SMAR 2019 – Fifth Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2019

Fibre-optic sensors in practical applications: challenges and technical needs for a successful use

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ABSTRACT: Fibre-optic sensors are widely used because of their technical and economic benefits. The scientific background is usually well developed; however, there are sometimes restrictions with respect to long-term reliable behaviour of sensor components and/or the long-term stability of the application itself. The first challenge when a decision for any sensor system has to be made is the appropriate selection of the sensor system that provides the required monitoring characteristic. In order to minimize problems in practical application of new sensor technologies, basic rules of validation and of on-site evaluation as well as guidelines and standards should be considered. Very important is, on the other hand, a well-understood communication between the owner and/or user of the structure and manufacturers of sensor components, physicists, and experts which apply sensors. All experts involved in different stages of the development process to create an efficient sensor system, should follow guidelines on how to specify the characteristics of the sensor system and characterize the sensor system's behaviour under all expected environmental loads and attacks. One of the most critical aspect concerns the evaluation of the sensor system's long-term operation on-site.

The presentation will focus on different essential aspects to achieve a long-term stable and reliable sensor system - the basis for a trustworthy monitoring system. Corresponding selected examples will be shown. The presentation will also provide news in related international standardization activities.

1 INTRODUCTION

Monitoring strategies have seen increased acceptance over the past years, and sensing components or even complex sensor systems are installed in various structures, such as in civil engineering, oil and gas engineering, marine and geotechnical environment to observe and evaluate their behaviour. If a non-conventional measurement system is to be used, the most frequently asked question is: Does it work reliably over many years, hopefully throughout the lifetime of the structure that is to be observed?

Calibration and functional verification after many years of use are more difficult. Are the sensors telling us the truth about the state of the structure and are the data interpreted correctly? Can the modelling of the structural behaviour and comparison with the measured data contribute to a better understanding of the structure under complex load conditions?

A special case of using the well-known FBG strain sensor technology is the separation of strain and temperature from the signal response. It requires the application of special measures or a sophisticated data analysis. The following chapters describe some experiences with the transfer of fibre optic sensor technologies into practice. Some critical comments and recommendations are given.

2 CREATING A FIBRE-OPTIC MONITORING SYSTEM

If the monitoring task is well defined with all accompanying technical, logistical and environmental conditions, the monitoring system can be created. Typically, the system designer can source the required components or even the entire measuring system from different suppliers. In a few cases, individual components have to be developed or adapted. However, choosing the optimal sensor system remains a challenge. Some aspects are considered below.

2.1 Interpretation of the sensor system characteristics

A fundamental prerequisite for the correct selection of the sensor system components is the correct communication of their specifications. On the one hand, the specific physical or metrological expressions describing fibre-optic sensor system components - generally all sensor systems - must be understood by the user community, for example by mechanical, civil or geotechnical engineers, who may not be familiar with opto-physical details. Manuals can help; better to use guidelines or standards that correctly describe physical and metrical expressions.

On the other hand, a clear and correct description of the products of manufacturers and suppliers is required. Unfortunately, not all datasheets comprehensively and correctly state the performance determining characteristics. Only two examples to clarify this problem: Sometimes, only precision is quantified in data sheets, not the measurement uncertainty. To know something about the precision of a sensor system is not sufficient because precise sensors can measure wrong because of a possibly unexpected offset (bias) or an incorrect calibration. Another problem occurs if the term ‘accuracy’ is quantified in data sheets. According to the international standards, accuracy is defined as closeness of agreement between a measured quantity value and a true quantity value of a measurand (acc. to VIM, 2012). The term accuracy comprises two aspects: a) difference between a measurement result and the “true” value [called trueness acc. to ISO 5725-1 (1994)], and b) the precision of measurement(s) expressed by the standard deviation and the indicated confidence interval. If only “accuracy” is quantified, no information is available about getting a measurement value close to the “true” one.

In order to obtain unique performance specifications for all components of a fibre-optic sensor system, i.e. to correctly interpret the system characteristics, all specifications and metrological terms must be used in accordance with the available international standards (see chapter 5). It should be self-evident that international units (SI units) are used to describe the results.

2.2 Selection of appropriate sensor type and related system components

Different fibre-optic sensor techniques are usually available to measure strain or deformation. It has not only to be considered the distinction between local or distributed measurements by using local sensors in an optical fibre (e.g. fibre Bragg grating (FBG) or Fabry-Perot sensors) or by using long sensor fibres with fully distributed measurement capability across the fibre length (e.g. distributed strain or temperature sensors), but also the choice of the best physical principle to perform the measurement. Important criteria for selecting the sensor principle including materials, especially for local or quasi-distributed measurements, are:

- Sensor size, robustness against mechanical and thermal attacks, bending, transverse pressure
- Sensitivity to a change in the quantity to be measured
- Number of power-consuming connecting points and neutrality of the line between sensor and recording device (changes in the cabling must not influence the sensor signal and its power)
- Stiffness and size of the sensor, which can influence the integrity or the deformation behaviour of the structure to be evaluated

- Properties, which affect the durability of surface-attached or embedded sensors, e.g. coefficient of friction, thermal residual radial stress, coating stiffness
- Resistance of the materials against chemical and environmental influences.

Another important aspect in the selection of the sensor system relates to the intended operating mode. Depending on the monitoring task, different operating modes may be required:

- Long-term data acquisition with interruption of data recording; data can be recorded periodically without turning off the measurement device, or the device is not active between recordings.
- Data acquisition with long intervals between measurements; the measurement device is usually disconnected and removed from the place of measurement. Next measurement could be done with another device.
- Continuous measurements over a limited period of a few weeks or months; the measurement device remains connected and will not be switched off.

Depending on these operating modes, the reliability of the recorded data can be compromised. The most critical case is the replacement of the device because disconnecting and reconnecting the measurement unit may already lead to a shift in the signal level with the result that the recorded measurement value has an unpredictable uncertainty. In such cases, it is no longer possible to relate the most recent results to the previous ones or to the initial value (zero-point shift or zero-point loss). Consulting engineers or users must therefore decide which measurement regime is intended to make the right choice of sensor system.

2.3 Specific application-related aspects

Sensor applications are not routine work. As a rule, each application has its own specific aspects, technical and logistical conditions, environmental and material specifics. If sensors are to be applied to the surface of components, then the method by which the sensor is fixed (anchored/clamped/glued) must be selected. If integral and/or segmented fibre-optic strain sensors are anchored or clamped, the fastening elements must be designed so that the quantity to be measured is not distorted. Not only the sensor materials but also the fastening elements must not age, especially under UV influence and mechanical vibration or permanent stress. In case of continuously fixed FBG strain sensors, the fixing length must exceed the defined gauge length by a few tens of the fibre diameter to avoid shear-lag problems at the edges (jump of Young’s moduli between the different materials glass/coating/glue/substrate/object of measurement.

Embedded sensors must not affect the behaviour of the object of measurement. Their position within the material must not deviate from the intended position. Small elements that fix the position of the sensor during manufacture must not affect the structure either. In particular, in composite structures in which fibre-optic sensors are embedded between textile layers, their position is important in order to avoid incorrect measurements or malfunctions. Another important aspect is to ensure the transfer of the measurand to the sensing element, for example, to introduce strain changes into the fibre-optic strain sensor or thermal changes into a FBG temperature sensor. The design of the interface determines the quality of the sensor function.

3 RELIABILITY ISSUES

Sensor systems used in laboratory environments provide reliable results as all influences can be estimated and the application/installation is generally successful. The on-site application can be challenging, as difficult conditions can cause assembly-related inefficiencies. Even if all design aspects are taken into account and the installation has been carried out precisely, installation uncertainties can influence reliability and long-term stability. The following sub-sections show the main sources of uncertain measurement results. As the most requested short-gauge length fibre-optic strain sensor type is the FBG-based strain sensor, the reliability aspects are exemplarily related to this particular sensor type.

3.1 Measurand transfer issues

If a FBG strain sensor fibre is to be installed at the surface of a structure, attachment is generally difficult because of the unsymmetrical interface structure. The strain transfer into embedded sensor fibres, especially FBG sensors, is considered to be much easier. Although surface-applied sensor fibres can be visually (roughly) evaluated, bonding defects and/or aging effects cannot be reliably detected. An alternative solution is the use of prefabricated fibre-optic strain sensor patches. They can be glued similar to resistance strain sensors, but ageing (shrinkage) effects after thermal cycling with the consequence of inacceptable measurement results cannot be excluded, see Schukar et al. 2012, Habel (2015). When optical fibres are embedded as strain sensors in homogeneous or orthotropic materials, the risk of its delamination from the composite layers under combined environmental and dynamic stresses is reduced. However, there may be aging or delamination effects that must be identified.

If sensor fibres containing a number of FBG strain sensors are attached to extended structure components to measure non-uniform strain distribution, e.g. in anchors or load-carrying members, the shear stress distribution over the fixed fibre part around every strain sensor has carefully to be considered. Due to materials used with different Young’s moduli, e.g. glass, polymer coating, adhesive, steel or concrete, shear stress is not uniform over the length of the strain sensor; it jumps at the end of the fixed area (see sub-section 2.3).

Strong influence on the strain transfer characteristic, and thus on the measurement uncertainty of the elongation, have adhesives, which are used for fixing of the optical fibre sensor to the surface of structures. For strain measurements, it is important to know - at least - the adhesive’s Young’s modulus and its behaviour under temperature and humidity influence. Not only the curing behaviour of the adhesive influences the ductility of the adhesive, but also the mechanical stress rate. Usually, its thermal expansion coefficient (cte) is five to ten times higher than that of metal, concrete or optical fibre. Due to this significant difference, stresses are introduced into the adhesive when the temperature changes. If the adhesive cannot transfer the thermally caused deformation of the sample to the FBG sensor, the selected adhesive is not suitable for sensor application.

Another problematic observation has been made in the study of commercial adhesives. Relevant properties of adhesives are very often not fully specified in data sheets, e.g. the temperature and humidity dependence of the Young's modulus or even the static and dynamic Young's modulus itself. We observed that adhesives did not show a constant strain gauge factor over the required temperature range with the consequence that those adhesive does not ensure correct strain measurements over the defined temperature range. Details on reliability problems with embedded and surface-attached sensors including methods how to reveal weaknesses and malfunction can be found in Schukar et al. (2012) and Habel (2015).

3.2 Evaluation and calibration issues

All system components that are acquired for measurements on the surface or inside a structure are calibrated and validated by the manufacturer. Strain sensors are provided with the sensitivity characteristic (k-factor), the technical data of devices can be found in data sheets. After installing strain sensors, the original calibration certificate of the sensors may not necessarily be valid due to uncertainties during the installation process and/or due to variable environmental and other factors. The big question is how the correct function of the strain sensor can be evaluated and how its actual k-factor is. If the component on which the sensor is installed cannot be moved to a lab equipped with appropriate test equipment, you can only answer this question by introducing a defined test load to the structure and evaluating the data provided by the sensor immediately after the installation. These data should be compared to other data that also describes the test load response. This test method makes it possible to evaluate the strain transfer behaviour and to define the effective sensitivity of (only) newly installed sensor. The same methodology is, however, not applicable after a longer period of operation because it is not possible to reveal whether a change in the sensor signal is caused by a change in the structure, a change in the attachment, or a change in the sensor itself due to environmental and mechanical conditions. Unfortunately, it is a fact that applied or embedded sensor elements cannot be re-calibrated after installation without removing them from the structure. The only alternative seems to be the installation of the strain sensor at separate plates that are mounted to the structure and can be disassembled later to take them to the laboratory for re-calibration or to use a mobile calibration facility close to the place of the monitored structure, Habel, (2019). Of course, devices can be recalibrated in laboratories, but that's not enough.

If removable sensor plates cannot be used, e.g. in the case of embedded sensors, the alternative is to create a model and reflect (simulate) using this model all real influences that occur on site (one example will be shown in chapter 4). This model could allow the simulation of long-term operating conditions, the testing and evaluation of the sensor’s bonding behaviour, and the study of the creep and delamination effects of the sensors used. A more future method is the use of self-calibrating fibre-optic strain sensors. Such a self-checking FBG strain sensor has been patented (2018), related methodologies are described in Baitinger et al (2014).

4 EXAMPLE FOR RELIABLE DATA ACQUISITION AND EVALUATION - MONITORING OF THE BERLIN MAIN STATION

Monitoring safety-related structures for large crowds such as airports, sports stadiums, concert halls or train stations requires reliable and long-term stable measurement techniques. All components must work safely and stably for the defined period of operation. The choice of the right measuring technology and suitable system components is of great importance. For all components of the measuring system, it should be possible from time to time to evaluate their correct functioning including the appropriate sensor characteristic.

Based on the monitoring example of Berlin Central Station, it should be shown which aspects had to be taken into account in order to minimize the measurement uncertainty in long-term monitoring. This example shows a complex monitoring from the beginning of construction to several years of operation.

The new Berlin Central Station in the heart of Berlin - near the Reichstag - is one of the outstanding architectural highlights in Berlin. The intersection station is made of steel and glass. In the upper area, there are four partially pre-stressed concrete bridges for the east-west railway line at a height of about 10 m above the street level, the north-south railway lines run underground at about -15 m. The building with five different levels has no continuous floors, but is open so that sunlight illuminates the underground platforms. The superstructure of the station, especially the wide glass roof, consisting of approximately 8,700 glass panes, is spanned over the four upper pre-stressed railway bridges. The glass roof is only supported by the outer part of the outer bridges. This type of support structure makes the glass roof particularly sensitive to settlement. The vertical displacements of adjacent bridge columns should not differ by more than 10 mm.

Due to the difficult soil in Berlin (mainly sand) and the Spree river in the immediate vicinity of the station, ground movements during construction were expected. The new station was adjacent to an existing railway line with a rather small city train station, where traffic was continuously in operation throughout the construction period of the new building. The old station was eventually demolished and the rails were connected to the new station after the commissioning of the new upper bridges. Demolition and excavation of the underground construction pit for the north-south railway route could also cause vertical displacements of the roof-supporting bridges.

Considering the overall situation, the German Federal Railway Authority decided to monitor the behaviour during construction, commissioning and during the first few years of operation by using a complex monitoring system. When vertical displacements of parts of the roof were detected, the bridges had to be raised or lowered at the support points. The question was what is to measure where, and how complex had the system to be? After contacting senior site engineers, it quickly became clear that the answers were not easy to find. A team of interdisciplinary engineers from different departments of BAM analysed the situation, clarified which deformations and changes in the structural behaviour had to be observed, defined the requirements of the system components and investigated which technologies are available on the market and which components must be developed or must be adapted to the given requirements. Finding the right monitoring strategy was only possible through interdisciplinary teamwork. The resulting monitoring tasks including the ancillary technical and logistical conditions were:

- Design of a complex physically redundant concept for monitoring of settlements and heaves with regard to architectural matters
- Successive installation of the measurement system components already during construction
- Deformation measurements by using electromagnetically-safe and almost maintenance-free sensing techniques (because of hardly access to the system components after installation)
- Selection of sensor principles for long-term reliable data acquisition including assessment of drift or creep effects; taking into account the fact that the connecting cables between sensors and devices must be interrupted several times during construction
- Redundant measurements of all relevant physical quantities by using different sensor techniques, that means, combination of innovative techniques with established monitoring and reference methods, e.g. fibre-optic strain sensors and conventional strain and displacement sensors (also combination of optical and electrical systems)
- Continuous automatic multitasking data recording including remote diagnosis of the system components’ function
- Dealing with possible damage during the construction phase and its elimination (a fibre-optic cable was actually destroyed by drilling a hole in concrete, and an installed sensor was destroyed by flooding during heavy rains).

To assess the long-term performance of the measurement technologies under all expected environmental influences, two pre-stressed model beams, 8 m long (300 mm x 400 mm) were equipped with the same monitoring system components installed in the station. One model beam was installed inside (room conditions) at BAM, the other one was installed outside to investigate the temperature and climatic influence. Both bends and torsions comparable to those of the station bridges due to the roof load and later the operating load were simulated, and so these model beams could be used to verify the mathematical models. The data from the station was recorded every four hours and visualized in the BAM laboratory in an interactive chart. The monitoring system project is extensively described in Helmerich (2009) and Habel (2009).

The greatest challenge was: Obtaining continuously reliable data about the structural behaviour from the beginning of the measurement to its end without losing the relation of measurements to previous ones due to many perturbing influences: interruptions in power supply, relocation and reconnection of the sensor cables during construction progress, and also replacement of sensors and cables due to destructions during the construction process. This was only possible by choosing, on the one hand, a fibre-optic principle that is insensitive to power interruption and to replacing connecting cables, e.g. the SOFO system. It allowed an absolute measurement of the sensor fibre length, i.e. concrete load. On the other hand, by selecting and developing a hydraulic force sensor-based levelling system that is insensitive to temperature and atmospheric pressure variations, which allowed automatic correction of drift and creep by cyclic unloading, that means, reliable and very accurate zero point correction measurements were possible. Using these described calibration and validation capabilities, all subsequent measurements can always be related to previous measurements, even if system components have been turned off or disconnected for a specific period of time. During excavation of the underground construction pit for the north-south railway, the limit value for vertical displacements of the bridges was exceeded. The vertical bridge position has therefore been corrected.

5 EFFORTS TO PROVIDE STANDARDS FOR USE OF FIBER-OPTIC SENSORS

When using new sensor technologies or advanced measurement systems, guidelines and standards that provide complete information on designing and using a sensor system and give valuable technical recommendations are helpful. They increase the trust of the user community in new monitoring approaches.

Sustainable progress in standardization of fibre-optic sensors began in 2006 within the European COST action 299 “FIDES” (Optical Fibres for New Challenges Facing the Information Society). Before that date, only singular activities could be observed in the IEC, SAE and the SEAFOM Measurement Specification Working Group. Highlights in standardization were the publication of the SEAFOM-MSP-01 guideline Measurement Specification for Distributed Temperature Sensing published in March 2010 (SEAFOM-MSP-01 2010), the COST 299 Guideline for Use of Fibre Optic Sensors published in 2010, and the VDI/VDE 2660 guideline “Optical Strain Sensor based in Fibre Bragg Grating - Fundamentals, Characteristics and Sensor Testing” published by the German VDI - “The Association of German Engineers” in 2010.

Following these activities, the first Generic IEC standard 61757 “Fibre optic sensors - Generic specification” was published in early spring 2012 and established the IEC Fibre-optic sensor standard family. Meanwhile, other standards in this family have been developed and published: the FBG-based strain sensor standard IEC 61757-1-1 “Fibre optic sensors - Part 1-1: Strain measurement - Strain sensors based on fibre Bragg gratings” and the distributed temperature sensor standard IEC 61757-2-2 “Fibre optic sensors - Part 2-2: Temperature Measurement – Distributed Sensing.” Currently, the following other standards in the IEC fibre-optic sensor family under development:

- IEC standard for FBG-based temperature sensors (IEC 61757-2-1) based on the German VDI/VDE 2660, pt.2 guideline published in December 2018 as a green paper. The confirmed bilingual German/English VDI/VDE guideline is expected in summer 2019; the first IEC 61757-2-1 draft is expected by the end of 2019.
- IEC standard for fibre-optic distributed strain sensors (IEC 61757-1-2), and
- IEC standard for fibre-optic distributed acoustic sensors (IEC 61757-3-2).

There are other fibre-optic sensor standardization activities to push and establish SHM systems. For example, there are activities in standardization of monitoring systems for underground structures in the ASTM Technical Committee F36 “Technology and Underground Utilities”, especially Subcommittee F36.10 "Optical Fiber Systems within Existing Infrastructure" (e.g. the standards F3079-14 and F3092-14), see Habel & Jeyapalan (2019).

Several other standard documents have also been published by SEAFOM. Its activities are focussed on facilitating the growth of fibre-optic sensing in subsea, dry tree, and land well applications as well as within subsea infrastructure. An overview is given at the website https://seafom.com/published-documents/.

6 SUMMARY

Designing a monitoring system, the main challenge is to select appropriate sensing technology and to have all reliability-related aspects such as calibration, validation and periodic approval of the right function in mind. This is mostly problematic because installed (not removable) sensors cannot be re-calibrated after a defined period of operation. Removable sensors, which can be re-calibrated in laboratory or sensing elements with self-calibration capability, are desired. There already concepts for FBG strain sensors with inherent self-calibration and self-check functionality; such forward-looking methods should be further explored.

Using the monitoring example of the new Berlin Central Station, it was shown how reliability requirements were met by the design of the components of a complex monitoring system. When new sensing technologies such as different fibre-optic sensors are used, the use of standards and guidelines is very helpful for suppliers as well as users of advanced measurement systems. One important method is to use models of real parts of a structure operating with the installed sensing systems under defined environmental conditions to simulate the expected behaviour of the structure and to understand the stability of the installed measurement systems.

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