International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 22, No. 3, September 2012, pp. 234–241

http://www.isope.org/publications

Reliability-Based Calibration of Fatigue Safety Factors for Offshore Wind Turbines

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This paper describes reliability-based investigations on the required safety factors—Fatigue Design Factors (FDF) values—to be used for fatigue design of steel substructures for offshore wind turbines. Design and limit state equations are formulated and stochastic models for the uncertain strength and load parameters are described. Further, the effect of possible inspections during the design lifetime is investigated. The results indicate that for fatigue critical details where the fatigue load is dominated by wind load, FDF values equal to 2.5 are required. If the wave load is dominant, slightly larger FDF values are required.

INTRODUCTION

The support structure for offshore wind turbines contributes a substantial part of the total cost of an offshore wind farm. In order to increase the competitiveness of offshore wind energy, it is therefore important to minimize the cost of energy considering the whole life cycle. In this paper, reliability-based calibration of partial safety factors to be used for fatigue design of steel support structures is considered. Safety factors used for the design of oil and gas support structures are generally calibrated to a reliability level larger than that required for offshore wind turbines. In this paper, safety factors are calibrated to a minimum reliability level both without and with inspections during the design lifetime.

Design equations are formulated to be used for deterministic, code-based design, and corresponding limit state equations to be used for reliability assessment. In the limit state equations, uncertain parameters are modeled as stochastic variables. In the design equations, safety factors for fatigue strength and load or equivalently Fatigue Design Factors (FDF) are used to secure the required reliability level. The deterministic, nominal fatigue design life is obtained as FDF multiplied to the service life, usually 20 to 25 years.

Since design and limit state equations are equivalent, a detailed model of the fatigue damage is generally not needed for a reliability-based assessment of fatigue safety factors. It is only important to model the uncertain parameters carefully. Three fatigue load cases are considered: 1) wave load dominant; 2) wind load dominant for a single wind turbine; 3) wind load dominant for a wind turbine in a wind farm. Stochastic models for assessment of the fatigue reliability are formulated for these 3 cases. SN-curves and Miner's rule with linear damage accumulation are used as recommended in most relevant standards, e.g. IEC 61400-1 (2005) and ISO 19902 (2007).

Required FDF values are shown in Table 1 for fatigue design in various standards: ISO 19902 (2007) and NORSOK (1998) for fixed offshore steel structures for oil and gas platforms, GL Guideline for the certification of offshore wind turbines (2005), DnV design of offshore wind turbine structures (2011), and EN 1993-1-9 (2005) Eurocode 3: Design of Steel Structures - Part 1-9: Fatigue. The FDF values shown for GL, DNV and EN 1993-1-9 are determined using a linear SN-curve with a slope equal to 3; the corresponding FDF values obtained using a slope equal to 5 are shown inside ( ). The FDF values are specified for critical and noncritical details and for details that can or cannot be inspected.

Failure Critical Detail	Inspections	ISO 19902	GL/DNV	EN 1993-1-9
Yes	No	10	2.0 (3.0)	2.5 (4.5)
Yes	Yes	5	1.5 (2.0)	1.5 (2.0)
No	No	5	1.5 (2.0)	1.5 (2.0)
No	Yes	2	1.0 (1.0)	1.0 (1.0)

Table 1 Fatigue Design Factors (FDF) required

For manned offshore steel-jacket structures for oil and gas production, typically a maximum annual probability of failure in the 10^{-5}–$5 \cdot 10^{-5}$ range is accepted, and for unmanned structures a maximum annual probability of failure in the 10^{-4}–$2 \cdot 10^{-4}$ range is accepted, e.g. ISO 19902 (2007) and OS-J101 (DnV 2011).

Reliability models are formulated for the cases with wind load only, mainly based on Sørensen et al. (2008). Next, reliability models are formulated for the case with wave load only, and finally fatigue design factors and corresponding partial safety factors are calibrated to reliability levels appropriate for offshore wind turbines. Linear and bilinear SN-curves and the consequences of fatigue failure of a fatigue critical detail are considered.

Initially, safety factors are calibrated assuming no inspections of the critical details. Next, reliability-based methods are presented as basis for assessing the influence of inspections on the required FDF values. In order to model the influence of inspections, a fracture mechanics model is calibrated to the same reliability level as the SN-curve approach. Finally, the resulting reduced FDF values in case of inspections are presented for different inspection qualities.

Received October 26, 2011; revised manuscript received by the editors March 19, 2012. The original version (prior to the final revised manuscript) was presented at the 21st International Offshore and Polar Engineering Conference (ISOPE-2011), Maui, Hawaii, June 19–24, 2011.

KEY WORDS: Offshore wind turbines, fatigue, steel support structures, reliability, inspections.