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Uncertainty Modeling and Fatigue Reliability Assessment of Concrete Gravity Based Foundation for Offshore Wind Turbines

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ABSTRACT

Evaluation of the fatigue limit state (FLS) for offshore wind turbine foundations is normally based on deterministic design approaches, where partial safety factors are used to account for load and resistance uncertainties. In this paper, the propagation of uncertainties related to structural, environmental and fatigue damage model parameters is evaluated by performing Monte Carlo fatigue simulations of a reference Gravity Based Foundation (GBF) supporting a 5 MW offshore wind turbine. A linear model for concrete fatigue damage is formulated based on the S-N approach, and fatigue structural reliability is evaluated using the FORM technique. Results indicate that the uncertainty related to wind turbulence intensity has the highest influence on fatigue loads during power production. Adopting a probabilistic damage model for concrete also increases the fatigue damage standard deviation by 60% and 85% for structures in water and in air, respectively. In addition, the assumption on Miner's rule uncertainty has a large influence on the structural reliability. A reduction of this uncertainty from Δ_{COV}=0.40 to Δ_{COV}=0.30 could increase the annual reliability index by 22%.

KEY WORDS: uncertainty; reliability; probabilistic design; fatigue; Monte Carlo; gravity based foundation; offshore wind energy.

INTRODUCTION

In the detailed design of offshore wind turbine (OWT) foundations, the structure has to be evaluated for fatigue to ensure that the structure withstands environmental loads throughout its intended design life (typically 25 years). Current design standards are based on deterministic approaches, where partial safety factors are used to account for uncertainties in loads and resistance models. This approach, however, can either be over conservative or unsafe. It has been shown that target reliability level for OWTs can be lowered compared to other fixed offshore structures due to lower risks and consequences related to failure (Marquez-Dominguez & Sørensen, 2012). Moreover, uncertainties related to environmental inputs, which affect reliability assessments, are site-specific. To achieve more robust and cost-effective solutions, relevant sources of uncertainties have to be accounted for when performing reliability analyses and calibration of safety factors.

Several studies have been made on uncertainty analysis and its effect on structural reliability. Karadeniz (2001) demonstrated a procedure for modeling uncertainties in spectral fatigue analysis of offshore structures. The study focused on inherent uncertainties in modeling the structure, environmental loads and fatigue damage phenomenon. For OWTs, Toft et al. (2016) investigated the effects of uncertainties related to wind climate parameters on fatigue loads of onshore wind turbines, and concluded that these contribute to about 10-30% of total uncertainty in the structural analysis. Uncertainties due to wind resource variability was also investigated by Murcia et al. (2017), focusing on fatigue assessment of wind turbine components using polynomial surrogates. The effects of uncertainties in soil properties on dynamic response and reliability of monopile foundations has also been previously investigated (Carswell, Arwade, DeGroot, & Lackner, 2015; Damgaard, Andersen, Ibsen, Toft, & Sørensen, 2015). For OWT foundations, the relevant uncertainties has been outlined by Negro et al. (2014), which includes, among others, uncertainties related to selection of load combinations, soil properties, and wave load models. These uncertainties can have a huge effect on fatigue reliability assessment, as demonstrated by Muskulus & Schafhirt (2015) on design optimization of monopiles and jacket foundations. A study on fatigue reliability of a reinforced concrete foundation supporting an onshore wind turbine suggests that uncertainties in the material S-N curve are also important for reliability assessment, and that current design rules still result to higher reliabilities than what is required for wind turbines (Marquez-Dominguez & Sørensen, 2013). Reliability assessments serve as bases for calibration of fatigue safety factors for wind turbine components, tower and foundation, as demonstrated in several studies (Marquez-Dominguez & Sørensen, 2012; Veldkamp, 2008).

This study focuses on uncertainty modeling and reliability assessment of fatigue damage accumulation on a reinforced concrete GBF. Stochastic input parameters related to structural properties, soil properties, environmental wind and wave loads, and probabilistic concrete fatigue damage based on S-N approach are considered. The