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Monitoring capabilities of sensor integration concepts in a "seismic wallpaper"

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ABSTRACT: For more than 12 years, the Institute of Reinforced Concrete Structures headed by Prof. Dr.–Ing. Lothar Stempniewski has been conducting research into textile reinforcement of masonry structures for protection against natural hazards, especially earthquake-induced loads. Research activities led to two commercially available products. One of them will later be referred to as "seismic wallpaper". The main characteristic of this system in comparison with standard reinforcing techniques, such as epoxy resin-based FRP, is the high degree of ductility. By using the seismic wallpaper, a high degree of reinforcement is achieved. Moreover, it is economically efficient in most application cases. Within the framework of the EU project MULTITEXCO (multifunctional textiles for the construction sector), the integration of sensing techniques in the seismic wallpaper is studied. This paper evaluates different sensing concepts in terms of their ability to monitor the structural state of masonry after or during a seismic event. For this purpose, a new approach to the assessment of sensing data by directly linking them to parameters given in standards or regulations, such as textile strain, is presented. The sensing concepts being evaluated include the integration of fibre optical sensors as well as the modification of the textile itself to a self-diagnostic composite.

1 INTRODUCTION

The test results discussed in this paper were obtained under the EU project MULTITEXCO. MULTITEXCO is a FP7 project co-funded by the European Community that started in October 2013. Its overall objective is the definition of guidelines and best practices for the optimal use of smart textiles in construction industry. In the last decade, advanced textile materials were developed as a result of a number of research and innovation projects addressing in particular the construction sector, which represents one of the biggest markets for composite products based on technical textiles. Aim of the MULTITEXCO project is to scientifically and technologically characterize the latest achievements in technical textile sector for the development of guidelines and pre-normative research enabling future standards in the EU.

In this paper, the main characteristics of two externally bonded textile reinforcing systems for masonry developed by KIT are discussed. For one of these strengthening systems, two sensor integration concepts are introduced. Test results are presented and discussed to determine the performance of the reinforcing system without any sensors. Finally, the test results of the sensor-equipped strengthening system are presented and the quality of sensor data is evaluated.

2 MASONRY STRENGTHENING SYSTEMS DEVELOPED BY KIT

Masonry is commonly used in construction. Its capability to withstand high vertical loads and its favorable construction-physical properties made it one of the most wide-spread types of construction worldwide. Due to the very brittle behavior, masonry is hardly capable of withstanding tension induced by horizontal loads caused by e.g. earthquakes. For over 60 years, externally applied reinforcing systems have been developed and are partly subject to normative regulations. The focus of research and standardisation activities has been on reinforcing systems with epoxy-based matrices. US and Italian building codes provide guidelines for the application and calculation of externally bonded reinforcing systems based on epoxy matrices. Recent developments led to an US guideline on reinforcing systems in inorganic cementitious matrices. KIT has been involved in research and development of external textile reinforcing systems for more than 12 years. The design philosophy behind these activities was strengthening primarily by increasing ductility. Wallner (2008) demonstrated that glass fibre fabrics embedded in epoxy-modified mortar significantly increase the maximum capacity and ductility of walls under in-plane loading. Münich (2011) developed hybrid-multidirectional reinforcing textiles to increase the performance of the system. Urban and Stempniewski (2012) used a similar system in a full-scale shaking table test of a retrofitted pre-damaged natural stone building. These research activities led to a commercially available system based on a special cementitious mortar without any epoxy.

KIT also developed a reinforcing system mainly for indoor masonry under out-of-plane loading. This system is based on a bi-axial glass-fibre fabric directly glued onto the plaster of an existing wall using very soft polyurethane glue. Due to the easy access to the textile even after application, this reinforcing system is preferred for sensor integration. Hereinafter, this system will be referred to as GFP system.

3 SENSOR INTEGRATION CONCEPTS - GFP RETROFITTING SYSTEM

In Liehr et al. (2009) and POLYTECT (2010) sensor integration concepts of fibre-optical sensors in a mortar-embedded masonry reinforcing system are presented. Mainly two types of fibre-optical sensors are chosen. These sensors can be integrated directly in the reinforcing textile in order to monitor modal parameters and displacements of beams and even full-scale brick buildings. Within the framework of the MULTITEXCO project, the approach to the selection of sensors and analysis of sensor data is modified. The integration concept for fibre-optical sensors will be referred to as GFP-1 approach below. As the use of fibre-optical sensors may be considered a high-tech monitoring approach with an already proven high accuracy in terms of data acquisition, the economic aspect must not be neglected. Especially costs for reading units are quite high and should be proportionate to the costs of retrofitting. The other sensor integration concept to be evaluated is therefore based on modifying the reinforcing textile during weaving using carbon fibres to form a self-diagnostic composite. This sensor integration concept will be referred to as GFP-2 approach below.

3.1 GFP-1 sensor integration approach (fibre-optical sensors)

The integration of fibre-optical sensors in reinforcing textiles has a high technical and economic potential. From the technological point of view, fibre-optical sensors allow users to monitor physical parameters, such as temperature, humidity, or strain. Depending on the used type of fibre and the data acquisition system, discrete or distributed, static or dynamic measurements can be carried out. From the economic point of view, the possibility to integrate sensors directly during the manufacturing process of a reinforcing textile might open up new markets for the

textile industry. In Measures (2001) fibre-optical sensing for structural health monitoring in the construction sector is introduced.
The feasibility of integrating fibre-optical sensors in reinforcing textiles has been demonstrated in POLYTECT (2010) and Liehr et al. (2009).
For this paper, integration of FBG fibre-optical sensors was studied only. FBG sensors have already been widely used for structural health monitoring in the construction industry (Majumder et al. (2008)). The integration of FBG sensors in reinforcing textiles is a relatively new research topic, although it was covered in POLYTECT (2010), Stefan Käseberg et al. and S. Käseberg, M.-B. Schaller, K. Holschemacher (2011). The main characteristics of using FBGs as strain sensors are:

- Discrete strain measurement.
- Relatively high accuracy.
- Possibility of dynamic measurements.

The results presented in this paper refer to a multiplex FBG sensor embroidered on the reinforcing textile.

3.2 GFP-2 sensor integration approach (self-diagnostic composite)

The principle approach of integrating carbon-fibre sensors in an existing reinforcing textile is described in detail in Muto et al. (2001). Measurement is based on the change of electrical conductivity of the carbon fibre due to axial elongation as a reversible effect (piezoelectric effect) and on the stepwise rupture of the carbon fibre itself. The latter effect influences the change of electrical resistance even more and is irreversible.
This paper focuses on the potential of this sensor integration approach that is based on the irreversible change of electric conductivity due to fibre rupture. This implies that significant damage is induced in the carbon fibre before failure of the reinforcing textile occurs. The ratio of maximum elongation and modulus of elasticity between reinforcing textile and carbon fibre sensors is crucial.

3.3 Evaluation of sensor data

The basic idea is to link sensor data to parameters specified in standards and regulations. It may be doubted whether the GFP system is subject to normative regulations, as the main documents are based on research data obtained for reinforcing systems using stiff epoxy matrices. First laboratory tests have shown that the GFP's governing failure mode under out-of plane bending loads is debonding, which is in agreement with the assumptions of the regulation documents. The failure mode of debonding can be described as a function of textile strain. Numerous standardised test procedures exist to define tension properties of reinforcing textiles. Hence, this parameter is also a good indicator of the state of the textile and the applied system.

Another important aspect of an economically reasonable monitoring concept is the required frequency of data acquisition. The economically most reasonable solution would be a threshold approach, which means that sensor data change irreversibly when a defined textile strain is exceeded. In the case of the GFP-1 approach, this implies that textile strain is irreversible. However, this cannot be said in advance and remains to be evaluated in further laboratory tests, which will not be discussed in this paper. In the case of the GFP-2 approach, the threshold approach can only be applied, if the carbon fibre is irreversibly damaged before the reinforcing system fails.

4 TEST RESULTS TO DEFINE THE PERFORMANCE OF THE REINFORCING TEXTILE WITHOUT SENSORS

4.1 Determination of tensile properties of the textile proper

A procedure similar to ISO 4606 has been chosen to determine tensile properties of the textile proper. The main characteristics of the fabric in weft direction, in the form of mean values of five tests fulfilling the requirements regarding the failure mode (no jaw breaks), are listed below (values in brackets for warp direction):

- Elongation at maximum load: 2.4 %
- Max. load (5cm wide strip): 3.8 kN

4.2 Determination of elongation limits due to debonding failure of the applied system

As described in ACI Committee 440: ACI 440.7R-10, debonding failure is taken into account by load reduction factors. These load reduction factors are based on scientific data for reinforcing systems with stiff epoxy matrices. In order to examine load reduction factors caused by debonding mechanisms, textile elongation at failure is determined using the following test set-up:

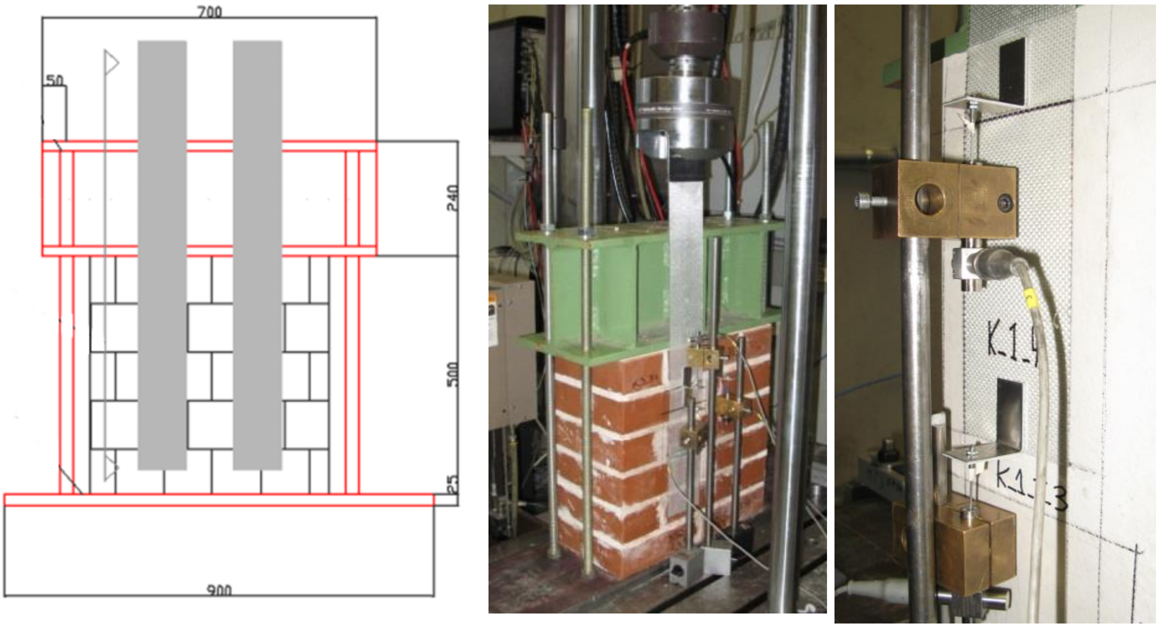

Figure 1: Test set-up to determine textile elongation at failure (debonding test)

The test set-up uses additional displacement sensors to determine crack opening and slippage.

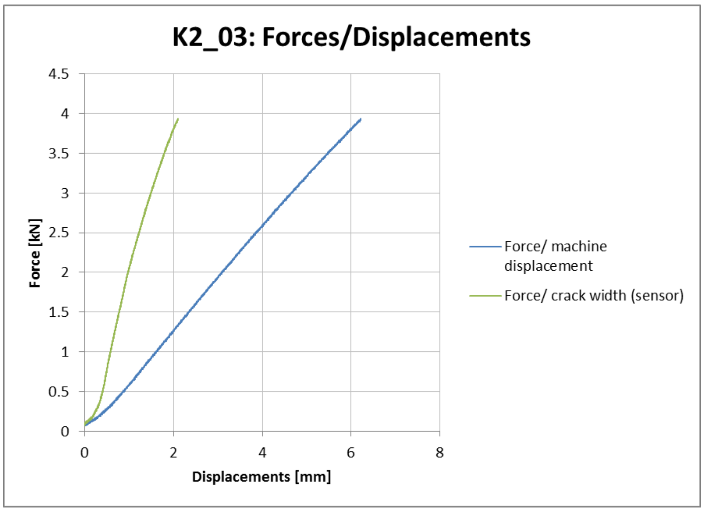

Figure 2: Result of a representative debonding test

The results illustrate the very soft behaviour of the system which cannot be compared to epoxy systems, as crack widths of about 2 mm may be reached.
Presented tests were carried out using plastered masonry. In order to obtain reproducible results, pull-off tests were performed. The results of these tests are interpreted as indicators of the expected bonding strength of the applied system. They did not vary significantly for all test specimens. The main results of the anchorage tests of the applied system are in mean values:

- Max. force at debonding (10 cm wide strip): 4.0 kN
- Degree of utilisation (in comparison to failure of the textile proper): 53%
- Degree of utilisation expressed as textile strain: 1.3%
- Required anchorage length: ~25 cm

5 TEST RESULTS TO EVALUATE THE GFP-1 SENSOR INTEGRATION CONCEPT

As already described, the textile was embroidered with multiplex FBG sensors.

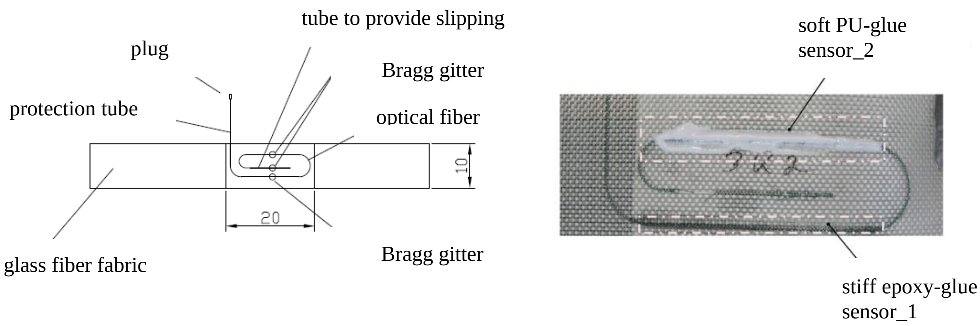

Figure 3: Embroidered FBG sensor

The test set-up for one 10 cm wide textile strip included two FBG sensors. The embroidering did not provide for any bonding and only served as a loose fixation of the fibre-optical sensor. For bonding, the sensor was glued on the textile. The bonding behaviour between the fibre-optical sensor and the reinforcing textile was examined by using two different glues. FBG

sensor 1 was glued using a very stiff epoxy resin. FBG sensor 2 was glued on the textile using the same soft PU glue that was used for the retrofitting textile. The sensor-equipped textile strip was subjected to uniaxial cyclic loading.
The loading program consisted of cyclic loading procedures. Each procedure included 15 load cycles. Procedure 1 comprised a maximum cyclic elongation of the textile strip of 0.2% (procedure 2: 0.4%, procedure 3 0.6%). In order to prevent dynamic effects, such as a dynamic increase in stiffness, frequency of the loading cycles was set to 0.01 to 0.05 Hz.
As the length of the textile specimen was given, machine data were used to calculate textile strain. The strain data acquired from the FBG sensors were then compared.

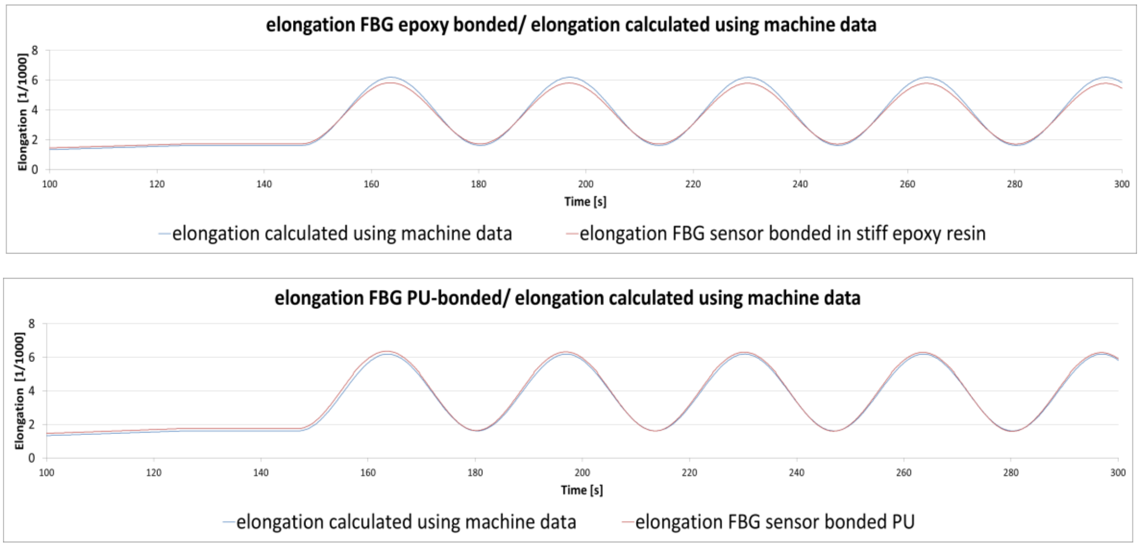

Figure 4: Test results of FBG sensors 1 and 2

The test results for the first 5 loading cycles of loading procedure 3 (max. elongation: ~0.6%) are shown in
Figure 4.
Both types of glue ensure sufficient bonding. The values measured differ by less than 5% from the strain data calculated using machine displacement data. The main difference can be seen for the peaks of maximum strain. Here, the epoxy-glued sensor differs more from the machine data than the PU-glued sensor. This effect is supposed to be caused by the local gain of stiffness resulting from the epoxy glue.

6 TEST RESULTS TO EVALUATE THE GFP-2 SENSOR INTEGRATION CONCEPT

Three different carbon fibre types were incorporated in the reinforcing textile during weaving. The carbon fibres were selected to examine the effects of maximum elongation and stiffness on the sensor performance.

Table 1. Main material data of the carbon fibres

Type	mass per length unit [tex]	Young's modulus [N/mm²]	elongation at break [%]
A	800	230000	2.1
B	198	230000	1.5
C	728	392000	0.7

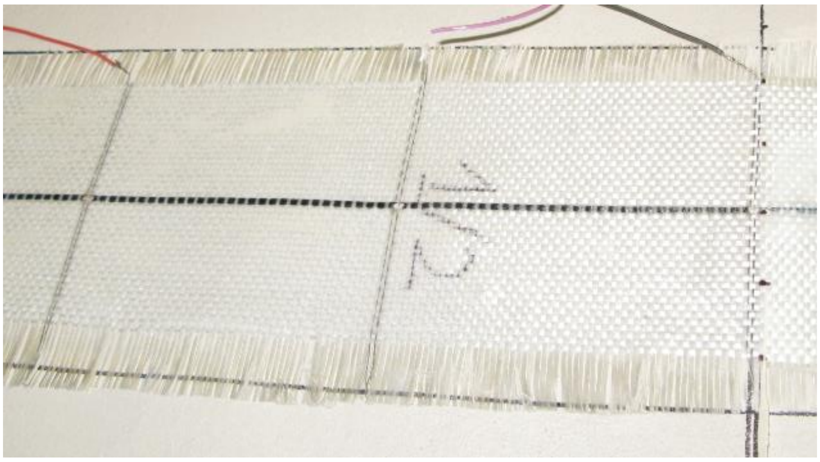

Figure 5: Carbon fibre incorporated in the reinforcing textile

The electrical resistances of the carbon fibre types varied between 40-80 Ohm/m. In order to monitor electrical resistance, highly conductive metallic fibres were integrated in the textile as well. The test procedure to evaluate the performance of the sensor-equipped textile was similar to the debonding test illustrated in Figure 1. The only difference consisted in the fact that the sensor-equipped textile was constantly monitored using a series circuit with a constant voltage of 10V. The change of electrical resistance was then calculated by using Ohm’s law. Axial load was applied using a constant machine speed of 0.5 mm/min. The test was conducted until debonding of the textile strip. Eight specimens were tested: Six specimens of carbon fibre types A and C and two specimens of carbon fibre B.

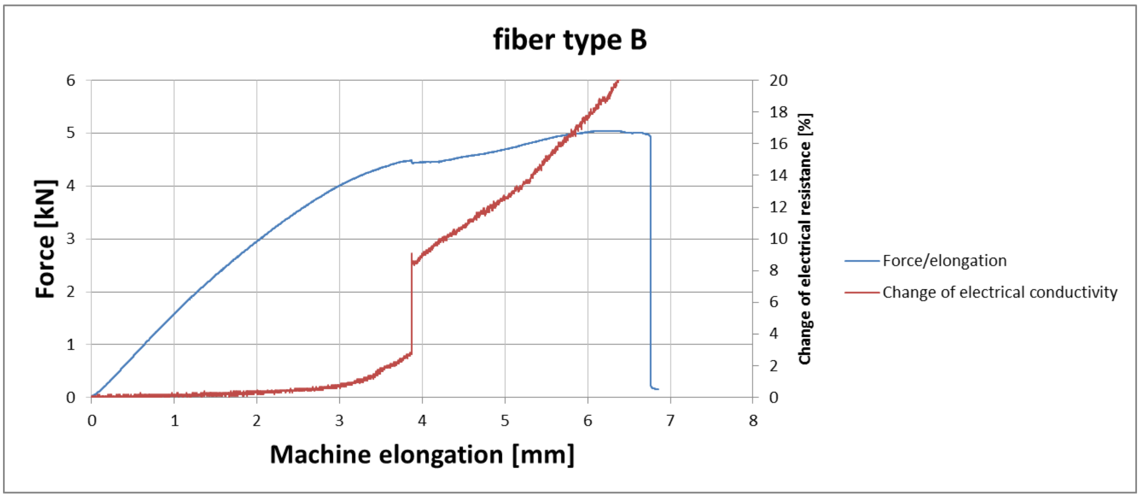

Figure 6: Test results for carbon fibre B

For carbon fibre types A and C, a reversible change of conductivity between 2-3% was observed before debonding. Carbon fibre type B exhibited an irreversible change of conductivity before debonding. The conductivity of a 10 cm textile strip changed suddenly at 4.5 kN, which roughly corresponded to 1.45% of the average textile elongation (max. carbon fibre elongation type B: 1.5%).

7 CONCLUSION

The GFP-1 sensor integration concept represents an accurate method to monitor textile strain. The soft PU glue which was also used for application ensured sufficient bonding. Additional tests of sensor performance on conditioned textiles (humidity and alkaline environment) will be conducted to examine the long-term bonding behaviour. Discrete data acquisition of FBG sensors initially appears to be a severe disadvantage of this sensor approach, because a-priori knowledge of the damage/crack formation is required. However, as the reinforcing system behaves very softly and failure mechanisms are induced by crack opening, this disadvantage is of less importance. Nevertheless, the required degree of redundancy remains an open issue.

The GFP-2 sensor integration concept only provides irreversible and significant data for an optimized bonding behaviour between the carbon fibres in the reinforcing textile and the plaster surface.

First test results indicate that maximum elongation is not the only material parameter governing carbon fibre damage within the hybrid self-diagnostic textile. Carbon fibre type B was the only fibre that was significantly damaged during the debonding test. The E-modulus and mass per length unit (tex-number) have to be further examined to determine their impact on test results.

Another problem is the relatively low average textile strain at debonding which mostly occurs before irreversible change of conductivity takes place. First tests with modified plaster surfaces (impregnation or modified roughness) considerably increase maximum elongation at debonding.

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