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Ramírez, José G. Rangel; Sørensen, John Dalsgaard

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WG7.5
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RBI OPTIMIZATION OF OFFSHORE WIND TURBINES

José G. Rangel-Ramírez * & John D. Sørensen *
* Department of Civil Engineering, Aalborg University
Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark
jr@civil.aau.dk, jds@civil.aau.dk.

ABSTRACT

Wind turbines for electricity production have increased significantly the last years both in production capability and size. This development is expected to continue also in the coming years. Offshore wind turbines with an electricity production of 5-10 MW are planned. Typically, the wind turbine support structure is a steel structure consisting of a tower and a monopile, tripod or jacket type foundation. This paper considers aspects of inspection and maintenance planning of fatigue prone details in jacket and tripod type of wind turbine support structures. Based on risk-based inspection planning methods for oil & gas installations, a framework for optimal inspection and maintenance planning of offshore wind turbines is presented. Special aspects for offshore wind turbines considered are the fatigue loading characteristics where usually the wind loading are dominating the wave loading, wake effects in wind farms and also the reliability level which is typically significantly lower than for oil & gas installations. An illustrative example is presented.

Keywords: inspection, reliability, decision analysis, fatigue, wake turbulence

1. INTRODUCTION

Risk Based Inspection (RBI) planning is addressed to achieve a suitable life-cycle performance by an optimal inspection, maintenance and reparation strategy; this efficient strategy entails an optimal control of deterioration in the structure, not neglecting important economical, technical and social aspects related with its overall performance.

Offshore Wind Turbines' operation and maintenance costs are much larger than for onshore structures, making RBI an important tool to accomplish substantial improvements in costs that will be considerable, bearing in mind the significant increase of this industry in production capability and size. Attending to this expansion, 5-10 MW Wind turbines are developed and going to harsh environments begin to be profitable options. In-place conditions as deep water depths, waves and wind farm location affects significantly the life-cycle performance of offshore wind turbines (OWTs). Depending on the site characteristics, typically, OWTs support structure is made of steel consisting of a tower and a monopile, tripod or jacket type foundation depending on the water depth.

RBI for oil & gas installations have been developed during the last two decades, see e.g. Faber et al. (2000) , Sørensen and Faber (2001) and Moan (2005), giving a theoretical guideline based on Bayesian decision theory that can be applied also to offshore wind turbines. This paper considers aspects of inspection and maintenance planning of fatigue prone details in jacket and tripod types of OWT support structures. Based on RBI methods for oil & gas installations, a framework for optimal inspection and maintenance planning of OWTs is presented. It is taken into account that for fatigue loading usually the wind load is dominating the wave load. Within wind load, wake effects in wind farms affect the reliability level, decreasing it in comparison with the oil & gas installation case. Further the influence of the control system is discussed.

In contrast to other structures, OWTs usually represent low risk of human injury, allowing the allocation of a minimum reliability level obtained by optimization of the risk-based preventive actions' costs. Conditioned and time-tabled actions (inspection, maintenance and repairing) can be optimized by applying pre-posterior Bayesian decision

theory approach permitting with feedback data, e.g. hot spots inspection data, inference of inspection results; actualized RBI strategy to accomplish suitable planned actions by adaptive strategies.

Wind farms, a viable source of electricity production, are involving additional technical and economical efforts related with the interaction of the OWT. Spatial correlation of OWTs entails turbulence conditions that affect the performance of neighboring wind turbines. Wake effects, coming from the decrease of wind velocity behind OWT and increase the turbulence results in increased wind load and decrease in OWT fatigue life. Other loads like waves and ice represent important aspect also to consider.

The fatigue failure limit state is primary addressed in this paper. Fatigue failure is located on:

- WIND TURBINE STRUCTURE:
  - Tower – welded steel connections
  - Hub
    - Hub – cast steel
    - Blade – glass fiber reinforce plastics (GPR), carbon fiber, composites…
  - Nacelle – made of cast steel, welded steel connections
    - Gear Box – gears, shafts…
    - Yaw mechanism – gears, ring…
- SUPPORT STRUCTURE:
  - Transition node – welded steel connections.
  - Jacket substructure – welded steel connections, cast steel nodes…
  - Tripod substructure – welded steel connections.

Active control affects considerably the response by wind action in structural and non-structural parts. Non-structural failure modes are related with start/stop operation and accidental/unusual loads that will affect these specific parts.

In water depths of about 20 m to 50 m, the use of jacket and tripod structures represents a feasible option that improves technical aspects concerning structural redundancy, damage distribution, scour conditions and dynamical behavior. Economically, jacket and tripod structures have certain advantages over monopole structures in larger water depths. Another important OWT part is the transition node between the jacket or tripod and the tubular tower. The transition node is a critical design element, needing special careful design concerning the fatigue performance.

RBI optimization of OWT is considered in this paper for fatigue prone details in jacket and tripod type support structures. Probabilistic models and representative limit state equations for ultimate structural fatigue failure are formulated. Illustrative examples are described, considering fatigue failure using both linear and bilinear SN-curves and for single and wind farm location.

2. OPTIMAL PLANNING OF INSPECTION AND MAINTENANCE

The time varying fatigue degradation in offshore structures is a highly uncertain process, making a probabilistic approach the best way to deal with the problem. Further, to assess the uncertainties arising from external randomness (external conditions, environmental exposure, etc) and models uncertainties stochastic modelling is a rational tool. Reliability-based and risk-based approaches for inspection and planning have been developed during the last decades, see Skjong (1985), Madsen et al. (1987), Thoft-Christensen and Sørensen (1987) and Fujita et al. (1989); and are being applied to outline RBI plans that have as main aim to improve structural reliability and minimize the life cycle overall costs.

The suitable decision plan to improve costs will be carried out in the framework of pre-posterior analysis from classical Bayesian decision theory, see Raiffa and Schlaifer (1961), Benjamin and Cornell (1970) and Ang & Tang (1975), and adapted to the particular case of OWTs.

In figure 2.1 is shown a decision tree for RBI planning for OWTs, The basic steps in the decision process are illustrated. The decisions and random outcomes could be summarized as follows:

- *Initial design phase*, in which the optimal design parameters $z=(z_1,z_2,z_3,..,z_n)$ are determinate. They have certain limits z_{min}-z_{max}. The interval z_{min}-z_{max} is established according codes and practice requirements.
- First interaction with external conditions, such as wind and wave climate; triggers a *state of nature* X_o. This random outcome, due to high-uncertain nature; is the part of the process in which reliability and simulation methods attempt to represent numerically time-deterioration process (wear, dent, corrosion, fatigue…) dealing with model uncertainties at the same time. If the statistical basis for evaluation of the uncertainties is limited then also epistemic uncertainties will become important.
- *Monitoring activities "e"* at the times $t=(t_1,t_2,t_3,..,t_i)$, include inspection, sampling and analyzing actions which result in inspection results *"S"* (degree of wear and corrosion, denting level, size of fatigue cracks…) that are

obtained depending on inspection quality $q=(q_1,q_2,q_3,..,q_n)$ (inspection techniques, technical expertise of inspectors…).

- Based on the obtained monitoring results, *Mitigation alternatives* will be considered according to fixed or adapting mitigation policy *d(S)*. Such policies are related to repairing or not repairing activities.
- *State of nature* X_i will be the beginning of new random outcomes. Theoretically, posterior states of nature depend on assumptions established to simplify the RBI process, e.g. assuming that repaired components behave like new component (see figure 2.1, dash line t_{i+1}-t_i) and repaired parts will have no indication at the inspection (see figure 2.1, dash-dots line t_i-t_o).

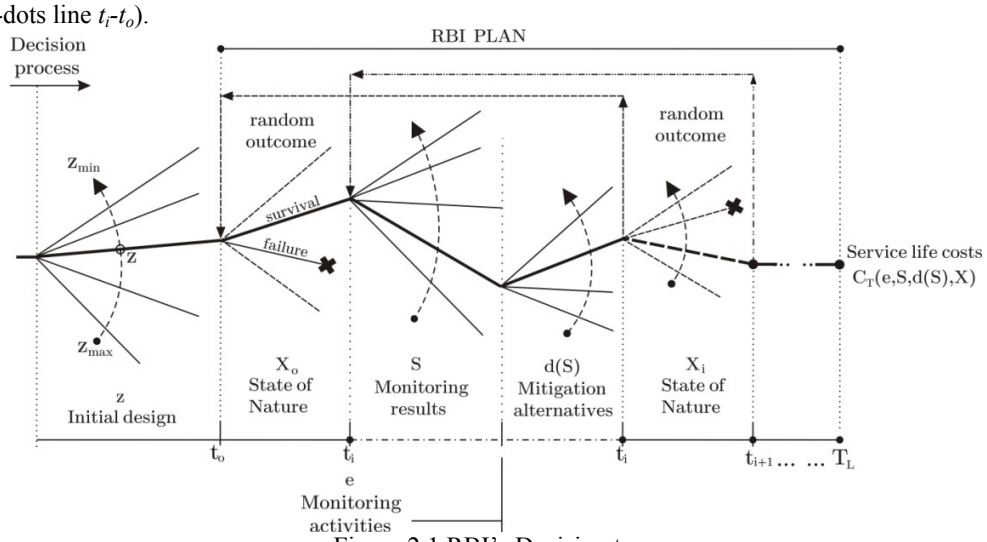


Figure 2.1 RBI's Decision tree

In Figure 2.1, $C_T(e,S,d(S),X_i)$ are the total service life costs. Overall cost optimization will be achieved by minimizing C_T:

$$min\, E[C_T(z,e,d(S),X_i)] = C_I(z) + E\left[C_{Insp}(z,e,d(S),X_i)\right] + E\left[C_{Rep}(z,e,d(S),X_i)\right] + E[C_F(z,e,d(S),X_i)] \quad (2.1)$$

$$\text{s.t.} \quad z_i^{min} \le z_i \le z_i^{max}, \qquad i = 1,2,\dots,n$$

$$\Delta P_{F,t}\big(t,z,e,d(S)\big) \le \Delta P_F^{max}, \quad t = 1,2,\dots,T_L$$

$E[C_T]$ is the expected (RBI action) costs in the service life T_L where C_I is the initial costs, $E\left[C_{Insp}\right]$ is the expected inspection costs, $E\left[C_{Rep}\right]$ is the expected reparation costs and $E[C_F]$ is the expected failure costs. Equation 2.1 is constrained by limits on design parameters and that the annual probability of failure $\Delta P_{F,t}$ has to be less than ΔP_F^{max}at all times, assuring a maximum annual risk-state. The n inspections are performed at times t_i, $i=1,\dots,n$ where $t_o \le t_1, t_2, \dots, t_n \le T_L$.

Total capitalized expected inspection costs are:

$$C_{Insp}\big(e,d(S)\big) = \sum_{i=1}^{n} C_{Insp,i}(q)\big(1 - P_F(t_i)\big)\frac{1}{(1+r)^{t_i}} \quad (2.2)$$

Where *ith* index characterizes the capitalized inspection costs at the *ith* inspection when failure has not occurred earlier, $C_{Insp,i}(q)$is the inspection cost of the *ith* inspection, $P_F(t_i)$ is the probability of failure in the time interval $[0,t_i]$ and r is the real rate of interest.

Total capitalized expected maintenance and repair costs are:

$$C_{Rep}\big(e,d(S)\big) = \sum_{i=1}^{n} C_{Rep,i}(q)P_{Rep_i}(t_i)\frac{1}{(1+r)^{t_i}} \quad (2.3)$$

Where *ith* index characterize the capitalized reparation costs at the *ith* inspection when failure has not occurred earlier, $C_{Rep,i}(q)$ is the cost of maintenance and repair (incl. loss of production) at the *ith* inspection and $P_{R_i}(t_i)$ is the probability of performing a repair after the *ith* inspection when failure has not occurred earlier and assuming no earlier repair action has been performed.

The total capitalized expected costs due to failure are:

$$C_F\big(e, d(S)\big) = \sum_{t=1}^{T_L} C_F(t)\Delta P_{F,t}\, P_{COL|FAT} \frac{1}{(1+r)^t} \tag{2.4}$$

Where t index represent the costs of failure at the time t, $C_F(t)$ is the cost of failure (incl. loss of production), $\Delta P_{F,t}$ is the annual probability of failure and $P_{COL|FAT_j}$ is the conditional probability of collapse or the structures given fatigue failure of the considering component j.

Considering posterior optimization of inspection plan, inspection and monitoring data can be use to update RBI plans making this process a recursive activity, see Sørensen et al. (1991). This approach can be used for OWTs' structural and mechanical parts (tower, blades, support structures, gears, shafts…). With inclusion of different-type components, more precise RBI should be carried out, taking into account the refinement in time intervals (years to months or day), structure conditioned-states (active or passive controlled OWTs) and non-usual or extreme external events.

Unlike oil & gas installations, OWTs response is often dominated by wind loading, including wind farm turbulence (wake effects). Wind intensity fluctuations are a significant feature to consider for fatigue failure limit state, causing typical load cycles per year (ν_{wf}=5x10^7 and ν_{rr}=1x10^7 cycles per year, wake effects and rotor response dominating case, respectively) that are larger compared with wave dominating cases (typically, ν_{wave}=1x10^6 cycles per year). Density function of stress ranges, that is obtained from the structural response by different counting methods (Rain-flow counting method, peak counting method…); will differ depending the response dominating cases. Generally, they can be modeled by a Weibull distribution.

3. WIND LOAD

The wind load at an offshore site is fairly different than at land sites. This variation is principally related with the difference of surface roughness, where sea roughness is typically much smaller than the land one. The wind stability statistics show that sea mean atmospheric stability is slightly on the stable side; whereas over land it is seen slightly unstable conditions on the average, see Frandsen et al. (1996). In addition to the ambient turbulence, OWTs inside of wind farms face certain unfavorable wind variations (see figure 3.1) with the increase of wakes behind others OWTs and the decrease of their fatigue life.

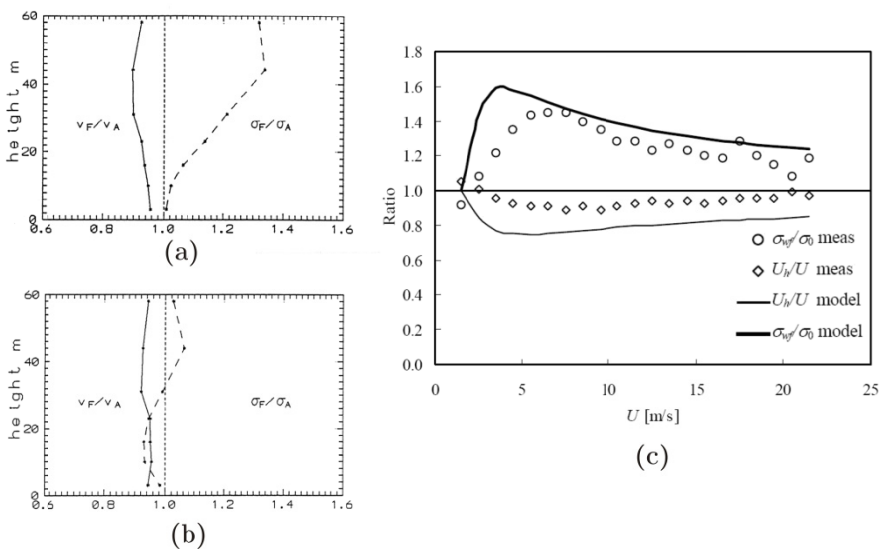


Figure 3.1 Ratios of wind speed (ν_F/ν_A) and standard deviation of turbulent wind speed fluctuations (σ_F/σ_A) vertical profiles inside and outside the wind farm. The indices "A" and "F" refer to meteorogical mast outside of wind farm and inside wind farm, respectively. Ambient wind speed between (a) 8<U<12 m/s and (b) 12<U<24 m/s from Frandsen and Christensen (1994). (c) Ratios of wind speed U at hub height and turbulence σ_u inside $(U_h\ and\ \sigma_{wf})$ and outside $(U\ and\ \sigma_o)$ the wind farm, as function of wind speed. The full lines are the model predictions, from Frandsen (2005).

Wind load stress effects are strongly related with the type of power control (pitch or stall) in the OWT. Moreover, the response is dependent on the OWT mode: standstill or operational. Within the operational case there are passive, active or mixed power control, assuring a rational output of electricity and protecting structural and electromechanical parts.

The turbulence intensity, defined as the standard deviation of the wind speed fluctuations divided by the mean (n-minutes) wind speed; represent an important aspect to consider because its effects on OWT's fatigue life. In this paper is used the following model for standard deviation of wake turbulence proposed by Frandsen, S. (2005):

$$\sigma = [(1 - N_w p_w)\sigma_0^m + N_w p_w \sigma_w^m]^{1/m} \tag{3.1}$$

where σ_0 is the turbulence standard deviation under free flow condition, σ_w is the maximum wake turbulence under wake condition, p_w(=0.06) is the probability of wake condition and N_w is the number of wakes to which the considered wind turbines is exposed to. It is assumed that the standard deviation of the response is proportional to the standard deviation of turbulence; while in certain situations (load, passive or active power control; complex geography, atypical terrain condition…) this simple relation with the response may be inadequate.

The above mentioned turbulence model demonstrates to be consistent (with a slightly conservative inaccuracy of 3-4%) when it is used with superimposed deterministic load component, see Frandsen (2005) and Sørensen et al. (2007).

4. PROBABILISTIC MODEL FOR FATIGUE FAILURE

In this section the probabilistic models for assessing the fatigue failure life based on SN-curves and fracture mechanics (FM) model are briefly mentioned. To evaluate the fatigue life is used the probabilistic model for fatigue failure described in Sørensen et al. (2007).

In the assessment of SN fatigue life, the deterministic design equation for free flow ambient turbulence is:

$$G(z) = 1 - \frac{\nu \cdot FDF \cdot T_L}{K_C} \int_{U_{in}}^{U_{out}} D_L\big(m; \sigma_{\Delta\sigma}(U)\big) \cdot f_U(U)\ dU = 0 \tag{4.1}$$

where for linear SN-curve:

$$D_L\big(m; \sigma_{\Delta\sigma}(U)\big) = \int_0^\infty \mathrm{s}^m \cdot f_{\Delta\sigma}\big(s|\sigma_{\Delta\sigma}(U)\big)\, ds \tag{4.2}$$

and bi-linear SN-curve:

$$D_L\big(m_1, m_2, \Delta\sigma_D\,; \sigma_{\Delta\sigma}(U)\big) = \int_0^{\Delta\sigma_D} \mathrm{s}^{m_2} \cdot f_{\Delta\sigma}\left(s|\alpha_{\Delta\sigma}(U)\frac{\hat{\sigma}_u(U)}{z}\right) ds + \int_{\Delta\sigma_D}^{\infty} \mathrm{s}^{m_1} \cdot f_{\Delta\sigma}\left(\mathrm{s}|\alpha_{\Delta\sigma}(U)\frac{\hat{\sigma}_u(U)}{z}\right) ds \tag{4.3}$$

$$\sigma_{\Delta\sigma}(U) = \alpha_{\Delta\sigma}(U) \cdot \frac{\sigma_u(U)}{z} \quad and \quad \hat{\sigma}_u(U) = I_{ref} \cdot (0.75 \cdot U + b); \quad b = 5.6\frac{m}{s} \tag{4.4a, b}$$

where ν is the total number of fatigue load cycles per year, FDF is the fatigue design factor ($FDF = T_F/T_L$), K_C is the characteristic value of K (mean $\log K$ minus two standard deviation of $\log K$), U_{in} and U_{out} are the cut-in and cut-out wind speed, respectively; $f_U(U)$ is the density function of mean wind speed U, D_L is the expected value of $\Delta\sigma^m$ given standard deviation $\sigma_{\Delta\sigma}$ and mean wind speed U in which $f_{\Delta\sigma}\big(s|\sigma_{\Delta\sigma}(U)\big)$ represents the density function for stress ranges given standard deviation $\sigma_{\Delta\sigma}(U)$ at mean wind speed U. This density function and ν can be obtained by counting methods, e.g. Rainflow counting.

In the 4.4a equation $\alpha_{\Delta\sigma}(U)$ is the influence coefficient for stress ranges given mean wind speed U ($\sigma_{\Delta\sigma}(U)/\sigma_{\mathrm{U}}(U)$), $\sigma_u(U)$ is the standard deviation of turbulence given mean wind speed U and z is the design parameter (e.g. proportional a cross sectional area). The 4.4b equation is the characteristic (90% fractil representative turbulence) ambient turbulence where I_{ref} is the (IEC-) reference turbulence intensity (equal to 0.14 for medium turbulence characteristics).

The corresponding limit state equation is:

$$g(t) = \Delta - \frac{\nu \cdot t}{K} \int_{U_{in}}^{U_{out}} \int_0^\infty (X_W \cdot X_{SCF})^m \cdot D_L\left(m; \alpha_{\Delta\sigma}(U)\frac{\sigma_u(U)}{z}\right) \cdot f_{\sigma_u}(\sigma_u|U) \cdot f_U(U)\ d\sigma_u\, dU \tag{4.5}$$

Where Δ is a stochastic variable modeling the uncertainty related to the Miner rule for damage accumulation, t is the life time in years, X_W is the model uncertainty related to wind load effects (exposure, assessment of lift and drag coefficients, dynamic response calculation), X_{SCF} is the model uncertainty related to local stress analysis and $\sigma_u(U)$ is modeled as LogNormal distributed with a representative mean turbulence (90% fractil value-IEC 61400-1) equal to $I_{ref}(0.75 \cdot U + 3.6)$ with a standard deviation equal to $1.4\, m/s \cdot I_{ref}$.

For a wind farm location the design equation is based on IEC 61400-1 (IEC 2005):

$$G(z) = 1 - \frac{\nu \cdot FDF \cdot T_L}{K_C} \int_{U_{in}}^{U_{out}} \left[\begin{array}{l} (1 - N_w \cdot p_w) \cdot D_L\left(m; \alpha_{\Delta\sigma}(U) \frac{\hat{\sigma}_u(U)}{z}\right) \\ + p_w \cdot \sum_{j=1}^{N_w} D_L\left(m; \alpha_{\Delta\sigma}(U) \frac{\hat{\sigma}_{u,j}(U,j)}{z}\right) \end{array} \right] \cdot f_U(U)\, dU = 0 \tag{4.6}$$

where N_w is the number of neighboring wind turbines, p_w is the probability of wake from a neighboring wind turbine (equal to 0.06), $\hat{\sigma}_{u,j}$ is the standard deviation of turbulence from neighboring wind turbine no. j:

$$\hat{\sigma}_{u,j}(U,j) = \sqrt{\frac{0.9 \cdot U^2}{\left(1.5 + 0.3 \cdot d_j \sqrt{U/c}\right)^2} + \hat{\sigma}_u{}^2} \tag{4.7}$$

where d_j is the distance between OWT normalized by rotor diameter to the neighboring wind turbine j and c is a constant equal to 1 m/s.

The limit state equation corresponding to the above equation is:

$$g(t) = \Delta - \frac{\nu \cdot t}{K} \int_{U_{in}}^{U_{out}} \int_{0}^{\infty} (X_W \cdot X_{SCF})^m \cdot \left[\begin{array}{l} (1 - N_w \cdot p_w) \cdot D_L\left(m; \alpha_{\Delta\sigma}(U) \frac{\sigma_u(U)}{z}\right) \\ + p_w \cdot \sum_{j=1}^{N_w} D_L\left(m; \alpha_{\Delta\sigma}(U) \frac{\sigma_{u,j}(U,j)}{z}\right) \end{array} \right] \cdot f_U(U) \cdot f_{\sigma_u}(\sigma_u|U)\, d\sigma_u\, dU \tag{4.8}$$

where

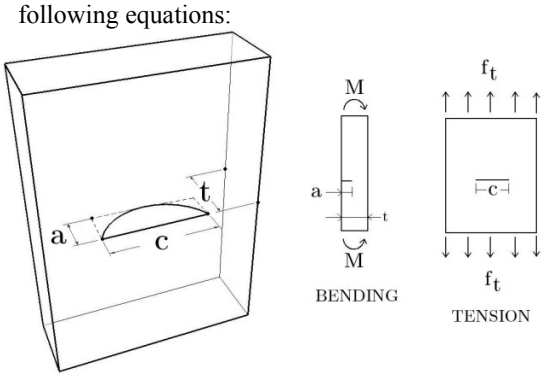
$$\sigma_{u,j}(U,j) = \sqrt{\frac{X_{wake} \cdot U^2}{\left(1.5 + 0.3 \cdot d_j \sqrt{U/c}\right)^2} + \sigma_u{}^2} \tag{4.9}$$

X_W is the model uncertainty related with wake turbulence model. The design parameter z is calculated with (4.1) or (4.6) and then used in limit state equation (4.5) or (4.8) to estimate the reliability index or probability for failure of the reference time t.

For the assessment of FM fatigue life is used a one dimension crack model (figure 4.1) where the crack length c is related with the growth crack depth a through a constant f_{cr}. It is assumed that life may be represented by fatigue initiation life and a fatigue propagation life. This is represented as follows:

$$N = N_I + N_P \tag{4.10}$$

Where N is the number of stress cycles to fatigue failure, N_I is the number of stress cycles to crack propagation and N_P is the number of stress cycles from initiation to crack through. The crack growth can be described by the following equations:



$$\frac{da}{dN} = C_A(\Delta K_A)^m \qquad a(N_o) = a_o \tag{4.11}$$

$$\Delta K_A = \Delta\sigma \cdot \sqrt{\pi a} \tag{4.12}$$

$$c(f_{cr} \cdot a_o) = c_o \tag{4.13}$$

Figure 4.1 surface crack idealization in plate under fatigue loads.

where C_A and m are the material parameters, $a_o$and c_o describe the initial crack depth a and crack length c, respectively, after N_I cycles and where the stress intensity range is ΔK_A.

The stress range $\Delta\sigma$ is obtained from:

$$\Delta\sigma = Y \cdot \Delta\sigma^{\mathrm{e}} \tag{4.14}$$

where Y is the model uncertainty variable related to geometry function and $\Delta\sigma^{\mathrm{e}}$ is the equivalent stress range. $\Delta\sigma^{\mathrm{e}}$ for a single OWT is calculated with:

$$\Delta\sigma^{\mathrm{e}} = X_W \cdot X_{SCF} \cdot \left[\int_{U_{in}}^{U_{out}} \int_0^{\infty} D_L\left(m; \alpha_{\Delta\sigma}(U)\frac{\sigma_u(U)}{z}\right) \cdot f_U(U) \cdot \; f_{\sigma_u}(\sigma_u|U)\, d\sigma_u \, dU \right]^{1/m} \tag{4.15}$$

and for a wind farm location case:

$$\Delta\sigma^{\mathrm{e}} = X_{wake} \cdot X_{SCF} \cdot \left[\int_{U_{in}}^{U_{out}} \int_0^{\infty} \left[\begin{array}{l} (1 - N_w.p_w) \cdot D_L\left(m; \alpha_{\Delta\sigma}(U)\frac{\sigma_u(U)}{z}\right) \\ +p_w \cdot \sum_{j=1}^{N_w} D_L\left(m; \alpha_{\Delta\sigma}(U)\frac{\sigma_{u,j}(U,j)}{z}\right) \end{array} \right] \cdot f_U(U) \cdot \; f_{\sigma_u}(\sigma_u|U)\, d\sigma_u \; dU \right]^{1/m} \tag{4.16}$$

The limit state criteria used in the FM analysis is related with the failure when crack exceeds a critical crack size:

$$g(t) = a_c - a(t) \tag{4.17}$$

where a_c is the critical crack size and a is crack depth.

For RBI planning the FM model is usually calibrated to result in the same reliability level as the code-based SN model. The RBI planning and maintenance is strongly related with inspection quality (inspection methods, technology, environmental conditions, inspectors' expertise, etc). The incorporation of these influential factors is attained by using a distribution of the detectable crack size or probability of detection curve (POD). Examples of POD equations are:

$$POD(x) = 1 - 1\Big/\left[1 + \left(\frac{x}{x_o}\right)^b\right] \tag{4.18}$$

$$POD(x) = P_O \cdot (1 - exp(-x/\lambda)) \tag{4.19}$$

Where x_o and λ are the minimum detectable crack size, P_O and b are distribution parameters depending on the inspection methods.

5. EXAMPLES

An offshore wind turbine with a steel jacket support structure is considered as support of an OWT. OWT's have an expected life time at 20 years and a design fatigue life time (T_F) of 60 years. For the Influence coefficient $\alpha_{\Delta\sigma}(U)$ is used the function in figure 5.1 (mudline bending moment – pitch controlled wind turbine) regarding this as a representative function in the support structure. This influence function is highly non-linear due to the control system.

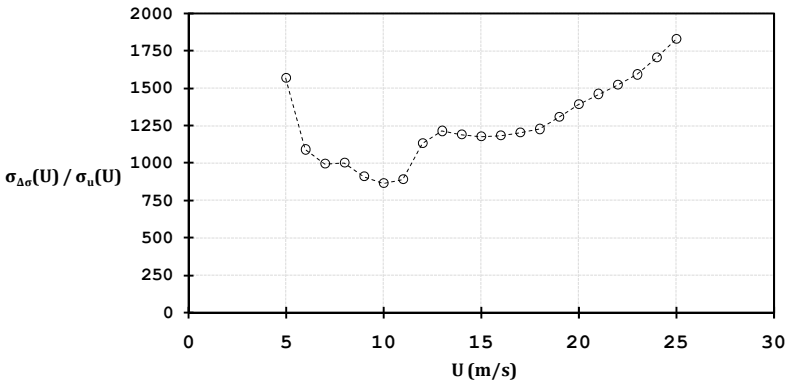


Figure 5.1 $\sigma_{\Delta\sigma}/\sigma_{\mathrm{U}}$ for mudline bending moment – pitch controlled wind turbine.

Wind turbine in wind farm (IWF) and alone/single (S) OWT location are considered. For each location is considered linear (L) and bi-linear (BL) SN-curve. In tables 5.1 – 5.3 are shown the stochastic models used.

Table 5.1 SN Stochastic model (welded steel detail).

Variable	Distribution	Expected value	Standard deviation	Comment
Δ	N	1.0	0.10	Damage accumulation
X_W	LN	1.0	0.10	Wind
X_{SCF}	LN	1.0	0.10	Stress concentration factor
X_{wake}	LN	1.0	0.15	Wake
m_1	D	3	--	SN-curve. Exponent (linear)
m_2	D	5	--	SN-curve. Exponent (bi-linear)
$\Delta_{\sigma D}$	D	71 MPa	--	Constant amplitude fatigue limit
Log K_1	N	Determined from $\Delta_{\sigma D}$	0.20	Material parameter
Log K_2	N	Determined from $\Delta_{\sigma D}$	0.25	Material parameter
T_F	D	60 years	--	Fatigue life
Nw	D	5/--	--	In-wind farm/single OWT
ν	D	$5 \cdot 10^7$	--	Fatigue cycles per year
$U_{in} - U_{out}$	D	5 – 25 m/s	--	Cut in – out velocities
pw	D	0.06/0.0	--	In-wind farm/single OWT
d_j	D	4.0	--	Normalized distance of OWT
Log K_1 and Log K_2 are assumed fully correlated				

D: Deterministic, N:Normal, LN:LogNormal, W:Weibull.

Table 5.2 FM Uncertainty modeling (welded steel detail).

Variable	Distribution	Expected value	Standard deviation	Comment
Ln Cc	N	$\mu_{ln\,Cc}$ (fitted)	0.77	Crack growth ratio
N_I	W	$\mu_0 = T_{init} \cdot \nu$	$0.35 \cdot \mu_0$	T_{init}(fitted), Initiation Time
Y	LN	1.0	0.10	Shape factor
X_W	LN	1.0	0.10	Wind
X_{SCF}	N	1.0	0.10	Stress concentration factor
X_{wake}	LN	1.0	0.15	Wake
a_c	D	50 mm	--	Critical crack size
a_o	D	0.4 mm	--	Initial crack size
f_{cr}	D	4.0	--	Crack length/depth ratio
Thickness	D	50 mm	--	thickness
m	D	3.0	--	Material parameter
Ln C_c and N_I are correlated with correlation coefficient $\rho_{ln\,Cc,N_I} = -0.5$				

D: Deterministic, N:Normal, LN:LogNormal, W:Weibull.

Table 5.3 Distribution parameters and Equations.

Variable	Distribution	Parameters	Comment
P_F	D	$1.0 \cdot 10^{-3}/1.0 \cdot 10^{-4}$	Annual max. prob. of failure
$F_U(u)$	$W(\alpha, \beta_U)$	$\alpha = 2.3\,, \beta_U = 10.0\ m/s$	Mean wind speed
$f_{\Delta\sigma_D}(\cdot)$	$W(\alpha_{\Delta\sigma_D}, \beta_{\Delta\sigma_D})$	$\alpha_{\Delta\sigma_D} = 0.8$	Stress ranges
$f_{\sigma_u}(\cdot)$	$LN(\mu, \sigma)$	$\mu = I_{ref} \cdot (0.75 \cdot U_i + 3.6), \sigma = 1.4 \cdot I_{ref}$	Mean turbulence
$POD(x)$	Equation (4.19)	$P_O = 1.0, \quad \lambda = 2.67\ mm^{-1}$	Probability of Detection
$N_1(s)$	$K_1 \cdot s^{-m_1}$	$s \geq \Delta\sigma_D$	SN curve linear
$N_2(s)$	$K_2 \cdot s^{-m_2}$	$s < \Delta\sigma_D$	SN curve bi-linear

D: Deterministic, N:Normal, LN:LogNormal, W:Weibull.

The design values z for each case are shown in table 5.4 (equations 4.1 and 4.6) and in figures 5.1 and 5.2 are shown the results of the assessment of the reliability with SN approach (equations 4.5 and 4.8). β and $\Delta\beta$ are defined as the cumulative probability of failure (P_F) and the annual probability (ΔP_F) of failure ($\beta = \Phi^{-1}(\mathrm{P_F(t)})$ and $\Delta\beta = (\Phi^{-1}(\mathrm{P_F(t)}) - \Phi^{-1}(\mathrm{P_F(t-1)}))$), respectively. It is seen that for bilinear SN-curve values of β and z are smaller than for linear cases. The design values for cases in wind farm location (wake turbulence) are larger than the ones exposed to free flow turbulence due to the accumulation of fatigue.

Table 5.4 *z*-design parameters

	IWF OWT, L	S OWT, L	IWF OWT, BL	S OWT, BL
Z	0.5654	0.4934	0.4253	0.3657

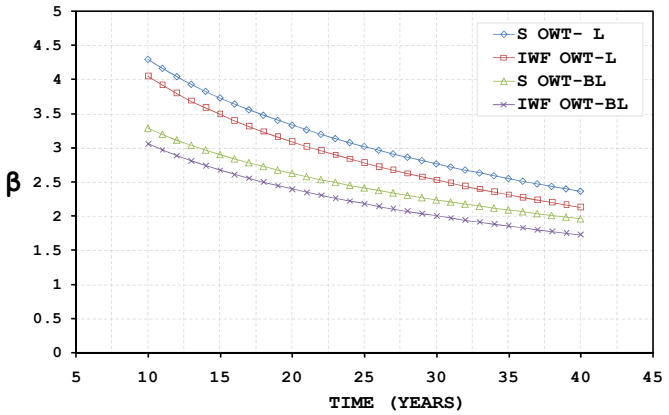


Fig. 5.1 Reliability indices for SN-approach corresponding to an cumulative probability of failure

For all the cases the calibration of fracture mechanic reliability curve in the interval 10 to 20 years (see figure 5.2)

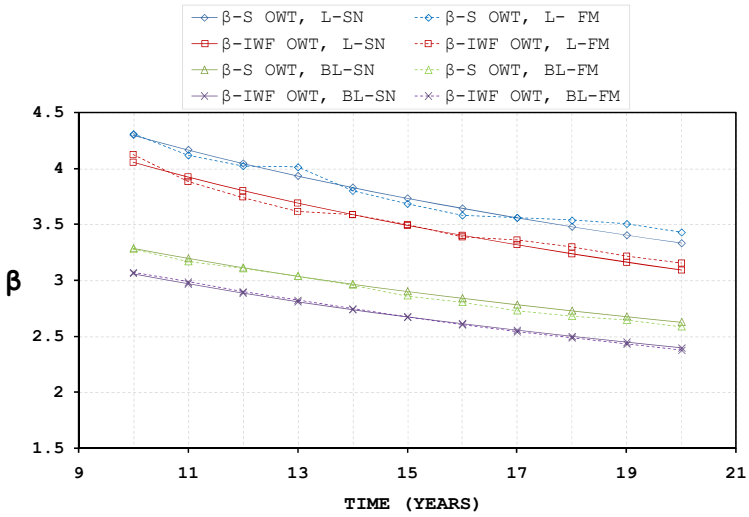


Fig 5.2 Reliability indices for SN- and calibrated fracture mechanics curve corresponding to the cumulative probability of failure.

In Figure 5.3 and table 5.5 is shown the resulting life-cycle assessment of reliability and inspection plan obtained with a maximum acceptable annual probability of failure equal to 1.0×10^{-3} and 1.0×10^{-4}. Comparing the first inspection time, slightly earlier inspections are coming out in-wind farm sites due to the increase of fatigue coming from wake turbulence. It is noted that in all four cases the design parameter z is determined by deterministic design such that the code-based design criteria is exactly satisfied.

Table 5.5 Inspections times as a function of the threshold on the maximum annual probability of failure.

		INSPECTION TIME	
		Maximum Annual P_F	
CASE	SN CURVE	1.00E-03	1.00E-04
IWF OWT	LINEAR	--	17
SINGLE	LINEAR	--	26
IWF OWT	BILINEAR	17	7,15,30
SINGLE	BILINEAR	23	8,17,38

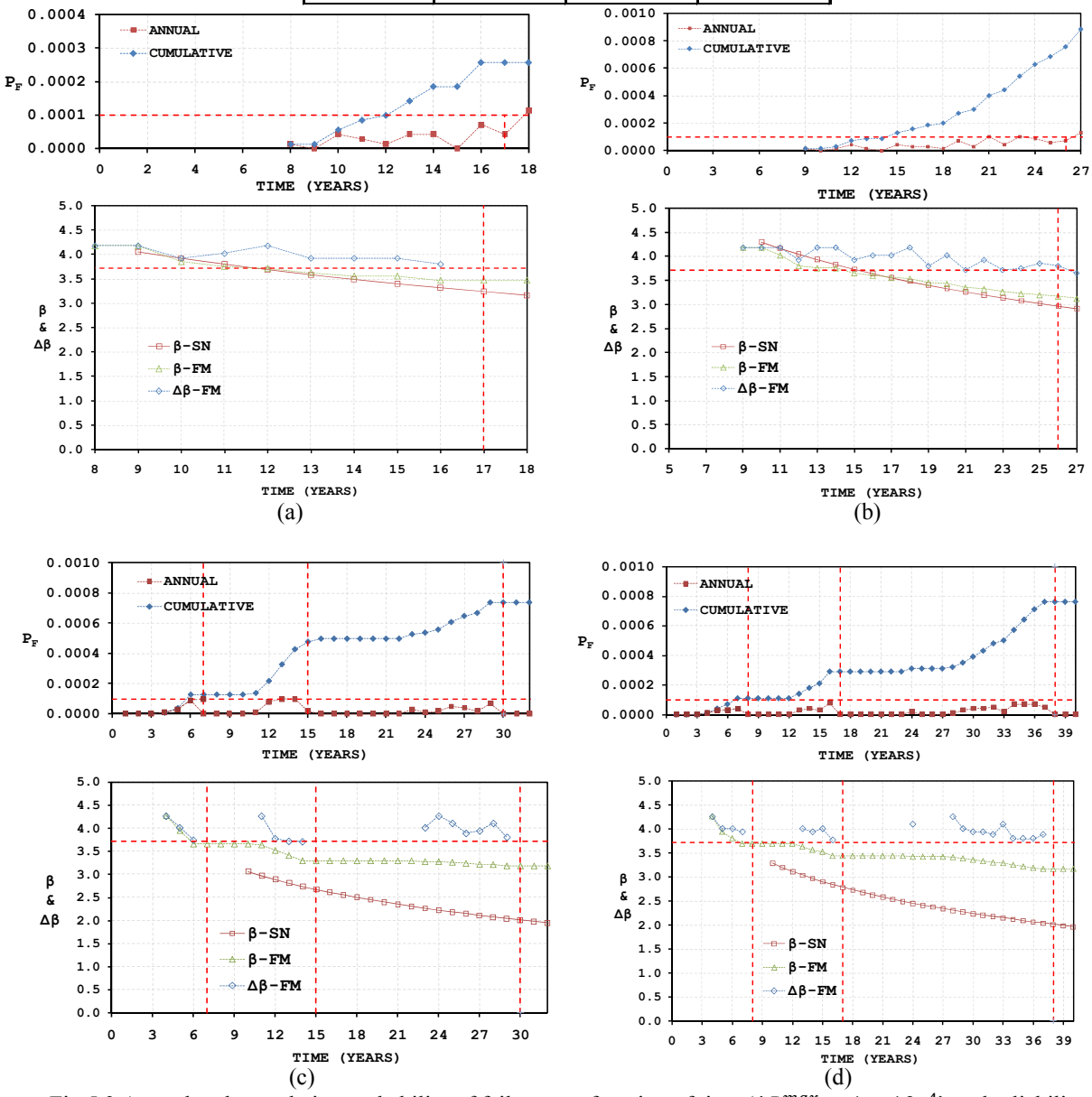


Fig 5.3 Annual and cumulative probability of failure as a function of time ($\Delta P_F^{max} = 1 \times 10^{-4}$) and reliability indices corresponding to the cumulative and annual probability of failure. (a) In wind farm OWT with linear SN-curve. (b) Single OWT with linear SN-curve. (c) In wind farm OWT with bilinear SN-curve. (d) Single OWT with bilinear SN-curve.

6. CONCLUSIONS

Based on risk-based inspection planning methods for oil & gas installations, a framework for optimal inspection and maintenance planning was applied for offshore wind turbines, addressing the analysis of fatigue prone details (single hot spots in the context of RBI for this work) at the jacket or tripod steel support structures. In wind park location and single OWT were taken into account by using a probabilistic model for fatigue failure included in an established code. This inspection optimization approach represents a viable method to outline inspection plans aimed at OWT, regarding its application to large structural systems (steel jacket, tripod and monopile as support structures). Furthermore, it may also be applied to other important components like blades, nacelle, yaw system, etc. Knowingly of the fast growth of wind industry (EWEA 2007) and offshore wind turbine parks, larger and complex cluster of such structural systems may potentially be benefited for optimizing the inspection and maintenance efforts and generate suitable inspection plans ensuring an acceptance criteria with respect to risk. Besides, this RBI approach may also be applied as a decision tool for estimating the consequences of a possible service life extensions and reduction (or strengthening) on the necessary maintenance and inspection efforts.

7. ACKNOWLEDGEMENTS

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