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ORIGINAL PAPER

# Evaluation of a large-scale bridge strain, temperature and crack monitoring with distributed fibre optic sensors

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**Abstract** Many structures like bridges are ageing and the necessity to measure the uncertain parameters is relevant. Crack-related parameters can be measured with traditional techniques like crack gauges and displacement transducers. A method that can detect and localise cracks as well as measure crack width is most favourable. Several distributed and quasi-distributed systems were introduced to the market and tested in recent years. This paper presents a large-scale Structural Health Monitoring project based on stimulated Brillouin scattering in optical fibres for an old bridge. The Götaälv Bridge is a continuous steel girder bridge with concrete bridge deck. Steel girders suffer from fatigue and mediocre steel quality and some severe cracking and also a minor structural element collapse have taken place. The system installed on the bridge measures strain profiles along the whole length of the bridge and detects cracks that are wider than 0.5 mm. Procedures like factory acceptance test, site acceptance test, laboratory testing and field testing are presented and analysed. Innovative technology was developed, tested and applied on the bridge. Heuristic knowledge was collected; conclusions are presented and discussed for future development.

**Keywords** Bridges · Field testing and monitoring · Maintenance and inspection

## 1 Introduction

Distributed and quasi-distributed fibre optic systems for large-scale monitoring have been developed and commercialised in recent years. Large-scale structures like dams, pipelines, concrete columns, tunnels, dykes, piles and roadbeds have been instrumented and monitored for temperature and strain changes [5, 8–11, 14, 15, 17]. Several feasibility studies and initial installations were performed around the world in order to test the principles, characteristics and applicability of these systems. Development in the technical field is rapid and new techniques are providing the opportunity to evaluate parameters that were not possible to be measured in the past. Crack monitoring is important as cracking may cause serious damage to the structure and deteriorate its performance and safety. A distributed method that can detect and localise cracks in large structures and different materials like concrete, steel and composite is most favourable.

The Götaälv Bridge in Sweden built in 1939 and showing some severe deterioration was the first large-scale bridge application that was installed with distributed fibre optic measuring system. As some severe cracking was noted in zones above columns and a minor collapse in a structural element took place, it was decided that the bridge needs to be refurbished and also monitored continuously for unusual

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strain changes as well as for crack detection and localisation. Several systems on the market were investigated in order to meet the harsh demands of the required system. A feasibility study with a test installation took place in order to evaluate the functionality of the system as well as to test the installation procedure on the bridge, in real conditions. Different kinds of tests, both small scale and full scale, were performed during the projects.

In total, five of the seven main longitudinal steel girders were provided with distributed fibre optic sensors based on stimulated Brillouin scattering in optical fibres [12]. Sensors were installed on the upper flange of the steel girder with the overall bonding method and are measured with laser-based technique called DiTeSt [9]. Potential problems can be identified and localised at any location along the single optical fibre with a spatial resolution of 1 m. The system sends automatically warnings to authorities by e-mail or text message.

This paper gives a short introduction to Structural Health Monitoring (SHM) activities in distributed sensing and crack detection technology. It also presents the novel technology that was developed and applied for the Götaälv Bridge. Results of the tests are enlightened and presented. Gathered knowledge is reported and discussed.

## 2 Previous research on distributed sensing and crack monitoring techniques

There is an extensive practice in monitoring strain and crack width with traditional strain gauges, crack gauges and displacement transducers [18, 19]. Also visual inspections are still widely used in order to perform crack detection but they are time and capital consuming, also unreliable in many cases. Old deteriorated steel structures with mediocre steel quality might have cracking that is hard to reveal if the steel is covered with several layers of old elastic paint.

Distributed sensing based on Brillouin scattering [12] consists usually of an optical fibre cable that is able to measure strain and temperature along its length, up to tens of kilometres.

Brillouin scattering takes place due to interaction of light with phonons in optical fibres. The phonons will shift the frequency of the light in order to the acoustic velocity of the phonons. The acoustic velocity in turn is dependent on the density of the glass and material temperature. The reason that the Brillouin frequency varies linearly with applied strain and temperature makes it possible to measure both parameters simultaneously along an optical fibre. The scattering phenomenon can be either spontaneous or stimulated. The spontaneous process is called Brillouin scattering and it requires only an extremely low level of the detected signal but sophisticated signal processing. The stimulated phenomenon is called stimulated Brillouin amplification and its advantage is a relatively stronger signal. The challenge is to produce a meaningful signal that maintains a stable frequency difference. The opto-electronics required for Brillouin system is complex and requires long coherency length, stable lasers, high-speed modulators, detectors and frequency discriminators. The system returns an average value of strain or temperature or both with selected spatial resolution. A spatial resolution of 1 m [7, 16] is sufficient for the most civil engineering purposes when tracking global changes. These new techniques provide for reliable distributed measurements for strain and temperature and also crack detection over long distances. This is really necessary when handling deficiently depreciated structures where structural collapse could occur.

Crack detection and crack width estimation and/or measurement by distributed technology are tested and discussed by [7, 20]. Bao et al. [1] tested non-linear strain response of the concrete columns to detect the de-bonding and cracks under loading and rotation conditions. Conclusion was that distributed Brillouin sensing technology is a powerful candidate to monitor the health of the structures and offers both local and global strain distribution to identify the early problems in the structures.

Shi et al. [17] also discuss related aspects monitoring geotechnical engineering structures like tunnel, foundation pit, slopes, piles and permafrost roadbed for railway with Brillouin Optical Time Reflectometer (BOTR). Nöther et al. [15] report on development using distributed sensing system based on stimulated Brillouin scattering for large earth structures like river and coastal dikes, dams, landfills, railway embankment and roads.

The extensive research work in the area of distributed sensing was performed at various scales. The first large-scale project that, besides basic scientific challenges, addresses important application-related issues is presented in this paper.

## 3 Description of the bridge

The Götaälv Bridge, built in 1936–1939, is a large steel girder structure with a concrete bridge deck combined for both road and light-rail traffic as well as pedestrian and bicycle lanes, see Fig. 1. The length of the bridge is about 950 m and seven continuous steel girders are supported on more than 50 columns. The bridge is the important connection between Hisingen and Gothenburg City and around 25,000 vehicles and 3,800 bicycles pass the bridge everyday [2, 13]. The 20-m wide navigation channel has a vertical clearance of 30 m. The dense light-rail traffic causes dynamic effects and the bridge openings cause a lot of unsymmetrical static loads during boats transits, especially in rush hours.

As the bridge structure was found to be in critical condition, a refurbishing work has taken place in order to upgrade the strength of the bridge to acceptable level. A Structural Health Monitoring System (SHMS) was also recommended to guarantee the safe usage of the bridge. Norwegian Geotechnical Institute (NGI) investigated the market in order to suggest the best solution for the purpose. A distributed fibre optic system was recommended in order to see the entire strain profile as well as crack detection/localisation along the whole bridge [2–4, 6, 13] after strengthening.

Temperature varies significantly longitudinally as well as transversally. This sets demands for good knowledge in temperature distribution. Some specific, characteristic spans of the bridge were furthermore measured with separate thermocouples in order to establish understanding for temperature-related aspects.

The aims of the project were as follows:

- to detect and localise cracks that may occur due to fatigue and mediocre quality of steel;
- to report automatically about high strain values, high strain variation as well as temperature values in short-term and long-term perspective;
- to send warnings to the traffic authorities as owner of the bridge.

All these are taking place over full longitudinal length of five chosen bridge girders. One measurement session including all sensors is performed every 4 h. Self-monitoring, friendly and understandable data visualisation is also performed. The bridge is in harsh condition as there is risk for a brittle rupture. The system is planned to last for about 15 years and the monitoring system should last to the end of the bridge’s service life.

## 4 Description of the selected monitoring system

### 4.1 Monitoring system in general

DiTeSt system based on stimulated Brillouin scattering in optical fibres is used on the Götaälv Bridge and stands for Distributed Temperature and Strain monitoring system.

The main components of DiTeSt system are the reading unit with specially developed software, sensors: sensing cable called SMARTape and sensor termination module. DiTeSt system is configured to send warning messages to the traffic authorities with well-specified scenarios like crack detection, high local strain or fibre brakeage. The authorities receive the message and can take the proper action without delay [4].

The DiTeSt reading unit is an innovative instrument providing for high intensity and stability of interrogating optical signal sent to sensor and featuring exceptionally high sensitivity to optical signal received back from sensor. These properties allow for important optical losses in sensors and very long range of measurement.

SMARTape is bonded to the structure with the so-called overall bonding method by gluing in order to transfer the strain distribution from the structure to the fibre. Polyimide-coated optical fibre that is embedded in a thermoplastic tape in the similar manner as the reinforcing fibres are integrated in composite materials is optimal for strain transfer. The tape is produced of glass fibre reinforced thermoplastic with Polyphenylene Sulfide (PPS) matrix [5] as the material has excellent mechanical and chemical resistance properties. Axial Young modulus of SMARTape is approximately 31 GPa and its thickness can be as low as 0.2 mm, see Fig. 2 for details.

The unique properties of the reading unit and the sensor led to selection of DiTeSt system for this project. The performance of the system is presented in Table 1.

### 4.2 Crack detection

DiTeSt system has been used for strain monitoring in several applications [9, 14]. The idea of detecting cracks bigger than 0.5 mm with DiTeSt system is to transfer the stress created by a crack to the longer section of the SMARTape in order to prevent the breakage of the optical fibre. Without delamination the most probable consequence is fibre breakage if a large strain concentration is induced quickly. But if the stress is transferred to longer section of the SMARTape, minimum 100 mm of delamination of the tape from the steel surface should

**Fig. 1** Side view of the Götaälv Bridge during bridge opening

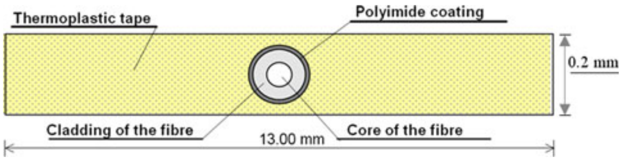

**Fig. 2** The scheme of the SMARTape cross-section is shown, note that the picture is not to scale

take place instead of the rupture, see Fig. 3 for illustration.

The crack is the event that occurs on very short length, smaller than spatial resolution of the system. As normal peak detection algorithm ignores the event, a special detection scheme was developed in order to be able to detect both peaks. Main peak is the result of strain averaging over spatial resolution of 1 m. The second peak is generated by local strain variation induced by crack and is presented in the form of spots in the Brillouin frequency diagram [16]. An example can be seen in Fig. 4: main peak on the left without crack and main and secondary peak on the right with crack occurrence. In the further text, these crack occurrence spots will be referred to as "crack spots". Isolated false "crack spots" are present sometimes because of high attenuation of optical signal generated by integration of optical fibre in composite tape, installation to bridge, and splicing. Therefore, a minimum appearance of four crack spots is needed in the software in order to avoid false alarms.

## 5 Description of the field and laboratory testing

### 5.1 Initial field testing

As the project was unique and no experience from the past on a large bridge installation existed, a test installation of selected fibre optic sensor technology was prepared at the early stage of the project. The purpose of the test was to confirm the most suitable installation procedure as well as verify the performance of the sensors and data acquisition system. Some typical, selected I-beams of the bridge were installed with sensors and a load test was performed, both clamping and gluing of the sensor to the beam were tested and also different positions on the beam.

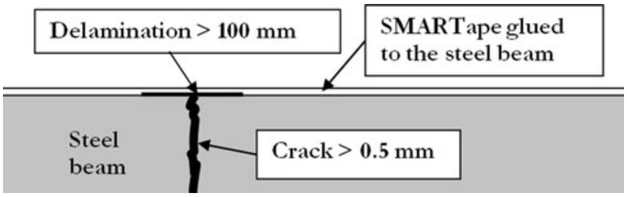

**Fig. 3** The idea of crack occurrence and delamination procedure in order to not break the fibre in SMARTape

Three different kinds of glues were tested in order to find the most suitable one. The gluing procedure is as follows: firstly, the surface is cleaned with alcohol as well as the sensor itself. Secondly, the clue is set to a few meters piece of the sensor and then finally the sensor is pulled cautiously in order to prevent bending and fixed to the surface. After that the sensor is covered with aluminium tape that will protect the sensors against water, dust, etc., and prevent foreign particles to reach the glue. The tests also included testing the adhesion of the glue to the sensor, to the painted surface and even to the clean steel surface, see Fig. 5 for test samples. Different aspects around tested glues were also cautiously discussed with the glue producer when making the final decision. More detailed description about initial field testing can be seen in [2].

### 5.2 Factory acceptance test (FAT)

FAT was performed in order to verify the crack detection method. These tests were performed in the presence of client and the purpose was to verify procedures concerning gluing, crack detection, delaminating of the SMARTape with high strain as well as the temperature compensation algorithm. The SMARTape was glued to painted metallic supports in order to test crack detection on a special set-up. Original protection paint was used in order to simulate real on-site conditions. Installation followed the procedure supposed to be performed on the bridge. The metallic supports were exposed to relative translation movement simulating crack opening. 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 immobilised while the other was movable. Translation was

**Table 1** The performance of the DiTeSt system

| | |
|---|---|
| Average strain resolution/accuracy/range | ±3 με/±20 με/−5,000 to +10,000 με |
| Crack detection lower limit | Opening of 0.5 mm over 100 mm |
| Crack localisation accuracy | ±0.1 m |
| Average temperature accuracy/range | ±1°C/−30 to +85°C |
| Spatial sampling interval/spatial resolution | 0.1 m/1 m |
| Bridge length equipped with sensors | ~5,000 m = 5 × ~1,000 m |
| Measurement time for whole system | <4 h |

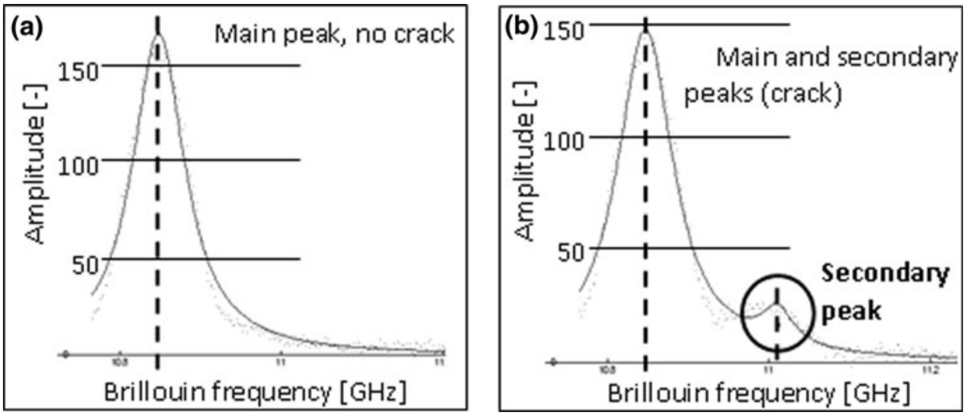

**Fig. 4** Brillouin frequency: main and secondary peak that is generated in case of crack occurrence (courtesy of Omnisens SA, Switzerland)

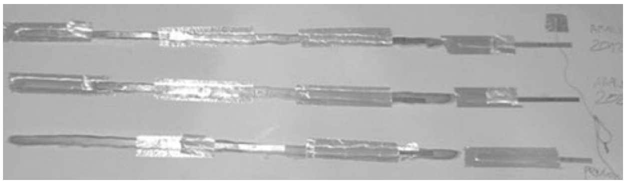

**Fig. 5** Test samples of SMARTapes glued with three different glues to clean steel surface as well as to the paint. The samples are covered with aluminium tape that protect the samples from environment in long term

imposed by micrometric screw and the relative displacement between two metallic supports was controlled using the dial gauge [6].

Secondary peak for crack detection is detected using special identification algorithm implemented in the software. Characteristically, the number of crack spots detected due to crack occurrence varies between 4 and 11 for given sampling interval of 0.1 m and spatial resolution of 1 m. The number of crack spots depends not only on total cumulative losses at the crack location, but also on local losses generated by crack. The test was performed so that a 100 mm piece of optical fibre was tensioned to pre-defined values simulating different crack widths, for further details of these tests, see [6].

### 5.3 Site acceptance test (SAT)

Two different SATs have taken place, one for the North Bridge, called SAT 1 and one for the South Bridge, called SAT 2. DiTeSt with complete set of connected sensors was tested for most vital functions and advanced performance of the system. A load test was performed as part of both SAT 1 and SAT 2. In order to understand and to evaluate the crack detection system, a number of tests with specially prepared test beams were performed with different crack opening scenarios as part of the SAT 2, for the south part of the bridge. These field crack tests are described in detail in the next chapter.

## 6 Description of the on-site crack detection test

In order to verify and improve the function of the crack detection system, it was decided to perform on-site testing. Four test beams were prepared according to client requirements and the test was performed as part of the SAT 2. Intention of the test was to answer questions around how the sensors behave in the presence of high strain or cracking and also if the alarms are generated as defined in the procedure.

Four steel test beams were prepared, painted and installed with SMARTapes in the same manner as in reality on the bridge in order to simulate on-site conditions. 2.5-m long U-cross-sections were manufactured by the owner, Traffic Authority of Gothenburg (Trafikkontoret). Every beam consisted of two 1.25-m long steel U-cross-section inversed and fixed in a row on a wooden support. Specimens were set with screws on the wooden support so that a gap in the middle was closed when installing the SMARTape. A gap opening was created by long tuning screw at the end of the beams. Metallic bolts were welded on both sides of the gap in order to serve as supports for mechanical calliper measuring the gap opening. The beams installed with SMARTapes can be seen in Figs. 6 and 7.

These test beams were then connected to one of the sensing loops of the system. Different crack opening scenarios were tested in order to understand the real behaviour. Special interest was paid on the delamination behaviour and propagation in time. As the system is designed to send warning messages, these were also controlled during the process.

Secondary Brillouin peaks are present when a crack occurs. This is seen as so-called “crack spots” on the strain profile in the DiTeSt software (see Sect. 4.2) The criterion was set up to be four “crack spots” within 0.6 m and it was expected that the delamination of the SMARTape would take place at least over the length of 100 mm. The warning message was also expected to be sent with minimum occurrence of four crack spots.

**Fig. 6** The test beams with installed SMARTape sensors before the test

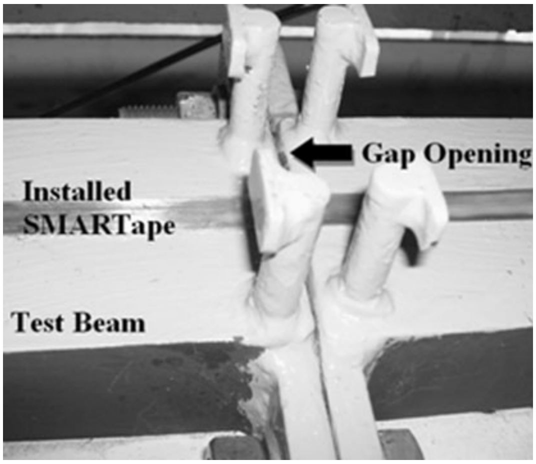

**Fig. 7** A detailed view to the test beam with an installed SMARTape, gap opening and metallic bolts visible

Hypothesis was that the crack should be detected, localised and automatically reported if the crack width exceeded 0.5 mm. Simulated cracks from 0.3 to 5.2 mm with slow, progressive and fast opening of the crack were tested. Every test was filmed by high-speed video camera.

## 7 Field and laboratory test results

### 7.1 Initial field testing results

Initial field testing confirmed the applicability of the system in real conditions. After testing it was chosen that the SMARTape would be installed on the painted steel surface by gluing. It was also decided that the sensor should be installed on the upper flange of the steel girder as the cracking is most likely to take place there. The clamped sensor was attached every meter with metallic clamps that were glued to the painted steel surface. The test location is very windy and the sensor was vibrating and giving uncertain results. In addition, due to long distance between the clamps, the sensor would be less sensitive to crack opening. The glued sensor showed stable results and gluing method was therefore decided instead of clamping.

A lot of interactions with different glue producers were performed before the field test and finally some of the most suitable ones were tested. It was important to find out the possible chemical reactions that might take place either between glue and sensor material or between glue and paint in long term. The selected glue was not only shown to be the best glue with good shear strength for full strain transfer but also able to delaminate with occurrence of high strain that is good in order to not break the fibre. In addition, the installation also gave some practical experience about working on the bridge at real conditions. This practical experience helped when designing the global system on the bridge, in installation planning and in decision making when proceeding with the project. More detailed information about the initial field testing and installation can be found in [2].

### 7.2 FAT results

FAT verified procedures concerning gluing, crack detection, delaminating of the SMARTape with high strain as well as the temperature compensation algorithm. FAT also showed that it is possible to detect cracks with the minimum width of about 0.5 mm that is redistributed over a length of 100 mm. The delamination mechanism was confirmed by the laboratory test. High Young modulus and strength of SMARTape significantly contributed to such good results. Crack detection algorithm with a special test set-up reported excellent performance and the repeatability of the test was high. More information of these FATs can be seen in [6].

### 7.3 SAT results

SATs confirmed selected fundamental functions of the DiTeSt units including channel switches, sensors, temperature cables and software on the main server. Two separate full-scale load tests that were carried out confirmed the static function of the system in addition to several other functions. These load test results as well as temperature study of the bridge are beyond the scope of this paper.

## 8 On-site crack detection test results

Results for the crack detection test on-site are described in detail in this section. An overview of tests that were performed in SAT 2 and later can be seen in Table 2.

### 8.1 Results for test 1

The gap was first opened to 0.3 mm in a few seconds, simulating the crack of the same magnitude. Neither delamination nor crack detection occurred. Afterwards the crack was rapidly increased to 0.7 mm and delamination noise was heard. The crack was detected and localised, and the warning message was sent. After that the gap was opened rapidly to 3.4 mm. The crack was detected and localised, and the warning message was sent again.

As there is a risk for larger cracks to occur on the bridge, it was decided to continue the test. This time the crack was rapidly increased up to 5.2 mm. Crack was not detected and therefore not localised and no warning message was sent. The measurement was repeated several times in the next 24 h, but the crack was still not detected. Due to local optical losses generated by crack, only three crack spots occurred. Delamination did occur but was shorter than half of spatial resolution and thus not detectable on the main strain trace (main peak). The measurement was retaken after 20 days and the crack was not directly detected either. Anyhow, this time a high value of strain over 9,000 micro-strains was noticed in the main trace. This means that delaminating increased in time and high tension became visible by main peak. In reality with the software running, a high strain would be detected and the crack would be detected indirectly. Figure 8 shows the different crack scenarios. Test 1a simulating a crack width of 0.7 mm shows up 4 crack detection spots around 7,000 micro-strains. Test 1b simulating a crack width of 3.4 mm also shows up 4 crack detection spots, this time around 10,000 micro-strains. Test 1c simulating a crack width of 5.2 mm shows up 3 crack spots in 2 measurements. Test 1d that was performed 20 days after the actual test also shows up 3 crack spots and a strain change over 9,000 micro-strains.

### 8.2 Results for test 2

The gap was opened rapidly to 1.6 mm, simulating the crack of the same magnitude. Delaminating was noticed by produced noise. The crack was detected, correctly localised and warning message was correctly sent. Five crack detection spots over 12,000 micro-strains were shown in the measurement plot. Therefore, test 2 behaviour showed the expected outcome, see Fig. 9.

### 8.3 Results for test 3

The gap was rapidly opened to 3.3 mm, simulating the crack of the same magnitude. Delaminating was noticed by produced noise. It was also measured and delamination east of the gap was 12.5 cm and 10.5 cm west of the gap. The total delamination length was 23 cm. Breakage of the optical fibre inside SMARTape was caused by this opening approximately 13.5 cm west of the gap. Although the optical fibre was broken, it was possible to complete the measurement since the light could pass through the breakage point. Due to reflection in breakage point, it was impossible to perform correct strain measurement and direct crack detection around the breakage point, but at that point signal saturation occurred. The signal saturation is recognised by the system as extremely high value of strain (at the limits of range); the crack was detected indirectly as extremely high absolute value of strain.

Delaminating started at paint–steel interface in the gap area, but then propagated to glue–sensor interface. SMARTape sensor is shown in Fig. 10. Portion of paper was inserted in both sides between sensor and glue in order to illustrate extremities of delaminated section. The fibre breakage point is also clearly visible as a glowing, bright spot on the right side of the figure.

### 8.4 Results for test 4

The gap was slowly opened to 0.6 mm, simulating the crack of the same magnitude. The crack opening was created during 12 min and 15 s. Delaminating of SMARTape did not occur. Only three crack detection spots occurred that were not sufficient to trigger the warning. The reason for having such a small amount of points was

**Table 2** Tests 1–4: test 1 was extended at site to include three different scenarios

| Test | Description | Crack opening (mm) | Delamination | Crack detection | Warning sent |
|---|---|---|---|---|---|
| 1a | Fast crack opening on Specimen 1 in two steps | 0.3 | 0.3 mm: no | Yes | Yes |
| | | 0.7 | 0.7 mm: yes | | |
| 1b | Progressive fast crack opening on Specimen 1 | 3.4 | Yes | Yes | Yes |
| 1c | Progressive fast crack opening on Specimen 1 | 5.2 | Yes | No | No |
| 1d | Measurement from 1 c repeated after 20 days | 5.2 | Yes | No | No |
| 2 | Fast crack opening on Specimen 2 | 1.6 | Yes | Yes | Yes |
| 3 | Fast crack opening on Specimen 3 | 3.3 | Yes | Yes | No |
| 4 | Slow crack opening on Specimen 4 during 12.25 min | 0.6 | No | No | No |

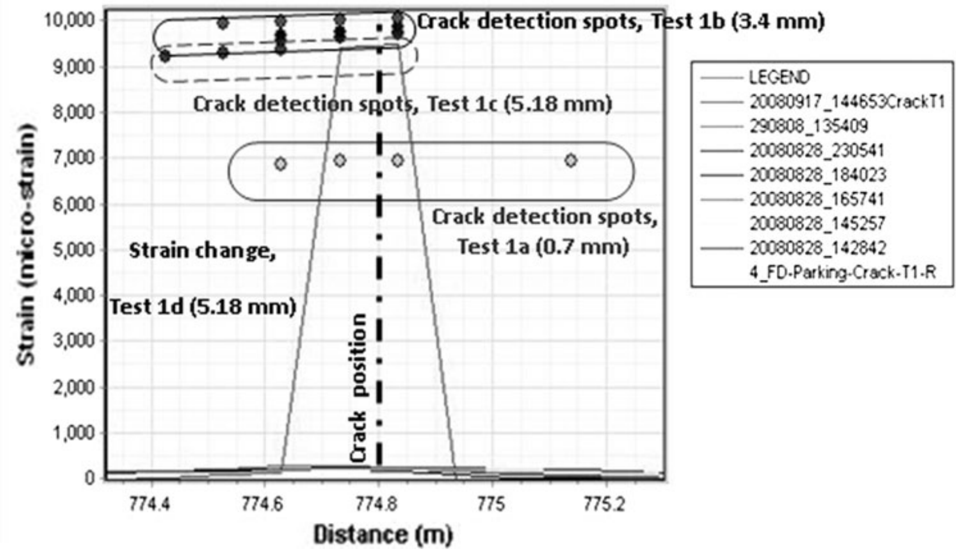

**Fig. 8** Crack test 1: different crack scenarios

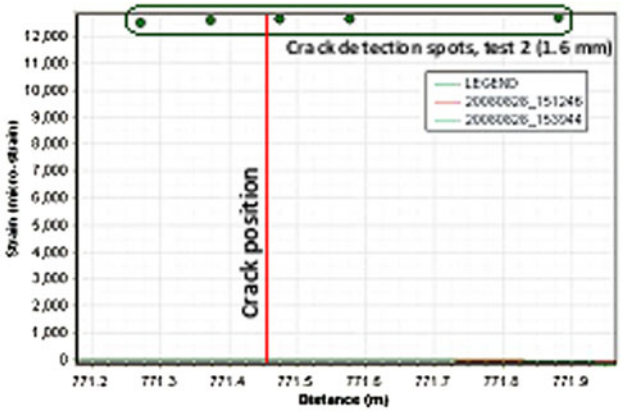

**Fig. 9** Crack test 2: detected "crack spots" seen with an opening of 1.6 mm

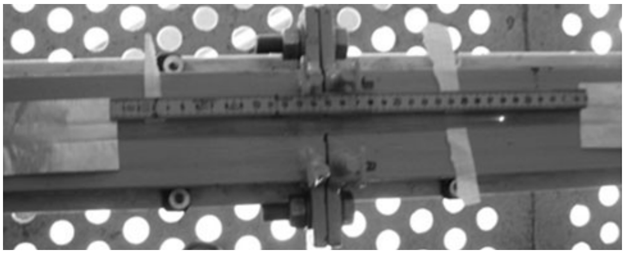

**Fig. 10** Crack test 3: delamination from the gap to both sides marked with portion of paper and fibre breakage seen as a glowing spot to the right of the gap

insufficient length of SMARTape subject to high strain and the length was insufficient because no delamination occurred. The test was repeated after 1 day and 20 days, but since no progress in delaminating happened, no crack detection was made, although some crack detection spots occurred.

## 9 Discussion

There is a huge activity in the market to find effective solutions and therefore the literature over several systems was overseen in order to get the depiction about the existing state. The novel method for crack detection and localisation using distributed fibre optic technology called DiTeSt with SMARTape sensors was presented. The method was successfully tested in laboratory and on-site, and implemented in monitoring of the Götaälv Bridge, Gothenburg, Sweden.

High attenuations of optical signal were noted with falling temperatures and temperatures below −8°C. Crack detection method is based on the development on crack identification algorithm implemented in DiTeSt system and SMARTape delamination mechanism. Crack detection does not work properly if having high attenuation. High attenuation was kept moderate by re-installing the sensors and repairing splices, as slightly different behaviour was noticed on the real conditions than with laboratory testing. Therefore, the full-scale beam test on-site was performed in order to clarify some insecurity.

Fast crack opening of 0.5 mm creates delaminating and is therefore successfully detected by the software. Slow crack opening does not necessarily create delamination and is not detected either. Anyhow, the delamination can occur in time and the crack will be eventually detected. If delamination does not take place, the sensor should fail due to stress concentration, and crack is detected indirectly as failure of sensor. Fast crack opening of 3.3 mm on the test beam created a breakage on the optical fibre. The consequence is that the light still might pass by and the crack is both detected and localised by DiTeSt system. If the fibre is broken so that the light is not passing by, it is necessary to make an Optical Time Domain Reflectometer (OTDR) measurement with a separate OTDR in order to establish the location of the breakage. For small crack openings, not bigger than 4 mm approximately, the delamination length is shorter than half of the spatial resolution and cracks are detected directly using crack identification algorithm. Bigger crack openings can create decrease in optical amplitude which may decrease performance of crack identification algorithm in case the cumulative losses are important, but in short term the delamination will progress and exceed by length half of the spatial resolution. Consequently, the crack becomes “visible” on strain trace and is detected as high strain value that will mean several thousands of micro-strain. For delamination shorter than tenth of spatial resolution, crack opening is small and considered as inoffensive for structure. Based on the results of the crack test 3, improvements of software were proposed in order to make possible identification of similar situations automatically. It is also important that the SMARTape that is used stands for really high quality in order to reach good results. The production of the tape must be optimised and the produced tapes must be controlled optically, mechanically and visually before the installation.

Designing a SHMS for an existing bridge with several malfunctions/deterioration is very delicate process indeed. Installation needs to be planned in detail and at early stage of the project. Still, many unexpected situations occur and this sets really high demands for both installation team as well as for the actual SHMS. The workforce needs to be very creative and the system needs to be adjustable during process if required with the kept stability and quality. Both various technical and practical expertise is needed. Also, good open communication between the different parts of organisation will help when finding flexible solutions with pioneer technology in the field with little or no experience from the past.

## 10 Conclusions

Distributed strain and temperature monitoring for long-term monitoring was implemented for the very first time on a large bridge structure. Novel crack detection and localisation system, based on development on crack identification algorithm implemented in DiTeSt system and SMARTape delamination mechanism, was developed, tested and implemented. Also new methods and procedures in installing, testing, modifying and improving a SHMS were developed, tested and proven, both in laboratory and on-site. The data management system is able to perform analysis and send warning messages.

A lot of heuristic knowledge was gathered; crack detection system that can detect, measure and localise cracks is optimal. In order to show redundancy, more tests should be performed, especially with crack detection system in order to get statistics. Also, the different distributed sensory systems need to be compared in order to find best procedures that should be further developed. Several distributed systems show really promising results for various applications and will certainly be used in large scale in very near future.

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