A Comparison of Strain Measurement Systems in a Tensile Experiment

Eike BARNEFSKE, Friedrich KELLER, Christian GEHMERT &
Harald STERNBERG, Germany

Key words: Fiber optical strain sensor, Fiber bragg grating, photogrammetric strain measurement, comparison of strain measurement methods, electric strain gauges, tensile experiment.

SUMMARY

This paper shows an experimental comparison of Fiber-Bragg-Grating (FBG) strain gauges, electrical strain gauges and the photogrammetric strain systems IVIEW and ARAMIS in a tensile test according to DIN EN ISO 527. Electrical strain gauges and photogrammetric strain measurement systems are commonly used for experimental and monitoring applications. An enhancement of these systems are fiber optical strain (FOS) gauges like the FBG sensor.

All investigated systems were installed on a sample body consisting of a Fibre Reinforced Polymer (FRP) composite. Three experimental tensile procedures in the given strain range of the FBG senor and a final procedure above the given strain maximum were taken.

The measured strain values from the different systems were compared and analyzed. Problems by the system comparison were detected and possible solutions were discussed. The effect of temperature changes over the time will be compansated.

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1. INTRODUCTION

Strain measurements are commonly used for structure health monitoring (SHM) and construction material investigations to detect failures and limits of materials and constructions. Variables strain measurement systems are available with variating properties for accuracy, registration mode or a working range. An enhancement of widespread photogrammetric and electrical strain measurement systems are fiber optical strain (FOS) gauges like the FBG sensors. The benefits of FOS strain sensors are low weight and the option to integrate the sensor in or on many different materials. Distances up to several hundred meters between the interrogator and the sensor, as well as the option to connect many independent sensors on one canal of the interrogator and high registration rate are ideal parameters for complex monitoring systems. The FOS sensor is non-sensitive of electromagnetic waves and can almost be used at any environment condition (Woschitz & Brunner 2011). Because of this characteristics and the possibility to measure the temperature with the same system and the compact construction, FOS strain measurement systems can be suitable for spacecraft application (Ecke et al. 2001) and the monitoring of buildings with a critical to safety of life construction like bridges (Chan et al. 2005 and Childers et al. 2001).

The paper presents potentials and limits of different techniques for strain measurement system on a practical tensile experiment were investigated using ARAMIS, IVIEW / GOM RTS, electrical strain gauges sensors and a FBG sensor.

2. MEASUREMENT SYSTEMS

Electrical strain gauges, photogrammetric strain measurement systems and FBG sensors use different initial observations to determine strain. The type of initial observation has an effect on the quality, real-time availability, the rate of measurements and sensitivity towards environment influences. Depending on the task the effects can limit the use of systems. Briefly the tested systems and the preparation of the measurement system are described and the restrictions are given.

2.1 Photogrammetric Strain Systems

The non-contact optical 3D deformation measuring system used to observe the expansion of the material was developed by GOM and utilizes a software package called ARAMIS (Version 6.3). The ARAMIS software is designed to run the sensor and controller, to process all measurements, to compute results and to perform the post-processing. The software allows full-field displacement and strain measurements. The sensor consisting of two CCD cameras were used at a resolution of 2448 x 2050 pixel (ARAMIS 5M sensor). The measuring volume varies and depends on the camera angle and the lens choice. The used camera setup consisted of 35 mm lenses with a camera angle of 25°. To ensure that the dimensional consistency of the measure is given a calibration of the measurement system is necessary. The sensor calibration was carried out with the CQ/CP 55 x 44 calibration cube. The measuring field was 65 x 55 mm. The depth of measuring volume depends on the aperture and was about 27 mm. With regard to the comparison the tensile force was imported via the A/D input of the sensor controller.

The GOM Real-Time Sensor is a software extension to the ARAMIS system. In Version 6.3 the GOM RTS package is included in the IVIEW application. It allows to measure single measurement points on the specimen surface in real-time and to perform calculations based on the coordinates of these points. Generally the camera images will not be stored during these operations as the computation is based on the live images of both cameras. For the tensile test the GOM RTS were used to simulate two strain gauges between two Points 0-1 and 2-3 (Fig. 3). Furthermore the camera images were stored for a following full-field strain calculation with ARAMIS.

The Aramis system requires a high contrast stochastic pattern on the investigated object. Commonly a white dull base layer and black stochastic pattern on the clean surface of the specimen will be applied. Smaller measuring volumes require a finer pattern than large measuring volumes. During the tensile test the sensor records pictures with a frame rate up to 15 Hz of the investigated specimen. With the Aramis 5M for strain measurements strains in the range from 20 µm/m – 20000000 µm/m can be measured by the system (GOM 2013b, GOM 2013c). The accuracy up to 10 - 50 µm/m can be reached. To analyze the deformation of the specimen corresponding picture points in any picture were measured. Generally a grid with a cell- (facet-) size of 19 x 19 pixels is used to summarize the picture point measurements to reduce the computing time. To ensure a complete coverage of the observed region each facet overlaps its neighbors by 21%. The displacement of the facets was calculated automatically and can be exported by various interfaces and formats (GOM, 2013a).

2.2 Foil strain gauges

Foil strain gauges (FSG) consist of an electrical active part (wire or grid) and isolator part which is flexible. Different types of insulator materials like polyimide or epoxide allow installing the strain gauges on almost any surface. Depending on the properties of the specimen the gauges have to be glued with an appropriate adhesive on the specimen or a self-sticking gauge can be used. The area for the strain measurement is limited to the active part of the electrical grid. A 50 mm long strain gauge is used for the investigation.

The electrical resistance of the foil grid or wire is observed and used to calculate a measuring voltage (Wheatstone bridge). The measuring voltage is proportional to the strain on the specimen surface. The voltage signal is assigned to a change of length. Using the electrical resistance with the Wheatstone bridge a high sensitive strain measurement is possible. The used K-LY type has a maximum tensile strain of 20000 µm/m and a minimum resolution of 8 µm/m (HBM Manual 2015). The effect of temperature change was reduced by a constant temperature conditions at laboratory of 20°C during the investigation. The registration rate at the investigation was 50 Hz.

2.3 Fiber Optical strain gauges

A fiber optical strain gauges is a special fiber optical sensor (FOS) to detect deformations or temperature changes. All FOS systems contain of a light source, photodiode which detects the reflected light, transport wiring and an active part (sensor). There are several commercial techniques for sensors available on the market. Systems using the Rayleigh variance are suited for continuous observation with one sensor for several meters. Sensors like SOFO or (FBG) sensors are designed to measure deformation or temperature changes at a certain point.

Using a FBG strain sensors light of a limited spectrum (1510 to 1555 nm) is emitted by an interrogator. The emitted light is transported by a coupler towards the FBG sensor. The FBG sensor contains a periodic grit pattern (□) in the fiber core. The marks of the pattern have a refractive index (n). The corresponding wavelength of the light (□) reflects at the sensor and travels back to an optical spectrometer (Woschitz & Brunner 2011).

□ = 2*n*□ (1)

Light with wavelengths that are not reflected continuously transmission in the fiber until a sensor with a pattern for the wavelength appears or the fiber ends (Fig. 1).

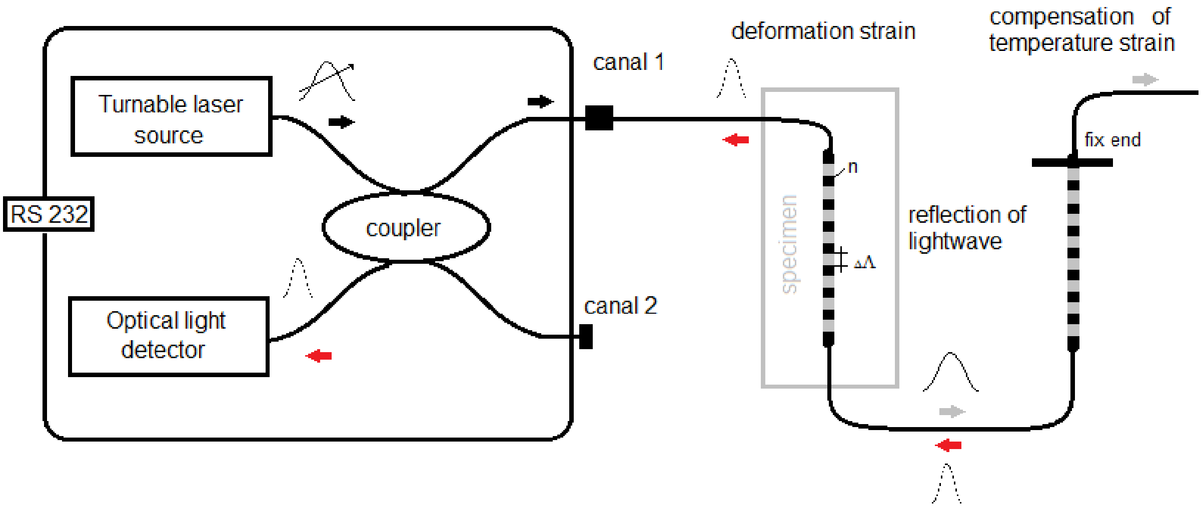

Figure 1: Principle FBG sensors at the setting of the tensile experiment

The reflected wavelength of any measurement at any sensor is registered. Changes of the wavelength over the time can be caused by temperature changes or deformation of the sensor. The difference between the initial and the current wavelength (□□) can be used to calculate the total strain of the sensor. For approximation with a k-factor of 1/0.78 and the first registered wavelength equation (2) can be used (Woschitz & Brunner 2011).

$$\mathrm{STRAIN} = 1/ k * \square\square/ \square \qquad (2)$$

In the case the calibration of the sensor known a more precise calculation of the stain is possible. The first order sensitivity at 20 °C (S1) can be calculated by the use of equation (3).

$$\mathrm{STRAIN} = \square\square * \mathrm{S1} \qquad (3)$$

An effective approach to determine the temperature strain (S_t) is a second loss sensor of the same type next to the sensor for detecting deformations. The registered strain at this sensor only includes the effect of the temperature. By subtracting the measurements of the strain of the two sensors at the same time the deformation of the specimen can be calculated.

The system used at the tensile experiment is a FiberPro SFI700 multi-channel interrogator which technical parameters are given in table 1. Two Miniature Polyimide Sensors are used to measure strain of the deformation and temperature change.

Table 1: Important technical parameter of the Interrogator FiberPro SFI700

Resolution wavelength	0,001 nm (~0.8 µm/mm)
Accuracy wavelength (strain)	0,01 nm (~8 µm/mm)
Measurement rate	5 Hz (max.10 Hz)
Working rage	35 nm
Interface	RS-232

3. TENSILE EXPERIMENT

To compare the preformats of the three different strain measurement systems at a tensile experiment with a flat Glass Fiber Reinforced Polymer (GFRP) specimen was executed at laboratory conditions. All manufacturers advised calibration procedures for the strain measurement systems were performed. The specimen was vertically installed at the test bench FRANK Modell 1020.

The installation of the strain sensor was setup by the instructions of the DIN EN ISO 527-4 appendix B. This recommended settings of the sensors placement are the common for investigations of material for construction purpose (Fig 3).

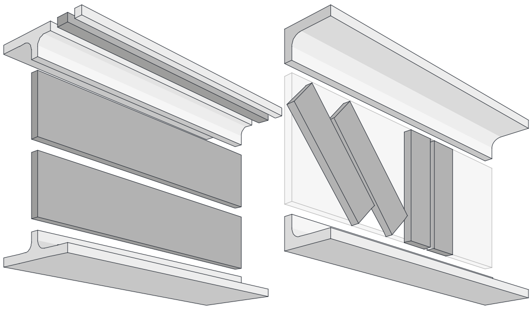

Figure 2: Cutting flat specimen from a structural profil

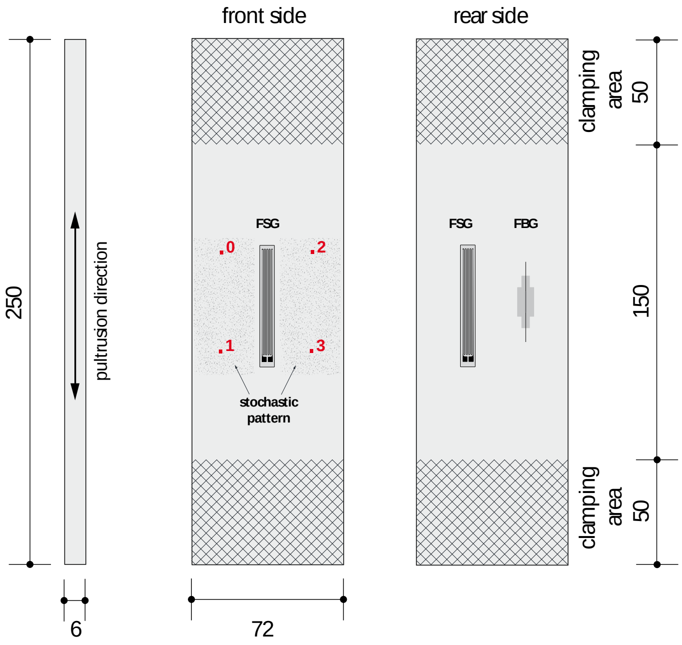

Figure 3: Placement of sensor on the specimen

On the front side a FSG sensor is glued in the center of the specimen. The covered sensor as well as the area to left and right is painted with a stochastic black and white pattern. At both sides two marks for the VIEW software were installed. The rear side was used for a second FSG and FBG sensor that are glued at the same height as the FSG sensor on the front side (Fig. 3 and 4).

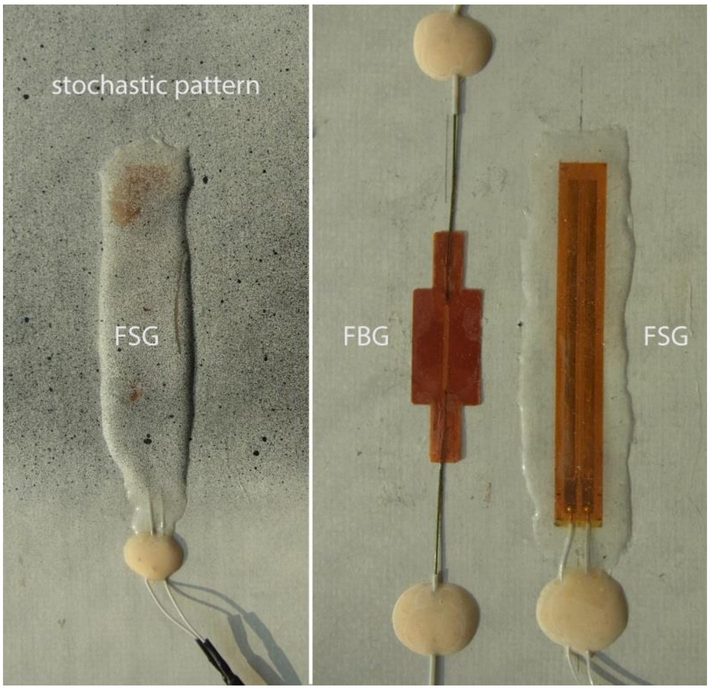

Figure 4: Installation of the sensor and pattern on the specimen

The flat specimen was cut from a pultruded GFRP structural profile (Fig. 2). Due to the excellent corrosion resistance and electrical isolation the field of main application are working platforms at offshore power plants and at railway construction as well as load bearing structure for cooling towers in chemical industry. Pultruded GFRP profiles consist of E-Glass fibre reinforcement (layers of longitudinal rovings with woven and complex mattings) in a thermoset resin based matrix.

The comparison of strain measurements of different systems using the same time is not possible, because the systems have different registration rats and delays caused by interfaces, conversion of the signal and wiring. To compare the measurements the acting tensile force is used. This force is measured with a 100 kN load cell as 10 V signal. The voltage signal is converted into a force and injected towards the strain measurement systems. For the measurement with ARAMIS and the FSG sensor commercial software is used. The FBG registration and conversion of the signal was preferment by self-written MATLAB scripts.

Four test runs using the four strain measurement systems simultaneously were carried out. The traverse speed of tensile bench was set to 1 mm/min during all tests. The test runs were realized after a warming up period of an hour for all systems. This warming up time is necessary to avoid errors caused by inertial system and external temperature changes. The first three runs were stopped at a force of about 26 kN or 2000 µm/m to avoid a damage of the FBG sensor. The last run was used to prove the maximum strain that could be realized by the FBG sensor. The breaking point of the FBG sensor was reached at a strain of 3438 µm/m. This valule is 37% above the maximum strain of 2500 µm/m.

The FBG sensor is highly sensitive towards temperature changes. Even at stable indoor conditions smallest changes could cause an error for the strain measurement. For the detection of strain changes forced by temperature a second similar FBG sensor was installed at the same channel of the interrogator.

4. RESULTS AND DISCUSSION

The processing of the stain measurements for all sensors was done by the respective system software. The conversion of the observations for the FBG sensors into strain was done with MATLAB using the calibration specifications. To compare the strain measurements systems the calculated strain and associated tensile forces was saved and loaded to a MATLAB script. As indicators for the comparison the maximum strain and tensile force of all runs were calculated (table 2) and the difference of strain at discrete tensile forces (table 3) were determined. Plots of the whole data were produced to identify and outlier and trends (Fig. 5).

The indicator maximum strain per runs show differences between values of the measurement systems within the approximate standard deviation (95%) for the FSG and IView system at all runs. The difference of FBG sensor to all other sensors at any run is above the uncertainty of the measurement systems. The smallest difference is 69 µm/m towards the Aramis system and to furthest with 190 µm/m towards the IVIEW system. ARAMIS has constant difference to IVIEW and FSG of 70 µm/m and is closest to the FBG output (table 2).

Table 2: Maxium strain and force mesurments

Run	**001**	**002**	**003**	**004**
Maximum force (kN)	26.9	26.2	26.4	47.2/46.8/47.4/46.5*
FBG Maximum strain (µm/m)	1963	1898	1902	3438
FSG Maximum strain (µm/m)	2093	2051	2058	3713
ARAMIS maximum strain (µm/m)	2023	1982	1985	3600
IVIEW maximum strain (µm/m)	2109	2068	2092	3182
* no simultaneously stop possible, beause FBG sensor was faild.				

The difference between run 001 to 003 increasted for the sensors FBG and FSG. This sensors are sticted to the specimen. It could not be exclude that after seval runs the adhesive starts to fail. The results of table 2 consider only one point of the measurement. To get an impression of the systems behavior on the complete tensile run for run 001 discrete differences are compared in table 3.

Table 3: Difference between the mesurements at discreat forces for run 001

Δ-Strain\force	**5 kN**	**10 kN**	**15 kN**	**20 kN**	**25 kN**
FBG/FSG (µm/m)	45	23	1	40	73
FBG/ARAMIS (µm/m)	35	27	28	10	13
FSG/ARAMIS (µm/m)	14	4	28	50	61
FBG/IVIEW (µm/m)	24	0	11	6	72
FSG/IVIEW (µm/m)	25	22	40	34	2
ARAMIS /IVIEW (µm/m)	11	26	11	17	59

The strain differences at forces during the runs are smaller than the results at the maximum tensile force. Besides of few exceptions all differences are within the systems uncertainties until a tensile force is above 15 kN. This exception is small and could be caused by local tension in the specimen. The increasing variation of the strain measurement systems can be explained by a decreasing accuracy of strain measurement by increasing strain, failing of the adhesive and delays on signal processing. The whole data of run 001 is shown in figure 5 and verifies the investigation of discrete points.

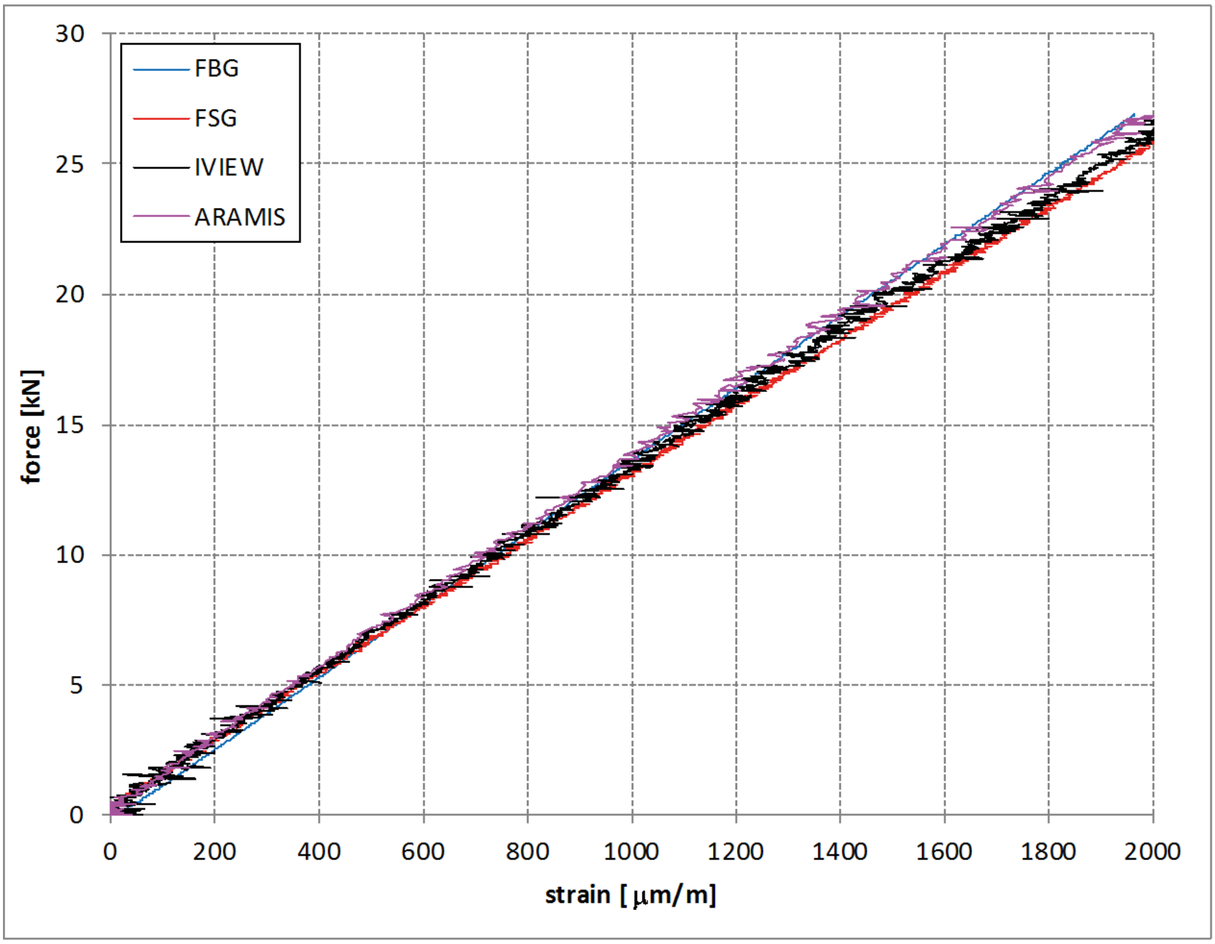

Figure 5: Comparison of different strain measurement system on surface of a specimen during changing tensile forces

The effect of temperature changes over the time of measuring was the biggest error source for the FBG sensor and needs to be compensated. Two approaches were tested to reduce this error. The first approach based on a priori and a posteriori measurements. The strain caused by the temperatures changes is linear and cubic interpolated. The advantage is that only one FBG sensor is needed. This simple approach suits for short observations in laboratory environment with small change of temperatures. The second approach is based on simultaneous measurements with a FBG sensor of the same model. The second sensor is fixed on one end and placed at a stable spot next to the tensile bench. Only strain changes effected by the change of temperature are registered. These observations were used to improve the measurements of the first sensor. This technique shows advantage for long time observations in environments with temperature changes of several degrees. All strain measurements were corrected.

5. CONCLUSION AND OUTLOOK

FBG strain gauges, electrical strain gauges and the photogrammetric strain systems IVIEW and ARAMIS are compared in a tensile test according to DIN EN ISO 527. The compared strain measurement systems use different primary observations to determinate the strain on specimen surface. Depending on the observations huge strain (ARAMIS), a high registration rates (FSG sensor) or noise reduction (FBG sensor) can be achieved. In material testing ARASMIS deliver a full-field strain measurement without large preparation time. Furthermore the measurement of small specimen for example in shear testing arrangement like ASTM D5379. The investigation shows the performance of the strain measurement system for tensile strains up to 2000 µm/m. Up to a strain of 1400 µm/m the differences between the compared system are within the expected uncertainties. For higher distensions the different sensors show different strain, which was caused by failure of the adhesive and inhomogeneous material of the specimen.

The investigation shows that the FBG sensor is a suitable alternative sensor for tensile experiments with small strain. Easy compensation of strain caused temperature changes can be done with a second sensor of the same model. The FBG sensor has advantages for installation at construction in extreme environment like for monitoring of offshore wind power plans or bridges. The sensor and the necessary equipment is compact, easy extendable, non-sensitive to most environmental influences and can even installed underwater.

The combination of the strain measurement systems will be used for further investigations and test for construction materials. Approaches of monitoring and controlling the behavior of buildings by strain measurement will be pursued.

ACKNOWLEGEMENT

The acquisition of the FBG interrogator and sensors was generous supported by the Holcim Deutschland AG.

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CONTACTS

B.Sc. Eike Barnefske
HafenCity Universität Hamburg
Überseeallee 16
20457 Hamburg
GERMANY
Email: eike.barnefske@hcu-hamburg.de

M.Sc. Friedrich Keller
HafenCity Universität Hamburg
Überseeallee 16
20457 Hamburg
GERMANY
Email: friedrich.keller@hcu-hamburg.de

Dipl.-Ing. Christan Gehmert
HafenCity Universität Hamburg
Überseeallee 16
20457 Hamburg
GERMANY
Email: christian.gehmert@hcu-hamburg.de

Prof. Dr.-Ing. Harald Sternberg
Institution: HafenCity Universität Hamburg
Überseeallee 16
20457 Hamburg
GERMANY
Email: harald.sternberg@hcu-hamburg.de
Web site: www.hcu-hamburg.de