# Applications of a fibre optic crack sensor in concrete structures

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ABSTRACT: Concrete structures deteriorate through the formation and propagation of cracks. Crack detection and monitoring is hence an effective means to assess the condition of structures for the development of appropriate maintenance schemes. For crack sensing in a concrete structure, the major challenge is that the exact crack location is often not known. If conventional point sensors are employed, the required number of sensors can become so high that the sensing scheme is no longer economically feasible. At HKUST, we have developed a novel fiber optic sensor that can detect and monitor cracks without prior knowledge of their locations. Moreover, a single fiber can be employed for the monitoring of multiple cracks. In this presentation, after describing the physical principle and fabrication techniques of the sensor, various applications of the sensor will be presented and illustrated with laboratory testing results. These will include monitoring of flexural crack under static and cyclic loading, detection and monitoring of multiple cracks, and crack sensing under restraint dimensional changes (due to shrinkage or thermal effects). Through these examples, the potential of the crack sensor for practical applications is demonstrated.

Keywords: Cracks, fiber optic sensing, monitoring, non-destructive evaluation

## 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. The limitations of point and integrated sensors in crack detection have been discussed in [1].

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 taking place along its length. If the optical fiber is coupled to a concrete structure in a proper way, any crack that forms 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. Next, how the sensor is fabricated is introduced. Then, results from recent experimental investigations will be described to demonstrate the practical applicability of the sensing concept.

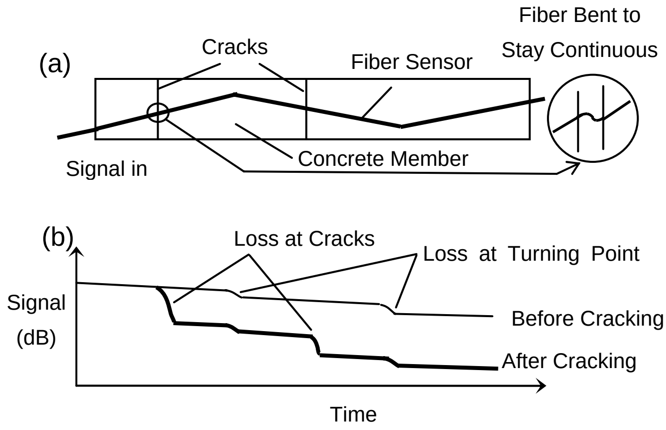

Figure 1. Concept of Distributed Sensing with the Novel Sensor

## 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)). The continuous declining of the curve is caused by attenuation of the optical fiber. 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 should be known. This is not a problem with most common structures. Further discussion of the sensing principle is found in [1,2].

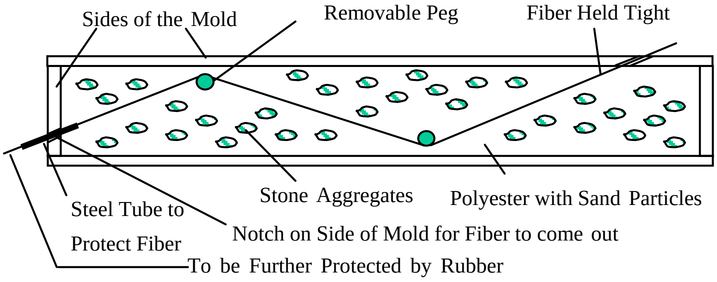

Figure 2. Illustration of the Fabrication a Sensor Sheet

## 3 SENSOR FABRICATION

A method to prepare the optical fiber sensor is illustrated in Figure 2. 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 one and half millimeters in thickness. Before polyester is added, releasing oil is sprayed 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 to minimize 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. (From our experience, the plate can be broken when the crack of concrete is about 0.08-0.1mm.) 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 2). 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.

## 4 EXPERIMENTAL RESULTS WITH THE CRACK SENSOR

### 4.1 *Crack Monitoring Under Monotonic Loading and Comparison with Theory*

As a first illustration of crack monitoring with the sensor sheet, a simple experiment involving the bending of a concrete beam is performed. The specimen and testing configuration is shown schematically in Figure 3. 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 (linear variable differential transformer) is placed across the notch at the same level of the sensor sheet along the depth of the beam on both sides. 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 Corning SMF28 fibers running at 30 and 45 degrees to the crack plane are shown and those for 3M FS-4224 fibers are shown in Figure 5. (Note: for single mode propagation, a 1550 nm LED light source and 850 nm LED light sources were employed respectively for SMF28 and and 3M FS-4224 fibers.) In the plots, the signal loss of the fiber was measured with an optical power meter, while the crack opening was obtained with the LVDT. Also shown in Figure 4 and 5 are the predicted power loss vs. crack opening relations obtained from the model by Leung et al [3]. Generally speaking, the agreement between experimental and theoretical results is good. The trend of test results is well captured by the theoretical model. At large openings, the experimental results show oscillations in the power loss that are not present in the theoretical results. These oscillations are believed to be due to a stick-slip effect caused by friction at the optical fiber/polymeric interface. Despite the application of releasing oil on the fiber surface, friction cannot be completely eliminated. From a practical point of view, this should not be a major issue. Significant oscillation only occurs at relative large openings when the high power loss value should have already prompted the owner of the structure to take appropriate action. The 'error' in the output signal resulted from the oscillations is therefore not important

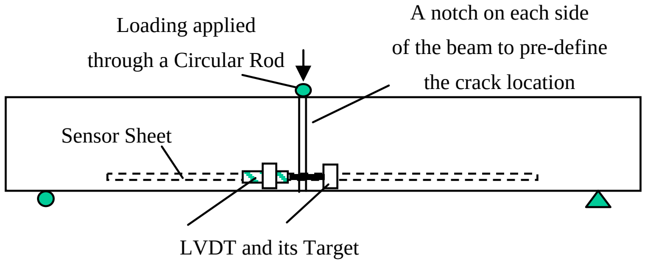

Figure 3. Test Configuration to Demonstrate the Capability of the Sensor sheet in the Monitoring of Internal Crack

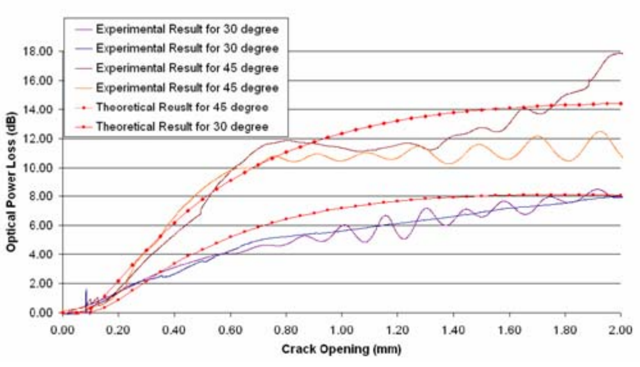

Figure 4. Experimental and Theoretical Results for Crack Sensors with Fiber at 30 and 45 degrees to the Crack Plane for SMF28

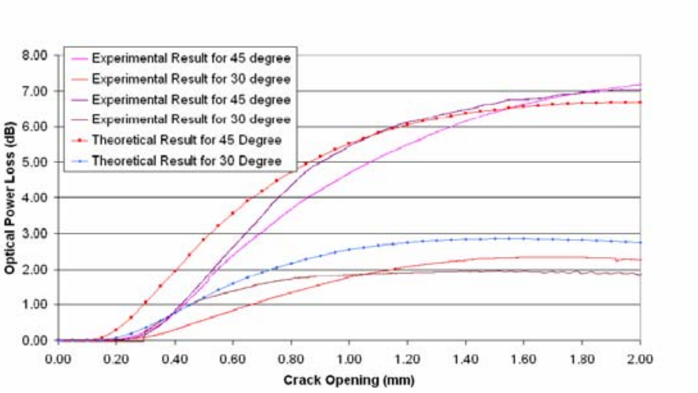

Figure 5. Experimental and Theoretical Results for Crack Sensors with Fiber at 30 and 45 degrees to the Crack Plane for 3M FS-4224

While the details of the theoretical model have been presented elsewhere [3], the reason for its development should be discussed. The performance of the crack sensor is directly related to the signal loss vs crack opening relation. High loss at small crack openings would increase the sensitivity of crack detection. However, since the dynamic range of OTDR measurement is limited, high loss at each crack will limit the total number of cracks that can be detected and monitored with a single fiber. For a given crack opening, the signal loss depends on many parameters including (i) the optical properties of the fiber, (ii) the fiber inclination angle to the crack, and (iii) the elastic properties of the fiber, the surrounding matrix and the protective polymeric coating on the fiber. Sensor design based on purely empirical testing will involve an extensive experimental program that is costly and inefficient. There is hence a need to develop a theoretical model for signal loss vs crack opening. With the model, simulation can be performed first to identify appropriate combinations of design parameters. The amount of trial and error testing can then be minimized.

To demonstrate the sensing of multiple cracks, a concrete beam with two pairs of matching notches cut on the sides was put under four-point loading (Figure 6a). Two sensor sheets were glued to the bottom of the beam, and the fibers from the two sheets were connected together with a mechanical splice (Figure 6b). Proper sensor performance requires the sensor sheet to crack together with the concrete member, so delamination of the sensor from the beam needs to be avoided. Roughening of the concrete surface followed by bonding with a thin layer of epoxy was found to serve the purpose. In the experiment, single point loading was first applied above each notch (with 1.4m loading span) to produce a crack. After cracks are formed at the location of the two notches, the beam is put under 4-point loading with 1.8m span as shown in Figure 6a. With the placement of sensors as shown in Figure 6b, the two cracks would induce bending and signal loss at four separate locations along the fiber. At the bottom of the beam, LVDTs were also placed across the notches. The measured signal loss along the fiber sensor could then be correlated to the actual crack opening.

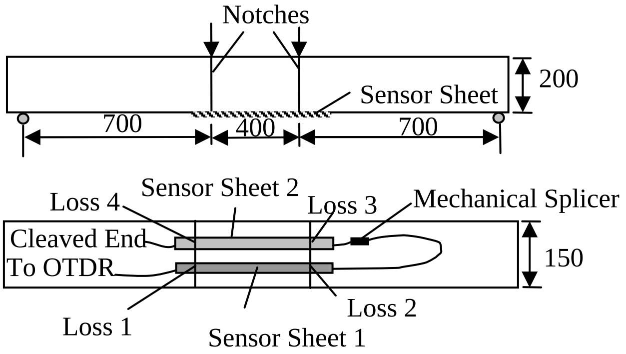

Figure 6. Test Configuration for the Verification of Multiple Crack Detection

To measure the loss of backscattered signal, an OTDR (Opto-Electronics OFM-20) was linked to the sensor sheets through a spool of fiber over 30m in length. With a long length of fiber before the sensor, the backscattered signals from the cracks will not be overwhelmed by the strong reflection created at the bulkhead connection of the OTDR. Figure 7 shows the OTDR record when two cracks (1.5mm and 0.6mm) had formed at the notched locations after loading was applied. From the plot of backscattered signal vs time, besides the reflection from the cleaved fiber end, we expect to see four major drops in the signal. However, three drops and a jump in the signal are identified instead. The jump was caused by strong reflection at the mechanical splicer. Indeed, this reflection was so strong that it flooded out the loss induced by one of the cracks on sensor sheet 2 (which is Loss 3 in Figure 6b). In the test, the length of fiber from the splice to sensor sheet 2 is much shorter than the length to sensor sheet 1. The test result has an important implication: if two sensors are to be spliced together, it is crucial to (i) ensure good splicing quality to minimize the Fresnel reflection at the splice, (ii) leave a sufficient length of fiber between the splice and each sensor to avoid the aforementioned problem.

From the x-axis of the backscattered signal plot, the distance of each drop from the OTDR can be obtained. The distance corresponding to the middle of each signal drop was found to be in good agreement with direct measurement along the fiber. Comparing Loss 1 and Loss 2 in Figure 7, it is clear that a more significant loss can be obtained at a larger crack opening. The first and last losses (Loss 1 and Loss 4 in Figure 7) were induced by the same crack along the beam. With the same crack opening, the same magnitude of loss (in dB) was indeed obtained. This result indicates that the loss vs crack opening relation at one point along a fiber is independent of the loss at other points. This is a very important characteristic of the single mode fiber that makes the sensing concept applicable to the quantitative measurement of crack opening at multiple points along the fiber.

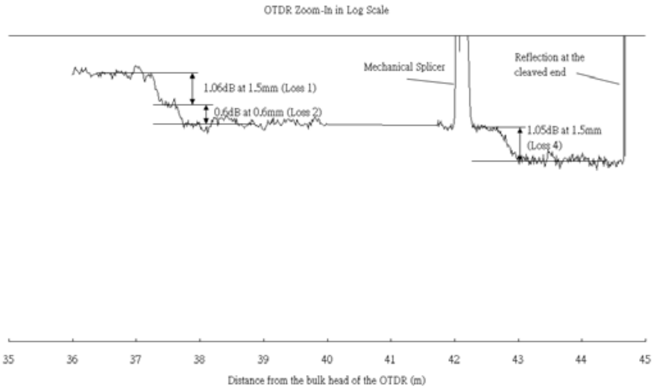

Figure 7. The Zoom-In of the OTDR Record showing the Presence of Three Cracks along the Beam and a Location of High Reflection

### 4.2 *Preliminary Work on Monitoring of Flexural Crack Under Cyclic Loading*

One of the potential applications of this optical crack sensor is to monitor structural damage under cyclic or seismic loading. Thus, the dynamic behavior of the sensor has to be examined. The same setup in Figure 3 was employed. Using a specimen with steel reinforcement, monotonic loading was first applied until the load vs. displacement curve approached a plateau. Sinusoidal loading was then applied from 20% to 95% of the peak load until the beam failed. During the cyclic loading, the load history, changes in crack opening and optical power loss were measured, and typical variations were shown in Figure 8. The results were plotted in a way that the value on the y-axis represents the loading (in kN), the optical power loss (in dB) and crack opening (in mm). There was only one major flexural crack at the mid-span of the beam. The continuous increase in crack opening was reflected by increasing optical loss. The fiber broke after 23 loading-unloading cycles. The crack opening propagated from 0.4mm at the beginning to 1.8mm when the fiber broke. Since the sensor was installed at the level of a quarter of the height from the bottom, 1.8mm crack opening at that level indicated severe damage of the beam. The results show that the fiber can survive quite severe structural damage in practice.

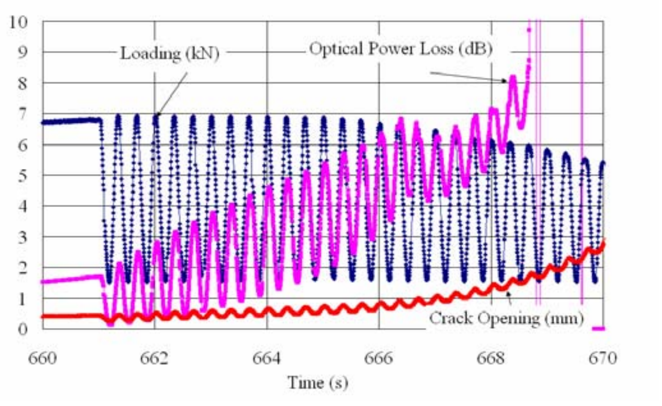

Figure 8. Variation of Optical Power Loss, Crack Opening and Loading with Time

The power loss at the crest (or peak point) of crack opening at each loading cycle is plotted in Figure 9 together with predictions from the theoretical model. Reasonably good agreement is again achieved. According to the results, if continuous optical signal monitoring is performed, it is possible to obtain the maximum crack opening during the loading cycles for damage assessment of the structure.

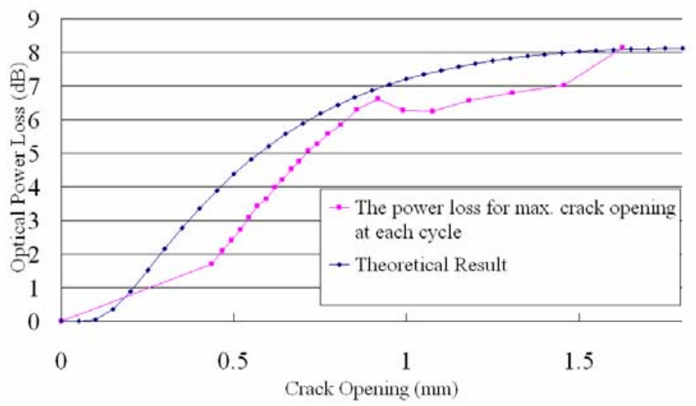

Figure 9. Comparison of Measured Loss at Maximum Opening in Each Cycle with Model Results

## 4.3 *Potential application on dry shrinkage crack monitoring*

When dimensional changes occur in a concrete member, due to shrinkage or thermal effects, cracking may occur in restrained parts of the member. Such cracks, if left undetected, will allow the penetration of water and corrosive agents that will affect the long-term durability of reinforced concrete members. For parts of the structure that are inaccessible (such as the sides of a buried foundation) or difficult to access (such as a large slope), the capability for remote crack sensing is highly desirable. To demonstrate the applicability of the proposed crack sensor in the detection of cracking under restrained conditions, shrinkage cracking was studied with the set-up in Figure 10.

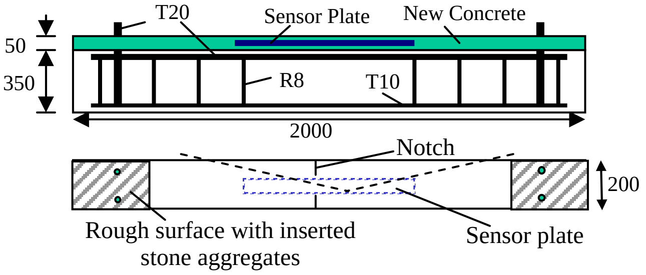

Figure 10. The Set-up to Demonstrate the Sensing of Shrinkage Crack

A 200x350x2000mm reinforced concrete member was first prepared to serve as a stiff base. At each end of the member, two T20 steel bars were installed vertically, and stone aggregates were inserted into the concrete surface to increase the roughness. After curing, the concrete base was allowed to dry for one month so further shrinkage would only occur at a slow rate. A 50mm layer of concrete was then cast on the base. Before casting, a thin layer of sand was added to the middle portion of the base member and covered with a plastic sheet to reduce the friction. On the concrete layer, a pair of notches was created at the middle section. An optical sensor was also embedded in the middle part for the monitoring of shrinkage crack. With the configuration described above, when shrinkage occurs in the upper concrete layer, loading will be transferred to the concrete base through the vertical steel bars and the roughened concrete surfaces near the two ends. Conversely, tension will be induced in the top concrete layer. As there is little bonding or friction along the middle portion of the layer, there is uniform tension along the length direction and the shrinkage crack will form at the notched location.

In the test, after the concrete layer was cast, it was cured for two days. Then, a fan was set up to blow wind on the specimen surface to accelerate the drying process. Right before the fan was turned on, the initial reading for the optical crack sensor was taken. Two days after the fan was on, a crack was observed to form at the notched location. The crack opening was measured with a hand-held microscope. The measured crack openings, together with the optical power loss for the crack sensor, were given in Table 1, for the first five days of accelerated drying. Also shown in Table 1 are theoretical crack openings obtained from the measured power loss and the model for signal loss vs crack opening. From the table, the theoretical crack opening is always smaller than the measured value. This may be due to the fact that the sensor is embedded inside the concrete layer. As crack opening increases towards the surface, the measured internal opening should be smaller than the surface opening. However, since the difference is not very large, we believe that the crack sensor can provide a reasonable estimate of the surface crack opening when restrained dimensional changes result in the formation of cracks.

Table 1: Summarized result of the shrinkage crack detection

| Day | Optical Power ($\mu$W) | Optical Power Loss (dB) | Crack Opening (mm) | Theoretical Crack Opening (mm) |
|---|---|---|---|---|
| 0 | 1.093 | ---- | ---- | ---- |
| 2 | 0.835 | 1.2 | 0.2 | 0.15 |
| 3 | 0.870 | 1.0 | 0.16 | 0.14 |
| 4 | 0.798 | 1.4 | 0.22 | 0.16 |
| 5 | 0.855 | 1.1 | 0.2 | 0.15 |

## 5 CONCLUSIONS

In this investigation, the principle of a fiber optic crack sensor is presented. Actual sensors have been fabricated and tested. Experiments have been performed on the monitoring of single and multiple flexural cracks under static loading, crack monitoring under cyclic loading as well as the detection of cracks under shrinkage restraint. The experimental power loss vs crack opening relations were found to be in reasonable agreement with theoretical results. Based on the results of the present investigation, the potential of the sensor for various practical applications is demonstrated.

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