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Online monitoring of wire breaks in prestressed concrete cylinder pipe utilising fibre Bragg grating sensors

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ABSTRACT

With steel prestressing wires tensioned around core, Prestressed Concrete Cylinder Pipe (PCCP) is a high-strength composite pipe designed for large-diameter water propagation and distribution. However, some PCCPs may fail after a certain time of service due to corrosion and deterioration. Real-time health monitoring of wire breaks is essential to assess the condition and avoid catastrophic failures of PCCPs. In this paper, a novel approach based on Fibre Bragg Grating (FBG) sensing technology, is presented to monitor and locate wire breaks in PCCP lines. FBG vibration sensors are utilised to capture the signals of wire break activities in the pipeline and obtain their locations. The online monitoring system and localization principle of wire break activities are described. Preliminary experiments were carried out on PCCPs with an inner diameter of 2 m, which were filled with pressurized water. Experimental results indicate that the wire break activity can be detected and located effectively by FBG sensors. The detection error of wire break locations is analysed. With unique features, the proposed non-destructive method is expected to be used for the online monitoring of wire break activities in long term for the condition assessment and performance prediction of PCCP lines.

1. Introduction

Prestressed Concrete Cylinder Pipe (PCCP) has been extensively adopted for large-diameter water propagation since its introduction during World War II, due to its large capacity, cost-effective price and good strength to withstand high internal pressure and external loading [1,2]. For example, almost 4000 km of mainly 4 m inner diameter PCCPs, has been laid in the Great Man Made River (GMMR) project in Libya for the water transportation from aquifers deep in Sahara desert to coastal regions [3,4]. The total length of PCCP lines used to convey pressurized drinking water or wastewater in North America, exceeds 35,000 km and many of them are already more than 50 years old [5]. In addition, PCCP is increasingly being employed in the South-to-North Water Diversion Project (SNWDP) in China in recent years [6].

Unfortunately, as infrastructure ages and deteriorates during a long service life (at least 50 years), catastrophic failures of PCCP may occur, due to its high internal pressure, large diameter and sudden rupture, which would cause serious damages to nearby people's lives and property [7]. Therefore, considering PCCP's strategic importance, high replacement cost and consequence of failure, continuous and effective condition monitoring and assessment approaches are critical to the risk analysis and maintenance of PCCP lines to prevent catastrophic failures, especially for the PCCPs which are typically buried and out of sight [8,9].

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Although a variety of factors can significantly affect PCCP's integrity and lead to failures, increasing number of wire breaks, which are caused by corrosion, hydrogen embrittlement, high internal pressures or overloading, are considered as the main cause of failures in PCCPs [10,11]. The strength of a damaged PCCP is not only related to the number but also to the locations of broken wires along the length direction of pipeline. Once a critical number of prestressing wire break failures occur in a PCCP, the concrete core may collapse and the steel cylinder may burst. In recent years, the industry has been focusing on inspection and monitoring of wire breaks for the condition assessment of PCCP lines in service, and considerable related research has been conducted in this field [12,13].

Several technologies, like electromagnetic inspection and acoustic monitoring, have been developed to obtain the condition information of prestressing wire breaks in PCCP lines, either directly or indirectly. For example, Remote Field Eddy Current/Transformer Coupling (RFEC/TC) and Polar ware (P-wave) inspections are currently two commercially available electromagnetic methods [14,15]. Although the electromagnetic inspection device could detect the number and locations of break wires existing in the pipeline, it takes an excessive amount of time and usually requires the pipeline to be drained. Using hydrophone and piezoelectric sensors, acoustic monitoring involves continuously monitoring the acoustic activity in a in-service pipeline to detect wire failures as they occur in real time, and provides the location and rate of wire failure activity [16]. However, hydrophones and piezoelectric sensors still have certain limitations that sometimes make it infeasible in actual practice [17,18].

A significant advance has been made in acoustic monitoring technology for PCCP lines through the application of fibre optic sensors [17]. Acoustic Fibre Optic (AFO) monitoring system was installed to monitor wire break activities in the PCCP lines which were in service [8,19]. Monitoring methods based on fibre optic sensors, have a major advantage over conventional non-destructive techniques in that they are capable of remotely distributed condition monitoring [20,21]. As one kind of the most popular fibre optic sensing technologies, Fibre Bragg Grating (FBG) has been extensively studied and applied for the real-time health monitoring, diagnostics and control in civil structures over the past decades [22–25].

FBG possesses unique advantages, including small size, immunity to electromagnetic fields, remote sensing, and large multiplexing capabilities [26,27]. Besides, FBG sensors are encoded by wavelength which is an absolute parameter, making the signal of FBGs immune to power fluctuations along the optical path. With light weight and small physical dimension, FBG is suitable to be embedded into, or attached to a structure.

When a wire break occurs in PCCP lines, the sudden strain energy release from the steel prestressing wire generates pressure waves that transmit into the pipeline filled with pressurized water. FBG vibration sensors installed in PCCP lines could be utilised to detect these pressure waves and capture the information of wire break activities in real time. In this study, based on FBG sensing technology, a new approach to monitor and locate the wire break activity in PCCP lines is proposed. The online monitoring system and localization principle of wire breaks are introduced. Propagation speed measurement of pressure wave and wire break detection experiments, were conducted in two PCCPs (inner diameter of 2 m) filled with pressurized water. Experimental data is analysed and experimental error is discussed. Preliminary experimental results indicate that the presented method is capable of detecting and locating wire beak activities. The monitoring information of wire breaks is useful for the condition assessment and estimation of deterioration rate for PCCP lines, and eventually contributes to the prediction of residual useful life, leading to timely actionable decisions.

2. Online monitoring system

To find a comprehensive maintenance approach and prevent undesirable and costly failures, online condition monitoring of in-service PCCP lines, has assumed a significant role in assessing their integrity and safety.

2.1. Prestressed Concrete Cylinder Pipe (PCCP)

As a kind of large-diameter and high-strength composite pipe, PCCP mainly consists of a mortar coating, steel prestressing wires, a thin steel cylinder, a concrete core, a bell ring, external and internal joint mortars, a spigot ring and rubber seals [28]. Fig. 1 shows the cross section of an Embedded Cylinder Pipe (ECP), which is one typical type of PCCPs [29]. The concrete core is the main structural load-bearing component in PCCPs. The steel prestressing wires produce a uniform compressive pressure in the concrete core to increase its strength and make it strong enough to resist the high internal water pressure. The mortar coating protects the prestressing wires form external physical damage and corrosion. The bell ring, spigot ring, rubber seals, and joint mortars (external and internal) are used for the convenient installation of two adjacent PCCPs. Most PCCP lines are designed as main lines to reach a minimum service life of 50 years.

2.2. FBG quasi-distributed sensing

Fibre Bragg Grating (FBG) is a special filter which is written by exposing a single mode optic fibre to a periodic pattern of ultraviolet light. When a beam of broadband light transmits in the optic fibre with an FBG in, a particular narrow band light would be reflected back by the FBG. The peak wavelength of the reflected light called Bragg wavelength, is defined as [22,30]:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where λ_B, n_{eff} and Λ are the initial central wavelength of an FBG, the effective refractive index of the core material, and the grating period, respectively. The wavelength shift of an FBG is simultaneously to strain and temperature change. Encoded by optical wavelengths, FBG sensors are independent of light levels, connectors, and fibre losses.

Multiple FBG sensors can be multiplexed by multiplexing technologies, including Wavelength Division