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Fatigue Crack Detection for Lifetime Extension of Monopile-based Offshore Wind Turbines

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Abstract

Lifetime extension becomes increasingly crucial for industry, since the first offshore wind farms face the end of their design lifetime. The remaining useful lifetime of offshore foundations is driven by fatigue design and loading; both are affected by uncertainty. This paper presents a conditional probability model to link results from inspections with numerical simulations of fatigue cracks. Crack sizes are simulated with a fracture mechanics model applying Paris' Law. The probability of detection of an existing crack depends on inspection technique and crack size. Results show that uncertainty about remaining useful lifetime significantly reduces after considering inspection outcomes. This decreases risks for the decision-making on lifetime extension of offshore wind turbines.

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Keywords: offshore wind energy; lifetime extension; remaining useful lifetime; fatigue crack propagation; crack detection; probability of detection; conditional probability; Bayesian analysis

1. Introduction

The operating life of offshore wind turbines (OWT) is limited to at least 20 years [1]. In the upcoming years the first wind farms reach the end of their planned service time. Lifetime extension of OWT is an option to save on investment and planning of new wind farms [2]. It would not only reduce costs and economize resources, but would also keep the environmental balance [2]. To address the question whether lifetime extension is feasible, the structural integrity of all wind turbine components must be assessed [3]. The remaining useful lifetime (RUL) of offshore wind support structures is driven by fatigue design and loading of the turbine [4,5]. Uncertainties in environmental, structural and operational conditions demand probabilistic assessment of fatigue cracks in the support structure. Fatigue crack

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growth is highly sensitive to input parameter variations, like initial crack size [4]. Crack propagation can be analyzed by means of a fracture mechanics model applying Paris' Law [4].

To the knowledge of the authors, public information about lifetime extension in the industrial sector of OWTs is rare, although some scientific publications are available. Kallehave et al. [14] point out that monopiles can be eligible for a longer lifetime based on measurements of first natural frequencies. Reassessment of the fatigue lifetime was performed for monopile substructure of OWTs in [15]. Ziegler [16] suggests an approach on 'structural reassessment, predictions on RUL, and a decision model' focusing on offshore monopile-based structures.

DNV GL [1] recently released a standard for lifetime extension of wind turbines and a related specification on certification [6]. This standard recommends 'a twofold assessment' for lifetime extension. The 'analytical part' can be realized either by deterministic approaches (simplified or detailed) or stochastic methods. The 'practical part' includes a detailed inspection scope. To assess whether lifetime extension of OWTs is feasible, each structure has to be inspected individually.

Underwater inspection of OWT foundations with a focus on fatigue crack growth is discussed in [7]. This guideline presents 'the use of probabilistic methods for inspection planning of fatigue cracks in jacket structures, semisubmersibles and floating production vessels' [7]. May et al. [8] point out health and safety risks which stem from underwater inspection in Health and Safety Executive (HSE) books. Risks as well as costs are qualitatively stated by May et al. [8] and Bussières et al. [9]. The American Society of Non-destructive Testing (ASNT) [10] and the Non-destructive Testing (NDT) Education Research Centre [11] provide an overview about further feasible inspection techniques for fatigue crack detection at offshore structures. Specified recommendations for crack inspection of monopile-based offshore structures are neither included in the report by DNV GL [7] nor by others [8,10,11]. However, analogies to monopiles are assumed in this study, since monopiles show similarities to other offshore structures.

DNV GL gives recommendations on the probability of detection (PoD) of a fatigue crack for the most common non-destructive inspection techniques [7]. PoD depends on inspection technique and crack size and is afflicted with large uncertainties. To reduce uncertainties Moan [12] presents a theoretical approach for stochastic analyses. This method is based on a conditional probability analysis applying Bayes' Theorem. Crack size distributions from simulations are updated using detection outcomes from inspections and their PoD. Lotsberg et al. [13] shows updated crack size distributions after inspections for jacket structures in the oil and gas industry by means of conditional probability models.

The novelty of this study is to update simulated crack size distributions at monopile-based OWTs with detection results from underwater inspection. The used method follows the strategy recommended by Moan [12]. This approach implements conditional probability analysis by means of Bayes' Theorem. Thus, this study investigates whether crack inspections lower uncertainties in RUL predictions for OWTs. The paper is structured in the following way. Section 2 introduces the stochastic fatigue crack growth model. In Section 3 the conditional probability model applying Bayes' Theorem is presented. Predictions of crack size and RUL considering detection results are discussed in Section 4. A brief conclusion is provided in Section 5.

Nomenclature

a	crack size = crack depth	N	number of cycles
a_0	initial crack size	n	time
a_{fail}	failure crack size	P	probability
a_n	crack size after n years	PoD	probability of detection
b	distribution parameter	S	stress range
B	number of bins	$\bar{S}_k$	mean value in stress range k
C	crack growth parameter	X_0	distribution parameter
K_j	stress intensity factor	Y	geometry parameter
m	material constant	z	event of detection