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University of Strathclyde Engineering

Corrosion and fatigue protection of offshore wind turbine structures using additive manufacturing technology (COATing)

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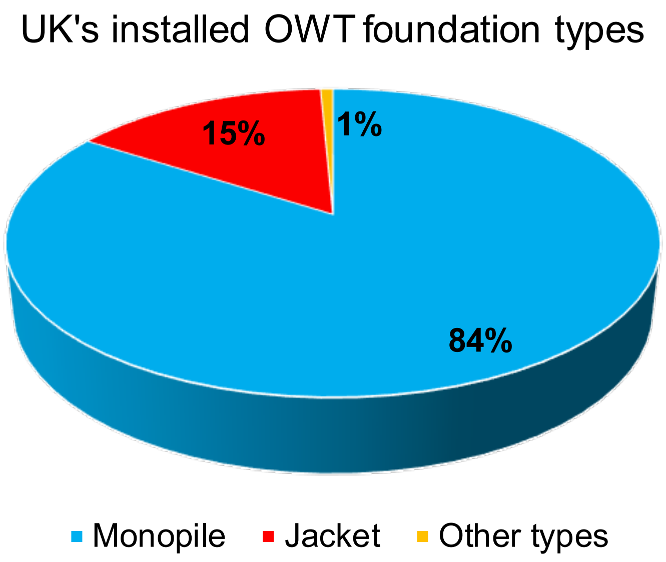
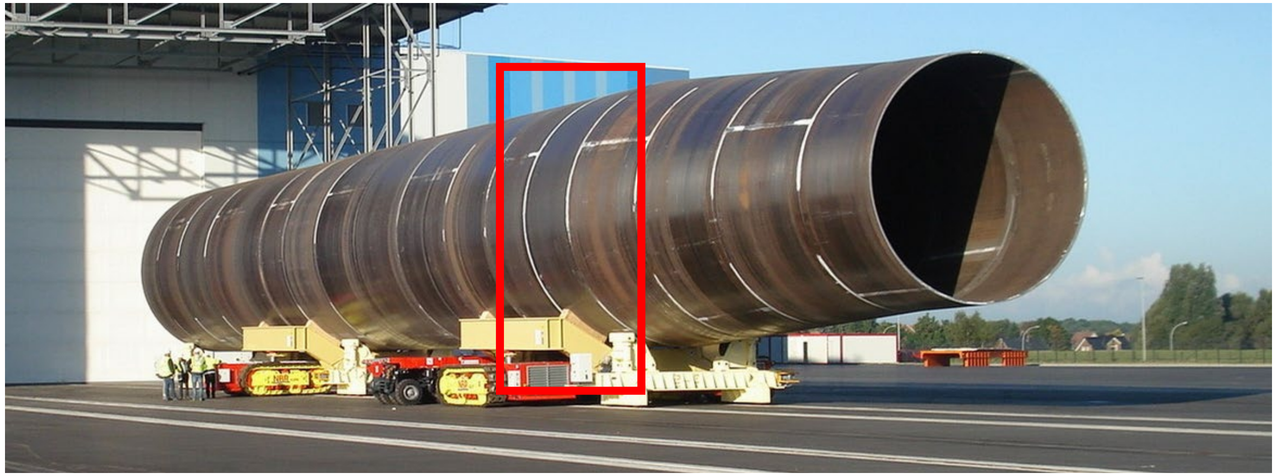
THE PLACE OF USEFUL LEARNING

Offshore Wind Turbine Support Structures

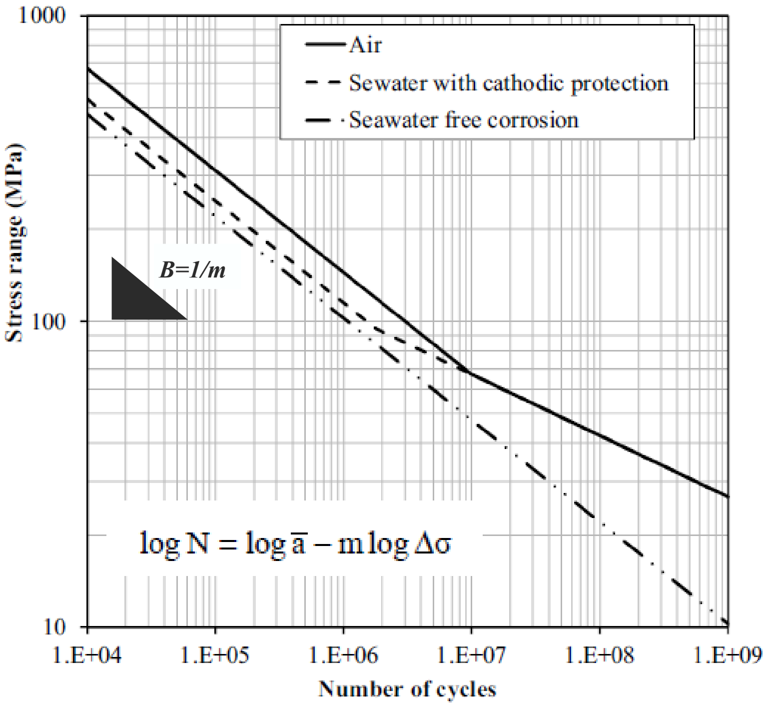
- ❑ Offshore wind turbine (OWT) structures consist of: support structure, transition piece and tower.
- ❑ The majority of the installed OWTs in the UK and EU are supported using monopiles.
- ❑ **Corrosion** and **fatigue** are the dominant **material degradation mechanisms** in OWT structures, particularly at the circumferential welds of monopiles, which are in direct contact with seawater and subjected to cyclic fatigue loading condition.
- ❑ The overall aim of this project was to enhance corrosion-fatigue life of OWT monopiles using advanced manufacturing technologies.



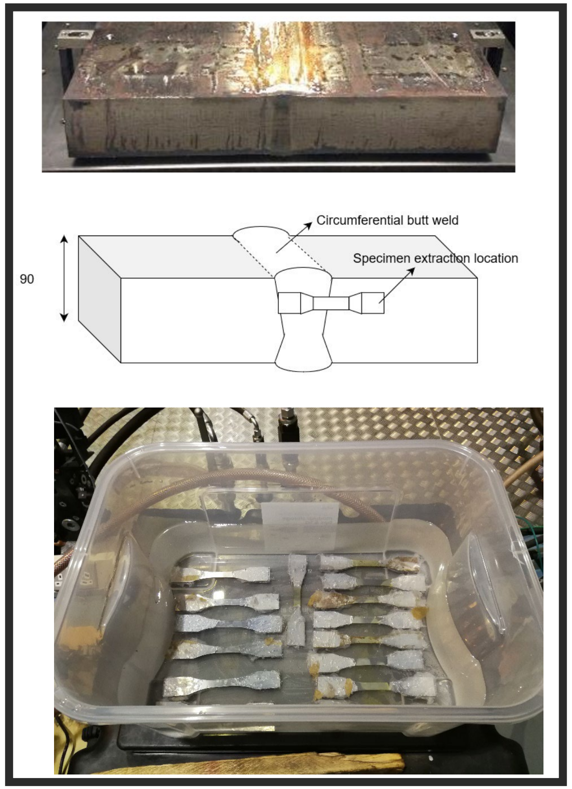


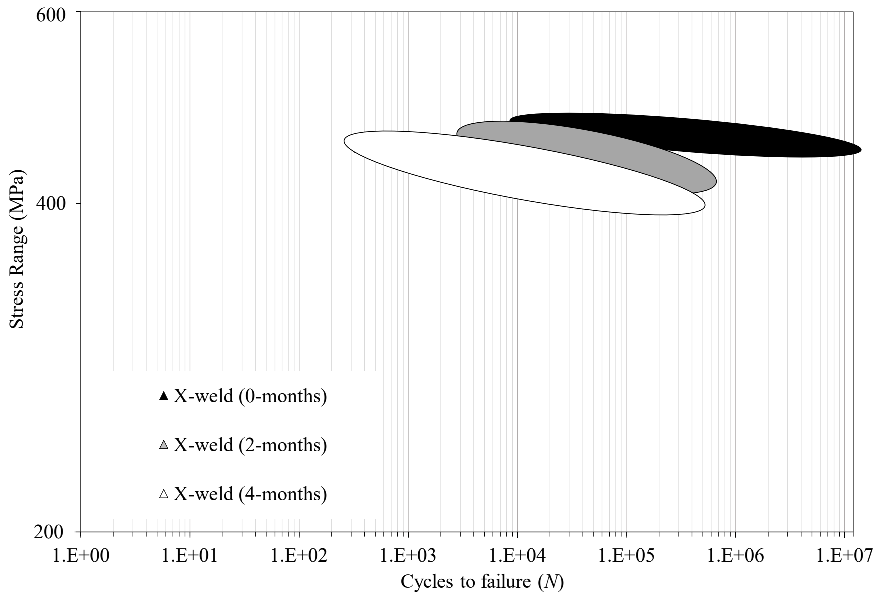
Corrosion effects on fatigue life of welds

- ❑ Monopiles are designed against fatigue failure, by employing appropriate S-N design curves recommended in international standards (e.g. DNV, BS) for different classes of weld (e.g. D, C1)
- ❑ Design curves heavily depend on the environment; air/cathodic protection/free corrosion
- ❑ In COATing project, the pitting corrosion effect on fatigue life of conventional welds (flush ground condition) was investigated by performing tests on S355 cross-weld specimens with 0, 2 and 4 months exposure to seawater, and **a time-dependent fatigue life reduction model was developed**.



S-N curves in air taken from DNV-RP-C203





$t_{seawater}\Uparrow \rightarrow B\Uparrow \rightarrow N\Downarrow\ (>>\times 3)$

Shamir, Mehmanparast et al. *Marine Structures*, 2023

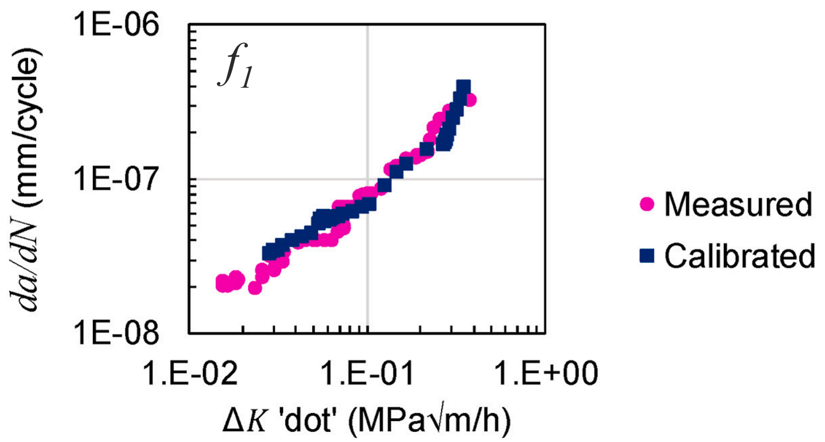
New Approach for Corrosion-Fatigue Analysis

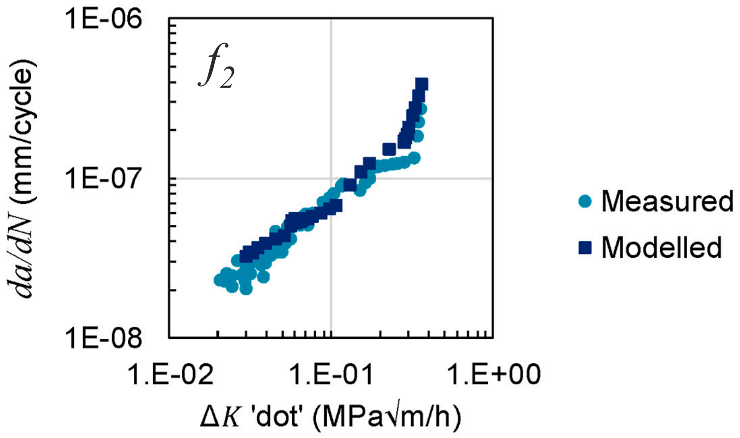
- The fracture mechanics parameter, ***ΔK***, which is commonly employed in analysis of fatigue crack growth data in air and seawater is **insensitive to the test frequency (i.e. time)**.
- To account for **time dependency in conjunction with cycle dependency**, new fracture mechanics parameters, $\Delta\dot{K}$ and $\dot{J}$ were developed in COATing to analyse corrosion-fatigue crack growth data more accurately.
- Subsequently, **a new model** was developed, and validated using S355 experimental data, to predict the corrosion-fatigue crack growth behaviour at different frequencies.

$$\left(\frac{da}{dN}\right)_{CF}[at\ \Delta\dot{K}_{CF}] = \varphi\left(\frac{da}{dN}\right)_{air}[at\ 10^{-\lambda}\ \Delta\dot{K}_{air}]$$

$$\lambda = \gamma P_{average}\left(1 - \frac{f_{CF}}{f_{air}}\right)$$

$$\varphi = 10^{\mu(1-f_{CF})}$$

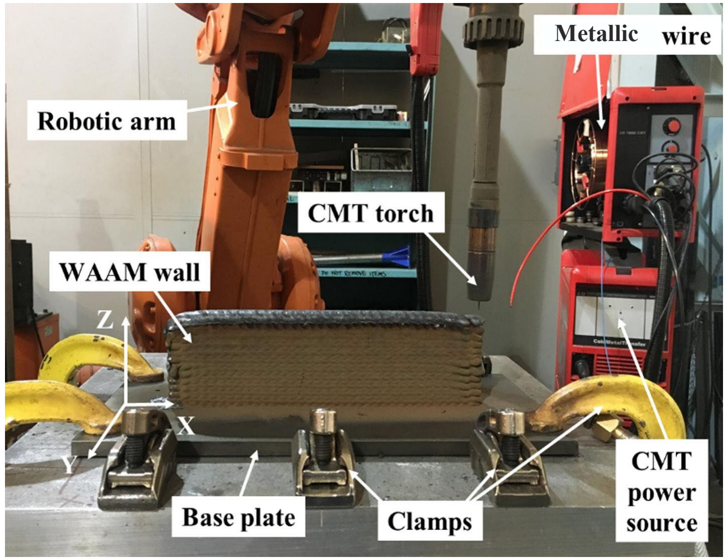




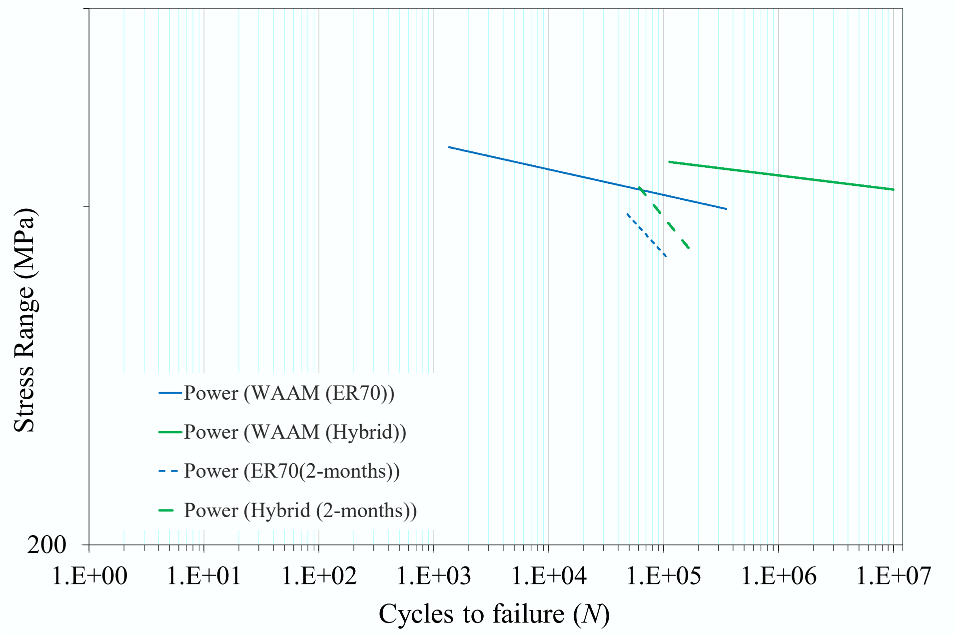
Ryan and Mehmanparast. *Mechanics of Materials*, 2023

Corrosion-fatigue life enhancement with WAAM

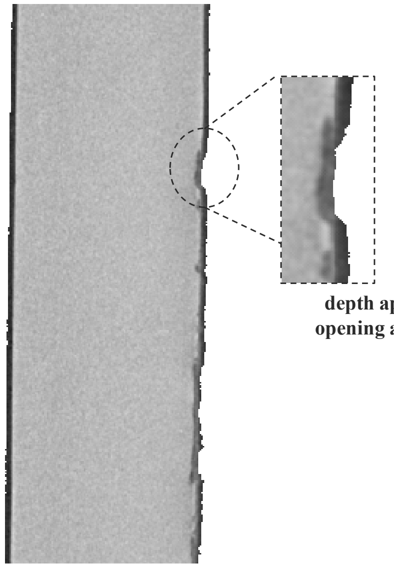
- Wire Arc Additive Manufacturing (WAAM) technology is suitable for rapid and large-scale fabrication
- Hybrid WAAM deposition was conducted by mixing two alloys, ER70 and ER90, with **complementary properties** (fatigue and corrosion resistance) in the melt pool
- **Hybrid WAAM has been found to enhance fatigue (≈ ×100) and corrosion-fatigue (≈ ×2) life**.
- This technology can be used as a **permanent coating technology** to protect critical parts of OWT monopile foundations such as circumferential welds.



WAAM set-up



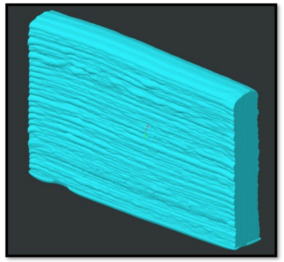
X-ray Computed Tomography (CT) analysis of pitted samples

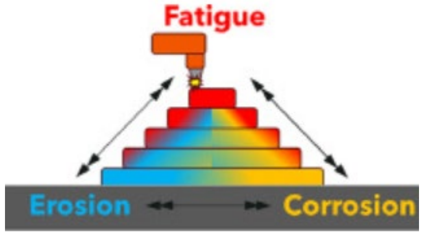


Research Continuation

- ❑ **CoTide** EPSRC-Funded Programme Grant: application of AM for life enhancement of tidal turbines support structures

- ❑ **WAMSS CDT EngD Project** (Fraser O'Neill): Development of new hybrid AM strategies for life enhancement of ORE structures





Conclusions

- ❑ Time-dependent models have been developed to accurately estimate the corrosion life reduction factor and corrosion-fatigue crack growth behaviour of welded steel structures.
- ❑ The indicative S-N curves show that hybrid (ER70+ER90) WAAM technology can significantly enhance fatigue and corrosion-fatigue life, compared to ER70.
- ❑ The feasibility study conducted in the COATing project has led to further research projects which aim at employment of AM technologies for life enhancement of ORE steel structures.

Publications

- Shamir, M., Igwemezie, V., Lotfian, S., Jones, R., Asif, H., Ganguly, S. and Mehmanparast, A., 2022. Assessment of mechanical and fatigue crack growth properties of wire+ arc additively manufactured mild steel components. *Fatigue & Fracture of Engineering Materials & Structures*, 45(10), pp.2978-2989.
- Shamir, M., Braithwaite, J. and Mehmanparast, A., 2023. Fatigue life assessment of offshore wind support structures in the presence of corrosion pits. *Marine Structures*, 92, p.103505.
- Ryan, H. and Mehmanparast, A., 2023. Development of a new approach for corrosion-fatigue analysis of offshore steel structures. *Mechanics of Materials*, 176, p.104526.
- O'Neill, F. and Mehmanparast, A., 2024. A Review of Additive Manufacturing Capabilities for Potential Application in Offshore Renewable Energy Structures. *Forces in Mechanics*, p.100255.
- O'Neill, F., Shamir, M. and Mehmanparast, A., 2024. Corrosion-fatigue life enhancement of offshore renewable energy steel structures using hybrid wire arc additive manufacturing technology. *Additive Manufacturing*, Under Preparation.

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