# Digital Twins-based deterioration prognosis of wind turbine tower under wind-wave-corrosion

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# MODENERLANDS Digital Twins-based deterioration prognosis of wind turbine tower under wind-wave-corrosion

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**SUMMARY:**
The Modular Energy Islands (MEI) concept illustrates promising potential in exploiting the plentiful Aeolian source at deep-water ocean through wind turbines, combined with other types of sustainable energies as are e.g. solar and wave ones. At the same time, the innovation of MEIs encounters a list of structural challenges due to the strong wind-wave loads and escalating corrosivity. Especially, the wind turbine tower with a fast-growing height becomes highly prone to corrosion-fatigue (C-F) deterioration in such harsh conditions. The present work proposes a digital twins-based prognosis approach to offer novel insights into the C-F deterioration of wind turbine towers in MEIs exposed to wind-wave-corrosion. At first, a C-F deterioration model is constructed in a coupled manner at the mechanism level based on experimental findings. Then, multi-physics simulations are carried out to derive the fatigue stress from the measured wind-wave spectrum. Similarly, the environment corrosivity is estimated from the site conditions, with the help of test data. On this basis, the most deterioration sensitive detail, i.e., the bolts in tower flanges, is investigated in depth. The results highlight not only the prominent sensitivity of bolt deterioration to wind-wave distribution, but also the remarkable influence by the coupled C-F effect.

*Keywords: floating wind, fatigue, corrosion deterioration, digital twins.*

## 1. INTRODUCTION

The concept of modular energy islands (MEI) (Rebelo, 2022) is proposed as a promising solution to exploit the plentiful and stable wind sources at the deep-water ocean through floating wind, combined with other type of renewable energies, as shown in Fig.1. Compared with the traditional application, the wind turbine tower in MEIs is exposed to the coupled deterioration of load-induced fatigue and environment-assisted corrosion, by which the deterioration can be notably accelerated (Adedipe et al., 2016). The present work aims to provide novel insights into the corrosion fatigue (C-F) deterioration of floating wind turbine towers, by integrating measured data, multi-physics simulations and prediction models via a digital twins-based prognosis approach. The following section 2 illustrates the methodology framework of the digital twins-based prognosis, including the mechanism modelling, multi-physics simulation and corrosion estimation. The key findings are discussed in section 3, along with the major conclusions drawn from the work.

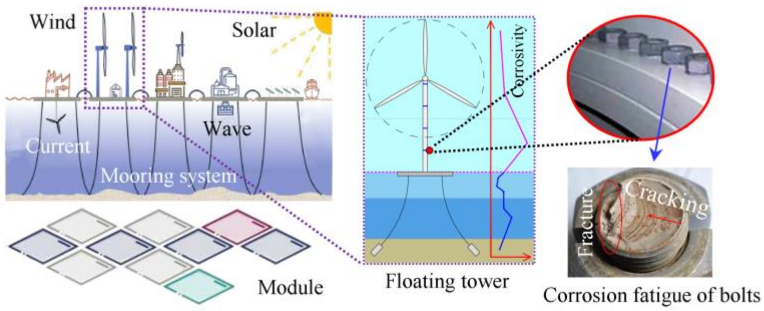



**Figure 1.** Concept of Modular Energy Island (MEI) and deterioration issue

## 2. DIGITAL TWINS-BASED DETERIORATION PROGNOSIS

### 2.1. Corrosion fatigue deterioration modelling

The present research focuses on the high-strength bolts in the ring-flange of the above wind turbine towers (Fig.1) due to its sensitivity to deterioration. In Fig.2, the 3-stage evolution model employed for the C-F deterioration is presented.

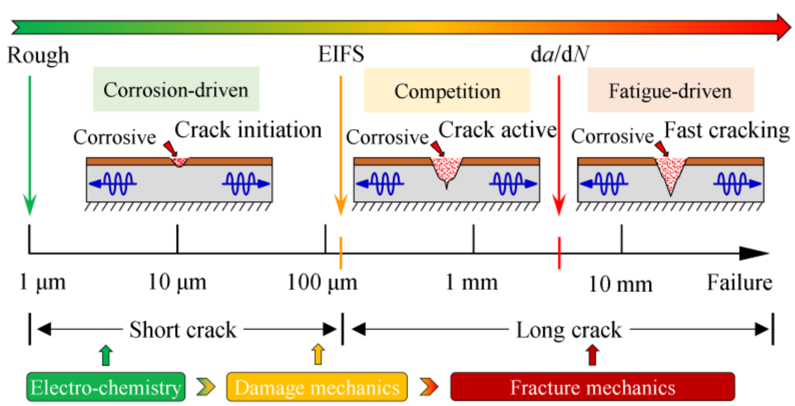



**Figure 2.** On the 3-stage corrosion fatigue deterioration model.

The 3-stage evolution can be illustrated by Equations 1a-c.

$$a_I = a_p + a_{EIF} \cdot \sum_i \frac{n_i \cdot \Delta\sigma_i{}^m}{N_{ref} \cdot \Delta\sigma_{ref}{}^m} \quad (1a)$$

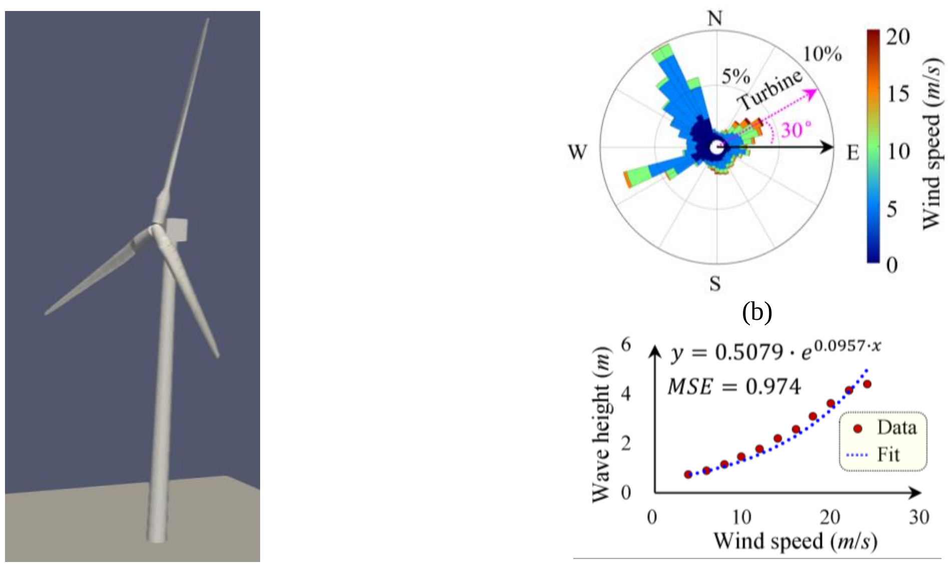
$$\frac{da_{II}}{dt} = \max\left(\frac{da_p}{dt}, C_f \cdot \frac{da_{fcg}}{dt}\right) \quad (1b)$$

$$\frac{da_{III}}{dt} = C_f \cdot \frac{da_{fcg}}{dt} \quad (1c)$$

where $a_I$, $a_{II}$ and $a_{III}$ are crack depth at the stages-I, II and III, respectively; $\Delta\sigma_i$ and $n_i$ are the applied stress range and the corresponding cycles; $\Delta\sigma_{ref}$, $N_{ref}$ and $m$ are reference fatigue strength, cycles and power index in the stress-life (S-N) model; $a_p$ stands for the pitting depth by the corrosion; $a_{EIF}$ is the effective initial flaw size that can be solved according to Liu & Mahadevan (2009); $a_{fcg}$ is the crack depth by fatigue, which can be determined by means of Fracture Mechanics (BSI, 2013); $C_f$ is the environment reduction factor determined by corrosivity.

## 2.2. Multi-physics simulation-based stress derivation

The case study selects the DTU 10MW reference turbine (Bak et al., 2013), in accordance to a floating platform anchored to the seabed by mooring chains (Gomez, P., 2015). The diameter of the 115.63 m-tall tower ranges from 8.30 m at the base to 5.50 m at the hub, with the thickness ranging from 38 mm to 20 mm. Figure 3a shows the numerical model established in the multi-physics simulation software OpenFAST (NREL, 2022). The observation in Gulf of Mexico (NDBC, 2022) are used to reproduce the wind-wave distribution, as shown in Fig 3b-c. The turbine is oriented along the distribution of high-speed winds, i.e. 30 degrees east by north. A strong correlation can be found between the wind speed and the wave height, as shown in Fig. 3b. The data are then incorporated into the developed model to derived stress spectra in bolts.




(a) (c)

**Figure 3.** Multi-physics simulation: (a) numerical model of the tower; (b) wind roses; (c) wind-wave correlation.

## 2.3. Corrosion estimation from site-specific data

The corrosion model proposed in ISO 9223 and 9224 (2012) is adopted to estimate the average thickness loss by corrosion, while a pitting factor of 2 is considered according to Hahin (1994). Table 1 lists the key environment parameter used in estimating the environmental corrosion.

**Table 1.** Environment parameters for corrosion estimation

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Annual average temperature | $T$ | ℃ | 20.6 |
| Annual average relative humidity | $RH$ | % | 83.0 |
| Annual average $SO_2$ deposition | $P_d$ | $mg/m^2/day$ | 7.3 |
| Annual average $Cl^-$ deposition | $S_d$ | $mg/m^2/day$ | 312.0 |

## 3. RESULTS AND CONCLUSIONS

Figure 4a shows bolt damages after 13.3 years of exploitation, when failure is predicted in several bolts. The critical bolts are found around the upwind region, following the direction of strong winds. A more detailed visualisation of critical bolts is presented in Figure 4b. The first bolt failure occurs very close to the turbine orientation after 12.7 years, which accounts for only half of the usual design life of 25 years. In addition, the most critical bolt is selected to investigate the service life under different corrosivity (ISO, 2012), as shown in Fig. 4b. As the corrosivity increase beyond C2, the service life drops below 23 years and decreases with the corrosivity.

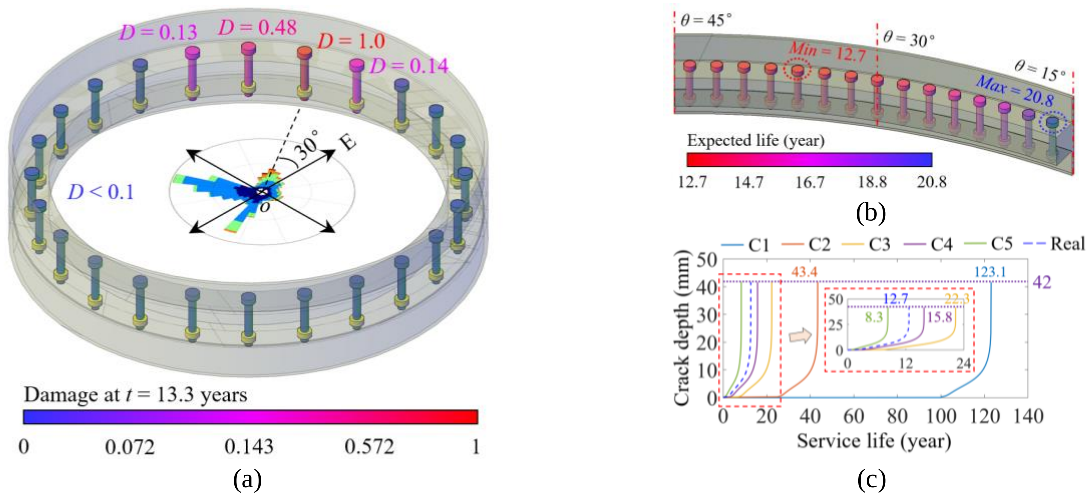


**Figure 4.** Digital prognosis of damage in bolts: (a) damage of representative bolts (flange re-scaled); (b) damage of bolts in critical region; (c) damage evolution of the most critical bolt under various corrosivity.

It is noted that according to the present work: (1) There is a strong correlation between the wind-wave distribution and corrosion fatigue deterioration of bolts in floating wind towers; (2) The C-F deterioration risks premature failure of bolt in floating towers escalating with corrosivity; (3) The digital twins approach offers a constructive basis for the real-time prognosis of bolts by integrating models and measurements, and further, support of condition-based managements.

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