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Smart Textiles for SHM of Geostructures and Buildings

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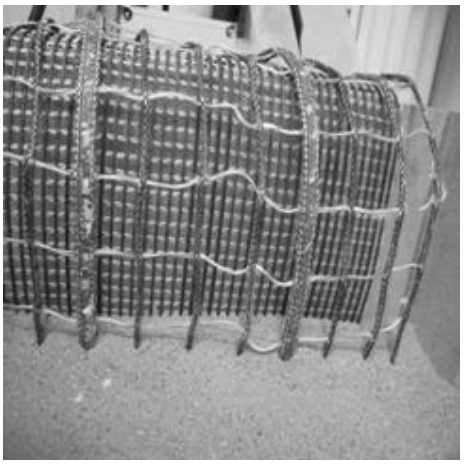
Distributed fiber optic technology offers the capability to measure strain and deformation at thousands of points along a single fiber up to tens of kilometers. This is of particular interest for the monitoring in the geotechnical structures where it allows the detection and localization of ground movements. Fiber optic sensing system offers ability to detect and localize deformation induced by geological assessments, allowing the monitoring of kilometers with a single instrument and localization of the event with a precision better than 1 meter.

Geo-textile structures are already well known in the field of geotechnical engineering. Beside reinforcing capability geo-textile can be equipped with monitoring system. Such an intelligent structure can provide both reinforcement and monitoring capabilities for geotechnical application and civil engineering. In order to get knowledge on the behavior of different typology of optical sensors integrated in geo-textile structures and embedded in soil exposed to local settlement, and to get knowledge on the interaction between optical sensor and geo-textile structures series of full scale tests were performed in laboratory under controlled conditions. The tests demonstrate that is possible to reliably localize the position of the settlements, from 2 up to 140 mm, within few minutes and with a spatial accuracy better than 1 meter. Moreover it is reliably possible to follow the evolution of settlement and analyze it qualitatively.

This paper presents the main results and conclusions carried out form tests.



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Smart Textiles for SHM of Geostructures and Buildings

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ABSTRACT

Distributed fiber optic technology offers the capability to measure strain and deformation at thousands of points along a single fiber up to tens of kilometers. This is of particular interest for the monitoring in the geotechnical structures where it allows the detection and localization of ground movements. Fiber optic sensing system offers ability to detect and localize deformation induced by geological assessments, allowing the monitoring of kilometers with a single instrument and localization of the event with a precision better than 1 meter.

Geo-textile structures are already well known in the field of geotechnical engineering. Beside reinforcing capability geo-textile can be equipped with monitoring system. Such an intelligent structure can provide both reinforcement and monitoring capabilities for geotechnical application and civil engineering. In order to get knowledge on the behavior of different typology of optical sensors integrated in geo-textile structures and embedded in soil exposed to local settlement, and to get knowledge on the interaction between optical sensor and geo-textile structures series of full scale tests were performed in laboratory under controlled conditions. The tests demonstrate that is possible to reliably localize the position of the settlements, from 2 up to 140 mm, within few minutes and with a spatial accuracy better than 1 meter. Moreover it is reliably possible to follow the evolution of settlement and analyze it qualitatively.

The above mentioned test and presented in this publication were carried out in the POLYTECT project (Polyfunctional Technical Textiles against Natural Hazards), financially supported by the European Commission within the 6th framework program.

1 INTRODUCTION

The monitoring of Geological structures, such as dike, embankment, landslide, etc., and buildings is becoming more and more important in the last few years [1,2]. The POLYTECT project (Polyfunctional Technical Textiles against Natural Hazards), carried out within the 6th framework program, and financially supported by the European commission, has the main aim of developing effective monitoring system to avoid failures, to have the capacity of planning maintenance intervention where necessary and get a better knowledge on the monitored structures to prevent major risks. Dimensions of the above mentioned geo-structures and buildings let the installation and choice of the sensor challenging. The use of the discrete sensors, short or long-gage is practically impossible, because it requires installation of thousands of sensors and very complex cabling and data acquisition systems, raising the monitoring costs. Therefore, the applicability of the discrete sensors is rather limited to some chosen cross-sections or segments of the structure, but cannot extend to full-length monitoring. Furthermore, in some particular application is very difficult to predict where a failure can

happen, making the selection of the sections that should be equipped and monitored very difficult. Recent developments of distributed optical fiber strain and temperature sensing techniques based on Raman and Brillouin scattering provide a cost-effective tool allowing monitoring over kilometric distances [3]. Thus, using a limited number of very long sensors it is possible to monitor structural and functional behavior of geostructures and buildings with a high measurement and spatial resolution at a reasonable cost.

Unlike electrical and point fiber optic sensors, distributed sensors offer the unique characteristic of being able to measure physical parameters, such as strain and temperature, along their whole length, allowing the measurements of thousands of points using a single transducer. The most developed technologies of distributed fiber optic sensors are based on Raman and Brillouin scattering. These systems make use of a non linear interaction between the light and the silica material of which the fiber is made. If light at a known wavelength is launched into a fiber, a very small amount of it is scattered back at every point along the fiber. Besides the original wavelength (called the Rayleigh component), the scattered light contains components at wavelengths that are different from the original signal (called the Raman and Brillouin components). These shifted components contain information on the local properties of the fiber, in particular strain and temperature. Figure 1 shows the main scattered wavelengths' components for a standard optical fiber. It can be noticed that the frequency position of the Brillouin peaks is dependent on the strain and temperature conditions that were present at the location along the fiber where the scattering occurred, while the intensity of the Raman peak is temperature dependent.

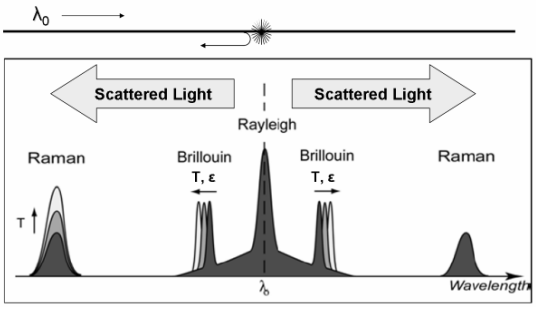

Figure 1. Light scattering in optical fiber

When light pulses are used to interrogate the fiber, it becomes possible, using a technique similar to RADAR, to discriminate different points along the sensing fiber by the different time-of-flight of the scattered light. Combining the radar technique, called OTDR (Optical Time Domain Reflectometry) in the optical-engineering field, and the spectral analysis of the returned light one can obtain the complete profile of strain or temperature along the fiber. Typically it is possible to use a fiber with a length of up to 30 km and obtain an average strain and temperature readings over 1 meter. In this publication we would talk of performances and capabilities of a distributed sensing system based on Brillouin scattering with a measurement range of 30 km and a spatial resolution of 1 m and a strain resolution of 20 με [4]. The aim of the tests reported here is to increase knowledge on the behavior of different typology of optical sensors integrated in geo-textile structures and embedded in soil exposed to local settlement, and to get knowledge on the interaction between optical sensor and geo-textile structures during series of full scale tests performed in laboratory under controlled conditions.

2 QUALIFICATION TESTS

2.1 Aim of the tests

Several model tests were performed at University of Kassel (Germany) in a period between June 2007 and September 2008. The aim of these tests was mainly:

1. to study the feasibility of implementing a full-optical monitoring system for geotechnical and masonry application;
2. to get knowledge concerning the behaviour of different types of sensors integrated in geo-textile and embedded in soil exposed to local settlement;
3. to get knowledge concerning the interaction between (a) sensors and geo-textile and (b) integrated sensors and soil.

2.2 Test bed set-up

Test bed was developed by the University of Kassel, while different type of sensors were developed and manufactured by SMARTEC SA. Several typologies of optical fiber distributed sensors, integrated and non-integrated in geo-textiles structures, were tested. Integrated and non-integrated sensors were embedded in sand within the test bed at different depth. The test bed which length was 9 m approximately was provided with set-up (inflating balloon), Figure 2, designed to create simulated settlement involving area of 0.5 m approximately at 5 m from the extremity (4 m from the other extremity). At the same location several displacement-meters, Figure 2, were installed in order to correlate the simulated settlement at location of fiber optic sensors with their measurements.

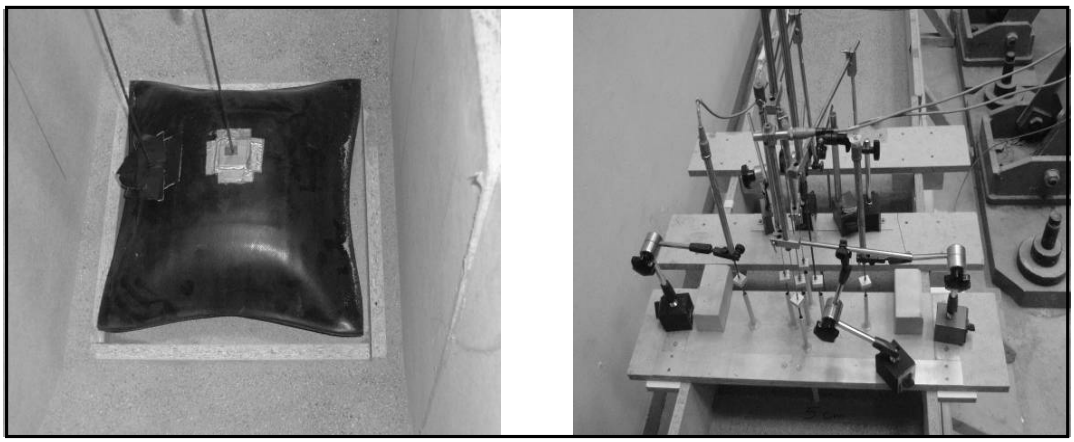

Figure 2. Inflating balloon on the left and vertical displacement-meters on the right

2.3 Description of SMARTEC sensors

Three typologies of SMARTEC sensors were used in the project: (1) SMARTprofile sensor, (2) SMARTube-v1sensor and (3) SMARTube-v2 sensor. All the sensors have been developed at SMARTEC premises with the aim of providing a simultaneous measurement of strain and temperature [2].

SMARTprofile is a distributed strain-temperature sensor that contains a total of four optical fibers, two strain fibers are directly embedded in a polyethylene matrix that transfer the strain from the monitored structure to the optical fibers, and two temperature fibers, initially strain

free, are placed in a loose plastic tube also embedded in the polyethylene matrix. SMARTube is a distributed strain-temperature sensor that contains a total of four optical fibers. Two temperature fibers, initially strain free, are placed in a loose plastic tube, and two strain fibers are squeezed between the temperature loose tube and an external protection thus transferring the strain from the monitored structure to the optical fibers. During the tests thanks to the acquired data, SMARTube sensor was optimized in dimensions in order to increase sensitivity to strain variation. After optimization further tests were performed to verify the goodness of the applied changes. The results and improvement are shown further in this text.

All three typologies of sensors were tested under controlled laboratories conditions. A comparative analysis between the behavior of the sensor integrated in geo-textile structures and the behavior of the sensor non-integrated in geo-textile structures was made. Beside this several geo-textile structures with different morphologic and mechanical properties were tested within the sensor to fulfill aim 3(a) and 3 (b).

View of the sensors during the integration in the test bed is given in Figure 3.

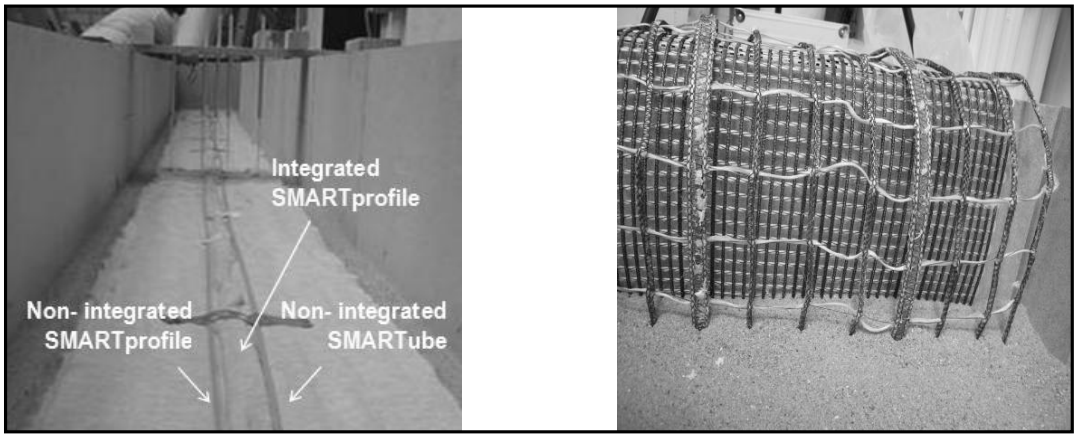

Figure 3. Examples of Distributed Strain Sensor embedded in geo-textile structures under test. SMARTprofile integrated in a filter-mat structure and non-integrated SMARTprofile and SMARTube-v1 on the left; SMARTprofile integrated in a geo-grid structure on the right.

2.4 Tests description and results

In order to gather useful and reliable results, several tests were performed under controlled conditions in laboratories of the University of Kassel. To generate controlled settlements the balloon was inflated in steps, the sensors were measured after each inflation step. In parallel, displacement-meters were also read in order to assess real simulated settlement at depth of different sensors. The measure of the displacement-sensors is really important to operate a correlation between the measured displacement and the variation measured by the optical sensors. Typical diagram obtained during tests is shown in Figure 4, where N.I. stands for non-integrated and I. stands for integrated. Non denoted peaks in the diagram correspond to optical fibers inside the loose tube of corresponding sensors of both SMARTprofile and SMARTube.

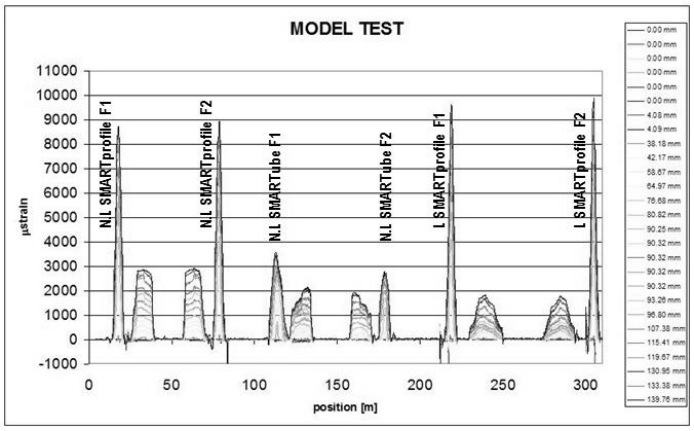

Figure 4. Typical diagram of strain distribution along sensors obtained during a test

2.5 Data analysis

All the collected data were analyzed to increase knowledge on optical sensors, geo-textile and their interaction. The data analysis includes:

1. verification whether the position of maximal strain occurrence coincide with the position of simulated settlement;
2. determination of maximal measured strain for each sensor;
3. determination of deformed length of sensor;
4. establishment of correlation between the simulated settlement and maximal strain.

These parameters were important in order to:

A. evaluate capacity of each sensor to detect and localize the settlement;

B. evaluate interaction between the soil and sensor and identify the best performing geo-textile for sensor integration;

C. evaluate sensitivity of each sensor and its capacity to qualitatively follow the evolution of settlement;

D. determine the maximal range of settlement that can be monitored by sensor (maximal allowed strain in optical fiber in long-term is 1.5%).

Typical diagram of strain distribution along the sensor is for integrated SMARTprofile given in Figure 5. This diagram is practically close-up taken from Figure 4. For presented sensor, maximal strain is determined from diagram and it occurred for every step of load at the position of simulated settlement. As the simulated settlement increased, the length of deformed part of sensor increased too, but it didn't exceed the length of the test bed confirming that the sensor is in very good interaction with soil (no sliding at extremities).

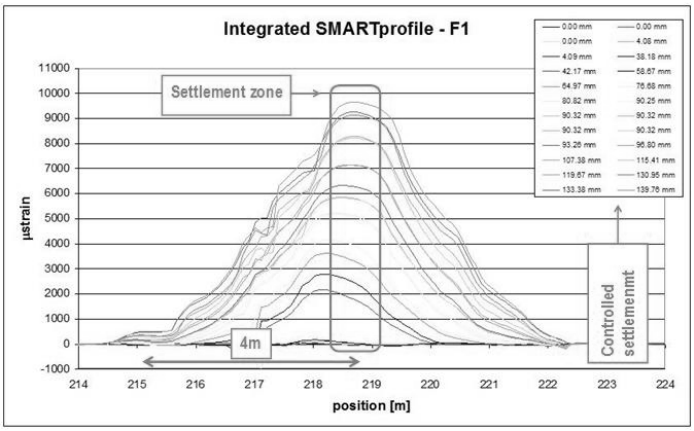

Figure 5. Example of measurements: measurement performed with strain-fiber F1 of integrated SMARTprofile

All the sensors were able to detect and localize correctly the settlement, but with different sensitivities. Sensitivity of sensors is evaluated in further text.

Summary of results related to above points 1) and 2) is for all GOF sensors given in Table 1.

Table 1. Summary of results related to determination of maximal strain and deformed sensor length

SMARTEC DISTRIBUTED SENSOR		
	Strain peak value (με)	Deformed length (m)
Filter-mat integrated SMARTprofile F1	9650	6.5
Filter-mat integrated SMARTprofile F2	9800	6.5
Non-integrated SMARTube-v1 F1	3580	>9
Non-integrated SMARTube-v1 F2	2720	8
Non-integrated SMARTprofile F1	8710	7.5
Non-integrated SMARTprofile F2	8930	7.5
Geo-grid integrated SMARTprofile F1	4210	6.5
Geo-grid integrated SMARTprofile F2	3710	6.5
Filter-mat integrated SMARTube-v2 F1	5100	7
Filter-mat integrated SMARTube-v2 F2	6950	9
Non-integrated SMARTube-v2 F1	4270	6
Non-integrated SMARTube-v2 F2	4050	6

The SMARTube-v1 sensor has the deformed length (width) bigger than the length of the test bed. This indicates that the transfer of deformation from the soil to sensitive optical fiber was not complete and either sensors slide with respect to soil or optical fiber itself slides with respect to sensor body or combination of both occurred. In addition, these sensors give mutually

incoherent results from the point of view of magnitude which confirms bad strain transfer between the soil and sensor.

Non-integrated SMARTprofile, Filter-mat integrated SMARTprofile, geo-grid integrated SMARTprofile, non-integrated SMARTube-v2 and filter-mat integrated SMARTube-v2 had the deformed length shorter than the length of the test bed which indicates that at extremities of the test bed the sensors are well retained by interaction with soil.

Both fibers of non-integrated SMARTprofile measured approximately the same value of strain and have approximately the same deformed length. Similar conclusion is valid for Filter-mat Integrated SMARTprofile, but this sensor has shorter deformed length and higher value of measured strain. This leads to conclusion that MFG enhances the interaction between the soil and sensor.

Both fibers of geo-grid integrated SMARTprofile measured approximately the same value of strain and have exactly the same deformed length. This is in good agreement with the results given by the previously tested samples of SMARTprofile. The only difference is the measured value of strain which is sensibly lower. A possible reason is a totally different interaction between the geo-grid and the soil in respect with the interaction between the filter-mat and the soil.

The two fibers of SMARTube-v2 presented different behavior in terms of measured strain. From Table 1 is possible to see how the maximum value of strain for fiber F2 is higher than F1 for equal vertical settlement; most probable explanation is the different interaction between the strain fiber and the external coating of the sensor (external protection).

In order to evaluate sensitivity of sensor, the correlation between measured deformation and settlement is examined. An example of the diagram deformation (average strain) vs. settlement is given in Figure 6.

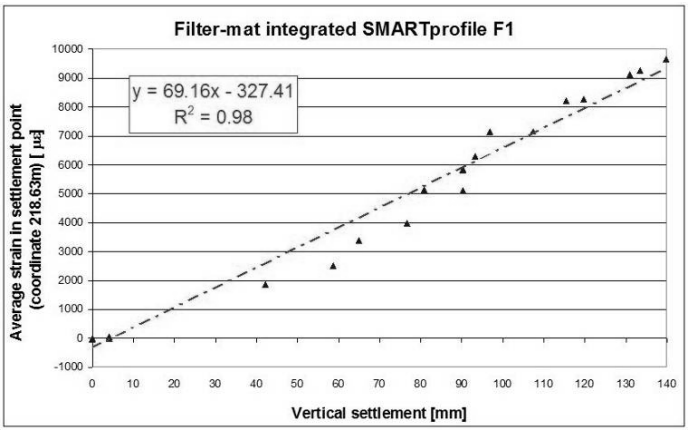

Figure 6. Example of diagram of deformation (average strain) in settlement point vs. settlement

Only non-integrated SMARTprofile, Filter-mat integrated SMARTprofile, non-integrated SMARTube-v2 and Filter-Mat integrated SMARTube-v2 had linear trend. This demonstrates that these sensors can be used to qualitatively follow the evolution of settlement because increase of settlement proportionally increases the maximal strain in sensor.

The reliable measurement of deformation started around 4 mm. This means that they are able to reliably detect as small settlements as 4 and 10 mm respectively.

Based on fact that the optical fiber is pre-compressed in SMARTprofile for approximately 0.5%, and considering that maximal strain in optical fibers in long term should not exceed 1.5%,

the SMARTprofile can safely be deformed for up to 2% (20000 microstrain). Extrapolating linear regression functions obtained for Filter-mat integrated SMARTprofile and non-integrated SMARTprofile it is concluded that these two sensors can measure in long term the maximal settlements up to 285 mm and 300 mm respectively.

The geo-grid integrated SMARTprofile sensor did not have linear correlation between the maximal deformation and settlement, thus increase of settlement did not generate a proportional increase in strain. Therefore, they can not be used to evaluate evolution of settlement. Also it is difficult to estimate what range of settlement they can measure, but it is probable that it is bigger than range of SMARTprofiles, with drawback that for higher levels of settlements, due to sliding, they may loose accuracy in determination of sliding location and may present area involved in sliding much bigger than it really is.

3 CONCLUSION

Data analysis and assumptions made on behavior of sensors led to the following conclusions:

1. All the tested distributed sensors were able to detect and localize settlement with different degrees of sensitivity.
2. Best performance in terms of soil-sensor strain transfer and sensitivity is obtained for Filter-mat integrated SMARTprofile (deformed length of sensor = 6.5m, detected settlement of 4 mm) and non-integrated SMARTprofile (deformed length of sensor = 7.5m, detected settlement of 4 mm); these sensors have comparable results between measurements of different fibres within 2.5%. These sensors present linear correlation between deformation (average strain) and settlement, therefore they can be used to qualitatively estimate evolution of the settlement.
3. Filter-mat integrated and non-integrated SMATube-v2 sensor presents a lower sensitivity compared to SMARTprofile sensor but as SMARTprofile present a linear correlation between deformations (average strain) and settlement, therefore they can be used to qualitatively estimate evolution of the settlement.
4. Filter-mat integrated sensors present lower initial sensitivity in respect with the non-integrated ones, but once “activated” becomes more sensitive; this demonstrates that filter-mat enhance the interaction between the sensor and soil for settlements bigger than 10 mm. Furthermore, the filter-mat assures additional mechanical protection to sensors.
5. Analysis of the behavior of geo-grid integrated SMARTprofile led to development of a new processing technique that allows quantitative estimation of the evolution of the settlement.
6. Further analysis has demonstrated that the above mentioned technique, especially developed for that sensors that do not present linear correlation between deformation and settlement, is successfully applicable to all the tested sensors. This allowed a quantitative analysis of the evolution of the settlement for all the tested sensors.

4 ACKNOWLEDGMENTS

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