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Influence of Wind Induced Fatigue Damage in the Reliability of Wind Turbines

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Abstract**—**Steel tubular towers serving as support structures for large wind turbines are subjected to several hundred million stress cycles caused by the turbulent nature of the wind. This causes high-cycle fatigue, which could govern the design of the tower. Maintaining the support structure after the wind turbines reach its typical 20-year design life has become a common practice; however, quantifying the changes in the reliability on the tower is not usual. In this paper the effect of fatigue damage in the wind turbine structure is studied whit the use of fracture mechanics, and a method to estimate the reliability over time of the structure is proposed. A representative wind turbine located in Oaxaca, Mexico is then studied. It is found that the system reliability is significantly affected by the accumulation of fatigue damage.

Keywords**—**Crack growth, fatigue, Monte Carlo simulation, structural reliability, wind turbines.

I. Introduction

TURBINE size in the last 30 years has grown from 50 to 5000kW. This has brought a new set of problems that needs to be solved. For small turbines a conservative design was affordable, this however is not true for current turbines, and taking the design to the limits has produced some unexpected failures. Turbines were initially designed only for extreme loads that were expected during its 20-year life; however, after several failures it became evident that wind turbines are fatigue critical machines. Despite this, the procedures used to calculate fatigue damage under random loading are less than satisfactory. The "de facto" standard in the wind industry is the Palmgren-Miner lineal damage rule; however, the qualitative nature of this method makes fracture mechanics a better candidate for the analysis conducted in this study. Lately the practice of refurbishing old wind turbines, while maintaining the support structure after the wind turbine reaches its typical 20-year design life has become increasingly common, this brings changes in the reliability of the structure that are not quantified.

In this study only fatigue loading is analyzed, particularly at the base of the structure, which is considered critical. Since only fatigue in the tower base is being studied, the turbine is considered parked, in order to simplify the calculations. The following diagram presents the methodology followed here.

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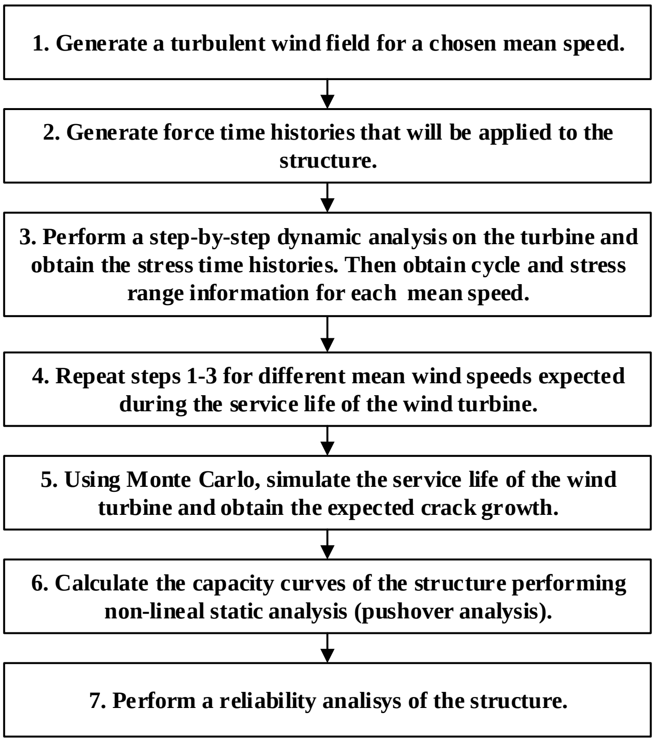

Fig. 1 Diagram of the used methodology

II. Turbulent Wind Field Generation

The longitudinal component of the turbulent wind in the prevalent wind direction is designated $U(z,t)$ and is usually designated as a mean wind speed $\bar{U}(z)$ which varies on a time-scale of several hours due to seasonal, synoptic and diurnal effects; and zero-mean turbulent fluctuations $u(z,t)$ superimposed, where z represents the height above ground and t is the time as seen in (1):

$$U(z,t) = \bar{U}(z) + u(z,t) \tag{1}$$

To estimate the increase of mean wind speed with height (wind shear) the following power law approximation is used [1]:

$$\bar{U}(z) = \bar{U}_{10}(z/10)^{\alpha} \tag{2}$$

where $\bar{U}_{10}$ represents the mean speed at a height of 10m and α is an exponent that approximates the power law to the logarithmic law and is dependent on the roughness length z_0, which varies according to the surface, and a reference height

z_{ref} that should be taken as half the height where the approximation is required.

Parameter α is estimated as follows:

$$\alpha = \left(1/\ln\left(z_{ref}/z_0\right)\right) \tag{3}$$

The turbulence intensity is defined by:

$$I = \bar{U}/\sigma \tag{4}$$

where σ is the standard deviation and for the longitudinal component is approximately constant with height, and is given by [2]:

$$\sigma_u = \frac{7.5\eta(0.538 + 0.09\ln(z/z_0))^{\rho} u^*}{1 + 0.156\ln(u^*/fz_0)} \tag{5}$$

where f is the Coriolis parameter, u^* is known as the friction velocity, and the parameters η and ρ are given by:

$$\eta = 1 - 6fz/u^* \tag{6}$$

$$\rho = \eta^{16} \tag{7}$$

The spectrum of turbulence describes the frequency content of wind-speed variations. For open terrain the Kaimal formulation is the most commonly used, that according to the IEC is given by [3]:

$$\frac{nS_u(n)}{{\sigma_u}^2} = \frac{4nL_u/\bar{U}}{(1 + 6nL_u/\bar{\bar{U}})^{5/3}} \tag{8}$$

where $S_u(n)$ is the autospectral density function for the longitudinal component, n represents the frequency in Hz and L_u is a length scale. Length scale is dependent on the surface rougness and the height above ground; far enough above the ground, $> z_i$, the turbulence is no longer restrained by the proximity of the surface and becomes isotropic. Considering $z_i = 1000{z_0}^{0.18}$ we have [4] :

$$^{x}L_u = 280(z/z_i)^{0.35}\ if\ z \le z_i \tag{9}$$

$$^{x}L_u = 280(z/z_i)^{0.35}\ if\ z > z_i$$

For the Kaimal spectrum

$$L_u = 2.329\ {}^{x}L_u\ .$$

The spatial variation of turbulence in the lateral and vertical directions is important, and in order to model its effects the spectral description of turbulence must be extended to include information about the cross-correlations between turbulent fluctuations at points separated laterally and vertically. These correlations can therefore be described by coherence functions as a function of frequency and separation between the points of interest. The coherence function is given by [5]:

$$Coh_{jk} = \exp\left(-\frac{C_{jk}\Delta_{jk}n}{\bar{U}_{jk}}\right) \tag{10}$$

where Δ_{jk} is the distance between points j and k, $\bar{U}_{jk}$ is the mean of the velocity in points j and k and C_{jk} is a spacing function between points j and k and the mean height of these $z_m = (z_j + z_k)/2$, and it is given by:

$$C_{jk} = \mathrm{b}\left(\frac{\Delta_{jk}}{z_m}\right)^{0.25} \tag{11}$$

where $b = 12 + 5\mu_b$ and μ_b is a normally distributed random number in the range (-1, 1) [5]

The wind field simulation was made using the Veers method, also known as the Sandia method [6]. A MATLAB script was developed to generate correlated time histories in all points in study, located along the blades and the tower. For each mean speed a 10 minute time history was generated, following industry standards for fatigue calculations.

III. Force Time History

To generate force time histories based on the wind field simulation the following is considered:

i. The wind turbine is parked.
ii. Only the longitudinal component of the wind is considered.
iii. Thrusting load is applied at the hub.

The force in each blade segment is given by:

$$F(t) = \frac{1}{2}\rho U(z,t)^2 A C_d \tag{12}$$

where $\rho = 1.23\ kg/m^3$ is the density of the air, A represents the projected area of the blade segment and C_d is the drag coefficient, that is approximated with plate theory and Timmer's equation [7], as follows:

$$C_d = C_{d,max}\sin^2\alpha \tag{13}$$

$$C_{d,max} = 1.980 - 5.203\, y/c$$

where α is the angle of attack and y/c is the ordinate of the airfoil at $x/c = 0.0125$.

IV. Fatigue Analysis

Once the dynamic stress at the tower base is obtained from the FEM model, the Rainflow counting method is applied to obtain stress histograms, for each chosen mean velocity. This is done in order to obtain the effective stress range given by [8]:

$$R_{eff} = \left(\sum f_i {S_i}^3\right)^{\frac{1}{3}} \tag{14}$$

where f_i and S_i are the stress range and its probability of occurrence from the stress histogram. Equation (14) is known as Miner's rule.

Fracture mechanics was used to estimate the fatigue damage based on linear crack propagation models. In this analysis technique, a crack subjected to N load cycles will grow from an initial length a_0 to a final length based on its crack growth rate (da/dN). The procedure to estimate the crack growth rate is determined by means of the Paris-Erdogan equation [9]:

$$\frac{da}{dN} = C(\Delta K)^m \tag{15}$$

where C and m are crack growth parameters that are dependent on the material and ΔK is the stress intensity factor range, which depends on the effective stress range, the crack length and the crack geometry. The stress intensity factor K_I to be used is obtained considering a plate of infinite length [10]:

$$K_I = \sigma_{tmax}\sqrt{\pi \mathrm{a}} \tag{16}$$

where σ_{tmax} is the remote tensile stress and a is the crack length.

V. Capacity Curves

Having obtained the crack growth in certain points of the structure it is possible to decrease the thickness at the tower base (considering that the crack is incapable of taking load), this considerations allows us to obtain capacity curves of the structure for any given number of years of service. The capacity curves, that represent displacement vs. base shear, are obtained with a FEM model using Non Lineal Static Analysis.

Once the pushover curve is determined, we need to convert base shear to equivalent nominal wind speeds, since the lateral forces for any given wind speed are known from the simulations we can represent the base shear as the summation of the forces applied in each point of the structure [11]:

$$V = \sum_{i=1}^{n} F_i \tag{17}$$

Monte Carlo simulation is then used to construct several wind speed-displacement curves based in the statistical analysis of the wind force time histories. The curves are used to obtain the vulnerability analysis of the structure.

VI. Vulnerability Analysis

The vulnerability of a structure is defined as the conditional probability of exceeding a limit state capacity for a given level of wind speed, which can be expressed as [12] :

$$F(y) = \mathrm{P}[U_c \leq y] \tag{18}$$

where $F(U)$ is the structural vulnerability at wind speed y for a given limit state. This vulnerability represents the cumulative distribution function of the limit state U_c.

VII. Case Study

A representative wind turbine for Mexico was used in this study. It corresponds to a 1500kW wind turbine with an 80m tower; similar turbines are used in several wind farms in the state of Oaxaca, Mexico. The reference model used is the AW70/1500 from Acciona Windpower, all the information that was not publicly available was completed from other sources, particularly NREL-5MW [13], DOWEC 6MW [14] and Nordtank NTK 500/41 [15].

Blade geometry was based on the LM 42.1 blade, with a 42.13m length; twist, chord and airfoil distribution are presented Table I.

TABLE I
BLADE PROPERTIES

r(m)	Twist	Chord (m)	Airfoil
0	0	1.893	Circular
1	0	1.893	Circular
2	0	1.925	Circular
4	0	2.238	Circular
6	0	2.678	DU99W350LM
8	10.8	2.958	DU99W350LM
8.5	10.8	2.975	DU99W350LM
10	8.23650605	2.927	DU99W350LM
12	7.72380726	2.773	DU99W350LM
14	7.21110847	2.569	DU97W300LM
16	6.69840968	2.337	DU97W300LM
18	6.18571089	2.107	DU91W2250LM
20	5.67301211	1.906	DU91W2250LM
22	5.16031332	1.731	DU91W2250LM
24	4.64761453	1.578	DU91W2250LM
26	4.13491574	1.443	S814
28	3.62221695	1.32	S814
30	3.10951816	1.206	S814
32	2.59681937	1.097	S814
34	2.08412058	0.991	S814
36	1.57142179	0.893	S814
38.355	0.96771897	0.793	DU93W210LM
40.861	0.32530738	0.634	DU93W210LM
42.13	0	0.04	NACA 64618

TABLE II
AIRFOIL Y/C VALUES

Airfoil	y/c
Circular	0.287
DU99W350LM	0.05
DU97W300LM	0.03
DU91W2250LM	0.026
S814	0.022
DU93W210LM	0.02
NACA 64618	0.02

Airfoil properties are presented in Table II.

An 8500 kg/m^3 steel density was used instead of the most usual steel density of 7850 kg/m^3 to account for paint, bolts, weld and joints that are not considered in the tower thickness. The tower was considered divided in 3 sections, each with different thickness, Table III presents the selected tower properties.

TABLE III
TOWER PROPERTIES

Tower weight	152600 kg
Blade weight	5900 kg ea.
Blade number	3
Nacelle weight	52300 kg
Hub weight	15200 kg
Rotor diameter	64.5 m
Tower height	80m
Base diameter	4.3m
Top diameter	2.13m
First section thickness	0.028m
Second section thickness	0.024m
Third section thickness	0.018m
Tower weight	152600kg
Steel type	S355
Young's module	210 GPa
Natural frequency	0.3529Hz

Analyzing entire service life of a wind turbine results computationally exhaustive as it contains the order of 10^6 periods of 10 minutes in a 20 year life. To simplify this procedure, Monte Carlo simulations are used:

i. The annual mean speeds follow a bimodal Weibull distribution.
ii. From the Rainflow counting method we can obtain parameters to be used to simulate the cycles and stresses on the tower.
iii. Material parameters are considered constants.

The annual wind speed distribution used was taken from data obtained in the state of Oaxaca and it follows a bimodal Weibull distribution instead of the most common unimodal distribution. Table IV shows the distribution parameters for the site [16].

TABLE IV
WEIBULL AND WEIBULL PARAMETERS

p	0.3799		
$\bar{U}_1$	3.603 m/s	$\bar{U}_2$	14.818 m/s
σ_1	2.212 m/s	σ_2	3.256 m/s
k_1	1.674	k_2	5.232
c_1	4.034 m/s	c_2	16.097 m/s

Table V presents the rest of the data used to simulate N periods of 10 minutes wind speeds that covers the years we require to study, allowing us to find the crack growth over time for different design lives.

TABLE V
MONTE CARLO PARAMETERS

Variable	Mean	S.D.	Distribution	Obsv.
a_0	0.11	-----	Exponential	[17]
C	1.29e-12	-----	-----	[18]
m	2.88	-----	-----	[18]
R_{eff}	Depends on $\bar{U}$	-----	-----	
N	Depends on $\bar{U}$	-----	-----	
$\bar{\sigma}$	Depends on $\bar{U}$	Depends on $\bar{U}$	Normal	

Once the crack growth rate is known, the methodology is applied to obtain shear-displacement capacity curves shown in Fig. 3. The equivalent wind speed pushover curves developed using Monte Carlo are shown in Fig. 4.

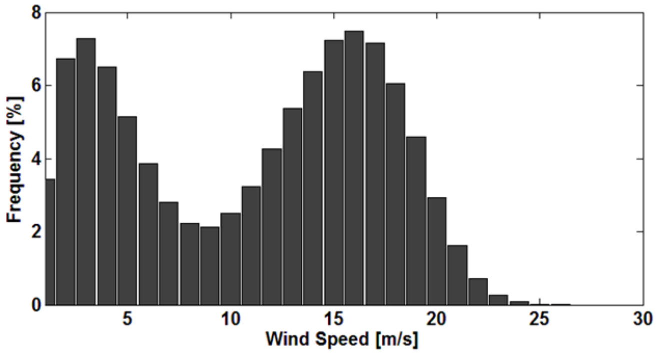

Fig. 2 Annual wind speed distribution

Collapse was chosen as limit state U_c, however it's not the only relevant limit state for structures under high wind loading, others, such as lateral drift could be used following the same procedure. With the equivalent wind speed capacity curves, the vulnerability curves are obtained by fitting the limit state points obtained in the simulation to a General Extreme Value distribution as shown in Fig. 5. The rest of the vulnerability curves can be seen on Fig. 6.

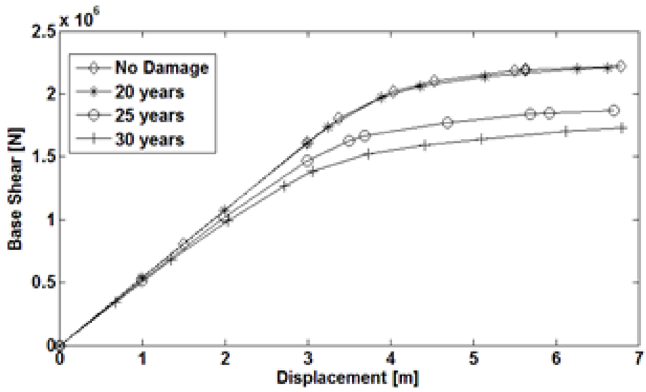

Fig. 3 Shear-displacement curves

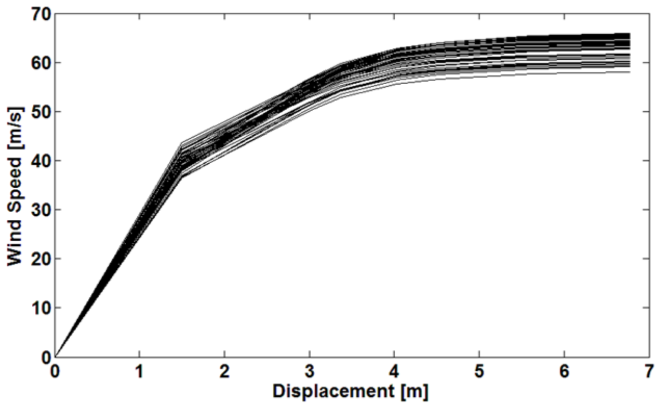

Fig. 4 Equivalent Wind Speed pushover curves for a No Damage state

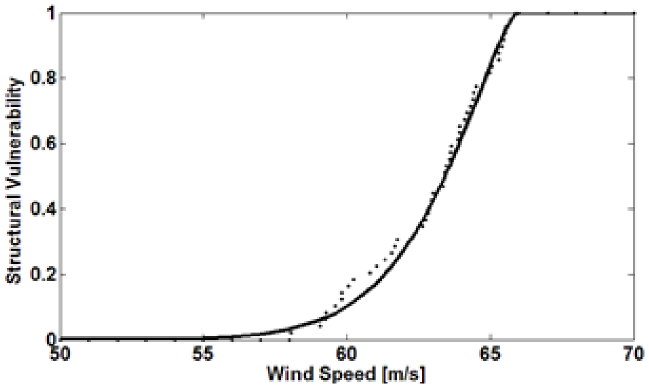

Fig. 5 GEV-fitted vulnerability curve for a No Damage state

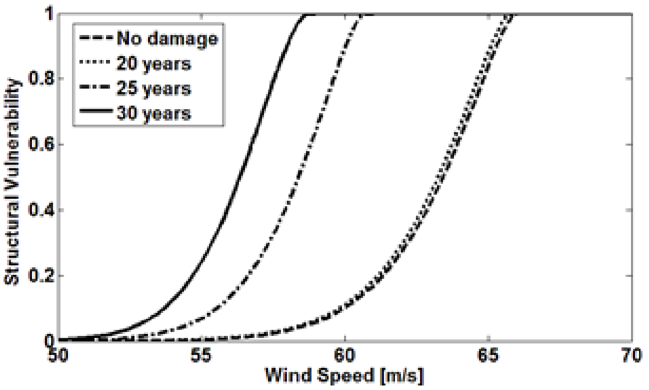

Fig. 6 Vulnerability Curves

VIII. Conclusions

A methodology to assess the influence of fatigue in the reliability of wind turbine support structures is presented. An important increase on the vulnerability of the structure when factoring the fatigue damage is observed. Considering a bimodal Weibull distribution of the annual wind speed increases the rate of fatigue damage in the structure compared to a traditional single Weibull distribution, this emphasizes the need of using the correct site wind distributions when analyzing fatigue damage in the practice.

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