Fatigue Assessment of Floating Offshore Wind Turbine Tower under Wind-Wave Coupled Loading

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ABSTRACT: Floating offshore wind turbine towers (FOWTs) shows promising possibilities in the exploitation of the affluent Aeolian source at the deep ocean. However, the taller FOWT is also highly prone to fatigue damage under the combination of wind-wave-servo loads, especially in the high-strength bolt of the ring flange connection between tower shells. This study carries out an in-depth fatigue life of bolts in tower flanges using the site-specific data, in which the reference turbine DTU 10MW is considered with both the floating and fixed-bottom foundations. Firstly, based on the in-situ wind data in Mexico Gulf, the wind-wave loading features are determined, including the wind speed, direction and correlation between the wave height and wind speed. Then, by employing the multi-physics simulation tool OpenFAST, the wind and wave data are transferred into random excitations as input to the numerical model. Accordingly, the load history is derived for the tower shell near the flange of interest, followed by a further transition into bolt forces via the load transfer function (LTF). Finally, for both the floating and fixed-bottom towers, the time-variant fatigue damage is estimated based on the bolt force and probability-stress-life (P-S-N) curve, while the fatigue life is predicted accordingly. Especially, the influence of floating foundations on the fatigue life of bolts is discussed through comparisons. In general, this study not only offers a constructive reference for the further application of FOWTs, but also highlights the urgent demands to improve the fatigue endurance of bolts by joint efforts from both the design, fabrication and maintenance.

Keywords: Floating offshore wind tower; Ring-flange connection; High-strength bolt; Fatigue assessment; Wind and Wave coupling.

1. INTRODUCTION

Wind turbines play a pivotal role in quest for sustainable energy, and their durability is essential for widespread deployment. The cyclic nature of wind loads imposes significant fatigue on the various components of the turbine, necessitating the implementation of fatigue analysis to assess their structural integrity and predict their service life. The present review by (Adedipe et al., 2016) delves into the intricacies of corrosion fatigue in offshore structures with a particular focus on its susceptibility to the pernicious effects of seawater, environmental factors, and mechanical loading. The study underscores the fundamental importance of corrosion fatigue analysis as a pivotal tool in the assessment of wind turbine service life. Beyond the issues, European Wind Energy Association (EWEA) draws attention to the critical impact of distinct foundation forms on wind turbine power analysis, an influential factor that warrants careful consideration in the context of future structural design and analytical efforts.

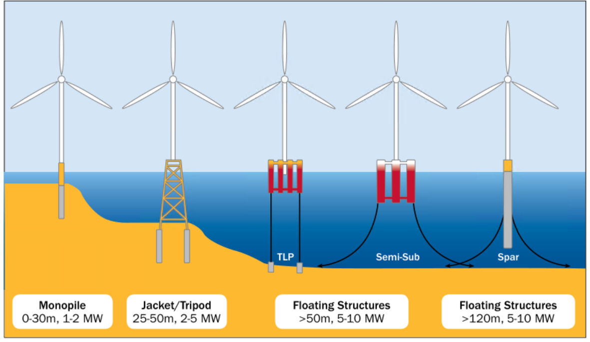


Figure 1. Offshore wind support structures. Figure adapted from EWEA

The present work aims to provide novel insights into the corrosion fatigue (C-F) deterioration of floating wind turbine towers regarding wind-wave coupled effects. The paper is organized as the followings: Section 2 establishes a 3-stage C-F crack growth model for the wind turbine bolts. Section 3 introduce the derivation method of fatigue stress from tower to the bolt by using load transfer function. Section 4 provides a detailed discussion of the crack depth evolution of the reference wind turbine. Section 6 draws key conclusions based on the investigation.

2. ASSESSMENT OF CORROSION FATIGUE EVOLUTION

The three-stage evolution model of corrosion fatigue describes the progression of fatigue cracks in metallic materials subjected to alternating loads in corrosive environments. This model is based on the notion that the initiation and growth of cracks occurs in three distinct stages.

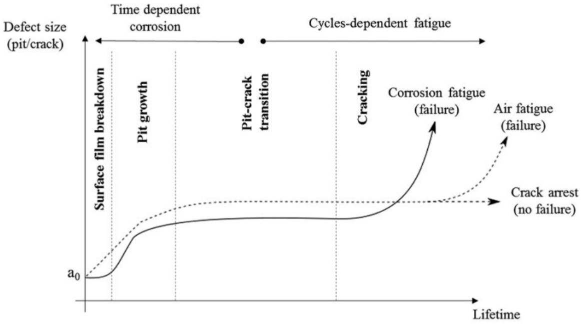


Figure 2. Three-stage evolution model of corrosion fatigue. Figure adapted from (Van der Sluys et al., 1997)

The Three-stage Evolution Model of Corrosion Fatigue describes the progression of fatigue cracks in metallic materials subjected to alternating loads in corrosive environments. This model is based on the notion that the initiation and growth of cracks occurs in three distinct stages.

Stage 1: Superposition of corrosion damage and fatigue damage: In this stage, both corrosion and fatigue damage contribute to the overall degradation of the material. The corrosion processes weaken the material and make it more susceptible to fatigue cracking, while the fatigue loading causes the small cracks to grow.

$$D_{S1} = D_{cor} + D_{fat} = \frac{a_{pit}}{a_{EIF}} + \sum_{i=1}^{n_{sb}} \left(\frac{n_i}{[N_i]} \right) \quad (1)$$

where

D_{S1} - Total (C-F) damage of stage 1

D_{cor} - Corrosion damage (by pit corrosion mainly)

D_{fat} - Fatigue damage before crack initiation (stage 1)

a_{pit} - Depth of corrosion pit

a_{EIF} - Depth of effective initial flaw (EIF)

n_{sb} - Number of stress blocks

n_i - Number of cycles for ith stress block

$[N_i]$ - Allowable number of cycles for crack initiation under i th stress block

Once the failure criteria of $D_{S1} = 1$ is achieved, crack initiation is assumed with the EIF depth a_{EIF}. Then, the crack evolution process is transformed into the Stage 2, in which the fatigue crack growth rate can be estimated from fracture mechanics.

Stage 2: In this stage, the material has lost some of its mechanical integrity due to corrosion damage, but the cracks are still small, and their growth rate is relatively slow. This stage is characterized by the interplay between corrosion damage and fatigue damage, as the corrosion processes continue to weaken the material while the fatigue loading causes the cracks to grow.

$$\frac{\mathrm{d}a_{S2}}{\mathrm{d}t} = max\left[\frac{\mathrm{d}a_{pit}}{\mathrm{d}t}, \frac{f_{load} \cdot \mathrm{d}a_{fcg}}{\mathrm{d}N_{load}}\right] \tag{2}$$

where

a_{S2} - Crack depth of Stage 2

t - Time indicator

f_{load} - Loading frequency

a_{fcg} - Crack depth estimated by fatigue crack growth

N_{load} - Number of loading cycles

Stage 3: corrosion-assisted fatigue crack growth. In this stage, the crack growth rate becomes much faster, and the crack length increases rapidly. The corrosion processes have significantly weakened the material, and the fatigue loading causes the crack to grow at an accelerating rate. This stage is characterized by a sharp increase in the rate of corrosion, which can lead to catastrophic failure of the material.

$$\frac{\mathrm{d}a_{S3}}{\mathrm{d}t} = \frac{f_{load} \cdot \mathrm{d}a_{fcg}}{\mathrm{d}N_{load}} \tag{3}$$

where

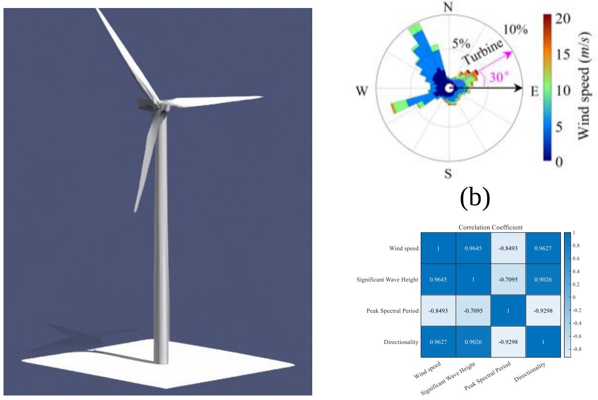
a_{S3} - Crack depth of Stage 3

Overall, the Three-stage Evolution Model of Corrosion Fatigue provides a useful framework for understanding the development and growth of fatigue cracks in materials that are exposed to corrosive environments. This model can predict the fatigue life of these materials and guide the design of structures that are resistant to corrosion fatigue.

3. ESTIMATION OF FATIGUE STRESS

3.1. Reference turbine and site

The present study endeavors to investigate the DTU 10MW reference turbine and its cognate floating platform (Bak, etc., 2013). The anchoring of the platform has been effectuated at a juncture 793.50 m distant from the fairlead and 837.46 m away from the centerline of the platform. The mooring lines deployed in the study are comprised of 97 mm studless chains, each having a length of 833.24 m in an unstretched state (Gomez, P., 2015). The tower, which boasts a height of 115.63 meters, is upheld by a semi-submersible foundation. The diameter of the tower shells oscillates between 8.30 m at the base and 5.50 m at the hub, while the thickness varies in proportion from 38 mm to 20 mm. A numerical model of the system was synthesized utilizing the multi-physics simulation software OpenFAST (NREL, 2022).



(b)

(a)

(c)

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

The wind-wave distribution documented in the Gulf of Mexico (NDBC, 2022) was utilized as a reference for simulating the environmental conditions, with a correlation of high magnitude observed between wind speed and significant wave height. The critical bolts identified in the study are aligned with the wind direction of the maximum wind speed. Subsequently, the established model was availed to calculate the stress spectra in the bolts. The orientation of the turbine has been set in alignment with the direction of the high-speed winds, which lie at a bearing of 30 degrees east of north. The model for estimating corrosion proposed in ISO 9223 and 9224 (2012) is adopted in this study. This model calculates the average thickness loss due to corrosion.

3.2. Derivation of fatigue stress

The stress that develops within a bolt due to the loads that are transferred through the bolt to the adjacent components is referred to as bolt stress. This stress can be determined by utilizing a load transfer function, which characterizes the manner in which the loads are transmitted through the bolt.

The load transfer function, in turn, takes into account several significant factors such as the mechanical properties of the bolt, the dimensions of the bolt, the pre-load applied to the bolt, and the geometric configurations of the components that are being connected by the bolt. This function can be derived using finite element analysis or other numerical methods.

Once the load transfer function is obtained, it can be employed in conjunction with the loads that are acting upon the structure to calculate the stress in the bolt. This information is of vital importance for assessing the suitability of the bolt for the intended application and for ensuring that the bolt will not fail under the imposed loads.

It is important to note that the stress within a bolt is not constant and can vary as a function of the loads acting on the bolt and the position of the bolt within the structure. This highlights the need to consider the load transfer function when computing the bolt stress, as it provides a more accurate picture of the stress distribution within the bolt.

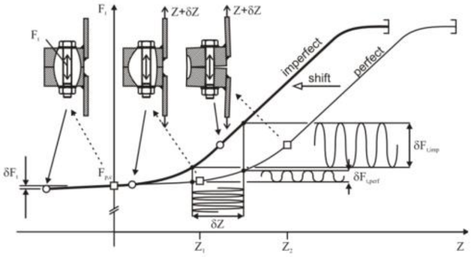


Figure 4. LTF Function by Schmidt

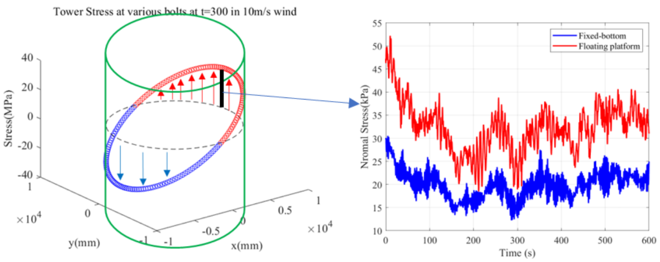


Figure 5. Stress history calculated for the most critical bolt and welds at 10 m/s wind speed

The stress spectra derived by cycle counting is obtained by using a sampling method that takes into account the actual distribution of wind speed and direction.

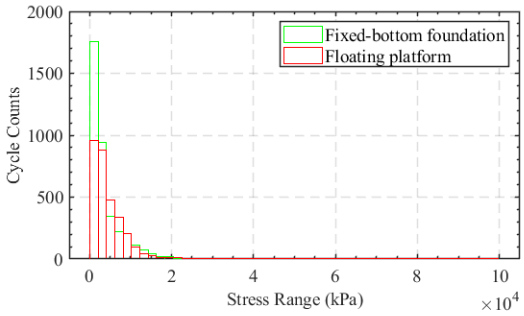
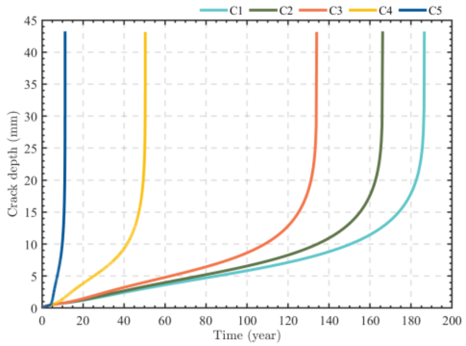


Figure. Stress spectra for the most critical bolt

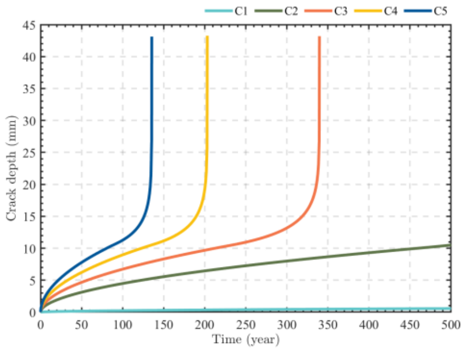
4. RESULTS AND DISCUSSION

4.1. Crack depth evaluation assessment

The P-S-N model proposed by Eurocode 3 (EC3) is employed, covering three phases with different power indexes.



(a) Floating platform

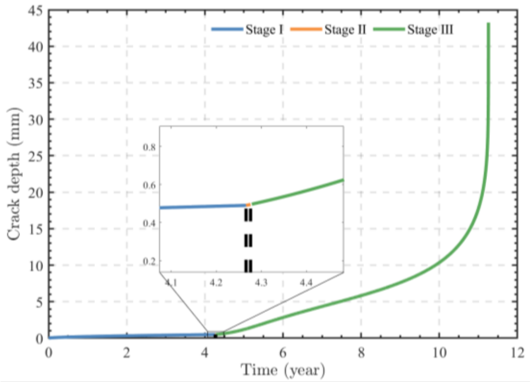


(b) Fixed-bottom

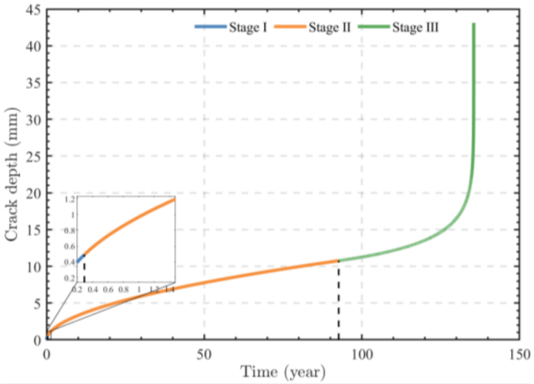
Figure 6. Crack depth evolution of the most critical bolt under various corrosivity

Results are depicted in Fig. 6, as corrosivity increases, the lifespan of the structure will correspondingly decrease. The required 25-year lifespan may not be met once the corrosivity level reaches C5. In the case of extremely high corrosivity levels like C5, specific measures must be taken to protect the structure and meet the necessary lifespan requirement.

4.2. Influence of floating foundations



(a) Floating platform



(b) Fixed-bottom

Figure 7. 3-stage crack depth evolution of the most critical bolt under C5 level

In floating wind turbine, the accelerated crack growth induced by high stress amplitudes on expedites the transition from the second to the third stage of corrosion-assisted fatigue, consequently leading to a significant reduction in fatigue life. In contrast, fixed-bottomed wind turbines with low stress amplitudes on bolts experience slower crack propagation through the second stage, resulting in a noteworthy extension of their fatigue life.

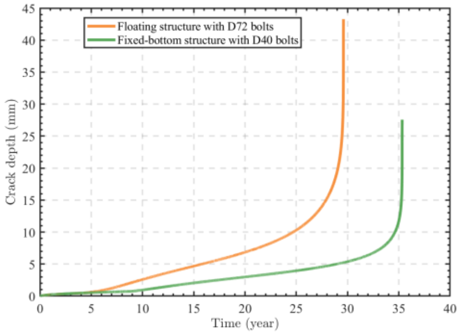


Figure 8. Crack depth evolution of bolts in WTs with different foundations

Figure 8 exhibits the propagation of cracks depth in the minimum size bolt required for a 25-year lifespan based on environmental parameters, at a particular wind turbine location. The bolt diameter needed for a fixed foundation amounts to 40mm, a mere 55.6% of the bolt diameter (72mm) required for a floating structure under similar loading and environmental circumstances. The design of bolt size for wind turbine corrosion fatigue necessitates a thorough contemplation of the comprehensive structural form and boundary conditions.

5. CONCLUSIONS

This study employs OPENFAST to simulate the dynamic response of wind turbine towers under the coupling of wind and waves. The response is subsequently transformed into bolt stress by means of the load transfer function. Corrosion fatigue progression is assessed using the Three-stage evolution model. Ultimately, the impacts of varying foundation forms on bolt fatigue life are juxtaposed. The research provides valuable insights into the evaluation of future bolt fatigue life and size design.

(1) Corrosivity plays a critical role in determining the service life of a structure, as it can cause significant damage and weaken the structure's integrity. To ensure the appropriate service life of a structure, engineers must carefully consider the corrosivity levels of the environment, select appropriate materials and coatings, and perform regular maintenance and repairs.

(2) The foundation form is crucial in the design of wind turbine bolt sizes for offshore wind turbines. The integrity and longevity of the mechanical system of the wind turbine depend on the bolt configuration, which is directly influenced by the foundation form. Structural engineers should prioritize the foundation form in their design process, taking into account environmental conditions and cost-benefit trade-offs.

6. REFERENCES

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