The paper was presented at the Ninth Meeting
"New Trends in Fatigue and Fracture" (NT2F9)
Belgrade, Serbia, 12–14 October, 2009

Branko Glišić[1], Daniele Inaudi[2]

INTEGRITY MONITORING OF FRACTURE CRITICAL BRIDGES

PRAĆENJE INTEGRITETA MOSTOVA KRITIČNIH U POGLEDU LOMA

Original scientific paper
UDC: 624.21.04
Paper received: 20.11.2009

Author's address:
1) Princeton University, E330 EQuad, Princeton, NJ 08540, USA, bglisic@princeton.edu
2) SMARTEC SA, Via Pobiette 11, 6928 Manno, Switzerland, Inaudi@smartec.ch

Keywords
- fracture
- bridge
- structural health monitoring
- distributed sensor

Ključne reči
- lom
- most
- praćenje integriteta konstrukcije
- senzorski merni kabl

Abstract

Many bridges worldwide are approaching the end of their lifespan and it is necessary to assess their health condition in order to mitigate risks, prevent disasters, and plan maintenance activities in an optimized manner. The fracture critical bridges are of particular interest since they have only little or no load path redundancy. Structural health monitoring (SHM) recently emerged as a branch of engineering with a great potential to help the assessment of structural condition. Distributed optical fibre sensing technology has opened a new possibility in structural health monitoring. Distributed deformation sensor (sensing cable) is sensitive at each point of its length to strain changes and cracks. Such a sensor practically monitors one-dimensional strain field and can be installed over all the length of monitored structural members (suspension cables, girders, etc.), and therefore provide for integrity monitoring, i.e. for direct detection and characterisation (including recognition, localization, and quantification or rating) of local strain changes generated by damage. Integrity monitoring principle for bridges is developed and presented in this paper. Finally, a large scale real on-site application is briefly presented.

Izvod

Mnogi mostovi širom sveta se približavaju kraju svog veka trajanja i potrebno je oceniti njihovo stanje da bi se umanjio rizik, sprečile katastrofe i na optimalan način uveo sistem održavanja. Mostovi kritični u odnosu na lom su posebno značajni jer imaju mali ili nikakav kapacitet opterećenja. Praćenje integriteta konstrukcije (SHM) je nedavno uvedeno kao tehnička oblast velikih mogućnosti da se oceni stanje konstrukcije. Tehnologija ispitivanja rasporedom optičkih vlakana je nova mogućnost u praćenju integriteta konstrukcije. Raspoređeni senzori deformacija (senzorski merni kablovi) su osetljivi u svakoj tački njihove dužine na promene deformacije i na prsline. Takav senzor praktično prati jednodimenzionalno polje deformacija i može se postaviti po čitavoj dužini komponente konstrukcije (kablovi ovešenja, nosači i druge) čije se stanje prati, i na taj način omogućava praćenje integriteta, tj. neposredno otkrivanje i karakterizaciju (uključujući prepoznavanje i veličinu ili značaj) promene lokalne deformacije prouzrokovane oštećenjem. Razvijen je principijelni postupak praćenja integriteta mostova i prikazan je u ovom radu. Konačno, ukratko je opisana stvarna primena na licu mesta, na realnoj konstrukciji.

INTRODUCTION

Fracture critical members are components in tension whose failure is expected to result in the collapse of the bridge or the inability of the bridge to perform its function, /1/. Fracture critical bridges are those who contain fracture critical members. Practically, a fracture critical bridge by design has little or no load path redundancy with respect to fracture critical members. Thus, the fracture critical bridge is not structurally deficient unless subjected to damage or deterioration – even a new bridge can be fracture critical (by design). Approximately 11% of US bridges are identified as fracture critical, /2/, which corresponds to more than 60 thousand bridges. Aging of these bridges and associated damage and deterioration induced by environmental degradation, wear, and episodic events like earthquake or impact, raise concerns about their safety and longevity.

The collapse of the I35W Minneapolis Bridge, /3/, is a sad reminder of the catastrophic consequences of a failure of a fracture critical bridge, /4/: loss of 13 lives, while 145 people were injured; unavailability of the river crossing generated economic loss of 400,000 USD per day for road-users. In addition, losses for the Minnesota economy were estimated to 17 million USD in 2007 and to 43 million USD in 2008. The cost of rebuilding the bridge was approximately 234 million USD, /5/.

A modern bridge must be able to "generate" and "communicate" information concerning the changes in its structural health condition and potential damage or deterioration, to responsible operators and decision makers, in-time–automatically or on-demand, and reliably. To achieve this, a modern bridge should be equipped with a "nervous system," a "brain" and "voice lines," i.e. with a structural health monitoring (SHM) system, 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, with important input for bridge managers.

The standard monitoring practice is based on the choice of a reduced number of points, supposed to be representative of the structural behaviour, and their instrumentation with discrete sensors, short-gage or long-gage. If short-gage sensors are used, the monitoring will give interesting information on local behaviour of the construction materials, but might miss behaviours 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, i.e. any phenomenon that has an impact on the global structural behaviour is detected and characterized. However, reliability of detection and characterization of damage that occurs in 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 in discrete points, while the distributed sensors are capable of one-dimensional (linear) strain fields monitoring. Distributed sensor can be installed along the whole length of 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 the structure can be reliably performed.

DISTRIBUTED SENSING

Distributed sensor (or sensing cable) can be represented by a single cable which 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, i.e. it provides with distribution of measurements along the sensor. Moreover, it requires a single connection cable to transmit the information to the reading unit, instead of a large number of connecting cables required in the case of wired discrete sensors. Finally, distributed sensors are less difficult and more economic to install and operate. Distributed sensing is made available by recent developments in domain of fibre optic sensing technologies, as represented in Fig. 1.

Three main physical principles are used in distributed sensing: Rayleigh scattering, /7/, Spontaneous Brillouin scattering, /8/, and Stimulated Brillouin scattering, /9/. Techniques based on Rayleigh scattering and Spontaneous Brillouin scattering are limited to short length, but that one based on Stimulated Brillouin scattering allows for monitoring of long structures. It is presented here in more detail.

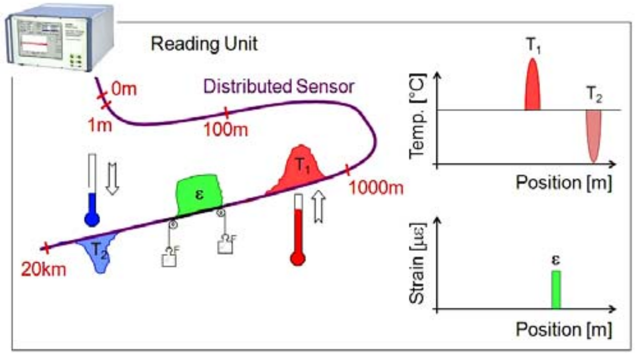

Figure 1. Schematic representation of distributed sensor.
Slika 1. Shematski prikaz mernog kabla

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 fibre. 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. 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, and allows for monitoring of very large lengths, /10/, e.g. 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, 50 km lengths can be reached. Remote modules can be used to triple monitoring lengths. Typical performance of the system used for monitoring fracture critical bridges is given in Table 1, /11/.

Table 1. Performance of the distributed sensing system used for monitoring of fracture critical bridges.
Table 1. Karakteristike sistema mernog kabla primenjenog za monitoring mostova kritičnih u pogledu loma

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

When strain sensing is required, the optical fibre 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, and an excellent bonding between strain optical fibre and the host structure is to be guaranteed. To allow such a good bonding it is necessary to integrate the optical fibre within a tape in the similar manner as the reinforcing fibres are integrated in composite materials. To produce such a tape, we selected a glass fibre reinforced thermoplastic with PPS matrix, /12/, of excellent mechanical and chemical resistance properties. Since its production involves heating to high temperatures (in order to melt the matrix of the composite material) it is necessary for the fibre to withstand this without damage. In addition, the bonding between the optical fibre coating and the matrix has to be guaranteed. Polyimide-coated optical fibres fit these requirements and were selected for this design. Details of thermoplastic composite tape with integrated optical fibre are given in Fig. 2.

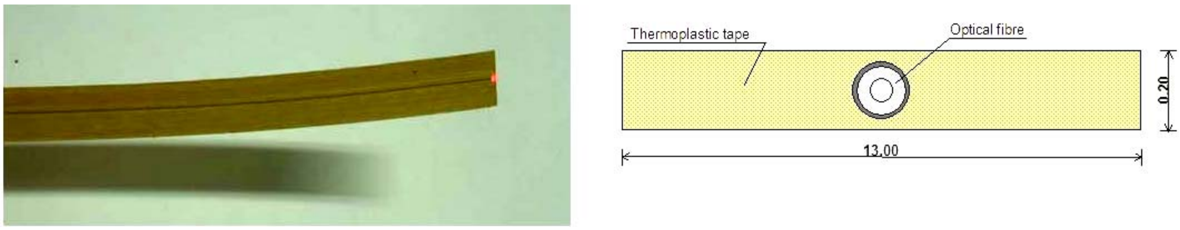

Figure 2. Distributed sensor details.
Slika 2. Detalji mernog kabla

Crack detection with distributed sensor

Although distributed deformation sensors are sensitive to strain at every point of its length LD, they measure at discrete points that are spaced by a constant value, called the sampling interval, and denoted with LSI, and the measured parameter is actually an average strain measured over a certain length, called the spatial resolution and denoted with LSR, /13/. Coordinates x_i of discrete measurement points (defined by the sampling interval) are defined as follows: $x_i = x_0 + i \cdot \mathrm{LSI}$, $i = 1,2,3,..., n$, n = integer (LD/LSI), 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 Fig. 3.

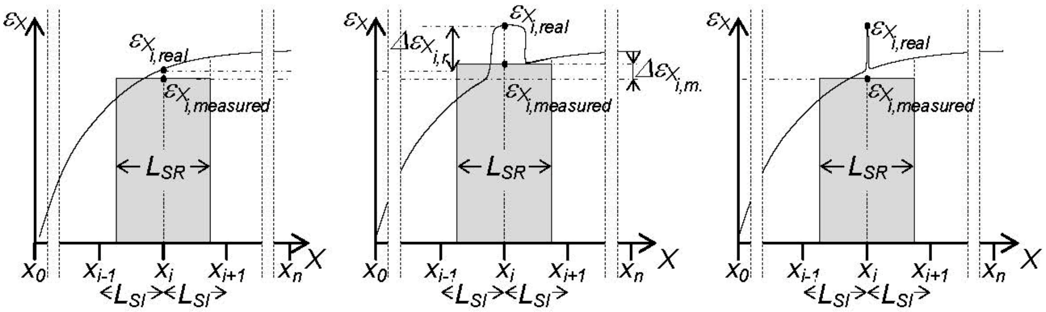

Figure 3. Simplified presentations of principle of distributed sensor measurement. (a) "smooth" strain change over LSR, av. strain measurement within accuracy specifications; (b) significant strain change over L ≥ LSR/2, detected by av. str. measur. as $\Delta\varepsilon_{i,m}$; (c) significant strain change over L < LSR/2 (crack), "invisible" in av. strain measurement.
Slika 3. Uprošćeni prikaz principa merenja pomoću mernog kabla. (a) „blaga" promena deformacija oko LSR, pros. izmerena deform. je unutar predviđene tačnosti; (b) značajna promena deformacija preko L ≥ LSR/2, otkrivena pros. merenjem deform. kao $\Delta\varepsilon_{i,m}$; (c) značajna promena deformacija preko L < LSR/2 (prslina), „nevidljive" u prosečnom merenju deformacija.

Let the real strain distribution along the sensor without crack is as presented in Fig. 3a. For each point with coordinate x_i the strain is averaged over the segment [x_i–LSR/2, x_i+LSR/2] as presented in Fig. 3a (gray area represents equivalent average strain), and the measurement value is attributed to point x_i. Difference between real and measured strain in point x_i is small (εx_i, measured ≈ εx_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 localised, but not accurately measured, as shown in Fig. 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 fibre such as generated by cracks, Fig. 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 Fig. 3c. In addition, high local strains can lead to physical rupture of the sensing optical fibre.

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 /14/. They are briefly summarised in this paper.

The encoding parameter for DiTeSt system is Brillouin frequency of light in optical fibre. 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 in Fig. 4a is obtained with spatial resolution of 1 m.

If the event that changes Brillouin frequency (strain or temperature change) occurs over length which is shorter than spatial resolution, but longer than its half, this event will be detected and localised 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 its tenth, 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, /15/. Example of secondary peak created with spatial resolution of 1 m, and localised strain of approximately 4000 με applied over 10 cm is given in Fig. 4b.

Crack opening is a typical event that may create localised change in Brillouin frequency, thus the diagram shown in Fig. 4b actually corresponds to the crack opening of 4 mm that acts over the length of sensing fibre of 10 cm. 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, /15/. These spots will be referred to as “crack spots” in the further text.

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

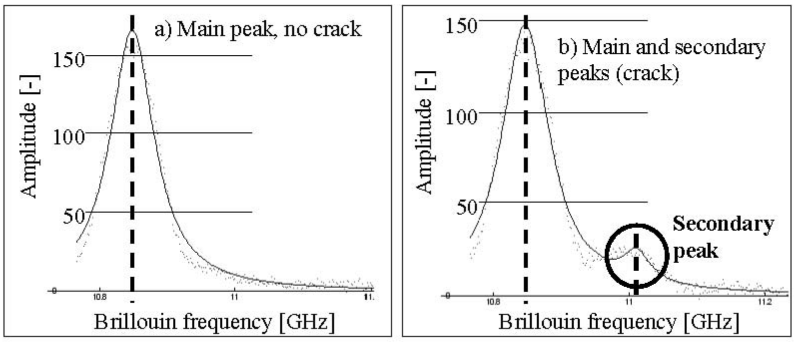

Figure 4. Main peak of Brillouin frequency generated by strain change in one point of the sensing optical fibre, and both main and secondary peaks generated in case of crack occurrence (courtesy of Omnisens SA, Switzerland).
Slika 4. Glavni pikovi učestanosti Brijuna nastali promenom deformacije u jednoj tački optičkog senzorskog vlakna, i glavni i sekundarni pik nastali pri pojavi prsline (ljubaznošću Omnisens SA, Švajcarska)

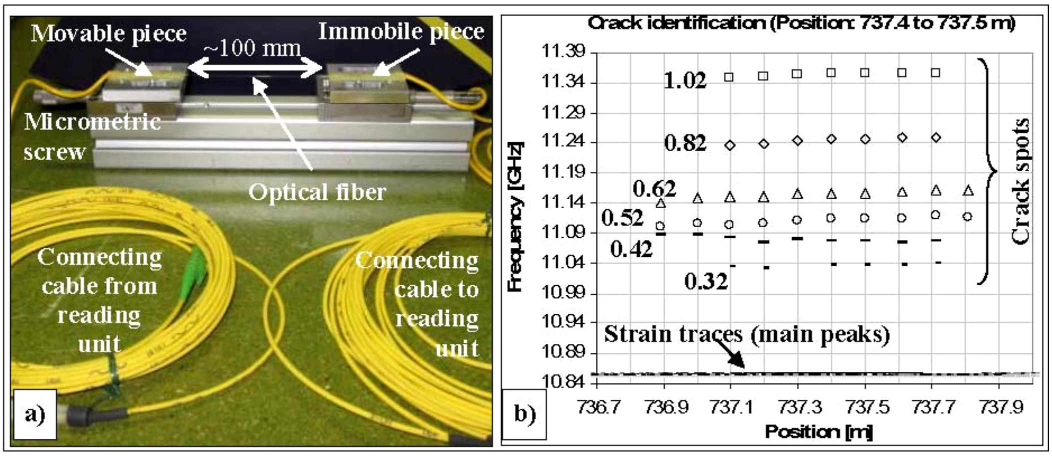

Figure 5. Crack algorithm testing set-up (a) and summary of results with successful crack detection (b).
Slika 5. Uređaj potreban za algoritam prsline (a) i pregled rezultata uspešnog otkrivanja prsline (b)

Having provided that the sensor is bonded to the structure in every point, the crack in structure generates concentrated strain and stress in sensor at crack location. The stress generated by crack is very high and there is 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 a mechanism of delamination of sensor at location of crack. The used adhesive is carefully selected in order to allow delamination of the sensor over length not shorter then 10 cm in case of crack opening of 0.5 mm or more. Delamination will help avoid breakage of sensor 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 sensor, composite tape and optical fibre. 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 sensor was glued to metallic supports that were then exposed to relative translation movement simulating crack opening. This 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 Fig. 6a.

The gap, simulating crack, was open for 0.5 mm. Delamination was noticed by characteristic noise, and verified visually. The 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 30%, while the length of delamination increased slowly in time for 50% approximately, and stabilised after few days. This indicates that after initial delamination is formed, delamination length slowly progresses in time and stabilizes after few days. Results of delamination tests proved the delamination mechanism and confirmed good selection of adhesive and installation procedures. Example of delaminated sensor after removal of protective aluminium tape is given in Fig. 6b.

After a series of laboratory tests that confirmed system capability to detect and localise crack occurrence with opening not smaller than 0.5 mm, the system is installed on the bridge and full-scale crack tests were performed. The results of tests confirmed a good performance of implemented crack detection method. Results are currently not enclosed, but they will be available soon.

Integrity monitoring

A distributed deformation sensor can be installed over the whole length of the monitored structural member, and therefore provide for direct detection and localisation of local strain changes generated by damage. The principle of integrity monitoring is given in Fig. 7, /13/.

Since distributed sensors provide for one dimensional strain field monitoring, they can be used with twofold purpose: for integrity monitoring and for distortion and shape change monitoring. Two parallel distributed sensors installed parallel elastic line of the girder for distortion monitoring, /13/, and shape change can be then determined by double integration of distortion. Typical bridge structural members that are candidates for integrity monitoring are the long beams, girders, decks, and suspension cables.

On-site application

Götaälvbron, /13/, the bridge over the Gota River, built in the 1930s is now more than 70 years old. As one of three communication lines between two sides of the Gota River, Götaälvbron is a bridge of high importance for the city of Gothenburg (Sweden). The bridge is more than 1000 m long and consists of a concrete slab poured on nine steel continuous girders supported on more than 50 columns. During the last inspection, a number of cracks were found in steel girders, notably in zones above columns, exposed to negative bending moments. These cracks are caused by fatigue due to the average quality of the steel. A view of the bridge is presented in Fig. 8.

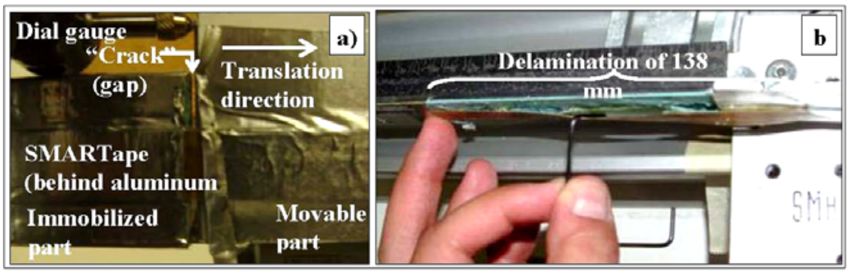

Figure 6. Delamination testing set-up before (a) and during (b) crack simulation.
Slika 6. Uređaj za ispitivanje raslojavanja pre (a) i u toku (b) simulacije prsline

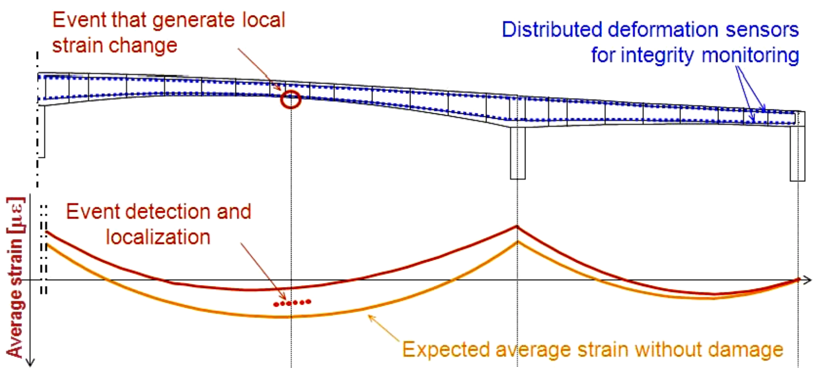

Figure 7. Schematic representation of integrity monitoring.
Slika 7. Shematski prikaz monitoringa integriteta

Figure 8. View of Götaälvbron bridge.
Slika 8. Izgled mosta u Geteborgu

The bridge is now repaired and traffic authorities (Trafikkontoret) would like to keep it in service for the next 15 years, but 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 caused by fatigue. Thus, continuous bridge integrity monitoring is applied, /14/.

The monitoring system selected for this project must provide for both crack detection and localisation and for strain monitoring. Since 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 fibre-optic monitoring system based on stimulated Brillouin scattering.

Summarising, the monitoring aim has been to apply long-term integrity monitoring of the bridge. Single tasks in monitoring system specifications the have been requested:

- To detect and localise new cracks that may occur due to fatigue;
- To detect strain changes unusual short-term and long-term;
- To detect cracks and unusual strain changes over the full length of five girders, in total 5 km;
- To perform one measurement session every 2 h;
- To perform self-monitoring; that is, to detect malfunctioning of the monitoring system itself;
- To allow user-friendly and practical data visualisation;
- To send by default warning messages to responsible entities;
- To function properly for 15 years.

The monitoring system for continuous monitoring of approximately 5 km of girders with distributed sensors was installed and successfully tested in 2007–2008.

DISCUSSION AND CONCLUSION

In the paper, one specific case of bridge integrity is considered and an accepted solution for long term monitoring is presented in detail. In the considered case, critical cracks occurred at the macro level, that enabled after diagnostics to design a proper repair action and to apply convenient set-up to continuously monitor structural integrity.

However, a similar problem has been recognised in almost all civil engineering structures, and also in many other structures (steel structures, pressure equipment). The problem of structural integrity has been considered in theoretical sense after introduction of fracture mechanics and damage mechanics, the diagnostics of structural state became a most important step, e.g. /16, 17/. It attracts the attention of scientists and researchers, on one hand, but also of the authorities worldwide, with the final goal to increase structural safety and reliability in service. For civil engineering structures, convenient codes and standards are prescribed for inspection and maintenance in order to control the integrity /18, 19/. Just to mention, in Denmark the public civil engineering structure can not be accepted without an attached detailed computer model.

The development of new devices, means and procedure to help integrity, as fibre optic sensors, /20, 21/, is the great help to achieve these goals.

Important attention is also paid in the application to bridges, /22, 23/.

Compared to simple strain measurement in a large number of discrete points, distributed sensing technology has a unique capability of monitoring one-dimensional strain fields. Consequently, the set-up can be installed over all the length of the structure and provide for direct damage detection, localisation, and quantification. Besides the high measurement performance, it requires simple connection to the reading unit, which significantly simplifies work related to cabling of the system.

The novel method for integrity monitoring of fracture critical bridges accepted in the case of Götaälvbron using distributed fibre optic technology based on Stimulated Brillouin scattering has been developed and presented here. The integrity monitoring method is based on crack or local deformation identification algorithm and sensor delamination mechanism. The method was successfully tested in laboratory and on-site, and implemented in monitoring of Götaälbrovn, Gothenburg, Sweden.

ACKNOWLEDGMENTS

The presented work and Götaälvbron project could never be realised without precious help and participation of several persons from several companies.

Authors of this article would particularly like to thank Frank Myrvoll, Ralph Omli, Eric Lied, and Per Debloug from Norwegian Geotechnical Institute (NGI), Norway, Benny Bergstrand, Leif Arvidson, Stefan Pup, Ingvar Larsson, and Jan Tuvert from Trafikkontoret, Sweden, Merit Enckell from Royal Institute of Technology (KTH), Sweden, and Fabien Briffod, Fabien Ravet, Marc Niklès and André Bals from Omnisens SA, Switzerland.

Great thank to Luigi Bernasconi and Alfred Rüegsegger from 3M–Switzerland, Jens C. Kärger from Gurit, Switzerland, Milan Djurić and Igor Maletin from Minova Bemek, Sweden, Florian Thiele from University of applied sciences Mittweida, Germany, and Daniele Posenato and Riccardo Belli, from SMARTEC SA, Switzerland.

REFERENCES

1. AASHTO LRFD Bridge Design Specifications, 3rd Ed., *American Association of State Highway and Transportation Officials,* Washington, D.C., 2004.
2. TRB, NCHRP Synthesis 354, Inspection and Management of Bridges with Fracture-Critical Details, A Synthesis of Highway Practice, *Transportation and Research Board*, Washington, D.C., 2005.
3. MnDOT, Bridge #9340, I-35W over the Mississippi River at Minneapolis, MN, Annual Bridge Inspection report, September 2001, *Minnesota department of transportation, Metro Division, Maintenance Operations, Bridge Inspection,* Roseville, MN, 2002.
4. Minnesota Department of Employment and Economic Development – DEED. Economic Impacts of the I-35W Bridge Collapse, 2009.
5. Minnesota Department of Transportation – MnDOT. I-35W St. Anthony Falls Bridge. FAQ, 2009.
6. Posenato, D., Lanata, F., Inaudi, D., Smith, I.F.C., *Model-free data interpretation for continuous monitoring of complex structures*, Advanced Engineering Informatics, 22 (1), 2008, pp.135-144.
7. Posey, R.Jr., Johnson, G.A., Vohra, S.T., *Strain sensing based on coherent Rayleigh scattering in an optical fibre*, Electronics Letters, 28th September 2000, Vol. 36, No. 20, pp.1688-1689.
8. Wait, P.C., Hartog, A.H., *Spontaneous Brillouin-Based Distributed Temperature Sensor Utilizing a Fiber Bragg Grating Notch Filter for the Separation of the Brillouin Signal*, IEEE Photonics Technology Letters, 13(5), 2001, pp.508-510.
9. Kurashima, T., Horiguchi, T., Tateda, M., *Distributed temperature sensing using stimulated Brillouin scattering in optical silica fibers*, Optics Letters, Vol.15, No18, pp.1038-1040, 1990.
10. Thevenaz, L., Facchini, M., Fellay, A., Robert, Ph., Inaudi, D., Dardel, B., *Monitoring of large structure using distributed Brillouin fiber sensing*, Proc. of 13th International Conference on Optical Fiber Sensors, Kyongju, Korea, SPIE, OFS-13, 3746, 1999, pp.345-348.
11. Glisic, B., Posenato, D., Persson, F., Myrvoll, F., Enckell, M., Inaudi, D., *Integrity monitoring of old steel bridge using fiber optic distributed sensors based on Brillouin scattering*, SHMII-3, The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure, Paper on conference CD, November 13-16, 2007, Vancouver, Canada.
12. Glisic, B., Inaudi, D., *Sensing tape for easy integration of optical fiber sensors in composite structures*, 16th International Conference on Optical Fiber Sensors, Nara, Japan, We 3-8, 2003.
13. Glisic, B., Inaudi, D., Fibre Optic Methods for Structural Health Monitoring, John Wiley & Sons, Inc., 2007.
14. Glisic, B., Enckell, M., Myrvoll, F., Bergstrand, B., *Distributed sensors for damage detection and localization*, *SHMII-4*, The 4th International Conference on Structural Health Monitoring of Intelligent Infrastructure, Paper on conference CD, July 22-24, 2009, Zurich, Switzerland.
15. Ravet, F., Briffod, F., Glisic, B., Nikles, M., Inaudi, D., *Submillimeter crack detection with Brillouin based fiber optic sensors*, IEEE Sensors Journal, Vol.9, No.11, pp.1391-1396, 2009.
16. Maneski, T., Ignjatović D., *Structural Performance Diagnostics*, Structural Integrity and Life, Vol.4, No1 (2004), pp.3-7.
17. Daničić, D., Maneski T., Ignjatović, D., *Structural Diagnostics and Behaviour of Bucket Wheel Excavator*, Struc. Int. and Life, Vol.10, No1 (2010), pp.53-60.
18. Svetel, I., *Information Technology Standards and Structural Life in Civil Engineering*, Struc. Int. and Life, Vol.7, No3 (2007), pp.167-176.
19. Svetel, I., *Application of Information Technology in Architectural – Civil Engineering Design for Object Integrity Realization*, Struc. Int and Life, Vol.5, No2 (2005), pp.77-86.
20. Kojović, A., Uskoković, P., Aleksić, R., Mitraković, D., Živković, I., Tomić, M., Brajović, Lj., Milinković, S., *Damage Monitoring of Composite Laminates by Means of Intensity Based Fiberoptic Sensors*, Struc. Int. and Life, Vol.5, No1 (2005), pp.19-30.
21. Živković, I., Maksimović, S., Aleksić, R., *Numerical and Experimental Analysis of Initial Failure of Composite Laminates with Embedded Fiberoptic Sensors*, Struc. Int. and Life, Vol.4, No3 (2004), pp.137-148.
22. Kirić, M., Grujić, B., *Application of Information Technology Standards for Non-destructive Testing of Bridges*, Struc. Int. and Life, Vol.7, No3 (2007), pp.177-185.
23. Gubeljak, N., *Application of Stereometric Measurement on Structural Integrity*, Struc. Int. and Life, Vol.6, No1-2 (2006), pp.65-74.