Fiber Optic Sensor for Measurement of Strain in Concrete Structures

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Synopsis: A novel fiber optic sensor was tested on reinforced concrete beams with the objective of monitoring strain due to flexural deformations. A Fiber Optic Bragg Grating (FOBG) sensor, developed recently at the United Technologies Research Center (UTRC) for monitoring of strain in structural composites, was used. The FOBG sensor was tested in beam models to measure load-induced strain. Results showed that the FOBG sensor can be accurately and effectively used to monitor strain for both existing and new concrete structures. A number of issues, such as sensor bonding to the structural component, sensor placement and practical instrumentation techniques, were addressed in this study.

Keywords: Beams (supports); deformation; fiber-optic sensor; flexure; gratings; models; reinforced concrete; strains; structures

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INTRODUCTION

The existing instrumentation techniques for monitoring the deformations of constructed structural elements, and those to be constructed, are mainly limited to the application of electrical principles using resistance strain gages, linear differential transformers and others. While these have served well, they nonetheless have major limitations in evaluating load-induced strains in facilities that have no prior instrumentation and those that are to be constructed, where remote sensing is needed. The main problems associated with these systems stem from their sensitivity to ambient electrical noise, magnetic fields and environmental degradation. This leads to low sensitivity and, at times, incorrect measurements. For example, using the available systems, monitoring of a reinforced concrete bridge deck, particularly under long-term basis and at several locations, is difficult and expensive.

Recent developments in the field of fiber optic sensors can eliminate many of the deficiencies mentioned above, and permit long-term and reliable monitoring of load-induced strains in constructed facilities. Fiber optic sensor systems may provide engineers with an effective tool for warning against impending failures, and also enable them to better predict the safe life of large structural systems. Although optical fiber strain sensors have been used in the aerospace and automotive industries [1,2,3,13], their potential use in monitoring civil engineering structures have only recently begun to attract attention [12].

Typical fiber optic strain sensors used presently for monitoring civil structural systems consist of microbend sensitive [5,6,12] and interferometric sensors [4,8,14].

When a microbend sensitive fiber is subjected to external pressure, a small amount of light will be lost by leakage from the core to the cladding of the fiber due to the phenomenon of microbending (Fig.1). The light attenuation by microbending can be correlated to the intensity of local stress and strain. Moreover, by using an Optical Time Domain Reflectometer (OTDR), the position of the stress or strain concentrations along the fiber may be pinpointed. The latter device determines the position and induced loss along a fiber by measuring the time delay of back reflections of a light pulse launched within a fiber of known index of refraction which governs light velocity.

Microbend sensitive fibers were used by Fuhr et al. [5] for qualitative monitoring of load-to-failure testing of a reinforced concrete beam. In this investigation, the main concern was the survivability of the embedded fiber optic sensor during the curing process of the concrete. Results of the investigation showed high correlation between fiber optic fault locations and stress-induced failure points in the concrete beam. In a related study, Fuhr et al. [6] instrumented a five-story concrete structure with the objective of monitoring stresses, vibrations and cracks. A number of issues, such as the embedment and placement of fibers in large structural elements, were addressed in this study. Microbend sensitive fiber sensors were also used by McKeehan et al. [12] for real-time monitoring of tensile strain changes in a pipeline in permafrost area. In this case, use of OTDR enabled accurate identification of the points along the pipeline undergoing excessive settlement.

In fiber optic interferometer sensor systems, any strain induced on the fiber produces a change in the phase of the modulated optical signal propagating over its length. Thus, phase change measurements during loading can be used to calculate the strain of the fiber. Although this concept has been applied to measurement of strain in structural composites in the aerospace and auto industries, its civil engineering application has been fairly limited. While a number of researchers have demonstrated the potential of interferometric sensors in civil engineering applications [4,8,12], their use for direct and quantitative measurement of strain is yet to be investigated.

In general, research in the past few years has demonstrated the potential of fiber optic sensor systems for on-line and accurate monitoring of civil engineering structural systems. Both microbend sensitive and interferometric fiber optic systems have been tried for measurement of strain in structural elements, particularly in concrete. Experience of the authors with microbend sensitive systems has shown that a number of fundamental issues, such as fiber measurement sensitivity, repeatability and practical ruggedization, make these systems difficult to implement for measurement of strain in structural elements, such as reinforced concrete. The need for further research became clear for development of an appropriate fiber optic sensor system for strain measurements.

In search of a sensor that can measure strain without losses, particularly if remote sensing is required, the authors used the Fiber Optic Bragg Grating (FOBG) sensor system developed by Morey et al. [10,11] and Meltz et al. [9]. Measured strains, from both embedded and exposed FOBG sensors on concrete beams, showed excellent correlation with the strains obtained from electric strain gages. A description of the FOBG sensor system and the experimental program with concrete structural elements is described below.

FIBER OPTIC BRAGG GRATING (FOBG) STRAIN SENSOR

Bragg gratings were first discovered by Hill et al. [1978] in standard telecommunications optical fiber by observing a refractive index change caused by the interference of two counter propagating waves in the fiber. The first glass composition to exhibit this property was germanium-doped silica, but since then many other glass compositions have been shown to have similar properties. Meltz et al. in 1989 made it possible to make useful devices through a direct ultraviolet illumination of the fiber core from the side of the optical fiber, the transverse holographic method. The physics of the refractive index change is not completely understood but it is believed to be a photo-induced redistribution of electrons and color centers in the glass.

Since the introduction of such useful devices, FOBGs have been used to build laser cavities, Fabry-Perot interferometers, and sensors. Bragg grating in single mode fibers have been used to measure vibration, strain and temperature. Bragg gratings in two mode optical fibers have also recently been shown to satisfy certain sensing applications [11]. High sensitivity measurements of strain have been shown by monitoring the phase shift of the Bragg reflection.

A FOBG is a longitudinal periodic variation of the index of refraction in the core of an optical fiber as shown in Fig.2. The spacing of this periodic index variation is determined by the wavelength of the light that is to be reflected. Only light which has a wavelength that is twice the optical path (spacing) is reflected. This results in a very narrow spectral line, approximately 1 Angstrom wide reflection band. The narrowness of this band provides good resolution during measurements. The condition that must be satisfied to get a reflection is

$$\lambda_{Bragg} = 2\ n\ D$$

where λ_{Bragg} is the wavelength of the reflected light; n is the average index of refraction in the core of the fiber; and D is the spacing of the periodic refractive index variation. As strain is applied to the fiber, the spacing of the periodic variation of the refractive index changes. In addition to mechanical deformation of the grating, the average index of refraction is also changed through the strain optic effect. These two effects work together to cause a shift in the Bragg wavelength reflected for an applied strain. By differentiating the Bragg condition expression and substituting an expression for the strain optic effect, one can express the fractional change in wavelength as a constant (K) times the applied strain (ε).

$$\Delta\lambda / \lambda = K\ \varepsilon$$

In the simplest configuration, the spectral shift of the Bragg reflection corresponds to an applied strain or temperature change. This can be measured by using a broad band LED source at 1300 nm launching light into a 3dB coupler with one end of the coupler connected to the fiber with the FOBG (Fig.3). The return end of the coupler is connected to a spectrometer which monitors the spectral shift of the reflection band (Fig.4).

EXPERIMENTAL PROGRAM

Prior to testing of FOBG sensors in concrete structural members, an experimental program was conducted using both single mode and multimode micro-bend sensitive fibers to assess their applicability as strain sensors in concrete. Micro-bend sensitive fibers were embedded in concrete by mounting the fibers on the reinforcing bars. They were also placed on the exterior of the bottom flanges of the concrete beams as exposed sensors. Various methods of fiber mounting on reinforcing bars were tried. These included straight mounting and coiling of the fibers around the reinforcing bars. The concrete beam models were 6"x6"x1'-8" in dimension with #3 size steel bars as reinforcement. The beams were subjected to third point loading for a constant moment zone, and the induced tensile strain in the steel reinforcement was measured by both micro-bend sensitive fibers and strain gages.

Although micro-bend sensitive fibers function well in places where discrete stress concentrations are clearly present, such as those shown in Fig.1, their performance as direct strain sensors along the length of reinforcing bars in concrete was found to be less than satisfactory. Results of this experimental program showed that issues such as fiber sensitivity, ruggedization and mounting, need to be further investigated if this type of optical fiber sensor is to be successfuly used in concrete structures.

Following the testing of micro-bend sensitive fibers, the authors searched for a more practical sensor for application to concrete structural elements. This search resulted in selection of FOBG sensor as a potential strain measurement sensor in concrete. Following some preliminary tests, an experimental program was conducted to assess the feasibility of using these sensors in concrete. Details of this experimental program are described below.

Structural Elements Tested

Fiber Optic Bragg Grating sensors were used to measure strain in concrete beams. Three-point bending tests were performed on small (2.5"x5"x2'-0") and large scale (8"x12"x10'-0") prismatic high strength reinforced concrete beams with embedded FOBG sensor and electrical strain gauges attached to their reinforcing bars. A Fiber Optic Bragg Grating sensor was also tested in an exposed position, mounted on the underside of the large concrete beam, with the objective of evaluating the sensor's performance on existing structures. A schematic diagram showing the cross sectional properties of the tested beams is presented in Fig.6.

The concrete for the beam models was proportioned for a 7-day compressive strength of concrete of approximately 11,000 psi by using Type III cement, and silica-fume as a mineral aggregate. The water-cement ratio was 0.28. The coarse aggregate was crushed stone of 3/8 in. maximum size and the fine aggregate was a natural local sand. Slump was about 6-7 in.

Fiber Optic Bragg Grating Sensors Application

The fiber optic Bragg gratings used were standard single mode telecommunication fibers with Germania-doped cores with the gratings being about 10mm (0.4 in.) in length. In all the embedded cases tested, the FOBG sensors were attached to the reinforcing bars in the concrete beam by placing them in a small V-groove cut on the bar and mounting with epoxy. Ideally bonding of the sensor to the bar should provide good strain compatibility between the two. However, due to the low elastic modulus of epoxy compared with those of glass and steel, some loss in strain can occur during the strain transfer process. In order to evaluate the strain transfer process, attachment of the FOBG sensor to the reinforcing bar was modelled by finite element method (FEM). The axisymmetric finite element model consisted of 150 solid elements depicting the actual geometry of FOBG sensor-epoxy-reinforcing bar system. Results of the evaluation showed that there was some loss in strain transfer from the reinforcing bar to the FOBG sensor (Fig.5), mainly due to the lower modulus of the epoxy in comparison to the moduli of steel and the FOBG sensor, which was glass. The loss, however, can be minimized by choosing epoxy compounds with high elastic modulus, and reducing the thickness of epoxy film between the sensor and the reinforcing bar.