Distributed Fiber-Optic Sensing and Integrity Monitoring

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Structural health monitoring is a process meant to provide accurate and real-time information concerning structural condition and performance. Needs for structural health monitoring in the past two decades increased rapidly, and these needs stimulated the development of various sensing technologies. Distributed optical-fiber sensing technology has opened new possibilities in structural monitoring. A distributed deformation sensor (sensing cable) is sensitive at each point of its length to strain changes and cracks. Such a sensor practically monitors a one-dimensional strain field and can be installed over the entire length of the monitored structural members (suspension cables, bridge girders, tunnel vaults, dam basis, etc.). Therefore, the sensor provides for integrity monitoring, that is, direct detection, characterization (including recognition, localization, and quantification or rating), and report of local strain changes generated by damage. An integrity monitoring principle for long bridges and tunnels is developed. Various distributed sensing techniques are summarized, and their potential for the use in integrity monitoring is compared. Finally, the first large-scale, actual on-site application is briefly presented.

The aging civil infrastructure of the United States is identified by several institutions [e.g., FHWA (*1*); TRB (*2*); and the National Institute of Standards and Technology (*3*)] as in critical need of improvement and renovation. In 2004, 77,796 U.S. bridges were identified as structurally deficient and another 80,632 as functionally obsolete (*1*). The rehabilitation cost for bridges in 2004 was $12.4 billion, and the cost to maintain highways and bridges for the period 2005 to 2024 is estimated to be $78.8 billion (*1*). The collapse of the I-35W Minneapolis Bridge is a sad reminder of the catastrophic consequences of structural failure: loss of 13 lives, injuries to 145 people, and unavailability of the river crossing generated economic losses of $400,000 per day for road users. In addition, losses for the Minnesota economy were estimated to be up to $17 million in 2007 and up to $43 million in 2008 (*4*). The cost of rebuilding the bridge was approximately $234 million (*5*).

Many structures of critical significance to the U.S. economy are approaching the end of their lifespan, and it is necessary to determine and observe their condition to mitigate risks, prevent disasters, and plan maintenance activities in an optimized manner. A present-day bridge must be able to generate and communicate information concerning the changes in its structural health condition and potential damage or deterioration induced by environmental degradation, wear, and episodic events such as earthquake or impact, to responsible operators and decision makers, in-time—automatically or on-demand. This must be done reliably as well. To achieve these requirements, a modern bridge should be equipped with a "nervous system," a "brain" and "voice lines," that is, with a structural health monitoring (SHM) system that is continuously in operation and able to sense structural conditions of the bridge. The system should be able to automatically detect the damage, characterize it (recognize, localize, and quantify or rate), and report it, providing important input for bridge managers.

The information obtained from monitoring is used to plan and design maintenance activities, increase safety, verify hypotheses, reduce uncertainty, and widen the knowledge concerning the structure being monitored. SHM helps prevent the adverse social, economic, ecological, and aesthetic impacts that may occur in the case of structural deficiency. It is critical to the emergence of sustainable civil and environmental engineering.

DAMAGE DETECTION

The standard monitoring practice is based on the choice of a reduced number of points, supposed to be representative of the structural behavior, and their instrumentation with discrete sensors, short-gage or long-gage. If short-gage sensors are used, the monitoring gives interesting information on the local behavior of the construction materials, but it might miss behaviors and degradations that occur at locations that are not instrumented. Using long-gage sensors, it becomes possible to cover the significant volume of a structure with sensors enabling a global monitoring of it, that is, any phenomenon that has an impact on the global structural behavior is detected and characterized. However, reliability of detection and characterization of damage that occurs in the locations far from the sensors remains challenging, since it depends on sophisticated algorithms whose performance is often decreased due to various influences that may mask the damage, such as high temperature variations and load changes, and outliers and missing data in monitoring results (*6*).

Distributed sensing technology offers solutions for improved and reliable damage detection. The qualitative difference between the monitoring performed using discrete and distributed sensors is the following: Discrete sensors monitor strain or average strain at discrete points, while the distributed sensors are capable of one-dimensional (linear) strain fields monitoring. A distributed sensor can be installed along the whole length of a structure, and in this manner, each cross-section of the structure is practically instrumented. The sensor is sensitive at each point of its length, and it provides for direct damage detection, avoiding the use of sophisticated algorithms. In this manner, integrity monitoring of structure can be reliably performed.

In this paper, various distributed sensing techniques are summarized, and their potential for the use in integrity monitoring is

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compared. An integrity monitoring principle for long bridges and tunnels is developed and presented. Finally, the first large-scale actual on-site application is briefly presented.

DISTRIBUTED FIBER-OPTIC TECHNOLOGIES

Distributed Sensing

A distributed sensor (or sensing cable) can be represented by a single cable that is sensitive at every point along its length. Hence, one distributed sensor can replace thousands of discrete sensors. Since the cable is continuous, it provides for monitoring of one-dimensional strain field. Moreover, it requires single connection cable to transmit information to the reading unit, instead of a large number of connecting cables required in the case of wired discrete sensors. The reading unit is commonly placed on the structure or very close to it, but if necessary (e.g., if electrical power is not available at the structure), it can be placed as far as a few kilometers from the structure. The data can be transmitted from the reading unit to the end user with the use of common wired or wireless telecommunication lines (phone lines, Internet). Finally, distributed sensors are less difficult and more economic to install and operate. An illustrative comparison between structures equipped with distributed and discrete sensors is shown in Figure 1 (this schematic drawing does not refer to the actual case).

Distributed Sensing Technologies

There are three main principles for distributed sensing in the domain of fiber-optic sensors: Rayleigh scattering (*7*), Raman scattering (*8*), and Brillouin scattering (*9*). Rayleigh scattering for strain monitoring is still under development. Raman scattering allows only temperature monitoring; thus, more details are given on Brillouin scattering, which allows both strain and temperature monitoring.

Brillouin scattering occurs because of an interaction between the propagating optical signal and thermally excited acoustic waves in the gigahertz range present in the silica fiber, giving rise to frequency-shifted components (*9*). It can be seen as the diffraction of light on a dynamic grating generated by an acoustic wave (an acoustic wave is actually a pressure wave that introduces a modulation of the index of refraction through the elasto-optic effect). The diffracted light experiences a Doppler shift, since the grating propagates at the acoustic velocity in the fiber. The acoustic velocity is directly related to the density of the medium that is temperature and strain dependent. As a result, the so-called Brillouin frequency shift carries the information about the local temperature and strain of the fiber.

Both spontaneous (*10*) and stimulated (*11, 12*) Brillouin scattering can be used for sensing purposes. The active stimulation of Brillouin scattering is achieved by using two optical light waves. In addition to the optical pulse, usually called the pump, a continuous wave optical signal, the so-called probe signal, is used to probe the Brillouin frequency profile of the fiber. The interaction leads to a larger scattering efficiency, resulting in an energy transfer from the pulse to the probe signal and an amplification of the probe signal.

A monitoring system based on stimulated Brillouin scattering is less sensitive to cumulated optical losses that may be generated in sensing cable due to manufacturing and installation. Also, it allows for monitoring of exceptionally large lengths (*13*); for example, in the case of strain monitoring, a single reading unit with two channels can operate measurement over lengths of 10 km, while in the case of temperature monitoring, lengths of 50 km can be reached. Remote modules can be used to triple the monitoring lengths. That is why the monitoring system based on stimulated Brillouin scattering technology was selected for the application presented in this paper.

Sensing Cables

The majority of effort in the domain of distributed sensing was employed in the research and development of the reading units, while much less effort was employed to perfect the distributed sensors. Consequently, only a few types of distributed sensors for strain monitoring have been under development, and they are at different advancement stages. When strain sensing is required, the optical fiber must be bonded to the host material over the entire length. The transfer of strain should be complete, with no losses due to slipping. Therefore, an excellent bond between the strain-sensing optical fiber and the host structure must be guaranteed. To allow such a good bond, the optical fiber is integrated within a cable-like shaped material, and integration procedures practically determine the performances of the sensor. The authors of this paper participated in sev-

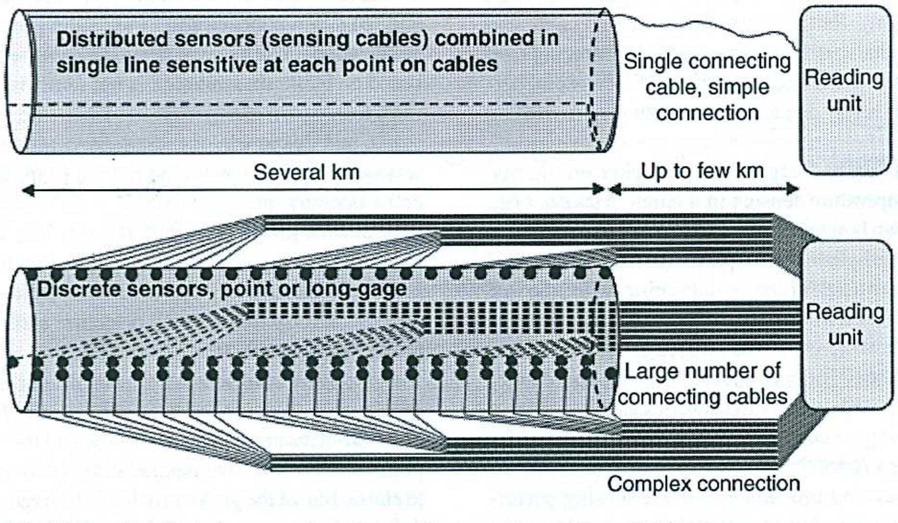


FIGURE 1 Distributed versus discrete monitoring: schematic comparison.

TABLE 1 Comparison of Distributed Strain Sensing Cables

	Strain Measurement Long-Term Performance						
Cable Type	Low Strain	High Strain	Wide Crack (damage) Performance	Fragility	Maximal Length of Cable per Channel	Applied on Large Structures	Approx. Cost (US$/m)
0.9 mm (⅓ in.)	Good	Moderate?	Poor?	Very high	Some km?	No	0.30
Tape	Very good	Very good	Very good	Moderate	<0.3 km	Yes	23.00
Ribbon	Good	Moderate?	Good?	Low	Some km?	No	30.00
Profile	Good	Moderate?	Good?	Low	4–6 km	No	18.00

NOTE: ? = Information not available.

eral successful developments of distributed sensors, which are briefly presented in this section, along with the work of other researchers.

Acrylate-coated optical fiber was embedded in the cylindrical plastic coating cable (*14*) with a typical diameter of 0.9 mm. This sensing cable has good sensing performance for lower levels of measured strain, and it has considerably low costs (about 30 cents/m). However, it is delicate to install due to fragility (*14*). Thus, costs of installation and protection can be elevated. The use of acrylate-coated fibers can moderate its long-term performance at higher strain levels, since slipping between the coating and the optical fiber can occur; consequently, the strain transfer from the structure to the optical fiber can be compromised.

Polyimide-coated optical fiber is embedded within the thermoplastic composite tape in a manner similar to the reinforcing fiber integration in composite materials (*15*). The typical cross-section width of the tape is in the range of 10 to 20 mm, while the thickness of the tape can be as low as 0.2 mm. The sensing tape was applied to an underground pipeline, concrete dam, and steel bridge (*16*). Further research was performed on this sensor, to develop a method for detection and localization of cracks (*17*). This sensor had shown very good performance in regard to high strain measurements and installation, but it features relatively large optical losses generated during the manufacturing process. Consequently, it suffices for monitoring of relatively short lengths (typically few hundreds of meters per channel). The cost of this sensor is approximately $23/m.

Four acrylate-coated optical fibers were integrated in a strong nylon ribbon reinforced with steel wires, and then they were employed in-field in a geotechnical application (*18*). This sensing cable has a good sensing performance for low strain levels, but it has elevated production costs (~$30/m). Surface installation of this cable can present some difficulties due to stiffness provided by reinforcing steel wires. The use of acrylate-coated fibers can moderate long-term performance at higher strain levels due to slipping between the coating and the optical fiber.

Several optical fibers can be integrated in a thicker profile that combines strain and temperature sensors in a single package (*19*). This sensor consists of two bonded and two free single-mode optical fibers embedded in a polyethylene thermoplastic profile. The bonded polyimide-coated fibers are used for strain monitoring, while the free acrylate-coated fibers are used for temperature measurements and to compensate for temperature effects on the bonded fibers. For redundancy, two fibers are included for both strain and temperature monitoring. The size of the profile makes the sensor easy to transport and install by fusing, gluing, or clamping. The sensor is designed for use in environments often found in civil, geotechnical, and oil and gas applications. This sensing profile has a good sensing performance. It features significantly lower optical losses, and it can be used for monitoring of considerably larger lengths, typically of several kilometers per channel. The cost of this sensing cable is $18 m. The performance of the four different distributed strain sensing cables is summarized in Table 1.

Commercially available distributed monitoring systems are expensive; their use for monitoring purposes is justified in cases where a large part of structure is to be monitored or an important impact on society is generated by structural malfunction, or simply where no other technology can fulfill the aims of monitoring.

INTEGRITY MONITORING PRINCIPLE

Distributed optical-fiber sensing technology based on the Brillouin scattering effect has opened up new possibilities in structural monitoring. A distributed deformation sensor is sensitive at each point of its length to strain changes and cracks. Such a sensor can be installed over the whole length of the monitored structural member. Therefore, it provides for direct detection and localization of local strain changes generated by damage. The principle of integrity monitoring is given in Figures 2 and 3 (*16*).

If no damage is present on the structure, the distributed sensing cable will provide with average strain measurement at each point, where the strain is averaged over the length called spatial resolution (typically 1 m). Spatial resolution is an adjustable parameter of the distributed monitoring system. At the position of damage-induced local strain change, the sensing cable actually provides with the following information: (*a*) the average strain value over the length of spatial resolution without taking into account the local strain change and (*b*) strain concentration indication (i.e., damage detection and localization). The average strain measurement of distributed sensing based on Brillouin scattering is not sensitive to local strain changes; thus, local strain changes are not taken into account while averaging strain, and that is why the strain concentration indication algorithm was developed. To avoid the rupture of the sensing cable in case of crack opening, the sensor is designed to delaminate from structure over a short length (typically 0.1 m). The simple delamination of sensing cable (e.g., due to bad gluing to the structure) will not be confused with damage since no strain concentration is present on it. The detailed description of crack detection algorithm and delamination principle is given in Ravet et al. (*17*).

Since distributed sensors provide for one-dimensional strain field monitoring, they can be used with twofold purpose: for integrity monitoring, as presented previously, and for curvature and deformed shape monitoring. Two parallel distributed sensors installed parallel to elastic line of the girder provide for curvature monitoring (*16*), and deformed shape can be then determined by double integration of

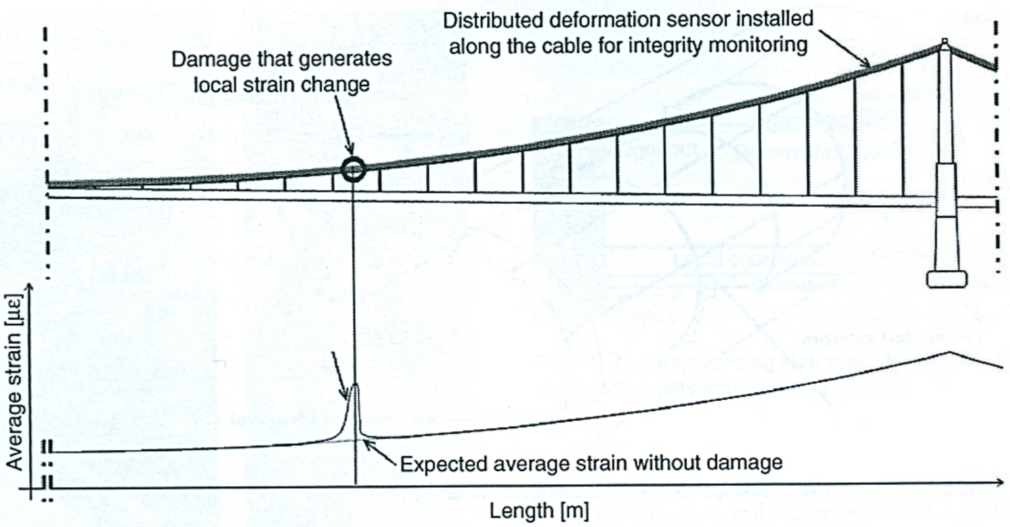


FIGURE 2 Schematic representation of integrity monitoring (*16*).

curvature. An example of a structure equipped with parallel sensors is presented in Figure 3.

The average curvature distribution is for undamaged structure determined from average strain measurements and geometrical properties of sensing cable (*16*), while deformed shape can be calculated by double integration of curvature along the elastic line of the monitored structure (*20*). If damage is present on the structure, it will be detected and localized by extracting the local strain effect from the optical system, using a special algorithm developed for the purpose. But the average strain and average curvature at the damage location may not be accurately determined, and neither may the deformed shape close to the damage.

Bridge structural members that are typical candidates for integrity monitoring are the long beams, girders, decks, and suspension cables. A similar concept can be applied for tunnels, as schematically presented in Figure 4 (*16*). Distributed sensors are installed on the walls and vaults of the tunnel in longitudinal and tangential directions. These sensors provide for crack detection and localization, and for detection of local average strain changes due to damage. In addition, the distributed sensors provide for average strain distributions and temperature monitoring. With adequate installation, they can also replace the multipoint extensometers in the soil (see distributed sensors in boreholes in Figure 4) and can be used for fire detection if temperature-sensing cable used for

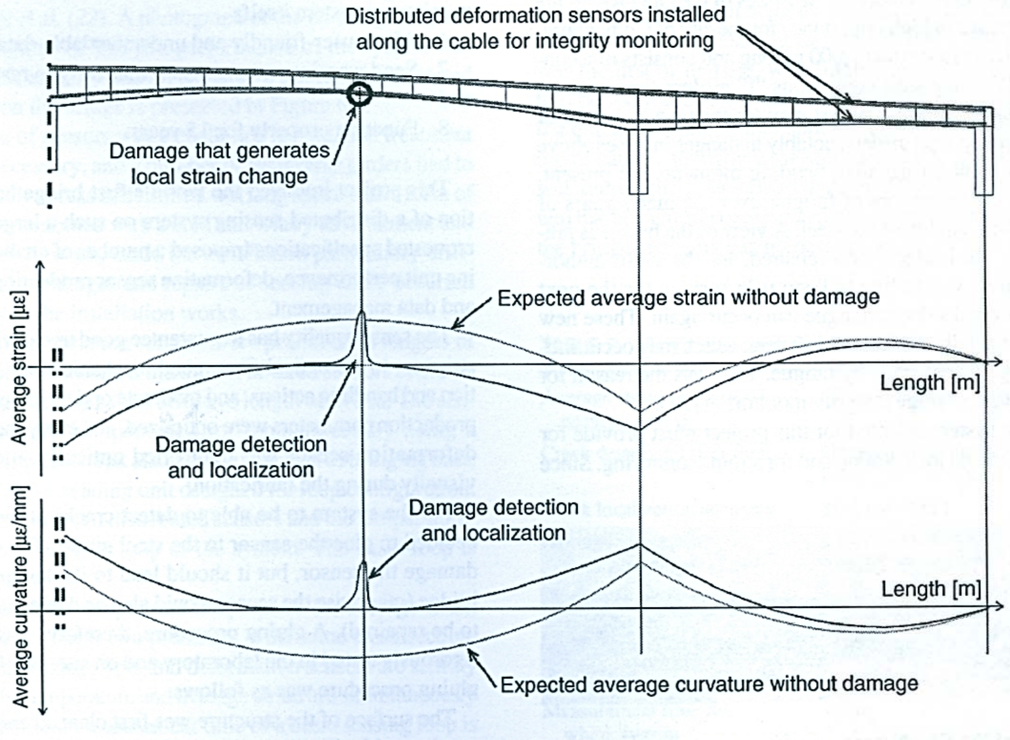


FIGURE 3 Schematic representations of simultaneous integrity monitoring and curvature monitoring (*16*).

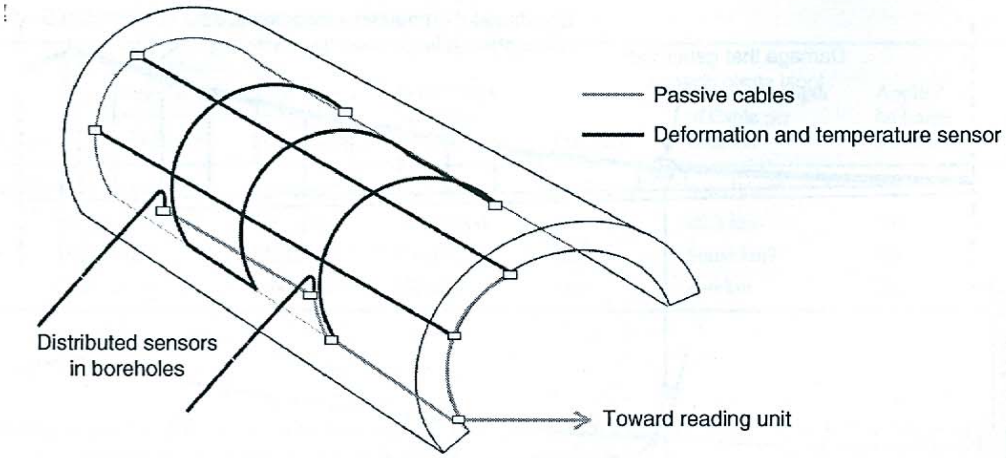


FIGURE 4 Schematic example of tunnel integrity monitoring (*16*).

temperature compensation is packaged and installed in accordance to fire detection norms. Taking into account the number of monitoring parameters and tunnel dimensions, distributed sensing techniques offer convenient, cost-effective, and multipurpose instrumentation.

Integrity monitoring was first applied at a relatively limited scale (*16*) on dams (250-m long joint) and pipelines (600-m long segment). Good results lead to the first large-scale application on bridges, as presented in the next section.

ON-SITE APPLICATION OF INTEGRITY MONITORING

The Götaälvbron, the bridge over the Gota River, was built in the 1930s and is now more than 70 years old (*16*). Being one of the three communication lines that connect the two sides of the Gota River, the Götaälvbron is a bridge of high importance for the city of Gothenburg, Sweden. The bridge is more than 1,000 m long and consists of a concrete slab poured on nine steel continuous "I" girders supported on more than 50 columns. During the last maintenance work, a number of cracks were found in steel girders, notably in flanges in zones above columns where significant negative bending moments are present. These cracks are consequences of fatigue over the many years of service and mediocre quality of the steel. A view of the bridge is presented in Figure 5. The bridge is now repaired, and the traffic authorities (trafikkontoret) would like to keep it in service for the next 15 years, but new cracks due to fatigue can occur again. These new cracks can lead to the failure of cracked girders, which may occur suddenly since damage is generated by fatigue. That was the reason for performing continuous bridge integrity monitoring (*21*).

The monitoring system selected for this project must provide for both crack detection and localization and for strain monitoring. Since the cracks can occur at any point or in any girder, the monitoring system should cover the full length of the bridge. These criteria have led the traffic authorities to choose a truly distributed fiber-optic monitoring system based on stimulated Brillouin scattering and tape sensor (see Table 1).

FIGURE 5 View of the Götaälvbron.

To summarize, the monitoring aim has been to perform long-term integrity monitoring of the bridge. Split into single tasks, the following specifications of the monitoring system have been requested:

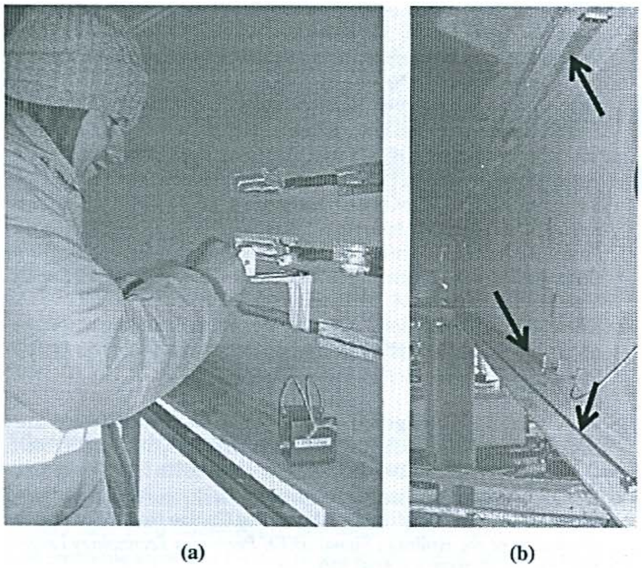
1. Detect and localize new cracks that may occur due to fatigue;
2. Detect unusual short-term and long-term strain changes;
3. Detect cracks and unusual strain changes over the full length of five girders (in total 5 km);
4. Perform one measurement session every 2 h;
5. Perform self-monitoring, that is, detect malfunctioning of the monitoring system itself;
6. Allow user-friendly and understandable data visualization;
7. Send warning messages automatically to responsible entities; and
8. Function properly for 15 years.

This project involved the world's first bridge having an application of a distributed sensing system on such a large scale. Thus, the requested specifications imposed a number of challenges to the reading unit performance, deformation sensor production and installation, and data management.

The sensor quality has to guarantee good transfer of strain from the structure to the optical fiber, good mechanical resistance to installation and handling actions, and moderate optical losses. That is why the production parameters were optimized, and every meter of distributed deformation sensor was controlled optically, mechanically, and visually during the fabrication.

For the system to be able to detect cracks at every point, it was decided to glue the sensor to the steel girder. The crack should not damage the sensor, but it should lead to its delamination from the bridge (otherwise the sensor would also be damaged and would need to be repaired). A gluing procedure, therefore, was established and rigorously tested in the laboratory and on site. Briefly described, the gluing procedure was as follows:

The surface of the structure was first cleaned and dried. Then the sensing cable (tape sensor) was bonded to self-sticking aluminum



(a) (b)

FIGURE 6 Photographs of activities for the bridge: (*a*) on-site test of distributed sensor gluing procedure and (*b*) installed sensor for full performance tests.

tape (which is wider than the tape sensor) on one side while the other side of the tape sensor was covered with the glue. Finally, the sensor was glued along with aluminum tape to the structure. Aluminum tape keeps the sensing cable in place until the glue is hardened and provides for long-term protection. Laboratory tests of the glue consisted of shear and peel tests at room temperature and after temperature cycling. On-site tests consisted of similar tests performed immediately after installation and 3 months after the installation. Separate tests were performed in laboratory and on-site to determine delamination in case of crack occurrence. More details concerning the tests are found in Glisic et al. (*22*). A photograph of the on-site gluing test is presented in Figure 6*a*. The full performance of the system was also tested in the laboratory and on site, and a photograph of tested sensors installed on the bridge is presented in Figure 6*b*.

The installation of sensors was a challenge itself. Good treatment of surfaces was necessary, and a number of transverse girders had to be crossed. Difficult access and limited working space in the form of a lift basket, often combined with a cold and windy environment and sometimes with night work, made the installation particularly difficult. Thus, several breakages and repairs of sensing cable occurred and slightly delayed the installation works.

The distributed deformation sensors were produced in lengths of 90 m. Owing to optical losses, a maximum of three sensors could be serially connected, making a total effective length of 270 m. The sensor measurements are compensated for temperature by using a temperature-sensing cable that also has the function of bringing back the optical signal to the reading unit designed for loop configuration. The three serially connected distributed sensors and the temperature-sensing cable create a basic loop of the system. The basic loop is presented in Figure 7.

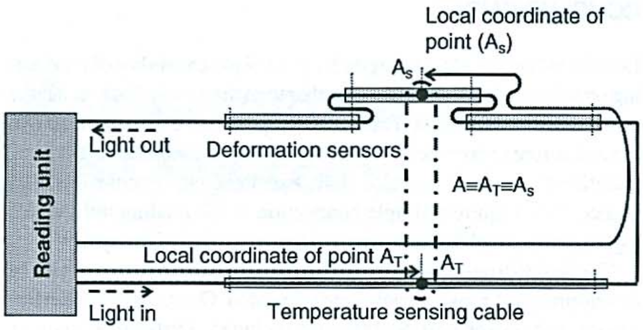


FIGURE 7 Basic sensing loop consisting of three 90-m SMARTape sensors and temperature-sensing cable.

Point A_T was used to compensate temperature for average strain measured at Point A_s. These two points are at the same cross-section. Since temperature-sensing cable and deformation sensors are serially connected, both the temperature and average strain are simultaneously measured. The maximal measurement time of a basic sensing loop is less than 7.5 min, and there is a total of 32 sensing loops installed on the bridge. Since two reading units were used, two sensing loops were read simultaneously, and total measurement time for whole system is less than 2 h.

The measurements were performed with a distance sampling interval of 0.1 m, making the total number of monitoring points bigger than approximately 100,000: 50,000 for noncompensated strain and another approximately 50,000 for temperature. Special software for data handling, crack detection, and short-term and long-term strain analysis has been developed.

The same software controls functioning of the reading units. In the case of crack detection, detection of unusual strain variation, or detection of a malfunction in the system, warnings are sent to responsible entities in the form of an e-mail and short service message, providing for redundancy in communication. On receipt of messages, the responsible entities are supposed to acknowledge they received the messages and to proceed according to established procedures. The final performance of the system is summarized in Table 2.

The system was installed in two periods: the north side of the bridge in the period of summer to fall 2006, and the south side of the bridge in the period spring to summer 2007. Since this application was the first of its kind, with limited previous experience, a 1-year trial period was allowed for detection of problems (typically improving quality of optical-fiber splices, repairs of broken sensors, rerouting of cables, debugging the software, etc.). The site acceptance test was successfully performed in August 2008, and since then the system has been in full operation. To the best of the authors' knowledge, the bridge currently has no new cracks.

TABLE 2 Performance of System

Average strain resolution–accuracy–range	±3 με/±21 με/–2,500 με to +6,000 με
Crack detection lower limit	Opening of 0.5 mm over 100 mm (~0.02 in. over 4 in.)
Crack localization accuracy	±0.1 m (~4 in.)
Average temperature accuracy–range	±1°C/–30°C to +85°C (±1.8°F/–22°F to +185°F)
Spatial sampling interval–spatial resolution	0.1 m/1 m (~4 in./~3 ft 3 in.)
Bridge length equipped with sensors	~5,000 m = 5 × ~1,000 m (~3.1 mi = 5 × ~0.62 mi)
Measurement time for whole system	< 2 h

CONCLUSIONS

Distributed sensing technologies have a unique capability of monitoring one-dimensional strain fields rather than the simple strain at a large number of discrete points. These technologies can be installed throughout a structure to provide for direct damage detection, localization, and quantification. In addition to their excellent measurement performance, they require a simple connection to the reading unit, which significantly simplifies the work related to cabling of the system.

Various distributed sensing technologies and advancements in the development of sensing cables are presented. Overall system performance and sensor cost analysis are included. Distributed sensory systems are expensive. However, their use is justified when a large part of a structure is monitored, or when structural malfunction may have a large impact on the society, or where no other technology can satisfy the objectives of monitoring.

Integrity monitoring based on distributed sensing in bridges and tunnels is presented. Besides the reliable direct damage detection and characterization, depending on the sensor layout, various parameters can simultaneously be monitored, such as curvature distribution and deformed shape of the bridges, and displacements and fire detection in tunnels.

A truly distributed fiber-optic monitoring system, based on the stimulated Brillouin effect, is for the first time applied on a large-scale integrity monitoring of the Götaälvbron in Gothenburg, Sweden. Five girders, with a total length of approximately 5 km (each girder is approximately 1 km long) are equipped with tape sensors. This system provides for bridge integrity monitoring, and for strain and temperature monitoring in the long term.

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