Integrity monitoring of old steel bridge using fiber optic distributed sensors based on Brillouin scattering

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ABSTRACT

Götaälvbron, the bridge over Göta river, was built in thirties and is now more than seventy years old. The steel girders were cracked and two issues are in cause of steel cracking: fatigue and mediocre quality of the steel. The bridge authorities repaired the bridge and decided to keep it in service for the next fifteen years, but in order to increase the safety and reduce uncertainties related to the bridge performance an integrity monitoring system has been mandatory. The main issue related to selection of the monitoring system has been the total length of the girders which is for all the nine girders more than 9 km. It was therefore decided to monitor the most loaded five girders (total length of 5 km approximately) and logically a fiber optic distributed sensing system have been selected. For the first time a truly distributed fiber optic sensing system, based on Brillouin scattering effect, is employed on such large scale to monitor new crack occurrence and unusual strain development. The monitoring system itself, the monitoring strategy, challenges related to installation and the data management are presented in this paper.

Keywords: steel girder bridge, integrity monitoring, distributed fiber optic sensors, crack monitoring, average strain monitoring, warning system, kilometric scale

1. INTRODUCTION

Being one of the three communication line that connects two sides of the Gota river, Götaälvbron is the bridge of high importance for the Gothenburg city (Sweden). The bridge is more than 1000 meters (~33000 feet) long and consists of concrete slab poured on nine steel continuous girders supported on more than 50 columns. During the last maintenance works, number of cracks was found in steel girders, notable in zones above columns where the important negative bending moments are present. These cracks are consequences of fatigue over long years of service and mediocre quality of the steel. The view to the bridge is presented in Figure 1.

Fig. 1. View to nearly one kilometer long Götaälvbron bridge.

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The bridge is now repaired and the bridge authorities 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 collapse of cracked girders which may occur suddenly since damage is generated by fatigue. That was the reason to perform continuous bridge integrity monitoring.

The monitoring system selected for this project, must provide for both crack detection and localization and strain monitoring. Since the cracks can occur at any point or any girder, the monitoring system should cover full length of the bridge. These criterions have led the bridge authorities to choose DiTeSt – truly distributed fiber optic monitoring system based on stimulated Brillouin scattering.

2. DITEST SYSTEM

2.1 General description

DiTeSt stands for Distributed Temperature and Strain monitoring system. The development of a fiber optics distributed sensor system relies upon using a known and reproducible method by which the measurand can interact with the light traveling within the fiber. The DiTeSt is based on a detection scheme using a non-linear optical effect named Stimulated Brillouin Scattering[1]. This scattering process is an intrinsic property of the propagation of light in the silica material from which the sensing fibre is made. The Brillouin scattering effect exhibits a well-known and reproducible response to external measurands such as temperature and strain.

The Brillouin interaction results in the generation of scattered light which experiences a frequency shift through the scattering process. This frequency shift depends linearly on the fiber strain and temperature. As a consequence, the scattered light has a slightly different wavelength than the original light and the departure from the original wavelength is directly dependent on the strain and temperature of the fiber. A system based on the analysis of the Brillouin scattered light in optical fibers is naturally devoted to perform strain and temperature measurement. Moreover, the distributed nature of the measurement can be easily implemented by using optical pulse and an adequate data acquisition.

The main components of the DiTeSt system are the reading unit with software, sensor and sensor termination module. The reading unit is connected to the first end of the sensor and can be placed remotely from the sensing area, since a section of optical fiber cable could be used to link the reading unit to the sensor itself without any performance degradation. The other sensor-end must be connected to either sensor termination module, which could be placed remotely from the sensor area as well, or lead back to the reading unit. In the former case the configuration of the system is called "single-ended" and in the later case the configuration of the system is called "loop".

Different types of sensor can be used depending on application: ordinary temperature sensing cable (-40°C up to 85°C), high temperature sensing cable (up to 300°C), SMARTape (strain) sensor and SMARTprofile (strain) sensor[2]. The sensors may be additionally protected in case of harsh environmental conditions. Schemas of the DiTeSt system are given in Figure 2.

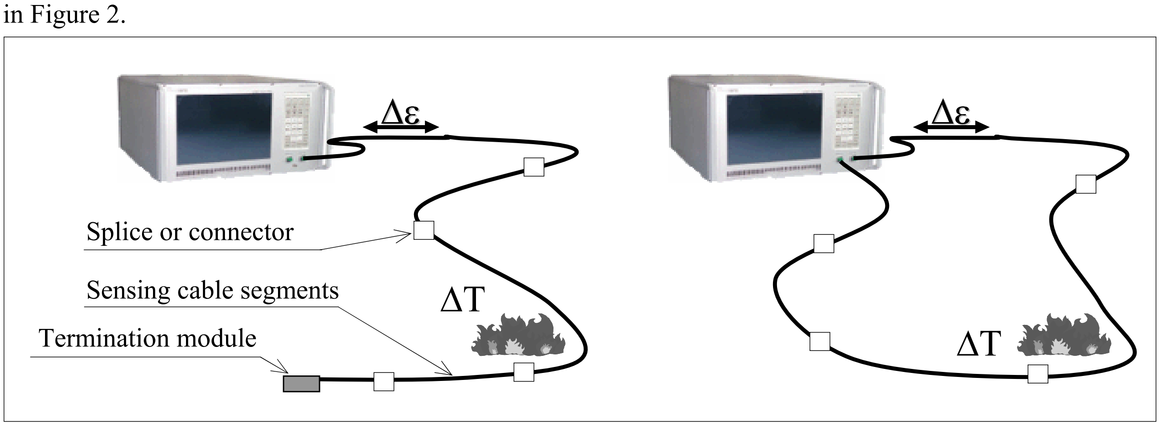

Fig. 2. Schemas of DiTeSt system configurations; left: single ended configuration; right: loop configuration.

2.2 SMARTape sensor

When strain sensing is required, the optical fiber must be bonded to the host material over the whole length. The transfer of strain is to be complete, with no losses due to sliding. Therefore an excellent bonding between strain optical fiber and the host structure is to be guaranteed. To allow such a good bonding it has been recommended to integrate the optical fiber within a tape in the similar manner as the reinforcing fibers are integrated in composite materials. To produce such a tape, we selected a glass fiber reinforced thermoplastic with PPS matrix[3]. This material has excellent mechanical and chemical resistance properties. Since it production involves heating to high temperatures (in order to melt the matrix of the composite material) it is necessary for the fiber to withstand this temperature without damage. In addition, the bonding between the optical fiber coating and the matrix has to be guaranteed. Polyimide-coated optical fibers fit these requirements and were therefore selected for this design.

The typical cross-section width of the thermoplastic composite tape that is used for manufacturing composite structures is in the range of ten to twenty millimeters, and therefore not critical for optical fiber integration. The thickness of the tape can be as low as 0.2 mm, and this dimension is more critical since the external diameter of polyimide-coated optical fiber is of 0.145 mm approximately. Hence, only less than 0.03 mm of tape material remains on top or bottom of the optical fiber, with the risk that the optical fiber will emerge from the tape. The scheme of the sensing tape cross-section, with typical dimensions, is presented in Figure 3.

The use of such sensing tape (called SMARTape) is twofold: it can be used externally, attached to the structure, or embedded between the composite laminates, having also a structural role.

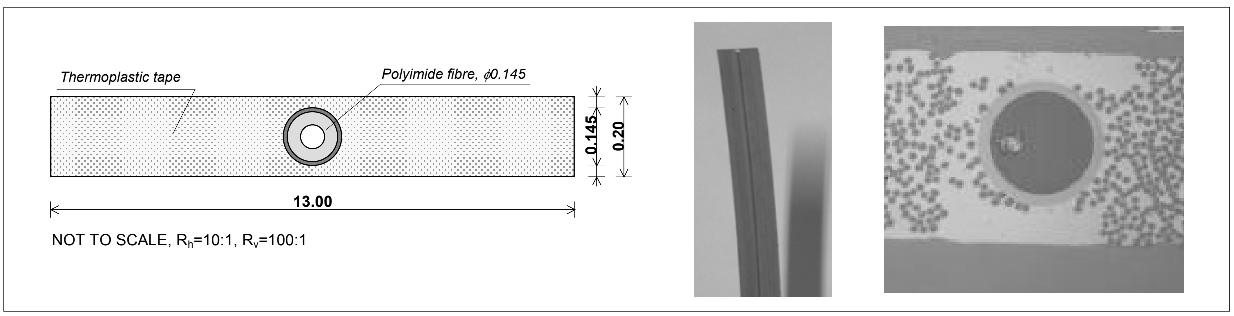

Fig. 3. Cross-section picture and micrograph of the sensing tape: SMARTape.

3. MONITORING SPECIFICATIONS

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

(1) To detect and localize new cracks that may occur due to fatigue

(2) To detect unusual short-term and long-term strain changes

(3) To detect cracks and unusual strain changes over full length of five girders, in total 5 km

(4) To perform one measurement session every two hours

(5) To perform self-monitoring, i.e. to detect malfunctioning of system itself

(6) To allow user friendly and understandable data visualization

(7) To automatically send warning messages to responsible entities

(8) To properly function for 15 years

Being the world first bridge application of distributed sensing system on such a large scale, the requested specifications imposed number of challenges to reading unit performance, SMARTape sensor production and installation and data management.

During the production of SMARTape, the optical fiber is exposed to strong mechanical and thermal actions. Consequently the sensor features very high losses and the reading unit must be able to read the sensors with up to 10 dB of cumulated losses with spatial resolution of 1 m. This performance is successfully achieved.

The crack is the event that occurs on very short length, much smaller than spatial resolution of the system. Usual gain peak detection algorithm therefore ignores this event. For the purposes of the project new gain peak detection scheme was developed in order to allow detection of both, main peak which is result of strain averaging over spatial resolution length of 1m and secondary peak generated by local strain variation induced by crack. An example of main and secondary peak is presented in Figure 4.

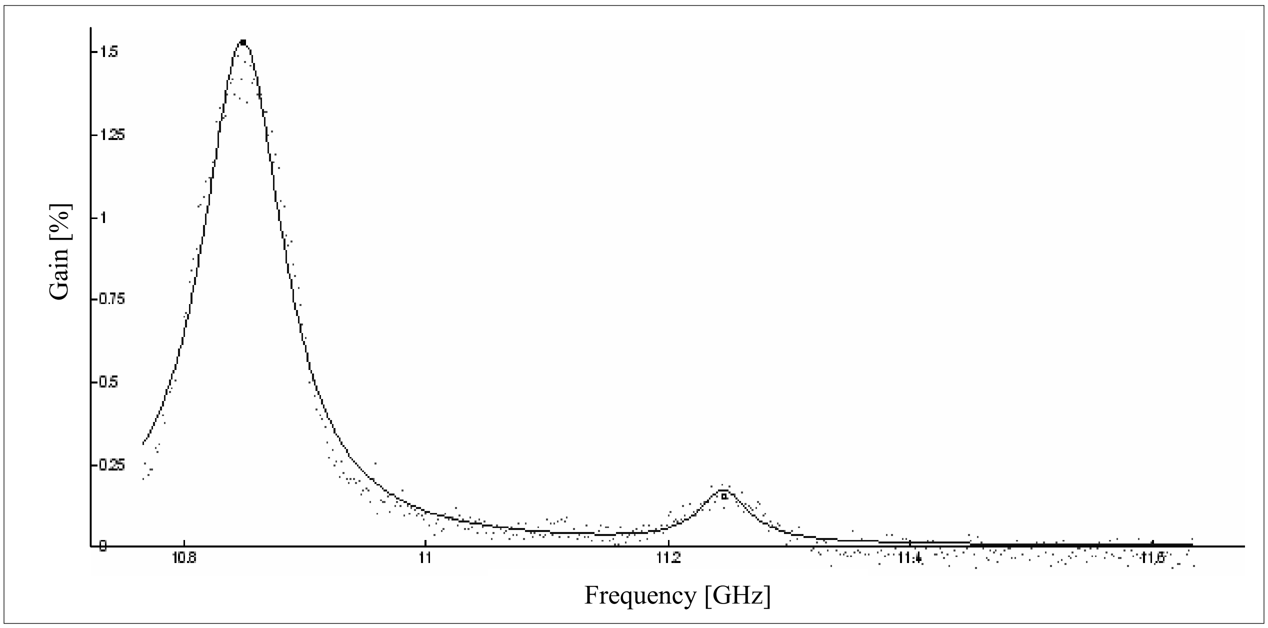

Fig. 4. Main Brillouin peak generated by stran variation over spatial resolution length, and secondary peak generated by crack.

On the gain characteristics corresponding to the position of fiber under strain simulating the crack, one distinguishes a secondary gain peak clearly corresponding to the lengthened section. When the fiber starts to be under local tension, it is possible to observe a week effect on the position of the principal peak and the signal is distorted by the presence of this second peak. The test demonstrated that it is possible to detect crack with a minimum width of about 0.5 mm that is redistributed over length of 100 mm.

The SMARTape 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 SMARTape was controlled optically, mechanically and visually during the fabrication.

In order for system to be able to detect the cracks in every point, it was decided to glue the SMARTape to the steel girder. The crack should not damage the sensor, but create its delaminating from the bridge (otherwise the sensor would be damaged and should be repaired). The gluing procedure was therefore established and rigorously tested in laboratory and on-site. Photograph of on-site gluing test is presented in Figure 5. The full performance was also tested in laboratory and on-site, and photograph of tested SMARTapes installed on the bridge is presented in the same figure.

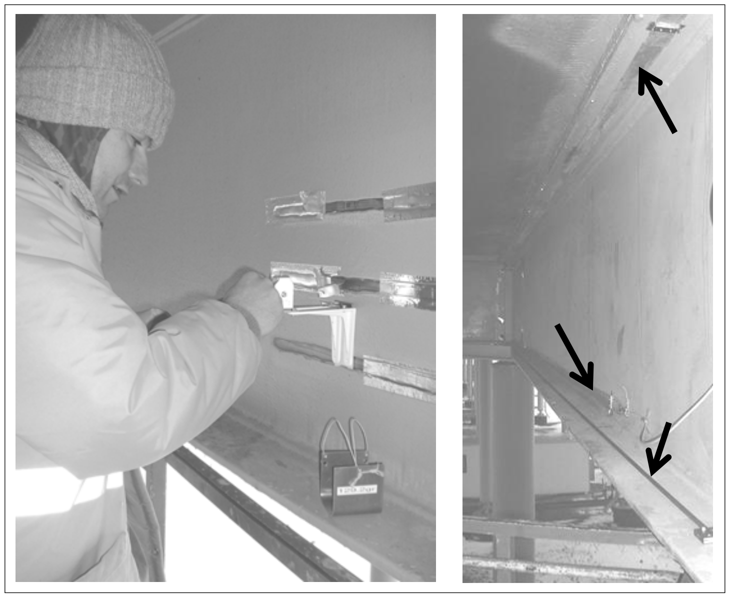

Fig. 5. On-site test of SMARTape gluing procedure (left) and installed SMARTapes for full performance tests (right).

The installation of SMARTape sensors was challenge itself. Good treatment of surfaces was necessary and number of transversal girders had to be crossed. Limited access and working space in form of lift basket, often combined with cold and windy environment and sometimes with the night work, made the installation particularly difficult. The view to bridge girders and part of installation team ready for work is given in Figure 6.

Fig. 6. View to bridge girders and part of the installation team.

The SMARTape sensors were produced in length of 90 m. Due to high losses, maximum three sensors could be enchained, making total effective length of 270 m. The measurements of SMARTape are compensated for temperature using the temperature sensing cable that has also the function of bringing back the optical signal to the DiTeSt reading unit designed for loop configuration. The three enchained SMARTape sensor and temperature sensing cable creates basic loop of the system. The basic loop is presented in Figure 7.

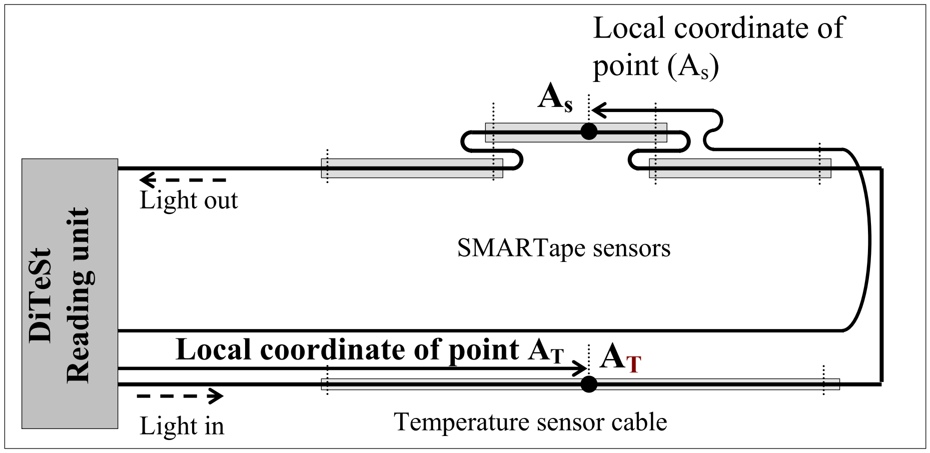

Fig. 7. Basic sensing loop consisting of three SMARTape sensor of 90 m and temperature sensing cable.

There is a total of twenty basic loops, two sets of five loops at South part and two sets of five loops at North part of the bridge. Each part of the bridge is monitored with different reading unit provided with 10 channels. The measurement time for single loop is less than 10 minutes for the strain range of 15000 με (-5000 με to +10000 με). Therefore, the measurement time for all the sensors is less than 2 hours.

The physical point A on the bridge is measured two times: first the temperature is measured at loop coordinate A_T and then the non-compensated strain at loop coordinate A_s. The temperature compensation is performed automatically by the software.

The span is a segment of the girder that is delimited by cross-sections supported by columns. One sensing loop can "cover" several spans, and two sensing loops can be overlapped within the same span. General position of spans and loops is presented in Figure 8.

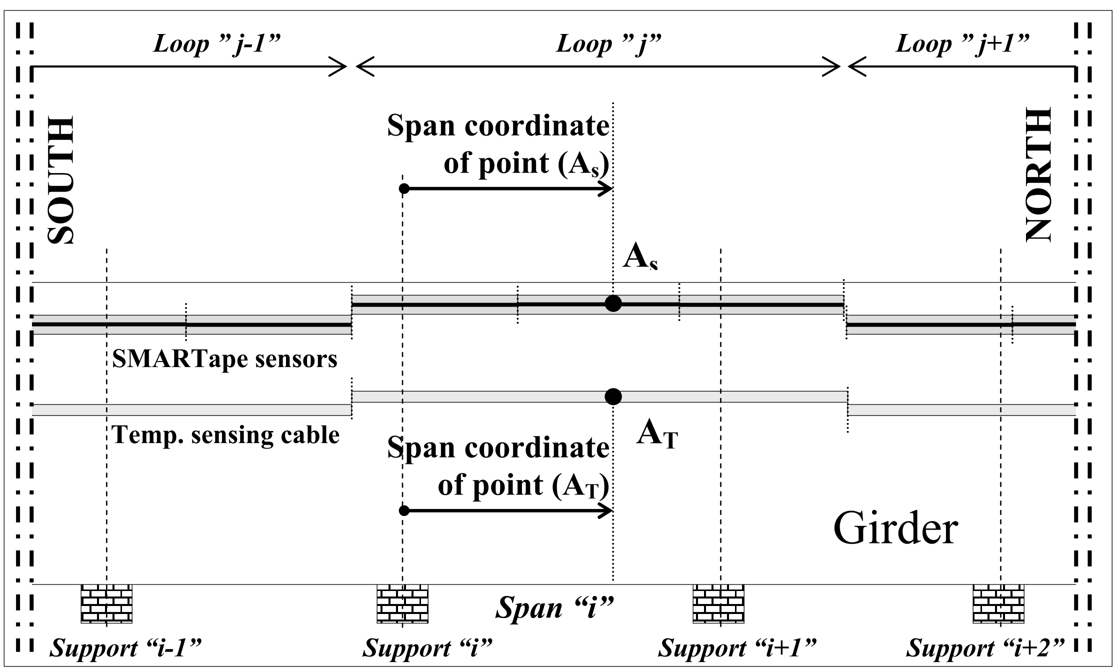

Fig. 8. General position of spans and loops.

The localization of events is performed with respect to bridge coordinate system indicating on which girder it happens (total of five beams equipped), and on what meter of the girder span (total of 55 spans of approximately 20 meters). The localization of events in this manner is very efficient and intuitive for the bridge maintenance team.

The DiTeSt system is provided with self-monitoring functions: automatic unblocking, detection of different types of malfunctioning such as cut of electrical power, cut of communication lines, unfavorable environmental condition (high or low temperature), physical damage of sensors etc.

The measurements are performed with distance sampling interval of 0.1m making the total number of monitoring points bigger than 100000 – 50000 for non-compensated strain and another 50000 for temperature. The special software for data handling, crack detection and short-term and long-term strain analysis has been developed. The same software controls the functioning of DiTeSt reading units. In case of crack detection, detection of unusual strain variation or detection of malfunctioning of the system, warnings are sent to responsible entities in form of e-mail, SMS and voice message, providing for redundancy in communication. Upon receipt of messages, the responsible entities are supposed to confirm they received the messages and then they will proceed according to established procedures.

4. SYSTEM PERFORMANCE

The system has been subject to different factory acceptance tests: sensing components and gluing procedure were tested first, the reading unit performances were tested afterwards and then the whole system including reading units, sensors and software were tested. All the tests were performed were supervised by the client. The achieved performance of the system is presented in Table 1.

Table 1. Performance of the system.

Strain resolution	±3 με
Strain accuracy	±21 με
Strain range	-5000 με to + 10000 με
Crack detection	Opening of 0.5 mm over 100 mm (1/5’’ over 4’’)
Temperature accuracy	±1°C (±1.8°F)
Temperature range	-30°C to +85°C (-22°F to +185°F)
Spatial resolution	1 m (3’-3’’)
Spatial sampling rate	0.1 m (4’’)
Total bridge length equipped with sensors	~5000 m (~16405’)
Measurement time per sensing loop	< 10 minutes
Measurement time for whole system	< 2 hours

The achieved performance of the system successfully fulfilled the requested specifications. At the moment of writing the paper, the installation of the system is coming to the end. A site acceptance test of the system will be preformed. Then, the field testing will be performed for few months, after which the system will officially be put in service.

5. CONCLUSIONS

Truly distributed fiber optic monitoring system called DiTeSt, based on stimulated Brillouin effect, is for the first time applied in a large scale for integrity monitoring of a bridge. Total of five girders, with total length of five kilometers (each girder is one kilometer long) are equipped with sensors. The DiTeSt reading unit was upgraded with special crack detection scheme. The SMARTape distributed strain sensors are combined with temperature sensing cables. Installation procedures were developed and tested in laboratory and on-site. The system is able to detect and localize cracks unusual and strain variations. In addition, it is provided with self-monitoring functions. The data management software is able to handle huge amount of collected data, perform the analysis and send warnings in form of e-mails, SMS and voice messages. The system was subject to serial of tests that have proven its performance.

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