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Sewerage tunnel leakage detection using a fibre optic moisture-detecting sensor system

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ABSTRACT

The design and development of a new fibre optic sensor system for the optical detection of leakages in sewerage tunnels is reported. The system developed overcomes the disadvantages of the usually employed camera based inspection systems which are relatively complex and, in addition, require cleaning of the structures to be monitored beforehand. The sensor concept created combines a Fibre Bragg Grating (FBG)-based humidity sensor and a swellable polymeric fibre optic sensor. Both sensors are located along the sewerage tunnel so that they can response immediately to any leakages that may occur. The swellable polymeric fibre optic sensor shows a response of 34.2 dB in the presence of water, a performance which is superior to that seen form other swellable polymeric fibre optic sensors reported so far. Furthermore, the resistance of both sensors to highly alkaline environments (pH 13.4), an important feature of such sensors was verified. Consequently, when compared to the use of conventional inspection techniques, the novel fibre optic sensor system provides a robust, relatively low-cost and continuous monitoring system well suited to use in sewerage tunnels.

1. Introduction

Approximately 20% of the public owned and more than 40% of the privately owned sewerage tunnels in Germany are damaged [1] and similar problems are seen across the developed world, due to the age of current infrastructure. The reasons for experiencing damage to these structures are various and are due, for instance, to excessive loading caused by obstructions, or corrosion, displacement, mechanical pressure or the penetration of roots, all of which can damage sewerage tunnels. The effect of this is often to cause flooding and landslides as well as the contamination of groundwater and ground soil and, hence, the outcome of such events can be long-lasting and the effects profound. It is clear that, as a consequence, efforts to achieve a better form of structural health monitoring of sewerage tunnels are essential to be able to predict such events before they occur and take mitigating action at an early stage, minimizing economic losses as a result.

To date, no sensor system or inspection technique has been reported that detects leakages in sewerage tunnels rapidly and simple. The most common technique to monitor the structural health of sewerage tunnels is a remote inspection using a video camera-based system. However, this technique only allows for an assessment of the sewerage tunnel at regular intervals, due to the complex nature of the inspection process, as well as the necessity for the cleaning of the sewerage tunnel beforehand, which is expensive and time-consuming.

It has been observed that leakages in sewerage tunnels, which are based on linings using water-impermeable concrete, occur mostly at the interface between sewerage pipes, followed by leakages along the sewerage pipes due to the formation of cracks [2]. The cracks occur first at the bottom of the sewerage pipe and propagate from the inside surface to the outside due to mechanical pressure.[1] Therefore, a more efficient approach to the detection of leakage can be obtained from the observation of moisture along a sewerage tunnel, as well as at the interfaces between any two sewerage pipes.

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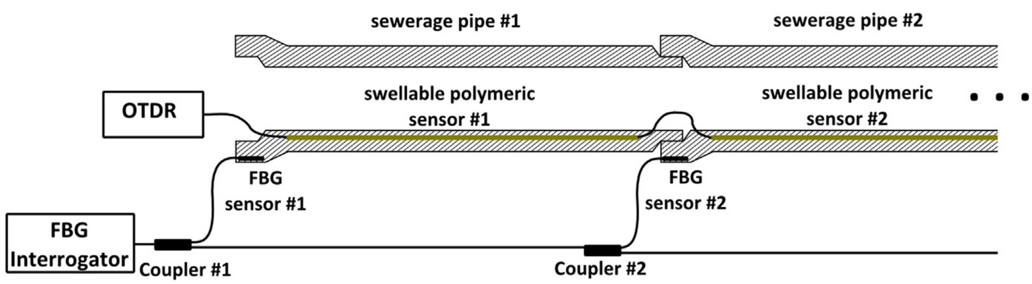

Fig. 1. Schematic of a fibre optic sensor system to detect leakages in sewerage tunnels. FBG-based humidity sensors are applied at the interface between two sewerage pipes. Fibre optic swellable polymeric sensors are applied to detect leakages along the sewerage tunnel.

Fibre optic sensors have the inherent advantage of being robust, electrically passive, easy to multiplex as well as the capability to be operated remotely. In the past, several different approaches to the design of fibre optic moisture sensors have been reported [3,4]. In terms of single-point fibre optic sensors a considerable level of research has been performed on the development and evaluation of fibre optic humidity sensors based on Fibre Bragg Gratings (FBGs) [e.g. 5,6] under a range of different conditions. In this approach, a hygroscopic coating such as using polyimide is applied to the FBG that swells in the presence of moisture, the result of which is an axial and radial strain in the fibre and, thus, to the FBG and this can readily be detected. Compared to the use of Long-Period Gratings (LPG) [7], and evanescent field [8]-based humidity sensors, FBG-based humidity sensors have the advantage of a linear response to humidity and they are easy to multiplex. In terms of distributed moisture sensing, a fibre optic based swellable polymeric system has been reported in previous work [9]. Such a fibre optic swellable polymer sensor consists essentially of a water-swellable hydrogel, which attenuates the light propagating in an optical fibre in the presence of water. Different approaches have been reported for the design of such fibre optic swellable polymeric systems of this type. For instance, a hydrogel coated central rod [9,10] or a hydrogel only [11,12] have been configured with an optical fibre by, for example creating a helically twisted thread with a winding pitch of several millimetres. The helically twisted thread acts to create microbends in the fibre so that, in the presence of water, the hydrogel swells and causes an attenuation of the light within the optical fibre. In this case the fibre optic swellable polymeric system, in combination with Optical Time-Domain Reflectometry (OTDR), can be used to locate any water leakages which may be distributed over a distance of several hundred metres [10].

The work reported in this paper focuses on the design and development of a detection system based on a suite of fibre optic sensors to detect and identify leakages in sewerage tunnels, with a fast response time. The main objectives of the work have been the identification and evaluation of damage events to sewerage tunnels using an optimized design of appropriate fibre optic sensors developed in this work.

2. Leakage detection of sewerage tunnels using fibre optic moisture sensors

A schematic of the novel fibre optic-based sewerage leakage detection sensor system is illustrated in Fig. 1. FBG humidity sensors are expected to be placed at each joint in order to detect leakages at the interfaces between sewerage pipes. As FBG-based humidity sensors are only single-point sensors, a fibre optic-based swellable polymeric sensor is used additionally, in order to detect leakages along the sewerage tunnel. Furthermore, in order to simplify the installation and use of the sensor system, both types of fibre optic sensors are integrated in each pipe of the sewerage tunnel. However, this requires that the moisture transport properties in concrete needs to be considered carefully as well.

If a concrete element is exposed to water unidirectionally, the unsaturated water flow is initially described by a combination of permeation and capillary suction [13]. Above capillary suction or if a concrete element is exposed to water vapour only, the moisture transport mechanism is characterized by diffusion caused by a partial water vapour pressure gradient. The development of moisture build-up in the concrete pores due to the diffusion of water molecules can be specified as due to adsorption of water molecules against the pore-walls for low relative humidity (RH) and as arising from capillary condensation on the water menisci formed in the pores by the adsorbed water molecule layers for high RH [13]. The dependence of the moisture content on the RH is known as the sorption isotherm. In the past, RH has been measured inside concrete in order to determine the moisture level [14]. While the measured RH is not a direct measure of the moisture content, it still can be correlated to deleterious effects such as shrinkage, thermal strain and diffusivity of the concrete sample [15].

According to the moisture transport properties in concrete, an appropriate location of both fibre optic moisture sensors is important for the proper detection of leakage. As shown in Fig. 1, the FBG-based humidity sensor should optimally be located at the bottom of each sewerage pipe interface in order to measure the ingress of moisture due to permeation and capillary suction of the ambient water caused by a leakage. By contrast, the swellable polymeric fibre optic sensor should be located near the inner surface of the sewerage pipe. However, determining this distance from the inner surface is critical where the distance has to be higher than the maximum capillary suction height of the applied concrete so that the swellable polymeric fibre optic sensor is only exposed to water in the case of a crack.

3. Design of the fibre optic-based moisture sensors used in this work

3.1. FBG based humidity sensor

A detailed description of the operation and packaging of the FBG based humidity sensor can be found elsewhere [16]. The FBG based humidity sensor employed consists of a bare and a polyimide (PI)-coated FBG, with both FBGs multiplexed in series along the fibre. The PI acts as a hygroscopic coating that swells in the presence of water vapour due to the adsorption of the water molecules and, hence, this effect causes strains on the FBG. The level of the strain experienced depends linearly on the applied RH and, thus, the ambient RH value can be easily determined by monitoring the shifts in the characteristic Bragg wavelength and comparing against a prior calibration using known values of RH. In order to measure accurately the value of the RH, the temperature cross-sensitivity of the PI coated FBG has to be compensated. Therefore temperature