Quasi Distributed OTDR Crack Sensor for Reinforced Concrete Structures

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Abstract

A quasi-distributed fiber optic sensor is developed for embedment in concrete structures. The sensor principles are simple, and therefore, practical for crack detection and deformation measurement in civil structural applications. The distributed sensor developed herein operates based on the intensity measurements of optical power. The sensor consists of a number of individual segments on one line, with gauge lengths designed according to the structural and materials requirements. An optical time domain reflectometers (OTDR) was employed for interrogation of the sensor signal. The study reported herein is aimed at demonstrating the applicability of this sensor in monitoring performance of concrete structures. Crack detection methodologies were established through experiments with plain concrete beams. Structural monitoring capability of the sensor was evaluated through experiments with reinforced concrete beams.

INTRODUCTION

Full-scale monitoring of structures requires sensing at multiple points and within large volumes. Therefore, many sensors are normally required. For this reason, various multiplexing technologies have been considered in civil structural applications (Sirkis, 1998). The Bragg grating has been the dominant sensor of choice in most cases (Morey, et. al., 1989, Kersey, 1993). Bragg grating sensor architectures have been successfully employed in concrete elements in order to monitor strains in reinforcing bars and prestressing tendons (Nawy, 1992). Distributed sensors are most suited for large structural applications, since all the segments of the optical fiber act as sensor, and therefore, the perturbations within various segments of the structure can be sensed. However, distributed sensors have not found widespread usage in civil structural applications. There is a need for development of optimum distributed sensing technologies for civil structures.

Two of the most widely employed distributed sensor methodologies correspond to optical time domain reflectometry (Ansari, 1997) and Brillouin scattering (Brown, et. al.,1998). In optical time domain reflectometry, Rayleigh or Fresnel scattering is used for transduction of structural perturbations. On the other hand, in Brillouin scattering the Doppler shift in the frequency of light is related to the measurands. It is also possible to develop sensors that provide average values of measurands over specific gauge lengths. A multi-gauge-distributed sensor is comprised of the assemblage of individual sensors in series, each measuring an average value of measurand over distinct segments. One such sensor is developed here for application in concrete structures. The basic principle of operation for the crack sensor is based on intensity variation of the optical power within the fiber due to the initiation and opening of cracks. This article reports on the functional characteristics of the sensor in terms of resolution, hysteresis, and sensitivity. Moreover, it demonstrates the applicability of the sensor in condition monitoring of reinforced concrete elements under monotonic and fatigue loading conditions.

METHODOLOGY

Optical Time Domain Reflectometers (OTDR) have been developed for characterization of anomalies in the telecommunication links. It is an important tool for detection of transmission irregularities due to splice losses, and local damage along the fiber length. OTDR also provides capability for one-port operation at the fiber input with no need to access the fiber output. In a basic OTDR measurement, a laser transmitter launches an optical pulse into the fiber under test. The optical signal travels through the optical fiber and then it is reflected back through the fiber into the OTDR. Signal reflection occurs due to Rayleigh and Fresnel back scattering events. Microscopic density fluctuations within the core of the fiber material give rise to refractive index impurities which in turn are responsible
for Rayleigh back scattering. Fresnel reflections originate from many points along the fiber where abrupt and discrete discontinuities occur in the index of refraction. One example is poorly spliced and or connectorized regions along the length of the fiber. Straining of the fiber within a segment bounded by the spliced regions result in intensity fluctuations of the reflected signal, which is due to the loss of optical power at the air-to-fiber interface in the spliced point.

**Single Gauge Sensor**

The multi-gauge sensor developed here requires optical segmentation of the fiber at several points along its length in order to create Fresnel reflection points. In this way, an optical fiber is divided into several gauge lengths through which monitoring of cracking and deformations are accomplished. The back-reflectied Fresnel signal is employed to pin point, \( L \), the location of the disturbance along the total length of the fiber. Moreover, the deformation is sensed through the intensity variations of the Fresnel-peaks in the back-scattered signal. Fresnel points can be created by using a special precision optical fiber cleaver in order to slice the fiber into a number of smaller segments, each representing a gauge length. The cleaved fibers are spliced along one line in order to create the distributed sensor. In the formulations to follow, both transmission and reflection losses are used in the transduction of the measurand.

A typical segment of a sensor between two Fresnel points is shown in Fig.1. The Fresnel signals are also given in the schematics representing the OTDR screen. It is assumed that the optical fiber consists only of one gauge length between the two Fresnel points representing the reference and reflector planes \( R_0 \) and \( R_1 \), respectively. The pulse of laser enters the fiber from the reference plane at \( R_0 \) with intensity \( I_0 \). It is partially transmitted and reflected at the reflector plane \( R_1 \). The reflected signals re-enter the OTDR and create the Fresnel peaks. The incident, transmitted and reflected signals are represented by \( I_0, I_T \) and \( I_R \), respectively. Accordingly only a portion of the incident signal is transmitted, whereas, the rest is reflected. The insertion loss, \( I_{lo} \), that represents the ratio of incident and the actual transmitted signal is given in logarithmic scale in decibels (db) as:

\[
I_{lo} = 10 \log \frac{I_0}{I_T} \quad (1)
\]

In a similar manner the return loss of the incident light is:

\[
R_{lo} = 10 \log \frac{I_0}{I_R} \quad (2)
\]

In the absence of strain, \( I_{lo} \) and \( R_{lo} \) remain constant. However, upon straining, \( I_{lo} \) and \( R_{lo} \) vary with strain. Variations in \( I_{lo} \) and \( R_{lo} \) are manifested in the amplitude of the Fresnel reflection peaks. Accordingly, the insertion and return losses can be employed for the determination of strain or deformation through the following relationships:

\[
\Delta I_{lo} = |I_{tol} - I_{lo}|
\quad (3)
\]

\[
\Delta R_{lo} = |R_{tol} - R_{lo}|
\quad (4)
\]

\[
\delta \quad \text{or} \quad \varepsilon = \alpha \Delta I_{lo} \quad \text{(or)} \quad \varepsilon = \beta \Delta R_{lo} \quad (5)
\]

Where, \( \Delta I_{lo} \) = insertion loss after strain
\( \Delta R_{lo} \) = return loss after strain
\( \varepsilon \) = average strain within the gauge length, \( d \), of the optical fiber
\( \delta \) = deformation of the optical fiber along the gauge length, \( d \)
\( \alpha, \beta \) = proportionality constant relating deformations and strains to the optical loss factors.
As noted in Eq.(6), both of the loss parameters, $\Delta I_{lo}$ and $\Delta R_{lo}$ can be employed for the determination of strain. However, at the same strain level, more sensitivity can be achieved with the reflection loss, since upon reflection the optical signal travels through twice as many Fresnel points.

$$\Delta I_{lo}(\Delta I_{lo}) = 10 \log \frac{I_0}{I_{ti}} \quad (i = 1, 2, \cdots, n)$$

$$\Delta R_{lo}(\Delta R_{lo}) = 10 \log \frac{I_0}{I_{ri}} \quad (i = 1, 2, \cdots, n)$$

where, $I_{lo}$ and $R_{lo}$ pertain to the insertion and return losses of the $i$-th segment at the reference plane. The reference plane, $R_{lo}$, corresponds to the point of laser pulse entry into the first segment ($i=1$). $I_{ti}$ and $I_{ri}$ are the transmitted and the return light intensities of the $i$-th fiber optic segment, respectively. $I_{lo}$ and $R_{lo}$ represent accumulated insertion and reflection losses from sensor 1 all the way to sensor $i$. To monitor and measure strain and deformation in the $i$-th sensor alone, it is necessary to obtain the insertion and return loss of the $i$-th fiber optic segment according to the following relationships:

$$I_{lo}^{(i)} = 10 \log \frac{I_{lo^{i-1}}}{I_{ti}} \quad (i = 1, 2, \cdots, n)$$

Fig. 1 A typical segment of the sensor between two Fresnel points and their peaks in the OTDR screen

Multi-Gauge Distributed Sensor

A distributed sensor consisting of $n$-segments in series is schematically depicted in Fig. 2. The insertion and return losses for the $i$-th reflector plane ($R_i$) with respect to the reference plane ($R_0$) is expressed as:

$$I_{lo}^{i} = 10 \log \frac{I_0}{I_{ti}} \quad (i = 1, 2, \cdots, n)$$

$$R_{lo}^{i} = 10 \log \frac{I_0}{I_{ri}} \quad (i = 1, 2, \cdots, n)$$

where, $I_{lo}^{i}$ and $R_{lo}^{i}$ pertain to the insertion and return losses of the $i$-th segment at the reference plane. The reference plane, $R_0$, corresponds to the point of laser pulse entry into the first segment ($i=1$). $I_{ti}$ and $I_{ri}$ are the transmitted and the return light intensities of the $i$-th fiber optic segment, respectively. $I_{lo}$ and $R_{lo}$ represent accumulated insertion and reflection losses from sensor 1 all the way to sensor $i$. To monitor and measure strain and deformation in the $i$-th sensor alone, it is necessary to obtain the insertion and return loss of the $i$-th fiber optic segment according to the following relationships:
By combining Eqs. 6 and 8, the following expressions may be derived:

\[
\begin{align*}
I_{lo}^{(i)} &= I_{lo}^{-1} \\
I_{lo}^{(i)} &= 10 \log \frac{I_{Ti}^{-1}}{I_{Ri}} = 10 \log \frac{I_0}{I_{Ti}} = I_{lo}^{-1} - I_{lo}^{-1}_{-1} \\
\end{align*}
\] (10)

Where, \( I_{lo}^{(i)} \) corresponds to the transmission loss of the \( i \)-th fiber optic segment alone. To develop an expression for the return loss of the \( i \)-th segment alone, Eq. (7) is used in the following manner:

\[
R_{lo}^{(i)} - R_{lo}^{-1} = 10 \log \frac{I_0}{I_{Ri}} = 10 \log I_{Ri} - 10 \log I_{Ri}^{-1} = (i = 2, 3, \cdots, n) 
\] (11)

Combining Eqs. (8) and (9) results in the following expression:

\[
R_{lo}^{(i-1)} - I_{lo}^{(i-1)} = 10 \log \frac{I_{Ti}^{-2}}{I_{Ri}^{-2}} - 10 \log \frac{I_{Ti}^{-2}}{I_{Ri}^{-2}} = 10 \log \frac{I_{Ti}}{I_{Ri}} \\
= 10 \log I_{Ti} - 10 \log I_{Ri} \\
\quad (i = 2, 3, \cdots, n) 
\] (12)
Return loss in the i-th segment, $R_{lo}^{(i)}$, is obtained by combining Eqs. (11) and (12):

$$
\begin{align*}
R_{lo}^{(1)} &= R_{lo}^{-1} \\
R_{lo}^{(i)} &= R_{lo}^{i} - R_{lo}^{i-1} + R_{lo}^{(i-1)} - I_{lo}^{(i-1)} \\
& \quad (i = 2,3,\ldots,n)
\end{align*}
$$

(13)

It is important to note that the $R_{lo}^{i-1}$ and $R_{lo}^{(i-1)}$ do not cancel out as they differ per definition. It is then possible to evaluate strain in the individual segments $i=1\ldots n$ through Eqs. (3), (4), and (5). The optical fiber sensor will be able to sense the cracking and the deformations within its various segments. Either one of the expressions for the insertion loss or the reflection loss would yield similar results. These expressions are directly programmed in the OTDR for real-time sensing and monitoring activities. The transform coefficients, $\alpha$ and $\beta$ in Eq. (5) which relate the intensity losses to strain, are determined through experimentation. This will be discussed next.

**EXPERIMENTAL PROGRAM**

Capability of the distributed sensor in sensing and measurement of crack widths were evaluated through a series of tests with reinforced concrete beams. Experimentation with reinforced concrete (RC) beams included both fatigue as well as monotonic loadings. Beam dimensions and the reinforcement pattern for the three RC beams are shown in Fig.3a. The RC beams were given alphabetic designations A, B, and C. Beam C was constructed with reduced rebars in order to produce larger crack widths. This allowed for assessment of the sensor’s capability in measuring a range of crack widths. The distributed sensor was strategically placed below the tensile steel in the concrete cover, near the bottom surface of the beam. At this location, it was easy to compare the crack detection and measurement capability of the sensor against visual observations and measurements. The single line distributed sensor consisted of six gauge lengths (457-mm) along the span ($F_1$ through $F_6$ in Fig.3b). In a typical formwork operation the optical fiber was stretched along the length of the beam at the desired depth, and then the concrete was poured. The fiber optic connector was placed in the formwork in the concrete during pouring operations and it was used for making connections to the OTDR during the experiments.

![Fig. 3 Beam dimensions, reinforcement, and fiber optic sensor gauge designations in RC-beams](image-url)
Beams were tested in a closed-loop servo-hydraulic testing system under four-point bending with loads applied at the middle third of the span. Beam A was subjected to fatigue loading for 1–million cycles at 5-Hz. Fatigue load amplitude was varied between 17.8 and 53.4 KN (4 to 12 Kips). Data acquisition posed a problem, since a tremendous amount of data was being accumulated for the duration of 1-million cycles. Accordingly, it was decided to program the system so that data could be collected after every 36000 and/or 72000 load cycles. At the end of the millionth cycle, the beam was loaded monotonically until failure. Cracking of the beam was monitored by the optical fiber sensor and visual inspections. Visual inspections involved marking the crack locations; their progression and measurement of crack widths by a micrometer scale graduated caliper (crack comparator). Beams B and C were instrumented in a manner similar to beam A and they were loaded monotonically until failure.

**Experimental Results**

The focus of the experimental observations was the pertinence of the sensor in structural monitoring applications. Survivability of the sensor under large deformation cyclic loads, crack detection and measurement capabilities, signal referencing after periods of data acquisition dormancy, and strain monitoring capabilities were among important observations made during this study. Accordingly, the sensor was embedded within the concrete in a location that was obviously prone to severe cracking and large deformations. This allowed for the evaluation of the crack sensor in terms of its practicality for structural monitoring applications.

A typical load versus center-span deflection curve for the reinforced concrete beam is shown in Fig. 4. This figure corresponds to beam A, which was fatigue loaded to million cycles and then the load was monotonically increased until failure. Several cracks formed along each individual gauge length of the optical fiber sensor (F₁ through F₆). The sensor detected the initiation of all the cracks along the span, and it measured crack widths along individual gauge lengths. Crack widths were acquired in a cumulative manner within the individual gauge lengths.

![Fig.4 Load-displacement relationship for beam A](image_url)

Crack patterns at failure, and crack width measurements as acquired by the optical fiber sensors in beams A, B and C are shown in Figs. 5 through 7. Fig. 5 pertains to beam A, which was loaded in fatigue. Crack widths after the first and 1-millionth loading cycles are compared in this figure. Figs 6 and 7 pertain to crack widths for beams B and C tested under monotonic loading conditions. It is possible to discern the effect of cyclic loading on crack widths by comparison of results for beams A and B since they had similar designs. As shown in Figs. 5 and 6, at the same load level of 12 kips, the maximum crack width in beam A after the millionth cycle was approximately 4-times larger than the maximum crack width in beam B. Deterioration of the beam due to cyclic loading is also apparent in Fig. 5 by observing that the cracks readily remained open during the unloading cycles.
Fig. 5 Distribution of cracks and crack openings for beam A

All visible cracks happened in the first loading cycle except those marked with loading cycles.

The first loading cycle:
- $P = \frac{P}{2}$ (P/2)
- $P = 2\,\text{kips} (8.896\,\text{kN})$
- $P = 8\,\text{kips} (35.584\,\text{kN})$
- $P = 10\,\text{kips} (44.490\,\text{kN})$

The $1,000,000^{th}$ loading cycle:
- $P = 2\,\text{kips} (8.896\,\text{kN})$
- $P = 8\,\text{kips} (35.584\,\text{kN})$
- $P = 12\,\text{kips} (53.376\,\text{kN})$

Crushing concrete:
- $F_1$
- $F_2$
- $F_3$
- $F_4$
- $F_5$
- $F_6$

Fiber optic:
- $0.02\,\text{in}$
- $0.508\,\text{mm}$

1,000,000th loading cycle:
- $P = 6\,\text{kips} (26.688\,\text{kN})$
- $P = 8\,\text{kips} (35.584\,\text{kN})$
Fig. 6  Distribution of cracks and crack openings for beam B

All visible cracks happened at load of $P=8\text{kips}(35.584\text{kN})$ except those marked with load values.
Conclusions

A multi-gauge-distributed sensor is developed for applications in concrete structures. The sensor operates based on the intensity measurements of optical power. An experimental program was undertaken in order to study the feasibility of the embedded sensor in detection of cracks and measurement of deformations in concrete structures. Experiments with plain concrete provided the basis for crack detection capabilities of the sensor. Subsequently the distributed sensor was embedded in the tension zone of reinforced concrete beams, where it would be easy to keep a good accounting of the cracks formed. This arrangement facilitated evaluation of the sensor in monitoring of cracks. Experimental program involved monotonic as well as fatigue loading of reinforced concrete beams. The multi-gauge sensor was capable of measuring the cracks widths within the individual segments of the sensor. These sensors do not exhibit hysteresis, and for this reason they can be used in applications pertaining to bridge structures where the mode of loading is that of fatigue. Future research should include sensors of various gauge lengths in order to match the sensor gauge to the size of the structural element.

Fig. 7 Distribution of crack and crack openings for beam C
References


