PROBABILISTIC DESIGN OF WIND TURBINE CONCRETE COMPONENTS SUBJECT TO FATIGUE

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Abstract

Wind turbines contribute significantly to the production of renewable energy. In order to minimize the Levelized Cost of Energy (LCOE) the cost of the wind turbine incl. tower and the foundation should be as low as possible but at the same time have a sufficient reliability. In this paper, focus is on wind turbine components which may be made of concrete such as tower and foundation. In traditional deterministic design based on design standards, partial safety factors are applied to obtain the design values. Improved design with a consistent reliability level for all components can be obtained by use of probabilistic design methods with explicit consideration of uncertainties connected to loads, strengths and numerical models / calculation methods. Wind turbines are basically designed based on IEC 61400-1:2019 which indicates a target reliability level that can be used for probabilistic design. In this paper, probabilistic fatigue models for concrete are presented based on the fatigue models in *fib* Model Code 2010, but extended within a stochastic modelling using a large dataset of fatigue tests. Generic uncertainty models for the fatigue load are applied. It is illustrated how reliability analyses can be performed within a probabilistic design framework.

Keywords: Wind turbines, Fatigue, Concrete, Reliability, Probabilistic design

1. INTRODUCTION

During the last decades, wind turbines for electricity production have increased significantly both in production capacity and in size; now with a rated power of 10MW, rotor diameters in the range of 160-200m and tower heights more than 100m; and even larger wind turbines are expected the next years to be installed offshore. Typically the tower and the substructure for offshore wind farms are made of structural steel, but concrete towers and substructures are been considered and also used as a cost-effective alternative to steel.

In traditional, deterministic design based on design standards, partial safety factors are applied to obtain the design values. Improved design with a consistent reliability level for all components can be obtained by use of probabilistic design methods with explicit consideration of uncertainties connected to loads, strengths and numerical models / calculation methods.

Furthermore, using a probabilistic design basis it is possible to design wind turbines such that site-specific information on climate parameters are applied. Wind turbines are basically designed based on the IEC 61400 series of standards where IEC 61400-1 ed. 4 [1] indicates a target reliability level which can be used for probabilistic design. In this paper, probabilistic fatigue models for concrete ae presented based on the basic, deterministic fatigue models in [2], but extended within a stochastic modelling framework and with parameters calibrated using a large dataset of fatigue tests. Generic uncertainty models for the fatigue load are applied.

The structural response of wind turbines is highly dependent on the wind turbulence, aerodynamics, dynamics of the structural system and of the control system applied. Further, wind turbines are manufactured in a series production based on many component tests, some subcomponent tests and a few prototype tests making it possible to update the knowledge through the design process, e.g. using a Bayesian approach.

In this paper, a general approach for probabilistic design is presented with focus on wind turbine components made of concrete such as tower and foundation, and especially the fatigue failure mode. It is illustrated how reliability analyses and probabilistic design can be performed within a probabilistic design framework considering a gravity based foundation for an offshore wind turbine.

2. PROBABILISTIC DESIGN

Structural components in wind turbines are designed considering a number of load combinations, see [1]:

- Failure during normal operation in extreme load or by fatigue (DLC 1)
- Failure under fault conditions (e.g. failure of electrical / mechanical components or loss of grid connection) due to extreme loads or by fatigue (DLC 2)
- Failure during start up, normal shut down or emergency shut down (DLC 3, 4 and 5)
- Failure when the wind turbine is idling / parked and does not produce electricity. Failure can be by extreme loads or by fatigue (DLC 6)
- Failure during transportation and installation (DLC 7)
- Failure during transport, assembly, maintenance and repair (DLC 8)

Wind turbine components can generally be divided in two groups:

1) Electrical and mechanical components modelled by the failure rate, λ. Further, the bath-tub model is often used to describe the time dependent behaviour of the failure rate / hazard rate, see e.g. [3] and [4]. Reliability of drivetrain components (e.g. the gear-box) has been considered in e.g. [5].

2) Structural components such as tower, main frame, blades and the support structure / foundation where failure modes can be described by limit state equations, $g_i(X)$. Parameters in the limit state equation $g(X)$ are assumed to be modelled by n stochastic variables $X = (X_1, \ldots, X_n)$. The probability of failure, P_F can be estimated using Structural Reliability Methods, e.g. FORM / SORM / simulation methods, see e.g. [6] and [7].

For wind turbines, the risk of loss of human lives in case of failure of a structural element is generally very small. Further, it can be assumed that wind turbines are systematically reconstructed in case of collapse or end of lifetime. Therefore, an appropriate target reliability level corresponding to a minimum annual probability of failure, ΔP_F^{max} is considered be $5 \cdot 10^{-4}$

(annual reliability index equal to 3.3), see [1] and [8]. More details on probabilistic design and reliability assessment of wind turbines can be found in [9], [10], [11] and [12].

In probabilistic design, it has to be verified that $\Delta P_{F,i} \leq \Delta P_F^{max}$ or $\lambda_{F,i} \leq \Delta P_F^{max}$ for all components for all DLCs where $\Delta P_{F,i}$ and $\lambda_{F,i}$ are used where relevant. Some representative stochastic models and limit state equations can be found in e.g. [8].

3. GRAVITY BASED FOUNDATION (GBF) CASE STUDY

As a case study, a reinforced concrete GBF of an offshore wind turbine (OWT) is considered as shown in Figure 1, see [13] for details. Reliability assessment wrt. fatigue failure and ultimate strength failure in compression of the concrete shaft is considered. The critical section is assumed to be the section just above lower ring beam as shown in Figure 1.

The OWT is installed in water depth of 25m. The outer diameter of the shaft at critical section is 6.5m. The thickness of the shaft (t) is considered as a design parameter.

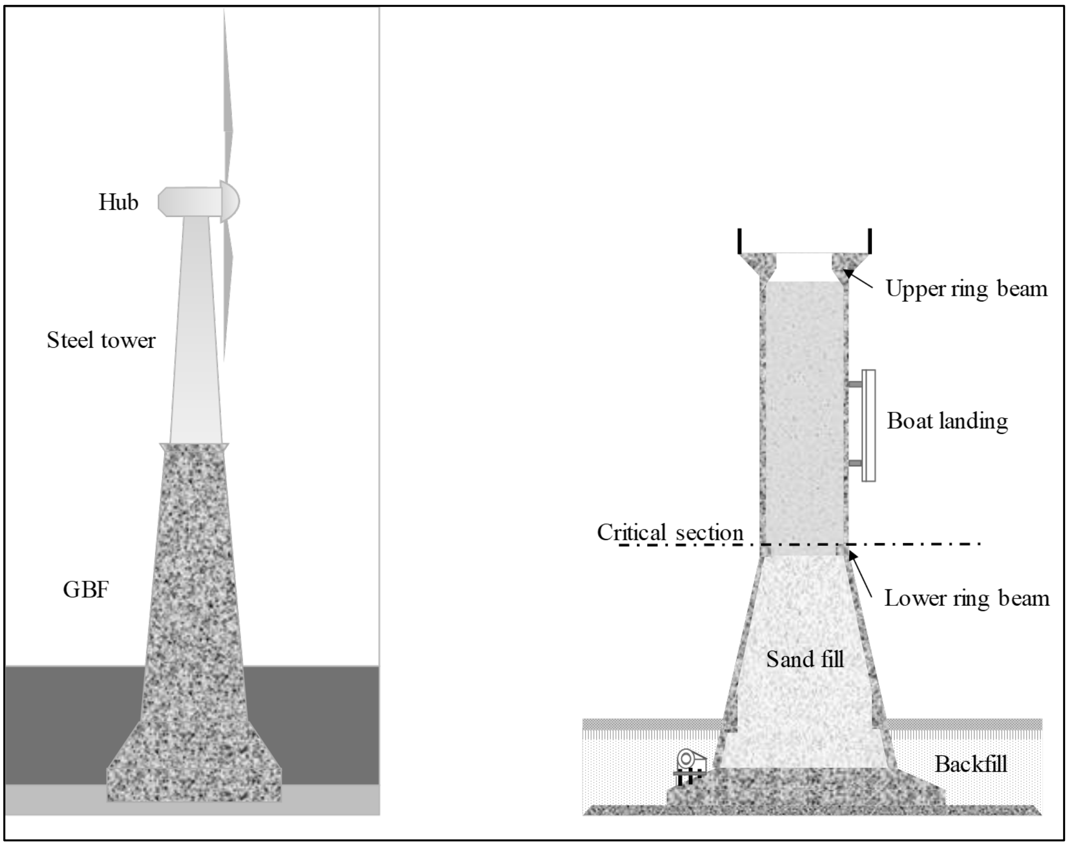

Figure 1: Typical GBF offshore wind turbine

Two limit states are considered in this paper, namely fatigue failure of the concrete in compression zone of the cross section (DLC 1.2) and extreme / ultimate strength failure of the concrete in compression (DLC 6.1). It is noted that it could also be very relevant to study yielding failure of the reinforcement in extreme storm conditions and tension fatigue failure of the concrete for cracked section given cracks in section due to extreme storm (multi-hazard scenario).

3.1 Fatigue limit state (DLC 1.2)

A probabilistic fatigue model for concrete is presented based on the basic, deterministic fatigue models in [2], but extended within a stochastic modelling framework and with parameters calibrated using a large dataset of fatigue tests, [14], [15] and [16].

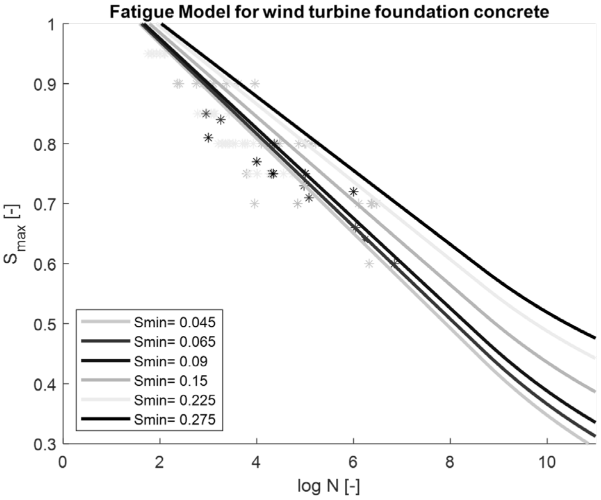

Figure 2: Fatigue strength model of concrete for GBF

Equation (1) shows a limit state equation based on Miner's rule where the number of cycles to failure is calculated based on [2] and [16]. Figure 2 shows graphical representation of fatigue strength model incl. fatigue test data while Table 1 shows the corresponding statistical parameters.

Table 1: Stochastic parameters

Parameter	Dist*	Parameters		Ref**
	Type	Mean	Std. Dev.	
X_1	N	1.13	0.03	Stochastic parameters associated with fatigue strength for compression-compression [16]
X_2	N	8.66	0.37	
ε	N	0.0	σ_ε	
σ_ε	N	0.88	0.07	
$\rho_{X_1,\sigma_\varepsilon}$	-	0.01		
$\rho_{X_2,\sigma_\varepsilon}$	-	-0.01		
ρ_{X_1,X_2}	-	-0.84		
X_W	LN	1.0	0.10	Uncertainty associated with wind loads
X_G	LN	1.0	0.05	Uncertainty associated with gravity loads
X_{PS}	LN	1.0	0.05	Uncertainty associated with pre-stressing loads
Δ	LN	1.0	0.30	[17]
X_{fc}	LN	1.0	0.14	Uncertainty in static strength of concrete
BM	G	186.7	40.4	Bending moment at critical section MN-m

$$g(t,z) = \Delta - \sum_{i=1}^{N_{\mathrm{Windspeeds}}} \sum_{j=1}^{N_{\mathrm{bins}}} \frac{n_{ij}t}{N_{S,ij}} \tag{1}$$

where

Δ	model uncertainty associated with Miner's rule
t	time in years $0 < t < T_L$
T_L	design service life of the GBF structure
n_{ij}	number of stress cycles per year in mean windspeed *i* in stress bin *j* (obtained by rainflow counting)
$N_{S,ij}$	number of stress cycles to failure of stress bin $S_{C,max,ij}$ and $S_{C,min,ij}$ modelled by

$$\log N_{S,ij} = \frac{X_2}{(Y - X_1)} \cdot \left(S_{c,max,ij} - X_1\right) + \epsilon \qquad \text{if } \log N_{S,ij} \leq X_2$$

$$\log N_{S,ij} = X_2 + \frac{X_2 \cdot \ln(10)}{(Y - X_1)} \cdot \left(Y - S_{c,min,ij}\right) \cdot \log\left(\frac{S_{c,max,ij} - S_{c,min,ij}}{Y - S_{c,min,ij}}\right) + \epsilon \qquad \text{if } \log N_{S,ij} > X_2 \tag{2}$$

where

$S_{c,max,ij} \quad = |\sigma_{c,max,ij}| / f_{cfat}$

$S_{c,min,ij} \quad = |\sigma_{c,min,ij}| / f_{cfat}$

$\sigma_{c,max,ij}$ and $\sigma_{c,min,ij}$ are maximum and minimum stresses used to obtain $S_{c,max,ij}$ and $S_{c,min,ij}$

$\mathrm{\sigma_{c,max,ij}(z) = X_G \cdot \sigma_G(z) + X_{PS} \cdot \sigma_P(z) + X_w \cdot \sigma_{WL_{max,ij}}(z)}$

$\mathrm{\sigma_{c,min,ij}(z) = X_G \cdot \sigma_G(z) + X_{PS} \cdot \sigma_P(z) + X_w \cdot \sigma_{WL_{min,ij}}(z)}$

$\mathrm{f_{cfat} \quad = \beta_{c,sus(t,t0)} \cdot \beta_{cc(t)} \cdot f_c \cdot (1 - f_c/400)}$

$\mathrm{f_c \quad = X_{f_c} \cdot f_{cm}}$

z design parameter

3.2 Ultimate limit state (DLC 6.1)

The ultimate limit state (ULS) for extreme storm conditions is considered, [18] with the following limit state equation for compression failure of concrete:

$$g(z) = R - S = fc - \left(\frac{BM}{I_{Cr}(z)} \cdot y + \frac{X_G \cdot G}{A_{Eq}(z)} + \frac{X_{PS} \cdot A_P \cdot f_{pa}}{A_{Eq}(z)}\right) \tag{3}$$

where

R	stochastic compression strength of concrete $= f_{cm} \cdot X_{fc}$
S	action effects, e.g. lateral bending moment, gravity forces, and pre-stressing force
BM	annual maximum storm bending moment at critical section due to lateral loads (wind and wave), Gumbel distributed, [18]
y	extreme fibre distance (outer radius of concrete shaft)
G	gravity forces on wind turbine, [18]
I_{Cr}	moment of inertia of cracked section obtained using by considering rectangular stress block of concrete in compression zone
A_{Eq}	$= A_c + A_R \cdot (m - 1)$, equivalent concrete area

A_c, A_R, A_P area of concrete, reinforcement and pre-stressing (m^2) respectively
f_{pa} maximum pre-stressing stress
m $= E_s/E_c$, modular ratio, ratio of modulus of elasticity of steel to concrete

3.3 Results and discussions

Reliability analyses as basis for probabilistic design are performed using the First Order Reliability Method (FORM), see [19] resulting in an estimate of the annual probability of failure P_F and the corresponding annual reliability index $\Delta\beta$.

The thickness of the GBF shaft (t) is considered as design parameter (denoted z in above section). Figure 3 shows the annual reliability index $(\Delta\beta)$ as function of thickness of the shaft (t) for different values of the reinforcement. It is noted that increase of the thickness of the shaft increases both fatigue and ultimate reliability indices increase, and also that an increase of the reinforcement (A_R) increases both fatigue and ultimate reliability indices. For all cases, ULS is governing.

Figure 4 shows the annual reliability index $(\Delta\beta)$as function of thickness of the shaft (t) with variation of pre-stressing. Increase in pre-stressing (A_P) induces additional pressure on concrete and thus reduces the reliability against fatigue as well ultimate strength failure. For all cases, ULS is governing. From Figure 3 and Figure 4 it is seen that to satisfy a minimum reliability requirement with an annual reliability index equal to 3.3, a design would require GBF shaft with thickness of 550 mm (minimum), reinforcement area of 0.2 m^2 (minimum) and pre-stressing area of 0.1 m^2 (maximum).

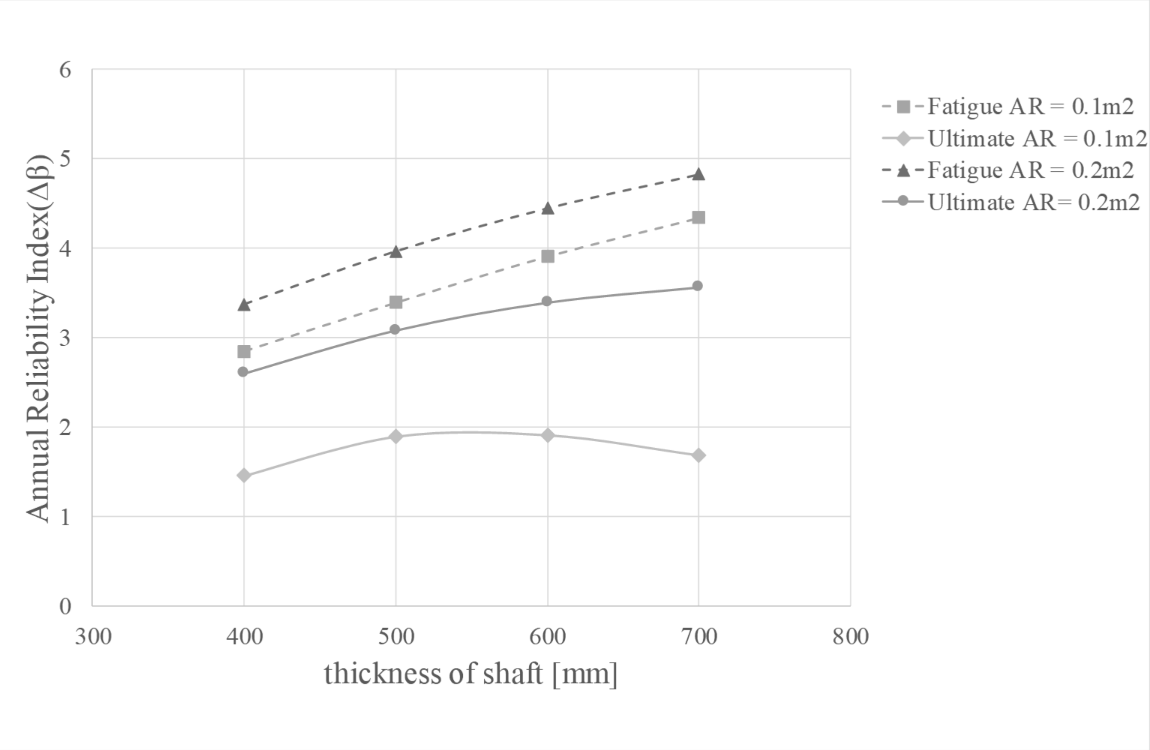

Figure 3: Sensitivity of reliability index to area reinforcement $A_P = 0.1$ m^2

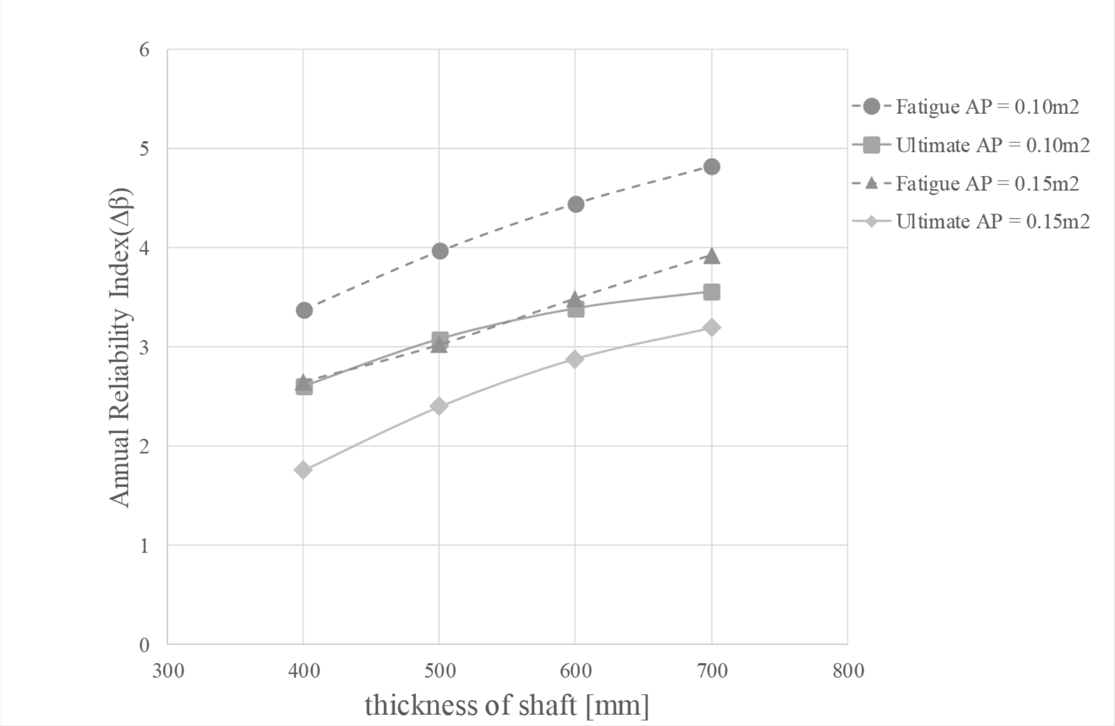

Figure 4: Sensitivity of reliability index to area of pre-stressing $A_R = 0.2\ \mathrm{m}^2$.

4. CONCLUSIONS AND FUTURE WORK

Probabilistic design of wind turbines has the potential to contribute significantly to reduction of the Levelized Cost of Energy and increased sustainability of wind turbines. The overall approach is presented in this paper and illustrated for offshore wind turbine tower and foundation made of concrete. The probabilistic design approach requires formulations of stochastic models for all uncertain parameters related to loads, strength and models, and development of limit state equation for the relevant design load cases. This paper only considers two of these limit states, but in future work stochastic models and limit state equations can be developed using the same principles for the remaining design load cases to be considered for design of wind turbines.

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