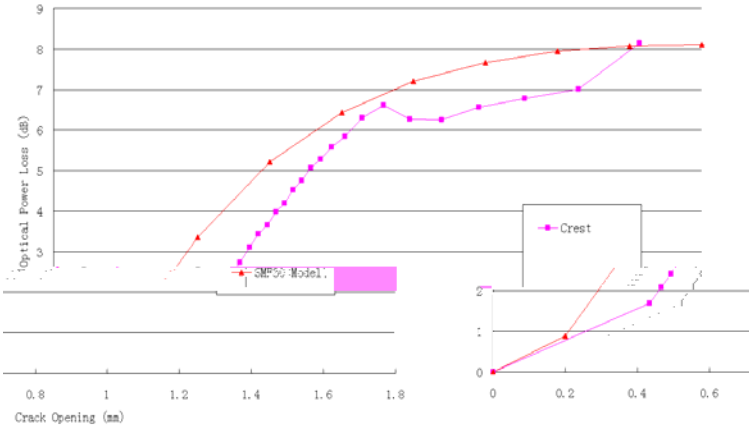

Figure 6. Comparison of loss between the model and the crest of crack opening in each cycle

loss is again in good agreement with the theoretical model. Based on the experimental and theoretical results, the potential of the sensor for practical applications is demonstrated.

7. REFERENCES

1. Leung, C.K.Y., Elvin, N., Olson, N., Morse, T.F. HE, Y.-F., A novel distributed optical crack sensor for concrete structures, Engineering Fracture Mechanics, Vol.65, pp 133-148, 2000
2. Leung, C.K.Y., Fiber optic sensors for concrete structures: the future, Non-destructive Testing and Evaluation, Vol.34, pp 85-94, 2001
3. Marcuse, D., Curvature loss formula for optical fibers, Journal of the Optical Society of America, Vol.66, pp 216-220, 1976
4. Nagano, K., Kawakami, S., Nishida, S., Change of the refractive index in an optical fiber due to external forces, Applied Optics, Vol.17, pp 2080-2085, 1978
5. Valiente, I, Vassallo, C., New formalism for bending losses in coated single-mode optical fibers, Electronics Letters, Vol.25, pp.1544-1545, 1989
6. Gauthier, R.C., Ross, C., Theoretical and experimental considerations for a single-mode fiber-optic bend-type sensor, Applied Optics, Vol.36, pp 6264-6273, 1997