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Structural health monitoring of grouted connections for offshore wind turbines by means of acoustic emission: An experimental study

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ABSTRACT

Grouted connections for offshore wind turbines are formed by attaching overlapping steel piles with an ultra-high strength cementitious grout. The structural performance of grouted connections is critical for the substructures in order to exhibit sufficient resistance to environmental loads. The long-term integrity of the grout core can be compromised due to the complex stress states present, leading to unexpected slippage and gaps in the steel-grout interface, grout cracking and water ingress. This paper presents the results of an experimental investigation on damage evolution and failure mechanisms occurring within grouted connections in laboratory-based bending tests using acoustic emission. A parametric analysis of the detected acoustic emission signals has been conducted. The acoustic emission activity has been correlated with load-displacement measurements and the observed specimen failure modes. For the tested grouted connections, the number of acoustic emission hits and the signal duration were employed to identify damage evolution during load application. Root mean square and the ratio of rise time to amplitude were found to be useful Key Performance Indicators (KPIs) for damage prognosis. Finally, an improved b-value analysis has been performed, and the computed drops were well-associated with grout cracking within the connection.

1. Introduction

Grouted connections (GCs) are commonly employed in fixed-bottom offshore wind turbine (OWT) substructures such as monopiles, jackets or tripods. They are formed by filling the annuli between concentric overlapping tubular steel piles – the monopile and the transition piece (TP), with an ultra-high performance cementitious (UHPC) grout. GCs are often referred as pile-to-sleeve connections due to their arrangement and are constructed to accommodate the transition from the foundation pile to the tower. Their structural performance is critical to the substructure, contributing significantly to the ability of the structure to withstand environmental loads arising from wind, waves and sea currents.

In 2009, monopile inspections revealed TP settlements and the overall performance of GCs was called in question [1]. Inspections of monopiles around Europe revealed TPs sliding by several millimetres [2,3] requiring costly mitigation measures [4]. Other typical defects that were reported, included grout cracking and gaps at the top of the GC [5]. To address these issues, extensive maintenance activities were required offshore; operators applied ad hoc solutions on a case by case basis, including the installation of internal brackets to prevent further TP sliding [5]. However, accessibility to OWT locations is affected by weather conditions and maintenance tasks require complete shutdown of the generator [6,7], leading to significant expenditure.

Nowadays, minimising unnecessary maintenance expenditure due to high costs and also enhancing the reliability of OWT substructures are some of the main challenges for the offshore wind sector [8,9]. In order to address these challenges, a transition to condition and/or predictive-based maintenance is necessary, compared to corrective and preventive strategies, which are commonly employed. Condition-based maintenance is based on the detection, identification and monitoring of damage evolution with time. Therefore, the operators can schedule maintenance

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Abbreviations

AE	Acoustic Emission
CSS	Cumulative Signal Strength
GCs	Grouted Connections
KPIs	Key Performance Indicators
NDT	Non-Destructive Testing
OWT	Offshore Wind Turbine
PAC	Physical Acoustics Corporation
RMS	Root Mean Square
SHM	Structural Health Monitoring
TP	Transition Piece
UHPC	Ultra High Performance Cementitious

activities more effectively reducing the operation and maintenance costs for OWTs by a significant margin [10–14]. However, condition-based maintenance is yet to be employed at a satisfactory level leading to higher cost for wind power generation. Considering the aforementioned and the lack of expert knowledge and experience on the long-term behaviour of UHPC grouts the need for effective monitoring tools for GCs is evident. For this purpose, structural health monitoring (SHM) is in the forefront for damage detection and evaluation, aiming to aid decision making by diagnosing the structural state of the element under examination, improving the reliability of OWT substructures [8].

The first application of Non-Destructive Testing (NDT) on GCs is presented in Ref. [4]. The authors extracted grout cores from in-service offshore monopile connections. A combination of ultrasonic pulse velocity and X-rays was employed to evaluate the condition of the samples based on their location across the length of the GC, showing promising results. Häckell et al. [15] presented a global approach using vibration-based monitoring of a GC while, a pilot study on the applicability of electromechanical impedance spectroscopy for defect detection was presented in Ref. [16]. Driven by the reported failures, an ultrasonic-based inspection method which was verified with experiments on small-scale steel-grout-steel samples and field trials is presented in [5]. Despite the limited number of research studies focusing on GCs, promising results have been reported, encouraging the use of SHM approaches for inspection and monitoring, to prevent future failures and reduce operational and maintenance expenditure.

Taking into consideration the offshore conditions and the type of loads exerted on an OWT, it is of great importance to be able to monitor the GC continuously. Acoustic Emission (AE) is an alternative NDT method with unexplored potential, which can be used remotely for real time monitoring [17]. AE is a passive technique which is employed to detect elastic energy changes caused by external motives [18]. Events such as cracking or debonding release energy waves [8], making AE a potential candidate for monitoring a GC. Some of the advantages of AE include ease of application, high-resolution tracking of cracking events and real time monitoring capabilities. Nonetheless, post-processing can be a tedious task due to lack of a unified approach and data analysis being dependent on acquisition systems. The use of AE for damage detection has already been employed for monitoring OWT blades [19]. In addition, it has been used in a variety of civil engineering applications to capture crack growth or degradation of brittle material. Specifically, for structures where cement-based material is present, AE focuses on damage quantification, source localisation and identification. Examples of such research works can be found in the literature (see, e.g., Refs. [20–23].

This paper presents the results of a laboratory-based experimental campaign on the feasibility of AE for damage detection and condition evaluation on GCs. The analysis of the acquired AE data is performed by means of waveform parameters utilizing statistical tools to investigate the implementation of such approaches in SHM systems for OWTs. Several AE signal features are examined as Key Performance Indicators (KPIs) for damage assessment within a GC and crack detection. Section 2 introduces the experimental campaign and Section 3 presents the test results. In Section 4 the KPIs for damage evolution are presented and discussed while Section 5 focuses on crack detection. Finally, the conclusions from this study are given in Section 6.

2. Experimental testing

The following sections summarise the key specifics of the laboratory-based experiments carried out at the structural laboratories of the University of Birmingham, UK. A detailed description of the experimental procedures that were followed is given in Ref. [24].

2.1. Geometry of specimens

Two identical cylindrically-shaped GCs (GC-1, GC-2) were designed and tested in bending under monotonic and fatigue loads. Within the scope of this paper, only the ultimate strength tests are considered for benchmarking purposes, aiming to identify KPIs for damage monitoring and crack detection within the grout core. The pile and sleeve were fabricated from S275 steel grade and circumferential square-profiled shear keys were fillet-welded across the length of the grouted region in overlapping positions, resulting in a total of four shear key pairs. The connection was achieved by pressure pumping an UHPC grout – Ducorit® S5R [25], in the annuli between the overlapping tubulars. The dimensions of the parts forming each GC are given in Table 1. The total span of the tested specimens was approximately 4.5 m with a total overhang of 200 mm.

Both specimens were grouted in a vertical arrangement depicting realistic grouting conditions and were left to cure in an upright position for three days. Subsequently, the specimens were supported horizontally until the test day. In order to overcome space constraints during curing, the specimens were prepared at different dates. The compressive strength of the grout was determined for each specimen from cubic samples as per BS EN 12390-3:2009 [26] on the day of testing. The average compressive strength of both specimens on the day of testing was 125.4 MPa.

2.2. Test set-up and loading protocol

The specimens were tested in a 4-point bending configuration as illustrated in Fig. 1. The load was applied to the specimens via a hydraulic jack and a load cell was used to record it. The hydraulic machine was load-controlled, and a spreader beam was used to distribute the load to the specimen on two semi-circular external flanges. It should be noted that the selected loading scheme is not entirely representative of the loads on GCs, however bending moments are the dominant effects in an offshore environment for

Table 1
Dimensions of GC specimens.

Notation (Units)	Pile	Sleeve	Grout
Length, L (mm)	2550	2550	610
Diameter (mm)	406	473.8	450.8
Thickness (mm)	8	11.1	22.4