Distributed polymer optical fiber sensors integrated in technical textiles for monitoring of masonry structures

Sascha Liehr[1], Mario Wendt[1], Katerina Krebber[1], Johannes Christian Münich[2], Lothar Stempniewski[2] and Heike Metschies[3]

[1] BAM Federal Institute for Materials Research and Testing, Berlin, Germany
[2] University of Karlsruhe, Karlsruhe, Germany
[3] Saxon Textile Research Institute (STFI), Chemnitz, Germany

ABSTRACT: Polymer optical fiber sensors (POF) based on the Optical Time Domain Reflectometry (OTDR) technique offer the unique feature to measure high strain up to 40 % fully distributed along the fiber. The advances in distributed POF strain sensor technology are concluded with respect to application in structural health monitoring. Special focus is placed on sensor integration into technical textiles aimed for reinforcement and retrofitting of masonry structures. These smart structures provide reinforcement capabilities as well as the possibility to detect the position and size of cracks in reinforced masonry. The motivation is to monitor the structural condition of masonry and heritage structures in earthquake-prone regions. Model tests show the applicability of the proposed sensor system for retrofitted masonry structures, which allows detecting cracks from 1 mm width and resolving their position with 10 cm precision. The first results of a field test of an unreinforced brick building on a seismic shaking table are presented. It is shown that POF sensors bonded directly on the walls can detect cracks in realistic application conditions.

1 INTRODUCTION

Today, fiber optic sensors have found niches in various fields of application to measure physical or chemical quantities. Besides electromagnetic interference immunity and multiplexing possibilities, the great advantage of fiber optic sensors is the ability to measure for example strain and temperature continuously distributed along the whole length of the fiber. One fiber can therefore substitute a large number of standard electrical transducers. The advantage of this sensor type is not only the increase in safety but also a commercial one since damages can be detected and repaired at an early stage, thereby reducing maintenance costs. One of the most common measurands for structural health monitoring applications is strain. Although many distributed strain sensor systems have been proposed, only few are commercially available and have been used for structural health monitoring purposes. According to Diaz et al. (2008), sensors based on stimulated Brillouin scattering provide high strain resolution and good spatial resolution measurement up to several tens of km. Other techniques, for example proposed by Froggat and Moore (1998), use coherent Optical Frequency Domain Reflectometry (OFDR) for distributed strain sensing. Also precise quasi-distributed fiber sensors, such as fiber Bragg gratings (FBG), are widely used. However, all these techniques use silica fiber as sensor medium and are therefore limited to low break-down strain of about 1 %. Here, the use of polymer optical fibers (POF) provides the solution when distributed measurement of high strain is required. Liehr et al. (2008) showed that, using the Optical Time Domain Reflectometry (OTDR) technique, it is possible to measure strain distributed up to 40 % using standard PMMA

POF. However, the relatively high attenuation of these fibers limits the maximum measurement length to 100 m. Liehr et al. (2008, 2009) reported that, using low-loss perfluorinated graded-index POF, the measurement length can be extended to 500 m at increased spatial resolution. The use of distributed POF strain sensors represents an excellent alternative to monitor extended structures of moderate lengths where high strain is expected. Possible monitoring applications are creeping slopes, dikes, embankments as well as concrete and masonry structures.

In this context, this work has been conducted within the EU project POLYTECT (Polyfunctional technical textiles against natural hazards). The objective of the project is to develop innovative technical textiles that not only fulfill a reinforcement function, but also enable health monitoring of structures on which the textile might be applied. The idea is to develop a ready-to-install product by directly integrating the optical fibers into the textile during the manufacturing process. The development targets various applications from geotextiles for earthworks to architectural fabrics. A major application within POLYTECT is embedded sensing and health monitoring of retrofitted masonry structures. This application arose from the necessity to protect and access the structural health of masonry and heritage structures in earthquake-prone regions. Typical faults to be detected would be cracks in the structure. Here, POF strain sensors with their ability to measure the resulting very high local strains as well as to resolve the location of cracks are very promising. In this paper, we present measurement results obtained by model tests simulating a step-wise crack opening of a retrofitted masonry wall. Crack detection with POF sensors is shown within a seismic shaking table test of a small-scale building.

2 SENSOR PRINCIPLE

Husdi et al. (2004) reported that the local scattering in POF increases with increasing strain applied to a fiber section. We use the Optical Time Domain Reflectometry (OTDR) technique to obtain the backscatter profile of the fiber. The measurement principle resembles simple radar technique; short laser pulses are sent into the fiber and the backscattered light for each laser pulse is recorded as a function of time. Using the group refractive index of the fiber and averaging a great number of backscattered pulses, one can calculate the backscatter signal as a function of distance. Depending on fiber length and accuracy, the typical measurement time is between one to several minutes. For our measurements, we used commercially available standard PMMA POF with 1 mm core diameter and a 2.2 mm PE coating and an OTDR interrogation unit from Sunrise Luciol with a 650 nm light source.

Figure 1 shows two different OTDR traces of the same fiber, one in unstrained condition and one with a section strained at 42 m.

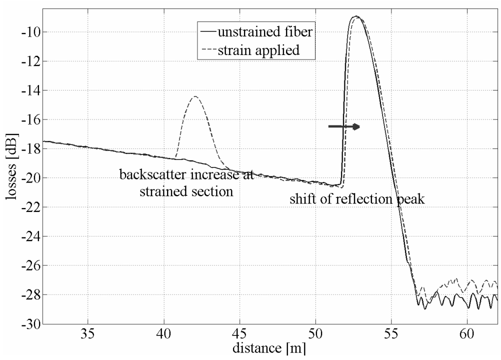

Figure 1. Sensor principle: two OTDR measurements, one of an unstrained fiber and one of a 1.4 m long section strained to 16 % at 42 m.

The increase of the backscattered light of a strained fiber relative to the reference measurement in unstrained condition resembles the strain sensor signal. A second possibility to evaluate the strain or length change of a fiber section is to compare the shift of reflection peaks along the fiber. Such peaks originate for example from Fresnel reflections at the fiber end or fiber connectors. Using this evaluation technique provides precise absolute length change measurement with a resolution up to 1.5 mm.

In order to use POF as a strain sensor, we conducted numerous investigations on the strain response and external disturbances. Whereas temperature has a minor influence on the OTDR backscatter signal, fiber bends with radii smaller than 20 mm result in optical loss and deteriorate the sensor signal and hence have to be avoided.

We use an automated setup to measure the sensor response to strain. The ends of a fiber section are fixed between two clamps. This fiber section is then incrementally strained by a PC-controlled step motor while automatically recording the OTDR data. The resulting increase of the backscattered light at the strained fiber section is shown in figure 2 for 17 measurements up to 16 % strain.

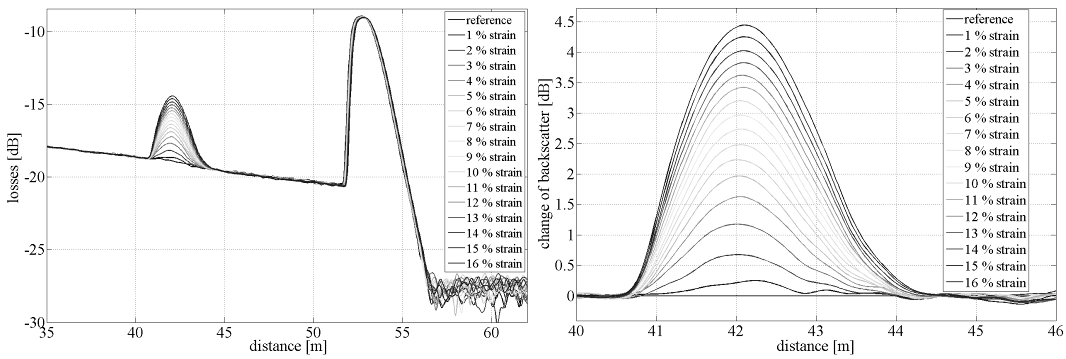

Figure 2. A 1.4 m-long fiber section at 42 m strained from 0 % to 16 %: OTDR traces for each strain step (left) and backscatter increase relative to the reference measurement (right).

The sensor characteristic is obtained by integrating the relative increase of the backscattered light and dividing it by the strained fiber length, which leads to a factor of backscatter increase. This characteristic is plotted in figure 3 for medium strain and high strain up to 45 %.

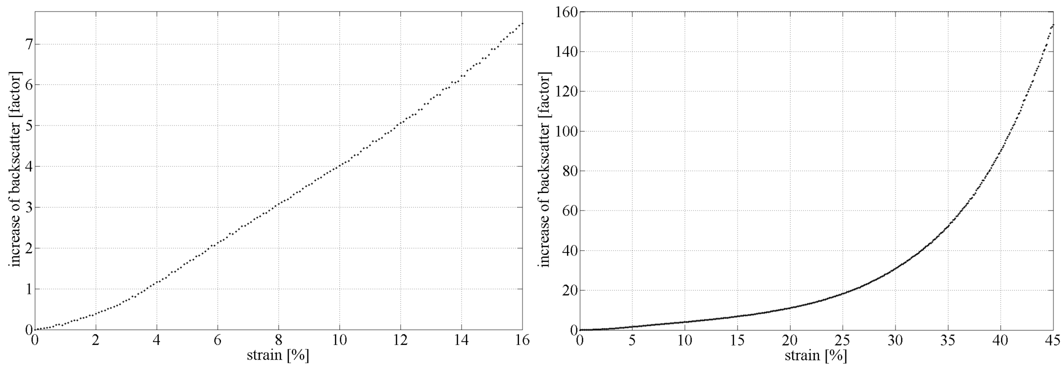

Figure 3. Sensor characteristic: integrated backscatter increase (factor) for standard PMMA POF

The sensor exhibits good repeatability of the strain response showing maximum variances equivalent to 0.5 % strain. However, as mechanical relaxation plays a role in polymers, we also observed a decrease of the backscatter level of strained fiber sections with time. This causes measurement inaccuracies when long-term processes are to be monitored.

3 MEASUREMENT RESULTS

In order to test the suitability of the POF strain sensor for crack detection in masonry structures, we conducted several small-scale tests with our partner, the Institute of Reinforced Concrete Structures and Building Materials (IfMB) at the University of Karlsruhe. The Saxon Textile Research Institute (STFI) integrated the POF into grid-like textiles samples of different mesh size and reinforcement properties. Using a cementitious resin matrix with epoxy finish, the textiles were applied on one side of two-stone samples, figure 4.

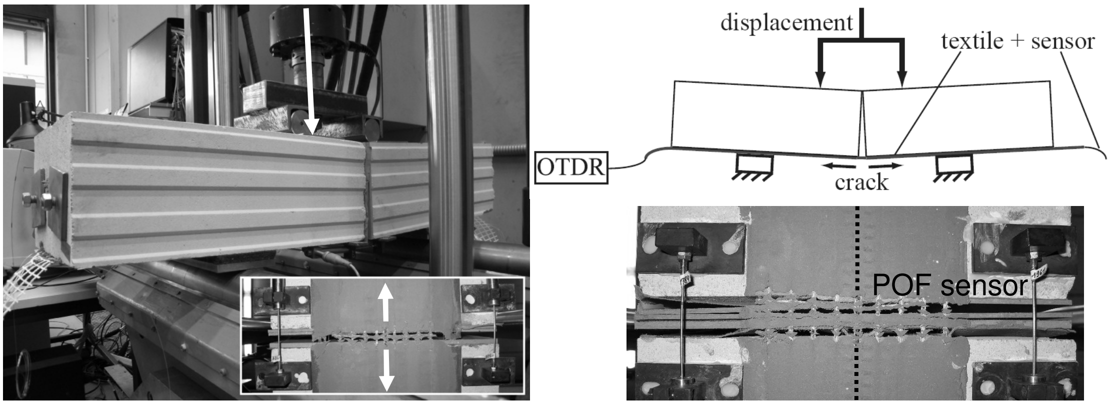

Figure 4. Test set-up at University of Karlsruhe: two-stone sample with sensor textile on the bottom side in the test set-up (left); schematic and crack opening on the bottom side perpendicular to the POF sensor (right)

By forcing a displacement to the upper side of the two-stone sample, we forced a crack opening perpendicular to the sensor fiber on the bottom side of the sample where the sensor textile is applied. The width of the crack was continually recorded using two displacement transducers bridging the crack between the stones. Due to the good integration of the sensor into the textile and the matrix, we have a very short effective gauge length of the sensor and therefore a very high local strain in the fiber at the position of the crack. Therefore, fully distributed sensing for this application is only possible using highly stretchable polymeric fiber sensors. Silica fibers would break immediately.

We conducted a series of tests with two-stone samples reinforced with various sensor-integrated grid-like textiles of different mesh size, integration technique and reinforcement properties and obtained promising results. Figure 5 shows exemplary for one test sample the OTDR measurement data obtained for different crack openings.

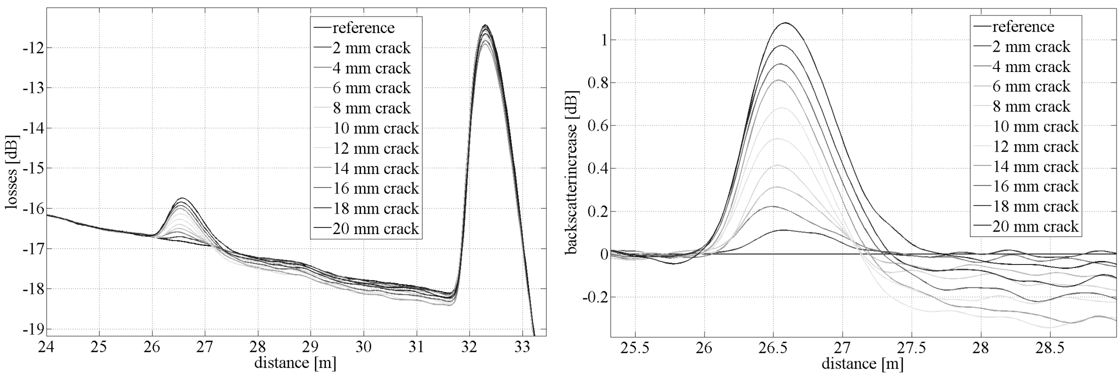

Figure 5. OTDR signals of different crack width (left) and relative increase of backscatter of the step-wise opening crack (right)

We detected an increase of the backscattered light with increasing crack width. The smallest detectable crack size was measured to be 1 mm. By using a fitting algorithm, the position where a crack occurs along the fiber can be determined with an accuracy of 10 cm.

By integrating the increase of the backscattered light relative to a reference measurement, a value related to the crack width can be obtained. This value however, depends on the integration of the sensor fiber into the textile and the kind of resin used to bond the textile to the wall. Since we tested various textile types and integration techniques, the obtained results are not directly comparable. Figure 6 shows the sensor signal (integrated backscatter increase) as a function of the crack width for three different textile types.

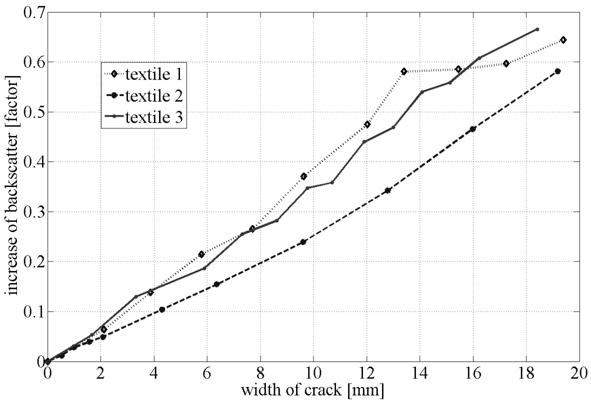

Figure 6. Sensor signal: integrated backscatter increase vs. width of crack

We are confident that, for a chosen textile type, integration and bonding technique, it is possible to achieve a good reproducibility of the crack width resolution. Therefore, further calibration measurements will have to be conducted. The relatively short sensor length compared to silica strain sensors is no drawback for this application since typical monitoring lengths would not be more than a few tens of meters.

4 SEISMIC TABLE TEST

Within the POLYTECT project, a first field test of a one-storey brick building on a seismic shaking table has been conducted. The test was organized and supervised by our partner, the Institute of Mechanics of Materials and Geostructures (IMMG). Among POF sensors, also FBG sensors, accelerometers, and strain gages have been installed by our partners. Figure 7 shows the POF sensors directly bonded to the wall with a cementitious resin matrix.

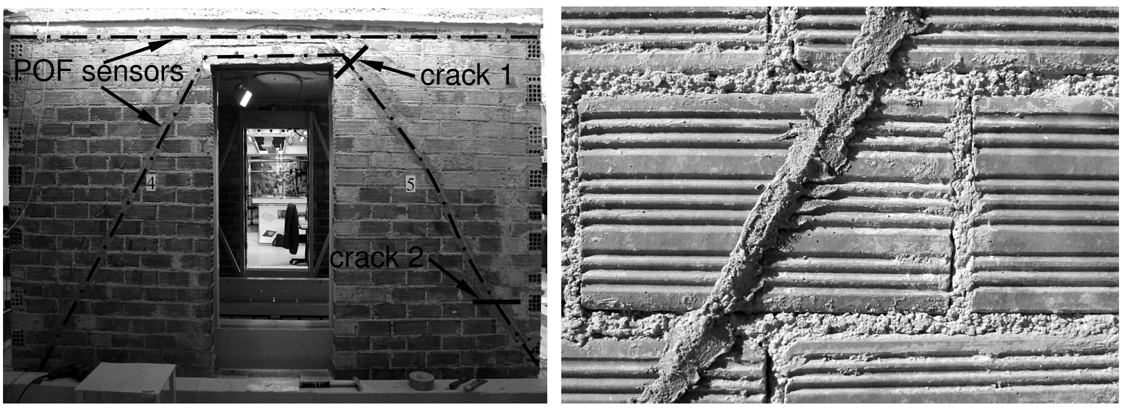

Figure 7. Brick building on the shaking table with POF sensors installed horizontally and diagonally

The testing procedure included several strong shocks, which resulted in structural damage of the building. The occurring cracks have been detected and localized with the POF OTDR sensor. Figure 8 shows exemplary the OTDR results for the sensor installed diagonally on the wall. Two cracks were detected by the sensor at the locations indicated in figure 7. The stronger signal is caused by a 2 mm crack at the corner above the door. A smaller, almost invisible crack has been detected at 150 cm distance from the first crack at the lower right corner of the wall.

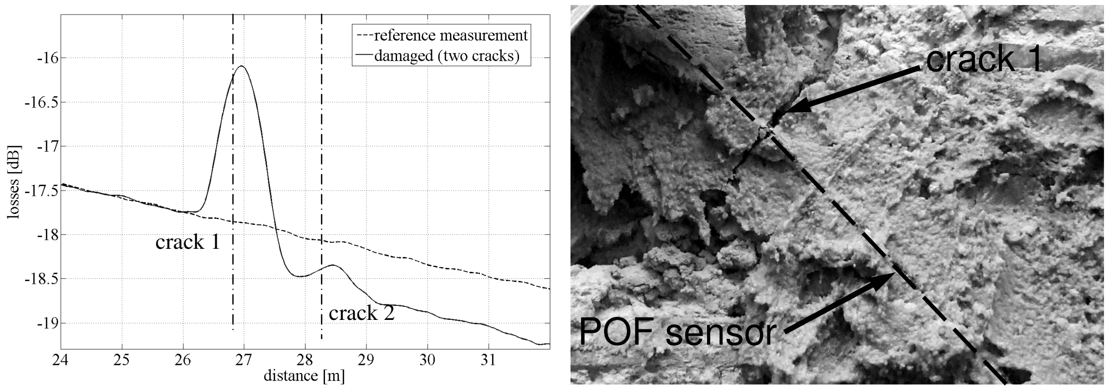

Figure 8. OTDR result showing two cracks at 27.0 m and 28.5 m (left) and the corresponding crack 1 at 27.0 m (right)

The magnitude of the backscatter increase at the position of the crack indicates that the width of the crack must have been greater than 2 mm during the shock applied to the building. Further seismic table tests of buildings retrofitted with sensor-integrated technical textiles for strengthening and monitoring purposes are scheduled within POLYTECT.

5 CONCLUSION

We demonstrated the possibility to detect and localize cracks from 1 mm width using distributed POF strain sensors. The POF OTDR sensor also allows estimating the width of a crack. The location of a crack can be resolved with 10 cm accuracy. Due to their high stretchability of 40 %, only POF sensors allow distributed measurement of the high strain occurring in this application. The physical properties of the POF OTDR sensor in combination with geometrical parameters (orientation, position of the sensor on the masonry structure) offer the possibility of identification and localization of cracks. In the framework of a SHM scheme, one can describe the damage state of a masonry structure in four steps: (1) existence, (2) location of crack on the structure, (3) failure type and (4) degree of damage. POF-based distributed measurement provides substantial information to answer points (1) and (2) and, to some extend, (3) and (4). In the case of a seismic shock, the estimation of the damage state of a masonry member necessitates the monitoring of deformation during the impact. Therefore, the consolidation of high speed sensor data with information from POF distributed measurements is able to produce valuable contribution to (3) and (4). The innovation of the monitoring system lays not only in the POF sensor technology, but also in the sensor integration into technical textiles for enforcement purposes. The textile acts as a reinforcement element and sensor support, ensures direct strain transfer from the masonry structure to the optical fiber and facilitates easy sensor installation to the structure. The results of a first field test with POF sensors directly bonded on an unreinforced brick building on a seismic shaking table were presented. The POF sensors reliably detected small and large cracks occurring after seismic shocks of the building under realistic application conditions. The targeted applications are masonry and heritage structures that are structurally vulnerable, for example in earthquake-prone regions. Future development targets using special low-loss perfluorinated POF that allow increasing the measurement length and enable monitoring of extended structures of up to 500 m length, such as bridges and tunnels.

6 ACKNOWLEDGEMENT

The presented investigations are financially supported by the European Commission within the 6th framework program and are carried out in the project POLYTECT "Polyfunctional Technical Textiles against Natural Hazards" (NMP2-CT-2006-026789). The authors gratefully thank for the financial support and the valuable cooperation of all partners involved.

7 REFERENCES

Diaz, S. Mafang, S., Lopez-Amo, M., Thevenaz, L. 2008 A high-performance optical time-domain Brillouin distributed fiber sensor. *IEEE Sensors Journal*, 8: 1268-1272.

Froggatt, M and Moore, J. 1998. High-spatial-resolution distributed strain measurement in optical fiber with Rayleigh scatter. *Applied Optics*, 37: 1735-1740.

Husdi, IR, Nakamura, K and Ueha, S. 2004. Sensing characteristics of plastic optical fibres measured by optical time domain reflectometry. *Measurement Science and Technology*, 15: 1553-1559.

Liehr, S, Lenke, P, Krebber, K, Seeger, M, Thiele, E, Metschies, H, Gebreselassie, B, Münich, JC and Stempniewski, L. 2008. Distributed strain measurement with polymer optical fibers integrated into multifunctional geotextiles. *Proc. of SPIE*, 7003: 700302-1 - 700302-15.

Liehr, S, Lenke, P, Wendt, M and Krebber, K. 2008. Perfluorinated graded-index polymer optical fibers for distributed measurement of strain. *Proc. of POF Conference*.

Liehr, S., Lenke, P., Wendt, M., Krebber, K., Seeger, M., Thiele, E., Metschies, H., Gebreselassie, B., Münich, J. C. 2009. Polymer Optical Fiber Sensors for Distributed Strain Measurement and Application in Structural Health Monitoring. *IEEE Sensors Journal,* to be published May 2009.