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Distributed sensors for damage detection and localization

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ABSTRACT: Distributed fiber optic sensing technology based on Brillouin scattering effect has been proven as a mean to assess average strain and average temperature distributions in structures. However, detection of damage such as crack is very challenging, since only a short portion of sensor, much shorter than spatial resolution of the system, is exposed to very high concentrated strain. Beside this, the sensing fiber itself suffers from concentrated stresses and may be broken. In order to resolve above mentioned issues, first the detection algorithm was improved in order to make system sensitive to measurand changes occurring over length shorter than spatial resolution, and second a special manner of sensor installation is developed in order to make possible for optical fiber to survive high concentrated stresses. The system is applied on Götaälvbron (Gota Bridge), Gothenburg, Sweden, for the first time at a large scale. Number of reduced and full scale tests was performed in order to assess performance of the system. The system, its implementation method and results of the tests are presented in this paper.

1 INTRODUCTION

1.1 Götaälvbron – Gota Bridge

Götaälvbron, Gothenburg, Sweden, consists of concrete slab poured on nine steel continuous girders supported on more than 50 columns, having total length longer than 1000 meters. Being one of the three communication lines that connect two sides of the Gota River, the bridge is of high importance for the city. Due to fatigue over long years of service (open for traffic in 1939) and mediocre quality of the steel, number of cracks occurred on girders, notably in the zones above columns where the important negative bending moments are present. The view to the bridge is presented in Figure 1.

The existing cracks were closed, girders were repaired, and traffic authorities (Trafikkontoret) decided to keep the bridge in service until the year 2020, but new cracks can occur again. These new cracks can lead to sudden collapse of cracked girders, since damage is generated by fatigue. In order to increase the safety, assess the structural health condition of the bridge in real time, and plan the related maintenance activities, the traffic authorities decided to perform continuous

integrity monitoring. Trafikkontoret mandated Norwegian Geotechnical Institute (NGI) as a consultant to propose appropriate monitoring system.

Figure 1. View to Götaälvbron.

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 of any girder, the monitoring system should cover full length of the bridge. These criterions have led the NGI to propose DiTeSt – truly distributed fiber optic monitoring system based on stimulated Brillouin scattering. SMARTEC provided monitoring system with associated software. Installation of monitoring system was performed by different contractors under supervision of NGI and in collaboration with Royal Institute of Technology (KTH) and SMARTEC.

1.2 DiTeSt monitoring system

DiTeSt stands for Distributed Temperature and Strain monitoring system. The DiTeSt is based on a detection scheme using a non-linear optical effect named Stimulated Brillouin Scattering, Thévenaz et al. (1998). 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.

When strain sensing is required, the transfer of strain from the host structure to the sensing optical fiber is to be complete, i.e. an excellent bonding between them is to be guaranteed, with no losses due to sliding or delamination. Such a good bonding has been realized in two steps. First, distributed strain sensor called SMARTape was developed, consisting of polyimide coated optical fiber integrated within a glass fiber reinforced thermoplastic composite tape with PPS matrix, Glisic & Inaudi (2003). Then the SMARTape was bonded to the structure using appropriate adhesive, tested in laboratory and on-site. Axial Young modulus of SMARTape was determined to be approximately 31 GPa, while the rupture strain was higher than 3%. Such high Young modulus and strength provides for stiffness necessary to ensure safe installation of long sensors. The scheme of the SMARTape cross-section, with typical dimensions, is presented in Figure 2.

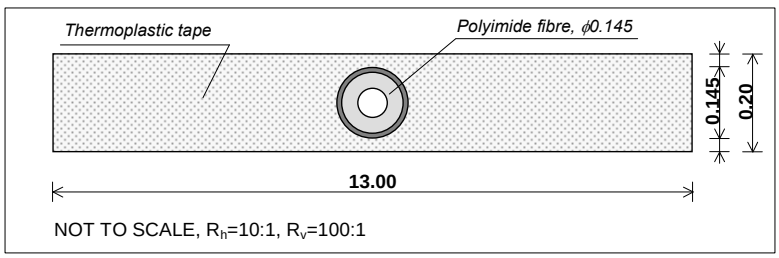

Figure 2. Schema of SMARTape's cross-section.

The performance of the monitoring system, as implemented on Götaälbrovn, is given in Table 1.

Table 1: Performance of the system.

Average strain resolution	±3 με
Average strain accuracy	±21 με
Average strain measurement range	-2500 με to + 6000 με
Crack detection lower limit	Opening of 0.5 mm over 100 mm
Crack localization accuracy	±0.1 m
Average temperature accuracy	±1°C
Average temperature range	-30°C to +85°C
Spatial resolution	1 m
Spatial sampling interval	0.1 m
Bridge length equipped with sensors	~5000 m (5 x ~1000 m)
Measurement time for whole system	< 2 hours

SMARTape sensor is designed for strain monitoring, while crack monitoring is particularly challenging. The specification for crack detection presented in Table 1 is reached only after the research and developments presented in this paper were made.

1.3 Distributed strain measurement and crack detection challenges

Distributed sensors are sensitive in each point along the sensing optical fiber to strain and temperature changes, which is particularly interesting for the monitoring of large structures, such as bridges, pipelines, dams, dykes etc. Although distributed deformation sensors are sensitive to strain at every point of its length L_D, they measure at discrete points that are spaced by a constant value, called the sampling interval and denoted with L_{SI}, and the measured parameter is actually an average strain measured over a certain length, called the spatial resolution and denoted with L_{SR}, Glisic & Inaudi (2007). Coordinates x_i of discrete measurement points (defined by the sampling interval) are defined as follows: $x_i = x_0 + i \cdot L_{SI}$, $i=1,2,3,\ldots,n$, n=integer(L_D/L_{SI}), where x_0 is the coordinate of the first point on the sensor. Mentioned parameters and principle of distributed sensor measurement are in a simplified manner presented in Figure 3.

Let the real strain distribution along the sensor without crack is as presented in Figure 3a. For each point with coordinate x_i the strain is averaged over the segment $[x_i-L_{SR}/2,\ x_i+L_{SR}/2]$ as presented in Figure 3a (gray area represents equivalent average strain), and the value of the measurement is attributed to the point x_i. Difference between real and measured strain in point x_i is small ($\varepsilon x_{i,measured} \approx \varepsilon x_{i,real}$) and depends on strain change along the length of spatial resolution.

Significant strain changes that occur over lengths shorter than spatial resolution, but not shorter than its half, are detected and localized, but not accurately measured, as shown in Figure 3b ($0<|\Delta\varepsilon x_{i,m.}|<<|\Delta\varepsilon x_{i,r.}|$).

This principle, however, is not valid for abrupt strain changes or concentrated strains in sensing optical fiber such as generated by cracks, see Figure 3c. In these cases the measurement resulting from a distributed sensing system can possibly lead to important measurement errors. Even very high strain changes that occur over lengths shorter than one half of the spatial

resolution are practically "invisible" for the system in common mode of functioning, as shown in Figure 3c. In addition, high local strains can lead to physical rupture of sensing optical fiber.

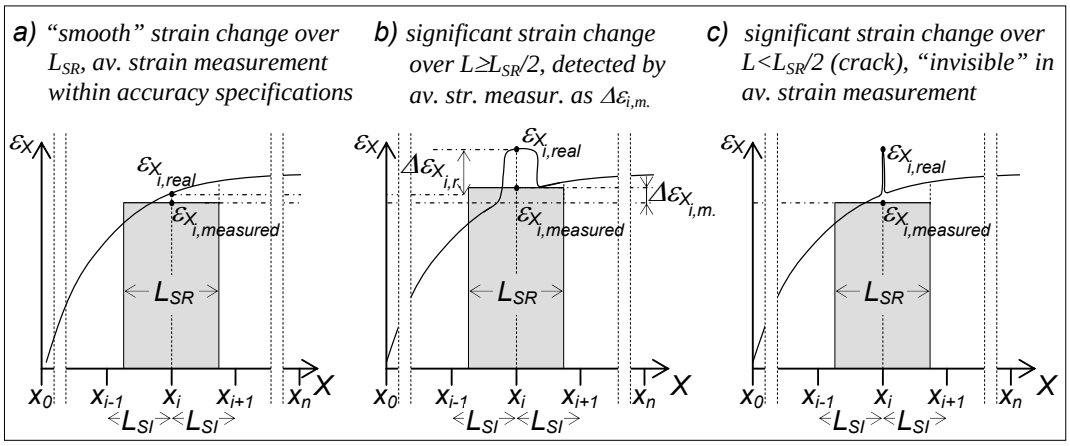

Figure 3. Simplified presentations of principle of distributed sensor measurement.

In order to deal with these issues two important improvements are made: (1) advanced algorithms allowing detection of events that occur over length shorter than one half of the spatial resolution and (2) appropriate sensor design and installation procedures, allowing for controlled strain redistribution over a length compatible with algorithm requirements and sensor mechanical properties, have been developed. These improvements were tested in laboratory and on-site, and presented in this paper.

2 CRACK DETECTION IMPLEMENTATION

2.1 Development of crack identification algorithm

The encoding parameter for DiTeSt system is Brillouin frequency of light in optical fiber. For every point of a distributed sensor, an average Brillouin frequency diagram is created by resolving integral of amplitudes for different scanning frequencies over the spatial resolution. An example of average Brillouin frequency diagram in a point of sensor, obtained with spatial resolution of 1 m, is given in Figure 4a.

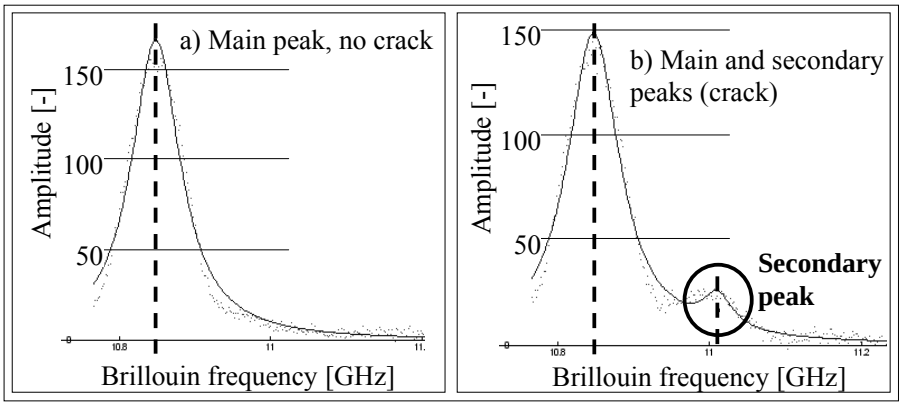

Figure 4. Main peak of Brillouin frequency generated by strain change in one point of the sensing optical fiber, and both main and secondary peaks generated in case of crack occurrence (courtesy of Omnisens SA, Switzerland).

If the event that changes Brillouin frequency (strain or temperature change) occurs over length which is shorter than spatial resolution, but longer than the half of the spatial resolution, this event will be detected and localized by main peak, but not accurately measured. However, should the event occur over the length that is shorter than a half of the spatial resolution, but still longer than tenth of spatial resolution, then due to small integration length this event will not be detected within the main peak, but it will create a secondary peak in Brillouin frequency diagram, Ravet et al. (2009). Example of secondary peak created with spatial resolution of 1 m, and localized strain of approximately 4000 με applied over 10 cm is given in Figure 4b.

Crack opening is typical event that may create localized change in Brillouin frequency, thus the diagram presented in Figure 4b actually corresponds to the crack opening of 4 mm that acts over the length of sensing fiber of 10 cm. For Götaälvbron the length of sensing fiber with localized high strain in case of crack is realized by delamination of SMARTape in zone around the crack.

Secondary peak is not detected directly, using the same detection scheme as for the main peak and it is not visible in the diagram of the main Brillouin trace. It is detected using special identification algorithm implemented in software and presented in diagram in form of spots, Ravet et al. (2009). These spots will be referred to as "crack spots" in the further text.

The number of crack spots detected due to crack occurrence depends on total cumulative losses at the crack location, but also on local signal amplitude changes generated by crack. Typically, it varies between 4 and 11 for given sampling interval of 0.1 m and spatial resolution of 1 m.

Several laboratory tests under the controlled conditions were performed in order to evaluate performance of the implemented algorithm. Tests consisted of tensioning 10 cm of optical fiber for different pre-defined values using set-up presented in Figure 5a. Tests confirmed excellent performance in terms of detectable crack opening, which was better than 0.35 mm over 10 cm (required 0.5 mm), and in terms of reliability – all the simulated crack openings were successfully detected and localized. Summary of results is given in Figure 5b.

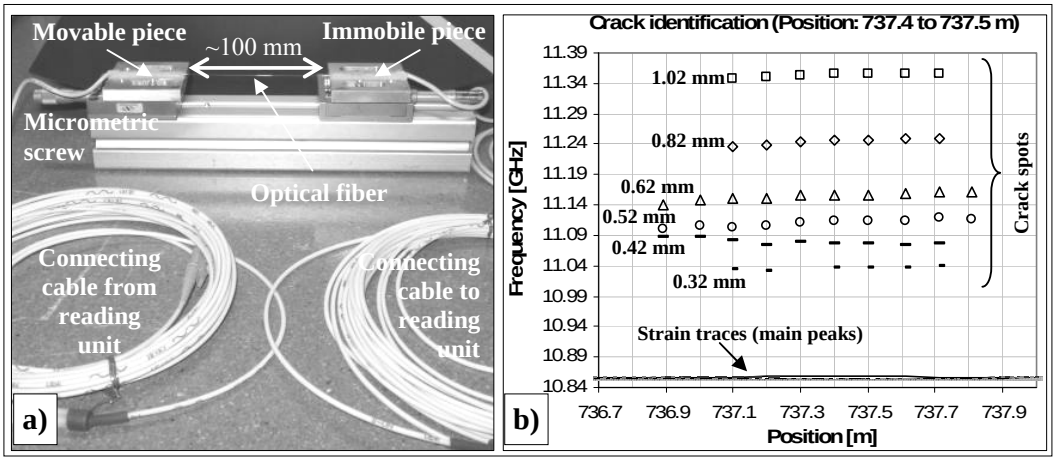

Figure 5. Crack algorithm testing set-up (a) and summary of results with successful crack detection (b).

2.2 Integrity of distributed sensor subject to high local strain – delamination mechanism

Having provided that SMARTape is bonded to the structure in every point, crack in structure generates concentrated strain and stress in SMARTape at crack location. The stress in SMARTape generated by crack is very high and there is a risk of breakage. On the other hand crack identification algorithm functions only if local stress is redistributed over length of minimum 10 cm.

To solve both issues, it was decided to create mechanism of delamination of SMARTape at location of crack. The adhesive used to install the SMARTape is carefully selected in order to allow delamination of the SMARTape over length not shorter then 10 cm in case of crack opening of 0.5 mm or more. Delamination will help avoid breakage of SMARTape by redistribution of the strain over minimum 10 cm and in case of crack opening of 0.5 mm it amounts to 0.5%, which is within the strength limits of both components of SMARTape, composite tape and optical fiber. Delamination also provides necessary strain redistribution for correct functioning of crack identification algorithm.

Delamination mechanism, selected adhesive and installation procedures were tested in laboratory in order to evaluate their performances. Special set-up was built. The SMARTape was glued to metallic supports that were then exposed to relative translation movement simulating crack opening. It was decided to paint metallic supports with original protection paint in order to simulate real on-site conditions. However, due to lack of paint, in some tests the metallic supports were not painted. The SMARTape was glued to metallic supports using the same installation procedure as in real case (installation on Götaälvbron), including protection with aluminum tape.

The relative translation movement was ensured by special metallic holders that forced the metallic supports to slide over straight lines and prevented all types of rotations. One metallic support was immobilized while the other was movable. Translation was imposed by micrometric screw and the relative displacement between two metallic supports was controlled using the dial gauge. The set-up is presented in Figure 6a.

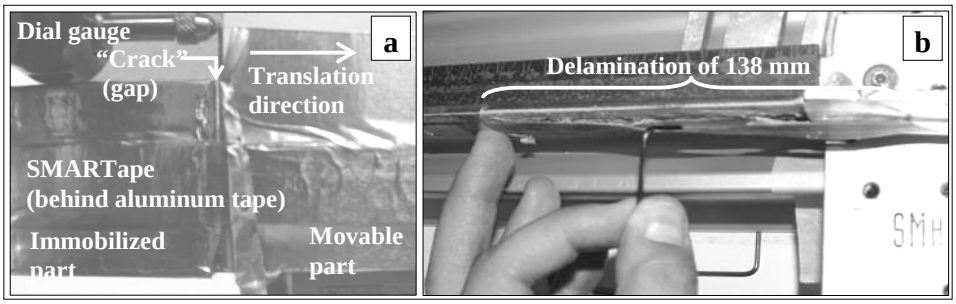

Figure 6. Delamination testing set-up before crack simulation (a) and during the crack simulation (b).

The gap, simulating crack, was open for 0.5 mm. Delamination was noticed by characteristic noise, and verified visually. On painted supports, delamination occurred mainly on interface steel-paint, while on non-painted supports delamination occurred on interface SMARTape-adhesive. In both cases initial delamination length was between 130 and 140 mm, i.e. bigger than tenth of spatial resolution of the system.

After initial delamination was formed, due to strong forces in the testing set-up, gap opening slowly increased for 30%, while the length of delamination increased slowly in time for 50% approximately and stabilized after few days. This indicates that after initial delamination is formed, delamination length slowly progress in time and stabilizes after few days. Propagation of delamination stops when the difference between tensional force in delaminated SMARTape and frictional forces acting over delamination length meet equilibrium with shear strength of weakest interface of the complex steel-paint-adhesive-SMARTape. Delamination progress is not an issue – if it exceeds one half of the spatial resolution, the crack is detected as a localized high value on main Brillouin trace, i.e. on average strain diagram. If necessary, excessive delamination can also be prevented by clamping extremities of the delaminated zone upon crack detection.

The results of delamination tests proved the delamination mechanism and confirmed good selection of adhesive and installation procedures. High Young modulus and strength of SMARTape significantly contributed to such a good results. Example of delaminated SMARTape after removal of protective aluminum tape is given in Figure 6b.

After a serial of successful laboratory tests that confirmed capability of DiTeSt system to detect and localize the crack occurrence with opening not smaller than 0.5 mm, the system is installed on the bridge and full-scale crack tests were performed.

2.3 Full-scale tests

Full-scale tests were performed using long specimens and the crack testing procedures provided by NGI with assistance from Trafikkontoret. Measurements were coordinated and performed by SMARTEC with assistance from KTH and Trafikkontoret, and data analysis of tests was performed by SMARTEC. The results of tests confirmed a good performance of implemented crack detection method. The results are currently not disclosed, but they will become available soon. View to specimens with SMARTapes and view to open gap simulating crack opening are shown in Figure 7.

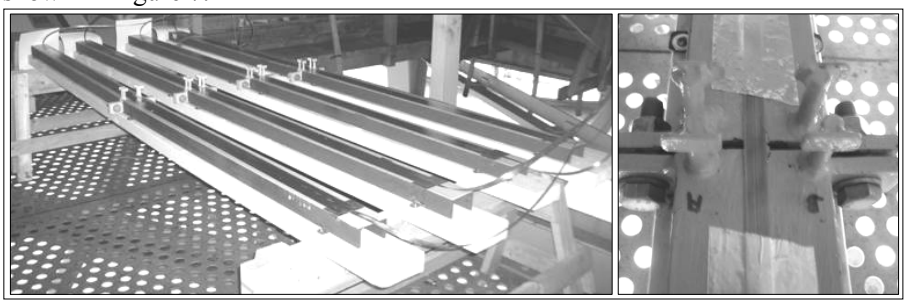

Figure 7. Tested specimens with installed SMARTapes (left) and opened gap (right).

3 CONCLUSIONS

The novel method for crack detection and localization using distributed fiber optic technology DiTeSt, based on stimulated Brillouin scattering effect, with SMARTape sensor is presented. The method was successfully tested in laboratory and on-site, and implemented in monitoring of Götaälbrovn, Gothenburg, Sweden. Crack detection method is based on development on crack identification algorithm implemented in DiTeSt system and SMARTape delamination mechanism.

Crack opening on the structure with width not smaller than 0.5 mm will create delamination of SMARTape, either on the steel-paint interface or on the adhesive-SMARTape interface.

For delamination lengths not shorter than half of the spatial resolution, crack is detected and localized as high value in main Brillouin trace, i.e. as an important strain change on average strain distribution diagram.

In case crack creates delamination shorter than half of spatial resolution but not shorter than one tenth of the spatial resolution, the crack is detected and localized using crack identification algorithm, based on secondary peak in Brillouin frequency diagram, Ravet et al. (2009).

Finally for delamination shorter than tenth of spatial resolution, the crack will not be detected immediately. However, in such a situation, it is expected that either delamination progress in time and exceed tenth of spatial resolution, or the sensing fiber is expected to fail due to high local stress concentration. In the first case crack will be detected and localized using crack identification algorithm, and in the second case it will be detected as a rupture of sensing optical

fiber and localized using OTDR device. The last scenario is expected also to happen for very big crack openings (several millimeters) combined with short delamination in a way that stress over delaminated SMARTape exceeds strength of the sensing optical fiber.

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