Requirements to Establish Fibre-Optic Sensors for Monitoring of Structures

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ABSTRACT

Fibre-optic sensors need to be more established in the sensor market. Their advantages have unquestionably been verified by numerous demonstrations. However, there are some open questions leading now and then to restraints in the user's community. The paper discusses examples where fibre-optic sensors provide outstanding knowledge about the structure's behaviour, but application is often challenging. Requirements are listed and open questions to be solved are discussed. Short outlook to standards useful for better design, characterization and application is given. Standards are the basis for establishing SHM systems, especially for safety-critical structural diagnostics.

KEYWORDS : *Fibre-optic sensor, monitoring, reliability, application.*

INTRODUCTION

Smart and light-weight structures are designed to save material and to enhance its operating efficiency. Efficient operation includes reduction of service costs, e.g. by only event-based maintenance instead of regularly planned maintenance cycles. This requires information about the structure's behaviour under load conditions as well as for the designed and possibly extended service life. Sensors are more and more integrated during manufacturing of components or during construction. A very efficient way is the embedment of optical fibre sensors due to their extremely small dimensions, their outstanding performance parameters, and in some cases, due to their immunity against lightning strokes and immunity against electromagnetic fields.

Depending on the material to be observed, the sensor fibres can be applied to the surface of structure components, or embedded into mineral-based building materials, into composite layers or pre-pregs of textile reinforced structures. Both versions have advantages and disadvantages, however, application and/or embedment is challenging in any case. In contrast to external sensors, integrated sensors are better protected against mechanical damage or weathering conditions. If the sensing part of the optical fibre including the leading fibre is embedded during production, less additional work is necessary during construction. However, how to prove the proper function of the sensors embedded during manufacturing? There might be a number of attacks to the sensing area between manufacturing, transportation, installation and putting into operation. Another point is the integration process itself. Especially, when non-homogeneous and/or orthotropic materials are used such as composite materials or layered structural components with non-smoothly located layers, the sensor area, e.g. the FBG element might suffer damage or perturbation by microbending or transverse pressure.

On the other hand, surface-applied sensors might be attacked by a number of environmental influences. To avoid such attacks, sensitive areas are protected. However, does the protecting material cause any problems in the performance characteristics of the sensing element?

How to handle such cases? Can we manage such problems? Can we assume long-term performance of such sensors? Or can such effects even be exploited for a better characterization of the sensor's performance? Reliability and stability aspects are very essential for serious establishment of integrated fibre-optic sensors on the market.

The following examples with very different, partly enormous demands on application and embedment of sensors will illustrate some important requirements to establish sensors for long-term monitoring.

1 CHALLENGES WITH SURFACE-APPLIED FIBRE-OPTIC SENSORS

1.1 Strain sensors in off-shore environment

Application of sensor to surfaces is very common. It seems to be easy because fixing of sensor fibres or sensor patches is similar to attachment of wire strain gauges. The sensitive area needs to be protected; different materials fulfilling environmental demands are used. However, there are many structures and facilities that are operated under very harsh conditions, e.g. wind turbines, oil platforms, gas pipelines or high-voltage offshore power cables. In such cases, sensors and related components are exposed to very specific attacks:

- Mechanical attacks due to strong waves, ice drift or indefinable ocean circulations
- ultraviolet radiation due to sun light
- mechanical stress due to thermal load over day/night and summer/winter cycles
- chemical attacks due to salt water and possible influences from oil and chemicals
- marine biology attacks due to sea-biological influences such as barnacles and fouling.

Figure 1 gives an impression how the components of surface-applied fibre-optic sensors are attacked in offshore environment.

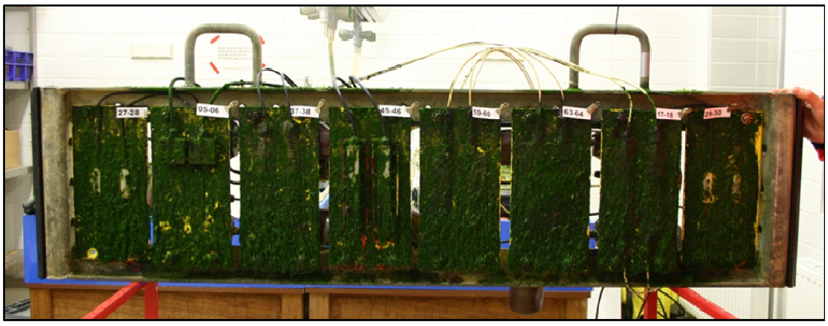

Figure 1: Detail of the test samples arrangement installed in the testing rack.

A number of plates on which fibre-optic strain sensors were attached and protected were installed in a testing rack at the quay wall of the Sylt island's harbour in List / Germany and exposed to the real sea-water conditions [1]. Different sensor attachment methods were tested to find out best procedures to enable long-term reliable strain transfer and to avoid use of wrong sensor protection method. The plates were differently attacked in the tidal zone that means, the upper plates were only moist in the maximum flow phase, the centered plates were more moistened, and the bottom plates were almost all the time under water. All plates were cyclically moved and all plates were dismantled and assessed every three months. As shown in Figure 1, the plates were densely populated with algae, barnacles and polyps (see Figure 2).

Figure 2: Detailed view at one of the exposed sensor-equipped plates. Clearly can be seen the marine biology vegetation (algae, barnacles and polyps at the leading cable).

The detailed investigation revealed that the barnacles crawl under the upper coating layer of the plates. Few polymer/elastomer sealing materials peeled off from the sensor zone. On the other hand, more stiff metallic housing showed already corrosion damage. And even some of the cable glands were damaged by mechanical wave influences. This led to penetration of water into the cables and likely to the sensors.
All these influences require special measures to protect sensors and cables from attacks to guarantee the sensor function - and eventually fulfil the monitoring task - over the period of measurement planned. In case of strain sensors, the most requested type of mechanical sensors in offshore facilities, the load or strain transfer from the measuring object into the sensitive element must be ensured in spite of all protective measures. Although a very safe protection of the sensing zone is out of the question, investigations to define guidelines and standards for appropriate application of fibre-optic sensors in offshore environment revealed that a too heavy protection has significant influence onto the sensor characteristics. The sensitivity of the fibre-optic sensor can decrease by up to 60 percent [2]. To find out such problems, a mobile calibration facility is used. It enables to control the sensor performance and/or the sensor characteristics.

1.2 Calibration requirements on-site

Of course, all pre-installed sensors must be tested and calibrated in lab before they are installed on-site. However, due to unknown influences during exposure or changes in the material behaviour, sensors should be re-calibrated on-site after a certain time of operation. Depending on the type of installed or attached sensors, special facilities are needed. If sensor plates are used that can be dismantled, a simple bending test facility can be used. Figure 3 shows such a facility.

Figure 3: Portable 4-point bending test facility for strain calibration on-site
(designed by H. Kohlhoff, BAM).

The portable test facility is based on a 4-point bending test procedure and can easily be moved to and used at the measurement location. It enables a step-less increasing bending of the test sample with the attached strain sensor. During the bending cycle, the optical response from the sensor can be recorded. In case of fibre Bragg grating (FBG) sensors, the spectrum of the Bragg signal can be recorded additionally. The amount of bending (deflection) can be measured by using two dial meters positioned at opposite sides of the FBG strain sensor. The deflection is correlated with the optical response from the strain sensor. For this facility, a deflection of 0.155 mm at both dial meters corresponds to a strain of 125 µm/m at the location of the sensor. This relation is only valid for sensors applied without stiff protecting components, e.g. without a thick metallic housing. As shown above, too stiff protection material can lead to stiffening of the system plate/sensor. In such a case, the plate geometry and its features (e.g. Young's modulus) without protecting material would change, and a correlation with strain is no longer possible. The bending moment cannot be considered as constant anymore and deviates from the ideal bending curve of a plate without installed sensor or with only attached tiny optical fibre.

2 CHALLENGES WITH EMBEDDED FIBRE-OPTIC SENSORS

2.1 Example: Pultruded intelligent profiles

Advanced and futuristically designed structures, such as very tall towers, slender bridges, high-speed boats and yachts use high-performance composite materials. In many cases, integrated monitoring systems are required to get information about the long-term behaviour of such structures or to identify critical stages during regular operation or under unexpected loading conditions. Integrated monitoring systems must meet a number of serious requirements: they must, for example, provide reliable data over the projected lifetime, it should be possible to check their performance after a certain time of operation, and they should be replaceable if damaged. Users want to be sure that they get credible data over the whole operation period, and that they can handle repairs and maintenance if needed.

One example of such high-performance structure materials with integrated sensors are pultruded profiles used, for instance, as load-carrying members in bridges. Figure 4 shows big profiles made from composite material and prepared for a bridge construction [3].

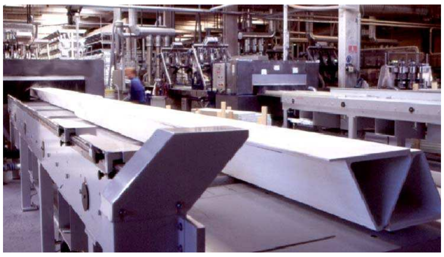

Figure 4: Pultruded profiles assembled to form a load-carrying bridge girder
(Photo: provided by University of Stuttgart, ITKE)

Such multifunctional profiles are mostly composed out of fibre-reinforced plastics (FRP) and manufactured by an automatic pultrusion process. The reinforcing fibres are handled as fibre bundles (roving) or fabric. The fibres are wetted with liquid polymer resin and then pulled through a heated mould (approx. 120 °C), where the polymer cures within a few minutes and where the profile is formed. The reinforcing fibres define strength and load bearing behaviour of the composite material, the resin holds the fibres in the desired shape, acts as protection against environmental impact and transfers stress between fibre layers. The finished profiled beam is then cut according to customized needs. The cut beams can be attached to each other with bolts or an adhesive layer.

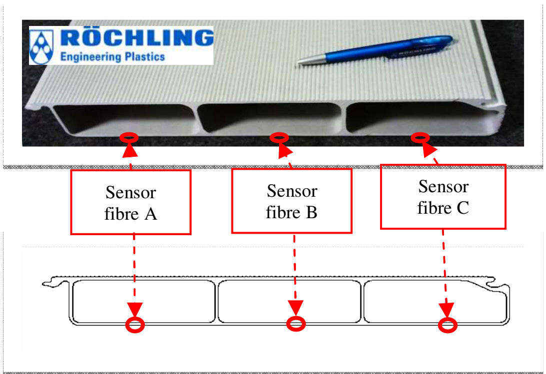

Figure 5: Pultruded profile of a test bridge to demonstrate the sensitive composite box girder.

In order to make pultruded beams sensitive, different optical fibre sensors such as Bragg grating sensors (FBG), segmented fibre sensors or fully distributed fibre-optic sensors can be integrated. Meanwhile, it is possible to provide large-scale cross sections with integrated sensors for monitoring purposes manufactured in a fully automated process. Such profile types were first in Germany used for a bridge constructed in 2008. The bridge deck was made from specially designed pultruded glass fibre-reinforced profiles. Figure 5 shows a profile with integrated fibre-optic strain sensors. Details about the intelligent bridge girder shown in Figure 5 are described in [3] and [4].

2.2 Example: High-performance timber girders

Another example concerns high-performance timber girders used as supporting member for roofs, bridges and other structures where the advantages of timber are to be exploited: low weight, high elasticity, aesthetic quality, renewable material. There are different possibilities to design the timber structure to reach high strengths combined with high durability. A common design is to glue single timber lamellas together and form a strong beam. Figure 6 shows lamellas equipped with fibre-optic Bragg grating sensors embedded in very small grooves and fixed with epoxy resin. The lamellas are then glued together and form the profile wanted.

Figure 6. Application of the sensor fibres to the surface of timber lamellas before completing the glued laminated timber girder at Schaffitzel Holzindustrie GmbH in Schwäbisch Hall/Germany.

Figure 7. Sensor-equipped girder in the test facility of the MPA Dresden GmbH/Germany.

Figure 7 shows a layered timber beam type designed for constructing a footbridge in a test facility. The embedded sensors enable investigating the load-bearing capacity of the designed beams as well as a later evaluation of the long-term adhesion behaviour of the glued beam lamellas. Details about sensors, their positioning as well as testing results are described by Hamann et al. in [5]. Before the regular use of such high-performance timber beams – and before such load-carrying material are accepted by the owners of structures -, integrated fibre sensors also enable to find out the appropriate adhesives and the best methodology to attach the sensor fibres. Extensive investigations have shown that the fibre-optic sensor technology used is suitable for short-term measurements as well as long-term monitoring. Field tests are necessary to evaluate all climatic and environmental influences and to define the ultimate load capacity and the long-term behaviour of this composite material.

2.3 Sensor integration requirements

In order to establish embeddable and/or attachable sensors on the very competitive sensor market, all application-related aspects must be well understood and the user must get credible results from the sensor over the whole operational period. That means, the sensor system must show a stable and reliable function under all operational and environmental conditions. The most important contribution to an appropriate function depends on the success of the integration procedure. There are a huge number of details, which must be known Following, only the most important requirements are listed:

- Checking the right position and function after embedment/application;
  Precise sensor position must be proved. Proper function of embedded sensors in the material after finishing the embedment procedure and after the structure component has been placed in operation must be proved on-site.
- Bonding of the fibre's sensitive area to the host material;
  Depending on the host material and the integration procedure, the adhesion of the fibre sensor to the measuring object to be monitored must perfectly work, that means, without creep, without delamination or unwanted perturbations during further processing of the material, e.g. thermally induced stress loading of the sensing element during thermal curing of composites. It should be considered that, in some cases, signal transmission sections of the fibre (between sensor sections) should not be fixed in the same way as the sensor. Any influence from fixed leading fibres to the sensing section, and "blur" the strain response from the area to be investigated must be avoided.
- Reliable, long-term stable bonding;
  It is a real challenge to ensure a long-term stable bonding of embedded sensor fibres in composite materials. There are many mechanical, climate and environmental influences that could disturb the sound bond between the different materials. The designer of the sensor system must find out which materials are appropriate to contribute to a long-term stable operation, i.e. degradation/ageing due to chemical and physical interactions of materials close to the sensor must be avoided. Especially for embedded strain sensors that are exposed to full climatic conditions and are dynamically loaded (sensors embedded in plates of wind turbines, in components of an aircraft or in machine foundations), careful choice of the fixing and protecting materials like adhesives and covering components is needed. This requires coupon tests and micromechanical investigations in lab to optimize the sensor bonding, and thus the strain transfer behaviour. Details are described by Habel et al. in [3].
- Validation of the proper sensor function;
  Validation of applied or embedded sensors is necessary to prove that the sensors reliably provide the responses demanded for a specific measurement task. Test facilities and procedures are necessary to fulfil validation according to standards or to the user's requirements. This is a very complex task and presents a challenge just when only coupon tests are possible. Basic methodologies, important aspects and useful facilities to get credible data from applied and embedded sensors are described by Habel et al. in [6].
- Ingress/egress point for sensor leads/cables;
  Already when the concept for integration of sensor fibres is made, the location of the ingress/egress area must be defined; these areas including sensor fibres must be designed for safe operation.

3 HOW TO FULFIL THE REQUIREMENTS?

The most recommended way to fulfil all requirements is to follow rules in designing, testing and installation of a sensor system. Meanwhile, there are few guidelines and standards to characterize, test and apply fibre-optic sensor systems. The standardization work is being continued in the Sub-Committee SC 86C of the International Electrotechnical Commission (IEC). The generic standard for fibre-optic sensors (IEC 61757-1) is available; standards for FBG-based strain sensors (IEC 61757-2) and for distributed temperature sensors (IEC 61757-3) will be published soon. This work will be continued; next standards for distributed strain sensors and FBG-based temperature sensors are discussed, the projects might be launched in the winter period 2014/2015. Users need handbooks or checklists which aspects and design criteria have to be considered. Not only a precise language in describing the performance of sensors and their components is urgently needed but also a comprehensive knowledge what to consider. For getting an optimally arranged sensor system, not only technical aspects but also economic issues [7] from saving a huge number of single sensors, faster installation process and calibration procedure, maintenance expenses, possible breakdown costs, to claims for compensation, if no sensors or inappropriate sensors were installed.

4 CHALLENGES - NOT YET SATISFACTORILY SOLVED PROBLEMS

When sensors are installed and connected, handling of important technological details must be mastered. Following, very challenging manually performed steps are considered:

- Methodology to fix sensors safely under extremely harsh installation conditions, e.g. offshore conditions, and to protect the sensor area and cable against mechanical, environmental, (sea-)biological and UV-radiation attacks.
- Protecting fibre-optic cables protruding from a structure or a sensor carrier (see Figure 2) so that aging of materials under harsh thermal, chemical, and mechanical conditions is avoided.
- Packaging and protecting the fibre-optic sensor itself over the whole service life of the structure without jeopardizing data integrity. The load or strain transfer from the measuring object into the sensitive element - sensor characteristics - must not be influenced.
- Connecting/repairing fibres cut or broken at the egress area (see Figure 5, fibres are cut), or repairing of hidden fibres broken inside of composite materials. If repair technologies are not available for solving such problems, a selected sensor technology will not be accepted.
- Checking the sensor performance after completing the installation or after a certain time of operation. If exact data retraceable to the start value of the measurement cycle, are needed; the calibration status has to be verified in situ. This task can be extremely difficult because possible local creep effects can perturb strain transfer or proper optical function. It should be stressed that this information is urgently needed when sensor reliability has top priority, such as in sensor systems installed in safety-relevant structures. To be sure that the sensors provide trustworthy signal responses, it is needed to know exactly, whether a change in the sensors signal is caused by a change in the structure, a change in the bonding zone or a change in the sensor itself due to environmental and/or mechanical influences. By now, it is hardly possible to calibrate and validate sensors applied to or embedded in large structure components. Weaknesses in bonding behaviour can hardly be revealed. Re-calibration and experimental validation of applied sensors is only possibly by dismantling the sensor or the sensor carrier.
- By now, FBG signal response analysis is not common to read out additional information about effects superimposing the sensor signal (e.g. temperature influence), decreasing the sensor performance or impending failure. FBG strain sensors with internal temperature compensation and self-checking capability that means that they provide information about an inappropriate sensor function, must be available to find full user's acceptance. A highly promising approach to get knowledge about beginning delamination of an embedded FBG sensor will be presented at the OFS Conference 2014 in Santander by Baitinger et al. [8].

CONCLUSION

Structure-integrated fibre-optic sensors provide great opportunities for monitoring of the structures' behaviour. However, the still quite young measurement technology can only be sustainably established for monitoring of critical or safety-relevant structures, if all steps from the choice of the right sensing technology for the specific measurement task, the design of the sensing components, from optimization of the fixing materials used in the interface zone, connection of the fibres with the leading cables to the validation of the whole sensing system for its stable operation are completely developed. Performance evaluation and repair technologies must be available.

The most difficult requirement is the performance validation of sensors integrated into big structures. Basically, all applied or embedded sensors can only be validated and calibrated by using of small-scale test samples in laboratory. Extensive investigations with such samples enable optimization of the necessary sensor components; the more parameters are optimized, the more reliable and durable operation can be expected for sensors installed later on-site.
One major open problem to be solved is the non-availability of field-appropriate validation and calibration methodologies. Embedded sensor elements can hardly (actually never) be re-calibrated after installation without removing them from the measurement object. Only disconnectable interrogators or measurement devices can be calibrated in laboratories. Once the precise function of integrated sensor systems can be checked at any time at the real structure, monitoring systems will get very high acceptance in the users' community. To manage that, diagnostic methodologies to get information about sensor-malfunction or significant perturbations have to be developed.
Another very important aspect concerns the repair of fibre-optic sensors damaged inside a structure. Repair of embedded sensors or optical fibres remains a challenge by now. If a fibre-optic sensor or a leading fibre integrated in a safety-relevant composite fails and cannot be repaired, the acceptance of such sensor systems tends to zero. This must be considered as a serious problem for the use of "intelligent" high-performance composite materials - and has to be solved.
A number of requirements will be met by using of standards that are increasingly available.

ACKNOWLEDGMENT

This paper refers investigations supported by the German Federal Ministry for Economic Affairs and Energy (BMWi), the Deutsches Institut für Normung e.V. (DIN) and by the European COST Action TD1001. The input from a number of cooperation partners was very helpful and is therefore highly valued and appreciated.

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