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Standards and guidelines - could they enhance user confidence in fibre sensor technology?

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ABSTRACT

Different experience from fibre sensor applications on-site has revealed the need of guidelines for developers, manufacturers, suppliers as well as users. Although best knowledge and well-founded experience are available in the fibre sensor community, a lack of technical instructions for all persons involved can lead to unreliable measurement results or even damage of sensing components. In contrast, manufacturing and application procedures according to generally binding technical rules will ensure long-term stable sensor systems and reliable measurement results. These rules have to include definitions of particular terms to describe the sensor and sensor system characteristics as well as methods to validate and use sensors properly.

Because FBG sensors are the most popular sensing techniques in very different fields, important aspects to structure a set of technical recommendations will be discussed, especially for the use of FBG sensors in experimental stress analysis and for structure monitoring.

Keywords: fibre optic sensor, guideline, validation, test method, characterization, structural monitoring, stability

1. INTRODUCTION

At the beginning of a sensor system design is the measurement task. Each design work and application procedure on-site has to fulfil specific demands. Therefore engineers have found out optimum answers with regard to all components of a sensor system. This work includes selection of an appropriate sensing method out of a multitude of possibilities. To find out the optimum solution, customers, consulting engineers and suppliers should first have a well-founded overview on fibre optic sensor technologies, available components and recording systems. They then have to analyze the measurement task, influencing service and environmental conditions. Depending on these prerequisite, the most appropriate sensing system consisting of optical source, optical fibre with a specific coating, sensor itself (extrinsic or intrinsic type), some components like connectors, beam splitters, and finally recording device can be selected. Unfortunately, sometimes the most appropriate sensor system has not been selected, and the customers were disappointed of the measuring results. What do so that the customer is satisfied and has confidence into the fibre optic sensor technology? Experience from fibre optic sensor applications on-site show that guidelines and standards are needed for developers, manufacturers, suppliers as well as users. Standards generally facilitate the use of technology, because they improve measurement accuracy, allow interchangeability, and enable cost reduction. With regard to documentary standards, market growth for fibre optic systems is promoted. Only the consideration of specific quality aspects for a sensor system protects reliable and long-term stable function and sensor signal recording.

This paper focuses on some important aspects that have to be considered when a measurement system is designed, sensors are applied onto or in a measurement object. Because a large number of fibre optic sensing systems bases on fibre Bragg grating (FBG) sensors, guideline and standardization needs will be considered here with regard to FBG applications.

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2. DIFFERENT GROUPS ARE DEALING WITH FIBRE OPTIC SENSORS

Whenever a measurement task must be processed, a multitude of different groups are concerned. These different groups need or want different information and following, different recommendations or guidelines have to be available.

- Users, customers:
- They want to get basic (not really scientific) information about functional principles and basic specifications of the alternative measurement method 'fibre optic sensor'. They are interested in quite cheap solutions, however, are mostly willing to pay an appropriate price if the new technology has advantages in comparison with the conventional one. In order to give them confidence in discussion with fibre sensor experts, customers should be able to follow a checklist with all important aspects that the supplier or consultant has to consider.

- Engineering consultants:
- Consultants need, first, an overview about available sensing methods and corresponding components to design fibre optic sensor systems. Customers would be well advised, if they receive not only one offer for a measurement system, or an offer from only one company. They should be able to compare different offers to find out the most effective sensor technology (sensor system). Alternative offers do not concern quality issues. High-demand systems for e.g. long-term measurements require high-performance systems; measurement tasks with low resolution demands or with only short-term measurement demands (e. g. without disconnecting cables) need quality systems with lower system performance. Consulting engineers have to estimate which system is the most effective for the user.

- Innovative companies or skilled personnel:
- They have to deal with clear performance specifications for fibre optic sensor systems as well as components of them. This requires a correct use of the expression of performance determining quantities, static and dynamic specifications. This must be done according to international standards and vocabulary for describing general terms in measurement technique. The correct terminology ensures that the interdisciplinary community of e. g. physicists, fibre optic experts, mechanical and civil engineers understand each other.

- Manufacturers:
- Companies which produce and deliver sensors or sensor components have to deliver validated product. This means that they have to confirm by examination and to prove the objective evidence that the particular requirements for a specific intended use are fulfilled. Validation of products as well as measurement methods can be carried out according to standard ISO/IEC 17025/2000 of the International Standardization Organization (ISO) [1]. For a specific intended use, the sensor or the measurement system works then as reliable as demanded.

Validation delivers the largest contribution to the user's confidence in fibre optic sensing system. Few necessary steps for fibre optic sensor systems have been described earlier [2], [3].

3. RELIABILITY / STABILITY-RELATED QUESTIONS FOR FBG SENSOR SYSTEMS

Guidelines or standards find only acceptance as a competent summary of valuable technical recommendations when all details of the performance-describing aspects of the whole sensor system are considered. Fig. 1 shows the general structure of a fibre optic sensor system. Behind this physical components a multiple of aspects and parameters which influence the performance of the sensor signal and the stability of system components are hidden. Nowadays, potential customers find almost all components commercially offered to design a sensor system. Some of the commercially available components like connectors, leading cables, FBG elements, reading devices are validated according to standards developed for data communication tasks, or according to the company's own rules; at least function tests have been carried out for those. However, most of the optical measurement equipments are sensitive to ambient temperature and pressure variations. For example, an OSA can have a temperature sensitivity K_T of about 10pm/K, that means, it corresponds to the same temperature sensitivity of an FBG. If such a read-out device is to be used in a sensor system installed on-site, calibration curve must be available. If the equipment has to be replaced later by another one with different temperature sensitivity, the measured strain or temperature signal does not represents the previous sensor characteristics.

In the following, the few of important questions will be considered.

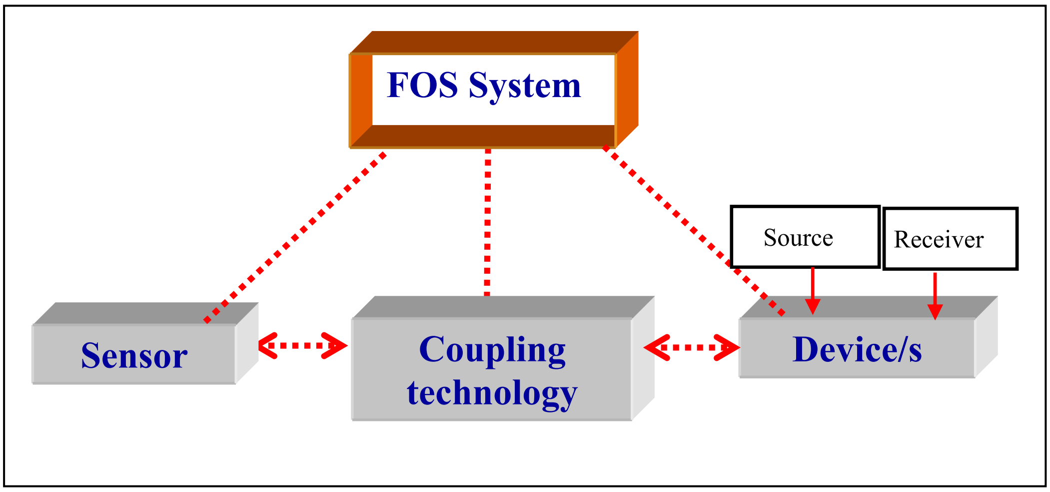

Figure 1. Main components of a fibre optic sensor system

3.1 Optical source, detector, modulation and demodulation

It is expected that the optical source delivers a signal with a sufficiently stable spectral and intensity characteristics which is needed for the respective modulation technique. Depending on the sensor signal resolution requirements, devices with different interrogation methods are used. In example, a spectroscopic method using CCD spectrometer provides a simple method with a quite good resolution. In contrast to this, devices that use interrogation methods on the basis of tuneable filters, fibre interferometers or planar integrated optical chips enable very high signal resolution. Stability and reproducibility of the wavelength measurement on FBG sensors decisively determine the uncertainty of the sensor system. This problem can be understood by considering two aspects. The first aspect concerns parameters of the FBG that define the Bragg wavelength. It is necessary to know the set-up wavelength of the grating. Using the definition that the width of a grating peak is defined by the distance of the two minimum points in the peak, the calculated Bragg wavelength λ_B differs from another estimation of the wavelength which bases on the -3 dB level definition. In this case, the amplitude has an influence to the λ_B estimation, and therefore the precision in estimation of the grating wavelength strongly depends on the grating characteristics (mainly strength, uniformity) [4].

The problem of wavelength stability of the measurement device was addressed already. Measurement devices for highly-precise wavelength reading use standard commercially available etalons, like gas cells, or at least wavelength-stabilised FBGs. It is obvious that only such device can be recommended for measurements under full climatic and temperature conditions. If customers are only able to finance low-cost devices for a specific task, the quite high uncertainty in measurement results has to be estimated and announced to them. In principle, it cannot be expected, that customers are able to know or understand all these aspects. On basis of the demanded uncertainty – and with the estimation of the real system-immanent uncertainty according to technical rules – engineering consultants can seriously recommend which method and device fulfils best the requirements of the customers.

3.2 Fibers, cables, connectors, other components

There are an almost unmanageable number of standards for optical fibres, cables, connectors, and other components. All these components are used in telecommunication and data communication systems. These international standards can be found in the International Standard Classification (ISC), nr. 33.180. In order to enhance the reliability of components, some investigations were made within COST 270; e. g. the connector group defined a reliability qualification test that resulted in the IEC standard 62005-9-2.

3.3 Signal transfer between measurand and sensing element

Another significant influence on the measurement signal comes from application of the FBG element. In case of strain sensor, the question is which amount of strain will be transferred from the structure to be evaluated to the FBG element in the optical fibre. Depending on the method of FBG application (embedded, fixed, surface-glued, and welded), the interaction between the measurand and the FBG is influenced by numerous factors. Almost each team uses another method to attach or embed FBG sensors, and use different coating and adhesive specifications even for similar measurement tasks. This very complex part of a measurement system has the largest uncertainty – actually skill-based uncertainty- as a consequence. In comparison with the above mentioned large number of commercially offered system components must be assessed that there is a lack of offers and established methods for the FBG application. It is still observed a lack of companies which offer application expertise according to generally accepted technical rules, and are willing to grant guarantee for specific application work. For example, the embedment of FBG strain sensors in rotor blades of helicopters or of wind turbines is, by now, mainly done by research institutions of research departments of companies.

It should be expected that the user community interested in fibre optic sensors (not primarily users of standard telecommunication or data communication equipment) more and more promotes and support R&D activities in this area to close the gap in the expert's knowledge, and to push the development or completion of corresponding guidelines and standards. It is also highly expected that international political and economical commissions such as the European Commission which are responsible for information society technologies will increase in future their attention to these reliability and standardisation aspects. Unfortunately, few proposals on support relating to this were rejected in the past.

In the following, selected interfacial aspects will be considered. Unfortunately, it is not possible to embrace all of the influencing effects in this paper. It is necessary to gather and to list all relevant influences that affect the measurement signal. For example, it has to be distinguished between stability aspects coming from the FBG itself and signal perturbations due to its application. Finally, it must be possible to clearly distinguish between information which comes from the sensor including surrounding affects [5], and the contribution from the structure to be evaluated. If it is not possible to discriminate between creep of the structure (measuring object) and creep of the adhesive used for bonding of the FBG sensor, the customer is not able to evaluate the real behavior of the structure. It is the largest challenge for fibre sensor experts to give an answer on that.

Assurance of long-term proper strain transfer for embedded FBG

If FBG elements are to be used as sensors to measure mechanical quantities (strain, pressure, bending, stress), the bonding behaviour of the gratings has particular influence. In general, two interfaces are involved: (a) the interface between the structural material and the fibre coating; and (b) the interface between the optical fibre and its cladding. The mechanical and physicochemical properties of the selected and/or existing materials are therefore very important in determining the performance of the sensor. A debonded interface or changes in the interface due to ageing of the involved materials would detrimentally affect transfer of the measurand to the FBG, and result in erroneous readings. Fatigue tests with acrylate-coated FBGs embedded in composite samples of wind turbine rotor blades revealed a continuously increasing aging effect in the FBG signal for exactly the same deformation values (150 µstrain after 1,600,000 cycles). Some more results are described in [6].

Another systematic influence on the measurement signal comes from the viscoelastic properties of the coating. It will affect both the static and dynamic response of the sensor. In every application case (embedment or surface application), the interfacial mechanics has to be well understood. Unfortunately, at the present time, there is no complete understanding of all these correlating effects yet because there is a lack in test methods to validate the strain transfer behaviour. In fact, there are standard testing approaches in the area of composite materials research to characterize the interface bonding between reinforcing fibre and matrix material. Fig. 2 shows such a testing facility to evaluate bonding of embedded fibres which is also used at BAM for characterization of embedded optical sensor fibres (see [6]). This method is not only used to characterize the shear stress development in the border zone coating/structure but also used to find out the appropriate coating for a specific fibre sensor because tensile stress in optical fibres can lead to delamination of the coating from the fibre surface. Research is, however, needed to correlate these test procedures with other interfacial parameters such as coefficient of friction, thermal residual radial stress, coating stiffness.

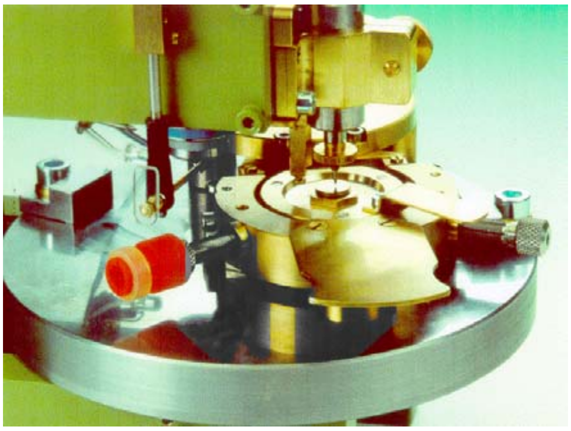

Fig. 2. Push-in test machine at BAM

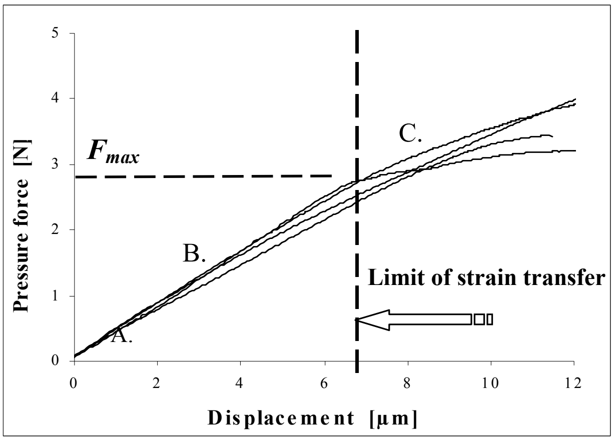

Fig. 3. Typical test result when evaluating the strain transfer characteristic (abscissa: displacement of the indenter, ordinate: force at the indenter)

Assurance of effective bonding for surface-attached FBG

The mechanics of strain transfer for surface-attached FBG sensors is more complex than that of embedded ones. Surface-glued fibre gratings produce an unsymmetrical interface structure, and an application method is needed that ensures a reliable and reproducible bonding of the fibre. Figs. 4 and 5 show some questions that arise for surface-attached fibres.

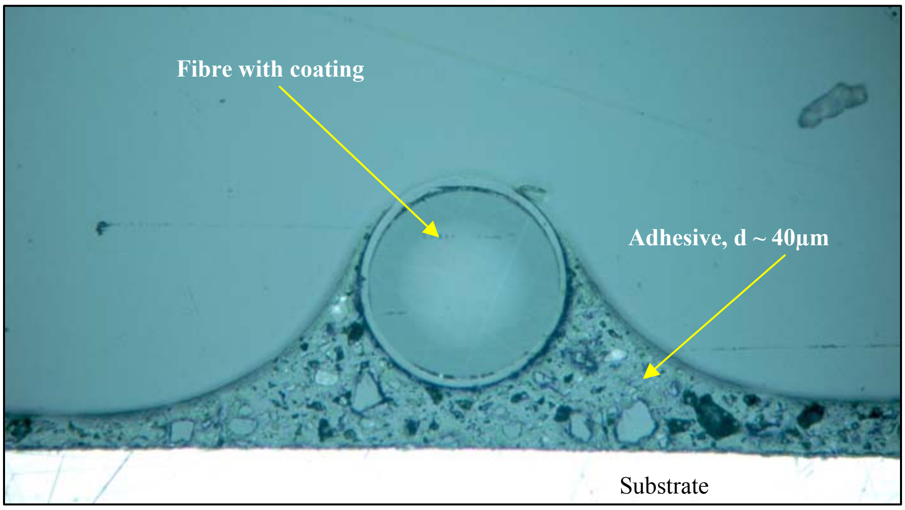

Figure 4. Optical fibre not optimally surface-glued by hand (courtesy of Mrs. Schlüter, BAM).

Just if FBG sensors are to be glued to metallic or composite surfaces, the adhesive properties, the adhesive geometry around the coating and the interaction of adhesive with the coating type is of exceptional importance. These details effect on axial and transverse strain transfer between the hosting material and the FBG sensor. In principle, fibres can be glued onto surfaces by hand or by using a device. In any case, a repeatable positioning of the fibre has to be ensured. This includes, first, the minimal thickness of adhesive between fibre and substrate as well as the contour around the FBG. In Fig. 4, the thickness between optical sensor fibre and substrate is quite large. On the other hand, variable stress conditions during shrinkage of the adhesive can lead to deformation of the coating material (Fig. 5). This coating deformation will more or less influence the strain transfer behaviour. Bubbles can be observed also in the adhesive material which will make the strain transfer inaccurate.

If there is no sufficient space to glue optical fibres without prefabricated support or patch onto surfaces, it demands great skill of the technical staff. In order to enable the application of optical fibre sensors onto surfaces generally educated personnel, guidelines for doing this work are compelling required. Use of established method helps to avoid inappropriate application of gratings.

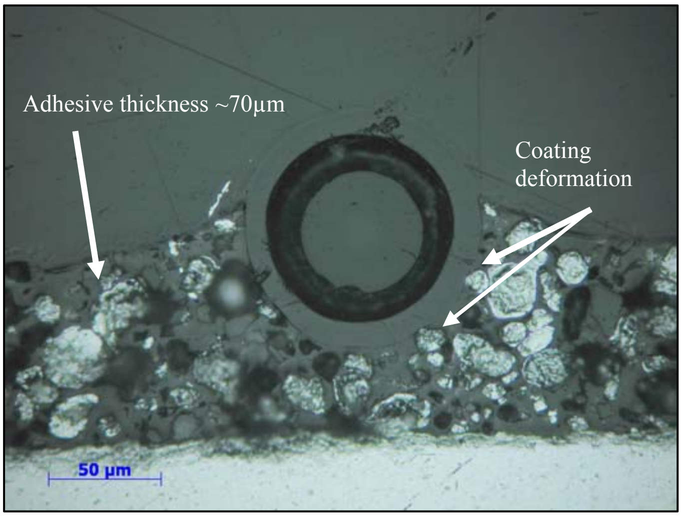

Figure 5. Optical fibre surface-glued that suffers from coating deformation (courtesy of Mrs. Schlüter, BAM)

Skilled workers as well as FBG users need sufficient material specifications (also humidity, temperature, and other physical influences) and information about the application procedure to be able to predict short-term as well as long-term performance of their sensors.

3.4 Practices for sensor installation procedure and sensor cabling

If the environmental conditions are harsh and the demands on durability high, fibre optic sensors should be integrated into materials such as composites or layered structures. The bias to the delamination of the sensor is then slighter. If only surface-attachment is possible such as in case of metals, or if the grating can only be installed at the structure after finishing it, a more practical and convenient method is the use of prefabricated patches. They can be made from glass fibre reinforced plastic substrates onto which the FBG is attached [7]; on the other hand, metallic supports can be used for the FBG that enable spot-welding as well as gluing. Fig. 6 shows such an example where the FBG is fixed in a groove of a tiny metallic plate by embedding it in glass material. This method avoids additional layers with different modules of elasticity around the grating.

Figure 6. Optical strain gage OS 310 (Micron Optics, Inc.) [8]

Another practical aspect of sensor installation concerns pre-tension of the sensor fibre (with the FBG). For example, in composites which will be subjected to tensile as well as compressive strain deformations, FBGs must be pre-tensioned as long as the curing process is not yet finished. This requires a special device which allows adjusting the tensile strain in the fibre. Fig. 7 shows such a device used during embedment of FBG arrays in composite blades for a wind turbine.

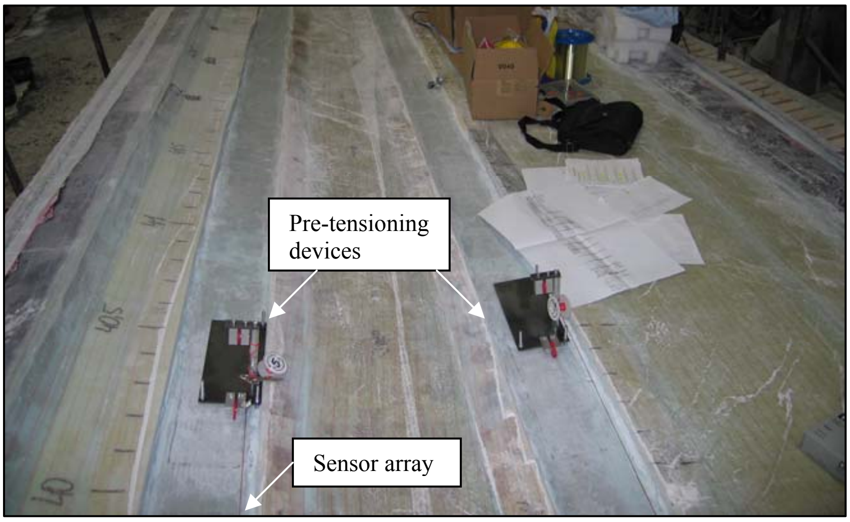

Figure 7. Embedment of FBG arrays using a special device to introduce tension (0.34 %), Photo: Hofmann, BAM

Apart from FGB sensor application procedure, cabling of the sensors must not be underestimated. Just under harsh mechanical or environmental conditions, splices and ingress/egress points are critical zones. For example, splices should also be embedded just as like the fibres. This is usually possible in large composite structure such as in huge rotor blades with sufficient thickness. However in steel structures, other methods have to be developed. Fig. 8 (left) shows a reliable solution to protect the splice joints by storage them in a small box. Fig. 8 (right) shows cable protection for the process when the anchors are introduced in the bore hole.

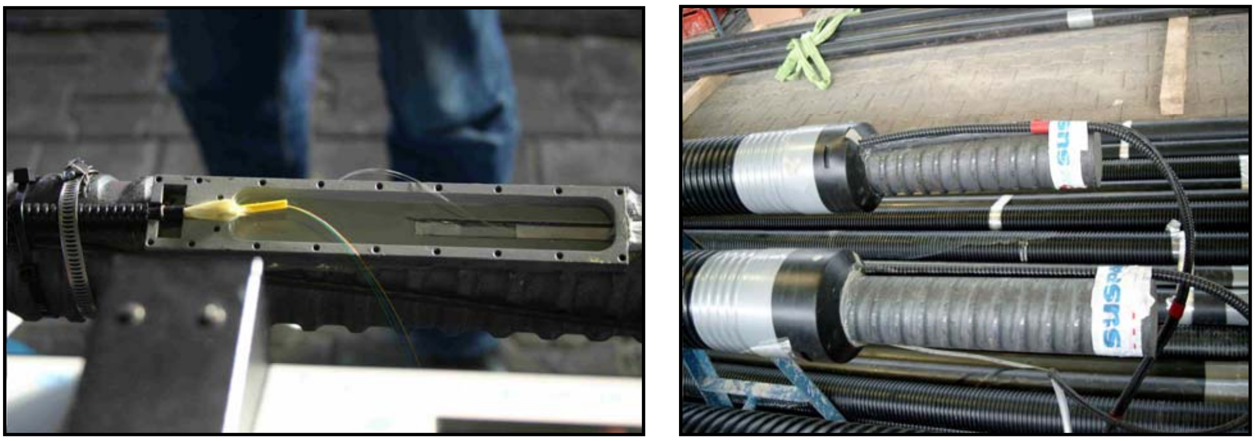

Figure 8. Attachment of FBG arrays onto heavy steel anchors for use in geotechnical engineering. Critical points are splice joints (left) and egress points (right) for heavy steel anchors. Photo: Hofmann, BAM

Based on the manifold experiences of fibre sensor experts in creating ruggedized packaging, the guideline should also comprise and propose packaging concepts that make sure that embedded or attached fibre optic sensors are fully protected over the service life of the structure without jeopardizing data integrity.

3.5 Characterization of operating performance conditions

The operating performance over a certain time up to years is not only influenced by the sensor characteristics and its application procedure but also on slow changes of the performance parameters of the electronic system, ageing of materials due to physical, chemical or temperature influences, exchange of components or repair of cables. In case of high-precision demands, changes in sensing characteristics must be carefully considered. This leads to the problem that calibration of the sensing system, and especially of the sensing element, should be made from time to time. The latter is, however, almost impossible or not possible, if sensors are integrated in the structure. Calibration of structure-integrated sensing elements always includes long-term influences from the measuring object. It is obviously the need to develop re-calibration methods and corresponding guidelines for structure-integrated fibre optic sensors.

4. CONCLUDING REMARKS

Although few companies have been developed a test programme to validate their products according to their own rules, a generally binding measurement standard or guidelines for fibre sensors are not available. In order to advance in this field, cooperation of all experts should be arranged. First activities are more or less started in few national groups (e. g. in VDI-GESA AK 17 in Germany [9]) as well as in international experts groups, e. g. COST 299 [10] or RILEM Technical Committee: Optical fiber sensors for civil engineering applications [11].

The more activities are developed to address open questions concerning reliability, reproducibility, stability, and technical rules are formulated, the more confidence will grow in the user community. Among other fibre optic sensor technologies, FBGs are the most common one. A set of guidelines should be developed first for this sensor type. In Europe, COST 299 action offers an efficient platform to discuss all relevant aspects and develop necessary guidelines. Within the COST working group 4: 'New challenges in fibre sensors' a study group 'standards and guidelines' is installed. Scientists and interested engineers with hands-on expertise can come together and push the necessary documents. Because of a variety of different aspects in a FBG sensor system, three core groups could be formed:

- Group 1: FBG instrumentation; characterization of interrogation systems
- Group 2: FBG sensor; characterization and application
- Group 3: Components application and service aspects.

Activities of these groups should be funded by industrial partners and interested institutions. These groups would also get a good opportunity to work out well-discussed proposals to earn additional funding from public sector. This would help to establish additional competent persons who will be fully available for this work. It should also be held contact to other groups founded in other regions of the world.

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