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Investigation of the fiber-optic strain sensors' behavior under offshore conditions to create standards for reliable application

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ABSTRACT: The application of fiber-optic sensors in offshore environment is a big challenge. Especially if sensors have to be installed in the tidal zone and components are exposed to extreme environmental attacks as well as mechanical loads. There are no sufficient experience on how to test selected materials, how to handle application and how remotely to assess the function of installed sensors operating several decades during summer and winter time. It has to be feared that installed sensor components could be damaged in case of heavy storms and strong waves or due to ice drift. Another danger is the biological attack to sensors. Not only the high amount of salt and UV radiation could degrade the protecting materials of sensor systems, it is well-known that sea biological influences such as barnacles and other types of fouling perturb the proper function of sensors or even lead to failure.

In Germany, a research project is being carried out to investigate the specific offshore influences to fiber-optic sensor systems with the objective to develop evaluation strategies and corresponding testing procedures and standards. The paper describes first results after harsh test cycles and gives first bullets for a corresponding standard for application in offshore environment.

1 INTRODUCTION

Sensors as a part of a monitoring system have to work reliably under the expected conditions. Before sensors and their components are selected, all possible influences that could impact on the sensor performance, the long-term stability of components, and thus, define the measurement quality of a sensor system must be analyzed. Usually, established sensor systems are well-understood and extensively tested under very harsh conditions. New and innovative sensor systems must of course also fulfill the requirement if used under harsh environmental condition. However, there are two important aspects: a) young, innovative sensor types are not yet fully understood how they might react to significant attacks, and b) not all complex influences that act as well as materials interactions can be simulated in test areas of laboratories. It is then absolutely essential to make some field tests to find out the behavior under real environmental conditions.

Because users want to be sure that the measurement system is long-term stable and well-applied, standards and guidelines are not only wanted but urgently needed. They should recommend how to apply, how to evaluate and how to repair measurement systems under harsh operation conditions. Unfortunately, there is still a big lack in standardization of application procedures and testing methods for fiber-optic sensors, see also Habel et al. (2011). But exactly such documents are especially needed for sensors to be applied under very harsh conditions such as in offshore environment or in mining area and in oil and gas facilities. Using here the example of fiber-optic sensor application in offshore environment, the paper gives basic impressions which attacks have to be considered, and what to consider when a guideline or a standard for application has to be developed.

2 SENSOR INSTALLATION IN OFFSHORE ENVIRONMENT - CHALLENGES

There are many structures and facilities that are operated under offshore condition such as wind turbines, oil platforms or gas pipelines or high-voltage power cables, and that need sensor systems. If there are special requirements with regards to electromagnetic interference or lightning safety, or if large areas of structures are to be monitored, fiber-optic monitoring systems are unavoidable. Sensors are then installed on the surface of structure components or are embedded in composite materials. Sensors and related components are exposed to several 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 other types of fouling.

All these influences require special measures to protect sensors and cables from such attacks to guarantee the sensor function over the period of measurement planned. There are a lot of investigations that should focus on revealing of problems avoiding an appropriate sensor function, e.g. Schukar et al. (2013). Another important aspect is that all protecting measures must not influence the measurement result. The load or strain transfer from the measuring object into the sensitive element must be ensured in spite of all protective measures.

The following chapters will show that all these aspects are not trivial and it is a hard challenge to meet the requirements with regard to measurement reliability and long-term stability.

3 TESTING METHODOLOGY

Generally, sensors are tested in laboratory or in large-scale testing facilities to check out the behavior under the expected loads and attacks. Mostly, materials used provide the most common problems. Their behavior must be known or they must be tested separately before their use. Also the interaction of materials must be investigated and tested. Any unwanted chemical or physical interactions must be excluded. Just in sea-water environment, the influences are very complex. We decided therefore to investigate the behavior of the sensor systems preferably under real influences in offshore environment because it is extremely difficult to simulate all the complex loads in laboratory environment. Additionally to these field tests, single influences are simulated in climate and special test chambers.

4 FACILITIES TO INVESTIGATE INFLUENCES UNDER OFFSHORE CONDITIONS

4.1 Climate chamber for salt-water attack tests

Salt-water tests were carried out in a climate chamber. In order to evaluate the suitability of optical cables connecting the sensors (patch cable) with the interrogating device, in total 9 cables with connectors were exposed to salt-water solution. The salt concentration corresponded to the salt concentration in the ocean (3.5 %). The open end of the cable connectors were dipped into the water (Figure 1). 20 temperature cycles were made over a period of 9 days (210 h) in the range from 5 °C until 65 °C. The attenuation of the cables was automatically controlled by a device. After these tests, the connectors were visually evaluated.

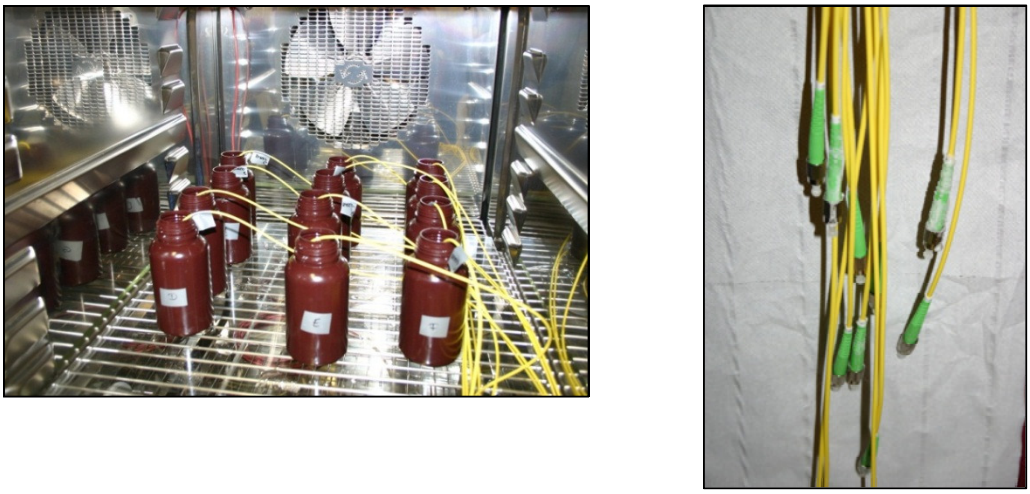

Figure 1. Climate chamber to test optical cables under salt-water influence. The picture right shows the connectorized cable ends.

4.2 Portable 4-point bending test facility

Before the strain sensor samples are to be exposed to real load tests in the field area, they must be calibrated in laboratory. However, after a certain time of exposure on-site, the sensors must be calibrated once more. In order to manage calibration on-site, a special calibration facility had to be developed for use outside of laboratory. Figure 2 shows the portable calibration facility. It is based on a 4-point bending test procedure and can easily be moved to the test location. It can be used outside and enables a step-less increasing bending of the test sample.

This facility is specially designed for plates with adhered or anyway fixed strain sensors. The plate is fixed in the facility, the sensors are connected to the recording device and the calibration cycle can be started. During the bending cycle, the optical response from the sensor can be recorded. In case of fiber 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 that would lead to stiffening of the system plate/sensor. In such a case, the plate geometry and its features (e.g. Young’s modulus) 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.

Figure 2. Portable 4-point bending test facility for strain calibration in the test field area (designed by H. Kohlhoff, BAM).

4.3 Testing rack for exposure of sensors to sea-water

In order to get real load conditions under sea-water attacks, a huge testing rack was installed at the quay wall on the harbor side of the Island of Sylt/North-West Germany (Figure 3). The plates with the sensor samples can be hooked in several racks whereas the racks are positioned in different levels with respect to the occurring sea-water level in this North Sea area. This way enables to expose the samples different conditions: the upper rack is located in the tidal zones and exposes the samples the sea-water only in the maximum flow phase. The centrally positioned samples are more exposed to sea-water, and the bottom samples fall dry only in the absolutely ebb phase for about one hour. The plates with the test samples are releasably fastened and the positions can be exchanged.

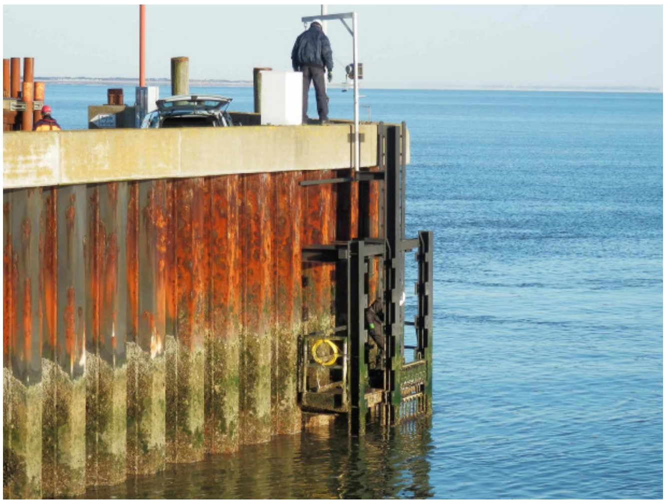

Figure 3. Location in the harbor area in List/Island of Sylt/Germany where the test samples are installed (Photo: GESO GmbH Jena, T. Pfeiffer).

5 TEST CYCLES AND FIRST RESULTS

Before the plate samples with differently installed fiber-optic strain sensors were exposed to single attacks, few basic measurements were made in laboratory. The coefficient of temperature was measured for all plates with installed FBG strain sensors; it was in the range from 20 pm/K until 25 pm/K. The calibration curve was measured and recorded for all samples.

5.1 Salt-water attack tests

The tests under salt-water influence showed serious damage at the connectors. It was surprising that the connectors at the dry end (!) were extremely crusted with salt. The reason for that was the fact that the salt-water was obviously flowing through the cable due to the capillary effect. At the dry end, the water evaporated then and the salt crystals were left. At the connectors stored in salt-water, corrosion was already found. The crusting and corrosion effects did not influence the attenuation of the fiber after cleaning the connectors; however, they could not be used anymore to connect the cable to a (rather expensive) measurement device. Figure 4 shows corrosion damage at the connector after exposure in salt-water for 210 hours.

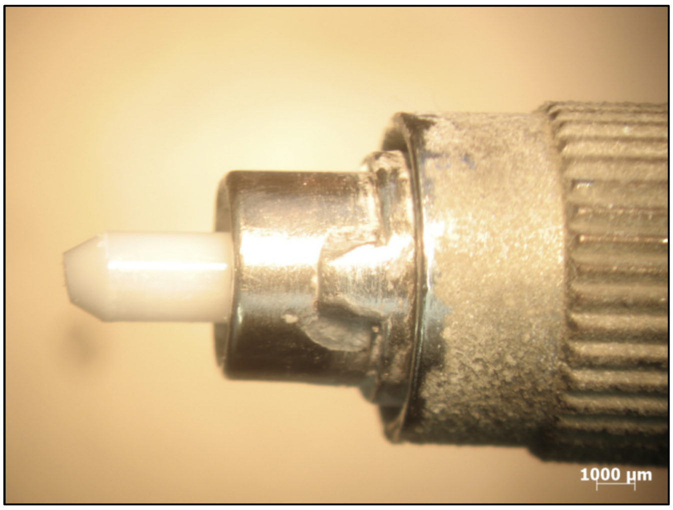

Figure 4. Connector corroded by salt-water influence during salt-water attack test.

It is obvious that salt-water must not penetrate the inner part of a connector and the optical signal must not be influenced by diffusing water.

5.2 Calibration by bending tests on-site

Before the plates with attached FBG strain sensors were exposed to offshore environment, the calibration curve was recorded in laboratory (virgin calibration) by using the portable calibration facility (Figure 2). The next calibration was carried out after being exposed the samples for 5 months in the testing rack to North Sea conditions. The actual calibration curve was compared with the virgin curve of the corresponding sample. The differences in the calibration curves clearly showed that the strain responses were different for the same mechanical loading. This behavior was caused by changes in the bonding of the protecting layers and in the covering materials, by aging of materials as well as by water inclusions, corrosion and delamination of parts of the sensors. It could be observed that in some cases a strong creep effect distorted the sensor signal. There were also observed some other effects, which have to be clarified by further investigations.

5.3 Exposure of sensor samples to sea-water

In the testing rack at the quay wall in List/Island of Sylt in Germany (Figure 3), in total 46 sensors differently attached to 23 plates were exposed to the real sea-water conditions. That means that 9 different attachment methods are being tested. The plates were hooked into the rack and placed one above the other. 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. After 5 months of exposure, all plates were cyclically moved: the bottom plane was moved to top, the middle to bottom and the upper plate was put to the center. After another 3 months the plates were dismantled and assessed. It was found that few of the connecting cables were torn due to severe wave attacks, and the plates were densely populated with algae, barnacles and polyps (see Figures 5 and 6). The plates were cleaned, damage was made good and all plates were remounted in such a way that they are now exposed to different attacks in comparison to the former ones. In this way, all plates can suffer the same attacks over the whole testing period.

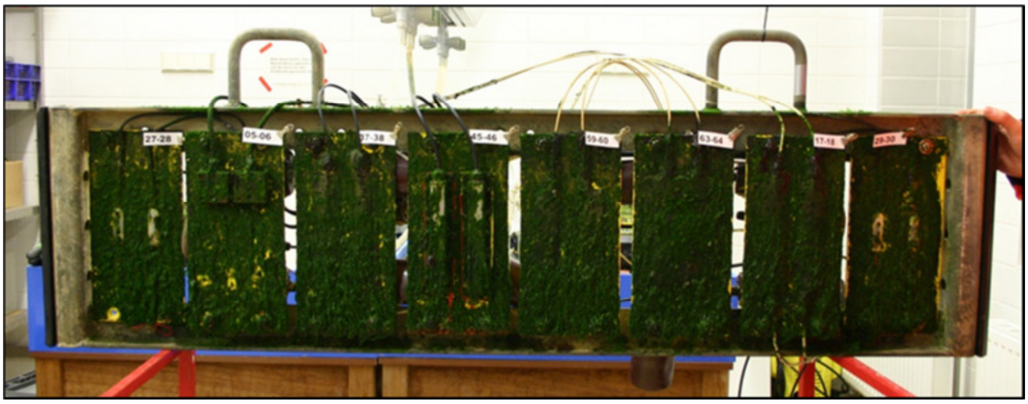

Figure 5. Detail of the test samples arrangement installed in the testing rack.

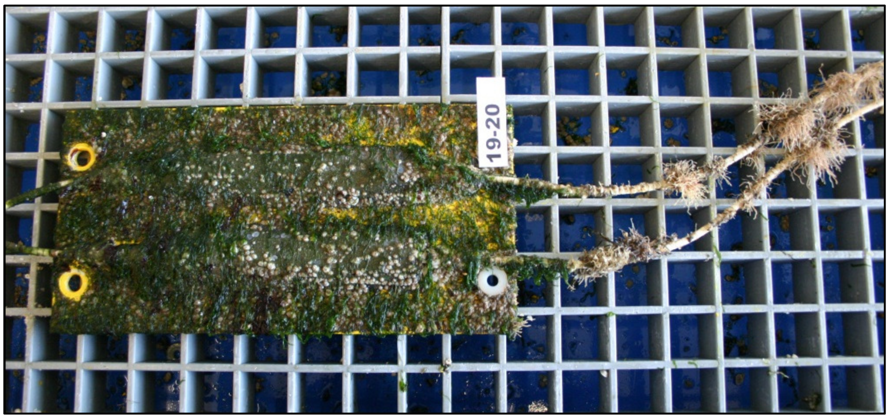

Figure 6. Detailed view of one of the exposed sensor-equipped plates. Clearly can be seen the marine biology vegetation (algae, barnacles and polyps at the leading cable).

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.

Additionally to the plates with the attached FBG sensors, a couple of sensor cables and connectors were exposed, too.

6 GUIDELINE FOR USE OF FIBER-OPTIC SENSORS IN OFFSHORE ENVIRONMENT

The extensive investigations of factors that influence the performance of sensor systems installed in offshore environment will lead to important statements that have to be considered in guidelines and standards. Standards are highly needed when sensor systems are to be installed in that harsh environment. Only few general documents are available for use of sensor systems in offshore environment. Standards for fiber-optic sensor systems in that environment are not yet available and must be developed. From these investigations described, already few bullets can be derived to create a standard. Important aspects concern:

- Definition of a requirement profile / exact loading conditions
- Requirements of the components of the sensor system to be used (cables, connectors, materials), if necessary, approval of suitability by additional tests
- Definition of calibration procedures including measurement procedure traceable to reference sensors
- Possible ways to install sensor system at offshore structure components
- Clarifying important performance parameters (e.g. coefficient of temperature, linearity/stability of characteristic curve)
- Recommendation for type of installation (kind of fixing)
- Covering/housing of sensor area including impact on sensor signal (e. g. strain transfer)
- Impact of marine biology vegetation on the measurement performance
- Possible ways to exchange/repair components under offshore conditions.

7 CONCLUSIONS AND OULOOK

In order to be able to use fiber-optic sensor systems in offshore environment, a number of open questions must be clarified. The most critical points are serious mechanical, climate and marine biology attack that lead to damage or at least influence the sensor system performance. First investigations revealed that common actions to protect sensor systems from impacts or damage are counterproductive because they could lead to critical influence on the measurement signal and the sensor response. Few examples of tests carried out with differently applied fiber Bragg grating strain sensors and exposed to real offshore conditions in the North-sea environment were described. These first results allow already to formulate first bullets for a standard to be developed to give the potential users and appliers knowledge what to consider and how to ensure long-term stable sensor systems and reliable measurement results in that environment. It was already found out that one of the key aspects concerns careful selection of components and approval of their suitability by specific simulated tests to ensure long-term stable and reliable operation. There are more investigations necessary to consider the extremely complex impact situation and following create a standard for application and validation of offshore-suitable sensor components and systems.

The test cycles in the North-Sea environment are being continued and other important simulated tests in a specially developed large testing chamber to reveal further critical aspects will be started soon. The first green standard document is expected to be published in the second half of 2014.

ACKNOWLEDGMENT AND REFERENCES

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