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Smart Technical Textiles Based on Fiber Optic Sensors

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1. Introduction

Smart technical textiles are by definition textiles that can interact with their environment. They can sense and react to environmental conditions and external stimuli from mechanical, thermal, chemical or other sources. Such textiles are multifunctional or even “intelligent” which is fulfilled by a number of sensors incorporated in the textiles. The embedded sensors are sensitive to various parameters such as temperature, strain, chemical, biological and other substances.

Technical textiles are commonly used within several industrial sectors ranging from medical, healthcare, earthworks, construction, civil engineering, transport, to name a few. Europe has driven substantial developments in technical textile technologies[1]. Smart technical textiles are going to stimulate the European engineering, transportation and construction industry and to improve human performance and health. For example, technical textiles are extensively used in construction in form of geotextiles for the reinforcement of earthworks and masonry structures. The retrofitting of existing masonry walls and soils structures by technical textiles gains more and more importance especially in connection with earthquake protection of historic buildings and protection of roads and railway embankments against landslides. Wearable health systems and protective clothing have been recognized as key technologies to improve the personal protection and health care of Europe’s citizens[2]. Smart biomedical garments and clothing act as “a second skin” and detect, for instance, vital signals of the wearer’s body or changes in the wearer’s environment.

The most effort in the past was made to integrate non-optical sensors into textiles. Optical fibers integrated in textiles were mostly explored for illumination or luminescent purposes. Smart technical textiles containing fiber optic sensors are still an exception. When integration of sensors into textiles is considered, optical fibers have a serious advantage over other kinds of sensors due to their fibrous nature. The optical fiber is similar to textile fibers and

can be ideally processed like standard textile yarns. Particularly, the integration of polymer optical fibers (POF), with their outstanding material properties, into technical textiles has not seriously been considered, until now. POF offer additional benefits to users. They are lightweight, robust, cheap and easy to handle. Especially because of their high elasticity and high breakdown strain POF are ideally suited for integration into technical textiles[3].

2. Geotextiles based on distributed fiber optic sensors for structural health monitoring

For stabilization and reinforcement of geotechnical structures like dikes, dams, railways, embankments, landfills and slopes geotextiles are commonly used. The incorporation of optical fibers in geotextiles leads to additional functionalities of the textiles, e.g. monitoring of mechanical deformation, strain, temperature, humidity, pore pressure, detection of chemicals, measurement of the structural integrity and the health of the geotechnical structure (structural health monitoring). Especially solutions for distributed measurement of mechanical deformations over extended areas of some hundred meters up to some kilometers are urgently needed. Textile-integrated distributed fiber optic sensors can provide for any position of extended geotechnical structures information about critical soil displacement or slope slides via distributed strain measurement along the fiber with a high spatial resolution of less than 1 m. So an early detection of failures and damages in geotechnical structures of high risk potential can be ensured.

Geotextiles with incorporated fiber optic sensors based on fiber Bragg gratings (FBG) were demonstrated in the past[4]. Monitoring systems based on such geotextiles can only measure quasi-distributed strain over limited lengths and the relative high price of the FBG-equipped geotextiles might be an additional drawback of the systems. The monitoring of extended geotechnical structures like dikes, dams, railways, embankments or slopes requires sensor technologies with gauge lengths of some hundred meters or even more. Sensor systems based on the stimulated Brillouin scattering in silica fibers have been used for such monitoring purposes. It was reported in the past about a geotextile-based monitoring system using the Brillouin optical-fiber frequency-domain analysis (BOFDA) for measurements of critical soil displacements of dikes[5]. However, the excellent measurement technique based on Brillouin scattering in silica fibers reaches its limits when strong mechanical deformations, i.e. strain of more than 1 % occurs. In such a case sensors based on silica fibers cannot be reliably used. Furthermore, silica fibers are very fragile when installing on construction sites and, therefore, special robust and expensive glass fiber cables have to be used. For that reason, the integration of POF as a sensor into geotextiles has become very attractive because of the high elasticity, high breakdown strain and the capability of POF of measuring strain of more than 40 %. Especially the monitoring of relative small areas with an expected high mechanical deformation such as endangered slopes takes advantage of the outstanding mechanical properties of POF. The monitoring of slopes is a very important task in the geotechnical engineering for prevention of landslide disasters and no reliable sensor methods exist, so far. To overcome the limit of glass-fiber-based geotextiles, a novel

distributed fiber optic sensor based on low-priced standard POF and using the OTDR (optical time-domain reflectometry) which is suitable for integration in technical textiles has been developed and demonstrated[6].

Such innovative textile-integrated distributed Brillouin and POF OTDR sensors for the above mentioned monitoring purposes have been developed within several German projects and the European project POLYTECT. The POLYTECT project has particularly focused on the development of polyfunctional technical textiles against natural hazards. The aim of POLYTECT has been to develop and investigate new multifunctional textile structures for the application in construction for the retrofitting of masonry structures and earthworks. The retrofitting of existing masonry walls and soil structures is particularly important for earthquake protection of historic buildings and protection of earthworks against landslides. The new and advanced textile structures containing optical fibers as sensors will be able to increase the ductility and the structural strength of masonry and geotechnical structures and to prevent structural damage[6]. For this, the sensors incorporated into the textile structures will monitor strain, deformation, humidity and will detect presence of chemicals. The development of the sensors carried out within the above mentioned projects has advanced and a number of field tests using distributed Brillouin and POF OTDR sensors have successfully been conducted.

2.1. Monitoring of geotechnical structures using distributed Brillouin sensors embedded in geotextiles

The use of stimulated Brillouin scattering (SBS) for distributed measurement of temperature and strain was already demonstrated 20 years ago[7]. The SBS is the most dominant nonlinear effect in single-mode silica fibers and can be described as a three-wave-interaction of two contra-propagating light waves and an acoustic wave in the fiber. Because of the strain and temperature dependence of the Brillouin frequency shift of the scattered light, sensor systems based on this effect can be used for distributed strain and temperature measurements. The first distributed Brillouin sensing systems named Brillouin optical-fiber time-domain analysis (BOTDA) operated in a time-domain, which means that a short pulse is sent along the fiber and the backscattered light is recorded over time and contains information about the strain or temperature along the fiber[8]. During the last two decades the performance of BOTDA sensor systems has improved steadily. The operating range of these sensors is typically in the order of 20-30 km for 2-3 m spatial resolution. Today, several devices based on this technique are commercially available.

In 1996 an alternative approach named Brillouin optical-fiber frequency-domain analysis (BOFDA) was introduced[9]. The BOFDA operates with sinusoidally amplitude-modulated light and is based on the measurement of a baseband transfer function in frequency domain by a network analyzer (NWA). A signal processor calculates the inverse fast Fourier transform (IFFT) of the baseband transfer function. In a linear system this IFFT is a good approximation of the pulse response of the sensor and resembles the strain and temperature distribution along the fiber (Fig. 1). The frequency-domain method offers some advantages compared to the BOTDA concept. One important aspect is the possibility of a narrow-band-

width operation in the case of BOFDA. In a BOTDA system broadband measurements are necessary to record very short pulses, but in a BOFDA system the baseband transfer function is determined point-wise for each modulation frequency, so only one frequency component has to be measured by NWA with a narrow resolution bandwidth. The use of a narrow bandwidth operation (detectors) improves the signal-to-noise ratio and the dynamic range compared to those of a BOTDA sensor without increasing the measurement time. Another important advantage of a BOFDA sensor is that no fast sampling and data acquisition techniques are used. This reduces costs. Particularly, the low-cost-potential of BOFDA sensors is very attractive for industrial applications.

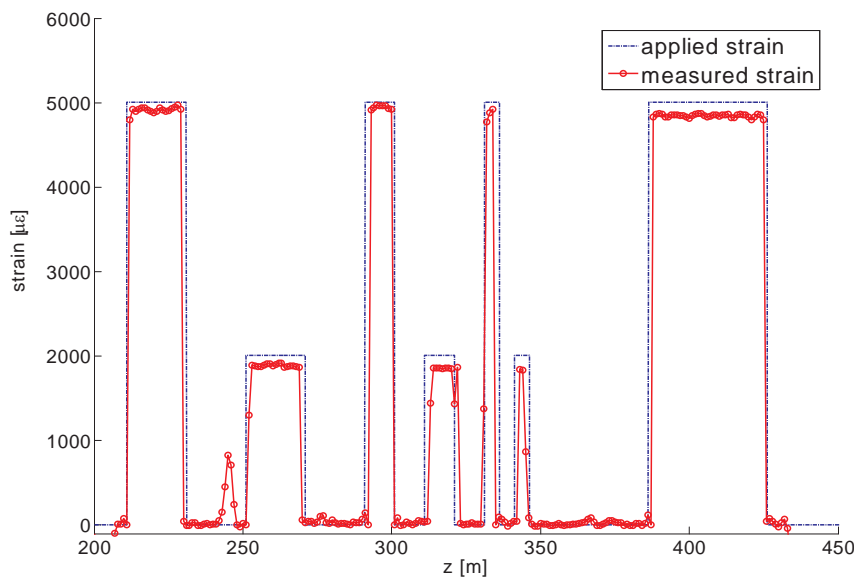


Figure 1. Distributed strain profile measured on a single-mode silica fiber using BOFDA.

As already pointed out, distributed Brillouin sensors are well qualified for the distributed monitoring of mechanical deformation (strain) of extended geotechnical structures like dikes, dams and highways of lengths of some hundred meters up to some kilometers and no alternative sensor techniques for such monitoring purposes exist so far. To push the development of such sensor systems in connection with innovative monitoring solutions based on smart technical textiles, several research projects have been running in Germany and Europe. The German research program RIMAX (Risk Management of Extreme Flood Events) has mainly focused on the development of intelligent monitoring systems for dike protection and was launched as a consequence of extreme floods in Germany in the past decade. A low-cost monitoring system based on the BOFDA technique and geotextiles containing silica fibers as distributed Brillouin sensors have been developed within the program[10].

Geotextiles are commonly used in dikes for reinforcement of the dike body and erosion prevention. By embedding sensing optical fibers in the textiles, distributed measurements of critical mechanical deformations/soil displacements of dikes of several kilometers can be re-

alized. So an early detection of failures in dikes, dams and other large geotechnical structures can be ensured in order to prevent a total collapse of these structures in case of natural disasters. An important task when considering integration of optical fibers in geotextiles is to ensure an accurate transfer of the mechanical quantities to be measured, i.e. of strain, from the soil to the textile and so to the fiber. For this, a stable and damage-free integration of the optical fibers in the geomats is of essential importance. The Saxon Textile Research Institute (STFI) e.V., Chemnitz, Germany has developed a technology to integrate optical fibers into geotextiles so that the sensing fiber is well affixed onto the textile and the integration procedure does not affect the optical and sensing properties of the fibers. Also the use of special coating and cable materials are of crucial importance to protect the fragile single-mode silica fibers against fiber-breakage during the integration into the textiles and the installation on construction sites. For that, a novel glass fiber cable was developed and manufactured by Fiberware, Mittweida, Germany to fulfill the above mentioned requirements on robustness and to assure accurate strain transfer to the sensing fibers[11]. Fig. 2 shows the special cable as well as different types of geotextiles with embedded glass fiber cables.

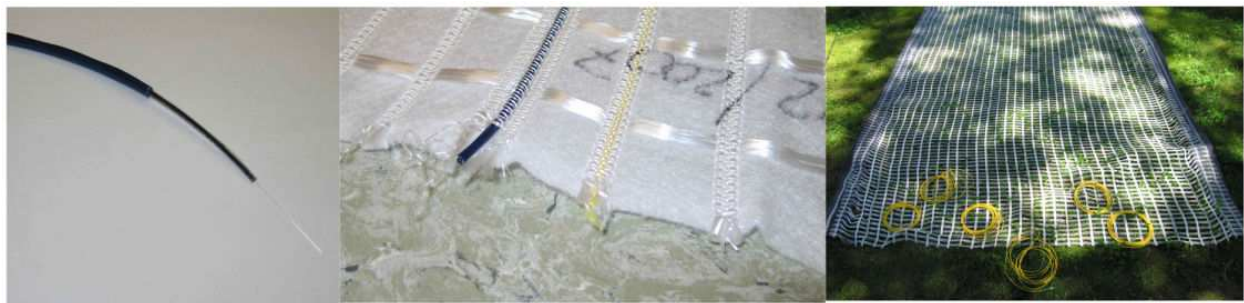


Figure 2. Special glass fiber cable for strain sensing manufactured by Fiberware, Germany (left) and two different types of geotextiles (middle: nonwoven geotextile, right: geogrid) manufactured by STFI, Germany with embedded glass fiber cables.

The BOFDA monitoring system has been optimized to fit the demands on dike monitoring: detection of mechanical deformation (strain) with a spatial resolution of 5 m over a distance range of up to 10 km. The functionality of the monitoring system and the fiber-sensors-equipped geotextiles has been proven in several installations and field tests in dikes and dams. For example, Fig. 3 shows the installation of geotextiles with embedded Brillouin sensing fibers in a gravity dam in Solina, Poland. A thin soil layer of several 10 cm put onto the geomats after installation has been proven to be a sufficient protection of the textile-integrated glass fiber cables against heavy machinery and construction work.

An application-like test was carried out at a laboratory dike (15 m long) at the University Hannover, Germany[11]. A sensor-based geotextile was installed on top of the dike and was covered with a thin soil layer. To simulate a mechanical deformation/soil displacement, a lifting bag was embedded into the soil and was inflated by air pressure. This induced a break of the inner slope of the dike and a soil displacement (Fig. 4). The soil displacement was clearly detected and localized by the BOFDA system. Fig. 5 shows the distribution of

the mechanical deformation (strain) in the dike measured by the BOFDA system at two different air pressure values.



Figure 3. Installation of a non-woven geotextile containing single-mode silica fibers as Brillouin sensors in a gravity dam in Solina, Poland.



Figure 4. Laboratory dike at the University Hannover, Germany and soil displacement in the dike.

As previously mentioned, a geotextile with embedded Brillouin sensing fibers was installed in a gravity dam in Solina, Poland to prove the feasibility of the whole concept in the framework of a real field test Fig. 6. The goal of the field test was to detect possible geophysical activities in the dam by the fiber-sensor-equipped geotextile of a length of 17.5 m manufactured by STFI, Germany and embedded in the soil. Distributed measurements by using a commercially available BOTDA system from Omnisens were conducted. Fig. 7 shows the distributed Brillouin frequency shift measured on the fiber section embedded in the soil. In the fiber sections between 205 m and 240 m (where the geomat was embedded in the soil) a mechanical load is assumed which results in a change of the recorded Brillouin frequency in these fiber sections.

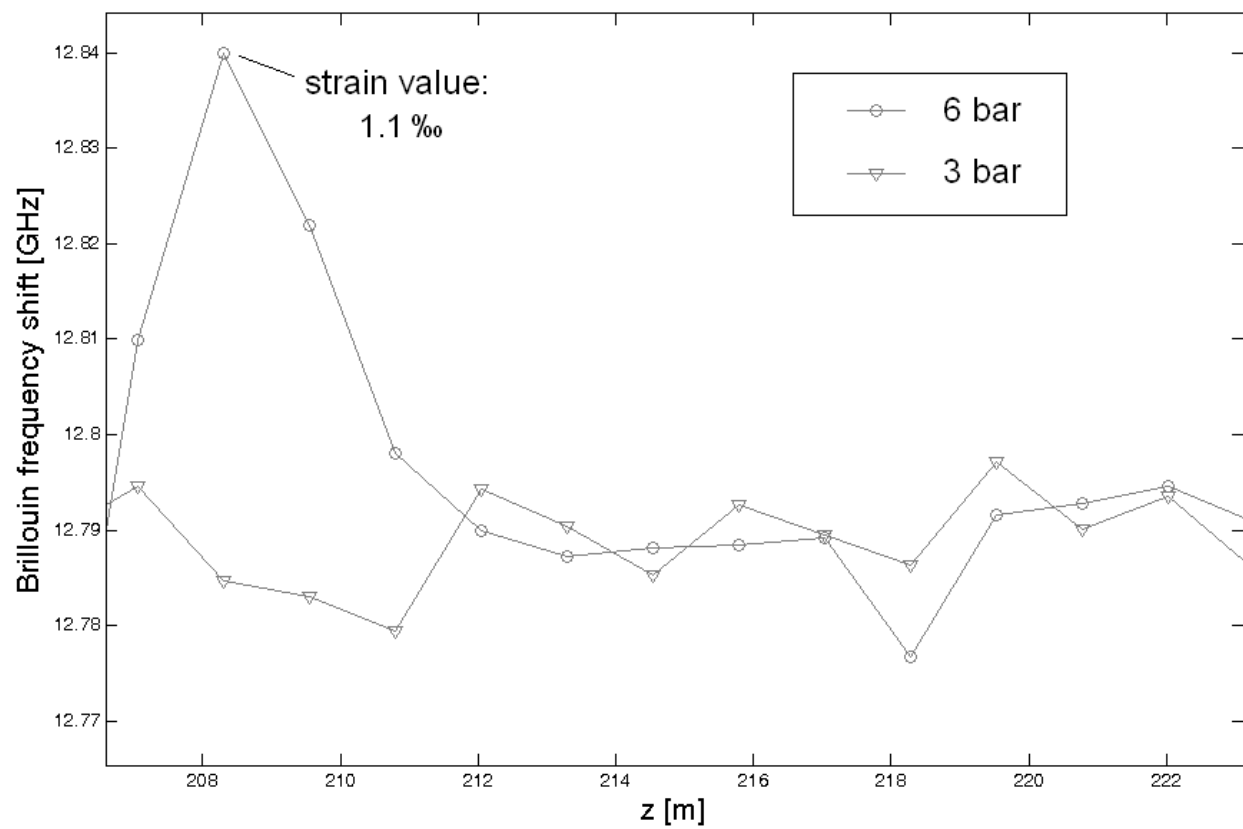


Figure 5. Detection of a soil displacement (strain) in the laboratory dike shown in Fig. 4 using the BOFDA system.



Figure 6. Gravity dam in Solina, Poland (left) and the construction site with the sensor-based non-woven geotextile before embedding in the soil and 3 years later (right).

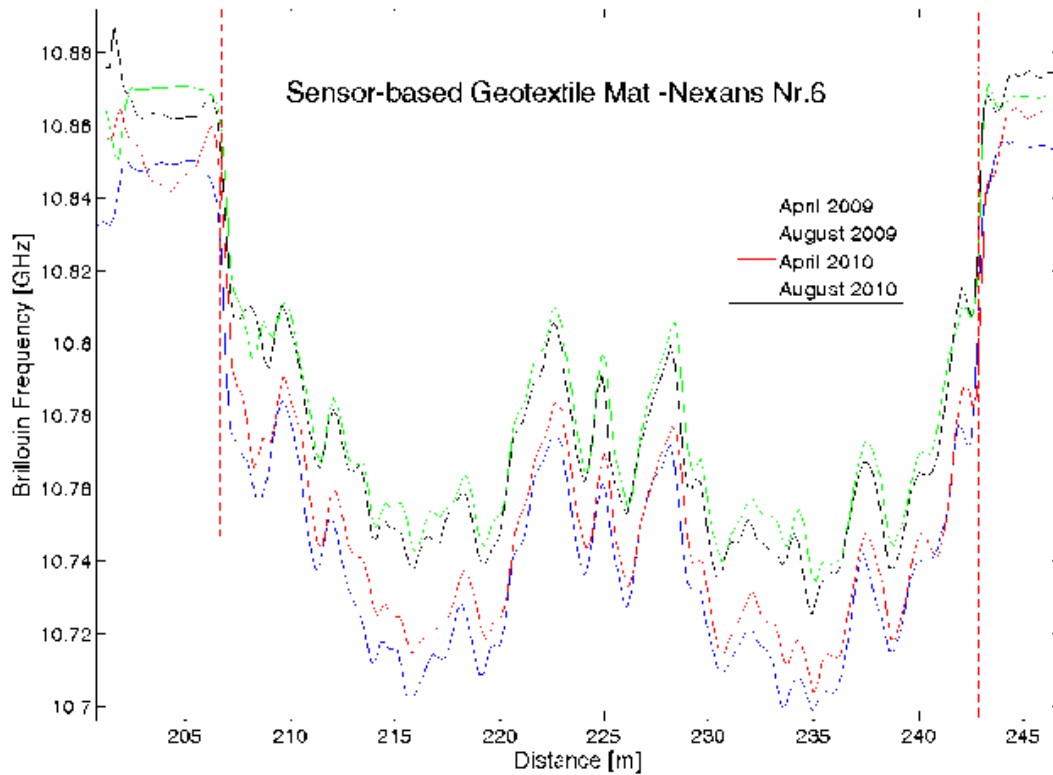


Figure 7. Distributed Brillouin frequency shift measured on the fiber section embedded in the soil (between 205 m and 240 m) 3 years after installation of the geomat.

With the objective of a cost-effective optimization of the BOFDA system a novel measurement concept based on a digital signal processing has been realized[11]. This concept employs a novel digital data acquisition technique, which takes advantage of the reduced bandwidth required in BOFDA sensor systems. The backscattered optical signals can be digitally sampled using state-of-the-art analog-to-digital converters and is processed off-line by means of modern digital signal processing methods, avoiding complex and expensive analog components such as filters, oscillators and circuitry for signal analysis. The digital optical signal processing features several advantages compared to the measurement process using NWA: less hardware is required, an increase of the dynamic range due to the offline signal processing and improvement of the data acquisition time is expected.

2.2. Monitoring of geotechnical structures using distributed POF OTDR sensors embedded in geotextiles

To overcome the limit of silica-fiber-based distributed sensors, a novel distributed strain sensor based on low-priced standard POF and using the OTDR technique for monitoring of mechanical deformations of geotechnical structures has been developed. Already published results showed that it is possible to measure distributed strain in POF using the OTDR tech-

nique[12]. In the framework of the German research project “Sensitive textile structures” (within the German program “ZUTECH” – “Future technologies”) and the European project POLYTECT further investigations of this effect with respect to the development of a new, distributed POF sensor embedded in technical textiles have been performed[6], [13].

The functional principle of the POF OTDR technique is very simple. An optical pulse is launched into the fiber and the backscattered light mainly caused by Rayleigh scattering is recorded as a function of time. The time interval from launching the pulse into the fiber until the return of the backscattered light (pulse response) depends linearly on the distance of the scattering location. The level of the backscattered light increases at locations where strain is applied to the POF. Fig. 8 (left) shows the OTDR response of an unstretched POF (solid line) and of a stretched POF (broken line) which is stretched at about 42 m on a 1.4 m long section by 16 %. Fig. 8 (right) shows the relative change of scattering of the stretched POF section at different strain values between 0 % and 16 % (calculated relative to the scattering of the unstretched fiber). The scattered light increases steadily with applied strain. Today, several OTDR devices for POF are commercially available on the market. In the described investigations a photon counting OTDR device from Sunrise Luciol has been used. The device operates at 650 nm, has a dynamic range of 35 dB and allows a measurement of Rayleigh scattering along a length of more than 100 m. The photon counting technique is ideal for achieving high dynamic range on very short sensing lengths. The two-point spatial resolution of the OTDR device is limited to 10 cm. An additional solution to evaluate the strain or length change of a fiber section is to evaluate the shift of reflection peaks along the fiber (see Fig. 8, left). Such peaks originate for example from Fresnel reflections at the fiber end or fiber connectors. This technique provides an absolute length change measurement with a resolution of up to 1.5 mm.

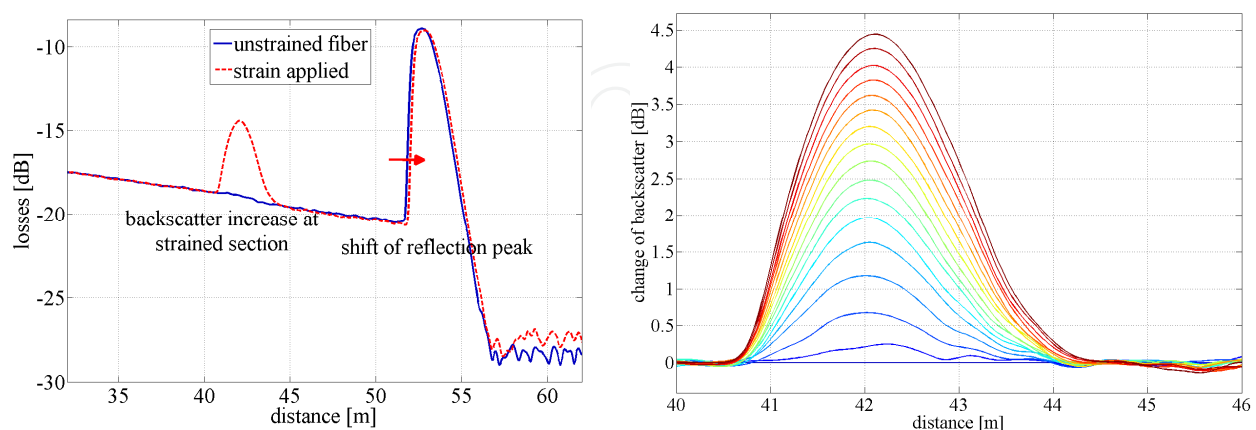


Figure 8. Left: OTDR trace of POF in unstretched condition (solid line) and of POF with a stretched fiber section at about 42 m (broken line). Right: Change of the scattering along a 1.4 m long POF section that is stretched from 0 to 16 % in steps of 1 %.

Fig. 9 shows the increase of the scattered light versus applied strain. A non-linear dependence between the OTDR signal (the backscattering) and the applied strain in the whole strain range was obtained. Strain of up to 45 % was measured using standard PMMA POF.

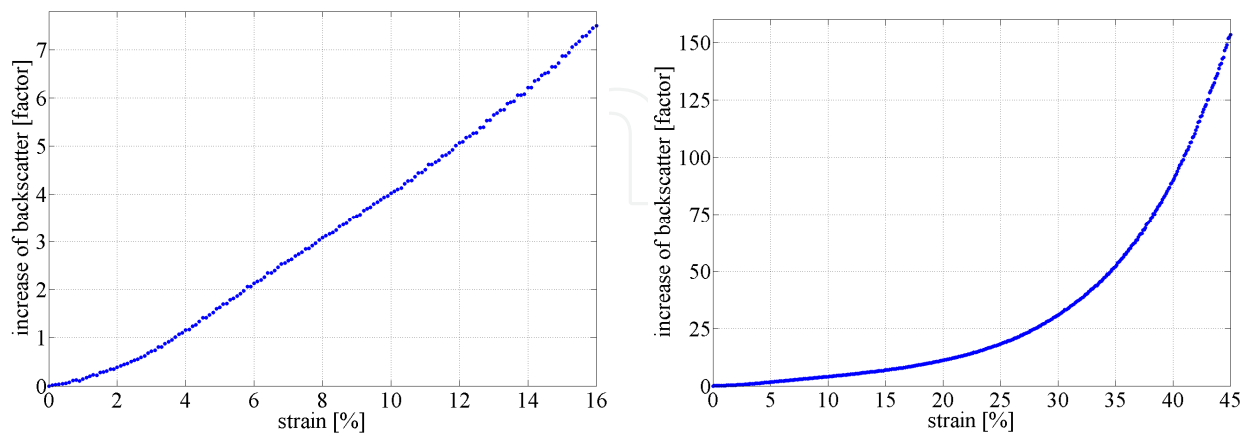


Figure 9. Change of the backscattering as a function of strain measured on standard PMMA POF.

The attenuation of standard PMMA POF limits the distance range of distributed POF OTDR sensors to about 100 m. Low-loss perfluorinated POF show a big potential as distributed strain sensors for long distances[14]. It has been shown that using perfluorinated POF it is possible to monitor fiber lengths of more than 500 m (Fig. 10, left). Recent research has demonstrated, that perfluorinated POF allow the measurement of very high strain values of up to 100 % (Fig. 10, right).

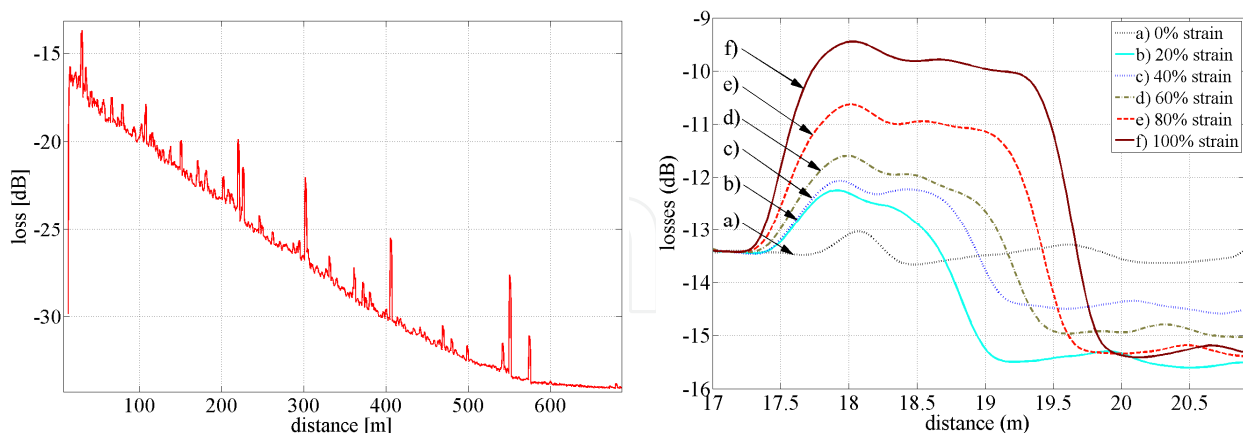


Figure 10. Left: OTDR trace of perfluorinated POF. Right: OTDR signal of perfluorinated POF strained up to 100 %.

Technologies for a damage-free integration of POF into different types of geotextiles have successfully been developed and demonstrated by several textile partners in Europe like STFI, Germany and Alpe Adria Textil, Italy. Fig. 11 shows the integration of POF into non-woven geotextiles at STFI e.V. as well as a geogrid containing POF. Already the first field

tests proved that the POF-equipped geotextiles are suited for installation on construction sites. POF-based geomats have successfully been installed in a railway embankment near Chemnitz, Germany (Fig. 12)[6]. All POF sensors have survived the installation on construction site without any damage. Their functionality has been regularly tested (Fig. 12, right).



Figure 11. Integration of POF into nonwoven geotextiles at STFI e.V. (left) and a geogrid containing POF (right).



Figure 12. Installation of POF-equipped geotextiles in a railway embankment near Chemnitz, Germany (left and middle) and OTDR traces measured on the textile-integrated POF (right).

During the last years, the POF-equipped geotextiles have successfully moved from the laboratory to the field. Several field tests have successfully been conducted, e.g. in an open brown coal pit near Belchatow, Poland[15]. The test was initiated, organized and supervised by Gloetzl Baumesstechnik GmbH, Germany in close cooperation with Budokop, Poland and the owner of the coal pit. A sensor-equipped geogrid was installed directly on top of a creeping slope. The 10 m long geogrid was manufactured by Alpe Adria Textil, Italy and comprised one standard PMMA POF. Fig. 13 shows the installation of the sensor textile on top of the slope. It is covered with a 10 cm thick sand layer. The textile is installed with the POF sensor bridging the cleft perpendicular to the opening. The geogrid was installed in a slightly corrugated way simulating realistic installation conditions.



Figure 13. Installation of a geogrid containing PMMA POF at a creeping slope in a brown coal pit near Belchatow, Poland.

Measurements were conducted before and after installation. Fig. 14 (left) shows the OTDR traces of the sensor fiber section (the magnitude of the backscatter increase relative to a reference measurement) in the middle of the textile where the fiber bridges the cleft. The figure clearly shows a backscatter increase due to strain in the fiber at the position where the cleft was opening. The high peak at about 35 m is caused by a very high and confined strain in the sensor fiber and textile. The magnitude of the backscatter increase corresponds to a maximum strain in the fiber of more than 10 %. Such high strain values can only be measured by POF sensors. Silica fiber-based sensor systems would have failed at a strain exceeding about 1 %.

Due to the gradual increase of cleft width, the overlying textile and therefore the sensor fiber change their absolute length. By evaluating the relative shift of the reflection peaks at both ends of the textile-integrated fiber, the values of the total elongation of the fiber sensor indicating the width of the cleft was obtained. Fig. 14 (right) shows a relative linear increase of the POF length with time. The measurements indicate that the creep velocity of the slope was constant during the time of observation with an average rate of about 2 mm per day.

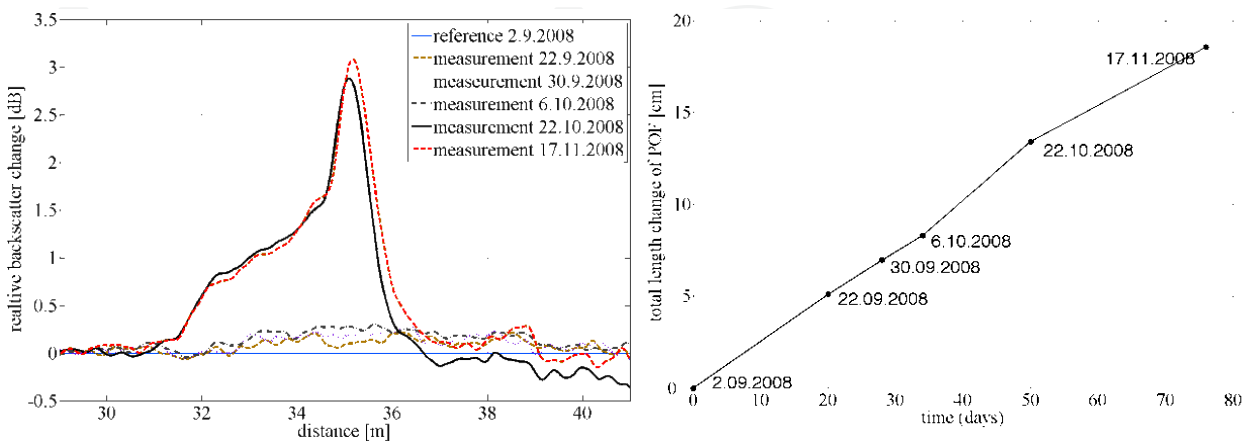


Figure 14. POF OTDR traces at the position of the cleft (left) and total elongation of the POF obtained by a peak-shift evaluation (right).

Recently, novel geogrids containing low-loss perfluorinated POF (PF POF) have been developed and manufactured by Alpe Adria Textil. Already the first field test has proved that the PF POF-equipped geotextiles are suited for installation on construction sites. PF POF-based geomats have successfully been installed at the creeping slope Kap Arkona at the German Baltic coast (Fig. 15, left). All PF POF sensors have survived the installation on construction site without any damage. At present, their functionality has been regularly tested by using the POF OTDR technique (Fig. 15, right).

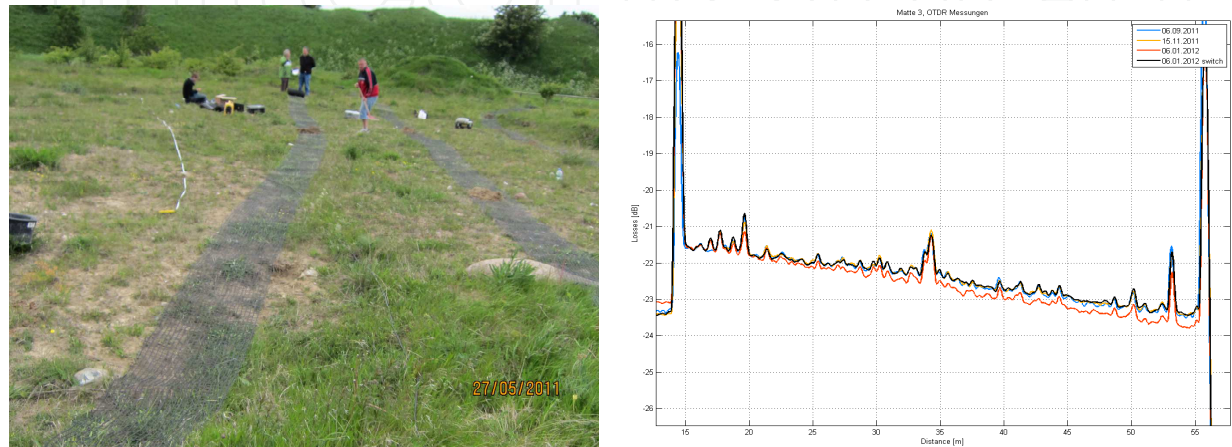


Figure 15. Left: Installation of PF POF-equipped geotextiles at the creeping slope Kap Arkona at the German Baltic coast. Right: OTDR traces measured on the textile-integrated PF POF after installation.

The successful demonstration of the distributed POF OTDR sensors in the field and the huge interest of the geotechnical industry in these sensors resulted in the development of the first commercially available product based on distributed POF sensors – GEDISE: Distributed Sensor Technique in Geotextiles using POF (Fig. 16). GEDISE is commercially available by Glötzl GmbH, Germany.



Figure 16. Leaflet of GEDISE: Distributed Sensor Technique in Geotextiles using POF (www.gloetzel.de).

2.3. Monitoring of masonry structures using distributed POF OTDR sensors embedded in technical textiles

The motivation to monitor masonry structures by sensor-equipped technical textiles is to strengthen the masonry body and enhance the ductility of the structures and at the same time to monitor the structural health and detect any damage of the structures, e.g. due to earthquakes. The development of sensor-based technical textiles containing fiber optic sensors for the retrofitting of masonry structures is an innovative task of the European project POLYTECT. The targeted applications are masonry and heritage structures that are structurally vulnerable, for example in earthquake regions. Typical structural damages that have to be detected are vertical cracks. POF sensors are very promising for that since they not only enable distributed strain measurement, they are also appropriate to detect very short strained fiber sections of a few millimeters that will occur in case of cracks. For example, Fig. 17 shows the monitoring of a crack opening in a masonry structure using a POF OTDR sensor. A technical textile containing POF was applied to the surface of the masonry sample[6]. Using the POF OTDR technique it was possible to detect a crack opening of 1 mm and also the increase of the crack width up to 20 mm in steps of 2 mm (Fig. 17, right).

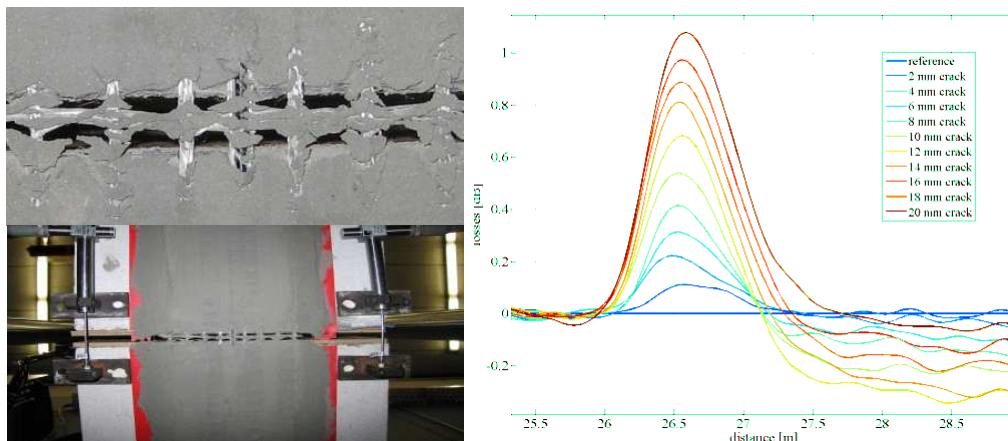


Figure 17. Monitoring of a crack opening in a masonry structure (Institute IfMB at the University of Karlsruhe, Germany) with a POF-equipped masonry textile (STFI e.V., Chemnitz, Germany). The right side of the figure shows POF OTDR backscatter signals at the location of the crack at different crack opening steps.

Using the POF OTDR technique a field test was conducted on an one-storey brick building on a seismic shaking table[16]. The test was organized and supervised by the Institute of Mechanics of Materials and Geostrutures (IMMG), Greece. Fig. 18 shows the POF sensors bonded to the wall with a cementitious resin matrix. The testing procedure included several strong shocks, which resulted in structural damage of the building. The task of the distributed POF sensors was to provide information about the existence and location of cracks in the structures. The occurred cracks were detected and localized with the POF OTDR sensor. Fig. 19 shows the OTDR traces measured on one sensor-fiber which was installed diagonally on the wall. Two cracks were detected by the sensor at the locations indicated in Fig. 18. The stronger signal at 27 m 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.

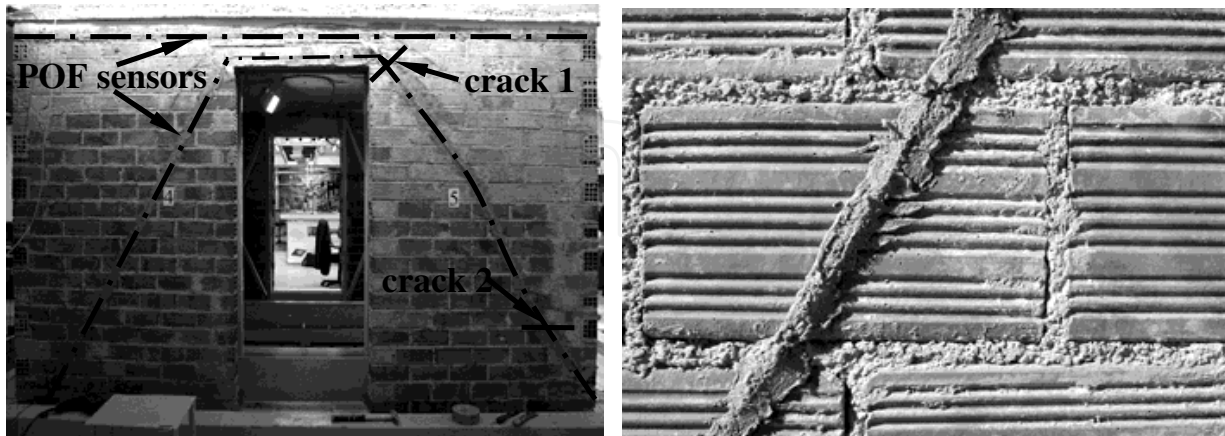


Figure 18. Brick building on a shaking table with POF sensors installed horizontally and diagonally.

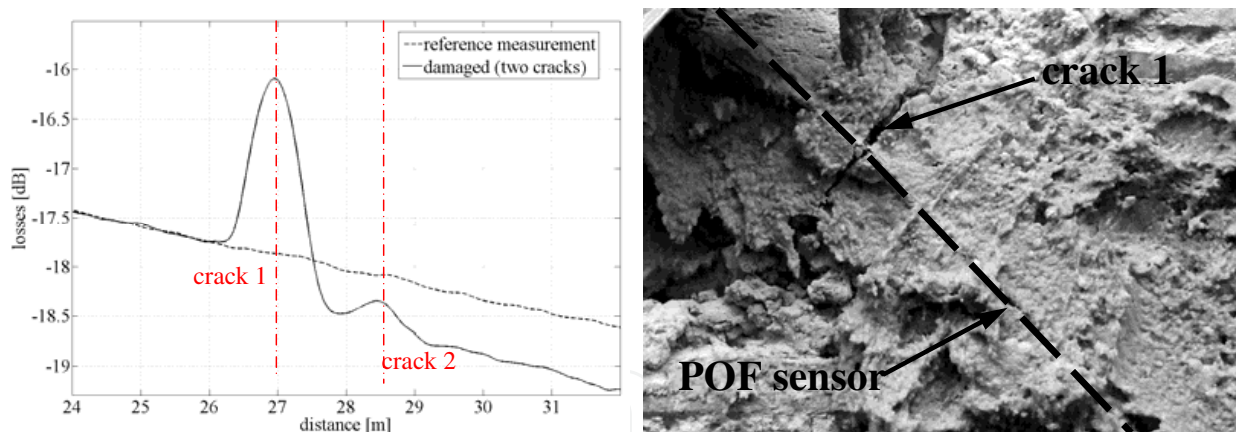


Figure 19. POF OTDR trace showing two cracks at 27.0 m and 28.5 m (left) and the corresponding first crack at 27.0 m of a width of 2 mm (right).

During the last years, several field tests have successfully been conducted on real masonry buildings reinforced by POF-sensors-based technical textiles, one of them on a masonry house at the Eucentre in Pavia, Italy (Fig. 20). The testing procedures of the textile-equipped masonry building included several strong seismic shocks (simulating earthquakes) that resulted in several cracks in the masonry walls. The occurred cracks were clearly detected and localized by the distributed POF OTDR sensor (Fig. 21) which demonstrated the potential of this technique to be used also for damage detection of masonry and heritage structures.



Figure 20. Application of technical textiles containing POF on a masonry building at the Eucentre in Pavia, Italy.

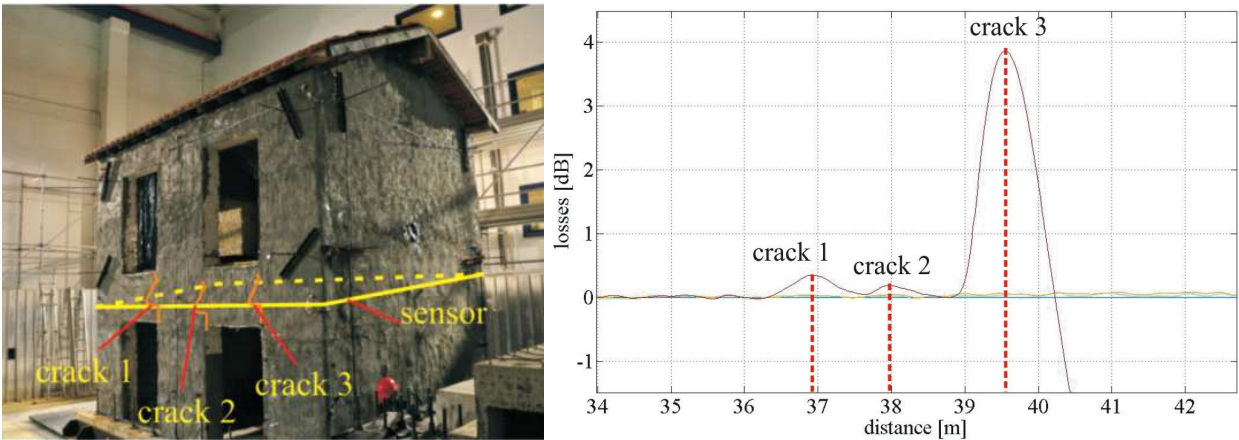


Figure 21. Detection of cracks in a masonry wall by a textile-embedded distributed POF OTDR sensor after several seismic shocks applied to the building.

3. Medical textiles based on fiber optic sensors for healthcare monitoring

Healthcare monitoring of patients and old people who require a continuous medical assistance and treatment is a subject of a number of research activities in Europe. In order to increase the mobility of such patients, the development of wearable monitoring systems able to measure important physiological parameters of the patients is targeted. Europe has considerably pushed the developments of such wearable biomedical clothing containing different types of sensors by a number of research projects.

The European project OFSETH (optical fiber sensors embedded into technical textile for healthcare) supported by the 6th European framework program, has investigated how various vital parameters such as respiratory movement, cardiac rate and pulse oxymetry can be

measured by fiber optic sensors based on silica and polymer optical fibers, embedded into medical textiles. As a result, wearable solutions for healthcare monitoring, for patients requiring a continuous medical assistance and treatment, are available. Despite of already existing electrical and also fiber optic sensors, OFSETH has achieved a breakthrough in the healthcare monitoring by combining the advantages of pure fiber optic sensor technologies and wearability of the textiles and so increasing the functionality of the sensor and the comfort of the system.

The OFSETH developments have targeted in the first place on the monitoring of sedated or anaesthetized patients under Medical Resonance Imaging (MRI)[17]. In this case electrical sensors cannot play a role; fiber optic sensors are advantageous because of their electromagnetic compatibility. The use of fiber optic sensors instead of electrical sensors will reduce the electromagnetic disturbance of the MRI field. Additionally, metallic parts and conductive wires of electrical sensors cause burns on the patient's skin in the MRI field. Fiber optic sensors are free from such metallic components and so burning hazard for the patients can be prevented. Besides, fiber optic sensors offer the advantage that the monitoring unit can be placed out of the MRI field and can be connected to the sensor by a fiber cable of some five or ten meters.

Anaesthetized patients are usually transferred from the induction room to the MRI room and back under anesthesia. A continuous monitoring of the patients from the induction to the end of the anesthesia is required but in fact the medical staff usually uses different monitoring devices during the whole procedure, because the most standard monitoring devices are not transportable or not MRI compatible. After the MRI examination, the patient is transferred back, still anesthetized, in the worst case without any monitoring system which puts the patients at risk of anesthetic complications. Therefore, a transportable monitoring system, able to follow the patients from the induction room to the MRI room and back without being removed is needed. The wearability of such a system will increase its functionality and the comfort to the user. Wearable monitoring systems can also be used in the ambulatory healthcare monitoring and the monitoring of Sudden Infant Death Syndrome. Therefore, OFSETH has mainly addressed the textile integration issues and in this context has extended the capability of wearable solutions for healthcare monitoring.

For MRI applications there is especially need to monitor the patients' respiratory parameters: respiratory movement and respiratory rate. Therefore, OFSETH has focused, among other things, on the investigation of textile-integrated fiber optic sensors for respiratory monitoring of patients during MRI examinations. For this purpose, medical textiles that incorporate silica and polymer optical fibers have been investigated where a wearable, adaptable and MRI compatible monitoring system has been targeted.

The feasibility of using fiber optic sensors for respiratory monitoring was demonstrated in the past. It has been reported on fiber sensors woven into bandages or attached onto garments mainly using FBG (fiber Bragg gratings) and LPG (long period gratings) based on silica fibers[18], [19]. However, the poor compatibility of these sensors with industrial textile processes limits their flexibility and use for medical monitoring purposes.

Human breathing movement causes typical elongations of the abdominal circumference of adults of up to 3 %. Using silica fibers, limited strain values of up to 1 % can be measured. Therefore, with a special focus on using POF instead of silica fibers, OFSETH has investigated different fiber sensor techniques for respiratory monitoring[20], [21]. A highly important criterion for selecting POF as medical sensor is its biocompatibility, especially in case of fiber breakage.

3.1. POF OTDR sensor embedded in medical textiles for monitoring of the respiratory movement

For the respiratory monitoring, there is an interest for the doctors to take information from both abdominal (for spontaneous ventilation) and thoracic (for intubated patients) movement[17]. Therefore, a distributed measurement of the respiratory signal, using only one monitor and one sensor fiber would be advantageous. Using an OTDR technique, it is possible to focus on a special part of the fiber and so to differentiate between abdominal and thoracic respiration. A distributed OTDR measurement makes possible to get only the required sensor information and to neglect loss contributions from non-sensing parts. In addition, an OTDR sensor system has the advantage of requiring only one fiber connection, which enables a quicker installation of the system on the patient.

A textile sample based on an elastic fabric containing a POF and manufactured by Centexbel and Elasta, Belgium was tested for the purposes of the respiratory movement monitoring by the OTDR technique. Since it was difficult to integrate a straight optical fiber into an elastic fabric, the textile sample uses a special macrobending sensor design developed by Multitel, Belgium (Fig. 22)[21]. The textile is divided in two sections: a short elastic part of about 10 cm whose length changes during the respiration and a longer non-elastic part. The POF is integrated into the elastic section to measure the elongation of the fabric due to the respiratory movement of the thorax or abdomen. The macrobending sensor design (described more detailed in Chapter 3.2) increases the sensitivity of the POF to the textile elongation and makes possible to detect small changes in the amplitude of the respiratory movement by the OTDR technique. Macrobending effects in POF induce changes of the backscattering in the corresponding area of the fiber that can be easily detected by the OTDR technique.

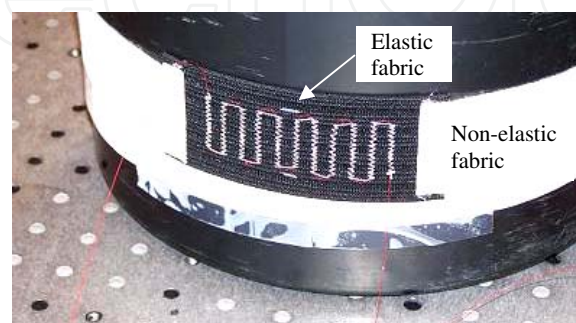


Figure 22. Textile sample containing a POF and based on the macrobending sensor design (textile: Centexbel & Elasta, Belgium; sensor design: Multitel, Belgium).

The feasibility of measuring the respiratory waveform and rate in real time by the POF OTDR technique was demonstrated on a healthy adult during normal breathing[21], [22]. The textile sample was attached around the abdomen of the adult and the elastic part of the textile was placed in the area experiencing the most elongation due to the breathing movement (Fig. 23). The sensor signal was acquired by a fast OTDR device produced by Tempo (OFM20), which operates at 650 nm wavelength, allows a two-point spatial resolution of 5 cm and has a dynamic range of > 20 dB. The device makes possible to measure an OTDR trace in less than 1 s with a sufficient SNR. This acquisition time is fast enough to measure normal human breathing. The changes of the abdominal circumference due to the breathing movement were recorded simultaneously. Fig. 23 shows the result and demonstrates the high potential of the POF OTDR technique for the considered monitoring purposes.

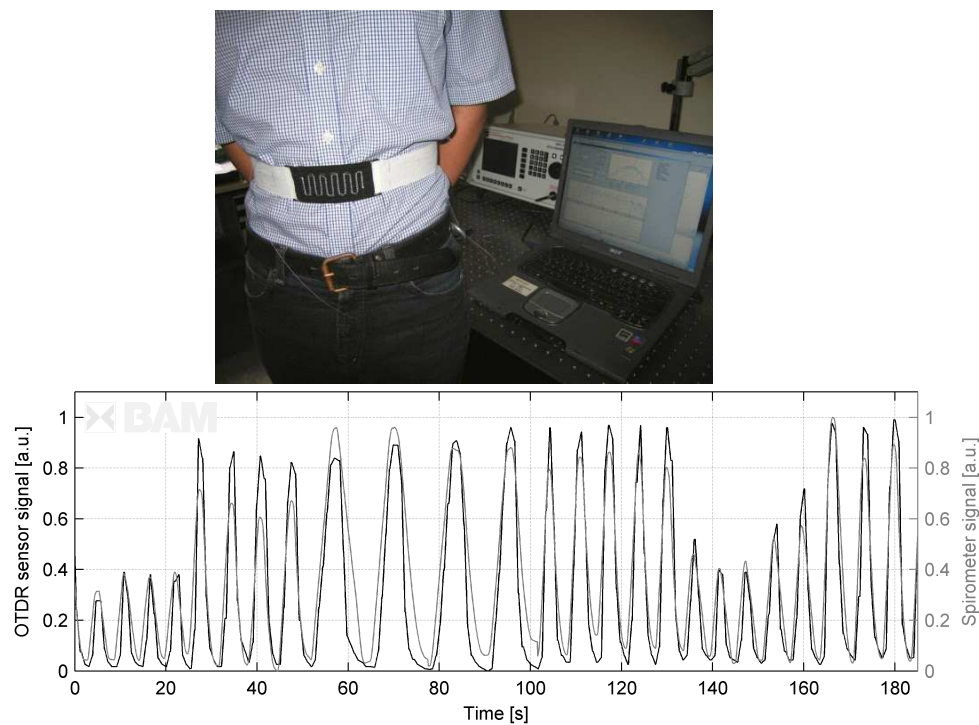


Figure 23. Monitoring of the respiratory abdominal movement of a human adult by POF OTDR sensor embedded in medical textiles (the OTDR sensor signal was compared with the signal measured by a spirometer).

3.2. Sensing harness for monitoring of the respiratory movement

Considering the influence of different patient's morphology as well as textile integration issues to let free all vital organs for medical staff actions during incident or respiratory accidents, different fiber optic sensors have been integrated into a harness allowing an efficient handling and continuous measurement of the respiratory movement[22]. European norms in terms of textile and the medical specification have been taken into account for the design of the sensing harness where the fiber optic sensors are strategically placed for measurement of thoracic and abdominal movements caused by the breathing activity without corruption

of one signal by another (Fig. 24). This design is composed of adjustable parts in order to fit the maximum of morphologies and to be worn both by men and women. The harness design keeps some places free, like the pre-cordium in order to facilitate resuscitation in case of cardiac arrest or hemodynamical failure, and give vital information on hemodynamical status during resuscitation. Access to the intra-venous infusion line has also been kept clear, for easy access during anesthesia or for resuscitation purpose. It has been ensured that there is no pressure on venous or arterial blood vessels which could obstruct the regular blood flow.



Figure 24. Sensing harness containing fiber optic sensors for the monitoring of patients under MRI. A thoracic respiration sensor is integrated in the black part (upper right); an abdominal respiration sensor is integrated in the white part (lower middle).

The elongation of the harness belt caused by the respiratory movement is measured using different fiber optic sensing principles based on FBGs and macrobending effects. The abdominal movement causes elongations of about 1-3%, which is much higher than for the thoracic movement which causes only a fractional percentage change. Therefore an FBG sensor which has high accuracy but a low strain limit is used for the thorax while for the abdomen a less accurate macrobending sensor is used which has a much higher strain limit.

The macrobending sensor developed by Multitel (Belgium) is based on bending effect of optical fibers (Fig. 25, left)[22]. Bends cause light coupling from guided modes into radiation modes and thus some power is lost. When the sensor textile is stretched, the curvature radius increases, and the bending loss decreases. Therefore the intensity variations at the output of the optical fiber will reflect the changes of the textile length, due to the respiratory movement. Macrobending sensors have the advantages that their interrogation is very simple: they require measurement of intensity changes, so the main components needed are an LED source and a photodiode. Standard single-mode silica fibers have been integrated into elastic fabrics, manufactured by Elasta (Belgium) during an industrial crochet fabrication process. The bending textile design has the advantage that the integration of the optical fibers

into textiles is relatively simple. The bending design also ensures that the optical fiber is not damaged at high strain during integration. Due to the relatively high amplitude of the abdominal movement the signal-to-noise ratio is high enough to monitor the respiratory rate.

For the monitoring of the thoracic respiration movement an FBG sensor developed by Centxibel (Belgium) and Multitel is used. Due to the FBG inscription process the fiber sensor is weakened, which reduces facilities for integration of the fiber into the textiles. For this reason, only optical fibers with sufficient robustness should be used and conventional textile fabrication processes as opted for the macrobending sensor are inadequate for the FBG integration. The optical fiber containing the FBG was thus stitched directly onto an elastic fabric[22]. The robustness of the sensor is guaranteed by an additional silicone coating and polymer attachment points on both sides of the FBG are glued around the fiber for a better adhesion of the sensor onto the fabric and easy stitching without impairing the sensor properties (Fig. 25, right).

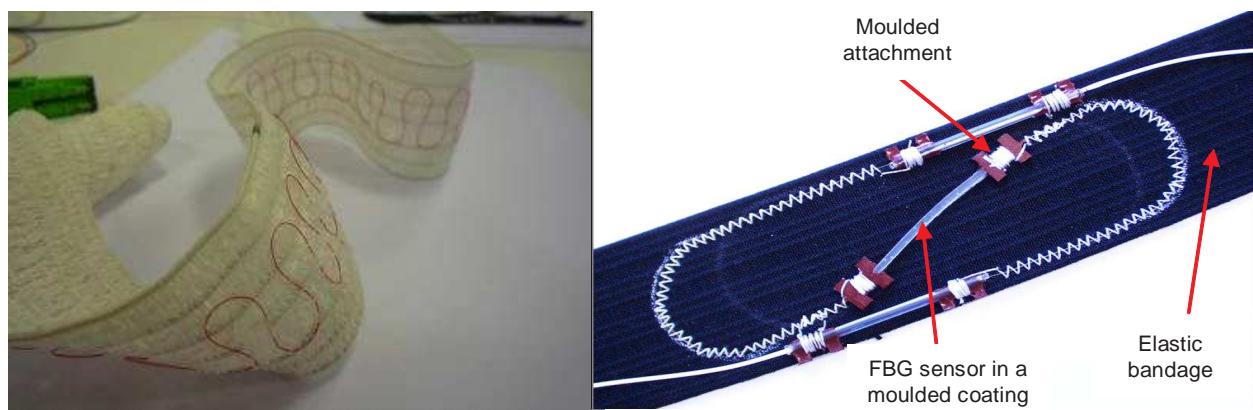


Figure 25. Left: Design of the macrobending sensor. A silica optical fiber was embedded into an elastic fabric during an industrial crochet fabrication process. Right: Design of the FBG sensor. A silica optical fiber containing an FBG was stitched onto an elastic textile.

The harness based on the macrobending and FBG sensor was validated on a simulator in MRI environment[22]. A simulator based on a movable table was used (Fig. 26, left). The displacement of the table was realized by a balloon connected to the medical respirator allowing air-flow circulation by controlling the amplitude and frequency of the movement through the volume or air injected. The signals of the respirator, the fiber sensor response and the gradient signals emitted by the MRI were measured in real-time. Several configurations in terms of volume and/or frequency, in or out of the MRI tube and in presence of or without the MRI gradient were simulated and tested. As a result, it was demonstrated that the displacement of the movable table is detected in terms of amplitude and frequency. The signals of the fiber sensors were not degraded even when the system was submitted to the gradient of the MRI equipment in and out of the magnetic field (inside and outside the MRI tube respectively), as shown in Fig. 26 (right, large picture). At the same time, a clinical validation of the system was carried out at a hospital of Lille, France on several healthy volunteers and patients of the hospital's intensive care unit. Fig 26 (right, small picture) shows the

typical signal patterns for both thoracic and abdominal movement detected by the textile-embedded FBG and macrobending sensor on healthy adults.



Figure 26. Left: Set-up of the MRI-compatible simulator of CIC-IT de Nancy, France. Right, large picture: Test of the FBG sensor in MRI environment. The first two curves are related to the respiration simulator, the third curve shows the FBG sensor response and the last three curves are related to the magnetic gradients of the MRI equipment. Right, small picture: Abdominal and thoracic respiration signals detected by the textile-embedded macrobending and FBG sensor during a clinical test on healthy volunteers.

3.3. Fiber optic sensors for personal protective equipment

The European project i-Protect (intelligent PPE system for personnel in high-risk and complex environments) develops an advanced personal protective equipment (PPE) system that will ensure active protection and information support for personnel operating in high-risk and complex environments in firefighting, chemical and mining rescue operations[23]. The PPE system will be ergonomically designed and fully adapted to end-users' needs as well as to working conditions. The core of the project is the development of advanced materials and sensors to be used for a multi-functional PPE. This includes a real-time monitoring of risk factors (temperature, gas, oxygen level), users' health status (body temperature, respiratory rate, heart rate) and important protection parameters (end-of-service-life, air pressure in compressed units). The PPE will be wireless connected to a rescue command center.

For the monitoring of the users' health status smart underwear containing fiber optic sensors is being developed. Special attention is paid to the development of a heart rate sensor to be used as a textile-integrated sensor in underwear. A first sensor prototype is based on macrobending effects in POF[23]. The POF macrobending sensor is stitched onto an elastic fabric (the design is similar to this shown in Fig. 25, left) and measures the small elongations of the textile which is caused by the heart movement. To increase the sensitivity of the sensor, the cladding of the POF was treated[23]. A sensor belt containing the POF sensor was tested on a healthy volunteer to measure the circumference changes due to the heart movement. The belt was wrapped around the chest of the volunteer close to the heart. Since the textile design is also sensitive to the respiratory movement, the POF macrobending sensor detects both the respiratory and heart rate at the same time (Fig. 27). A signal processing should be performed to filter the weak heart beats signals. It is expected that by using a

modified textile and sensor design it must be possible to improve the sensitivity of the POF macrobending sensor to the heart movement. Alternatively, conventional monitoring techniques like plethysmography could be adapted for the purpose of such applications.

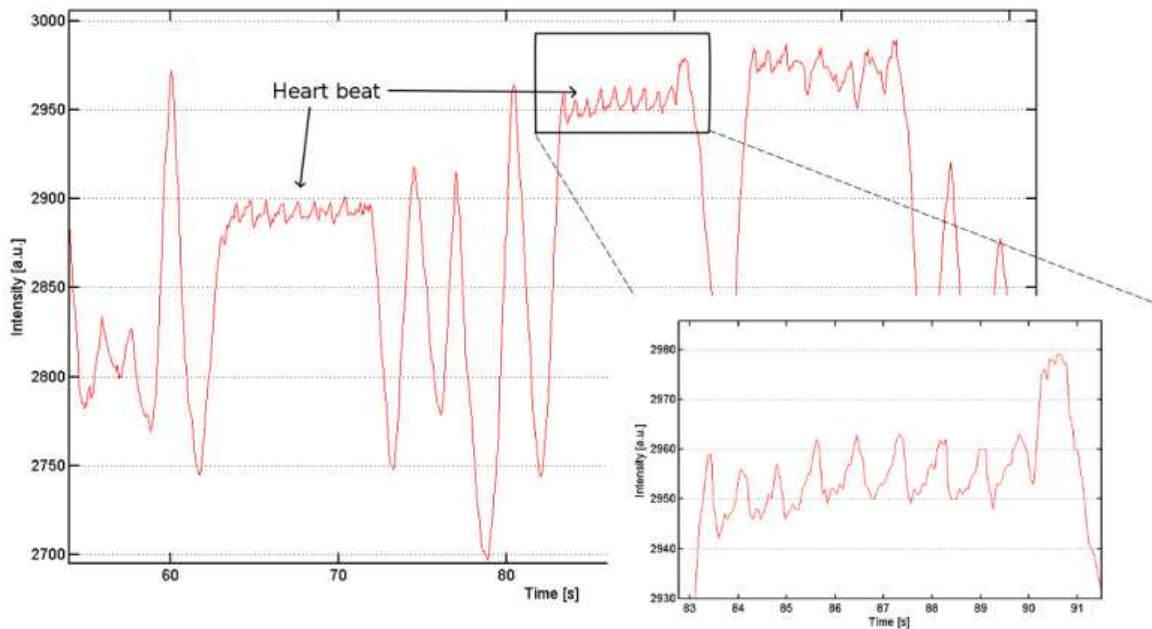


Figure 27. Monitoring of the heart rate of a healthy volunteer by using a textile-embedded POF macrobending sensor.

4. Conclusion

A number of research activities considering the development of novel smart technical textiles based on fiber optic sensors are running in Europe. Such smart technical textiles with embedded optical fibers are a potential new market niche for fiber optic sensors.

Several German projects and the European project POLYTECT have developed novel geotextiles with embedded distributed Brillouin and POF OTDR sensors for monitoring of geotechnical and masonry structures, providing an alarm signal in case of structural damage. Particularly sensors based on POF take advantage of the high robustness, high elasticity and high break-down strain of POF allowing distributed sensing of strong mechanical deformations of soil and masonry walls. Multifunctional, smart technical textiles incorporating fiber optics sensors are a cost-effective solution to increase the structural safety of such structures. The breakthroughs include the use of such textiles for reinforcement and at the same time for monitoring of earthworks and masonry walls, giving online information on the state and the performance of the structures and so preventing a total collapse. Such on-line and long-term monitoring systems will improve the chance

of an early detection and the location of “weak points” and damages, and will make it possible to react rapidly and to control damages.

Novel monitoring systems based on medical textiles with embedded fiber optic sensors will be used at medium-term in the healthcare monitoring and for personal protection of rescues in high-risk environments where standard, non-optical monitoring systems show significant limits. Such medical textiles containing fiber optic sensors have been developed in the European projects OFSETH and i-Protect for the monitoring of the respiratory movement of anaesthetized patients under MRI and for the monitoring of the health status of rescues. Especially for MRI applications where transportable and MRI compatible devices are needed, pure fiber optic sensor solutions and the wearability of the textiles are advantageous. The design and comfort of such sensor systems will extend their use from hospitalization to the ambulatory healthcare monitoring and homecare.

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