

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

Heng, Junlin; Zhang, Jiaxin; Dong, You; Kaewunruen, Sakdirat; Baniotopoulos, Charalampos

License:
Creative Commons: Attribution (CC BY)

Citation for published version (Harvard):
Heng, J, Zhang, J, Dong, Y, Kaewunruen, S & Baniotopoulos, C 2023, 'Digital Twins-based deterioration prognosis of wind turbine tower under wind-wave-corrosion', The 16th ICWE International Conference on Wind Engineering, Florence, Italy, 27/08/23 - 31/08/23.

[Link to publication on Research at Birmingham portal](#)

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

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

Junlin Heng¹, Jiaxin Zhang², You Dong³, Sakdirat Kaewunruen⁴, Charalampos Baniotopoulos⁵

¹Shenzhen University, Shenzhen, China, j.l.heng@szu.edu.cn

²The Hong Kong Polytechnic University, Hong Kong, China, jiaxinnn.zhang@connect.polyu.hk

³The Hong Kong Polytechnic University, Hong Kong, China, you.dong@polyu.edu.hk

⁴University of Birmingham, Birmingham, United Kingdom, s.kaewunruen@bham.ac.uk

⁵University of Birmingham, Birmingham, United Kingdom, c.baniotopoulos@bham.ac.uk

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.

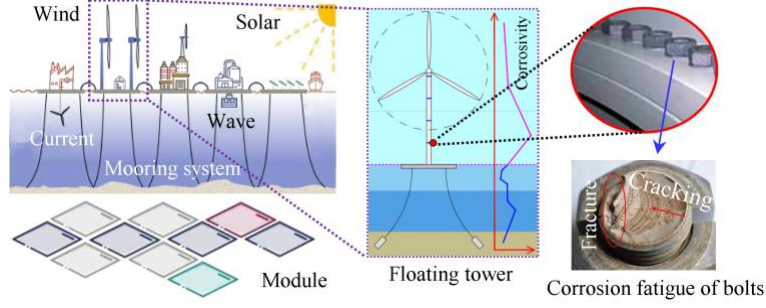


Figure 1. Concept of Modular Energy Island (MEI) and deterioration issue

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.

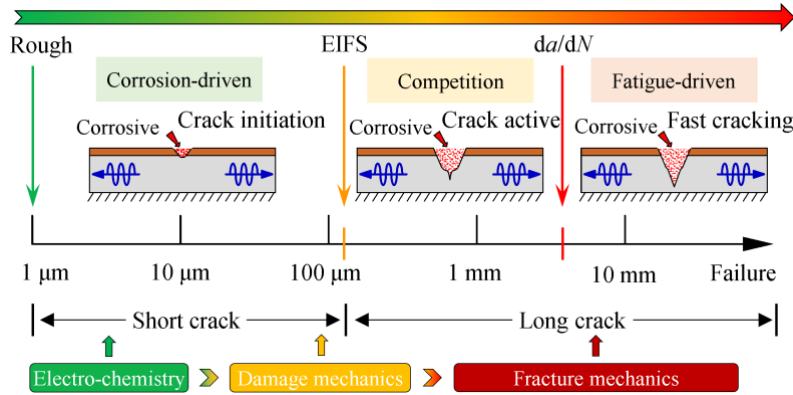


Figure 2. On the 3-stage corrosion fatigue deterioration model.

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.

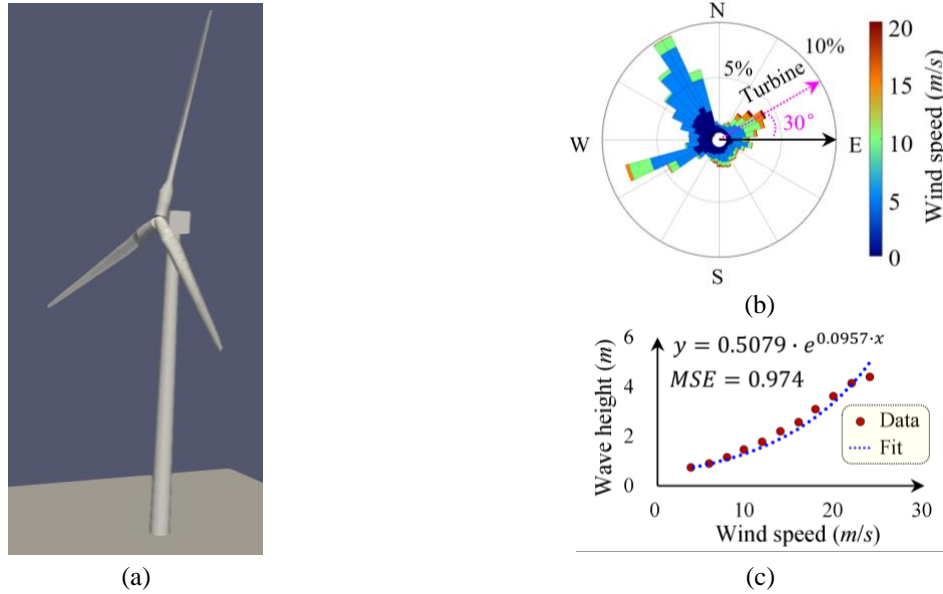


Figure 3. Multi-physics simulation: (a) numerical model of the tower; (b) wind roses; (c) wind-wave correlation.

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	$^{\circ}\text{C}$	20.6
Annual average relative humidity	RH	%	83.0
Annual average SO_2 deposition	P_d	$\text{mg}/\text{m}^2/\text{day}$	7.3
Annual average Cl^- deposition	S_d	$\text{mg}/\text{m}^2/\text{day}$	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.

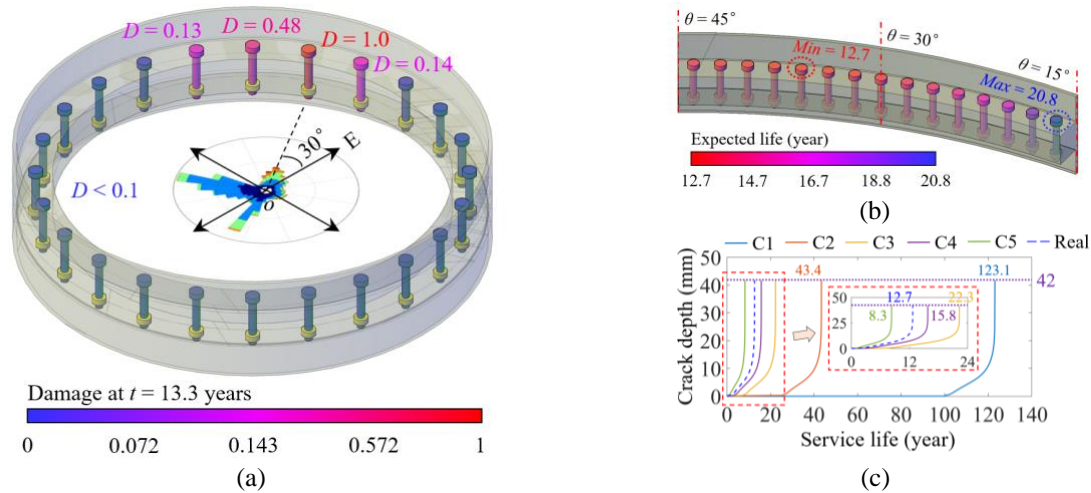


Figure 4. Digital prognosis of damage in bolts: (a) damage of representative bolts (flange re-scaled); (b) damage of bolts in critical region; (c) damage evolution of the most critical bolt under various corrosivity.

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.

ACKNOWLEDGMENTS

The support of the COST Action MODENERLANDS (CA20109), MSCA Fellowship via URKI (EP/X022765/1), Royal Society (IES\R1\221036) and (IES\R1\211087) and National Natural Science Foundation of China (52208182) is acknowledged with thanks by the authors.

REFERENCES

- Rebelo C., Modular Energy Islands for Sustainability and Resilience, Proceedings of “Coordinating Engineering for Sustainability and Resilience (CESARE’22)”, 6-9 May, 2022. Jordan.
- Adedipe, O., Brennan, F., & Kolios, A., 2016. Review of corrosion fatigue in offshore structures: Present status and challenges in the offshore wind sector. *Renewable and Sustainable Energy Reviews*, 61, 141-154.
- Liu, Y., & Mahadevan, S., 2009. Probabilistic fatigue life prediction using an equivalent initial flaw size distribution. *International Journal of Fatigue*, 31(3), 476-487.
- British Standards Institution (BSI), 2015. Guide on methods for assessing the acceptability of flaws in metallic structures, BS7910:2013+A1:2015. London: British Standard Institution.
- Bak C, Zahle, F, Bitsche R, Kim T, Yde A, Henriksen LC, Natarajan A and Hansen MH, 2013. Description of the DTU 10 MW Reference Wind Turbine. DTU Wind Energy Report-I-0092, Roskilde, Denmark
- Gomez, P., Sánchez, G., Llana, A., Gonzalez, G., 2015. Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m. <https://cordis.europa.eu/project/id/640741>
- National Renewable Energy Laboratory (NREL), 2022. OpenFAST – an open-source wind turbine simulation tool. <https://github.com/openfast>
- National Data Buoy Center (NDBC), 2022. <https://www.ndbc.noaa.gov/obs.shtml>
- International Organization for Standardization (ISO), 2012. Corrosion of metals and alloys - Corrosivity of atmospheres. Brussels: ISO.
- Hahin, C., 1994. Effects of corrosion and fatigue on the load-carrying capacity of structural and reinforcing steel (No. FHWA/IL/PR-108). Illinois. Dept. of Transportation. Bureau of Materials and Physical Research.