Instrumentation

John Dunnicliff

Introduction
This is the eleventh episode of GIN.
. . . One separate article this time, and a few items for the "column".

Fiber Optic Sensors

In GIN-6 (*Geotechnical News. December 1995, page 33*) I suggested that fiber optic sensors appear to be part of an emerging technology that is likely to play an increasing role in our specialty as the years go by. That issue of GIN included an article by Tsang and England, "Potential for Fiber Optic Sensing in Geotechnical Applications". In the September 23, 1996 issue of Engineering News Record, an article about fiber optic gages reported on bridge monitoring by Dr. Rola Idriss at New Mexico State University. I asked Dr. Idriss to expand on this article for GIN: here it is. Even though the two articles refer to monitoring of a reinforced concrete and steel structure, I don't think that the technology should be ignored by those of us involved with geotechnical instrumentation. However, a few words of warning. It seems that this technology is still at the research stage (particularly the readout instrumentation), and that engineering practitioners should wait a while before relying on fiber optic sensors for monitoring strain. As I hear/learn more, I'll tell. Watch this space!

Time Domain Reflectometry - A Short Course

In GIN-8 (*Geotechnical News. June 1996, page 36*) I talked about another emerging technology, time domain reflectometry (TDR). That issue included an article by Kevin O'Connor on applications of TDR for measuring volumetric water content, rock and soil deformation, water level, and contaminant transport. GIN-9 (*Geotechnical News. September 1996, page 29*) included an article by Kane and Beck on the use of TDR for monitoring unstable slopes, in which the authors indicated that this can, in appropriate situations, be a time-saving and economic replacement for inclinometers.

On Tuesday, July 15, 1997, the day prior to GeoLogan 97 at Utah State University in Logan, Utah, Kevin O'Connor (GeoTDR, Inc.) and Chuck Dowding (Northwestern University) will be conducting a full-day short course, with the following content:

- Geotechnical and Environmental Applications of TDR
- Hands-on Experience with a Variety of TDR Equipment
- Overview of TDR Probes and Installation Procedures
- Hands-on Experience with Remote Data Acquisition via Serial Communication
- Hands-on Experience with Remote Monitoring Using Data Logger System
- Visual and Quantitative Analysis of Data
- Interpretation of Waveform Changes

To register, obtain a registration form from: *Utah State University, Registration Services, Continuing Education Conferences, 5005 University Blvd., Logan, UT 84322-5005; or fax to (801) 797-0636 or (801) 797-0036.* I hope to see you there.

Warm-Up Time for Inclinometer Probes - A Reminder

For many years, most manufacturers of inclinometers have recommended that, after lowering an inclinometer probe to the bottom of a casing, it should be left there for at least ten minutes to achieve temperature stabilization, with the power on. There are two components of this: electrical warm-up and the need to achieve a uniform temperature throughout the mechanical components. The advent of memory-equipped readout units, which include a displayed "ready" symbol to indicate that readings are stable, appears to have led to some incorrect reading techniques.

I was recently involved in a court case during which the quality of inclinometer data became a significant issue, and adequacy of warm-up time was important. I asked Slope Indicator Company to recommend good practice: their recommendation is given below:

Slope Indicator's manuals recommend a warm-up time for inclinometer probes. Users are asked to power up the probe, lower it to the bottom of the casing, and then wait 5 to 10 minutes before starting the survey.

The warm-up period allows (1) the electronics of the probe to warm up and stabilize and (2) the mechanicals of the probe (wheels and housing) to match the temperature of the water in the casing.

What happens if the user omits the warm-up period? Readings taken during the first 5 or 10 minutes of the survey may contain an offset error, while later readings in the same survey will not be affected because the probe has warmed up. When readings are processed, the offset error may look like movement at the bottom of the borehole.

How severe are the errors? The offset error will be smallest when a warm probe (25° to 30° C) is lowered into 12° C water, which is the typical groundwater temperature in moderate climates. In such conditions, a shorter, 3 to 5 minute warm-up period will provide good results. The offset error will be greatest when the probe is cold. For this reason, be sure to allow at least 10 minutes warm-up time for cold probes.

Slope Indicator's Digitilt DataMate readout unit displays a graphic "ready" signal to indicate that both A and B axis readings are stable and ready to record.

The ready signal is not intended to monitor the warm-up period and should not be used for that purpose.
So here's the reminder. DON'T start reading as soon as the "ready" signal appears. Wait. In my view, a good instruction to reading crews is always to wait 10 minutes. It may save a lot of grief later!

Temperature Sensitivity of Earth Pressure Cells

We all should know that, if we fill a somewhat rigid container with liquid, then warm up the container, the liquid will expand and generally its pressure will increase. Now think of a hydraulic earth pressure cell, with a tube connecting the liquid to a pressure transducer. Temperature sensitive? Yes.

Most manufacturers provide a temperature calibration for the transducer, and a temperature sensor within the transducer. But what about a temperature calibration for the cell itself? Can't do. When temperature changes at an installed earth pressure cell, the "correction" depends on the extent of restraint given to the cell by its surroundings. Sure, we could develop a cell calibration by immersing the cell in water at various temperatures, but this doesn't model field conditions correctly, because during the calibration there's no restraint.

In a full-embedment installation, where cells are buried within fills, this issue is rarely important, because the cells are usually below the zone of temperature change. However, if contact earth pressure cells are exposed to changing ambient temperature, such as at the faces of mechanically stabilized earth walls, soil-nailed walls and other types of retaining walls, data accuracy can be severely downgraded, and there doesn't appear to be a viable method for temperature correction.

Some work on this issue is being done at UMass, Amherst, where a full-size retaining wall has been built, to model a bridge abutment, and instrumented with contact earth pressure cells. I hope to report on this work in a future issue of GIN, and to provide guidelines on how to deal with it. If any reader has experience with this, I'd welcome hearing about it.

Automatic Readout Unit for Magnet/Reed Switch Extensometers

GeoTechnical Systems Australia Pty., Ltd. has developed a prototype of an automatic readout unit for magnet/reed switch extensometers, termed an "automatic magnetic extensometer controller (AMEC)". The device is not yet fully field tested. However, a major potential user reports on being very impressed by a demonstration: "relatively simple, robust, easy to fix, with easy ability to revert to manual readings if needed".

I'll report more when I know more - it may be useful for readers who struggle with the "should we spend money on reading crews or on automated hardware?" question.

Systematic Approach to Planning Monitoring Programs Using Geotechnical Instrumentation

This message is for those of you who use Chapter 4 (title as above) in my instrumentation book. That was written 10 years ago, and in 10 years we all learn some things! In the next issue of Geotechnical News I'll include a "revised Chapter 4".

The Open Standpipe Piezometer - A History

How many of you think that Arthur Casagrande was the first person to use an open standpipe piezometer, also known as a *Casagrande piezometer*? (Casagrande, A. 1949, "Soil Mechanics in the Design and Construction of the Logan Airport," J. Boston Soc. Civil Eng., Vol. 36, No. 2, pp. 192-221. Reprinted in Contributions to Soil Mechanics, 1941-1953, Boston Society of Civil Engineers, Boston, pp. 176-205.) Not so: credit Daniel Bernoulli.

I've just been reading a remarkably readable book "Five Equations that Changed the World", which tells of Bernoulli's "Law of Hydrodynamic Pressure". He was trying to find a way of measuring the pressure of water flowing through a pipe, primarily as a means for measuring blood pressure in the human body.

In about 1730:

Bernoulli punctured the wall of a pipe and attached to this small hole one end of a glass straw. Allowing water to flow through the pipe as usual, he watched, waited, and then noted with elation that as the water flowed past the opening, a small column of water rose up in the glass tube and stopped at a certain height. He had done it! That height was a measure of the flowing water's pressure. If the water rose high up the glass tube, it meant that, at that point, the water pressure flowing within the iron pipe was large. Conversely, if the water barely rose up the glass tube, it meant that, at that point, the water pressure flowing within the iron pipe was small. And in all cases, happily, no water was spilled in making the measurements.

Yes, I know, I'm mixing up velocity head with pressure head, but I thought it made a good story. Seriously, this <u>is</u> a remarkable book. By Michael Guillen. The other four equations are:

- The Universal Law of Gravity: Isaac Newton
- The Law of Electromagnetic Induction: Michael Faraday
- The Second Law of Themodynamics: Rudolf Clausius
- The Theory of Special Relativity: Albert Einstein

My town librarian said "must reading for every high school student". You too?

Closure

Please send contributions to this column, or a separate article for GIN, to me: 16 Whitridge Road, South Natick, MA 01760. Tel. (508) 655-1775, fax (508) 655-1840.

Proost! (Holland).

(New readers, or readers with short-term memories, may wonder what that's all about. Each GIN so far has ended with a "toast", consistent with the international flavor of this magazine. My best source is a somewhat stained Tuborg beer mat, provided by Birger Schmidt, that has about 25 versions, so we have a long way to go before starting on repeats or changing the format!)

Highway Bridge Monitoring Using Optical Fiber Sensors

R.L. Idriss, A D. Kersey and M. Davis

Introduction

Currently, to monitor strain in a bridge, resistance strain gages (RSGs) are most commonly used. RSGs can be installed on site and connected by wires to computers and recorders located on or beside the structure. Quite often, the wire connections are difficult and time consuming to install and maintain. For large structures, there is also the added problem of increased electromagnetic noise due to the length of the wires. Fiber Bragg Grating Sensors offer an alternative to resistance gages.

What are Fiber Bragg Grating Sensors?

The Fiber Bragg Grating (FBG) sensor is a segment of an optical fiber that has been internally modified by exposure to ultraviolet light. With current fabrication technology FBG sensors are easily produced in existing telecommunications grade optical fiber through a side exposure technique. A typical configuration consists of exposing a small portion of the optical fiber to two interfering beams of ultraviolet light. This creates a small periodic modulation of the refractive index of the core of an optical fiber, with usually an index variation of only between 10^{-5} to 10^{-3}. Due to the periodic nature of the index perturbation only one optical frequency will resonate in the structure. Therefore, if broadband light is traveling in the core of the optical fiber, the incident energy at such a resonant frequency will be reflected back down the optical fiber, with the remaining optical spectra unaffected, as shown in Figure 1. The center wavelength of this resonance condition in a FBG can be expressed as:

$$\lambda_{\beta} = 2n_{eff}\Lambda \qquad (1)$$

where n_{eff} is the effective index of refraction of the core and Λ is the period of the refractive index modulation. The period can be adjusted by changing the relative angle of the two interfering ultraviolet beams to create gratings with different Bragg wavelengths. As can be seen by Eq. 1, any change in the periodicity of the refractive index modulation or the overall index of refraction will change the Bragg wavelength. Consequently, any temperature or strain induced effects on the FBG can be determined by the corresponding shift in the center Bragg wavelength, as illustrated in Figure 1.

If we look at strain induced shifts only and assume isothermal conditions, the change in λ_B is given by:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-p_e)\varepsilon \qquad (2)$$

where the strain over the length of the sensor is $\varepsilon=\Delta L/L$, and p_e is the effective photoelastic constant for the fiber (approximately 0.22 for silica glass).

Bragg gratings can be multiplexed via their inherent wavelength encoded properties by writing several gratings in-line in a fiber at different nominal Bragg wavelengths, as illustrated in Figure 2.

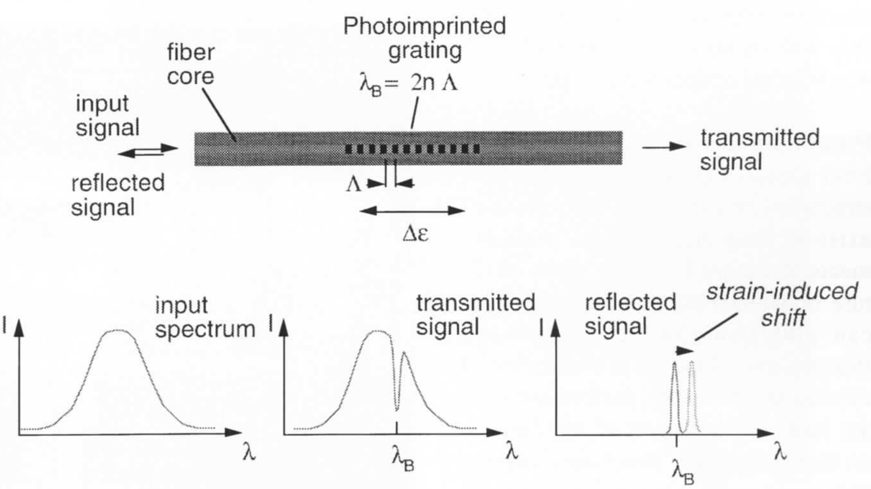

Figure 1: Operation of a FBG element as a wavelength-encoded strain sensor.

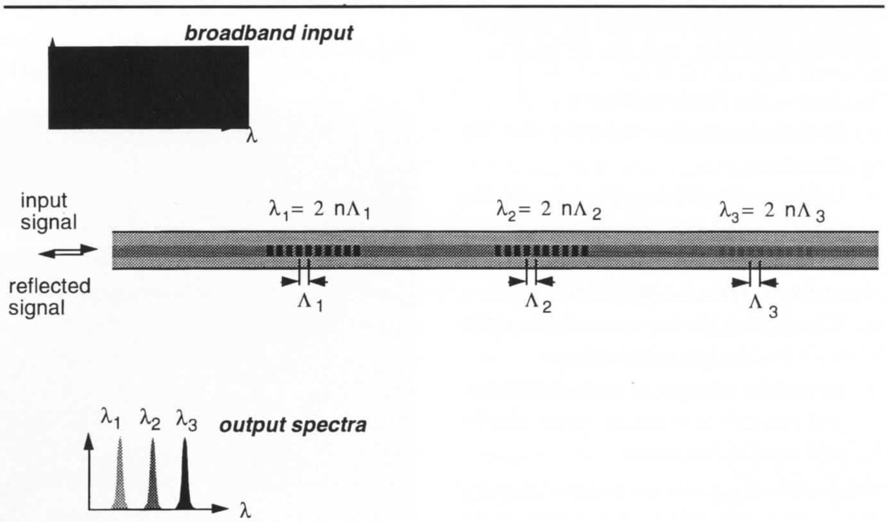

Figure 2: Wavelength-division multiplexing of in-line FBG elements.

Fiber optic sensors possess a number of unique advantages when compared to RSG sensors. These advantages include immunity to electromagnetic noise, and ease of multiplexing (merging of data from several channels into one channel) for multi-point strain monitoring.

Probably one of the most attractive features of optical fiber sensors is this inherent ability to serve as both the sensing element and the signal transmission medium, therefore greatly simplifying the instrumentation of large structures.

Fiber Bragg Gratings can easily be multiplexed (up to 100) along a single optical fiber string. The wavelength encoded nature of the output provides the basis for the multiplexing of these sensors. This can be realized by wavelength division multiplexing several sensors where each grating is "written" on the fiber with its personal Bragg resonance at a different optical wavelength.

Practical Applications

FBG sensors can be embedded in new structures, or bonded to the surface of existing structures. Strain measurements at critical locations in the structure, obtained from a monitoring system can give quantitative, simple and straightforward means of evaluating an existing structure, it's performance under load, and the effect of any damage on its capacity and structural integrity. This could result in better decision making, more efficient management and major cost savings.

An installed system can be designed as a versatile tool, that can be used to:

- Assess the loading history
- Define a baseline behavior for the structure
- Evaluate the effects of damage on the capacity and performance
- Assess the effectiveness of repairs and maintenance programs.
- Check the performance compared with the design assumptions
- Remotely monitor critical structures, and provide a warning when abnormal conditions occur.

The strain data generated can be directly incorporated in the inspection file and into life cycle management of the structure.

A Full Scale Smart Bridge

In a collaborative work between the Naval Research Laboratory (NRL) and New Mexico State University (NMSU) an FBG system was investigated for highway bridge monitoring and damage evaluation. The system, intended to complement existing bridge inspection methods, was designed and integrated at the construction stage in a full scale laboratory bridge. The test structure is a 40-ft simple span non-composite steel girders and reinforced concrete deck bridge (fig.3).

48 FBGs were used to monitor the bridge, with sensors embedded following a grid pattern in the slab, and attached to the bottom flange of the girders. RSG and FBG Sensors were placed side by side to compare results.

Figure 4 shows a photograph of the system in use. The instrumentation system had the capability to monitor 12 FBG sensors along each of 5 separate fibers for a total of 60 sensor elements.

The bridge was monitored during construction and curing of the slab. Baseline strain data were obtained for the intact structure, then damage was introduced in the form of a series of cuts imposed at mid-span of an exterior girder with the final cut resulting in a half depth fracture of the girder. The after-fracture response was monitored using the sensor system. Figure 5 shows the real time response of the FBGs located in the slab when the fracture was introduced.

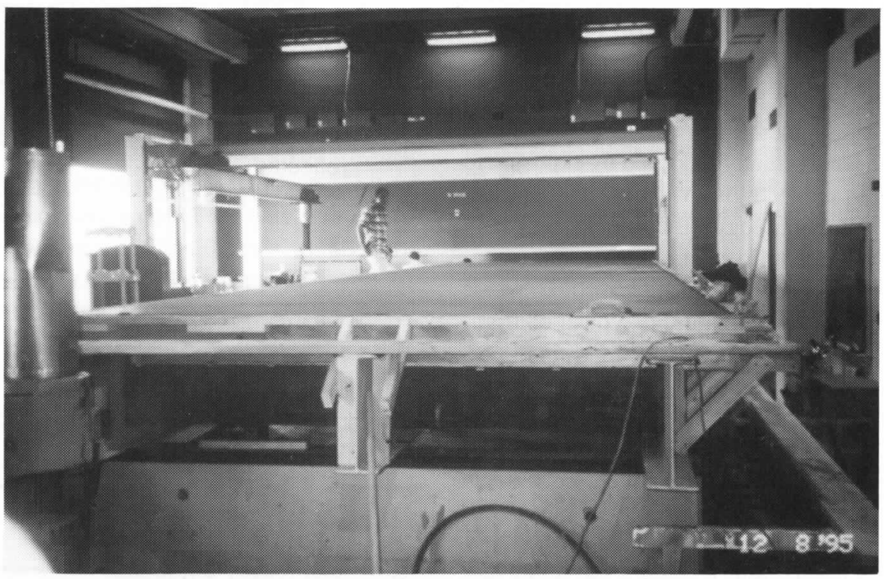

Figure 3. Laboratory Bridge

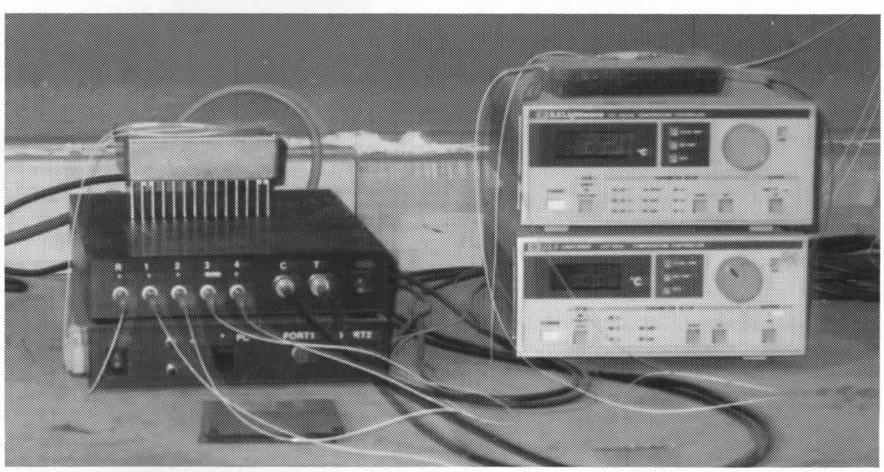

Figure 4. Data Acquisition System

Conclusions

Several conclusions can be drawn from this project:

- This work has successfully demonstrated the utility of fiber Bragg gratings for sensing of structural strain. The data obtained using the FBG sensor system and a conventional RSG system compared within 5%.
- The test results showed the monitoring system to be a very useful bridge diagnostic tool. When damage was introduced in the bridge, the monitoring system indicated that damage had occurred, along with the time and the location of the damage.

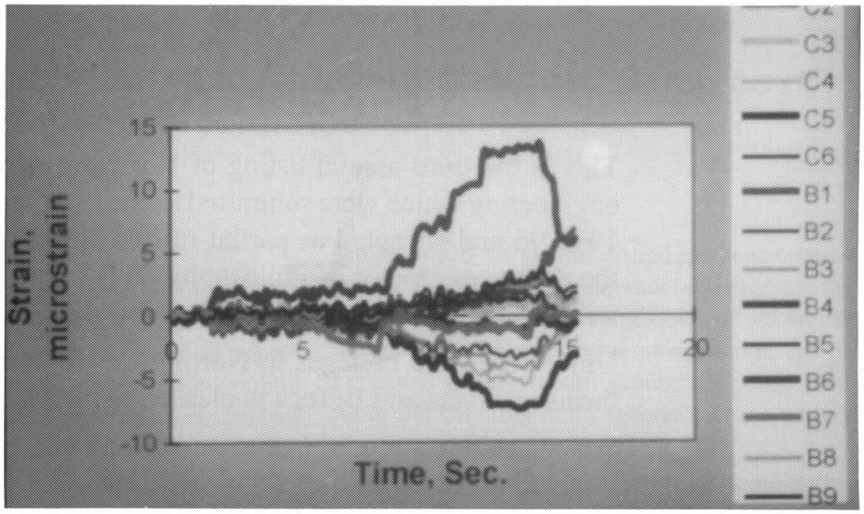

Figure 5. (a) Strain In The Slab At Fracture

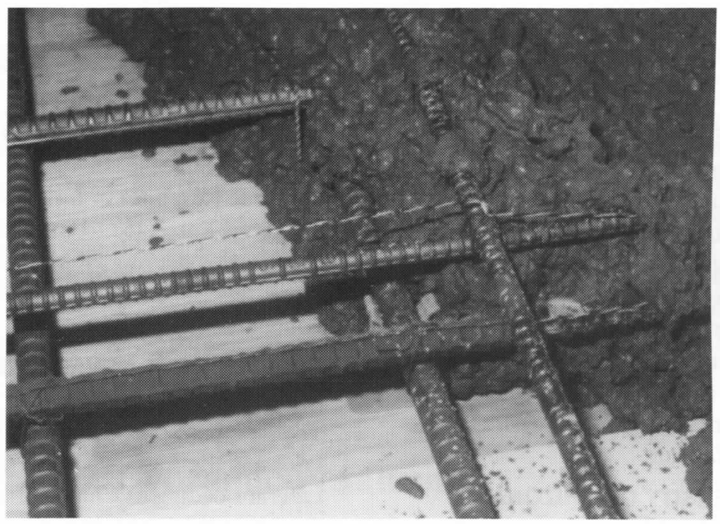

Figure 5. (b) Sensors In The Slab

Where is the Technology Going?

Further development work is required to improve several key aspects of this technology such as:

- Development of instrumentation systems that can interrogate large numbers of sensors, systems which can be left on-site and interrogated via a wireless link.
- Create improved, more rugged sensor assemblies, connecting fiber cables and instrumentation hardware to meet field conditions.
- Development of a suite of sensors for other parameters, such as extensometers, temperature sensors, crack-opening detectors, accelerometers, load cells, and pressure monitors (weigh-in-motion sensors), based on a common FBG sensor format.
- Development of applications to pavement and subgrade monitoring. In connection with an interagency agreement between the Corps of Engineers and the Federal Highway Administration the sensors are scheduled to be evaluated this year in test pavement sections at the Corps of Engineers Frost Effects Test Facility at Hanover, NH.

Acknowledgment

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