Impact of corrosion loss on the structural response of Offshore Wind Turbine monopiles

SUMMARY

This study investigates the impact of corrosion on the structural response of OWT monopiles using analytical and numerical analysis. OpenFAST is used to simulate the coupled aero-hydro-servo-elastic response of NREL 5 MW OWT supported by a monopile. The monopile and tower are modeled using a Euler–Bernoulli beam element formulation and are subjected to turbulent wind and irregular wave loading. The effect of uniform corrosion on the monopile's structural response and stress in different corrosion zones is then investigated. Results show that metal loss due to corrosion increased the stress in the monopile by more than 5%. Stress changes differ across various corrosion zones, and the splash zone shows the highest increase in maximum stress. Incorporating corrosion loss and the associated stress changes into fatigue assessment and extreme loading conditions is essential for accurate life estimation.

Keywords: *Offshore wind turbine deterioration, Wind load, Long-term steel corrosion, Remaining life estimation, OpenFAST*

1. INTRODUCTION

Wind energy is gaining a larger share in global energy portfolios. Offshore wind capacity worldwide is projected to reach about 560 GW by 2040—approximately fifteen times today's capacity (International Energy Agency, 2019). Furthermore, many OWTs are nearing the end of their planned service life, urging consideration of life-extension studies (Natarajan et al., 2020). Monopile foundations are widely used in offshore wind farms because of their cost-effectiveness and simplified installation in shallow-water projects (Lombardi et al., 2013). Offshore wind turbine (OWT) monopiles are subjected to ongoing ageing and material degradation in severe marine conditions, which affects their structural reliability. Marine corrosion is one of the most significant causes of deterioration in OWT monopiles due to its potential economic and structural implications. Reliable estimation of stresses in OWT support structures under gravity, wind, and wave loads is critical. Metal loss due to corrosion must be taken into account when analyzing the structure under aero-dynamic and hydro-dynamic loads.

2. CORROSION OF OWT MONOPILES

Uniform corrosion is identified as a leading cause of damage due to corrosion in OWT support structures (Brijder et al., 2022). Even in case of pitting corrosion, the progressive merging of individual pits can eventually result in a pattern similar to uniform corrosion. Thus, it is important to consider the effect of uniform corrosion within structural analysis of OWTs. This study utilizes a bi-modal corrosion model (Melchers, 2003) for estimating metal loss in OWT monopiles in submerged zone. Figure 1 shows the corrosion zones defined by DNVGL-RP-0416 (DNV GL, 2021) for OWT support structures. Research on steel corrosion in seawater shows that splash and submerged zones exhibit more severe degradation than other regions (DNV GL, 2021). Previous studies on corrosion of offshore steel structures show that corrosion loss in the splash zone is approximately twice the loss in the submerged zone, and the buried zone exhibits about half the corrosion loss of the submerged zone (Aghasibayli & Brennan, 2019). Since the bimodal corrosion model utilized here has been calibrated for the submerged zone, corrosion losses in the splash and buried zones are derived using these established ratios (Okenyi et al., 2024).

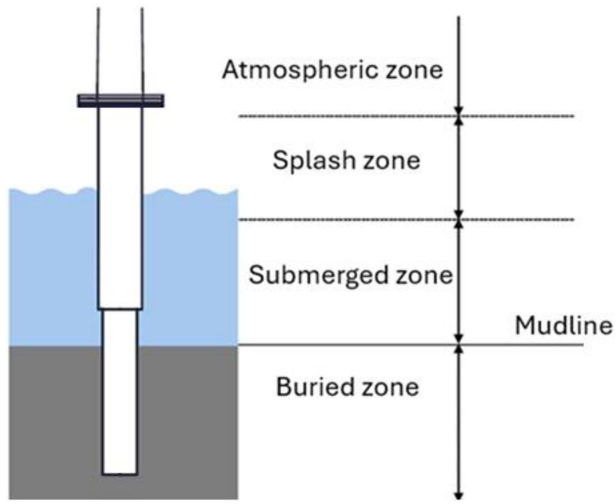

Figure 1: Corrosion zones in sea-water for OWT monopiles

3. MODELING AND ANALYSIS OF OWT MONOPILES

This study implements a 5 MW offshore wind turbine (OWT) model from the OC3 project (Jonkman & Musial, 2010). The NREL 5 MW OWT with the OC3 monopile configuration is modeled in OpenFAST software to run fully coupled aero-hydro-servo-elastic simulations. The simulation is performed for 60 s (for the abstract) with a time step of 0.005 s, guaranteeing high-resolution structural response in offshore condition. Aerodynamic analysis is performed using AeroDyn and InflowWind, which provide a turbulent wind inflow. The wind field corresponds to a mean wind speed of 12 m/s at 90 m hub height, with turbulence intensity of 0.14 according to IEC 61400-1 (International Electrotechnical Commission, 2019). Hydrodynamic analysis is performed using HydroDyn based on irregular wave kinematics and a water depth of 20 m. Structural dynamics is modeled by ElastoDyn for the turbine and SubDyn for the support structure (monopile). Pitch and torque control are handled through the ServoDyn module.

The corrosion model is applied to estimate metal loss and the remaining cross-sectional area of the OWT monopile in various corrosion zones including splash, submerged, and buried zones. The cross-sectional properties, including outer diameter and wall thickness, are updated and incorporated into the SubDyn module in OpenFAST. Analyses are then performed for both the corroded and pristine monopile.

4. RESULTS

Figure 2-4 indicates the tensile stress time history in the monopile under fore-aft wind loading at three different elevations: 20 m below mean sea level (buried zone), 10 m below mean sea level (submerged zone), and at mean sea level (splash zone).

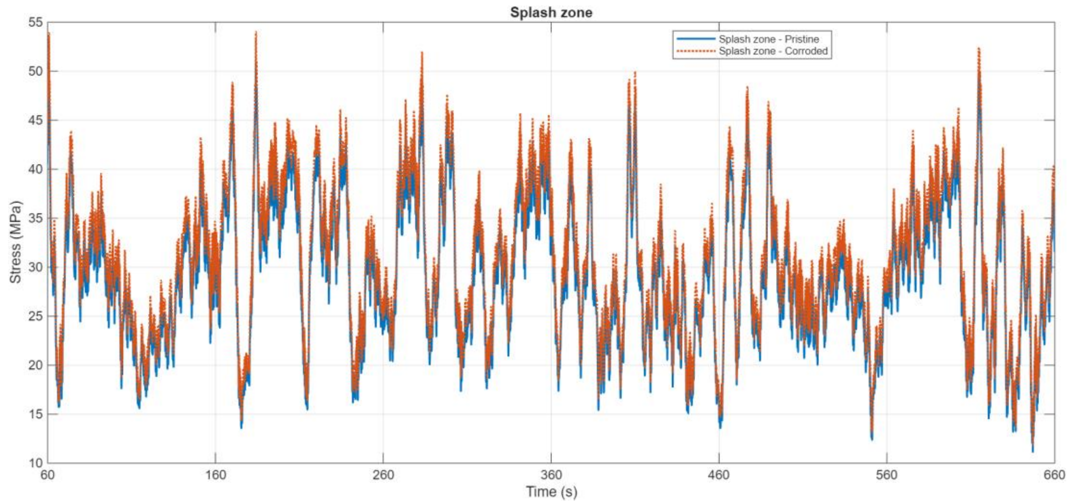

Figure 2: Stress time-history in monopile at the splash zone

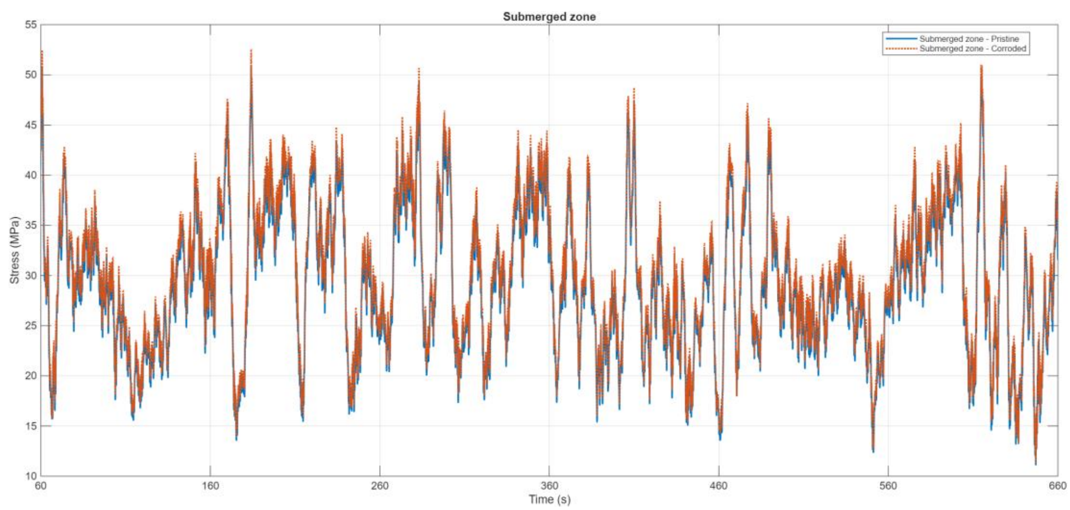

Figure 3: Stress time-history in monopile at the Submerged zone

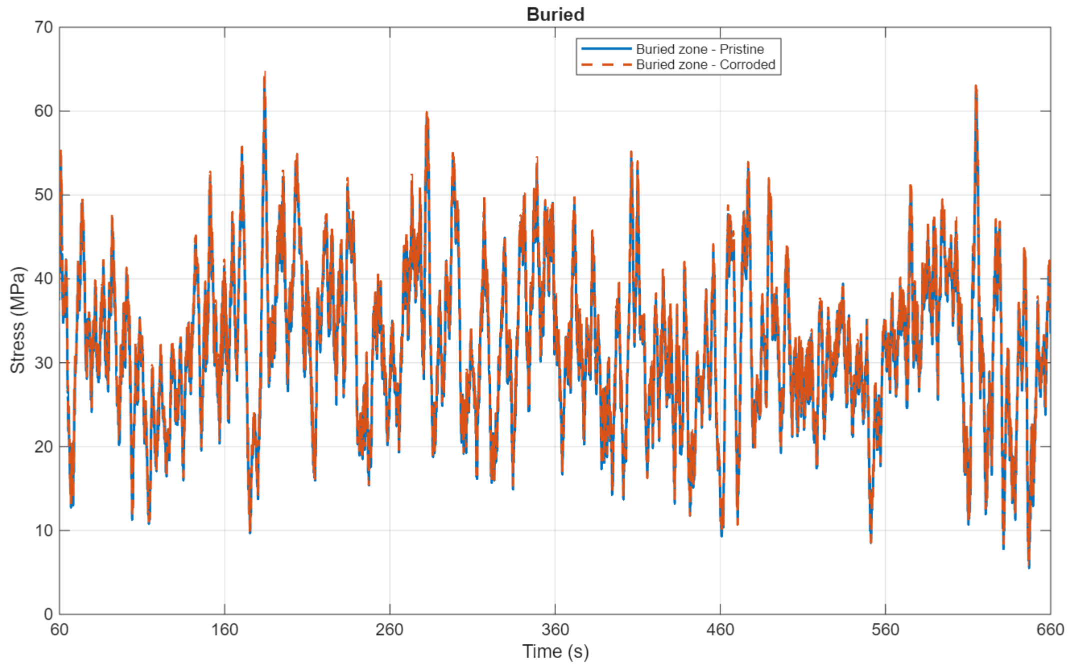

Figure 4: Stress time-history in monopile at the buried zone

Figure 5 shows the maximum stress for both the pristine and corroded monopiles, indicating the impact of corrosion on maximum stress. The figure shows that corrosion results in increases of 5.4%, 2.6%, and 1.3 % in the maximum stress of the monopile within the splash, submerged, and buried zones, respectively.

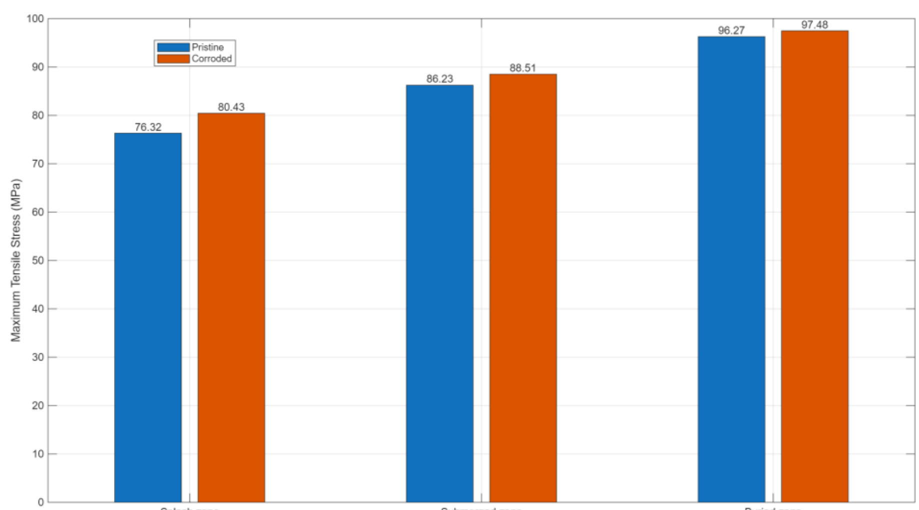

Figure 5: Maximum stress at monopiles in different corrosion zones

Figure 6 illustrates the maximum fore-aft bending moments for the pristine and corroded monopiles in the splash, submerged, and buried zones. The results indicate that the bending moments for the pristine and corroded monopiles are almost identical across all zones, with only very small differences between the two cases. The pristine monopile exhibits marginally higher maximum bending moments; however, the differences remain negligible and below 1% in all zones.

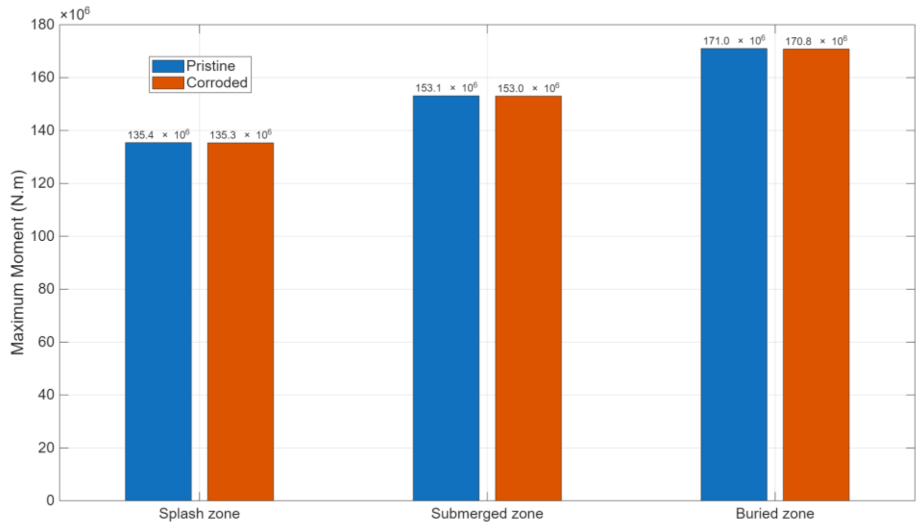

Figure 6: Maximum fore-aft bending moments at monopiles in different corrosion zones

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