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Deterioration of cracks in onshore wind turbine foundations

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ABSTRACT

Cracks can occur in reinforced-concrete onshore wind turbine foundations due to factors such as the use of substandard concrete mix, mistakes in foundation design or multi-stage concrete pouring under challenging weather conditions. Cracks are routinely identified via above ground inspections and follow-on examination of excavated underground surfaces and are repaired, for example with resin injection and grouting. Their impact on the structure or the efficacy of the repair are often unknown as crack degradation during normal operating conditions is unexplored. In this work, sub-surface cracks in an onshore wind turbine foundation have been instrumented with fibre-optic based strain sensors in an attempt to determine severity and magnitude of deterioration over time. Here we determine cracks monitored show a small magnitude of deterioration over the initial 9-month period after sensor installation, suggesting that repair is not required. We propose a novel methodology for the classification of the types of deterioration evident in cracks as “reactive”, “permanent” and “behavioural”, and demonstrate methods to extract these types of deterioration. Such methods will continually be developed over time as further knowledge of crack behaviour is gained to determine appropriate limits and identify the optimal time to repair.

1. Introduction

Onshore wind turbines are becoming a focus of structural health monitoring (SHM), due to their hugely increasing role in renewable energy generation. As of 2017, onshore wind energy makes up 22.5% of the world’s renewable capacity [1,2]. Extending the life of these assets, or even ensuring they reach their design life is vital for the continued investment and maximisation of environmental benefits. To date, mostly the mechanical moving systems (gearbox, generator) are instrumented, likely due to the higher failure rate [3,4]. Other implementations focus on dynamical strain behaviour in the tower or blades, analysing the fatigue damage [5,6]. Support structures (usually gravity-based, reinforced concrete foundations) are the least monitored part of an onshore wind turbine despite being safety critical structures. Cracking of the concrete is of primary concern, as water ingress can cause corrosion to the steel reinforcement. This warrants the monitoring of any cracks in onshore wind turbine foundations to ensure an irreversible state is not reached.

Cracks appear in other reinforced concrete structures, however, SHM sensor systems are not always applied post-damage. Generally, SHM involves monitoring structural loading using sensor systems such as accelerometers or strain gauges. These structures exist in urban, public or transport infrastructure [7–9], the oil and gas industry [10] and aerospace [11]. Sensors have replaced the conventional manual inspection for SHM as they provide benefits such as: measurement of sub-surface damage [12], potentially less expensive long term cost and continual uninterrupted accurate measurements. One such application for SHM sensor systems is damage detection [13–15]. Cracks in concrete are usually repaired immediately without further severity analysis. There is also the possibility that cracks reappear over the repaired section, as these locations are usually of weakest structural integrity or highest loading. This can cause increased costs in the long term.

All of the aforementioned SHM systems focus on monitoring characteristics such as structural strains, vibrations, wind speed, temperature, displacements and crack initiation; damage degradation is not always the primary concern. Monitoring damage degradation could provide a more informative description of the structure’s health and ensure damage is fixed at the optimal time, avoiding the unrequired long term costs of repairing damage of low severity.

The main concern with foundation cracking is that a more extensive network of wide cracks can increase the likelihood of corrosive and detrimental agents such as moisture, chlorides and sulphates penetrating concrete and reaching steel. Not all cracks will affect a structures integrity, however it is this corresponding likelihood that

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increases the overall risk. Thorough assessment may be required prior to sensor installation to determine if cracks are appropriate to measure, which may include evidence from manual inspection that cracks show opening over time. Combining this - damage progression monitoring to onshore wind turbine support structures may provide a more effective way to monitor the health of onshore wind turbine foundations. One example of this has been carried out on an onshore wind turbine embedded can foundation design by Currie et al. [16]. The damage witnessed was at the can-foundation interface, and is therefore specific to this foundation design.

In this work, the objective is to monitor cracks witnessed on the face of an onshore wind turbine gravity foundation to investigate the rate of degradation. Optical sensors known as fibre Bragg gratings (FBGs) were utilized in this study due to the range of advantages they possess. These include: immunity to electromagnetic interference, multiplexing ability, small size, robustness, and long-life capability [17–19]. Ko et al. [8] replaced the electrical accelerometers in a bridge load monitoring system with FBGs due to these benefits [20]. Some FBG systems have also been implemented to detect the onset of damage in structures [13], where sensors were placed along points of highest loading, allowing eventual damage initiation to be detected. Sensor installation and verification is reported in [21]. In the following, cracks are analysed for deterioration over the initial 9 months of monitoring. Although loading will be directly related to turbine operation, such a system could be adopted for any type of concrete structure exhibiting cracks.

This paper is structured as follows: Section 2 provides an overview of the sensor design, installation and description of the strain extraction equations. Section 3 provides a brief description of the wind turbine loading model (explained in detail in [21]) and extrapolation of the tower strains to crack displacements. Section 4 outlines the results found over the initial 9-month period, defining the types of deterioration and methods to extract them. A discussion is then presented in Section 5 including an outline of the planned future work. Finally, a conclusion is provided in Section 6.

2. Sensors

2.1. Fibre Bragg gratings

FBGs have been used to measure a variety of physical quantities including strain, displacement, temperature, pressure, and current [22,23]. Ultra violet light of modulating intensity is used to create a periodic alteration of the refractive index in an optical fibre, establishing the Bragg grating. Broadband light incident on said FBG incites a narrow band reflection centered around the Bragg wavelength peak, λ_b, measured and saved using an interrogator system (Fig. 1). This peak wavelength is shifted for a bonded FBG by temperature change, ΔT, and any applied linear strain, ϵ_z, shown in Eq. (1):

$$\frac{\Delta\lambda_b}{\lambda_b} = K_T\Delta T + K_\epsilon\,\epsilon_z \tag{1}$$

here K_T and K_ϵ are the temperature and strain sensitivities of the FBG respectively. An unboned FBG temperature sensor ($K_\epsilon = 0$), multiplexed to and in thermal contact with the strain FBG, is used to perform compensation. The FBG temperature sensor design is described in [24]. Using this, we can extract the temperature compensated linear strain, ϵ_z, applied to the bonded FBG.

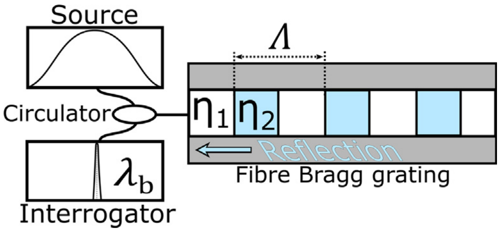

Fig. 1. FBG operation: broadband source guided through FBG causes reflection of a narrow band of wavelengths, the peak of which is centered around Bragg wavelength λ_b. The value of λ_b is dependent on the modulation between refractive indices η_1 and η_2, and grating period Λ.

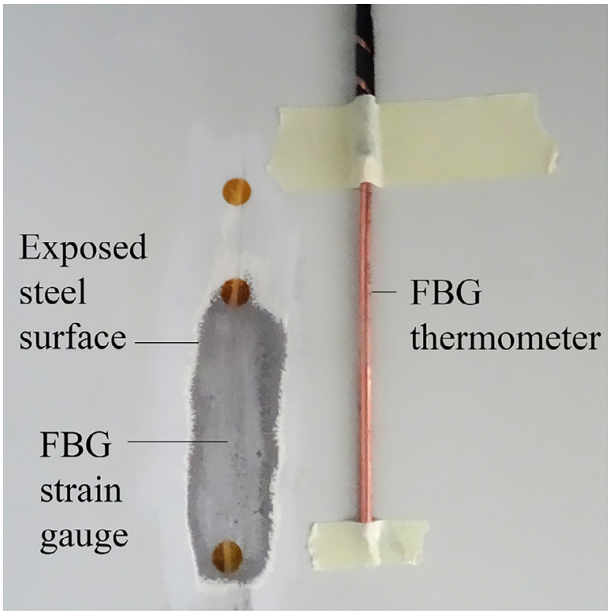

Fig. 2. Tower Module: strain FBG is epoxied to tower wall, with temperature FBG isolated [21].

2.2. Tower modules

Tower sensor modules consisted of one bonded FBG and one unbonded FBG thermometer, as shown in Fig. 2. A total of four of these modules were installed within the tower, 50 cm above ground level. Locations were chosen relative to the known prevailing wind direction, to allow monitoring of the overturning moment strains. An octagonal gravity-based slab foundation is illustrated in Fig. 3, labelled with sensor locations and direction of prevailing wind.

2.3. Foundation modules

The locations of the unique cracks monitored in this study are shown in Fig. 3. Foundations of this type, with multiple-stage concrete pouring are prone to crack initiation between plinth-rib interface. Over time, due to issues with steel reinforcement design combined with continuous dynamic loading, these cracks can develop and widen. In this case, the cracks have propagated to the face of the plinth (as illustrated in Fig. 3). Previous excavation campaigns carried out by the turbine operator have provided evidence that these cracks do open over time. The current method for repair is grout-injection, which involves using pressurised or jet equipment to fill the void with grout in order to strengthen the section or reduce ingress. From supervisory control and data acquisition (SCADA) data, the mean wind speed during the monitoring period considered in this work is ≈ 5.67 ms^{-1}, suggesting conditions at this site are temperate.

One particular face crack monitored is shown in Fig. 4. Plinth and face cracks prior to sensor installation are shown in Fig. 5. Monitoring crack widening is imperative, as width is directly related to penetration depth [25], and water or chloride reaching steel can cause corrosion. Monitoring cracks over the long-term, notifying if specific limits are reached, will allow understanding of the foundations health and allow maintenance to take place at optimal times.

Monitored cracks were chosen based on a number of factors, the