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Link to publication from Aalborg University

13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2016, 20-22 January 2016, Trondheim, Norway

Reliability Analysis of Fatigue Fracture of Wind Turbine Drivetrain Components

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Abstract

One of the main challenges for the wind turbine industry currently, is to reduce the cost of levelized energy, especially for offshore wind. Failures in the wind turbine drivetrain generally result in the second largest down times of the wind turbine, hence significantly increasing the cost of operation and maintenance. The manufacturing of casted drivetrain components, like the main shaft of the wind turbine, commonly result in many smaller defects through the volume of the component with sizes that depend on the manufacturing method. This paper considers the effect of the initial defect present in the volume of the casted ductile iron main shaft, on the reliability of the component. The probabilistic reliability analysis conducted is based on fracture mechanics models. Additionally, the utilization of the probabilistic reliability for operation and maintenance planning and quality control is discussed.

Keywords: wind turbine; drivetrain; proabilistic reliability analysis; fracture mechanics.

1. Introduction

   The constantly increasing energy demand together with environmental consciousness, poses new challenges to develop economically competitive and highly capable renewable energy devices. The use of offshore wind turbines is widely regarded as one of the most favorable solutions to the aforementioned challenges.

   However, offshore wind turbines located in deep waters are exposed to harsh environmental conditions including extreme winds, temperatures, waves and lightning storms. These severe conditions significantly increase the cost of

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offshore wind project erection, operation and maintenance (O&M) and reduces the reliability of the wind turbine. Therefore, the levelized cost of energy (LCOE) of electricity produced by offshore wind turbines is relatively high according to the research performed in [1]. Furthermore, experience shows that the offshore O&M may contribute up to 30% of the COE [2].

The cost of offshore O&M increases due to the dependency on the weather condition, vessel availability in addition to the energy losses due to the down time of the turbine. Eventual failures in the wind turbine drivetrain module may typically result in around 25% of the total down time [3]. Larger energy losses are observed only from the failure in the power module, however drivetrain failures are usually more expensive to repair due to crane costs.

This paper addresses the influence of the defects, usually present at the cast iron components, on the reliability of the wind turbine and the utilization of developed methods for O&M planning and quality control. The wind turbine main shaft, in this paper, is regarded as the component of interest. Hence, the crack propagation models are developed with the assumption that the pre-existing defects are located in the main shaft and consequently subjected to lifetime loading history of the component.

Crack propagation models were developed using two fracture mechanics methods, namely the Paris and Walker laws [4,5]. The main difference between the aforementioned models being that the Walker laws takes into account the influence of the mean stresses, which are known to be important when using the more simple SN-curve approach for design. Thus, the influence of the mean stress on the fatigue fractures is investigated in the following analysis. The crack propagation models are used as a basis for the probabilistic reliability analysis. The probabilistic approach is chosen due to the fact that mechanical drivetrain components designed by a code based, deterministic approach is generally unable to account for the random variabilities inherently present in the design variables. A probabilistic model of uncertainties associated with the considered crack propagation models is developed and applied to estimate the probability of failure, in both ultimate and fatigue limit states. The reliability analysis is conducted by the use of first order reliability method (FORM). The general methods and techniques utilized for risk and reliability assessment are presented in the following sources [6,7,8]. It is further noted that a probabilistic approach linked with fracture mechanics models for crack development can be used as basis for reliability- and risk-based planning of inspections and maintenance.

1.1. Wind turbine drivetrain

The low speed rotations of the turbine's hub are transformed into electrical energy, by the use of the wind turbine drivetrain. Generally, wind turbine drivetrain module is mounted onto the bedplate of the wind turbine nacelle and contains the following components: main bearings, main shaft, gearbox, brake, and generator [9]. The wind turbine drivetrain with the aforementioned configuration can be seen in Fig. 1.
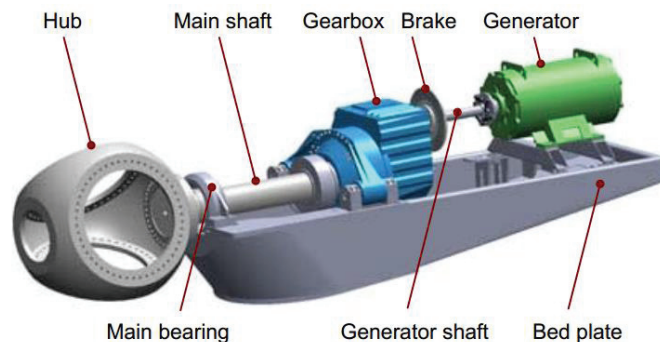

Fig. 1. General wind turbine drivetrain configuration [9].

The drivetrain module components are subjected to highly dynamic and random cycling loading through its lifetime, hence failures in both ultimate and fatigue limit states are relevant for their design.

2. Statistical analysis of the defect data

The wind turbine main shaft, due to quite complex geometry is usually manufactured by casting. Nodular cast iron EN-GJS-400-18-LT is considered is this research, as a representative general material used by the wind turbine manufacturers for main shaft casting. Two iron casting methods are analyzed in this paper, namely sand and chill casting. Representative information about the defects are obtained from scans, see [10]. Due to the nature of the tests performed in [10], for the purpose of this paper it is assumed that every discontinuity in the ferritic matrix including nodules, porosity and shrinkages are referred to as defects. Additionally, it is assumed that the defect distribution is representative in size and can be used as the basis for initial cracks. The defects seen in general cross-sections for both casting methods are illustrated in Fig. 2.
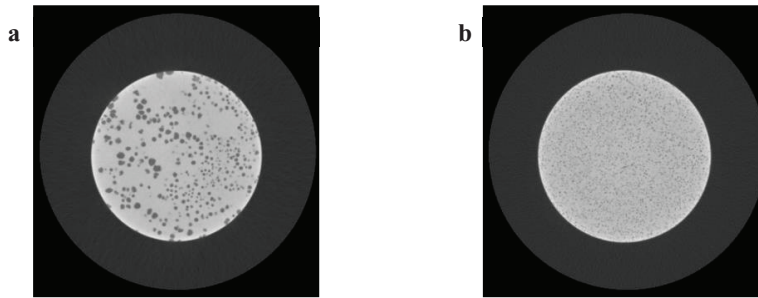

Fig. 2. The cross sections of sand (a) and chill (b) casted specimens, from [10].

It can be seen in Fig. 2, that the defects and nodule size in the sand casted test specimen are significantly larger than the ones observed in the cross section of the chill casted specimen. The data gain from both casting methods were subjected to a statistical analysis. It is observed that the (initial) defects from the sand casted specimens were of a more critical size, therefore only the sand casted data is considered for further analysis.

The distribution of typical defects observed in the sand casted scan data, with a mean value of $\mu=8.42\cdot10^{-6}$ m, is fitted to a Weibull distribution and discretized in 10 intervals. The centers values of the aforementioned intervals are representative of the distribution quantiles, which are used to gain 'deterministic' values for initial cracks for the crack propagation models. The fitted Weibull distribution together with the aforementioned intervals and quantiles can be seen in Fig. 3. Additionally, a stochastic variable related to the height and width (a_0/c_0) ratio of the initial crack is used in the probabilistic reliability analysis in order to introduce variability to the initial crack size.
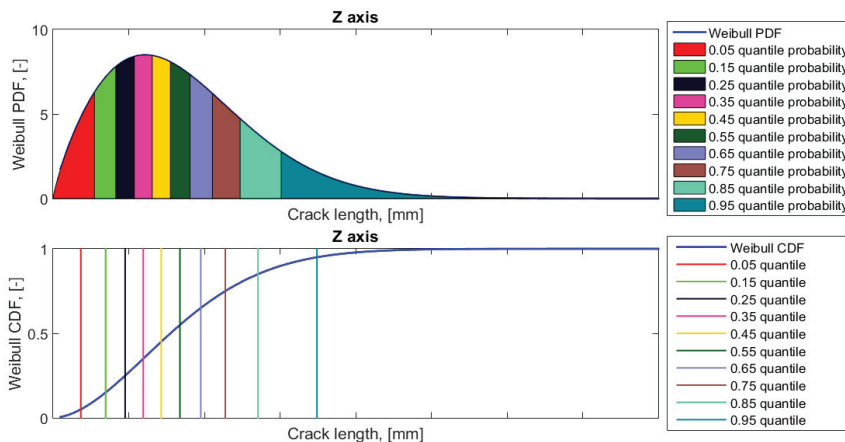

Fig. 3. The discretization of sand casted defects Weibull distribution.

3. Loading history

The considered main shaft of wind turbine is assumed to be subjected to a 25 year loading history. The loading history is obtained as a combination of the internal reaction moments gained from HAWC2 simulation for specific wind speed loadings weighted by the wind speed distribution of a class IC wind turbine [11]. The number of specific wind speeds within the 25 years are calculated and utilized together with corresponding loading in order to obtain randomized cyclic loading vector. This loading vector is transformed into resulting stresses, a sample of which can be seen in Fig. 4. It should be mentioned, that for the purpose of this analysis the main shaft is assumed to be subjected only to torsional stresses (τ).
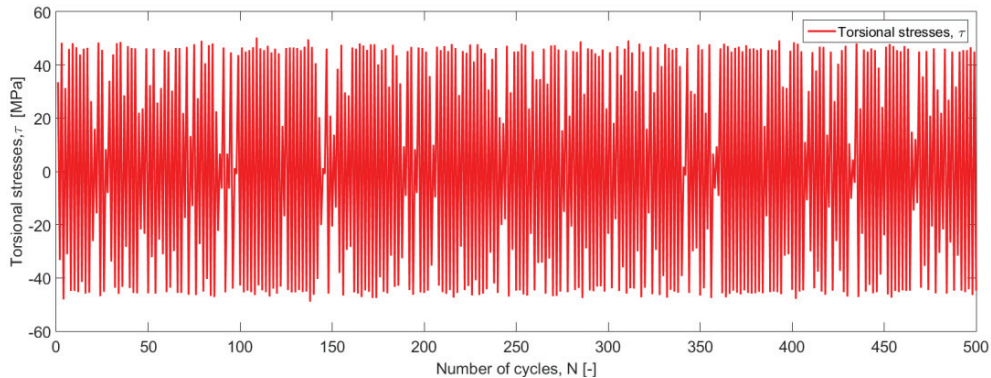

Fig. 4. A sample of torsional stress loading history.

4. Crack propagation models

Two crack propagation models are assumed to describe the stable fatigue crack growth, namely the Paris and Walker laws. The Paris law in eq. (1) is the general model, commonly used for fatigue facture models. The model describes the sub-critical crack growth relationship to the stress intensity factor range (ΔK), and was introduced in [4]. The second model, Walker law in eq. (2), was chosen for its ability to empirically account for the mean stress influence on the stable fatigue crack growth [5]. It is assumed that the crack growth is in opening mode, meaning that loading stress is normal to the plane of the crack. It is noted that the purpose of this paper is not to establish a detailed fracture mechanics model, but a model that is representative and can be used for probabilistic analysis and can be calibrated to the results obtained by an SN-curve methods based on a larger number of tests.

$$\frac{da}{dN} = C\left(\Delta K\right)^{m} \tag{1}$$

$$\frac{da}{dN} = \frac{C\left(\Delta K\right)^{m}}{\left(1-R\right)^{m(1-\lambda)}} \tag{2}$$

5. Probabilistic reliability analysis

Two probabilistic reliability models, namely one-dimensional (1D) and two-dimensional (2D) are created to analyze the reliability of the main shaft subjected to a lifetime of torsional stress loading. The aforementioned models are created by the use of stochastic and deterministic variables. The stochastic variables described by a specific

distributions, are utilized to account for the variability present in a standard design. Each model is analyzed using two limit state equations, which are subjected to reliability analysis conducted by the use of the first order reliability method (FORM) [6]. The design goal is to reach the required annual reliability index level of the design is β=3.3, as specified in in CD IEC61400-1 ed. 4 [11].

5.1. Design variables

The variables in this paper considered as stochastic variables are modelled based on the information in [12,13]. The stochastic variables with according distributions and distribution parameters can be seen in Table 1.

Table 1. Stochastic variables.

Variable	Distribution	Mean	COV	Definition
X_R	Lognormal	1.0	0.10	Model uncertainty for load bearing model
X_{dyn}	Lognormal	1.0	0.05	Uncertainty related to modeling dynamic response
X_{exp}	Lognormal	1.0	0.15	Uncertainty related to modeling of site assessment
X_{aero}	Gumbel	1.0	0.10	Uncertainty in lift and drag coefficient assessment
X_{str}	Lognormal	1.0	0.03	Uncertainty related to response computation given the external load
a_0/c_0	Lognormal	0.62	0.4	Crack height to width ratio
T_0	Normal	18	0.83	Temperature variability
U	Uniform	0	1	Random number for the calculation of K_{IC} realization

Some parameters in the probabilistic reliability models are modelled as deterministic values and are modelled based on the information in [12,13,14,15]. The values of deterministic variables can be seen in Table 2.

Table 2. Deterministic variables.

Variable	Value	Unit	Definition
a_0	Varies	mm	Crack height, gain for 10 quantiles.
C	$4 \cdot 10^{-4}$	-	Paris law material constant
m	4.4	-	Paris law material constant
λ	4	-	Shape parameter for three parameter Weibull distribution
T	5	ºC	Operating temperature
T_{27J}	-50	ºC	Temperature corresponding to a CVN of 27 J
σ_y	240	MPa	Yield strength
B	150	mm	Shaft thickness
K_{th}	8.54	MPa√m	Threshold parameter

5.2. Limit state equations

Two probabilistic reliability models were analysed. The first, 1D reliability model is formulated based on a failure criteria related to the stress intensity factor (K_I) exceeding the fracture toughness value (K_{IC}). When the K_{IC} value is surpassed, the crack growth becomes unstable and exponential, which can no longer be described by fracture mechanics laws considered in this paper. The limit state equation is defined by eq. (3).

$$g(t) = K_{IC} - X_{dyn} X_{exp} X_{aero} X_{str} K_I(t) \tag{3}$$

The second, 2D reliability model is based on failure in the ultimate limit state, investigating the ability of reduced, due to cracks cross-section area ($A_{reduced}$) to resist the loading torsional stresses applied to full cross-sectional area (A). If the $A_{reduced}$ is not able to resist the torsional stress loading a sudden, similar to an ultimate limit state failure can occur. The limit state equation is defined by eq. (4).

$$g(t) = \sigma_y X_R A_{reduced}(t) - X_{dyn} X_{exp} X_{aero} X_{str} \tau A \tag{4}$$

5.3. The annual probability of failure

The accumulated probability of failure for each year is obtained by using the limit state equations, eq. (3) and eq. (4), in a FORM analysis. Furthermore, in order to obtain the annual probability of failure, the accumulated probability of failure for each year is conditioned on survival up to that year. The annual probability of failure is obtained by eq. (5).

$$\Delta P_{F,Annual}(t) = \frac{P_{F,Accumulated}(t) - P_{F,Accumulated}(t-1)}{1 - P_{F,Accumulated}(t)} \tag{5}$$

where: $P_{F,Annual}$ – annual probability of failure
$P_{F,Accumulated}$ – accumulated probability of failure

5.4. Total probability of failure and reliability index

The total probability of failure in a critical volume of the main shaft is approximated by combining the probability of failure given a specific quantile crack size ($P(g(t)/a_0=x_i)$) with the probability that such initial crack exists in the critical volume considered ($P_{Existance,i}$). The $P_{Existance,i}$ is calculated by integrating the probability density function areas, presented in Fig. 3, over each quantile considered in the analysis. The obtained probability is weighted with the probability that the orientation and the shape of the initial crack is critical ($P_{Orientation}$). For the purpose of this analysis the probability of crack orientation and shape is assumed $P_{Orientation}=0.25$. The final probability of failure and the final reliability index are obtained by eq. (6) and eq. (7):

$$P_F(t) = \sum_i \Delta P_{F,Annual}\left(g(t)|a_0 = x_i\right) P_{Existance,i} P_{Orientation} \tag{6}$$

$$\beta = -\Phi^{-1}\left(P_F(t)\right) \tag{7}$$

where: P_F – final probability of failure
β – final reliability index
Φ^{-1} – inverse standardized normal distribution function.

6. Results of reliability analysis

The accumulated reliability index using the first probabilistic reliability model can be seen on the left side of Fig. 5. In addition, the annual reliability index, adjusted for the survivability, can be seen on the right side of Fig. 5. The results show that the annual reliability level of most quantiles falls below the implicit target annual reliability β=3.3 given in CD IEC61400-1 ed. 4 [11] and in the background document [6].
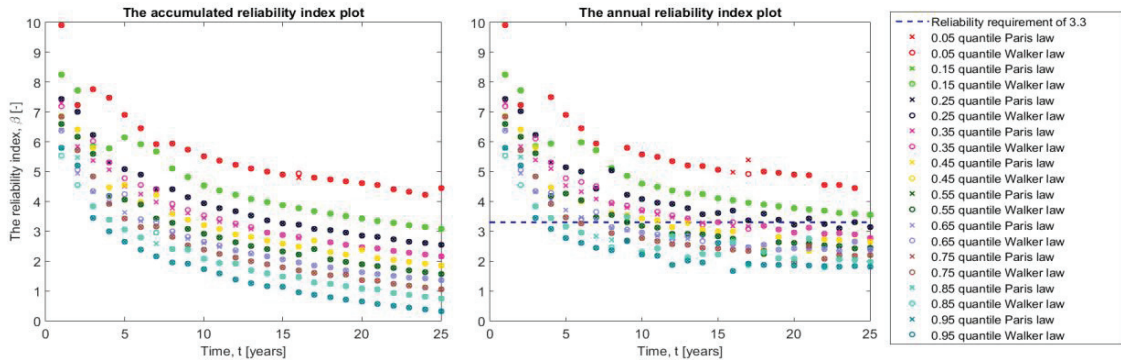
Fig. 5. The accumulated and annual reliability levels of 1D model.

The accumulated and annual reliability indices for the second probabilistic reliability model can be seen in Fig. 6. It is seen that the reduced cross-section does not influence the reliability of the component significantly. This reflects that the cracks typically need to be very large before influencing the load bearing capacity. It is noted that the two models can be combined in one model using limit state equations based on the Failure Assessment Diagram approach, e.g. described for welded details in [12].
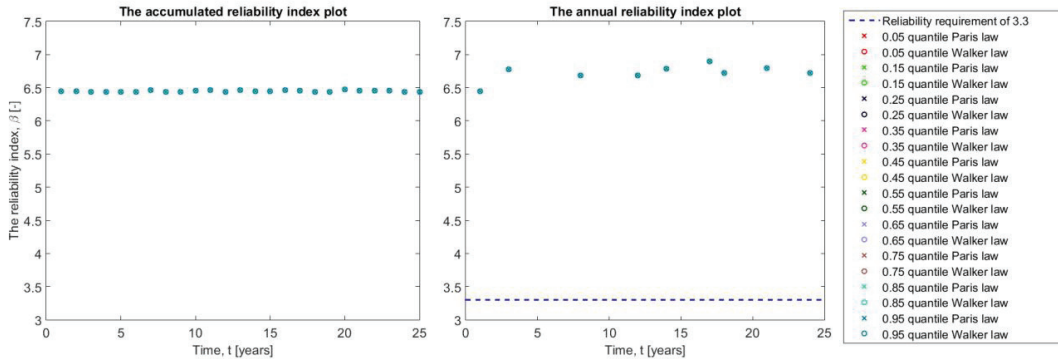

Fig. 6. The accumulated and annual reliability levels of 2D model.

The reliability index of the main shaft is calculated using the results in Fig. 6 and Fig. 5, combined with the probabilities of existence and orientation\shape can be seen in Fig. 7. It is noticed, that the initial crack gained from the first four quantiles reaches the design requirement of β=3.3 in the 1D model.
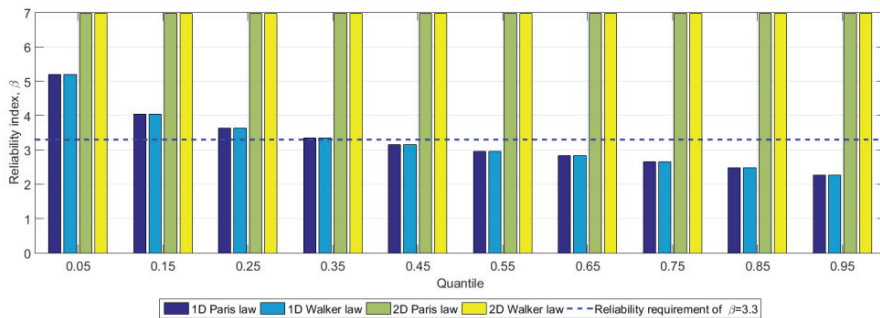

Fig. 7. Total reliability indexes for both 1D and 2D models calculated for specific quantiles.

The total probability of failure and the reliability index calculated for each model can be seen in Table 3. It is observed, that the both 1D models do not satisfy the design requirement of β=3.3, while the 2D model meets this requirement. This indicates that the safety factors used for design by the 1D model should be increased.

Table 3. Total probabilities of failure and reliability indices.

	1D Paris law	1D Walker law	2D Paris law	2D Walker law
Final probability of failure, P_F	$2.76 \cdot 10^{-2}$	$2.76 \cdot 10^{-2}$	$1.563 \cdot 10^{-11}$	$1.563 \cdot 10^{-11}$
Final reliability index, β_F	1.9174	1.9173	6.6405	6.6405

7. Conclusions

In this paper, the pre-existing defects analysis on the main shaft reliability was performed. The reliability was analysed by two probabilistic models. Based on the results gained via the one-dimensional probabilistic reliability model, it can be observed that if the 50% quantile for the initial crack sizes is representative and with critical crack orientation then the annual reliability index falls below the target reliability index value of 3.3 after 10 years. This indicates that O&M inspections should be performed around this time. Furthermore, it can be observed that the four smallest initial crack size quantiles achieve the reliability index requirement, hence these crack sizes can be used as a acceptance limit for quality control methods. The total reliability indexes reveal that the main shaft cross-section considered in the example does not meet the design safety requirements, due to the fact that both the Paris and Walker law based one-dimensional models do not satisfy the design reliability requirement of β=3.3. It can be noticed from the two-dimensional model that the crack growth does not reduce the reliability of the main shaft significantly throughout the lifetime of the component.

The example results indicate that the mean stress influence does not significantly influence the reliability of the main shaft. This can be concluded from the fact that the difference between the total reliability results gained using Paris law crack propagation model and the ones using Walker model is insignificant.

Future work will include expanding the reliability models to incorporate a Failure Assessment Diagram model. This model would combine the 1D and 2D probabilistic limit states.

Acknowledgements

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