# Bridge Maintenance, Safety, Management, Life-Cycle Performance and Cost

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# New method for detecting & measuring cracks on concrete using fiber optic sensors

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ABSTRACT: Advances in the production of optical fibers have made possible the recent development of innovative sensing systems for health monitoring of civil structures. The main reasons for this development are the reduced weight and dimensions of fiber optic sensors, the strong immunity to electromagnetic interference, the improved environmental resistance and the scale flexibility for small-gage and long-gage measurement. This paper provides an overview of the challenges in developing a new fiber optic sensor that can be employed to monitor flexural and tensile cracks on RC structures. The methodology in detecting and localizing the formation of flexural cracks in various locations and sensor's capability in measuring a range of crack widths is demonstrated through testing of instrumented RC beams subjected to sustained and repeated loading.

## 1 INTRODUCTION

The identification and evaluation of degradation of the structural performance is an important criterion for maintenance intervention on new bridges, and to repair or upgrade those already built. Nowadays in practice, the identification of deterioration in Reinforced Concrete (RC) structures is often executed visually, and when it is necessary a deeper investigation using various instruments will be performed. Usually the principal parameters to be determined in the evaluation of RC structure include: cracking, spalling, deflection, stains, erosion, and corrosion. The cracking can accelerate steel reinforcement corrosion in the concrete structure which is inciting spalling and also stains. In practice, this is the most commonly used parameter in inspections to propose maintenance intervention and preventing moisture infiltration.

In current design procedures (ACI 318 and AASTHO LRFD Standard Specifications for Highway Bridges) attenuation and control of cracking is done for obtaining acceptable appearance and for long-term durability of concrete by maintaining adequate distribution of cracks and reasonable limit on crack widths. In bridge structures cracks need to be repaired if they reduce the strength, stiffness, or durability to an unacceptable level, or if the function of the structure is seriously impaired. In practice the reparation of cracks is done after the cause is established, and determined whether the observed cracks are indicative of current or future structural problems, taking into consideration the present and anticipated future loading conditions. This involves first a field observation to identify the location and extend of cracking, then a review of drawings, specification, and construction and maintenance records. When all these do not provide the needed information a complex field investigation and structural analysis are recommended.

Collection of crack data is difficult and time consuming because a manual and expensive survey has to be involved in the process, which always requires the intervention of specialized equipment and operators. Due to the nature of the subjective survey, it is very difficult to obtain results that are accurate, repeatable, and reproducible. Thus, there is a need to automate the cracking survey process to improve safety and achieve more objective and consistent data of structure cracking. Today, the implementation of a statistical system to detect, locate, and measure the flexural and tensile cracks in any RC structure is one of the greatest difficulties encountered. In the future, it can be possible to establish a fracture control procedure in the design, fabrication, and maintenance of elements in bridges. If it is properly implemented, the fracture control plan can be capable to ensure the global safety of the RC structures during its service life based on the theory of structural reliability using random variables as the width and spacing of cracks.

A sensor for the reliable detection and monitoring of cracks in concrete structure was first proposed by researchers at MIT and Brown University (Leung et al. 2000). This technique does not require prior knowledge of the crack locations, which is a significant advantage over existing crack monitoring techniques. Moreover, several cracks can be detected, located and monitored with a single fiber. However, the crack direction is needed to measure the crack opening. An ideal application of the sensor, to monitor flexural cracks in bridges, was recently proposed (Olson 2002). To achieve the requirements in the monitoring of cracks on bridges the sensor was improved by researchers of the University of Minho, in Portugal, and of the Hong Kong University of Science and Technology, in China (Diaz de Leon et al. 2004).

The work presented herein introduces the development of the new distributed fiber optic crack sensor for RC structures. The sensor construction is simple and practical for applications to large RC elements. The capability of the sensor in monitoring the formation of flexural cracks, and measure the cracks widths through testing of instrumented RC beams subjected to sustained and repeated loading is demonstrated.

## 2 RESEARCH SIGNIFICANCE & OBJECTIVES

From long-term durability and aesthetic standpoints, crack control procedures in current design codes of RC structures have the intention to control and minimize the expected probable crack widths under service loads through reinforcement detailing (i.e. CEB-FIP and EC2 gives the European approach to crack width evaluation and permissible crack widths). For the proportioning of reinforcement during design, Table 1 presents a general guide for what could be considered reasonable crack widths at the tensile face of RC structures for typical conditions (Nawy 1968). For aesthetic reasons crack widths ranging from 0.15 to 0.30 mm could be considered unacceptable (Halvorsen 1987).

Table 1. Guide to reasonable crack widths, reinforced concrete under service loads.

| Exposure condition | Crack width, mm. |
|---|---|
| Dry air or protective membrane | 0.41 |
| Humidity, moist air, soil | 0.30 |
| Deicing chemicals | 0.18 |
| Seawater and seawater spray, wetting and drying | 0.15 |
| Water-retaining structures | 0.10 |

The monitoring of cracks on RC structures requires sensing at multiple points; therefore many sensors are normally required. The spatial resolution of each measurement should be small, and within a few centimeters (as minimum it is assumed to be the cover thickness) so that formation of a crack in various locations of a structure could be detected.

The practical approach for crack sensing involves the development of a distributed fiber optic sensor with the capability of making measurements from only one side of the structure. The sensor can be employed to detect, locate, and measure the crack widths of flexural and tensile cracks on RC structures. The basic principle of operation for the crack sensor is based on intensity variation of the optical power within the optical fiber due to microbending in the fiber by the initiation and opening of cracks. Flexural and tensile crack widths can be expected to double with time for members subjected to either sustained or repeated loading, depending on the environmental conditions. Based on the crack control design procedures the minimum and maximum resolutions required to measure crack widths are functions of the tolerable crack widths versus exposure conditions in reinforced concrete. In view of the fact that it is desirable to detect and measure a crack width ranging between 0.2 and 1.0 mm, the sensitivity of the sensor needs to be sufficiently high. However, for the optical sensor studied in this work, to detect many crack requires that the sensitivity not to be too high. Otherwise, only a limited number of cracks could be detected and monitored since the dynamic range of any Optical Time Domain Reflectometer (OTDR) is not unlimited.

The primary objectives of the work were: 1) To examine the sensor's methodology in detecting and localizing the formation of cracks in various locations; 2) To evaluate the sensor's capability in measuring a range of crack widths with respect to the sensitivity and control of the sensor response; and 3) To demonstrate the applicability of the sensor in monitoring flexural cracks on RC beams subjected to sustained and repeated loading.

## 3 SENSOR METHODOLOGY

A sensor for the reliable detection and monitoring of cracks in concrete structure has recently been developed (Leung et al, 2000). The sensor is based on the principle of distributed optical fiber microbending. An optical fiber is embedded in the concrete element in a "zigzag" shape (Fig. 1). Using OTDR equipment, the light intensity distribution along the fiber is measured. Before the formation of cracks, the backscattered signal along the fiber should follow a relatively smooth curve. In the straight portions of the fiber, the small loss is due to absorption and scattering. In the curved portion (where the fiber turns in direction), macrobending 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 90º has to bend to stay continuous. This perturbation in the fiber is very abrupt, and thus can be considered as microbending. This microbending results in a sharp drop in the optical signal. This intensity loss is detected and located by means of the OTDR equipment. Also, from the magnitude of the drop, the crack opening can be obtained if a calibration relation is available.

This technique does not require prior knowledge of the crack locations, which is a significant advantage over existing crack monitoring techniques. Moreover, several cracks can be detected, located and monitored with a single fiber. However, the crack direction needs to be known. An ideal application of the sensor is in the monitoring of flexural cracks in bridges, which may appear at arbitrary locations along the deck, but essentially perpendicular to the spanning direction. A method for applying the sensor to existing structures was recently proposed and involves the use of a Sensor Plate (Olson 2002, Leung et al, 2005). The sensor plate is a polymeric plate that works as a transducer with an embedded optical fiber; the principle is that once a crack forms in a structural element, the bonded polymeric plate will crack in the same direction of the crack, the interface of the polymeric matrix surrounding the fiber will allow the fiber to slide into the crack and undergo bending.

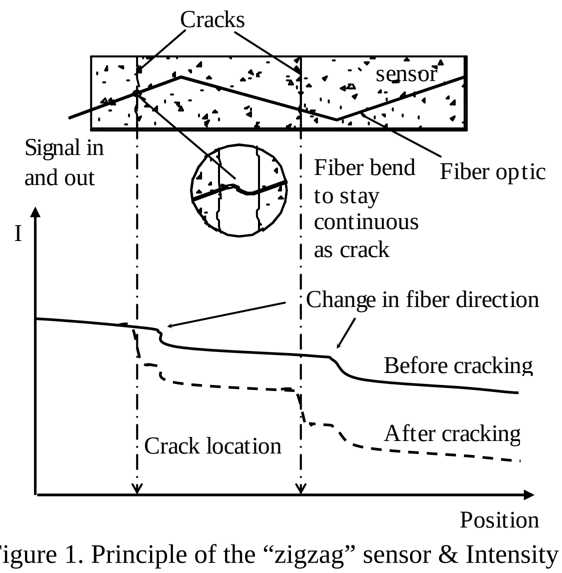


Figure 1. Principle of the "zigzag" sensor & Intensity along the fiber, measured by means of the OTDR.

Therefore, for the crack sensor to work properly, the bonding between the sensor and the concrete member has to be assured, if debonding occurs the sensor plate will not be able to pick up the crack opening; likewise, the polymeric material implemented to build the transducer plate should have the necessary brittle mechanical behavior to break right after cracking occurs in the concrete structure. Moreover, the polymeric matrix of the transducer plate surrounding the optical fiber should allow a reliable sliding of the fiber when the crack is opening; a tight-fitting can develop the undesirable breakage of the optical fiber. In addition, to guarantee a similar boundary condition when the microbending of the fiber occurs, similar interfacial conditions between the matrix and the polymeric coating around the fiber should be assured; any imperfection of the matrix around the fiber could cause unequal light loss intensity for the same crack aperture. To achieve these requirements for the monitoring of cracks on bridges the sensor plate was recently improved by Diaz de Leon et al. (2004).

## 4 EXPERIMENTAL PROGRAM

The main purpose of the experimental program is to evaluate the sensor's capability in measuring a range of crack widths, while the methodology to detect and localize the formation of flexural cracks in various locations at the tension face of RC beams subjected to sustained and repeated loading was examined.

The experimental program consisted of testing two RC beams. Beam dimensions were 20 x 40 cm with a span of 200 cm. They were tested under four-point-bend loading in a closed-loop material testing system (Figure 2). Near the center span of each beam, there were two 20 mm notches separated by 40 cm at both lateral faces . The purpose of notching the beams was to define the initial location of cracking. Two Linear Variable Differential Transform (LVDT) were employed for monitoring the crack opening. The LVDT attachment was designed to monitor the opening of the crack at the level of the optical fiber sensor. The specimen loading was accomplished under displacement control at 0.5 mm/sec. In regard to the loading condition, the RC beams were given alphabetic designations A and B. Beam A was subjected to repeated loading, while beam B was subjected to sustained loading.

To detect and compare the measurements of cracks for the same location with different sensor plates, two plates with different additives (Sand 200 and Abrasive 1200 at 20% volume density; Diaz de Leon et al. 2004) in the polymeric mixture were placed in a single line along the fiber, and they were strategically attached parallel to the tension face at the center span of the RC beams. The sensitivity of the sensors on beam A and B corresponded to the optical fiber at an angle of 30º and 45º respectively. Figure 3 shows the implemented configuration of installed sensors and overall connections of beam A.

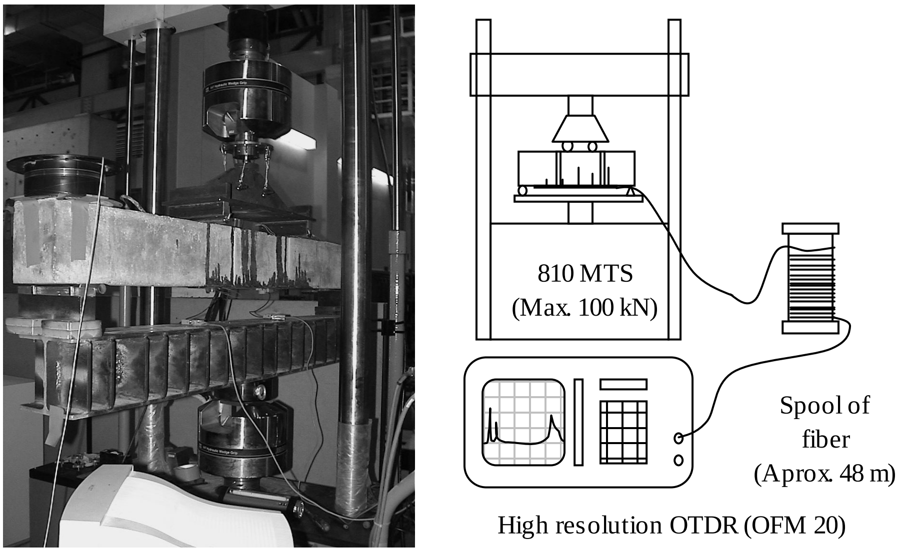


Figure 2. Experimental Set-up for reinforced beams.

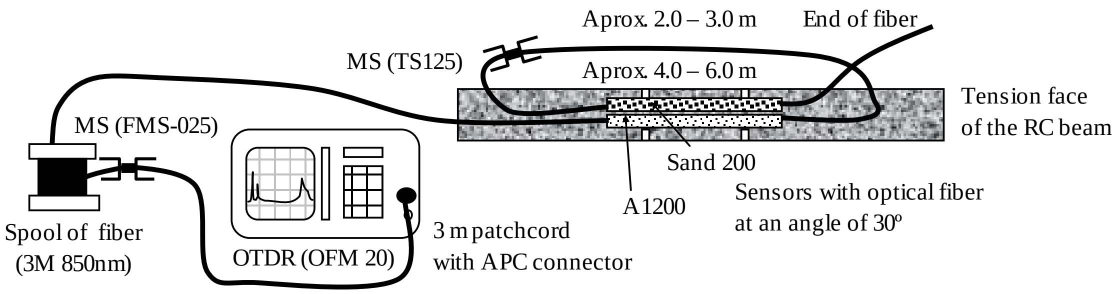


Figure 3. Configuration of installed sensors and overall connections on beam A.

The configuration of beam A included a reusable mechanical splice (TS125) between sensors. To eliminate the reflection induced by the Mechanical Splice (MS), the beam B did not include any mechanical splice. 3M single-mode optical fiber was implemented in all configurations and sensors tested, with a High Resolution OTDR (OFM 20) using a wavelength at 850 nm in Rayleigh Operation. Noticed the OTDR was linked to the sensors with a mechanical splice (FMS-025) through a spool of fiber, to avoid lose of crack signals due to the strong reflection created at the bulkhead connection, which was made using a patch cord with an APC connector.

The global assessing system was checked several times using the OTDR; screens of the OTDR were captured before starting of the experimental program. Figure 4 and 5 shows the initial screen of the OTDR for beam A and B respectively. In both figures, the approximate location of the beams and sensors are indicated. Figure 4 highlight the insertion loss and Fresnel reflection of the reusable mechanical splice TS125. According to the Figure 3, this event can be considered as location reference between sensors (A1200 and Sand 200). It can be noted from Figure 5 that the spool of optical fiber for the beam B is shorter; because the implemented fiber on the sensors can not be used once again the test on beam A was done.

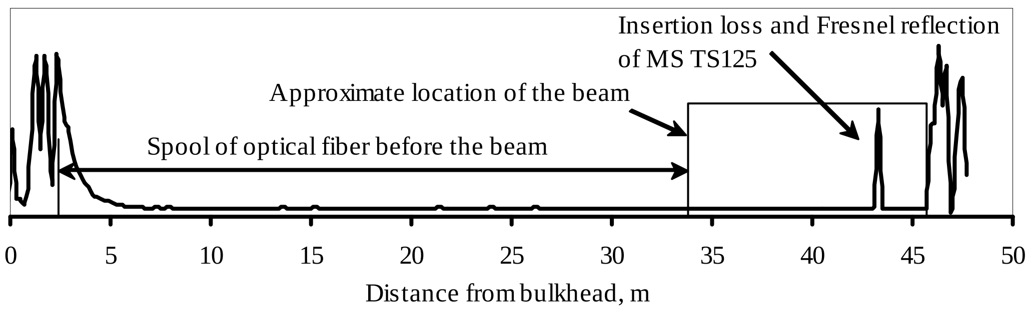


Figure 4. Entire OTDR screen capture showing no cracks on beam A.

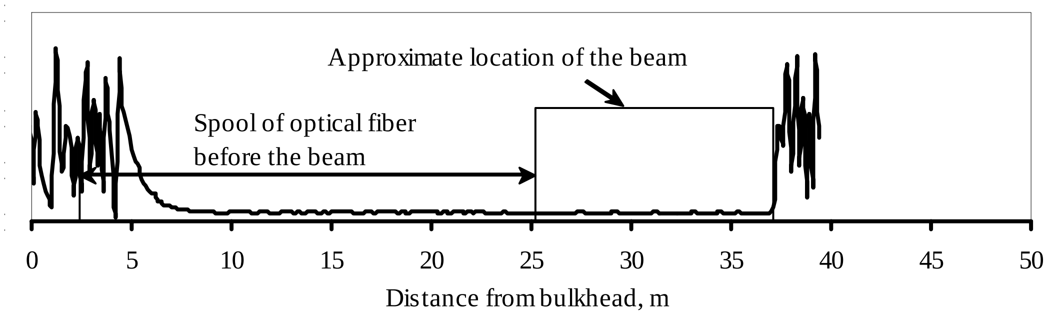


Figure 5. Entire OTDR screen capture showing no cracks on beam B.

### 4.1 *CONTROL OF THE SENSOR RESPONSE*

To have the control of the sensor response it is necessary to increase the number of cracks that could be detected and monitored. It is well understood that the sensor remains dormant until the polymeric plate breaks and the crack width acquires the size corresponding to the minimum resolution of the sensor. To control the failure behavior of the polymeric plate, the incorporation of fine particles has been studied (Diaz de Leon et al. 2004).

Experimentation on beam A corresponds to the opening and closing of cracks under repeated loading. Three cycles of loading and unloading were performed. Figure 6 shows the cracked condition of the beam A after reaching the maximum load at the second cycle. To assure proper data acquisition the maximum loading was maintained for intervals of 25 minutes, since the acquisition can be programmed with the OTDR to be executed in real time after locating the cracks.

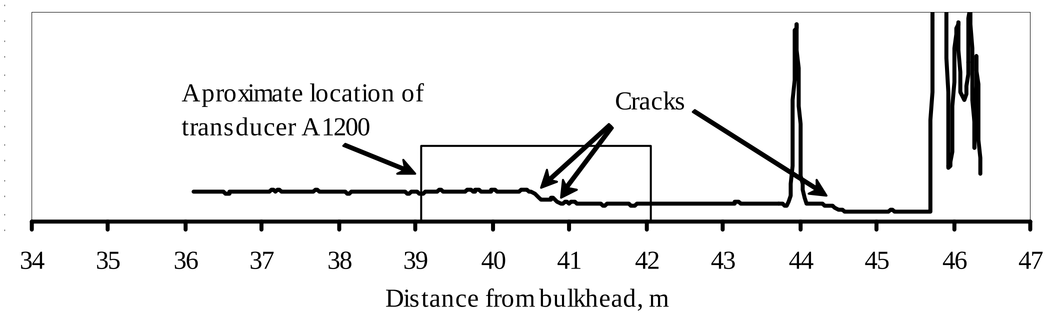


Figure 6. OTDR screen capture showing the location of cracks on beam A.

The control of the sensor response can be observed when the transducer A1200 reported only two cracks. The third crack after the Fresnel reflection in Figure 6 corresponds to the transducer Sand 200. After unloading and starting of the third cycle of loading the optical fiber was broken in the sensor of Abrasive A1200. To continue monitoring the cracks the sensor of Sand 200 was activated by linking the spool of fiber directly to the reusable mechanical splice (TS125). Figure 7 shows the enlarged OTDR screen showing four cracks in the beam location. The second and third drops of intensity are approximately 2.90 and 1.30 dB, corresponding to the LVDTs 2.50 mm and 1.60 mm of crack width.

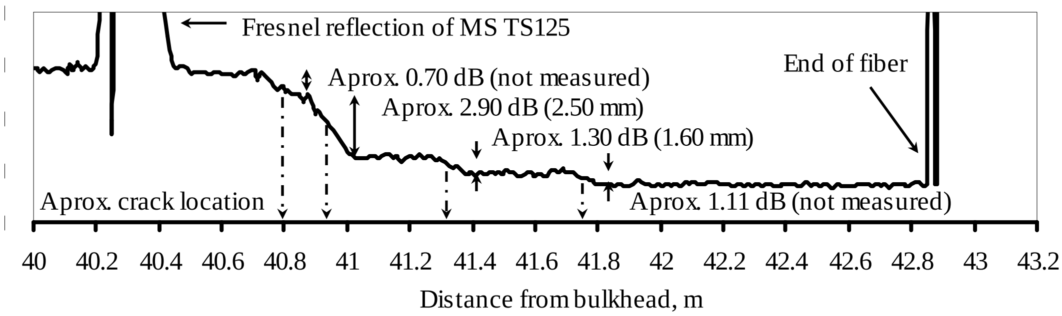


Figure 7. Enlarge OTDR screen capture showing the location and size of cracks on beam A.

Based on the examination of results and visual observations throughout the test, the undesirable breakage of the optical fiber was developed by fatigue when the crack was opening and closing around a size bigger than 2.0 mm caused by the tight-fitting of the fiber when it was bonded outside the transducer plate during the attachment. Since the configuration of using two sensor plates in parallel can help to prevent this problem it is recommended to protect the fiber to allow a reliable sliding inside the transducer.

## 4.2 *SENSITIVITY OF THE SENSOR*

The sensitivity of the sensor is associated with the range of crack widths that it can measure; it depends on the type of optical fiber and the angle of intersection of the fiber to the cracks. Several experimental calibrations, with analytical model to study these variables were done and proposed (Leung et al, 2005).

Experimentation on beam B corresponds to the opening of cracks under a monotonic loading until failure. Six consecutives increments of loading and final unloading were performed. Figure 8 shows the cracking condition of the beam B after the third increment of loading. By visual inspection it was found that only one crack was opening at the bottom of the beam. The location of the first and second drop of intensity corresponded to the crack crossing the transducers A1200 and Sand 200 respectively. Notice that for the beam B also, the configuration of placing two different polymeric plates in a single line along the fiber attached parallel to the center span was used.

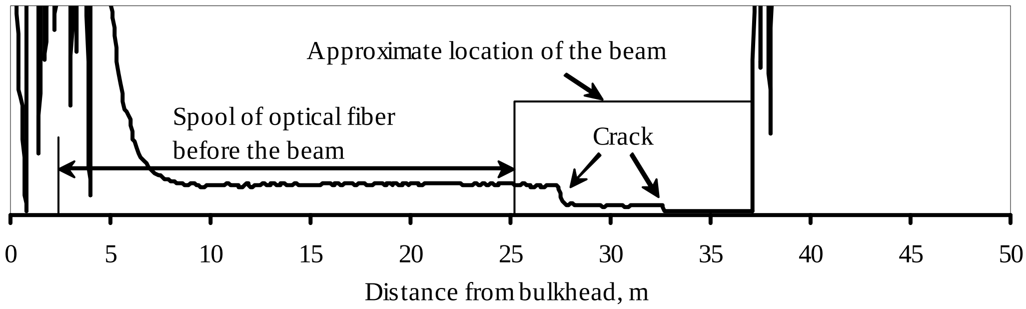


Figure 8. OTDR screen capture showing the location of cracks on beam B.

Figure 9 shows the comparison between calibration curves of the intensity loss vs. crack aperture and results from experimental program. Regarding the sensitivity the standard error for the sensors with the optical fiber at an angle of 30º and 45º were 0.32 and 0.30 respectively. Based on the results, it is recommended to use the sensitivity at an angle of 45º when 3M optical fiber using a wavelength of 850 nm is considered. Otherwise, the sensor at an angle of 30º can be used only to detect and localize the formation of cracks.

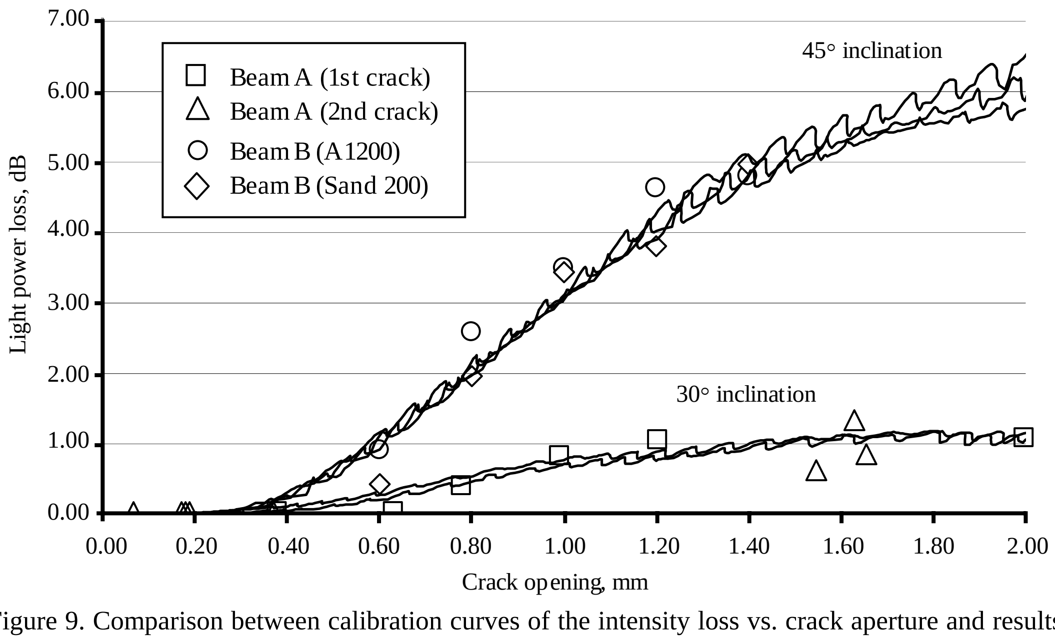


Figure 9. Comparison between calibration curves of the intensity loss vs. crack aperture and results from experimental program.

## 5 CONCLUSIONS

This paper presents an overview of challenges in developing a new fiber optic sensor that can be employed to detect, locate, and measure the crack widths of flexural and tensile cracks on RC structures. The methodology and description of improvements introduced to be feasible in practice were explained and discussed. The capability of the sensor in monitoring the formation of flexural cracks, and to measure the crack widths through testing of instrumented RC beams subjected to sustained and repeated loading was demonstrated.

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