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Fibre optic sensors for the structural health monitoring of building structures

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Abstract

In this work different fibre optic sensors for the structural health monitoring of civil engineering structures are reported. A fibre optic crack sensor and two different fibre optic moisture sensors have been designed to detect the moisture ingress in concrete based building structures. Moreover, the degeneration of the mechanical properties of optical glass fibre sensors and hence their long-term stability and reliability due to the mechanical and chemical impact of the concrete environment is discussed as well as the advantage of applying a fibre optic sensor system for the structural health monitoring of sewerage tunnels is demonstrated.

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1. Introduction

Fibre optic sensors are well suited for the structural health monitoring (SHM) of civil engineering structures. In contrast to conventional measuring instruments, e.g. electrical sensors, fibre optic sensors are resistant to electromagnetic interference and are robust so that they can withstand harsh environments. Moreover, due to the low light attenuation of optical glass fibres they can be multiplexed and interrogated over several kilometres. In the past

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different fibre optic sensors have been developed in order to measure several physical and chemical parameters. For instance, different fibre optic strain and temperature sensors have been applied for the SHM of civil engineering structures such as dams [1], bridges [2] and sewerage tunnels [3].

In this work fibre optic sensors for the SHM of concrete based building structure are presented. Since the formation of cracks and the resulting moisture ingress is critical for concrete based civil engineering structures a fibre optic crack sensor and two different fibre optic moisture sensors are reported. Moreover, the degeneration of fibre optic sensors due the chemical and mechanical impact of the concrete environment is discussed. The advantage of a fibre optic SHM sensor system is demonstrated based on monitoring the structural health of a sewerage tunnel system.

2. Fibre optic moisture sensors

In order to detect the moisture ingress into building structures two different fibre optic humidity sensors have been developed. A swellable polymeric fibre optic sensor has been designed for the distributed moisture monitoring. This sensor allows in combination with an OTDR (optical time domain reflectometer) the spatial determination of the failure position and hence the position of the moisture ingress by measuring the attenuation. Furthermore, a single-point relative humidity (RH) fibre optic sensor based on a polyimide coated Fibre Bragg Grating (FBG) sensor has been created. Due to the wavelength encoded RH readings several polyimide coated FBG sensors can be easily multiplexed and interrogated simultaneously.

2.1. Distributed moisture sensing

A schematic of the fibre optic swellable polymeric sensor developed is shown in Fig. 1a [3]. The sensor consists of a polyvinyl alcohol hydrogel rod, an optical single-mode (SM) fibre, a device to cause micro bending of the fibre and a protective felt wick. The hydrogel swells in the present of water without dissolution and presses the SM optical fibre against the ‘micro bending’ device that causes an attenuation of the light transmitted through the optical fibre. The ‘micro bender’ device developed was realized by using a helically twisted thread, which covers both the polyvinyl alcohol hydrogel and the optical SM fibre. The hydrogel rod was fabricated from polyvinyl alcohol by dissolving polyvinyl alcohol granulate in deionized water with a subsequent freeze-thaw cycle polymerization and drying at room temperature for one week. Following this, the optical SM fibre SMF-28e+ from Corning was helically-twisted around the polyvinyl alcohol rod and tied to the polyvinyl alcohol rod by applying a helically-twisted thread. Finally, the whole sensor was covered by using a felt wick, which acts as a protective cover, as well as extending the water-exposure area of the polyvinyl alcohol rod. A picture of the fabricated fibre optic swellable polymeric sensor is illustrated in Fig. 1b.

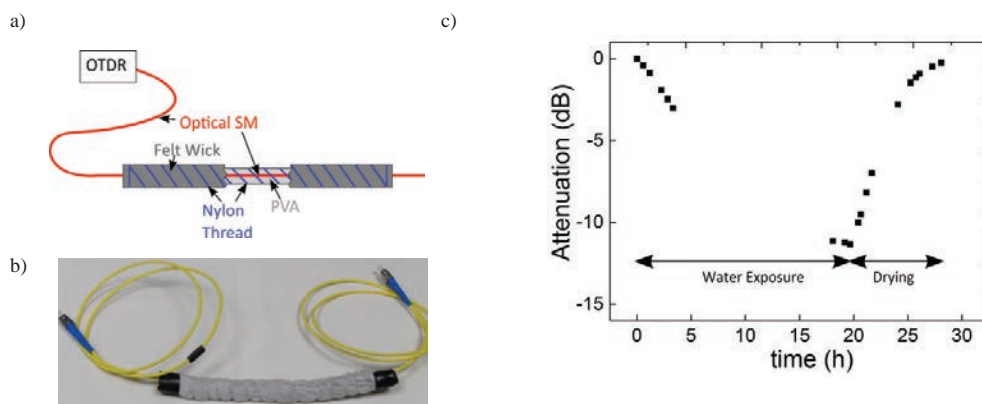


Fig. 1. Schematic (a) and picture (b) of the developed fibre optic swellable polymeric sensor for the distributed moisture monitoring. Response of the sensor when exposure to water and dried at room temperature (c).

At the beginning of the evaluation the light attenuation characteristic of the fibre optic swellable polymeric sensor without the use of the felt wick was characterised. For the experiments an 8 cm sensor element with a diameter of 8 mm and a thread winding pitch of 8 mm was immersed in water with subsequent drying at room temperature and the light attenuation as well as the response time was measured. The obtained result is displayed in Fig. 1c. The measured maximum attenuation when the sensor is immersed in water is sufficient to allow the detection of the moisture ingress in the concrete structures by using an OTDR system. Following this, the performance of the sensor with and without the felt wick cover was evaluated. The experiments are based on a 40 cm long sensor element with and without felt wick cover. In Table 1 the measured attenuation of the sensor elements after four days are summarized when water was dripped on the sensor elements. The sensor element with felt wick shows a much higher light attenuation. The reasons for the enhanced level of light attenuation and thus greater sensitivity of the sensor element with cover might be due to the water storage and the water transfer capabilities of the felt wick employed.

Table 1. Performance of the sensor with and without felt wick cover

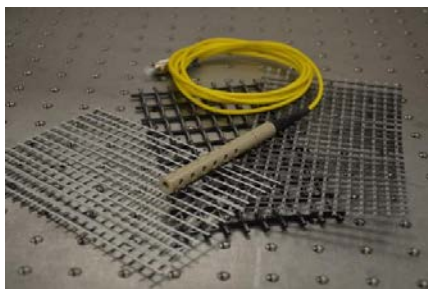
Sensor packaging	Attenuation after four days (dB)
No cover	2.3
Felt wick	34.0

2.2. Single-point humidity sensing

A detailed description of the single-point FBG based humidity sensor can be found in [3]. The polyimide coating of the FBG acts as a hygroscopic coating that swells in the presence of water vapor due to the adsorption of the water molecules. This effect causes strains on the FBG and the level of the strain experienced depends linearly on the applied RH. Consequently, the RH value can be easily obtained by tracing the reflected Bragg wavelength. Since the polyimide coated FBG is inherently sensitive to temperature as well a second bare FBG is multiplexed in series along the fibre in order to measure the ambient temperature and hence to compensate the temperature cross-sensitivity of the polyimide coated FBG.

The fibre optic single-point humidity sensor has been fabricated by inscribing two FBGs in a photosensitive optical glass fibre using a KrF excimer laser and the phase mask technique. Following this, one FBG was coated with polyimide by applying the dip coating technique. Furthermore, an appropriate sensor packaging has been designed in order to protect the fibre optic single-point humidity sensor from deleterious environmental effects. The sensor packaging is based on a perforated PEEK housing and a permeable PTFE membrane to protect the sensor against dirt and chemicals. The fabricated single-point fibre optic humidity sensor including the sensor packaging is shown in Fig. 2a. In Fig. 2b the shift of the Bragg wavelength of the polyimide coated FBG is illustrated for different RH values at room temperature. According to the measurement the sensor shows a linear response with a small hysteresis. The different RH values have been obtained by using the climate chamber (Mettler CTC256) and the sensor has been interrogated using a broadband light source (Opto-Link ASE), a 3dB coupler and a spectrometer (Ibsen I-Mon E).

a)



b)

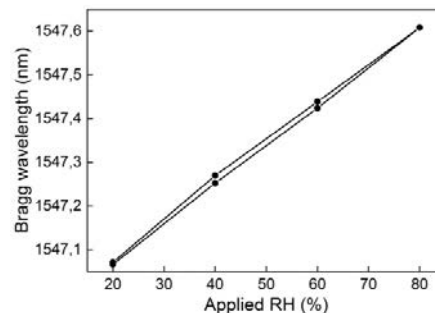


Fig. 2. Packaged single-point fibre optic humidity sensor based on a polyimide coated FBG and a bare FBG temperature reference sensor (a) und corresponding response to applied relative humidity (RH) level (b).

3. Fibre optic crack sensor

The developed fibre optic crack sensor is based on textile net structure with an integrated optical SM fibre. The textile net structure is designed to transfer elongation due to cracks of the concrete structures to the optical fibre. Since the failure stress of optical glass fibres is relative low the integrated optical fibre will break at relative small crack sizes and the position of the crack and hence the failure position of the concrete structure can be identified by using an OTDR. In addition to the sensing function the textile net structure can also be used for the reinforcement of the concrete elements.

For the integration of the optical fibres into the textile structures different techniques (stitching respective knitting) have been investigated. Here the aim was to identify an integration technique that introduces low bend losses into the optical SM fibre and that provides the best bonding. In terms of low bending losses the best result was obtained with the bend optimized optical SM fibre from Corning. In Fig. 3a the stitching of an optical fibre on the surface of a textile net structure is illustrated. After finishing the stitching process the whole textile based sensing structure was stabilized by applying a copolymer coating. A fabricated fibre optic crack sensor is shown in Fig. 3b.

The performance was evaluated by embedding the textile based fibre optic crack sensor into a concrete block with dimensions of 100 cm x 15 cm x 15 cm and cracking the fabricated concrete element after curing at a defined location by applying a load using the three point flexural test. By simultaneous monitoring the attenuation of the optical fibre and measuring the crack size the sensor performance was characterized. The fabrication of the concrete block with an embedded textile based fibre optic crack sensor is shown in Fig. 3c. For the experiment the textile based sensor was also used as reinforcement of the concrete block. The light attenuation of the optical fibre was measured during the experiment using the dB-meter from FiboTec. In Fig. 3d the measured attenuation of the textile based fibre optic crack sensor at different crack sizes are illustrated. At a crack size of 1.4 mm the optical fibre inside the textile net structure broke and indicated the failure of the concrete block.

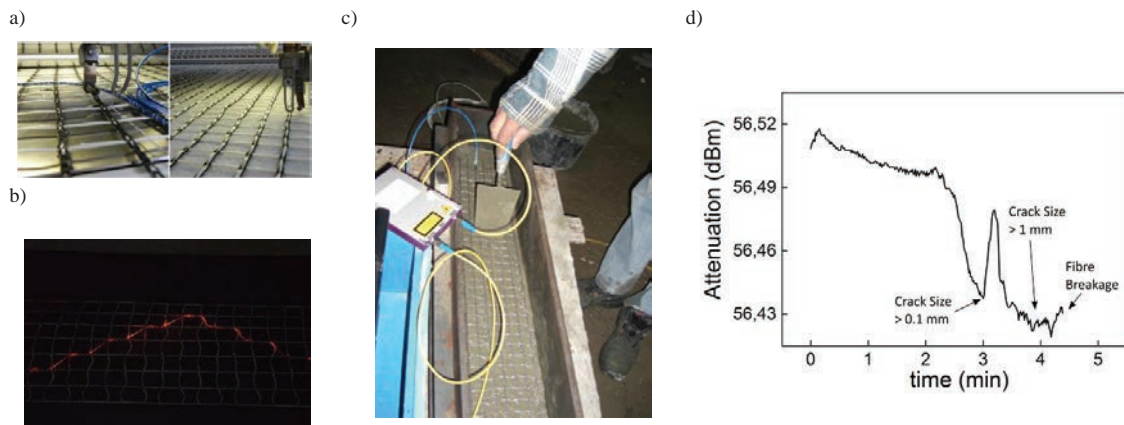


Fig. 3. Integration of a SM optical fibre in a textile net structure (a) and fabricated fibre optic crack sensor (b). Embedding sensor in a concrete block for evaluation (c) and measuring attenuation of the optical fibre depending on the crack size (d).

4. Long-term stability and reliability of fibre optic sensors in concrete environment

The long-term stability and reliability of fibre optic sensors in a concrete environment is critical since the chemical and mechanical impact of the concrete degenerates the mechanical properties of the optical glass fibre. In the past *Habel* [4] investigated the change of the mechanical properties and hence the long-term stability and reliability of optical glass fibre sensors due to the concrete influence. Usually hermetic fibre coatings are applied in order to allow flaws on the fibre surface to grow only to a subcritical amount and hence to keep the strength degeneration of the optical fibre to an acceptable minimum. Since common polymer based fibre coating are destroyed due to the harsh mechanical and chemical influence of the concrete environment they are not suited for the

SHM of concrete based building structures. According to the investigation from *Habel* in 2003 the best result in terms of SHM of concrete elements using fibre optic sensors was achieved by using a non-economic plasma-polymer coating.

Within a research project, which is part of the BMBF founded consortium “C³- Carbon Concrete Composite” [5], we are currently investigating optical fibres with carbon coatings for the long-term application in concrete environments. The C³-consortium has been awarded with the national German sustainability award in 2015. Optical fibres with carbon coating have been developed for fibre optic sensor application in the oil and gas industry. Primarily they have been designed in order to prevent the hydrogen bleaching of the germanium-doped fibre core. However, since the carbon coating is relatively resistant against the highly alkaline concrete pore water it provides the potential to enhance the long-term stability and reliability of the optical fibre sensor in concrete based SHM applications.

5. Application example: SHM of sewerage tunnels using fibre optic sensors

Sewerage tunnels can be damaged due to excessive loading caused by obstructions, corrosion, displacement, mechanical pressure or the penetration of plant roots, for example. The damage often causes flooding and landslides as well as the contamination of groundwater and ground soil and, consequently, the outcome of such events can be long-lasting and profound. Therefore, it is essential to provide improved SHM systems for sewerage tunnels in order to be able to predict such events before they occur and thus minimizing economic losses as a result.

The most common SHM technique of sewerage tunnels is a remote inspection using a video camera-based system. However, this technique only allows for an inspection of the tunnel at regular intervals, due to the complex nature of the inspection process as well as the necessity for cleaning of the tunnel beforehand, which is expensive and time-consuming. Therefore, due to the inherent advantages of fibre optic sensors as explained in the introduction they could provide a new approach towards the rapid and simple monitoring of the structural health of sewerage tunnel structures.

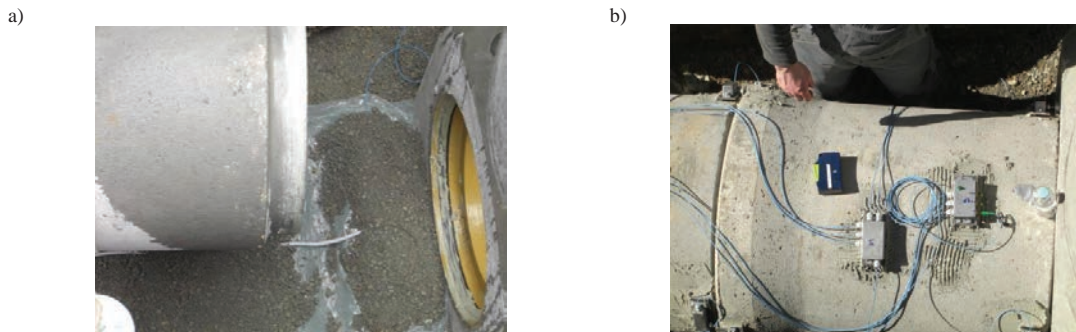


Fig. 4. Fibre optic sensor system for the SHM of sewerage tunnels. Installing fibre optic humidity sensors (a) and fibre optic tilt sensors and fibre optic splitters for sensor multiplexing on the top of the sewerage pipe (b).

During a renewal of a sewerage tunnel system in Meiningen, Germany, a fibre optic sensor system has been installed in order to monitor the structural health. The fibre optic SHM system for sewerage tunnels is based on fibre optic humidity and fibre optic tilt sensors. Both kinds of sensors are located at the interface between two sewerage pipes. At each interface two tilt sensors are applied to detect a tunnel misalignment and the humidity sensors are utilized to detect the resulting water outlet. The fibre optic humidity sensors have been fabricated in-house as described in chapter 2.2. The fibre optic tilt sensors are based on FBGs as well and were provided by AOS GmbH. Both, the fibre optic humidity and fibre optic tilt sensors were multiplexed in series using conventional fibre splitters and were interrogated using a wavelength-tuneable OTDR, which was provided by FiboTec. In Fig. 4a and 4b the positioning of the fibre optic humidity sensors and the installed fibre optic SHM system are illustrated. The splitters and the fibre optic tilt sensors have been clued on the top of the sewerage pipes, as shown in Fig. 4b. In Table 2 the measured RH and temperature values from both fibre optic humidity sensors at the sewerage pipe interfaces are summarized. The measured temperature values verify that both humidity sensors withstand the installing of the

sewerage tunnel and are operating properly. Furthermore, the results indicate that the sewerage tunnel is operating well. Currently, long-term measurements are performed.

Table 2. Measured RH and temperature values from both fibre optic humidity sensors after tunnel installation

Sensor:	Measured RH (%):	Measured Temperature (°C):
Sensor #1	35,73	10,56
Sensor #2	45,01	9,36

6. Summary

In order to detect the moisture ingress into concrete based civil engineering structures two different fibre optic humidity sensors and a fibre optic crack sensor have been developed. A swellable polymeric fibre optic sensor has been designed for the distributed moisture monitoring and is based basically on a polyvinyl alcohol hydrogel rod, an optical SM fibre and a micro bending device. This sensor allows in combination with an OTDR the spatial determination of the failure position and hence the determination of the moisture ingress location. Furthermore, a single-point fibre optic humidity sensor based on a polyimide coated FBG has been created. The sensor shows a linear response to applied RH values and due to the wavelength encoded RH readings several polyimide coated FBG sensors can be easily multiplexed and interrogated simultaneously. The developed fibre optic crack sensor is based on a textile net structure with an integrated optical SM fibre. The textile net structure is designed to transfer elongation due to cracks of the concrete structures to the optical glass fibre and hence to break the optical glass fibre at a certain crack size. The current embodiment of the fibre optic crack sensor detects cracks with a size of 1.4 mm. Also critical for fibre optic glass sensors that have been embedded in concrete based civil engineering structures is the chemical and mechanical impact of the concrete environment. Since fibre optic glass sensors with common polymeric coatings are not suited for this kind of application in a current research project the degeneration of fibre optic sensors with carbon coatings due to influence of the concrete environment is investigated.

Furthermore, the advantage of a fibre optic SHM sensor system is demonstrated based on monitoring the structural health of a sewerage tunnel. The sensor system consists on fibre optic humidity and fibre optic tilt sensors, which are located at the interface between two sewerage pipes. Currently, long-term measurements are performed. The current implementation of the fibre optic sewerage tunnel SHM system is only able to monitor the structural health at the interfaces between two sewerage pipes. Therefore, in future application also fibre optic sensors such as humidity and/or strain sensors will be applied along the pipes in order to provide a distributed sewerage tunnel SHM system. Since the fibre optic sensors are applied outside the sewerage tunnel, they are only capable to detect physical damages. However, in a future version of the sensor system with increased sensitivity and optimized sensor placement it might be possible to follow the evolution of cracks including micro-cracks to predict the onset of damage.

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