ELSEVIER

Cement and Concrete Composites 19 (1997) 3–19

0958-9465/97/$17.00+0.00

PII:S0958-9465(96)00038-8

State-of-the-art in the Applications of Fiber-optic Sensors to Cementitious Composites

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Abstract

Optical-fiber sensors are emerging as a superior non-destructive means for evaluating the condition of concrete structures. In contrast to existing non-destructive evaluation techniques, optical fibers are able to detect minute variations in structural conditions through remote measurements. Structures fully integrated with optical fibers will be able to monitor the initiation and progress of various mechanical or environmentally-induced degradations in concrete elements. Recent advances in fiber-optic sensor technology and the possibility of their use in concrete structures have instigated the development of a number of research activities. Owing to inherent interdisciplinary nature of the field of fiber optics, the expertise of the researchers active in the research and development of fiber-optic sensors covers a wide spectrum of disciplines including concrete engineering, as well as opto-electronics and physics. This article is intended for rapid dissemination of the current state-of-the-art in this emerging technology. However, because of the interdisciplinary nature of the subject, a brief discussion on the physical nature of optical fibers is also presented. © 1997 Elsevier Science Limited

Keywords: Optical fiber sensors, nondestructive evaluation, smart materials, composite materials, infrastructure, concrete, localized sensors, distributed sensors, Bragg gratings, interferometric sensors, intensity sensors, Fabry-perot sensor, polarimetric sensors, cracks, microcracks, air content, fiber reinforced concrete, impact loading, crack tip opening displacement, bridge testing, high strength concrete, reinforced concrete, glass fiber reinforced plastic.

INTRODUCTION

Optical fibers have been developed for long-distance data transmission in the telecommunications industry. However, in their earliest application, optical fibers were conceived as a medium for transmission of light in medical endoscopy. The use of optical fibers for applications in the telecommunications industry actually started in the mid 1960s, and ever since has gone through tremendous growth and advancement. The development of optical-fiber sensors started in earnest in 1977 even though some isolated demonstrations preceded this date.[1–4] The increased use of advanced composites in aeronautics instigated the need for new damage detection techniques for monitoring the integrity of structural components while in service. Therefore, fiber-optic sensors have been extensively employed as real-time damage detection tools in advanced aircraft and space vehicles. External perturbations such as strain, pressure, or temperature variations induce changes in the phase, intensity, or wavelength of light waves propagating through optical fibers. This change in one or more of the properties of light can then be related to the parameter being measured. Optical fibers are geometrically versatile and can be configured to arbitrary shapes. The smart material concept takes advantage of the geometric adaptability of optical fibers. In this technology, optical fibers are embedded within the structural material for the purpose of real-time damage assessment. Besides ruggedness, flexibility, and extremely small size (250 μm in diameter), optical fibers are immune to electric and electromagnetic interference, which can seriously affect the performance of electric and piezoelectric sensors. The most attractive feature of fiber-optic sensors is their inherent ability to serve as both the sensing element and the signal transmission medium, allowing the electronic instrumentation to be located remotely from the measurement site. This is especially useful for remote monitoring of the condition of bridges. Moreover, the advantages of using embedded fibers in composite materials include dimensional and material compatibility. The fibers do not degrade during curing, they do not corrode, and bond strongly to the matrix. Incorporation of the fibers during the processing stage also offers the opportunity to monitor the condition of structural elements during fabrication.[5–7]

The success of optical-fiber sensor technology in the condition monitoring of composite materials led to a limited number of research and development activities in the civil engineering discipline. A number of researchers realized that this emerging field of technology could impact on the condition monitoring of civil structures in order to improve durability, safety and efficiency of the infrastructure system. Proper application of fiber-optic sensors to large civil structures requires understanding of certain fundamental methodologies pertaining to sensor transduction mechanisms as well as sensor multiplexing strategies. Fundamental issues such as the sensor type, embedment techniques, instrumentation required, and number of sensing locations have been among practical concerns facing civil engineers. Since cracking is among the most important parameters that directly influence the structural design and durability of concrete construction, much of the fiber-optic research has been concentrated on applications to concrete. The geometric adaptability of optical fibers facilitates the embedment process in concrete elements during construction, and therefore provides a powerful tool for the detection of cracks. Applications to concrete are not limited to measurements of deformations, and optical fiber sensors have also been developed for other applications. It is the objective of this article to briefly describe the developments in this area. However, owing to the interdisciplinary nature of the subject, it is imperative to present a brief discussion on the physics of optical fibers and general methodologies pertaining to sensors.

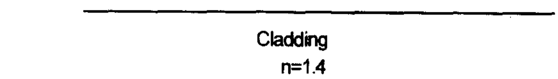
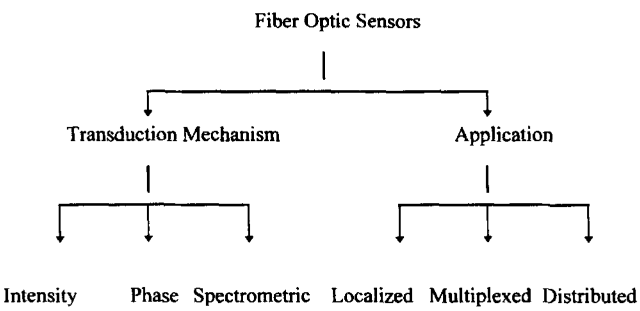


Fig. 1. Basis for light transmission in optical fibers.

BACKGROUND

Transmission of light through optical fibers can be explained by Snell's law and the concept of total internal reflection. According to Fig. 1, as indicated by the refractive index, **n**, when light travels from a fiber core that has a high refractive index into the cladding with a lower index, the light wave is totally reflected back into the core. Depending on the diameter, and the refractive indices of the core and cladding, optical fibers may carry either only one (single-mode), or many modes (multi-mode) of the light wave. Typical single-mode fibers have a core, cladding, and protective coating diameters of respectively 5, 125, and 250 μm. Multi-mode fibers require a larger core diameter to allow the propagation of various modes through the length. The core, cladding, and coating diameters in typical multi-mode fibers are 50, 125, 250 μm, respectively. Multi-mode fibers are easier to work with owing to their larger core diameters for coupling the light into and out of them. The core and cladding are usually made from quartz (SiO_2), and doping with germanium dioxide (GeO_2) creates the core's higher refractive index. Since this yields a brittle construction, for mechanical protection, a plastic coating surrounds the cladding and therefore gives flexibility to the fiber.

The properties of optical fibers allow innovative approaches for the design of optical sensors. For this reason, an enormous number of fiber-optic sensor types have been developed over a very short period of time. Fiber-optic sensors have been classified in a number of different ways. For instance, they can be categorized based on the application, or the transduction mechanism. These classifications are diagrammatically depicted below:



Localized fiber-optic sensors determine the measurand over a specific segment of the optical fiber, and are similar in that sense to conventional strain or temperature gages. Sensing based on intensity modulation pertains to light intensity losses that are associated with straining of optical fibers along any portion of their length (Fig. 2). Sensors taking advantage of this phenomenon are termed intensity- or amplitude-type sensors. The advantages of intensity-type sensors are the simplicity of construction, and compatibility with multi-mode fiber technology. Spectrometric sensors are widely employed in the sensing of chemical reactions, and remote monitoring of contaminants in ground water.[8,9] The transduction mechanism in these types of sensor is based on relating the changes in the wavelength of light to the measurand of interest, i.e. strain. An example of such sensors for measuring strains are Bragg grating type fibers[10] (Fig. 3). Introduction of Bragg gratings into fibers can be achieved by either external or internal manipulations. These sensors are intended for use as a localized fiber-optic sensor. However, a number of researchers have developed innova-

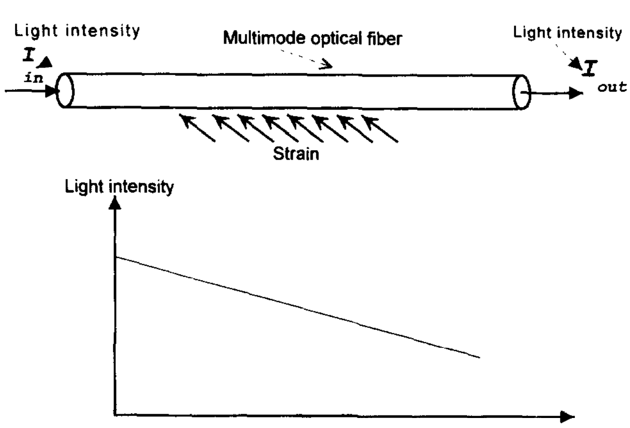


Fig. 2. Optical fiber intensity sensor.

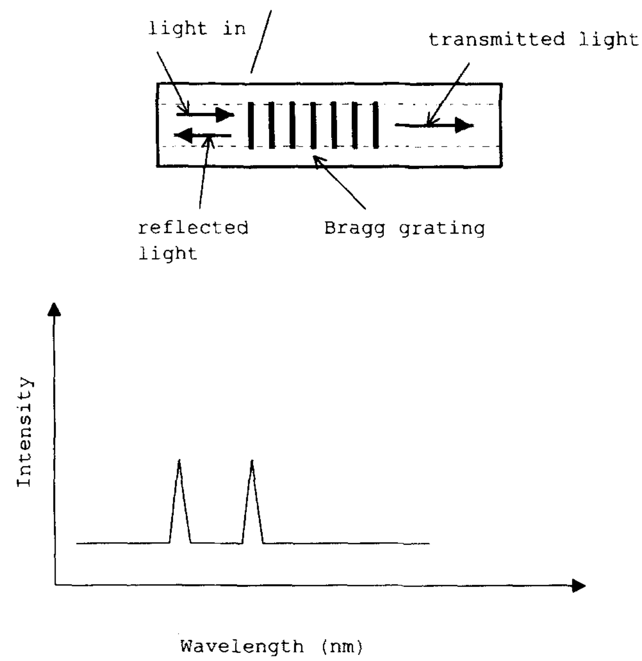


Fig. 3. Strain-induced shift in wavelength for a fiber-optic Bragg grating.

tive methods for development of multiplexed Bragg grating sensors.[11,12] The optical instrumentation for Bragg-type sensors are highly intricate, as they require sensitive spectrometers for detecting the minute changes in the wavelength of light. However, they are highly sensitive, and very reliable for measurement of strains. Phase sensors cover a broad range of optical phenomena for sensing purposes. A number of different configurations can be employed for measuring the change in the phase of light by an interferometric sensor (Fig. 4). Interferometric sensors are highly sensitive for measuring strains. However, they require the interference of light from two identical single-mode fibers, one of which is used as a reference arm and the other is the actual sensor. An exception to a two-arm interferometric sensor is a single-fiber Fabry–Perot type sensor.[13] In a Fabry–Perot type sensor, the fiber is manipulated in such a way so as to form two parallel reflectors (mirrors), perpendicular to the axis of the fiber. The interference of the reflected signals which are formed in the cavity by the two partial mirrors creates the interference pattern. A Fabry–Perot sensor is only capable of providing localized measurements at the cavity formed by the two mirrors. The interference pattern generated at the output end of the phase sensors is sinusoidal in shape and is directly related to the intensity of the applied strain field. The period of this waveform con-

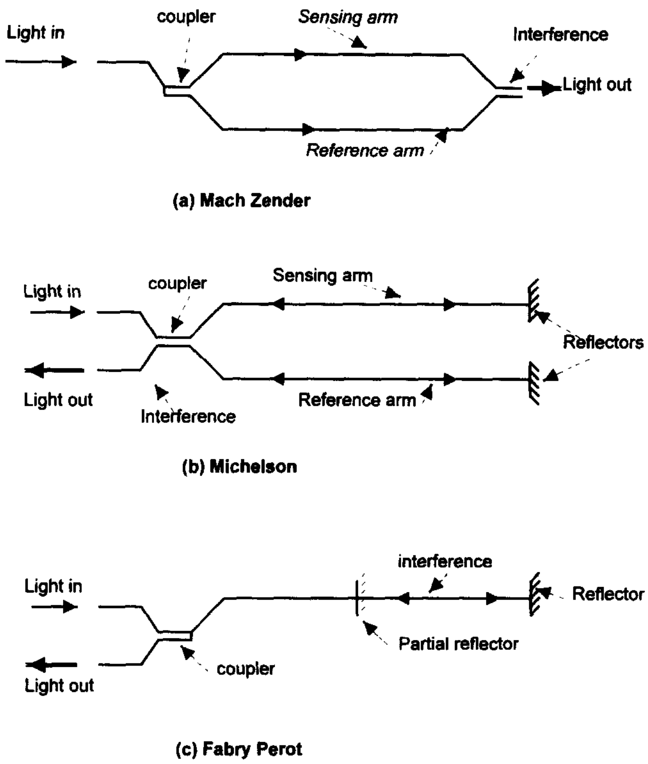


Fig. 4. Fiber-optic interferometric sensors.

stitutes a fringe (Fig. 5) and, if properly calibrated, it relates the optical signal to the magnitude of the measurand (i.e. strain).

Polarimetric sensors form a special class of phase sensors, and take advantage of the polarization characteristics of light for transduction.[14–16] Fringe shifts due to external perturbations in polarization maintaining (PM) single-mode fibers are caused by the interference of two mutually perpendicular polarized waves. The advantage in using a PM fiber for polarimetric transduction is that, unlike their interferometric counterparts, only one fiber is needed for sensing the measurand. Therefore, from the viewpoint of practical application, polarimetric sensors offer similar simplicities as those offered by intensity sensors. Polarimetric sensors are more sensitive than the intensity type. The sensitivity of polarimetric sensors is dependent on the polarization characteristics of the fiber, such as birefringence, and the beat length. Theoretically, polarimetric-fiber sensors can be made as sensitive as the interferometric types. However, the birefringence of the currently available PM fibers is not sufficient for optimum sensitivity.

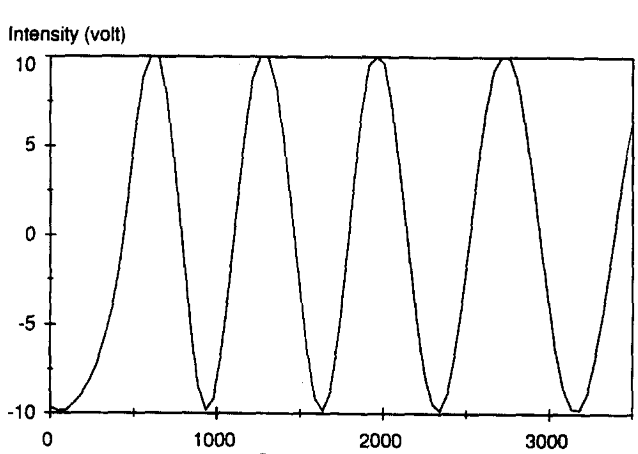


Fig. 5. Typical fringe pattern generated from phase sensors.

Multiplexed sensors are usually constructed by combining a number of individual sensors for measurement of perturbations over a large structure. Theoretically, it is possible to use optical switching and other innovative ideas for this purpose. A promising technique is based on wavelength division multiplexing by using Bragg gratings.[11,12] In this technique, a broad-band light source, defined as light containing a number of wavelengths within a certain region of the spectrum, is employed for scanning a number of Bragg grating type sensors in series and/or in parallel. The reflectance wavelength of each Bragg grating is slightly different from the others. In this way, wavelength shifts of individual sensors are recognized, detected, and then related to the magnitude of strain at specific sensor locations (Fig. 6).

Distributed sensors make full use of optical fibers, in that each element of the optical fiber is used for both measurement and data transmission purposes. The purpose of making measurements by distributed or multiplexed optical fibers is to determine locations and values of measurands along the entire length of the fiber. These sensors are most appropriate for application to large structures owing to their multi-point measurement capabilities. A distributed sensor permits measurement of a desired parameter as a function of length along the fiber. The most widely employed distributed sensing technique is based on measurement of propagation time delays of light traveling in the fiber based on the measurand-induced change in the transmission of light. An optical time-domain reflectometer (OTDR) is used for this purpose.[17,18] A pulsed light signal is transmitted into one end of the fiber, and light signals reflected from a number of partial reflectors along the fiber length are recovered from the same fiber end. By using this concept, it is pos-

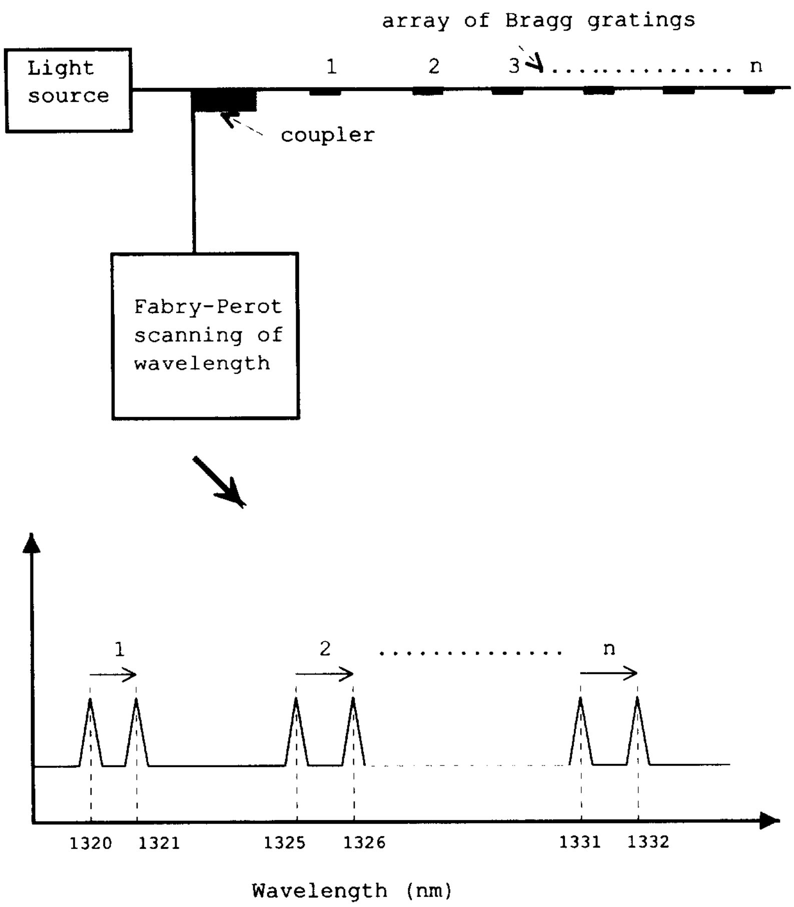


Fig. 6. Multiplexed Bragg grating sensor array.

sible to determine the distance to the strain field, d, by way of the two-way propagation time delay, $2t$, through the simple relationship (relating velocity and distance):

$$d = 2t \times v \tag{1}$$

where v is velocity of light in the fiber, and $2t$ is the time required for the two-way travel of the signal from individual reflectors. Since the velocity of light is known, an OTDR is capable of detecting the location of strain fields $(d_1, \ldots, d_n)$ through measurement of reflected time signals (Fig. 7).

FIBER-OPTIC SENSORS IN CEMENTITIOUS COMPOSITES

The emergence of optical fibers as a promising means for the detection of cracks and the measurement of strains in composite materials led to an outburst of new applications in the aeronautics industry. However, it was not until the late 1980s when researchers in the civil engineering discipline started experimenting with the idea of using optical fibers in conjunction with construction materials. In 1988, under a contract from the Federal Highway Administration, Ansari developed a fiber-optic sensor for determination of the air content in freshly mixed concrete.[19] The sensor was based on measurement of the reflected intensity of light through the tip of an optical fiber in contact with fresh concrete (Fig. 8). As shown in Fig. 9, the intensities at the interface between the optical fiber and any other medium such as fresh

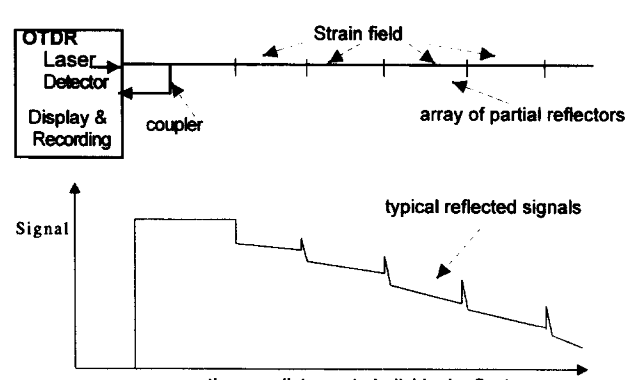


Fig. 7. Distributed sensing through an optical-fiber time-domain reflectometer.

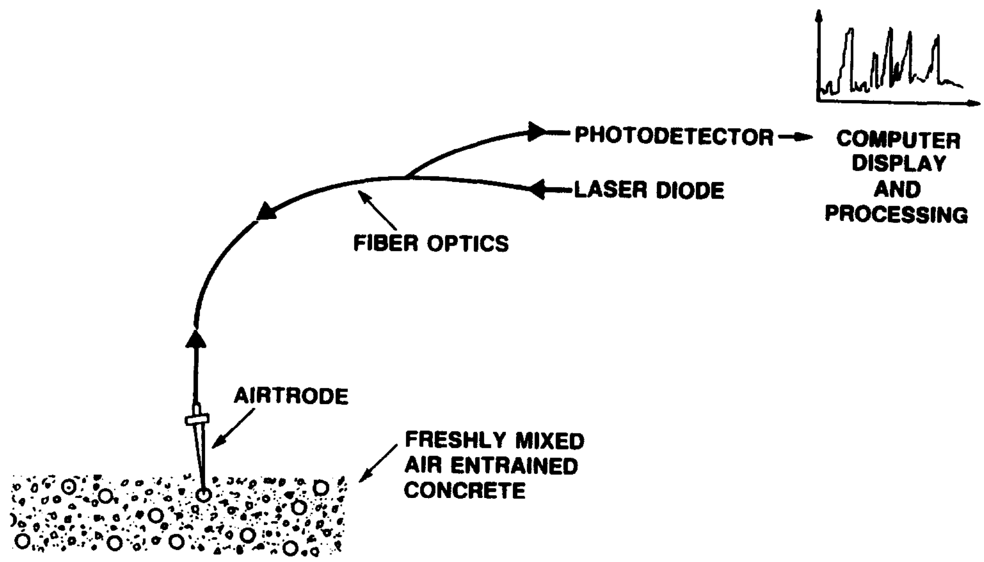


Fig. 8. Detection of air bubbles in fresh concrete by an optical fiber.

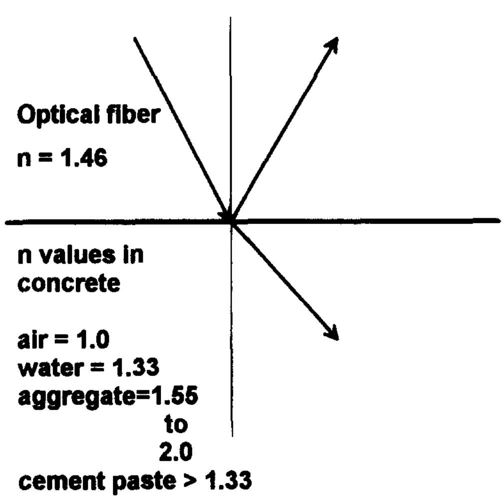


Fig. 9. Modulation of light intensity at the fiber-to-concrete interface according to Snell's law.

concrete are modulated according to Snell's law. As the sensor tip moves through fresh concrete, it comes into contact with concrete constituents including aggregates, paste, water, and air. Reflectivities conform to the refractive indices of the constituent materials (Fig. 9). According to the refractive indices shown in Fig. 9, reflectivities at the interface between air and the optical fiber will be an order of magnitude larger than at the interfaces with the other constituents. The kinematics of relative motion between the sensor tip and individual constituents of varying dimensions in concrete will give rise to a reflectivity pattern indicative of the air content (%) in the concrete. Figure 10 is representative of a reflected signal pattern as received from an optical fiber for a period of

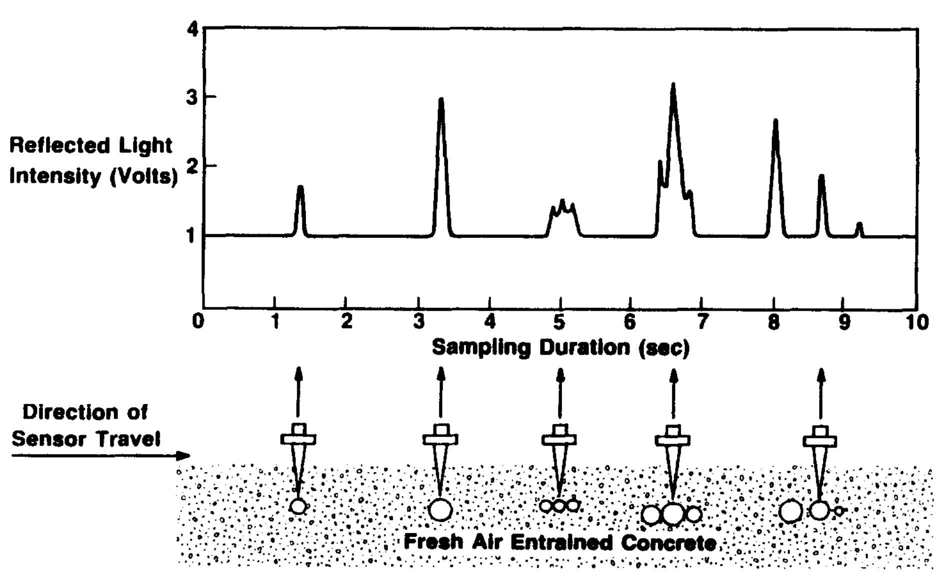


Fig. 10. Effect of bubble size and spacing on the amplitude of the reflected signal.

10 s in concrete.[20] Larger reflectivities correspond to air bubbles, and the percentage of air in the fresh concrete is determined from statistical analysis of the data in Fig. 10.

Rossi and LeMaou embedded a series of optical fibers in laboratory concrete beams as well as in concrete caissons for larger structures.[21] Their research involved crack detection on the basis of light intensity loss in the embedded optical fiber. The principle is based on the finding that an optical fiber embedded in a piece of concrete breaks as soon as a crack propagating in the material reaches the fiber, causing complete disappearance of the luminous signal transmitted through the fiber (Fig. 11). As discussed earlier, optical fibers are protected against breakage by polymeric coatings. Therefore, Rossi and LeMaou deliberately removed the protective coating prior to embedment of the optical fiber in concrete in order to cause fiber fracture. Special steel pipes were employed for placement of the optical fibers in concrete in order to protect the fiber from breakage during construction.

Nanni *et al.* employed polarimetric optical fibers for embedment into cylindrical concrete specimens.[22] The sensitivity of this sensor was examined in two experiments involving axial as well as radial compression. The sensor was calibrated against compressive load, and indicated a direct relationship between the resolution of measurements and embedment length (gage length) of the fiber. The sensitivity of the fiber-optic sensor was also examined in experiments involving lateral pressure to cylindrical concrete specimens. The results were illustrated empirically via the relationship between the interference fringes and the measurand under consideration. Nanni *et al.* also analyzed the interface bond characteristics of the fiber with respect to the surrounding concrete matrix. Through their analytical work they were able to develop a simple model to describe the stress-transfer mechanism between the concrete matrix and the optical fiber.

Ansari and Navalurkar developed an intensity-based optical-fiber sensor for measurement of crack-tip opening displacements (CTODs) in steel-fiber-reinforced concrete (FRC) beams subjected to impulsive loading.[23] A multi-mode optical fiber was embedded in notched FRC beams. The sensor employed in this study was based on measurement of the intensity loss due to deformation. The authors modified the basic arrangement of an intensity-type sensor according to the mode propagation characteristics of light in order to increase the sensitivity of the sensor. A major portion of the energy associated with the electromagnetic field is carried through the fiber by way of fundamental modes. Fundamental modes of light propagate at angles much larger than the critical angle of

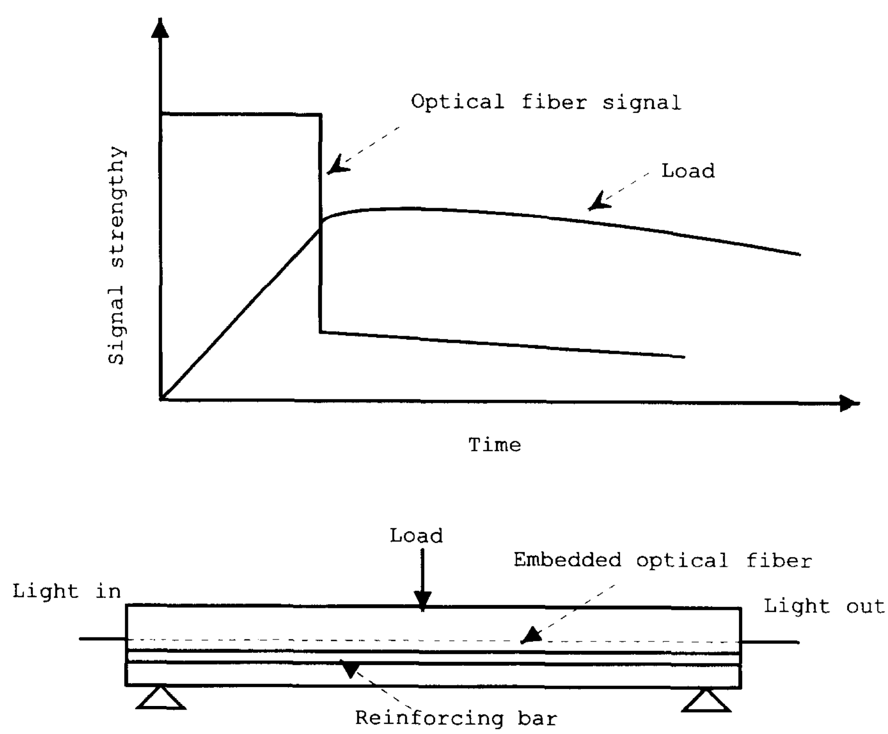


Fig. 11. Detection of cracks in reinforced concrete through light intensity drop.

incidence. These modes refract into the cladding only when the curvature of the bend is significantly increased beyond a critical level (Fig. 12). A reduction in the number of fundamental modes is associated with significant intensity loss. Ansari and Navalurkar used this phenomena in a special sensor arrangement in order to increase the intensity loss due to deformations and therefore increase the sensitivity of measurements. According to the arrangement shown in Fig. 13, the curvature due to circular bend positions the propagation angles of the fundamental modes near the critical level. Crack-opening displacements result in further bending of the bent optical fiber and a large decrease in light intensity. These sensors were calibrated, and were embedded in an FRC specimen. A Charpy impact machine was employed for applying an impulsive load with a velocity of 110 cm/s to the beam specimen under three-point bend conditions. Figure 14 depicts typical results displayed in a digital oscilloscope after completion of an experiment, the results consisting of the fiber-optics (CTOD) data as well as the load and load-point displacement values as a function of time. The optical fiber had a displacement resolution capability of about 5 μm, and was capable of measuring the CTOD of FRC beams through their fracture displacement ranging from 100 to 170 μm. The fracture energy of the FRC beams was evaluated through a J-integral scheme by using the dynamic CTODs measured by the optical-fiber sensor (Fig. 15).

Wolff and Miesseler employed fiber-optic sensors for monitoring of prestressing force, and crack formations in the Schiessbergstrasse triple-span bridge (total span length of 53.0 m) in Germany.[24] The three-span concrete slab bridge is designed with partial prestressing comprising 27 glass fiber prestressing tendons. For measurement of prestressing force, Wolff and Miesseler integrated four of the optical-fiber sensors within the tendon during their fabrication. They embedded a further four optical fibers on the top, and another four on the bot-

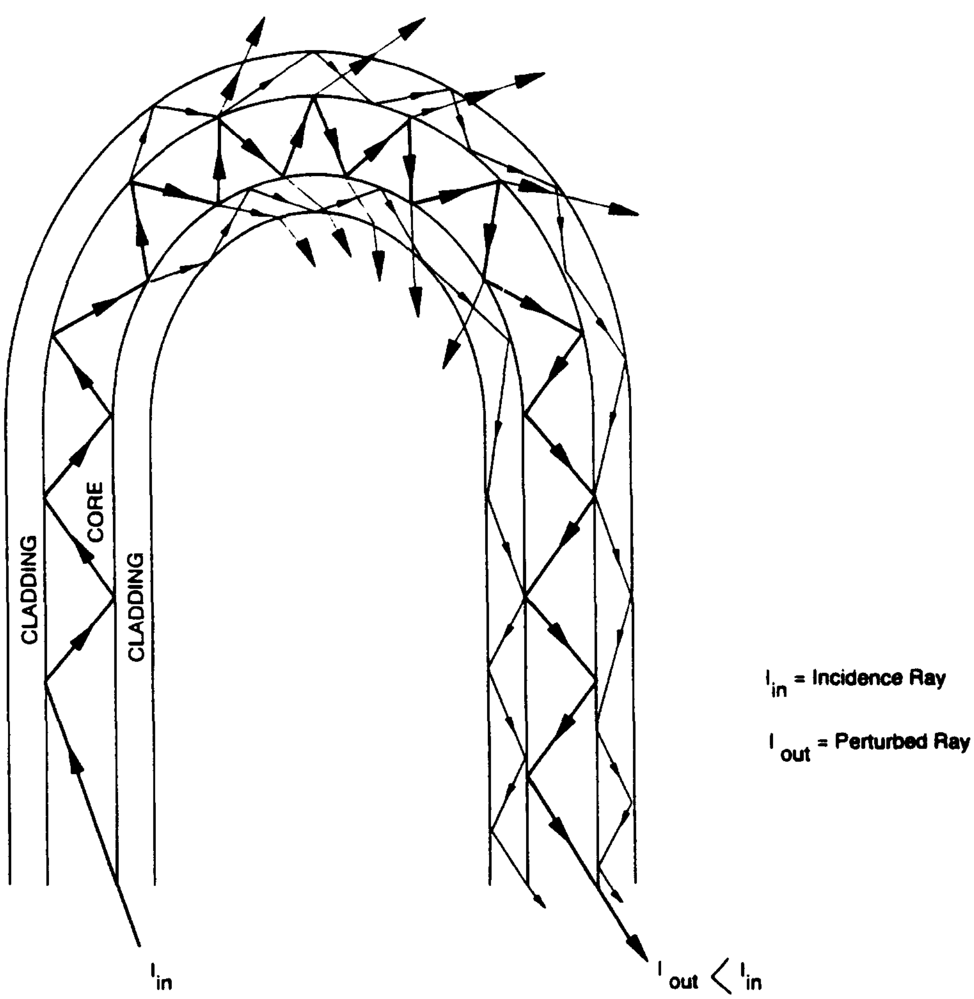


Fig. 12. Light-intensity perturbation in an optical fiber due to macro bend effect.

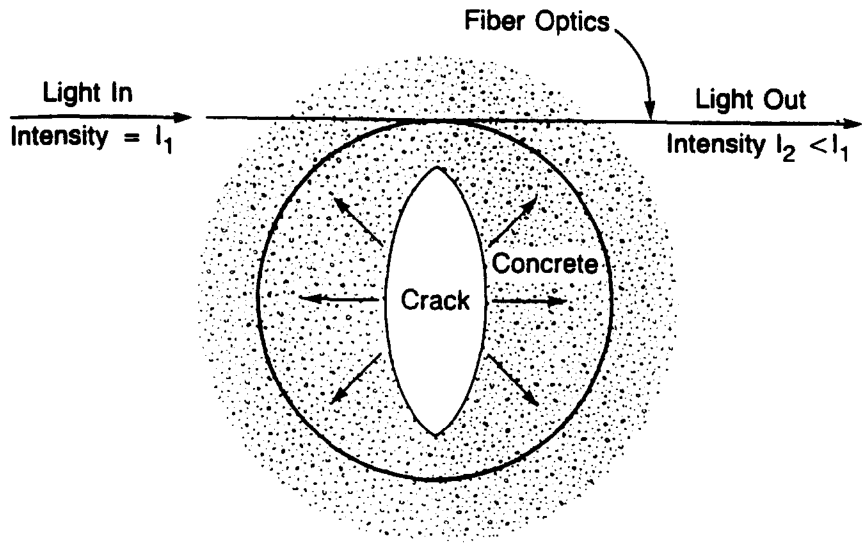


Fig. 13. Fiber-optic CTOD sensor for concrete.

tom portion of the slab for monitoring the formation of cracks in the tension zone. Wolff and Miesseler report crack detection capabilities with an accuracy of 0.15 mm. The Schiessbergstrasse bridge is part of an ongoing study for monitoring prestressing losses, and fiber-optic sensor data are linked to the telecommunications fiber-optic line via a telephone hook-up.

Maher and Nawy employed Bragg grating type sensors for measurement of reinforcing bar strains in high-strength concrete beams.[25] Their experiments involved three-point bend tests on beams having 3.05 m of span and a rectangular cross-section of 25.4 cm by 30.5 cm. The 7-day nominal compressive strength of the concrete for these beams was 76 MPa. The reinforcing bars were instrumented with fiber-optic Bragg grating sensors as well as conventional strain gages for comparison. Bragg grating sensors were epoxied into a small V-groove cut on the reinforcement. Bragg grating sensors were also attached to the underside of these beams in an exposed configuration for evaluating the sensor's performance in existing structures. Figure 16 illustrates the cross-sectional properties and the location of Bragg sensors with respect to the steel reinforcement in the beam. As shown by the measured strains in Fig. 17, optical fibers and strain gages provided comparable results.

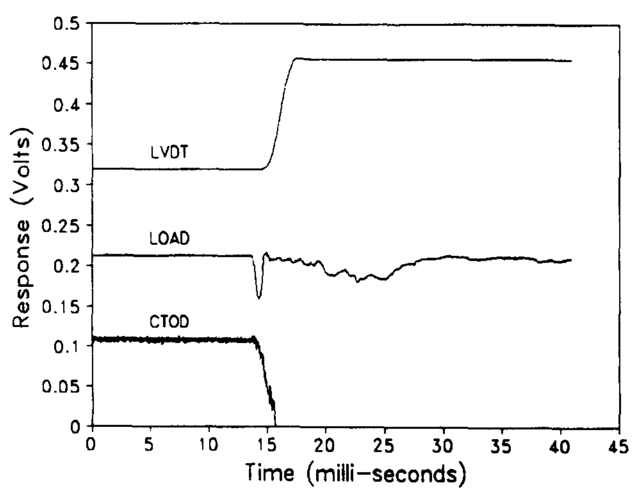


Fig. 14. Experimental data after an impact test.

Accumulated data from experiments with cementitious composites allowed researchers to develop increased knowledge about optical fibers for further applications. Mendez developed a comprehensive synthesis of the available information for such a purpose.[26] Claus *et al.* developed a Fabry–Perot interferometric fiber-optic sensor for the measurement of strain.[27] With this sensor they were able to measure structural deformations as small as 0.1 nm. Figure 18 gives a schematic drawing of the sensor construction. The sensor consists of a single-mode optical fiber used as the input/output medium, and a multi-mode fiber used as a reflector. As shown in Fig. 18, these optical fibers are arranged in such a way as to form a small air gap in between their ends. Reflection from the glass-to-air interface at the front of the air gap (reference reflection) and the reflection from the air-to-glass interface at the far end of the air gap (sensing reflection) gives rise to an interference pattern. The two fibers are allowed to move within a silica tube, and changes in the length of the air gap between the two fibers as a result of strain creates changes

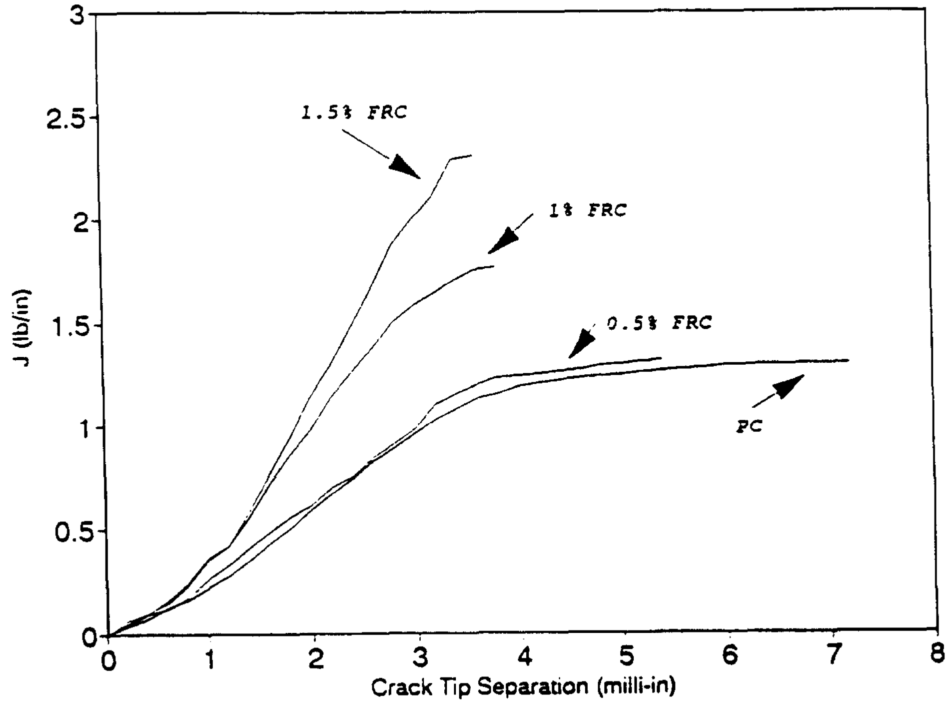


Fig. 15. Fracture energy of FRC subjected to impact loading in terms of J vs CTOD.

in the phase difference between the reference and sensing reflections. Masri *et al.* employed these sensors in a one-third scale model of a reinforced concrete multistorey frame joint prototype. Strain gages were placed on the main steel rebars and on selected beam and column stirrups. Two fiber-optic Fabry–Perot sensors were attached at each conventional gage location to enable comparison of the results. Figure. 19 illustrates the location of the various gages within the concrete joint. The performance of the optical-fiber sensors was examined under a variety of static and dynamic tests. Strain values

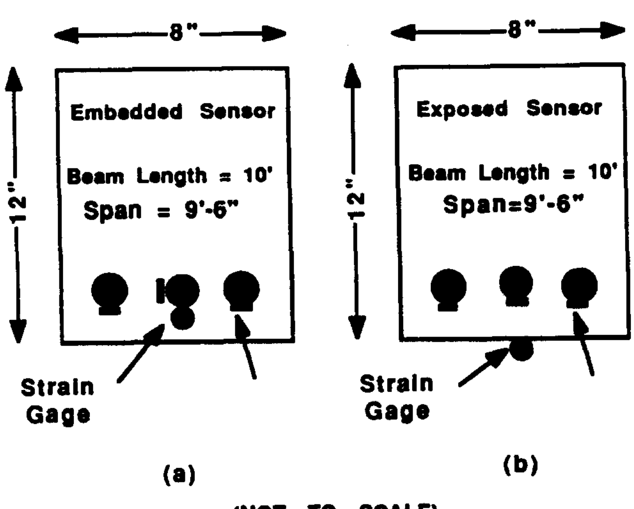


Fig. 16. Reinforced concrete beam cross-section depicting location of sensors (Maher and Nawy[25]).

from an optical fiber and a strain gage at a typical sensing location are compared in Fig. 20. These results indicate a one-to-one correspondence between the two measurement techniques.

Zimmerman and Claus developed an optical time-domain reflectometer (OTDR) strain sensor for the distributed measurement of strains at various segments along the length of anchoring tendons.[29] The feasibility of such a monitoring system was examined through application in a concrete wall anchoring system. As indicated in Fig. 7, the distributive measurement capability of an OTDR is based on time-of-flight measurements. In structural mechanics, strains are defined by the measurement of deformations within gage lengths. This is accomplished by ascribing a fixed length within prescribed markers, and monitoring the changes in length by transducers such as clip-gage extensometers, or linear variable differential transformers (LVDT). Zimmerman and Claus developed the strain-monitoring system in the time domain by using reflectors (partial mirrors) in marking the boundaries of fixed gage lengths. These markings, in the time domain, appear as two pulses delayed by a fixed time interval. Any length changes (deformations) within the prescribed gage length shift the time delay according to the polarity of the deformations (Fig. 21). Figure 22 is a schematic diagram depicting the instrumentation involved

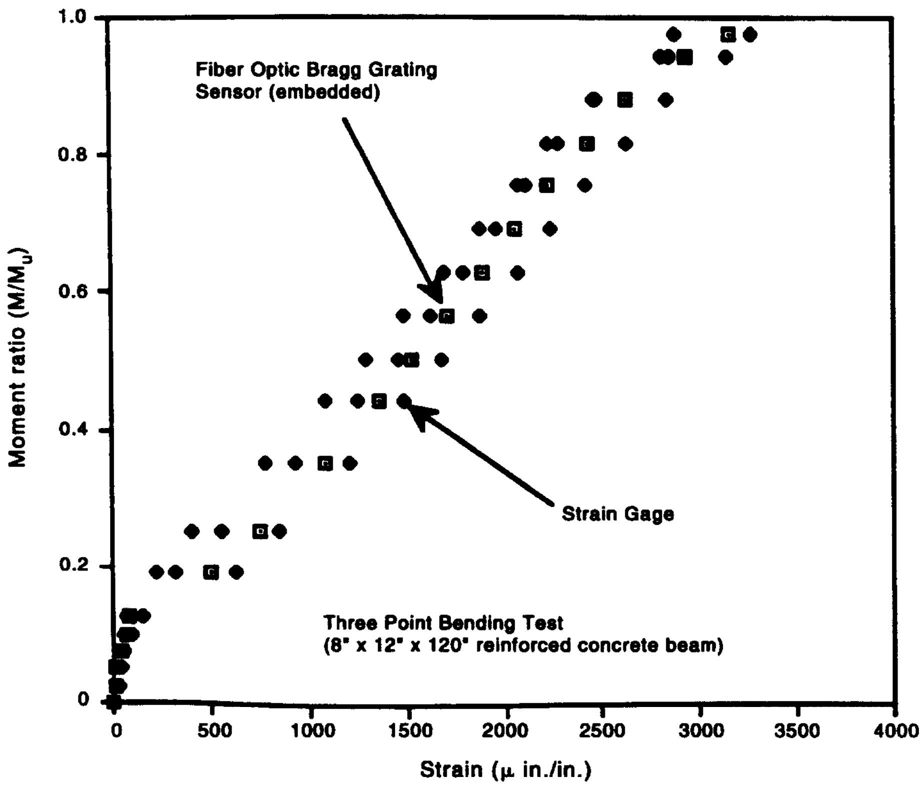


Fig. 17. Comparison of fiber-optic and strain-gage data (Maher and Nawy[25]).

for the sensor system including the OTDR, fiber-optic array, and typical signal output. Figure 23 illustrates employment of the distributed sensor system for monitoring of a composite-grouted tendon in a concrete wall. This monitoring system is inherently redundant since measurements can be made from either end of the sensor. Results from experiments with this system indicated a displacement resolution capability of $\pm 260\,\mu$m per individual gage length.

Optical fibers have provided unique sensing and measurement capabilities for condition monitoring of concrete structures. For instance,

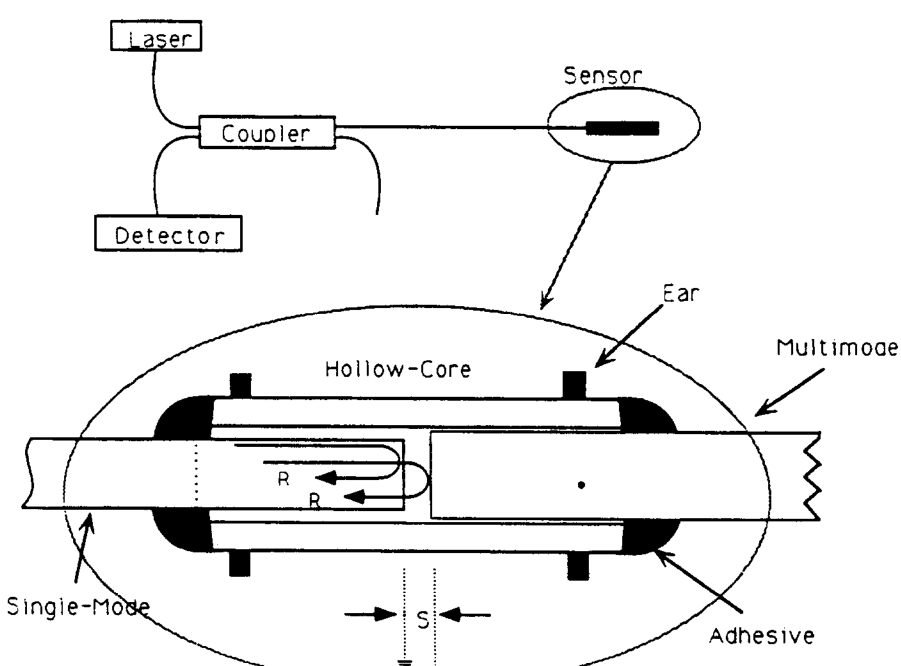


Fig. 18. Fabry–Perot sensor system and geometry (Claus *et al.*[27]).

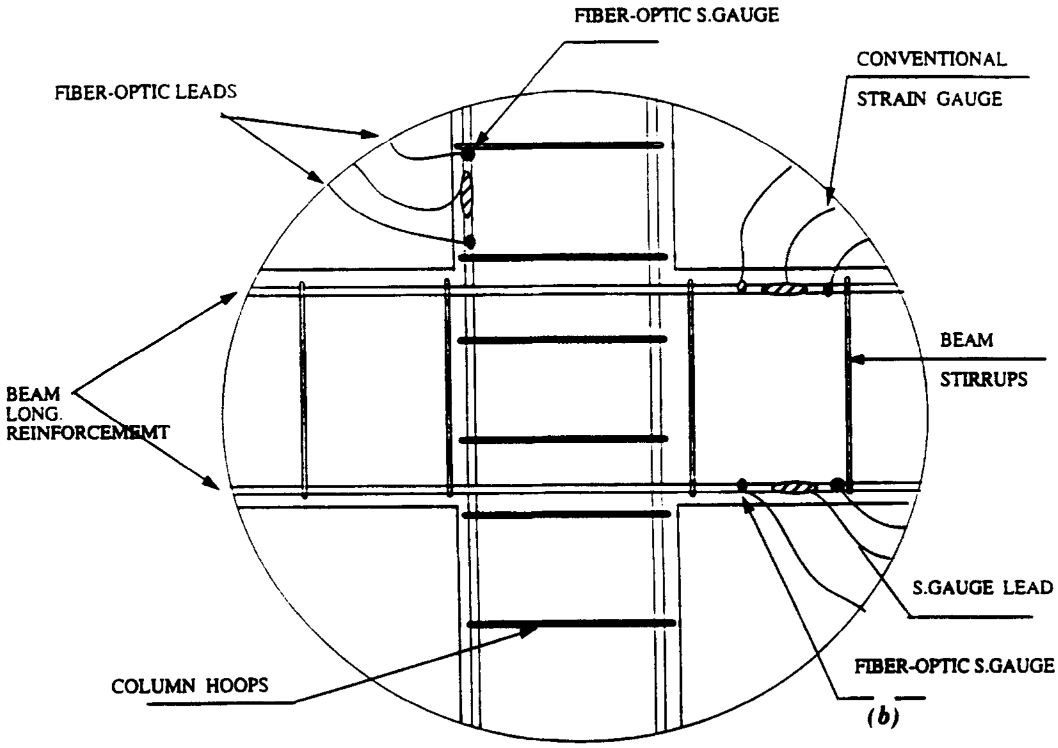


Fig. 19. Reinforced concrete joint details and sensor locations (Masri et al.[28]).

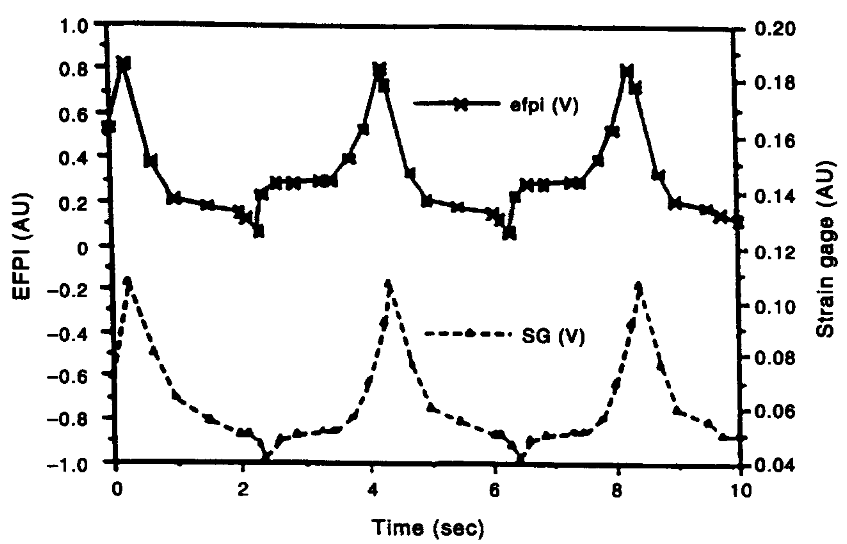


Fig. 20. Comparison of fiber-optic and strain-gage measurements (Masri et al.[28]).

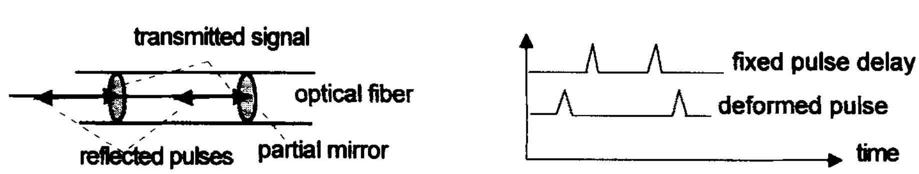


Fig. 21. Time-domain definition of gage-length and pulse-shift defined displacement.

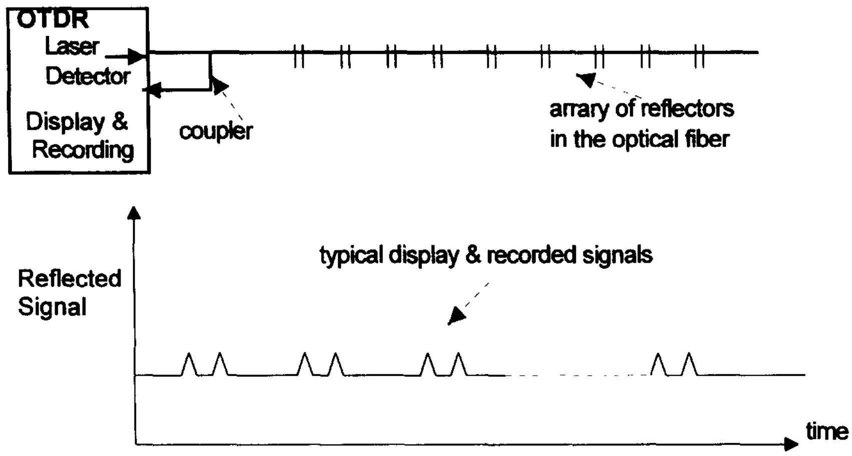


Fig. 22. Optically discretized fiber-optic sensor for distributive sensing.

Michie *et al.* have reported the development of a distributed fiber-optic sensing system for detection of grout in ducts containing steel reinforcing tendons.[30] The system was employed for monitoring the progress of grout as it is pumped along the length of the prestressing duct in a beam. This is an important application, as this sensor will detect voids and improperly grouted tendons. Detection of voids in grouted ducts is of importance since the prestressing steel in voided areas is not protected and is prone to corrosion. The system employed by Michie *et al.* uses a combination of optical time-domain reflectometry, and chemically sensitive polymers (hydrogels) that swell upon reaction with water. The optical fiber is held in contact by a helically wound Kevlar thread to a glass-fiber-reinforced plastic (GFRP) rod (Fig. 24). The GFRP is coated with the hydrogel and, when in contact with water, the hydrogel swells and causes the fiber to deform locally by squeezing it against the thread. This causes the microbending effect in the fiber at the point of swelling, and the loss in light intensity is related to the presence of water at this point. By using an OTDR, it is possible to detect the presence

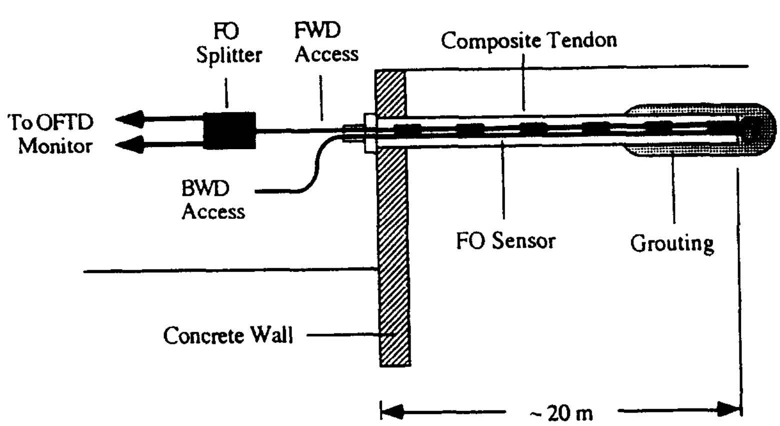


Fig. 23. Distributed sensor for concrete wall anchoring system (Zimmerman and Claus[29]).

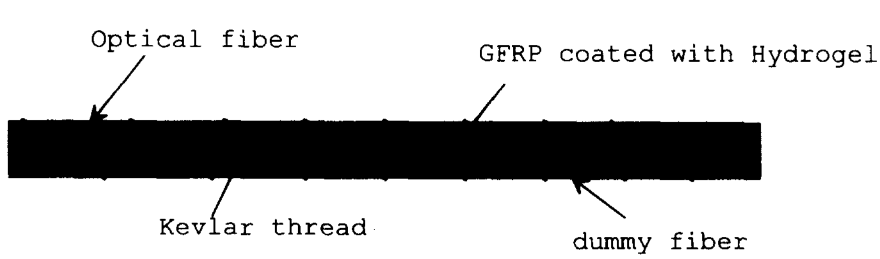


Fig. 24. Optical-fiber sensor arrangement for detection of moisture (Michie *et al.*[30]).

or absence of moisture at specific points along the length of the tendon.

The two-span Beddington Trail Bridge in Canada consists of 26 precast prestressed concrete girders. These girders were prestressed with three types of prestressing element which included conventional steel strands as well as new carbon-fiber composite cable, and the Leadline Rod. Measures *et al.* employed fiber-optic Bragg grating sensors in order to monitor the in-service condition of all the tendon types.[31] The primary objective of this project was to monitor the long-term behavior of these tendons in terms of losses due to stress relaxation and creep. The Bragg gratings were attached to the prestressing elements and subsequently embedded in concrete girders. The sensor array was strategically located within various segments of the bridge, and the condition monitoring activities spanned over a period of almost two years. These sensors have been able to provide for static as well as dynamic monitoring of strains in the girders. A resolution of 1 $\mu\epsilon$ over a dynamic range of about 10000 $\mu\epsilon$ is reported by the researchers.

Habel and co-workers performed a variety of laboratory as well as field experiments in order to evaluate the performance of optical fibers in condition monitoring of large structures. For instance, they employed a Fabry–Perot sensor for condition monitoring of a cracked box girder in Berlin's Charlottenburg Bridge.[32] The sensor was attached to the exposed prestressing steel, and a crane moving at various speeds was employed for load testing of the bridge. They were able to measure the natural frequency of the bridge as well as the load-carrying capacity of the cracked girder. They also employed the Fabry–Perot sensor for measurement of the strains associated with hydration of concrete in a wall.[33] The most important study performed by Habel's group involves a comprehensive set of experiments in order to determine the durability of optical fibers in the alkaline environment characteristic of concrete.[34] Integrity of the coating material is important to the survival of the optical fiber in concrete. A number of coating materials including acrylate, polyimide, and fluorine polymer types were tested under alkaline solutions with pH levels as high as 12.4. These studies were performed over a period of 5 months after which the integrity of coatings was evaluated with a scanning electron microscope. Their results indicated that, in applications pertaining to concrete, coatings based on fluorine-containing polymers were more durable than the other coating types.

Fuhr *et al.* reported the installation of fiber-optic sensors into the Stafford Medical Building at the University of Vermont.[35] This study describes the practical issues involved for successful embedment of fiber-optic sensors into large concrete structures. These include the construction crew, embedment techniques, and development of schemes for protection of optical fibers when forms are removed from the concrete elements. They also developed an impact response testing technique through measurements of elastic waves in concrete slabs by means of an embedded optical fiber.

Chen *et al.* developed a new fiber-optic sensor for the measurement of internal strains and deformations in cementitious composites.[36] The sensor is of the intensity type, and involves the measurement of strains and deformations by evaluating the intensity variation of speckle patterns caused by mode redistribution within a multi-mode optical fiber. Evaluation of the sensor for measurement of the displacements associated with cracks was accomplished by embedment of these sensors in single-edge notched three-point bend concrete specimens. A frame grabber image digitizer was employed for acquisition of speckle patterns from the output end of the fiber, and the image data were numerically evaluated in order to determine the strain. Figure 25 depicts calibration data for the speckle-based sensor. As shown in this figure, the sensor provides sufficient sensitivity over its dynamic range. The experimental beam set-up as well as the on-line calibration scheme (cantilever beam) are presented in Fig. 26. Figure 27 provides a comparison of the crack-opening displacements measured by the optical fiber at the crack tip (CTOD) with the displacements measured by an LVDT at the crack mouth.

CONCLUSIONS

The state-of-the-art in the applications of fiber-optic sensors to cementitious composites has been presented. As demonstrated by the work of many investigators, the research effort has been focused on embedment of optical-fiber sensors in concrete elements. A structurally integrated sensing system could monitor the state of a structure throughout its working life.

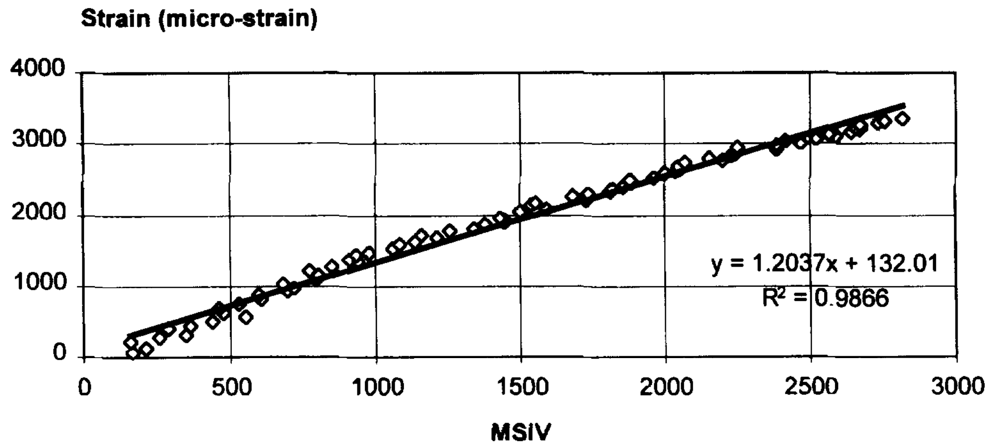


Fig. 25. Variation of optical signal as a function of strain.

These structures, occasionally termed as smart, are able to detect environmental degradations and warn if any excursions deviate from accepted values. A number of investigators have demonstrated that integrated sensing systems could also monitor the health of various structural components during construction, leading to improved quality control. As the field of concrete engineering is also evolving, the need for use of optical fibers for monitoring the state of concrete structures becomes more pronounced. For instance, several investigators have

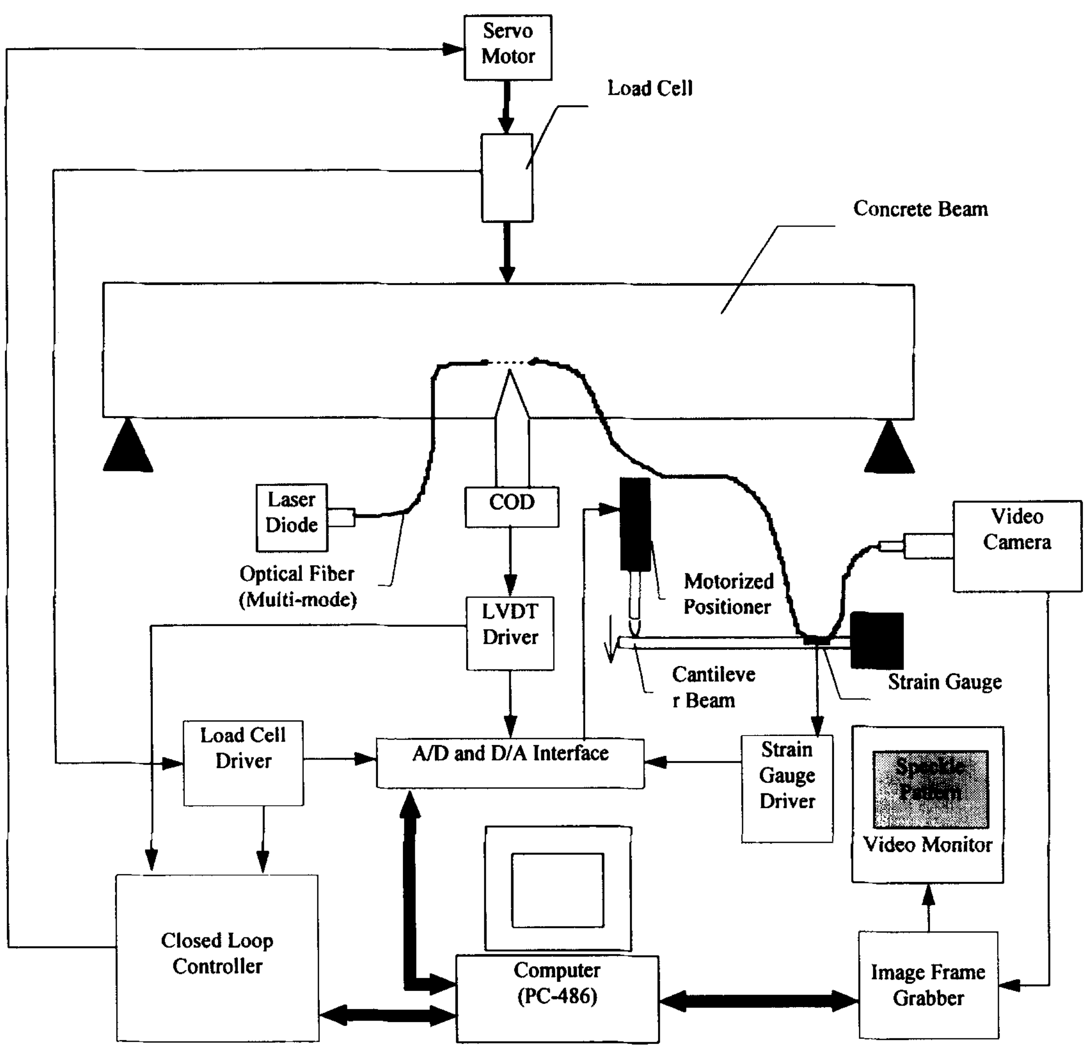


Fig. 26. Experimental set-up.

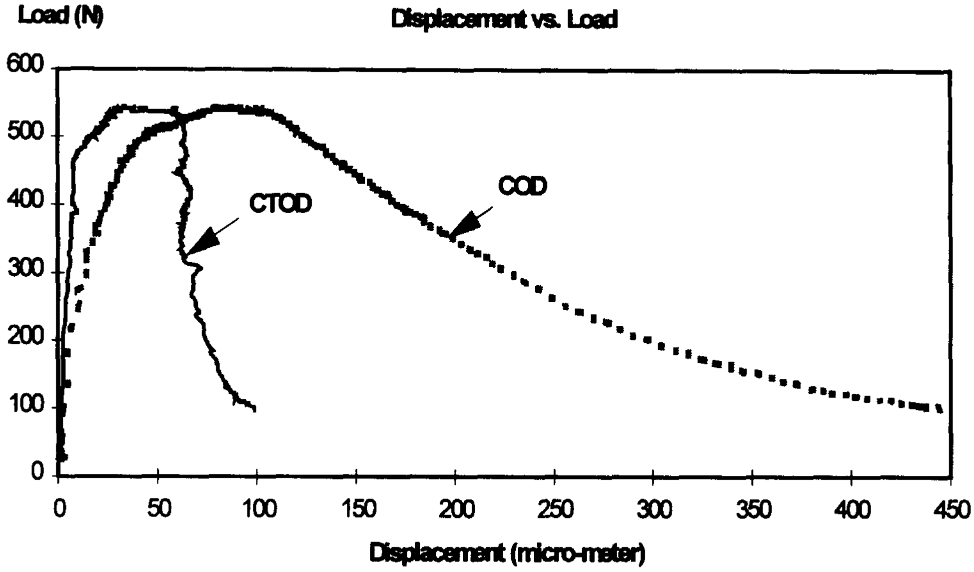


Fig. 27. Comparison of fiber-optic CTOD data vs LVDT crack-mouth opening displacement (CMOD) values.

employed the optical-fiber sensor systems in conjunction with new materials and designs, i.e. non-metallic reinforcement, and advanced fiber composites for prestressing elements. Obviously, this is an important area of activity, since a lack of sufficient knowledge about the behavior of such materials requires appropriate means for health monitoring as well as data for further understanding of structural behavior.

It needs to be understood that the ultimate goal for employment of optical-fiber sensors in structural applications is capability for real-time distributed sensing of perturbations. Current state-of-the-art for distributed measurements is limited owing to technological challenges involved in the production of robust and yet economically feasible instrumentation. The field is still at a stage of infancy, and many obstacles need to be removed prior to its full implementation in large structures. This is a highly interdisciplinary field and requires expertise in concrete engineering and computing as well as in physics, and opto-electronics. However, the success of this emerging field is of paramount importance to the future of concrete engineering. As in any other multidisciplinary activity, although the start will be slow, the technological advances will follow an exponential path. Researchers rely on materials and instrumentation developed for the communications industry, mainly due to the fact that there are no dedicated tools for sensor research. The opto-electronics industry has not seen the potential for this market and it will take few more years before concrete technologists witness industrial competition and leap-frog advances in the field. Most of the activities are being conducted at academic institutions and with very limited funds. However, research organizations have begun to realize that the revitalization of public works infrastructures requires advancement through innovation in emerging technologies. For this reason more funds are being allocated for the research and development of optical-fiber sensor systems which will eventually pave the way for better-built structures.

ACKNOWLEDGEMENTS

This work was made possible by the National Science Foundation grant No. CMS-9402671.

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