Autonomous Crack Response Monitoring on civil structures with Fiber Bragg Grating displacement sensors

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ABSTRACT

This paper describes an advanced application for fiber Bragg grating (FBG) sensors. We report the results of an autonomous crack response monitoring that was performed with a highly efficient, modified monitoring unit, performing static long term measurements and the simultaneous recording of dynamic events at the same time. A crack displacement sensor with an adjustable measurement range for the measuring of fast-sampled short term data as well as for the long term behavior of a critical structural damage of a civil building is presented.

Keywords: fiber optic sensors, fiber Bragg sensors, strain measurement

1. INTRODUCTION

It is commonly accepted that due to their small dimensions fiber Bragg grating (FBG) sensors do hardly irritate structures [1][2]. Beside this the Bragg gratings are known as long term stable sensors that can measure many years without any zero point offset. Therefore FBGs can be efficiently used for the monitoring of civil and industrial structures in terms of damage recognition or evaluating ageing processes. A number of papers has been released dealing with damage strain and/or temperature monitoring of such structures.

In our application, we considered Bragg grating sensors for long-term monitoring of the displacement of cracks and gaps in concrete structures. With the proposed system, the crack width itself has actually not been measured, but the variation of the crack width. The cracks had been induced by recent natural or artificial seismic events. Especially ancient buildings are of huge interest for the described system in order to observe already existing damages. Occasionally and subsequently occurring seismic waves (induced by earth quakes or explosions that propagate along the earth surface) cause strain in large structures. The high resolution monitoring of this strain was described in [3].

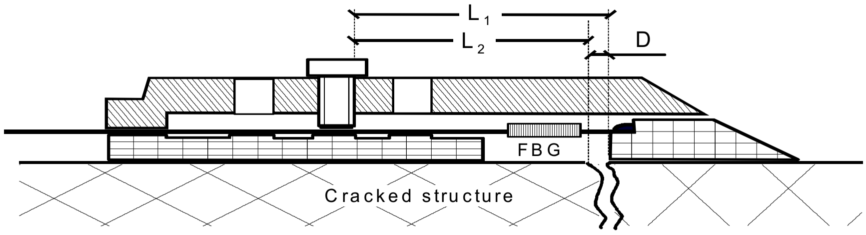
However, this measurement technique fails in the case that the structure is pre-damaged which results in cracks. If these cracks are present nearly all strains occurred by tensions that are orthogonal to the crack direction will vanish. The result is a displacement of the parts of the cracked structure. Several techniques are known to observe the crack movement,. and interpolating the relation between crack movement and critical damage [4][5].

The majority of these techniques is tailored to either the observation of short term movements, or the interrogation of long term behavior. We introduce a system which is capable to record both the static and the dynamical states of a crack displacement.

2. SENSOR CARRIER

The shearing movement of a crack depends often on the particular situation. While one type of cracks will only move few micrometers, others will shear off up to a centimeter or more. The most types of cracks we encountered moved around 0.1 to 2.5 millimeters.

It is known that for a sensor FBG, a sensible limit is 1 percent pulling strain, whereas the resolution is approx. 10^{4}. In the case of a measurement base length of 100 mm and an expected maximum gap opening of 1.2 mm, the strain limit value might be exceeded. On the other side, a crack sensor should not have too large dimensions, especially for indoor measurement. Therefore we adapted a special transmitting sensor carrier with fiber Bragg gratings based on the usually used configuration for high-resolution measurement strains in solid structures [2]. In opposite to that former configuration we now used a setup with adjustable measurement range, depending on the expected crack movement amplitude.



$L_1 = 120$ mm

$D = 1$ mm

$L_2 = 119$ mm

$GF_{FBG} = 0.79$

Fig.1: Sensor carrier with adjustable gear ratio to adapt the measurement to the expected crack movement amplitude

The Bragg grating we used in our field test, has a length of 15.0 mm, and a peak reflectivity of 95 %. The peak reflection wavelength was at 1546.745 nm, and the used fiber is Coning SMF 28. A pre-strain of 3.0 nm was applied onto the FBG. The sensor consists of two main parts to be fixed on both sides of the crack while the re-coated FBG spans the gap *(Fig.1)*. Both parts consist of a base plate and a top plate that is carrying the fiber fixture. The base plate has been fixed and guided well in order to measure the crack movement in a pre-defined direction that is typically directed orthogonal towards the crack direction (in accordance to the crack displacement).

A constant temperature near the FBG presumed, the relation between the crack displacement ΔD and the Bragg wavelength change $\Delta\lambda/\lambda_0$ can be described as follows:

$$\Delta D = \Delta L_1 = L_1 \cdot GF_{FBG} \cdot \frac{\Delta\lambda}{\lambda_0} \qquad (1)$$

By varying the length L_1 with the fiber fixture, it is possible to change the measurement range for a given value of $\Delta\lambda$ that is typically 12 nm, with respect to the expected movement amplitude. The value GF_{FBG} is known for SMF 28 as 0.79. The temperature dependence of a crack is hardly predictable, due to the complexity of the measurement object (i. e. concrete). Therefore, the temperature has also to be monitored. Within the length L_1, the thermal expansion without any other movement leads to a crack displacement ΔD_T of

$$\Delta D_T = \Delta L_1 - (\alpha \cdot \Delta\vartheta \cdot L_2) \qquad (2)$$

which can normally be neglected. The thermally induced wavelength shift $\Delta\lambda_T$ is given by

$$\Delta\lambda_T = TC \cdot \Delta\vartheta \cdot \lambda_0 \qquad (3)$$

The temperature difference $\Delta\vartheta$ induces a wavelength shift dependent on the temperature coefficient $TC = 6.4 \cdot 10^{-6} \cdot 1/K$, which has to be subtracted from the wavelength shift that is induced by the displacement.

3. MONITORING UNIT SYSTEM DESIGN

For monitoring the Bragg grating sensor we use several setups that allow a high resolution measuring of vibrations as well as a long-term measuring of strains [3][7]. After some preparing tests we modified an appropriate setup which is commercially available to enable the system to measure both modes simultaneously.

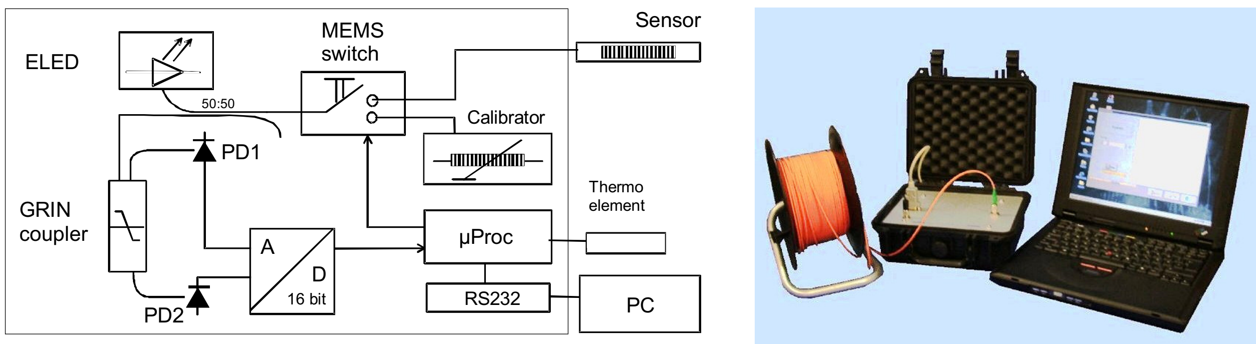


Fig. 2: Self-referencing monitoring system for simultaneous long-term / event monitoring

The interrogation technique that is based on a GRIN lens coupler, two photodiodes PD1 and PD2, and a highly accurate calibration module combined with a temperature compensation, has a permanent internal referencing and is very fast – the two main aspects for a successful crack monitoring [6].

The currents of the photodiodes are converted into digital voltage signals by a 16-bit Analog-Digital Converter (ADC) and are processed in a micro-controller (µProc) with a common RS232 interface. An external computer controls the self-calibration, measuring, triggering and saving of the signals. [3]

The calibrator based on an actively stabilized FBG has a wavelength stability of 1 pm within a temperature range of 5°.. 45°C. Therefore the need for an additional stabilization of the GRIN coupler is void. The permanent calibration cycle is also software controlled and performed by an optical MEMS switch that is specified with a fatigue factor near zero and an infinite lifetime. During the last years, these components got widely spread due to their excellent performance figures like switching times of <0.2 ms and the dramatically dropped prices.

The measurement cycle has sampled values with 500 Hz bursts over 5 minutes, regularly interrupted by a referencing cycle after that time. The bursts were checked for detectable dynamic events by comparing the values with a trigger value [5]. Since one or more values exceed this value, the whole burst will be saved in the data logger. If all values remain below that trigger limit then an average value was calculated from the burst values. This average value is saved for the long term monitoring, and corrected for the temperature induced wavelength shift. For cost reasons, the temperature measurement was not performed by a second FBG but a standard thermocouple.

4. MEASUREMENT RESULTS

Based on the adjustable sensor principle in *Fig. 1*, we set up some different sensor configurations. We focussed on the ability for an easy installation as well as for a reliable and reproducible measurement. The use of the translating mechanics induces an uncertainty in terms of the constancy of the zero value as well as for the strain transmission from the object to the silica core in the fiber. Especially the zero shift is a known fatigue problem with nearly all kinds of sensors whereas the strain transmission can be determined with an initial calibration.

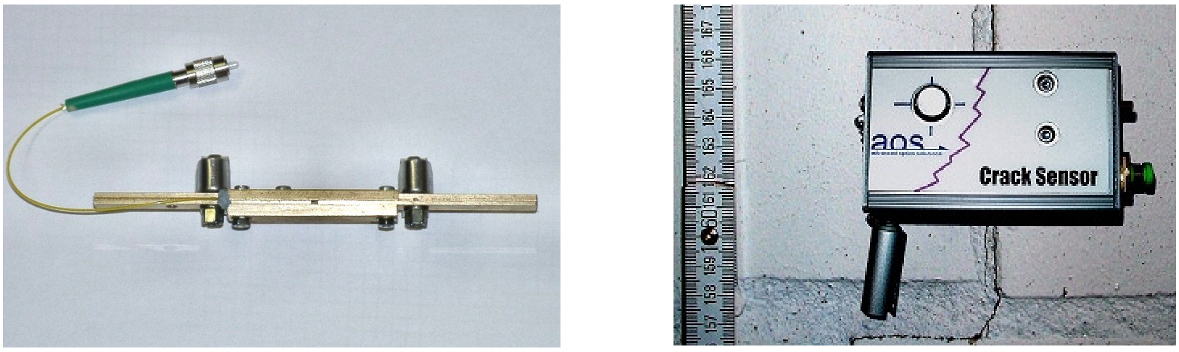


Fig 3: a) Model of a crack monitoring displacement sensor in an open design. *b) More compact model of a crack sensor applied over a vertical crack (MBC Dr. B. Mueller, Leipzig, Germany).*

First field test were carried out in a cottage in Ebersbach near Dresden, ca. 4000 m far from a greywacke stone pit. The crack was vertically aligned in a wall of a room, 4.5 m above the ground. Due to this relatively long distance, we expected a very small blast induced crack displacement.

We applied a sensor with an open design across the crack in order to exclude instabilities of the mechanics of a compact design like shown in *Fig 3b*. The sensor base has been fixed with a glue that is normally used for electrical strain gages. From the date of mounting (22. 06. 2004), we have performed measurements within a period of about two months.

The results in *Fig. 4* show a good correlation between the ambient temperature and the crack displacement. It is obvious that after the blast event the crack width has changed of about one micrometer. The used monitoring system showed an excellent performance for the long term measurement as well as for the dynamic response of the crack.

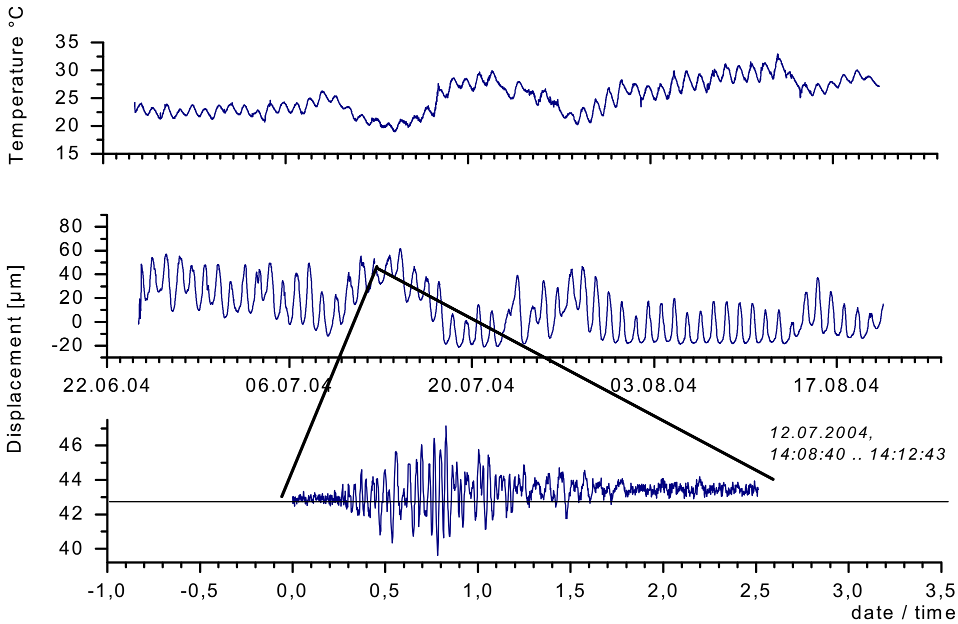


Fig. 4: Long term autonomous crack monitoring of a brick wall. The top graph shows the ambient temperature of the sensor, the middle graph shows the crack displacement, and the bottom graph displays the blast induced seismic wave, that results in a dynamic crack movement.

5. CONCLUSIONS - FUTURE WORK

We have presented a simple sensor system that is able to perform the monitoring of a structural crack's event-related short term behavior as well as a simultaneous long term behavior. Conventional passive crack sensors mostly allow an incremental long-term monitoring, it is hardly possible to watch the crack behavior, the night and day movement and/or dynamical movement induced by events like construction works, etc. Known advanced conventional autonomous crack monitoring (ACM) systems [4] require much more efforts and instrumentation, and compensation techniques for the known stability problems with electrical strain gauges in terms of their long term behavior.

Therefore, despite of the significantly higher price, the fiber Bragg grating crack sensors can find their application field in the surveillance of critical cracks in structures at risk, i. e. ancient buildings. Furthermore, the measurement results can give a fast and obvious information about the destruction potential of impacts on the cracked structure due to the possibility to monitor these events in time. So an autonomous monitoring may help to better pre-estimation compared with current conventional techniques. The future work will be concentrated to build up a compact cost effective, rugged, and easy to handle sensor design which will allow an installation of the measurement system by the end user who is not familiar with fiber optics. From our point of view, especially the fiber handling is the most important issue to establish fiber optic sensors in new fields of application.

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