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Uncertainty Modeling and Fatigue Reliability Assessment of Offshore Wind Turbine Concrete Structures

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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 concrete foundation for offshore wind turbines. Concrete fatigue damage models are formulated based on the S-N approach, where the resistance model uncertainty is calibrated against experimental fatigue tests. Results indicate that the resistance model uncertainty governs the concrete FLS assessment. This underlines the importance of improving estimates of model uncertainty by conducting experimental fatigue tests at lower stress cycle amplitudes and at different mean stress levels.

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 argued 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 and 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 of onshore and offshore wind turbines. Toft et al. (2016a) 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 the total uncertainty in structural reliability analyses. Uncertainties due to wind resource variability were also investigated by Murcia et al. (2018), 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 been previously investigated (Carswell et al., 2015; Damgaard et al., 2015). For OWT foundations, the relevant uncertainties have been outlined by Negro et al. (2014) and Velarde et al. (2019), 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 and 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 result in higher reliabilities than what is required for wind turbines (Marquez-Dominguez and Sørensen, 2013).

This study focuses on uncertainty modeling and reliability assessment of fatigue damage accumulation with focus on a reinforced concrete gravity-based foundation (GBF), and demonstrates the potential of using Monte Carlo-based linear regression models (Sin et al., 2009) for uncertainty and reliability analysis. Stochastic input parameters related to structural properties, soil properties, environmental wind and wave loads, and stochastic concrete fatigue damage based on the S-N approach are considered. The results provide insights on the sensitivity of fatigue loads to various input parameters, and evaluates the structural reliability with respect to concrete fatigue failure. The results of this study are relevant for reliability-based design and for calibration of safety factors for OWT concrete structures.

ASSESSMENT OF UNCERTAINTIES

In probabilistic design of structures, the load and resistance are modeled by stochastic variables to account for the uncertainties. These uncertainties are generally classified into two subgroups: (1) aleatoric uncertainties which are related to physical random processes, such as variability in soil properties, material strength, and metocean conditions; and (2) epistemic uncertainties which are related to uncertainties associated with models, measurements and statistics (due to a limited number of observations). The latter can be reduced by improving the models, by increasing the measurement accuracy, and by increasing the number of data samples (Sørensen and Toft, 2010). In fatigue design and assessment of OWT structures, both types of uncertainties have to be considered. Table 1 summarizes the sources of uncertainties considered in this study, which are uncertainties related to structural inputs,

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