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# VALIDATION OF STRAIN SENSORS TO ACHIEVE RELIABLE MEASUREMENT RESULTS

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Fibre optic strain sensors are increasingly used and sensor systems are provided with specifications. Even if the performance is well specified, the strain characteristics of the sensor, strain transfer factor, mechanical stability under thermal influences, the performance of applied strain sensors can seriously differ from virgin sensor's the performance. The contribution will therefore focus on issues that can deteriorate the sensor function or reduce the reliability of measurement results. Aspects are considered how to come to reliable strain measurements and how to validate strain measurements of applied sensors.

Strain measurement in structures with the purpose of long-term structural health monitoring must provide reliable information about the structure's behavior over the whole period of use. The user must be sure that installed sensors are validated and work to the utmost satisfaction. For this purpose, sensor systems are tested using special facilities. Because it is not easy to characterize the strain transfer quality from the host structure into surface-applied strain sensors, a unique testing facility has been developed. Originally developed for fiber Bragg grating based sensors, the KALFOS facility (= **cal**ibration of **f**iber **o**ptic **s**ensors) can also be used for electrical strain sensors. Calibration measurements are referenced by unbiased Digital Image Correlation (DIC) and Electronic Speckle Pattern Interferometer (ESPI) methods. The strain transfer behavior can experimentally be analyzed and investigated under combined thermal and mechanical loading conditions and allows revealing weaknesses in commonly used attachment methodologies. The deformation of all members (particularly the coating/substrate - adhesive combination) in the sensing area is physically independently gained and recorded. Results achieved allow precise description of the strain transfer function, validation of the long-term strain sensor characteristics, matching of specific measurement requirements with environmental conditions, and, moreover, the verification of standards for use of strain sensors.

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# VALIDATION OF STRAIN SENSORS TO ACHIEVE RELIABLE MEASUREMENT RESULTS

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ABSTRACT: Fiber optic strain sensors are increasingly used and sensor systems are provided with specifications. Even if the performance is well specified, the strain characteristics of the sensor, strain transfer factor, mechanical stability under thermal influences, the performance of applied strain sensors can seriously differ from virgin sensor's the performance. Therefore the contribution considers validation issues to come to reliable strain measurements and how to validate strain measurements of applied sensors. A new validation facility will be presented.

## 1 INTRODUCTION

Validation issues are very practical issues. A huge number of strain sensors are available on the market; the young fiber optic strain sensor technology conquers the market more and more because a number of specific advantages. Fiber optic sensors are therefore widely demanded for measurement in hostile environments, for monitoring and evaluation of critical structures, for early detection of damage and stability risks, and for monitoring of new high-performance materials. Long-term measurements and measurements under extreme environmental conditions need long-term stable and reliable measurement systems.

Certainly, customers expect optimal performance from their sensor system; however, fiber optic strain sensor systems sometimes created from single components of different providers need not automatically to work to the best advantage. And, not every manufacturer of sensor components offers application expertise including a warranty claim. From the reliability point of view, systems with components perfectly adapted to each other promise reliable measurement data. All components should be validated, calibrated and perfectly matched. Guidelines provide a directive for manufactures, such as the VDI/VDE Guideline 2660 (2010).

The contribution focuses on issues associated with applied strain sensors. It discusses problems arising out of the application quality, the selection of bonding materials, environmental influences, mechanical loading or thermal stresses. Research activities and international networks to fill some of the gaps are mentioned.

## 2 STRAIN TRANSFER ISSUES

Whatever type of mechanical sensor and fixing method (embedded, clamped, continuously surface-glued, and welded) are used, enduring reliable strain transfer from

the measurement object into the sensing element must be ensured over the complete period of operation. Irrespective of the mode of sensor fixation, the sensor fiber and/or the fiber optic sensing element has always to be bonded to a support component or to a fixing element, and finally to the measuring object for the expected operating conditions. In order to avoid uncertain measurement results, a number of aspects have to be considered:

Physical-mechanical properties of fixing components (substrate, adhesives, protecting layers/
coating), materials combination sensing element/measuring object, and covering must be known and characterized for the total environmental range
- proof of sensor position accuracy
- thermally induced stress loading of the sensing element during component manufacturing or application
- sensitivity of all components (sensing element, leading fiber, connectors and splices, opto-electronic components) to mechanical and thermal influences
- attacks from aggressive media
- chemical and physical interactions of materials close to the sensor.

From our point of view, the appropriate strain transfer from the sensor to the measurement object is most important, brings the largest uncertainty and must therefore be verified. Following, few hidden problems that reduce the reliability of a sensor system are considered for the example of surface-attached FBG sensors.

### 2.1 Surface-attached sensors

A reliable and reproducible bonding of the sensor fiber onto any surface is not easy to reach. Principally, the strain transfer into embedded FBG sensors seems to be easier. Although surface-attached sensor fibers can visually be evaluated how the sensor is fixed at the surface and is often found to be good, extensive investigations revealed that bonding defects and thermal influences can lead to erroneous signal readings. Examples of strain transfer evaluation and details are given in other papers, e. g. Schukar et al. (2011). Alternatively, pre-fabricated fiber optic sensor patches are also used for strain measurements at surfaces; however, patches are quite complex. The patch itself or the adhesive used could shrink. Test revealed that few commercially offered strain patches show aging effects after thermal cycling resulting in an unacceptable measurement result Schlüter et al. (2010).

### 2.2 Embedded sensors

Embedding of fiber optic strain sensors to measure deformation of structure components is in case of high thermal loads rather recommended than surface application, e. g. for wind turbine blades or airplane wings, because surface-glued fiber optic sensors produce an unsymmetrical interface structure and can be damaged. However, the long-term operation of embedded fiber optic sensors might become a challenge, particularly when non-homogeneous and/or orthotropic materials are used such as composite materials or layered structural components. It must be

ensured that the sensitive area, e. g. the FBG element or any sensing fiber is surrounded on all sides by the bonding or the hosting material. Another problem arises, when high temperatures lead to a local deformation of coating materials or during cooling-down phase shrinkage effects occur. Fig. 1, right shows deformation of the coating acting as

bonding interface due to increased thermal strain during curing; Fig. 1, left shows delamination of the sensing fiber area due to shrinkage of the material to be evaluated.

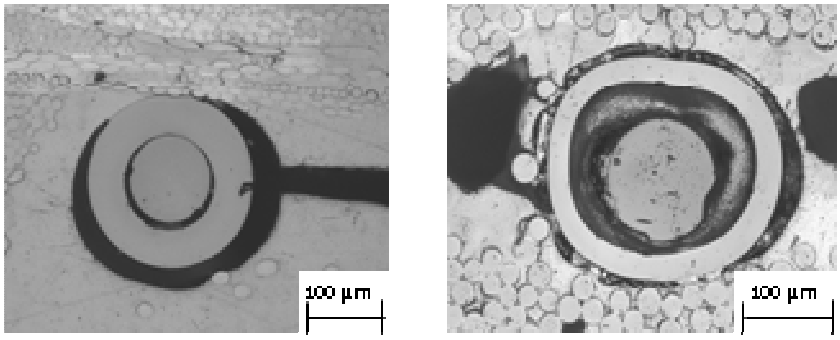



Figure 1. Strain transfer problems with embedded fiber optic strain sensors. Inappropriate choice of fiber coating and wrong method to integrate FBG strain sensors into reinforced epoxy resin components. (small fibers around the optical fiber are the reinforcing glass fibers), left: one-layer high-temperature acrylate coating , right: two-layer standard acrylate coating), Habel et al. (2011).

Another important issue for embedded fiber optic sensors to be validated concerns the stress/strain conditions in the interface area between sensing element and structural material under operating loads (shear stress development). Assuming that an embedded optical fiber strain sensor has completely bonded along the fiber length with the material, elastic stress transfer will be the dominant mechanism at the interface up to a definite stress level. The elastic shear stress distribution along the optical fiber is constant, with exception at its ends if the fiber ends inside the matrix material. If the sensor is located in the area along the fiber where the shear stress is constant, it will work without systematic error. There are no irregularities in shear stress distribution. However, a more realistic situation is that the sensor fiber will have a non-constant shear stress distribution along the sensing length caused by reduced bond strength due to irregularities in the sensor surface or in the matrix material to be evaluated. This could lead to a premature debonding of the sensor from the matrix and its function could fail early. Although the sensor, in this case, delivers any signals, no correct measurement result is achieved. Details about shear stress development and bonding validation in the interface area are described in Habel & Bismarck (2000).

## 3 EVALUATION AND CALIBRATION ISSUES

Basically, all equipment used for on-site measurements (sources, interrogators, sensors) including equipment for subsidiary measurements, such as environmental conditions, shall be validated and calibrated before being installed and put into service. However, everybody must make it clear that applied or embedded sensor elements cannot be re-calibrated after installation without removing them from the measurement object. It is extremely difficult to get validated data from them after a certain time of operation because it is not possible to reveal whether a change in the sensors 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. This basic problem leads always to a certain amount of uncertainty which cannot be exactly defined. In order to reduce this

uncertainty, two ways are imaginable: a) sensors are designed to allow evaluating the function of the sensitive element, and b) facilities are available which allow re-calibrating installed sensors on-site. By now, neither of the two methods has thus far been initiated. The only way, by now, is the prediction of the long-term sensor function of applied and embedded sensors using test samples installed in validation and calibration facilities in labs.

For surface-applied strain sensors, the newly developed KALFOS facility can be used. This facility allows simulating long-term operating conditions, testing and evaluating the bonding behavior, and investigating creep and delamination effects of applied sensors. Embedded sensors, on the other hand, can only be evaluated until now by investigating representative test samples in single-fiber push-out test facilities, Habel & Bismarck (2000).

## 4 VALIDATION FACILITY "KALFOS"

### 4.1 Methodology

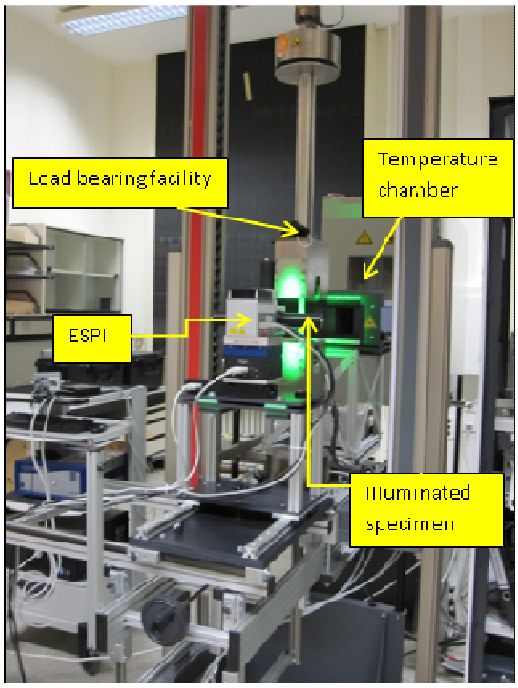
The new validation facility at BAM allows the physically and application-type independent validation of surface-attached strain sensors. It enables exploration and investigation of the strain transfer mechanism including all influences affecting the strain measurement. The methodology used helps to reveal weak points in the strain transfer because the common method validating glued sensors with another but very precise glued sensor which are applied in the same manner, does not tell anything about the application reliability. In other words, for reliable information about the strain state of the specimen, non-contact unbiased reference technologies have to be used.

### 4.2 Description of the facility

The KALFOS facility (= **cal**ibration of **f**iber **o**ptic **s**ensors) consists of a load bearing facility that allows introducing a mechanical stress to a host structure, and a temperature chamber (Fig. 2). The temperature chamber, which is mounted on a separate movable carrier and therefore mechanically isolated from the load bearing facility, allows combined temperature/load cycling in a temperature range from -60 °C to + 100 °C. The specimens can be loaded up to 20 kN tensile force. That way, the tests can be carried out under fully simulated and reproducible environmental conditions. In order to compare the strain information provided by the sensor with that of the host material under loading conditions, two non-contact optical systems are used: a) Digital Image Correlation (DIC) technique and b) Electronic Speckle Pattern Interferometer (ESPI) system. These non-contact validation techniques allow referencing the specimen deformation and visualizing the relative movement between the sensor and the strained specimen, and is therefore not affected by any attachment problems, e.g. by the adhesive used for commonly chosen resistance strain gages as 'reference' sensors. Using this methodology, the strain in all involved materials, the specimen, the adhesive and the fiber optic sensor can be analyzed objectively.

DIC is a three-dimensional measurement technique that determines the coordinates of points on an object when images are taken at different positions. Therefore, a random black-and-white pattern has to be applied to the specimen surface in the desired measurement area. The black- and-white pattern is divided into facets of a specified number of pixels. For each facet, a three- dimensional coordinate is determined. Before

starting the measurement, the camera system has to be calibrated, and a reference image is taken. Every image of the deformed specimen is com-



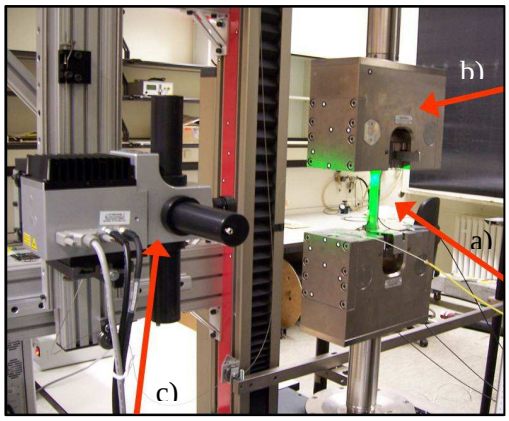




Figure 2. KALFOS testing facility with the loading frame and the clamping jaws (center), the temperature chamber (behind the jaws) and the DIC camera system (in front of the jaws).

Figure 3. KALFOS testing facility with ESPI reference system; a) clamping jaws, b) tensile specimen, c) ESPI system.

pared with the reference image taken at the beginning. That way, a displacement vector and the corresponding strains on the specimen surface can be obtained. A possible relative movement between specimen and fiber can be detected with a resolution individually depending on the number and size of the facets and will easily be depicted in a false-color image. The ESPI system is based on the physical principle of speckles, which can be observed when laser light is reflected by optically rough surfaces. The speckles form a characteristic “finger print” of illuminated surfaces. When the surface deforms, the speckles displace then. It is possible to track the speckles and to calculate the materials strain values from this speckles displacement.

Details of the optic reference systems are described in Schlüter (2010) and Schukar et al. (2012). DIC can be used when large deformations have to be measured, up to 100 % strain. The resolution of the DIC system depends on the number and size of facets, and is in the range of 2 µm (in displacement). The ESPI system (Fig. 3) can be used when very small deformations, e. g. in the range of 100 nm, have to be detected. The resolution of the ESPI system under perfect alignment conditions is up to 30 nm in deformation. When the ESPI system is embedded in the KALFOS facility, a deformation resolution of 100 nm can be reached. The maximum strain range is limited

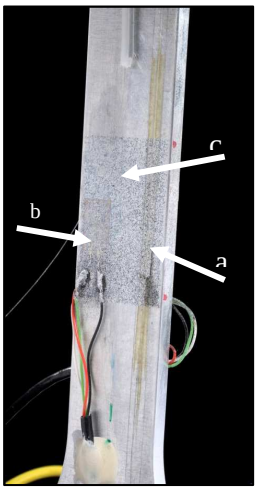
to the number of fringes in the measurement field, that the system is able to differentiate. The usual number of fringes for this system is up to 20, which are good to handle and calculate. The measurement fields for the ESPI system are very small compared to DIC. Additionally, to guarantee a certain number of fringes for the deformation calculation of each measurement step, the ESPI sensor has to be moved along to the movement of the specimen itself. A special ESPI-holder was designed that allows the movement of the cameras in three directions, (x, y and z) to optimally locate the ESPI in front of the measurement target. Additionally, the carrier construction allows the ESPI cameras to move along with the deformation of the host material in order to keep the measurement field in its focus. Because of the ESPI's extreme sensitivity with respect to dynamic vibrations, the whole facility is based on damping elements. The system control panels and all measurement units are mechanically separated from the testing facility itself. The ESPI system and load bearing facility are controlled by complex process software especially developed for this purpose.

## 5 EXAMPELS OF EXPERIMENTAL INVESTIGATIONS

The usefulness of the KALFOS validation facility is shown with two types of investigations: characterization of strain transfer of surface-attached sensor fibers and surface-attached strain sensor patches. For both investigations, the characteristics of the adhesive used to fix the strain sensors must be known because the adhesive mainly influences the strain transfer behavior. Commercially available adhesives exist in wide variety and often their characteristics are not clearly specified in the datasheets. In order to optimize the mechanical bond strength and the ductility of the bonding are, the adhesives to be used must then be characterized. Details, how important parameters and characteristics can be determined, will be described in Schukar et al. (2012). If temperature and humidity influences on the adhesive as well as its curing process are not clarified, the strain transfer cannot be understood and/or optimized.

### 5.1 Validation of a surface-attached optical fiber as strain sensor

In order to characterize the strain transfer function of surface-applied FBG strain sensors, test coupons have been manufactured with a FBG attached to its front side and resistance strain gages glued on the front and back for comparison (see Fig. 4). In this case, both sensor types were referenced by DIC. Therefore, a random black-and-white pattern had to be sprayed onto the specimen. The measurement area consisting of this black-and-white pattern was then divided into single facets measuring 15 x 15 pixels. The deformation of the facets with increasing and decreasing load was then evaluated by comparison with a reference image while the specimen was unloaded. The strains of the specimen, of the sensors and in the adhesive were finally calculated from the measured deformations.



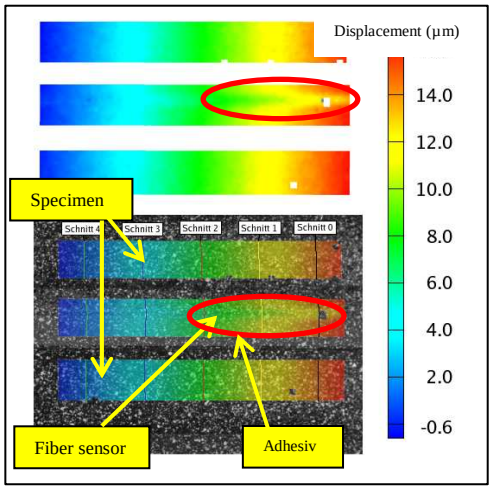




Figure 4. Tensile test coupon with surface-applied FBG strain sensor and resistance strain gages. a) FBG strain sensor, b) resistance strain gage, c) measurement field

Figure 5. DIC response from a strained test coupon with attached FBG sensor with the components: sensing element (fiber), adhesive and tensile specimen. The sensor lags behind the movement of the specimen for higher displacement values.

A typical deformation response of an inappropriately applied FBG sensor under tensile stress is shown in Fig. 5. For growing displacement, the resulting movement of the attached FBG sensor is seen to lag behind the actual movement of the specimen (red ellipse). Such a behavior indicates poor strain transfer between the measuring object and the sensor. In other words, the sensor signal may hypothesize that the load on the specimen is less; however, in reality the load might have been exceeded the limit of the structure. The sensor works unreliable and cannot be qualified.

This behavior becomes obvious when the strain values measured with the optical fiber sensor, and the strain values obtained from the substrate surface and the adhesive by using the DIC system, are compared. In Fig. 6 is shown that the sensor signal does not match with the strain of the substrate. Clearly, as already observed in Fig. 7, the fiber sensor lags behind the actual strain of the substrate because of the inappropriate application.

Comparing directly the relative Bragg wavelength change over the strain of the substrate surface (measured with DIC), the determined gage factor in this case is only 0.6. This low gage factor already indicates a bad application. The gage factor of an appropriately and reproducibly applied strain sensor must be in the range of 0.7 to 0.8.

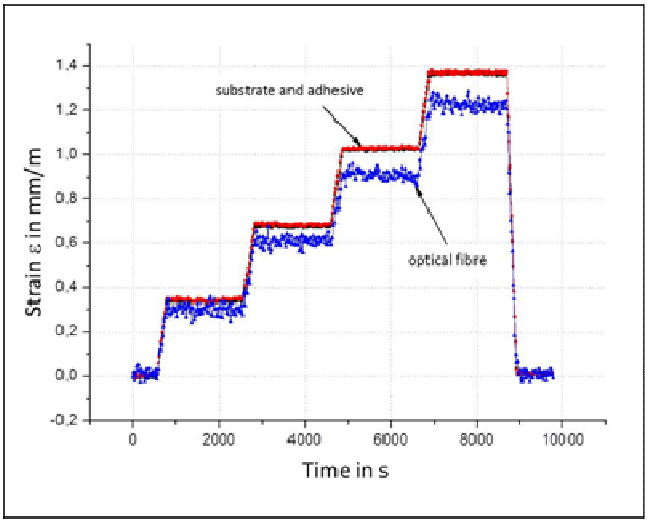



Figure 6. Comparison of the strain measured with the FBG sensor and DIC system for different load steps. At higher loads, the strain measured with the optical fiber sensor is less than the actual strain on the surface of the substrate and of the adhesive measured with DIC

## 5.2 Validation of fiber optic strain sensor patches and resistance strain gages

Similarly to application of resistance strain gages, fiber optic strain sensors are designed in the form of sensor patches. This often helps to apply fiber optic strain sensors under difficult application conditions. Several companies offer FBG patches that can be attached to surfaces, less often embedded into materials. Because the strain transfer from a measuring object into an applied patch is more complex than into a fiber, validation of applied sensor patches is highly recommended. The same applies to resistance strain gages (RSG); their strain transfer characteristics should also be evaluated.

In order to check the strain transfer characteristics of the established RSG technology, test samples with attached RSG sensors have been manufactured. Of course, it was observed again that in the case of a poor application the strain transfer from the tensile specimen into the resistance strain gage was also reduced. Moreover, Fig. 7 shows that the KALFOS facility is even able to detect critical changes in the bonding behavior of a RSG that cannot be identified from the measurement signal response. From the false color image (Fig. 7, right) can be seen, that in the loading test the left upper corner of the strain gage has already begun to delaminate from the specimen. This can also clearly be observed in the displacement curve over the section length. In contrast to this information, the strain measurement response shows perfect strain results and does not provide any indication of beginning failure of the strain gage. This can obviously be explained by the fact that the meander structure of the resistance wire in that area has not yet been affected by the ongoing process of delamination. The same effect can occur with fiber optic strain gages. In such cases, the users of strain sensor systems are not aware that their applied strain gages degrade earlier than its estimated life. The validation facility KALFOS is therefore an important tool to determine (with representative specimens) how likely it is that the sensor will remain secure during the

lifetime in a particular application. To our knowledge, current test methods will not identify such critical areas of applied sensors which is becoming a bit of a problem for a reliable signal recording.

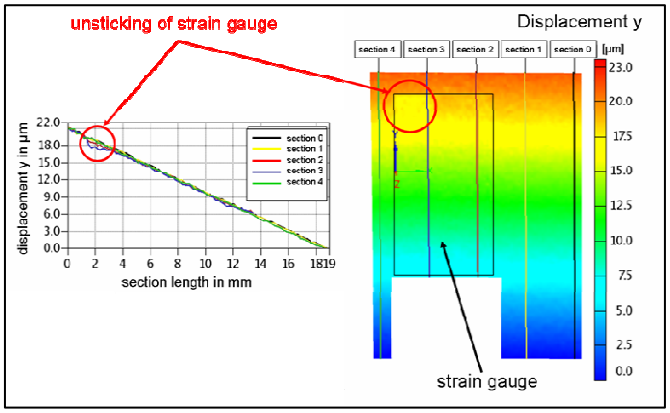



Figure 7. Early damage of a surface-attached resistance strain gage under loading. Delamination at the left upper corner of the gage cannot be identified from the common sensor signal response.

## 5.3 Investigation of strain sensor's aging behavior

In many cases applied strain sensors are dynamically stressed. In order to validate strain sensors for long-term measurements under dynamic loads, aging test should be carried out. In the following, two examples shall show how important such investigations are. Fig. 8 shows aging test results obtained from fiber optic strain patches attached to a surface of a carbon fiber reinforced composite carrier (thickness: 6 mm). Flexural fatigue tests were carried out with a cycling frequency of 0.5 Hz. The first 50,000 load cycles were carried out with an elongation of ± 1 mm/m; after that, the elongation was increased every 10,000 load cycles by ± 1 mm/m. One patch (see picture in Fig. 8) showed critical bonding behavior. Comparing the bonding behavior of fiber optic strain patches with RSG, it can generally be stated from our investigations that RSG failed significantly earlier than the fiber optic ones.

Another important demand for strain sensors is their resistance to temperature stresses. Applied strain sensor must not show aging effects when they have to work under high temperatures. In addition to the durability, the sensor characteristics must be specified and validated for the desired operating temperature range. Several commercially available fiber optic patches specified by the manufacturers for an operating temperature range of 80 °C were tested.

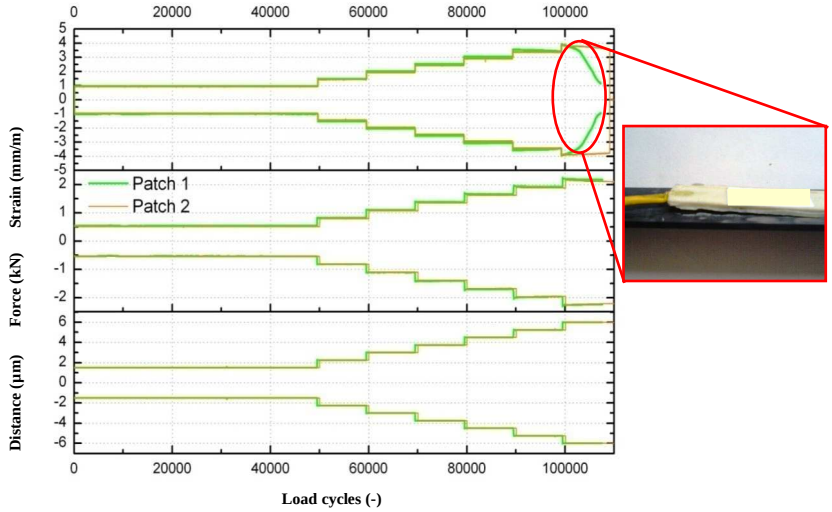



Figure 8. Delamination of the patch from the surface occurs at ± 4 mm/m.

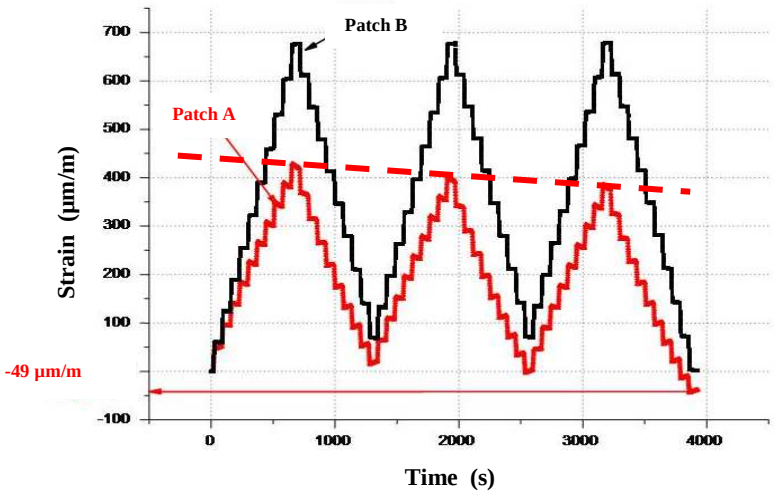



Figure 9. Fatigue test of fiber optic strain sensor patches at ambient temperature of 80 °C. The inclined dashed line (red) shows that the strain response of patch A is not stable after cycling; the introduced strain does not appear correctly.

Fig. 9 shows one of the strain cycling tests results for the maximum indicated temperature of 80 °C. It can be seen that patch A decays at 80 °C after few cycles at a strain of about 400 µm/m. The strain offset after cycling due to relaxation was -49 µm/m. This means that no proper strain transfer is possible with such a product because of its instability with temperature although specified.

## 6 SUMMARY AND CONCLUSION

The practical use of fiber optic sensor research results requires validation of their reliable function over a long period of time. Availability of seriously approved sensors will enhance the confidence of the user community concerning reliability, reproducibility and stability of sensor products.

In order to come to validation results, validation facilities are needed. A reliable validation of embedded sensors is difficult or not yet possible. However, surface-applied sensors can be validated and calibrated by using physically and application independent referencing methods. Such methodology enables evaluation of all the effects that influence the measurement results and it enables qualification of the sensor's performance after manufacturing and after application. The paper presented a new validation facility "KALFOS" that uses a non-contact method which enables full-field measurement of displacements and strain in all directions. This makes it therefore possible to visualize the relative movement between a surface-applied strain sensor and the strained specimen. The reference systems ESPI and DIC, which are intrinsic parts of the validation facility, are not affected by any influencing factors that occur when other sensors are applied for comparison. These optical systems provide very high displacement resolution (down to 30 nm for ESPI and 2 µm for 3 DIC). Using this facility, all materials involved in the sensor zone: tensile specimen (support, carrier), adhesive, and the sensing element itself (optical sensor fiber, fiber optic patch or resistance strain gage) can be analyzed objectively (k-factor, reliability-relevant changes in spectral response of FBG). This provides additional knowledge about material behavior, and weaknesses of surface-applied strain sensors can be revealed. It is possible to analyze and characterize all types of surface-applied sensors e. g. RSG, piezo-foils, sensor patches incl. their components) under combined mechanical and thermal or climatic loads. This validation facility has great importance to verify definitions of component requirements and quantitative statements for new or in existing standards and company guidelines, e. g. proof of K-factor.

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