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Modelling fatigue degradation of the compressive zone of concrete in onshore wind turbine foundations

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HIGHLIGHTS

- The fatigue behaviour of the onshore wind turbine foundations was investigated.
- The cyclic loads on the foundation produced a change in the stress distribution.
- The fatigue behaviour of foundations was affected by concrete compressive strength.
- The fatigue behaviour of foundations was influenced by the size of embedded ring.

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ABSTRACT

Embedded rings are widely used in onshore wind turbine foundations to resist uplift and compressive forces at the interface of steel towers and concrete foundations. These embedded rings are subjected to high-cycle fatigue loading due to the high ratio of the live load to dead load in such structures. The properties of concrete in the anchorage zone of the embedded ring change with time and its strength deteriorates under the effects of the cyclic loads. Therefore, research has been initiated to investigate the local deterioration of foundations and its effect on the whole structure. This paper presents a numerical study on the fatigue behaviour of the concrete foundation of onshore wind turbines. A constitutive model was developed for the onshore turbine foundation at the section level for fatigue loading. The model in the initial state was verified against strain data from nonlinear finite element simulations with regard to the strain distribution characteristics in the cross section. The fatigue theoretical model provided a realistic description of concrete foundation fatigue processes and their redistribution characteristics. A parametric study was performed to investigate the effects of different parameters that would influence the fatigue life of the foundation. The results of this study may help explain the fatigue behaviour of foundations under repeated loads and thus lead to a more accurate depiction of the actual long-term behaviour of foundations.

1. Introduction

Embedded rings are widely used in onshore wind turbine foundations to resist uplift and compressive forces at the interface of steel towers and concrete foundations. The concrete in the anchorage zone of the embedded rings is subjected to high-cycle fatigue loading due to the wind-induced fatigue loadings under normal turbine operating conditions. The ratio of the live load to dead load in wind turbine foundations is much higher than that in traditional building structures. Moreover, the significant increases in the blade span and tower height give rises to larger amplitude of loads exerted on foundations, causing concrete in foundations to operate at higher stresses. The concrete in the compressive zone of foundations may experience high cycling resulting in fatigue accumulation. The wind turbine is designed to operate for 20 years and the life time of foundations should be greater for economic reasons. Therefore, the design of wind turbine foundations should fulfil long-term life-cycle design. It is important to acknowledge the fatigue of concrete in the compressive zone and its effect on the overall performance of the structure.

Steel ring anchors are designed to resist both compressive and uplift forces. The capacity is determined by the bearing of concrete above or below the bottom flange and the shear resistance of the failure surface on both sides of the bottom flange. The bearing pressure is variable around the circumference of the embedded

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ring as a result of wind direction and the position of the rotor. Concrete located on both sides of the bottom flange is prone to crack resulting from several mechanisms including shrinkage and repeated loading. When the load is removed, the residual concrete cracks cannot fully close, leading to a reduction in shear resistance capacity. Thus, the shear resistance of the failure surface can be neglected conservatively. It is assumed that the uplift capacity is the sum of the bearing capacity of concrete in the compressive zone above or beneath the bottom flange. Wind turbine foundations lack redundancy and are therefore sensitive to changes in the properties of local concrete in the anchorage zone.

Several forms of damage are observed in existing foundations worldwide every year. The literature reveals particular interest in fatigue damage in foundations caused by the connection of the embedded ring. A study of wind turbines with damage in foundations located in Germany and Denmark reported that core samples through the height of the foundation showed visible fatigue cracks below the bottom flange of the embedded ring [1]. The large vertical movement of towers has been noted in a number of turbines in several sites in the UK with some turbines showing failure early in their operational life and others taking longer to develop symptoms [2]. In China, a significant number of wind turbine towers have exhibited large differential movement in Guangxi Province [3], Fujian Province [4], Shandong Province [5], and Yunnan Province [6]. Long-term cyclic loading has been shown to cause the crushing of concrete in the anchorage zone of the inserted ring, resulting in reduced rotational stiffness and, in return, a decrease in the bearing capacity of the foundation. These findings indicate that current fatigue calculation methods are insufficient in capturing the real long-term behaviours of wind turbine foundations.

Recent studies reporting numerical and experimental analyses of onshore wind turbine foundations have focused on the static behavioural characteristics of foundations. Zhou [7] developed a finite model to study the stress-strain field of foundations under different turbine operating modes. A damage plasticity model was used for the stress and strain relations in the concrete. The anchorage zone of the embedded ring was considered to be the most critical part of foundations. The local pressure around the bottom flange was low under normal operating conditions and was high under extreme loading conditions. Kong [8] conducted pull-out tests on a small portion of a wind turbine foundation to investigate the bonding stress distribution between the embedded ring and concrete. However, in real foundation, the embedded ring de-bonded from the concrete owing to the shrinkage of the concrete at an early stage or vibration of the tower during operation. Currie [9] proposed a wireless structural integrity monitoring system to monitor the stability of turbines experiencing excessive vertical movement. LVDT sensors were installed on the surface of the foundation to measure displacement patterns and subsequently provide alerts of any significant movements of the embedded ring. The literature provides only a general description but lacks specific analysis of the long-term behaviour of foundations. The effect of fatigue damage on the structural behaviour of the integrated response of wind turbine towers has not been sufficiently investigated.

The basic method of evaluating structural fatigue behaviour involves S-N curves, plots of stress range S against the number of cycles to fatigue N [10]. Different S-N curves, which are provided in current design codes (i.e. DNV-OS-J101, Fib Model Code 2010, GL 2010), differ from code to code [11]. They only apply to fatigue life estimation of a single concrete element subjected to a constant-amplitude stress level. However, regarding onshore wind turbine foundations, the stress and strain distributions vary along the circumference of the bottom flange of the embedded ring. Implementing design method of S-N curves, which ignores radial and circumferential stress gradients, would result in conservative results in fatigue assessments of wind turbine foundations. Moreover, information on strain is not included in S-N curves, and therefore the evolution of strain and stress of foundations over the lifetime of the structures cannot be obtained.

The fatigue behaviour of concrete is reflected by the increase of plastic strain and the reduction of modulus. Experimental tests for compressive fatigue have been performed by Okamoto [12], Tanigawa and Uchida [13], Lam [14], Imran and Pantazopoulou [15], Bahn and Hsu [16], and Osorio [17]. More recently, particularly during the 1990s and 2000s, several material models for the fatigue failure of concrete in compression were developed which could be implemented in FE analysis. Models have been proposed by, for example, Papa and Taliercio [18], Alliche [19], Krӓzig and pӧlling [20], Maejawa and EI-Kashif [21], and Mai and Le-Corre [22]. Such degradation processes must be evaluated at the structure level using a tangent stiffness matrix as the source of damage information [23]. Most of the models are difficult to use to solve real structural problems owing to the considerable computational effort required by these large models. Thus, simplified methods are required in the design and assessment of wind turbine foundations.

The aim of this study was to develop, validate and utilize an analytical tool for predicting the structural response of wind turbine foundations in the long term. Both a finite element model and a fatigue theoretical model were implemented, and the results for the initial state were compared. The fatigue algorithm was extended to predict the evolution of fatigue damage and the residual strength of the foundation at the section level. The objectives of the numerical analysis were to:

(1) Simulate the pressure distribution in the anchorage zone along the circumference of the bottom flange of the embedded ring under a significant moment using the finite element model and the fatigue theoretical model. Comparisons of the stress distributions yielded by the two methods show good agreement, and therefore, the assumption of the strain profile used in fatigue analysis was verified.
(2) Simulate the long-term behaviour of the foundation during degradation at the section level with the fatigue theoretical model. The algorithm was used to simulate the stress profile and trace the evolution of material parameters under fatigue loading.
(3) Evaluate the effect of various parameters on the fatigue behaviours of the wind turbine foundation based on the fatigue theoretical model.

2. Fatigue theoretical model

The consequent degradation of a foundation leads to a decrease in local stiffness and strength. This study attempted to reproduce the damage evolution in the contact areas between the bottom flange of the embedded ring and the concrete foundation. For this reason, a nonlinear fatigue algorithm is indispensable for this type of modelling. The semi-empirical fatigue algorithm proposed in this paper is an application of that proposed by Zanuy et al. [24]. To model the degradation of a foundation in two-dimensional space, the change in the normal strain at the section level in the foundation is consistent with the assumption for a plane section. This model focuses on variable amplitude cycles for different small segments of a cross section in the foundation resulting from constant amplitude eccentric cyclic loads.

2.1. Failure criterion based on deformation

In several investigations, a strong relation between the development of strain in a static test and that in a fatigue test has been