Combined static and dynamic monitoring of civil structures with long-gauge fiber optic sensors

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ABSTRCT

Long-gauge SOFO® sensors have been in use for the last 10 years for the monitoring of civil, geotechnical, oil & gas and other structures. More than 3500 sensors have been installed worldwide in a number of different structure types. The original demodulation system is based on low-coherence interferometry and is particularly suitable for the monitoring of long-term static deformations.
This paper reports the development and testing of a new sensing system based on Fiber Bragg Gratings and allowing the monitoring of both the static as the dynamic response of structures. The sensors are based on the well-proven SOFO packaging and allow the measurement of deformations over measurement basis of 2m, with a resolution of 1 microstrain and a frequency of 250 Hz. The system is insensitive to temperature variations, electromagnetic disturbances (electric power lines, lightning) and has demonstrated excellent long-term stability and durability. Each sensor also contains a temperature gauge, useful for the evaluation of the ambient parameters.

This contribution describes the FBG-based MuST system, its functional principles and its performances in laboratory and field tests. The field installations include the monitoring of concrete bridges.

INTRODUCTION

Rapid growth in demand for value-added techniques for health monitoring of structures has focused worldwide interest on optical fibers sensors as the provider of an effective solution to measurement problems [1]. Recent advances in measurement technology have demonstrated that fiber optic sensors are suitable for the monitoring of full-scale civil structures [2]. When installed on structures, these sensors allow for monitoring important parameters such as deformations, temperatures, pH values, and gas concentrations. Given the exceptional stability and the flexibility with which large structures can be instrumented with an optical fibre sensing network, [3,4] it can be reasonably expected that optical fibre sensors will become the backbone of measurement systems dedicated to monitoring the state of the infrastructure worldwide. Notwithstanding this enormous potential, present developments are far from fulfilling the promise that the fibre optics sensor technology holds in structural health monitoring.

In this context, the development of a long-gauge-length fibre optic sensor system, better known by the acronym SOFO®, can be considered as a significant achievement in the area of structural strain monitoring in civil engineering structures. The system has the potential of monitoring structures over long periods of time, and has been successfully embedded or surface-mounted in a variety of materials such as concrete, steel, and mortar. The sensors can have gauge length of up to 20 m and can measure deformations of up to 1% in elongation and 0.5% in shortening.

In many civil applications, the high frequency response and extremely long gauge-length of the SOFO system are not always necessary, but it would be beneficial to combine static and dynamic strain measurements as well as temperature measurements using a single demodulation unit. The use of sensors based on fiber Bragg gratings can provide an effective solution in these cases. Combining the well-proven SOFO packaging and MicronOptics swept laser interrogator, the MuST system constitutes a much needed complete monitoring system based on fiber Bragg grating sensors and including all components from sensors to data acquisition units to software. This allows, civil and structural engineers to benefit from this technology, without needing special training in fiber optics.

SYSTEM DESCRIPTION

The MuST system is composed of three sub-systems:

- Sensors for strain, deformation and/or temperature
- Reading unit for the demodulation of the sensor
- Software for data acquisition, management and analysis

Deformation sensors

The FBG deformation sensors are transducers that transform a static or dynamic distance variation into a change in reflected wavelength of a pre-stressed Fiber Bragg Grating that can be measured with SMARTEC's FBG reading units. The sensor is composed of active and passive parts. The active part contains the measurement fiber and measures the deformations between its two ends, transforming it into a wavelength shift of the Fiber Bragg Grating. The passive part is insensitive to deformations and is used to connect the sensor to the Reading Unit. In the passive part of the sensor, it is possible to install a loose Fiber Bragg Grating for temperature sensing and compensation.

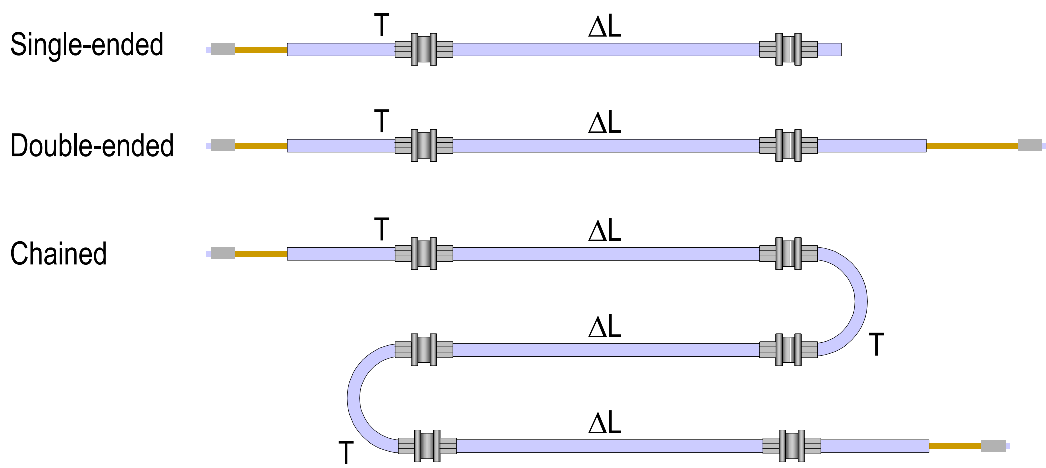

Figure 1 MuST Deformation sensors setups

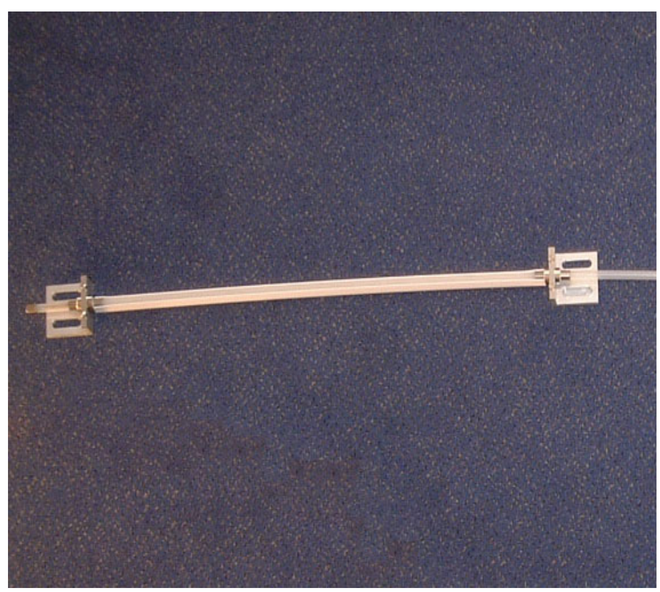

Figure 2 MuST deformation sensors installed in concrete and with L-brackets for surface installation.

The sensors are available in single-ended, double-ended and chained configuration (see Figure 1). It is possible to connect up to 5 full-range sensors (4 with temperature compensation). The sensors are terminated with E2000 connectors.
The sensors are based on the SOFO sensor packaging design and can be quickly and easily installed without affecting the construction schedule. They can be directly embedded in concrete and mortars, or surface mounted (see Figure 2).

The following table resumes the performances that have been obtained with these sensors:

Length of active zone (measurement basis)	0.25 to 2m
Length of passive zone (connecting cable)	1.4 m to 50 m
Pre-tensioning of the measurement fiber	0.5% of the length of active zone (others on special request)
Connecting cable protection options	Standard cable with protecting tube (recommended for embedding or surface mounting in protected conditions); Stainless steel protecting tube (recommended in harsh conditions or for length superior to 50m); Simple cable without protecting tube (recommended for laboratory conditions).
Measurement range	0.5 % in shortening, 0.75 % in elongation
Wavelengths for strain sensors (nm)	1520, 1530, 1540, 1550, 1560 at 0 strain (others upon request)
Strain resolution / accuracy	0.2 mẹ̃2 me (using SMARTEC's FBG reading unit)
Temperature measurement range	-40°C to +80°C
Operating temperature · Passive zone · Standard active zone · Special active zone (upon request)	 -40°C to +80°C -50°C to +110°C -50°C to +170 °C
Temperature resolution / accuracy	0.1 °C / 0.5 °C (using SMARTEC's FBG reading unit)
Wavelengths for temperature sensors	1521, 1523, 1525, 1527, 1529 nm at 20°C (others upon request)
Waterproof	5 bars (50 m deep in water), 15 bars upon request

Temperature sensors

The FBG Temperature Sensor String is a multi-point sensor designed for measuring temperatures at different locations along a single cable line. The sensing elements are Fiber Bragg Gratings that transform a temperature change into a change in reflected wavelength of a Fiber Bragg Grating.
The sensor is composed by an armored cable congaing 1 to 4 optical fibers (see Figure 3). Each fiber can contain up to 25 measurement points allowing a maximum total number of 100 measurement points. All sensors are measured simultaneously and in real-time (response time ca. 1s). The cable is available in three versions for ordinary temperatures, for high temperatures and for fire detection applications. The sensors are available in single-ended or double-ended configuration, and the sensors are terminated with E2000. The sensors can be quickly and easily installed without affecting the construction schedule. They can be directly embedded in concrete and mortars, or surface mounted.
This sensor is an interesting alternative to distributed sensing systems, in the cases where a reduced number of measurement points is required.

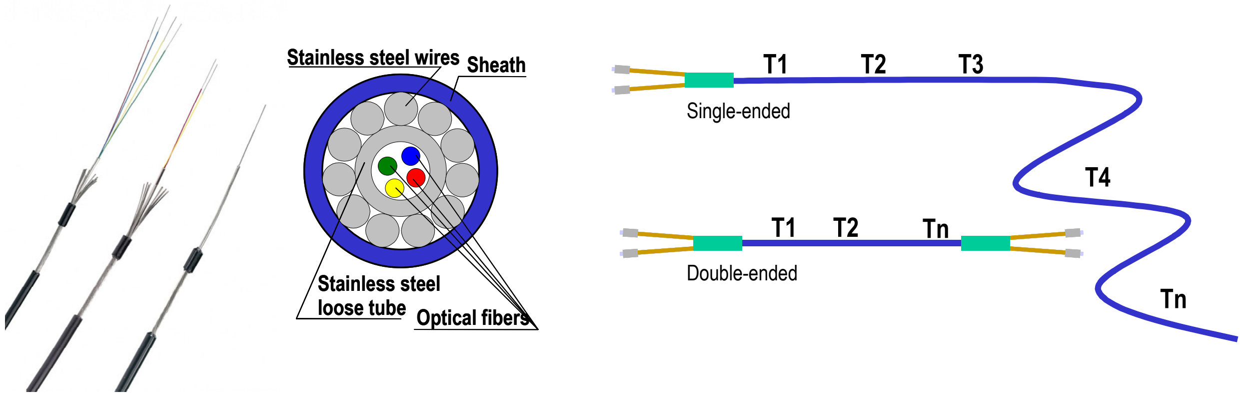

Figure 3 MuST temperature sensors design. The sensing fibers are encapsulated in an armored cable.

The performances of the MuST temperature sensing cables are summarized in this table:

	Ordinary temperature cable	**High temperature cable**	**Fire detection cable**
Components	Single mode optical fibres with FBG sensors, stainless steel loose tube and stainless steel armouring Option: Polyamide (PA) sheath	Single mode optical fibres, stainless steel loose tube and stainless steel armouring	Single mode optical fibres, stainless steel loose tube, stainless steel armouring and Flame Retarded Non Corrosive (FRNC) sheath
Temperature ranges for sensing cables	-55°C to +85°C in long-term -65°C to +160°C in short-term -60°C to +85°C storage	-65°C to +300°C in long-term -5°C to +50°C installation -65°C to +300°C storage	-40°C to +70°C in long-term -65°C to +300°C in long-term with damage to FRNC sheath -5°C to +50°C installation -40°C to +70°C storage
FBG configuration	Up to 25 gratings per fibre, interlaced	Up to 25 gratings per fibre, interlaced	Up to 25 gratings per fibre, interlaced
Temperature Resolution /Accuracy	0.02 °C / 0.2 °C	0.02 °C / 0.2 °C	0.02 °C / 0.2 °C
Max. number of fibres	4	4	4
FBG spacing	250 mm to 50 m	250 mm to 50 m	250 mm to 50 m
Wavelengths for sensors	1521 to 1569 in 2 nm steps	1521 to 1569 in 2 nm steps	1521 to 1569 in 2 nm steps
Cable diameter	2.2 mm without sheath 3.8 mm with PA sheath	3.5 mm	5.5 mm
Cable weight	17 kg/km without sheath 22 kg/km with PA sheath	36 kg/km	58 kg/km
Minimal bending radius	35 mm without tensile load 55 mm with tensile load	70 mm without tensile load 90 mm with tensile load	110 mm without tensile load 140 mm with tensile load
Maximal tensile strength at 20°C	1100 N in long-term 1600 N in short-term	2500 N in long-term 3500 N in short-term	2500 N in long-term 3500 N in short-term
Max. crush resistance	700 N/cm without sheath 1200 N/cm with PA sheath	300 N/cm	320 N/cm
Max. hydrostatic pressure		15×10^7 Pa (1500 bars)	

Measurement system

The MuST (Multiplexed Strain and Temperature Monitoring System) Reading Unit is a Fiber Bragg Grating (FBG) demodulator based on the proven Micron Optics engine and integrated in a weather tight steel housing designed for permanent installation in any structure that requires continuous monitoring. The MuST Reading Unit allows to simultaneously measure up to 4 sensor strings with up to 128 sensors per string (some restriction apply depending on the sensor type and measurement ranges). Through the use of an optional integrated optical switch, it is possible to monitor up to 16 sensors strings sequentially (4 by 4). The MuST reading unit is available in a ruggedized casing or in rack- mounted versions (see Figure 4).

The MuST Reading Unit was designed for surface installation and for specific project requirements. The FBG housing grants protection from water (IP 65), rodents, accidental crashes and a key lock grants protection against vandalism.

The MuST reading unit provides a high optical power, rapid measurement rate of up to 512 FBGs on four fibers. It has been designed with an advanced tunable laser capable of a maximum scan rate of 250 Hz over a 50 nm range. The user can choose scan frequencies from 1 to 250 Hz at fixed increments. The software allows averaging on up to 10'000 samples to further increase the resolution. The data is transmitted to the PC running the SOFO SDB software via a standard Ethernet connection. Remote connection is possible via modem or wireless LAN.

Figure 4 MuST Measurement system for permanent installation in field conditions.

The main characteristics of the MuST reading unit can ba summarized as follows:

Measurement resolution	0.2 pm, corresponding to approximately 0.2 με and 0.02 °C
Repeatability	2 pm, corresponding to approximately 2 με and 0.2 °C
Wavelength Range	1520 to 1570 nm
Maximum number of FBG sensors	32 per channel (64, 128 optional)
Available channel count	1, 2 or 4 for parallel simultaneous measurements 8 or 16 for sequential measurements
Power Dynamic range	15 dB (25 dB optional)
Measurement frequency	50 Hz, 100 Hz or 250 Hz for simultaneous channels, use of sequential switch reduces acquisition rate.
AC power supply	230 V 50 Hz / 110 V 60 Hz Auto detect
DC Power Supply	24 VDC
External connections	Ethernet RJ45 data connection, 1, 2, 4, 8 or 16 optical ports, power supply.
Dimensions	~ 500 mm x 600 mm x 210 mm
Weight	~ 25 kg
Temperature / Humidity	-20°C to 40 °C (with heating option) / 90% non condensing

Software

The SOFO SDB software is an integral part of SMARTEC monitoring systems. It is fully compatible with all SMARTEC monitoring systems and in particular is designed for the data acquisition, data representation and for the control of SOFO reading unit, MuST, SOFO Dynamic, SOFO optical switches, and other data acquisition devices. SOFO SDB is also used to store and manage data in database form. Figure 5 shows an example of data representation that can be obtained with the SDB software package.

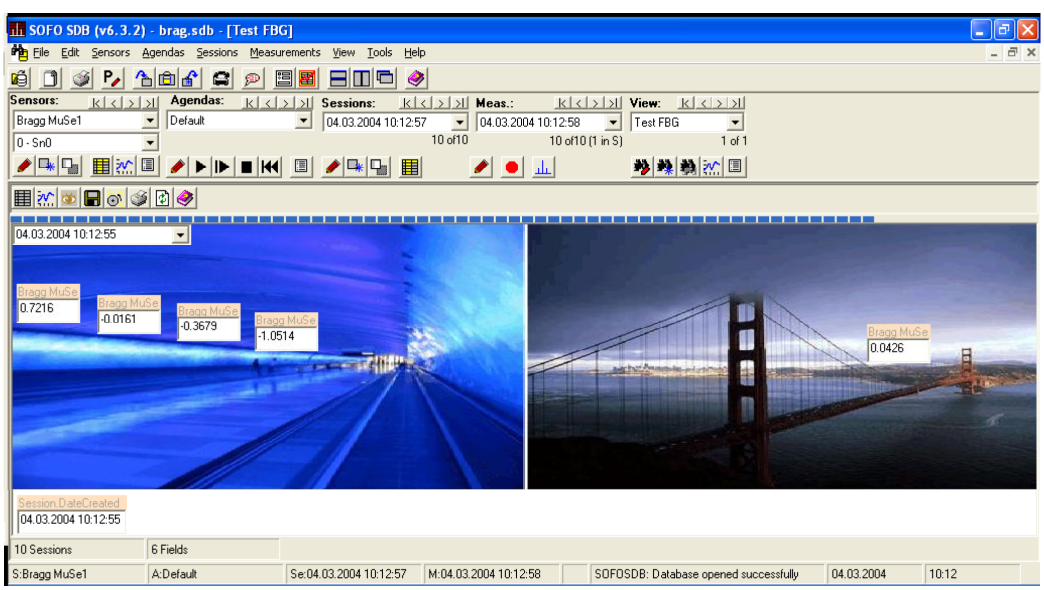

Figure 5 SDB View software for data visualization.

APPLICATION EXAMPLE: CHARACTERIZING SOILS THAT SUPPORT BRIDGE STRUCTURES

Researchers at the University of California at Los Angeles (UCLA) are working with the California Department of Transportation (CALTRANS) to study how lateral loads are transferred from soils to concrete-steel structures in an earthquake. Soils are traditionally modeled as a network of individual non-coupled springs. But these models are not sufficient to predict how, when and where a stucture might fail in an earthquake. CALTRANS wanted to know more. Specifically, they wanted to validate and/or improve upon widely-used soil mechanics data maintained by the American Petroleum Institute.

CALTRANS teamed with geotechnical engineers from UCLA to build a testbed where bridge stacks are tested to failure. The basic premise is that as the concrete bends, engineers can deduce how the soils are acting upon the structure. In this case, strain is measured, curvature is calculated from the strain, and the spring constants of the soils are indicated by the curvature.The test shaft eventually forms a plastic hinge when concrete reaches a critical strain. Electrical sensors (linear variable displacement transducers (LVDTs)) are attached to the reinforcing steel bars (rebar) in the structure. But the rebar tends to slip relative to the concrete as failure begins. FBG sensors are embedded in the structure so that they accurately measure the strain in the concrete even after the rebar begins to plastically deform. The FBG sensors, in a special package designed by SMARTEC SA, are suspended in position while the concrete is poured around them.

Figure 6 Bridge stack being prepared for destructive test, sensors installed on rebars.

Results of the first test (Figure 6) are still being developed as statistical analyses are performed on the test data [4]. Visual inspection of the FBG sensors and initial review of the data show that the optical sensors performed well. Early results are encouraging enough that a second test with more sensors is being prepared at the time of this writing.

CONCLUSIONS

The monitoring of new and existing structures is one of the essential tools for a modern and efficient management of the infrastructure network. Sensors are the first building block in the monitoring chain and are responsible for the accuracy and reliability of the data. Progress in the sensing technology can therefore be produced by more accurate measurements, but also from systems that are easier to install, use and maintain. In the recent years, fiber optic sensors have moved the first steps in structural monitoring and in particular in civil engineering. Different sensing technologies have emerged and quite a few have evolved into commercial products. This paper presented a complete system based on fiber Bragg grating sensors and useful for the static and dynamic monitoring of civil structures. The sensors can be embedded or surface mounted on new and existing structures. The reading unit can perform both static, long-term measurements as dynamic analysis at up to 250Hz frequency. Finally the software allows the management and publication of the resulting data.

The presented application example shows how the MuST system can be effectively used for the monitoring of a massive concrete structure and to study its interaction with the ground under earthquake actions.

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