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Application of fiber Bragg grating in local and remote infrastructure health monitoring

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ABSTRACT

Developing uses for emerging fiber optic technology may help to manage the health of smart structures by providing an accurate strain profile and history of structural members. One specialty fiber optic application is the use of Bragg Gratings, which can measure pointwise the strain. First, practical application of this technology is reported. Next, the accuracy of Bragg Grated fibers was validated and a method to install the delicate fibers in a full size reinforced concrete beam was developed, both in the laboratory and in the field. Finally, remote sensing of the sensors through the Internet is explored.

RÉSUMÉ

Le développement d'utilisations pour la technologie émergeante des fibres optiques peut aider à gérer la santé des ouvrages en fournissant un profil précis des contraintes et l'historique des éléments structurels. L'une des applications spécialisées des fibres optiques est l'utilisation du réseau Bragg, qui peut mesurer la contrainte par points. L'application pratique de cette technologie est d'abord présentée. Ensuite, la précision des fibres du réseau Bragg a été validée et une méthode pour installer ces fibres délicates dans une poutre de béton renforcée de taille normale a été développée, en laboratoire et sur le site. Enfin, on discute de la détection à distance au moyen d'Internet.

1. INTRODUCTION

With the increased public and political concern about the decay of our national infrastructure, and the health hazard caused by insufficient containment of hazardous contaminants, there is an urgent need for an effective method to monitor crack formation and strain history. In addition, due to limited financial resources, a decision support system, which can properly prioritize structures which truly need immediate rehabilitation, is highly desirable. Of major interest is the continuous monitoring of crack formation and strain history.

The above requirements should be met by a system simple to install, sensitive enough to provide early warnings, easy to maintain, and reliable to operate. Furthermore, the system should be flexible enough to monitor more than one physical variable, and compact enough so as not to interfere with the measurand. It is the authors' opinion that only fiber optics can play such a role.

Most failures manifest themselves by premature cracking which is not always easily observable. In steel bridges, lock gates, and other major steel structures, it is highly desirable to readily pinpoint a crack as soon as it forms. In those instances, a fiber can be layered on the surface so as to intercept any potential crack. Crack detection could then be performed by a variety of techniques, with the least expensive one being intensity measurement attenuation. However, this method cannot locate the crack. Location could be achieved by illuminating the fiber with a visible light source, and following the path of the fiber until the crack is seen to emanate from the cracked fiber. Should the exact location of the crack be desired, without relying on visual evaluation, an Optical Time Domain Refractometer (OTDR) could be used to locate the crack with a resolution proportional to its cost.

For concrete structures, crack detection is of relevance only in massive unreinforced structures. In reinforced concrete design, it is assumed that concrete has to crack before the reinforcement is activated, so cracks are expected in tension regions. One of the major challenges in dam safety evaluation is the determination of internal cracks. This is often accomplished through careful examination of extracted cores. Hence, fiber optics technology could play an important role if fibers can be placed inside a core which is then filled with mortar. This embedded fiber could then act as a crack detector and, as shown later, a tool to measure internal strains.

Crack detection is also of major importance in the safe operation of hazardous material containment including biological, chemical and nuclear waste. Containers could be properly instrumented to alert operators about cracking which may lead to leakage.

In many cases, it is highly desirable to accurately and continuously measure the strain in a structure. This, in conjunction with proper analysis, could lead to early warnings of an imminent disaster and would give operators ample time to remedy the situation. Hence, point-wise strain measurements in a number of infrastructures are highly desirable.

In steel structures, surface strains can be monitored in zones of high stress concentration, and be used for fatigue analysis in real time.

In concrete structures, cracks are not as sharply defined as in metals. A crack would manifest itself by first expanding a so-called Fracture Process Zone (FPZ) composed of micro-cracks which exhibit a discontinuity in displacements, but a continuity in stress. Internal fiber optics-based measurements could provide a 3D map of the FPZ's exact form which has only been speculated through numerical studies. For dams, which are heavily instrumented structures, the ability to record strains internally is of major importance as those readings could then be systematically correlated with precise finite element studies and/or external measurements.

2. LITERATURE SURVEY

Most of the early development of fiber optic sensors was for either military or aerospace applications. Usages included acoustic sensors for submarine warfare, strain and pressure sensors for smart structures, and temperature sensors. With the end of the Cold War, there is increasing interest to diversify these early developments into civilian use. Following are a few attempts reported in the literature.

To the best of the authors' knowledge, the first use of fiber optics in concrete was by Rossi [1] to detect concrete cracking. Tests were first performed in a laboratory, and then the method was applied to a submerged concrete structure which had to be watertight.

Ansari [2] measured the air voids in air-entrained concrete from the change in light intensity transmitted through an optical fiber cable.

Nanni *et al.* [3] measured the change in refractive index of a fiber embedded in concrete to determine the internal strain. Concrete specimens under axial tension and compression as well as radial compression with embedded fibers were tested, and optical power versus strain was plotted. It was determined that the highest sensitivity occurred when the applied pressure bisected the polarization axes. Also, the optical power was a sinusoidal function of the applied strain, where the amplitude and period of the curve determined the precision and range of strain measurement.

Ansari [4] measured the crack tip opening displacement (CTOD) in notched reinforced concrete beams by placing a bent fiber inside the specimen and correlating the intensity attenuation with the CTOD.

Fibers have been attached to reinforcing bars in a five-story building by Fuhr and Huston *et al.* [5].

Miesseler and Wolff [6] wound a metal wire around a fiber in order to increase the effect of concrete cracks on the intensity of transmitted light. Under high strain, the wires would squeeze the fiber, thus causing significant intensity loss. This type of sensor was used to monitor concrete bridge cracks, as well as glass fiber reinforcement in prestressed concrete components.

Embedded fibers have also been used to monitor curing and load-to-failure testing of a one meter long concrete beam reinforced with two #4 bars, by Fuhr and Huston *et al.* [7]. First, the survival of the fiber during the 28 days curing process was monitored through intensity transmission measurements. It was speculated that, through local microbending, intensity attenuation would occur. Then, the specimen was loaded up to failure, and transmission measurements along a fiber wrapped around a rebar were monitored. It was shown that transmission drastically dropped when cracking occurred. A post-mortem analysis with a 5 cm resolution OTDR (Anritsu MW920A) correctly predicted crack location.

Using a high-resolution OTDR to emit a very narrow (< 200 *ps*) pulse-width, highly stable optical pulse at a wavelength of approximately 850 nm, strains in anchoring tendons were monitored by Zimmerman and Claus [8]. The output of the laser is split for interferometric readings. The active fiber was physically segmented with partially reflective markers ("reflectors") such that the integral strain between any two adjacent reflectors could be monitored by measuring the relative time delay of the respective reflections. The typical sensor's overall length was approximately 20 m with access fibers no longer than 80 m. Concrete wall anchoring systems were also monitored using a similar approach.

Using intensity loss in a fiber surrounded by a small chain, Rosseland [9] measured crack formation in a reinforced concrete beam. A similar technique was also used to monitor strain in a prestressing tendon by Wolff [10].

Fiber optic monitoring of dams has also been reported in work by Koester and Wolff [11]. Crack openings were recorded by measuring intensity loss along a bent fiber placed across the crack, and post-tensioning tendon elongation was monitored by placing two reflective mirrors in a fiber and their distance from a reference point measured by an OTDR.

Narendran *et al.* [12] used a Mach-Zehnder interferometric setup to determine the fracture parameters of a notched Plexiglas specimen.

A model was developed by Kim *et al.* [13] to separate strains from temperature effects in Fabry-Perot sensors.

Most recently, Klink *et al.* [14] instrumented a newly built prestressed concrete bridge with Bragg grating sensors for long-term monitoring. The effects of prestress, thermal, and live load on strains are being recorded.

From this brief, but comprehensive, survey, it appears that most techniques rely on integrated measurements along a non-negligible portion of a fiber to measure strain indirectly. Intensity loss-based measurements cannot provide point-wise measurements, and are at best good indicators of the averaged measurand. Interferometric or polarimetric methods require complex instrumentation and data reduction, which must be independently calibrated.

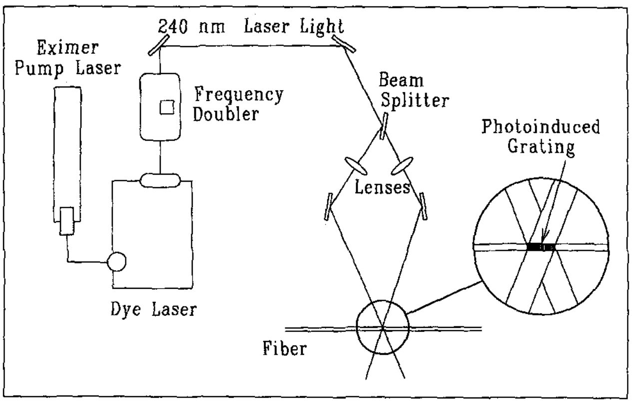


Fig. 1 – In-fiber holographic grating.

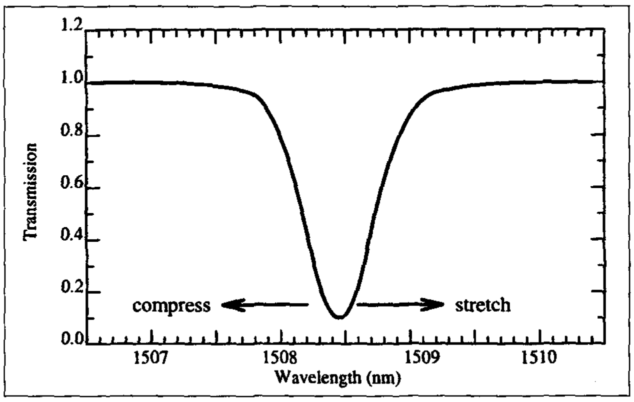


Fig. 2 – Strain induced shift of a center wavelength.

3. FIBER GRATING

One of the most promising of emerging technologies in fiber optics for strain measurement is based on in-fiber Bragg gratings (FBGs) [15]. The method consists of first "burning" a series of closely spaced lines along a fiber. This grating will in turn inhibit the transmission of light at a certain wavelength. Light propagating in the core of an optical fiber containing a Bragg grating will be reflected by the periodic variations of the refractive index, which comprise the Bragg grating. The reflected light will generally be out of phase and will tend to cancel, except when the wavelength of the incoming radiation satisfies the Bragg condition, as shown by Melle *et al.* [16].

Gratings on a fiber are formed using a pulsed ultraviolet source tuned to (or near) 240 nm. Two beams from that source form an interference pattern along a short length of fiber (about 5 mm), Fig. 1. The grating amplitude is determined by the width of the interference pattern and by the exposure time. The grating strength as a function of exposure time varies depending on the concentration of the various dopants in the fiber. The center wavelength λ which will be affected by the grating is equal to the spacing L between adjacent lines. Hence, strain will be directly obtained from:

$$\varepsilon = \frac{\Delta L}{L} = \frac{\Delta \lambda}{\lambda} \tag{1}$$

and elongation of the optical strain gage will be simply equal to the wavelength shift which can be directly measured, Fig. 2. Furthermore, there is a small photoelastic effect which will cause axial deformation to induce very small changes in the refraction index. However, this secondary effect was neglected in this study. Thus, conceptually, there is great similarity between a fiber grating strain sensor and a foil gage strain gage. However, the former has the major advantage of not only being independent of calibration, but also providing stable long-term measurements without drift.

Many gratings, on the order of 100, can be theoretically written in a single fiber at desired locations, Fig. 3. Once all gratings is in place in the sensor fiber, source and analysis instrumentation are incorporated to produce the sensing systems. The fiber is illuminated with a super-luminescent diode, which is a broadband source. Light reflected from the fiber (one can also look at transmission) is analyzed using a spectrum analyzer. The analyzer provides $s(\lambda)$, the reflected (or transmitted) signal as a function of wavelength. Alternatively, the reflected light can be analyzed by a tunable fiber Fabry-Perot filter, as demonstrated by Kersey *et al.* [17]. This arrangement would also allow multiplexing of numerous gratings. An alternative approach to measure the phase shift consists of splitting the back-reflected light into two beams, one of which is spectrally filtered so that its transmitted intensity is determined by its wavelength, while the other beam is used as an intensity reference. The resulting ratio of the two intensities then determines the wavelength of the back-reflected light [16].

The precise center wavelength and reflection amplitude of a grating are sensitive to the strain of the fiber at the grating location. Once prepared, the fiber is embedded into the specimen or simply attached to an existing structure. It will then respond to longitudinal deformations.

The strain range for the fiber is limited by the glass-limiting strain which is approximately one percent. The resolution itself was governed by the spectrum analyzer, and was equivalent to one micro-strain. Finally, there is a certain temperature dependency which is equivalent to about 10 pm per degree Kelvin. For the base wavelength of 1546.79 nm, this is equivalent to about 6.5 micro-strains. However, this effect is strongly mitigated by the fact that the thermal mass of concrete is such that temperature variations inside the structure are negligible. Furthermore, this could be compensated by a thermistor for possible corrections.

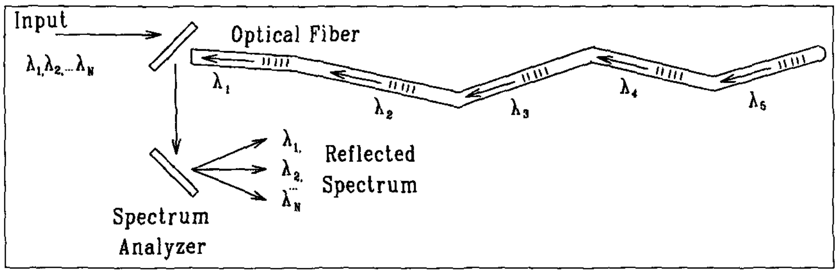


Fig. 3 – Multiple fibers.

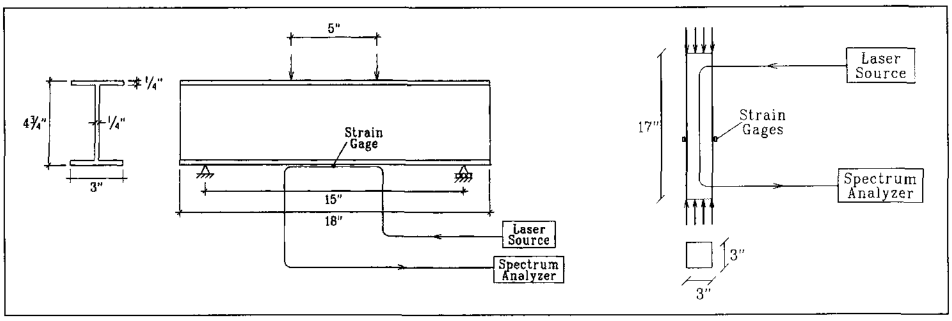


Fig. 4 – Aluminium and concrete beams

4. LABORATORY EXPERIMENTS

4.1 Fiber grating sensors for aluminum beams and concrete

In a set of preliminary tests, the fiber grating technique was applied to measure surface and internal strains in aluminum and concrete structural components, respectively. Since the primary objective was to directly correlate strain measurements from optical fiber with those obtained from an electric strain gage, and from theoretical considerations, the specimens were kept as simple as possible.

In the first one, Fig. 4, an aluminum section was instrumented with both an electric and an optical strain gage on the lower flange, and then quasi-statically loaded. In this preliminary investigation, we did not attempt to quantify the effect of various resins on the strain response; however, as shown later, the correltation between fiber optic reading and strain gages was excellent.

For the concrete test, a fiber was embedded inside a prismatic specimen and an electric strain gage was mounted on the surface, Fig. 4. The specimen was then quasi-statically loaded axially, and strain measurements were compared.

In both cases, the center wavelength (and hence the spacing between adjacent gratings) was set to 1,546.79 nm. Thus, the theoretical "gage constant" to convert phase shift to microstrain would be equal to:

$$\frac{\Delta\lambda}{\varepsilon} = 1.546 \mu\mathrm{m} \qquad (2)$$

that is, each 1.546 pm (10^{-12} m) shift in wavelength will correspond to one microstrain. A positive shift will correspond to a tensile strain, and a negative one to compressive strains.

Upon loading, the load, strain and wavelength shifts were recorded by a load cell, strain gage and optical spectrum analyzer, respectively. Fig. 5 illustrates the load and unload versus strain measurements.

From the strain versus wavelength shift diagram, we observe the near-perfect linearity between these two measurands. In the case of the aluminum specimen, it should be mentioned that the discrepancy between strain gage and fiber reading can be attributed to the shear lag effect, as those two sensors were not placed exactly on the same location.

4.2 Reinforced concrete beam with embedded Bragg gratings

A full-size reinforced concrete beam was cast in the laboratory. The design called for a twelve feet-six inch long beam, sixteen inches deep and ten inches wide. The reinforcing steel in the longitudinal direction was (2)-#5's top and bottom. #3 stirrups were provided at seven inches on center, with the stirrups surrounding the top and bottom reinforcing steel. Concrete compressive strength was determined from cylinder tests to be 4,600 psi.

The bottom reinforcement was instrumented with strain gages along the rebar, and the concrete itself had two

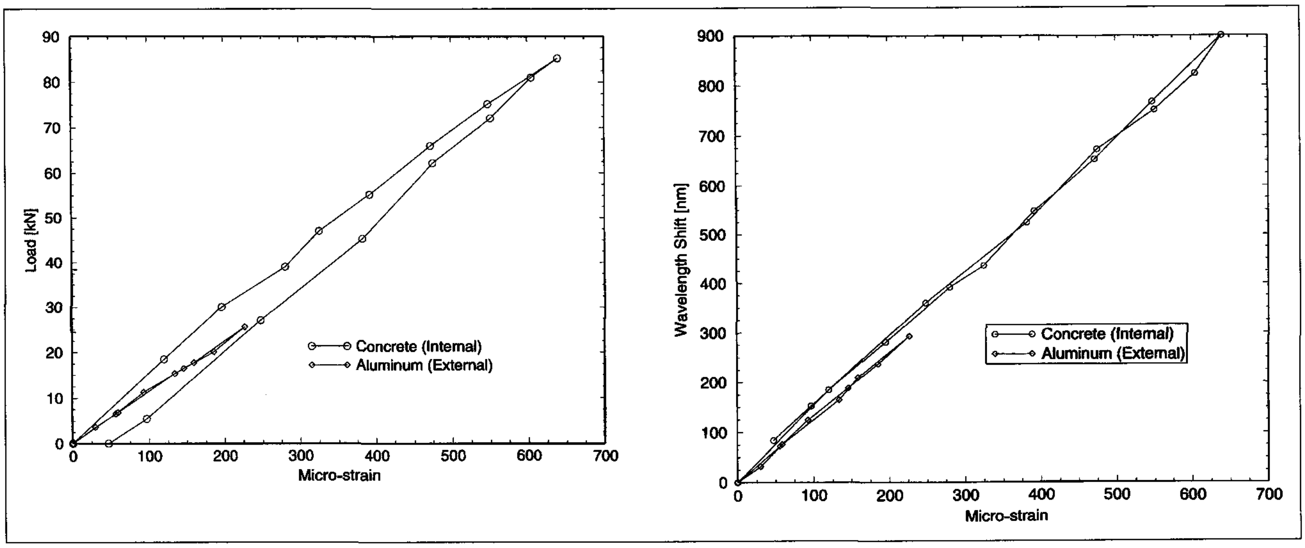


Fig. 5 – Load *versus* strain, and wavelength shift *versus* strain.

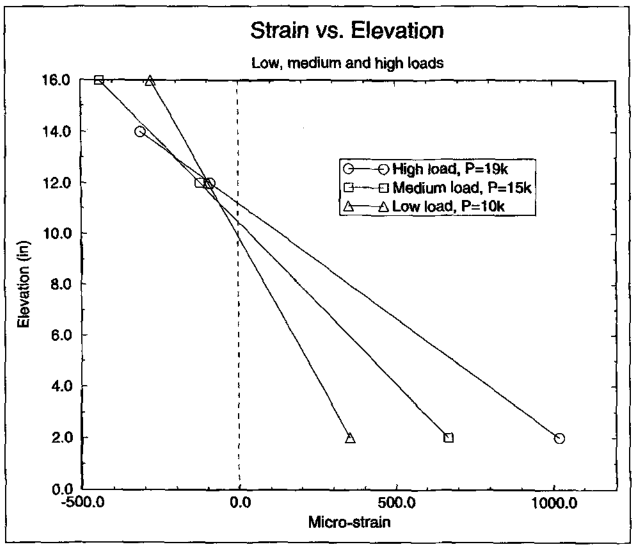


Fig. 6 – Locating the neutral axis.

FBGs installed at two and four inches from the top surface. The fibers were centered in the width of the beam and oriented with the treated length of the fiber parallel to the long axis of the beam. Each end of the two specialized fibers then protruded from the top of the beam. As such, it was necessary to protect the protruding fiber optic ends with small-diameter shrink-wrap sleeves. The fibers were protected and positioned inside the beam by threading the fibers into a flexible plastic tube, and hanging the plastic tubes with wire hangers. The wire hangers were tied to the reinforcing steel, with loops in the hangers for the tubes. The concrete was placed, the tubes were extracted, leaving the fibers in place, and the concrete was vibrated to consolidate the fresh concrete around the fibers.

The beam was then loaded through two point loads, at third points of the beam. Loads, displacements, strain and wavelength shift were recorded.

4.3 Results

The beam was loaded in six cycles and taken to failure during the last one. During the course of the test, the specified load would be applied and maintained constant in order to measure load, surface transducers, tension steel strain gage readings, along with strain readings from both of the Bragg Grated fiber optics.

It is useful to observe the strain profile of the beam at several load levels in order to assess the reliability of the fiber optics transducers. Three of the strain profiles examined help to demonstrate the overall trend revealed by the data. In Fig. 6, the vertical axis is the height of the beam, with zero located at the bottom of the beam. The horizontal axis is the microstrain reading from the data, with compression taken as negative. Fig. 6 shows a number of readings taken at different loads. Each of the profiles shows a nearly linear strain relationship, and the neutral axis (zero microstrain) rising towards the top of the beam as loads increase.

The important trend revealed by this figure is capturing the rise of the neutral axis as loads increase. The combination of conventional and fiber optic strain measurement technology has demonstrated the ability of Bragg grated fiber optics to measure the compressive strains in reinforced concrete beams.

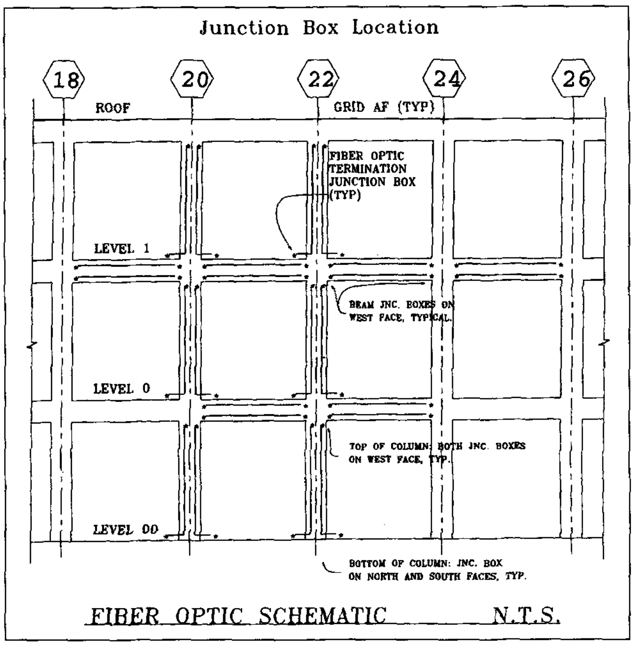


Fig. 7 – Beams and columns with optical fibers.

Based on the testing of this beam, recommendations may be made for future sample preparation. From the experience of casting with the wire hangers suspended from the reinforcing steel, it is recommended to use this system in future installations. The loops of wire held the protective tubing securely in place, within approximately one-quarter inch of the desired location.

5. FIELD EXPERIMENTS - ITLL BUILDING

5.1 Fiber optic sensor location

A structure currently being constructed at the University of Colorado is the Integrated Teaching and Learning Laboratory (ITLL). This instructional facility will have numerous sensors to record various physical parameters of the building (such as electrical, acoustic, thermal, lighting, fluid, data transfer on the ethernet network, vibrating wire strain gages and other parameters). Accordingly, we have complemented this extensive network of sensors by instrumenting six beams and six columns, Fig. 7.

5.2 Fiber position in members

As in the laboratory experiments, the position of the fiber within the member will be controlled by using hangers tied to the reinforcing steel. For example, the column cross section has four continuous fiber optics. Two are Bragg-grated, and two are plain single-mode. The fiber positions within the column were governed by the need to keep the concrete vibrator from getting entangled with the protective tubing and hangers. By keeping the fibers near the reinforcing steel cage, it was hoped that the fibers would avoid any snares. By locating the fibers towards the outer edges of the column, it is also more likely to capture any bending effects of the column, while still capturing the expected compressive strains.

5.3 Installation considerations

To install fiber optics in a large project such as ITLL, the contractor, architect, owner, and fiber installer (among others) must diligently coordinate their efforts. Practical installation aspects were discussed with each group, and each group provided insight. To allow the fibers to exit the member, a method of protection at the member surface had to be devised. It was determined that the method of using conventional electrical conduit to direct the fiber to the member surface would probably work best. The conduit could be connected to a recessed junction box, and the bare fiber ends rolled and stored in the boxes. This method allows access to the fibers, while keeping them safe from being damaged during subsequent construction. Several rounds of revisions were required to fine tune the junction box locations. The locations had to satisfy the architectural and structural concerns, while keeping the structure as easy as practicable to construct.

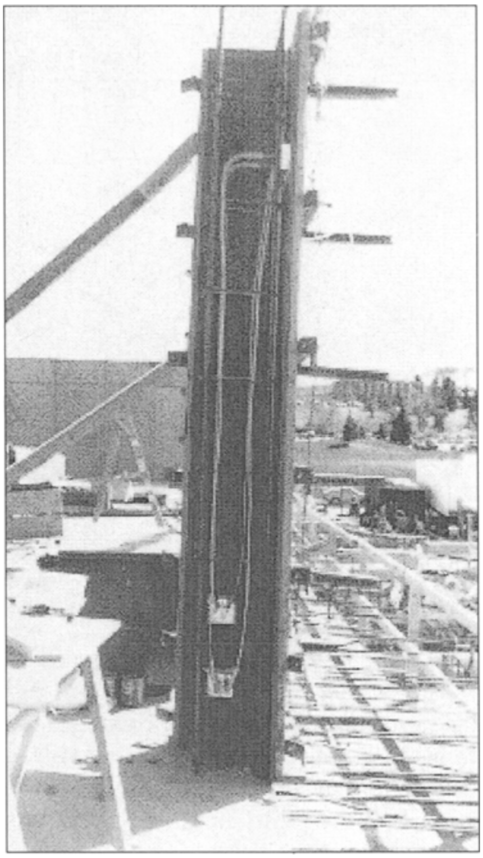


Fig. 8 – Elevation view of a column with a completed fiber optic installation.

5.4 Field installation

As one of the preliminary steps in this undertaking, a mock-up of the reinforced concrete members to be instrumented was built. This step provided the contractor, architect and University personnel with a chance to review the installation process and to better understand the requirements of the project.

The first fiber installation of two columns at the lowest level was in January of 1996. The last installation, at the top level, was performed the following April. The timing of the installation was coordinated with the contractor and architect to minimize delays in the schedule. As construction progressed outside, lab work involved preparing wire hangers and stringing fiber optics through protective tubing. Once the reinforcing steel and formwork were in place, laboratory personnel could attach the wire hangers, install conduit bends to the junction boxes, and subsequently thread the protective tubing (with fibers inside) through the junction boxes and hangers.

On the day the concrete was placed, two field personnel were required. While concrete was being placed, each end of the protective tubing would be grasped, and a slight tension applied to the tubing. This prevented the tubing from being entangled inside the formwork, while the concrete was placed into the formwork.

After placing the concrete, the contractor was responsible for vibrating the concrete while the protective tubing was still in place. Next, one person would firmly grasp one end of the fiber optic protruding from the junction box. The person at the other end would then extract the protective tubing by firmly grasping and pulling its exposed end. This process was completed for each of the fibers in the member.

The structural member would then be vibrated briefly a second time, to collapse any voids left when extracting the tubing. Careful handling of the vibrator was very important to avoid snagging the fiber optics. Coordination and cooperation with the workers was very important at this stage of the operation. Through this technique, we ensured proper fiber protection during installation, and adequate surface bond during service.

After completing the pulling of all protective tubing from the fibers, the lead ends would be wrapped into spools, and taped into the security of the junction box. The contractor provided lids to cover the junction box openings, and these were screwed into place. Stripping of the forms was accomplished with conventional methods, since the fiber optic ends were protected inside the junction boxes during this process.

A column is shown in Fig. 8 with the hangers, protective tubing, conduit and junction boxes installed. This elevation view shows two junction boxes at the bottom of the column, and one of two junction boxes is visible at the top of the column. The white tubing visible in the center of the column is the polyethylene tubing used to protect the fibers during the placing of concrete. The Bragg grated fiber optics were threaded into the tubing before installation.

Six beams were instrumented with fiber optics. A typical installation is shown in Fig. 9. The other end of the beam would have a similar installation, allowing access to pull the protective tubing out after the concrete has been placed. The tubing is withdrawn while the concrete is still fresh, and the concrete is further vibrated to collapse any voids left by the protective tubing.

Currently, the fiber installation has been completed and construction of the building continues. In the future, the fibers will be connected to electrooptic devices and used to monitor this portion of the building. Planned applications include ongoing building monitoring and academic instruction.

5.5 Remote sensing through the Internet

Through the explosive use of the Internet, it is now possible to remotely monitor field-installed sensors. In preparation for such a monitoring system, a Java-based prototype was developed and will be briefly explained. Java is a recently released programming language which has the advantage of being platform-independent, or able to run on almost any computer type (Unix, PC, Macintosh) for which an internet browser has been written. The program reads a text file on the host machine, produced from data of the building, and then displays it. Java programs are small binary files that are temporaraly copied to the viewer's machine, which is then run by the user's internet browser. This one, in turn, could access the World Wide Web site to display relevant information.

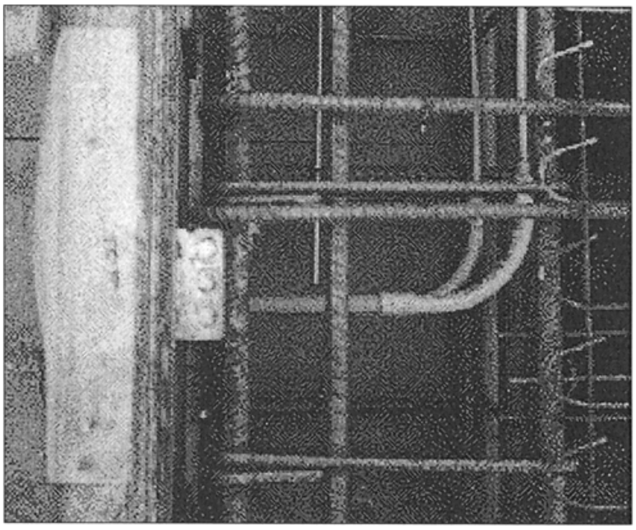


Fig. 9 – View from above beam showing the configuration of a junction box (left), conduit and protective tubing.

First, an external standard video-camera can take a picture of a site (constructiuon of the ITLL building in this case) and transmit it every specified time to a server, Fig. 10.

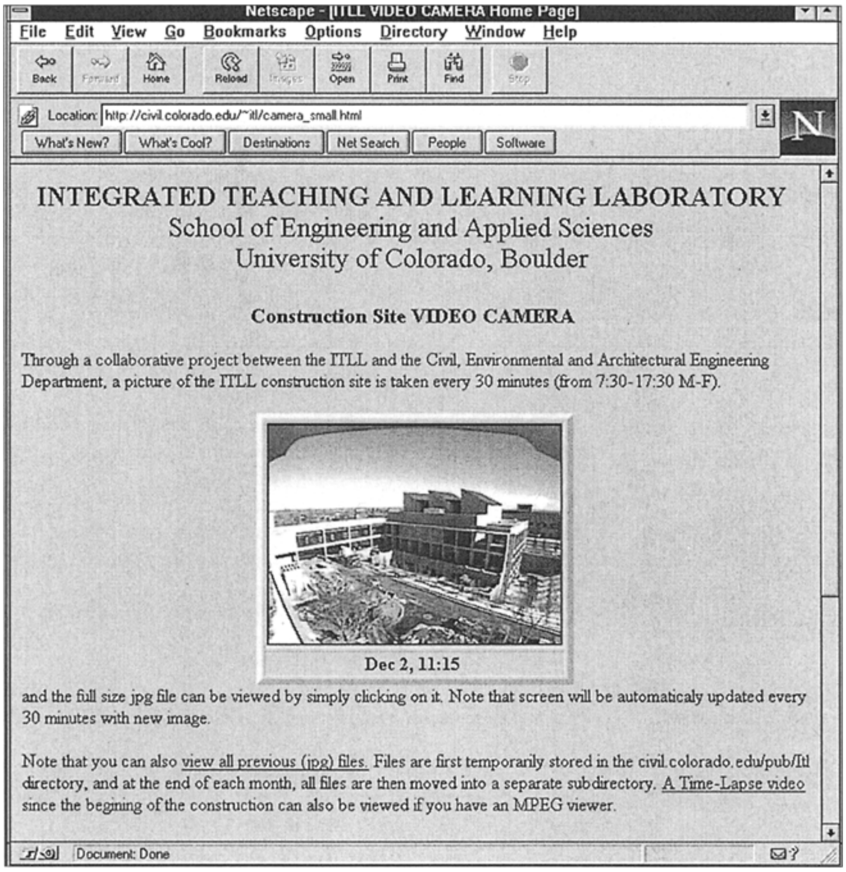
Then, the user has access to engineering drawings through a scrollable environment without any degradation of the file resolution (http://civil.colorado.edu/˜saouma/SM).

Finally, another Java-based application would enable the user to view in real time the sensor's current value and its histogram, Fig. 11.

Such a monitoring system, when combined with fiber optics-based sensors, could in the future prove to be of great importance to real-time health monitoring of structures.

6. CONCLUSIONS

The use of FBGs in the monitoring of strain in structural members shows great potential for use in the emerging field of smart structures. The accuracy of FBGs has been shown with proof tests in the laboratory. It has also been demonstrated that use of this technology is compatible with a variety of conventional building materials. A practical and effective method has been developed to install fiber optics into cast-in-place concrete structures. The ITLL Building is a demonstration project of the potential for FBGs in the area of structural monitoring.



http://civil.colorado.edu/~itl/camera_small.html

INTEGRATED TEACHING AND LEARNING LABORATORY
School of Engineering and Applied Sciences
University of Colorado, Boulder

Construction Site VIDEO CAMERA

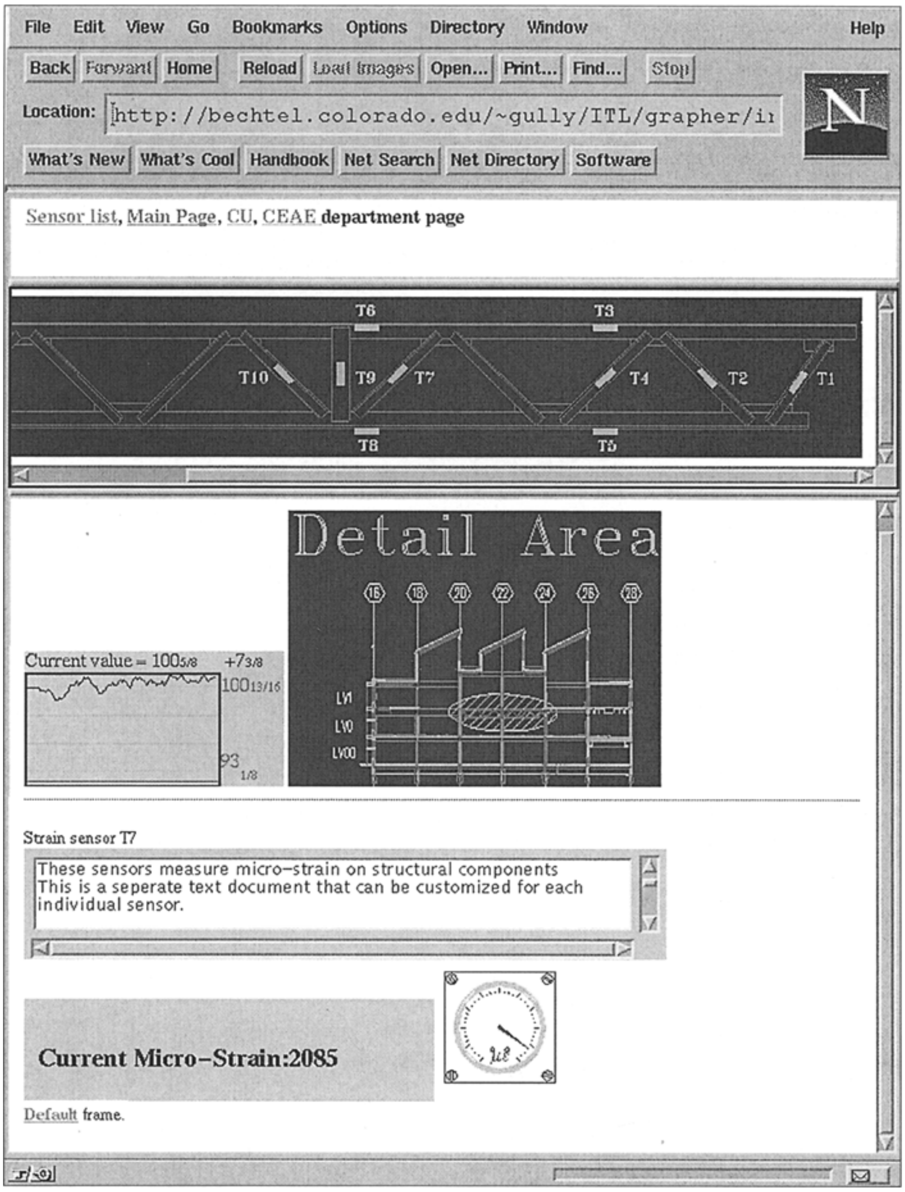
Through a collaborative project between the ITLL and the Civil, Environmental and Architectural Engineering Department, a picture of the ITLL construction site is taken every 30 minutes (from 7:30-17:30 M-F).

Dec 2, 11:15

and the full size jpg file can be viewed by simply clicking on it. Note that screen will be automaticaly updated every 30 minutes with new image.

Note that you can also view all previous (jpg) files. Files are first temporarily stored in the civil.colorado.edu/pub/Itl directory, and at the end of each month, all files are then moved into a separate subdirectory. A Time-Lapse video since the begining of the construction can also be viewed if you have an MPEG viewer.

Fig. 10 – On-line video picture of the ITLL building site.



Sensor list, Main Page, CU, CEAE **department page**

These sensors measure micro-strain on structural components
This is a seperate text document that can be customized for each individual sensor.

Current Micro-Strain:2085

Default frame.

Fig. 11 – Protoype of a Java-based viewer for the ITLL building gages.

Also presented is a prototype of an internet-based monitoring system which could play a major role in effective structural health monitoring systems.

ACKNOWLEDGMENTS

This project would not have been possible without the cooperation of a number of individuals and organizations. Thanks are extended to Paul Leef and the ITLL Project team, M.A. Mortenson Construction Co. and the CU Structures Laboratory staff. A special thanks to Nicholas Gully who has developed the Java-based applications.

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