Corrosion Management of Offshore Wind Turbine Towers and Transition Pieces

A Deeper Look at Coatings

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Agenda

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The Offshore Wind UK Landscape

- The rising demand of renewable energy has driven the offshore wind industry into deeper waters, in search of:
  - Larger, unrestricted space.
  - Reduced environmental and social impact.
  - Higher average wind speeds
  - Relatively low wind turbulence.
- Offshore wind farms face significant challenges:
  - Harsh marine environments.
  - Dynamic loads due to operation.
  - Unmanned structures with limited that access need complex and expensive maintenance procedures.
  - Moving into deeper waters significantly increases CAPEX and OPEX costs.

The Offshore Wind UK Landscape

Offshore Wind Net Zero Roadmap

- The UK already has 13.8 GW of offshore wind capacity, powering millions of homes.
- The aim is to reach 50 GW of offshore wind deployment by 2030, including up to 5 GW of floating offshore wind.
- Over £ 50 bn in construction capital expenditure needed to build offshore windfarms in the UK by 2030.
- This ambition is supported by a strong pipeline of investment-ready projects and a stable policy framework, creating a conducive environment for large-scale investments.

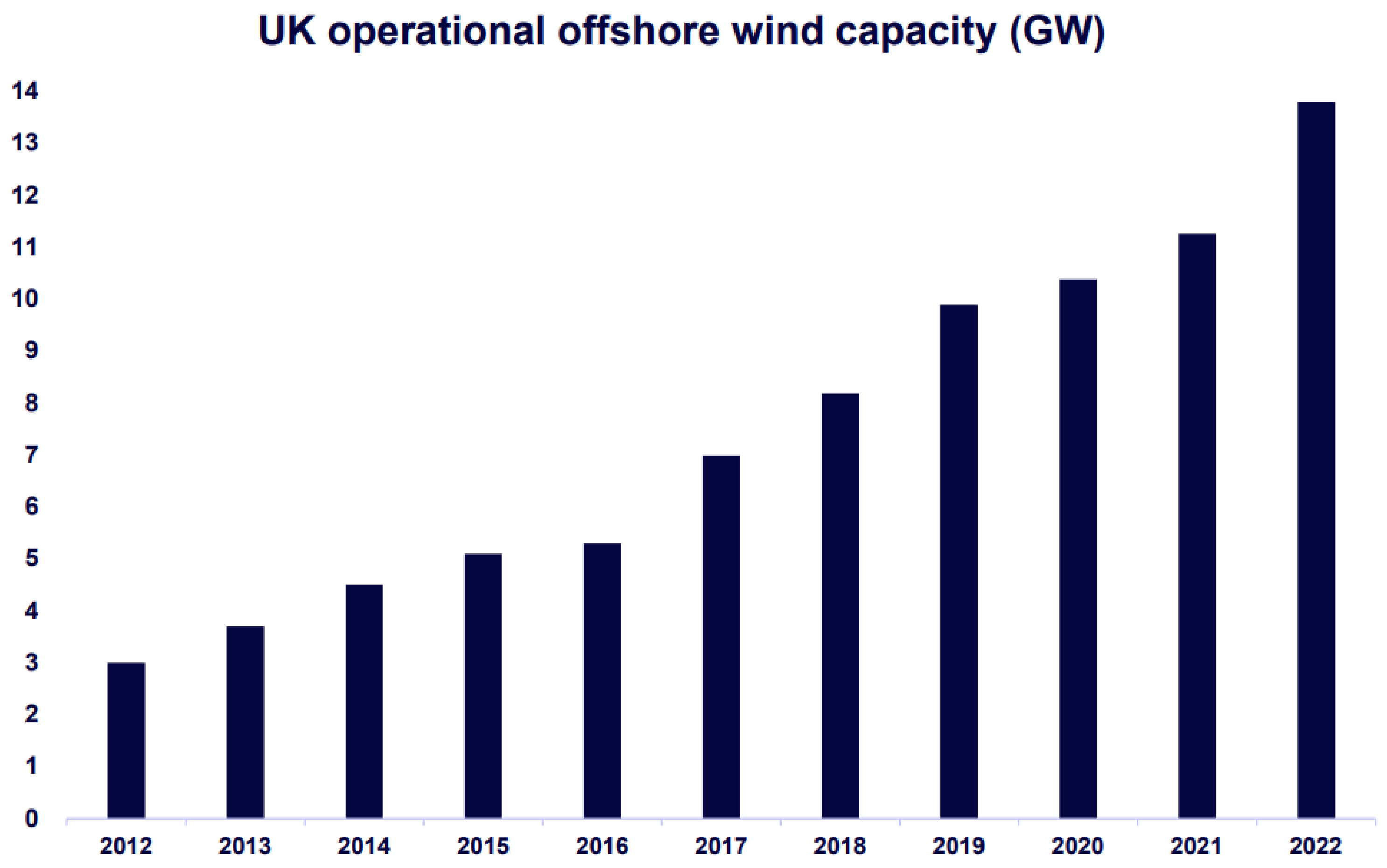

Figure 1: UK operational offshore wind capacity (GW) (HM Government, 2023)

Offshore Wind Turbines Structures

- An offshore wind energy device is composed of a foundation, a transition piece, a tower and turbine.
- The selection of foundation type depends both on site characteristics, and maturity and track record of the different design types.
- In deep waters, monopiles are the most commonly used support sub-structure, representing 80% of installed substructures in Europe.

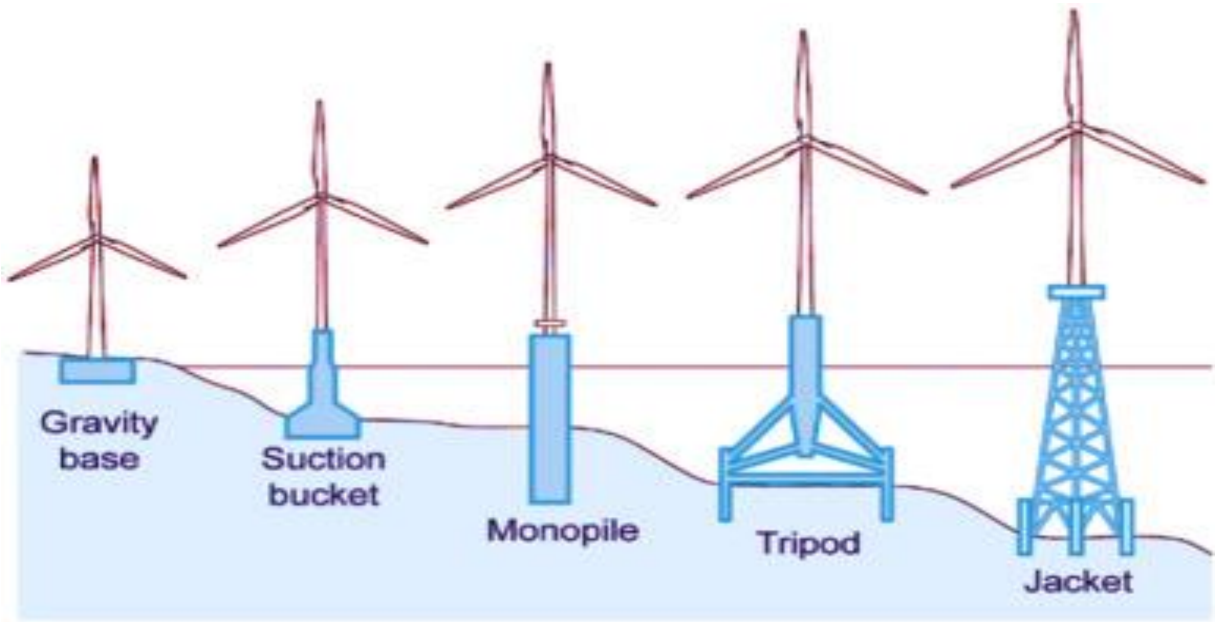

Figure 2: Fixed-bottom foundations commonly used in the offshore wind industry (Moulas, Shafiee, & Mehmanparast, 2017)

Corrosion Protection of Offshore Wind Turbines

- Marine corrosion has been a problem for the oil and gas industry for decades, and it has been common practice to adapt corrosion protection methods originally developed for oil and gas structures to offshore wind devices.
- Although not entirely successful, it was a solid foundation for the industry to build upon.
- Operation and maintenance (O&M) constitutes around 30% of the costs of energy from offshore wind turbines. The improved protection and inspection practices should reduce the expected cost of O&M throughout the lifetime of the components.
- The corrosion protection of offshore wind turbines will generally include the following:
  - Corrosion allowance (CA)
  - Cathodic protection (CP)
    - Internal and External
  - Protective coatings
  - Use of corrosion resistance materials

Protective Coatings

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- European wind farms are currently coated with multi-coat schemes, with potential scheme changes across the length of the tower.
- Expectations from Protective Coatings
  - Rapid application process (last step)
  - Low investment costs
  - Long lifetime
  - Maintenance free
- Experiences from existing structures suggest that protective coating durability is highly dependent on:
  - Coating workmanship
  - Steel surface preparation
  - Design of weld seam & coating application over welds
  - Installation of the turbines
  - Severity of the environment
  - Coating composition

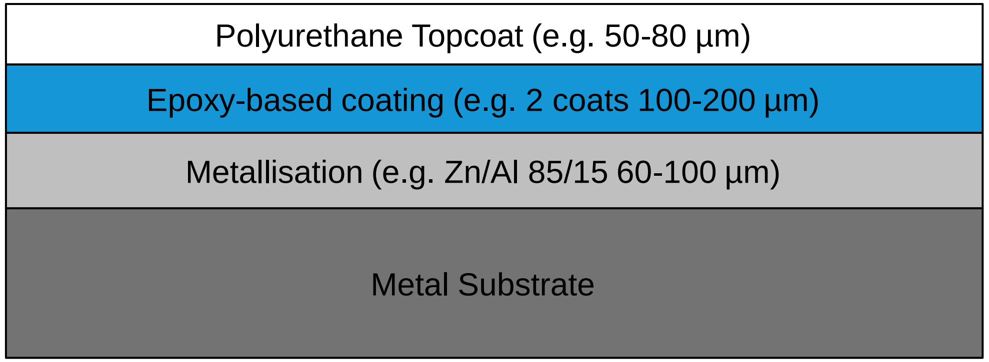

Figure 3: Recommended scheme for C5-M environments

Assessment of Protective Coatings

- The performance of protective coatings in marine corrosion protection is often studied through laboratory tests, which produce accelerated degradation with controlled environmental factors. Many researchers have established that generally there is not a good correlation between the results obtained through accelerated aging tests and real environmental degradation.
- Given the wide range of factors affecting coating durability, it is not expected that laboratory test prescribed in standards such as ISO 20340, ISO 12944, and NORSOK M-501, to model/predict the behaviour of coatings in the field.
- Studies have highlighted the importance of a hybrid approach involving the correlation of laboratory test, field test data and predictive models.
- To understand the corrosion protection needs we need to understand coatings and their behaviour.

Assessment of Protective Coatings

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- In the assessment of coating, it is imperative to understand the underlying physics of the curing film, the effects of mechanical stress on the film, and the way the film responds; to fully comprehend coating failure and therefore, avoid it and ensure good coating performance during the component's lifetime.
- Stresses due to film formation act against adhesion and excessive stresses may cause coating failure and degradation.
- Additionally, they may reduce the coating's capacity to undergo further stresses during service.
- Knowledge of the elastic modulus and residual stresses of supported coatings is crucial for the understanding and modelling of the mechanical behaviour of protective coatings.
- Due to the viscoelastic nature of coatings, any improvements or contributions in the field of coating's mechanical properties will involve dynamic mechanical analysis (DMA).

Understanding Protective Coatings: Solvent Borne Convertible Coatings

- The three main sources of internal stresses in the coatings are:
  - film formation (curing)
  - variation in temperature (thermal)
  - variation in relative humidity (hygroscopic).
- In general, the complex system of stresses (internal and external) experienced by the coatings is influenced by the following factors:
  - coating's chemistry and composition
  - curing mechanism
  - thickness
  - age
  - conditions under which film formation took place
  - service condition in which the film operates.

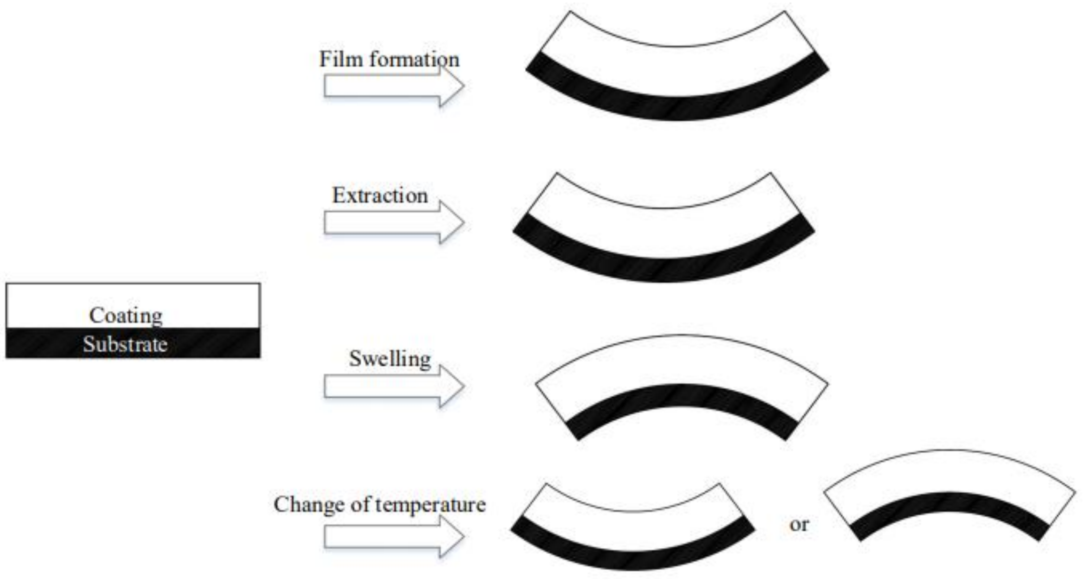

Figure 4: Residual stresses in organic coatings

Understanding Protective Coatings

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- Main factors influencing the magnitude of curing stresses are the elastic or Young’s modulus, Tg of the coating, plasticising effects of residual solvent, pigmentation and crosslinking degree, and application temperature.
- Curing stresses are also affected by factors at the molecular level, configuration and conformation affect molecular movement.

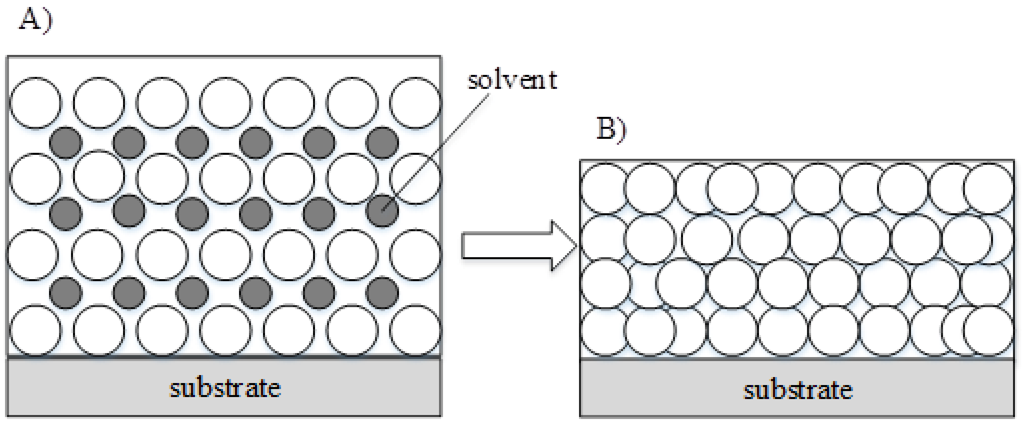

Figure 5: Representation of A) wet paint with solvent spread throughout ar dry/cured coating without solvent.

Understanding Protective Coatings

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Scanning Electron Microscopy (SEM)

- Evaluation of heterogeneities in coatings

Weight Loss Kinetics (Solvent-borne coatings)

- Evaluation of solvent evaporation kinetics at chosen heat treatments/cure schedules

Dynamic Mechanical Analysis (DMA)

- Calculation of elastic modulus, thermal expansion coefficient and glass transition temperature

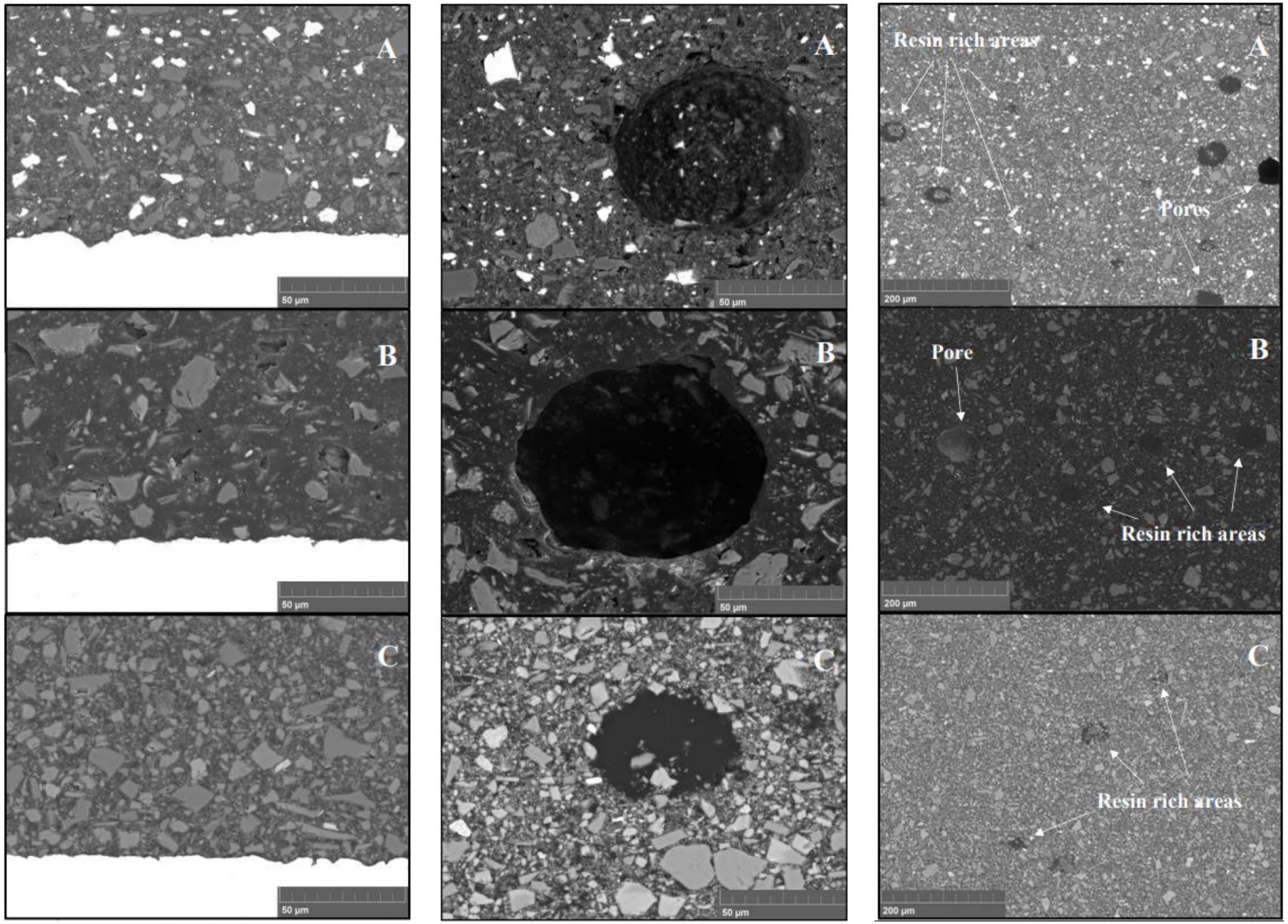
Cantilever Beam Method

- Assessment of the curvature of supported samples and calculation of internal residual stresses

Table 1: Coating description from technical data sheet

Name	Description	Application
Coating A	Two component polyamide adducts cured, high build epoxy paint which combines relatively high-volume solids with a short drying time	1) Intermediate coating (Zinc rich primer + coating A + PU overcoat) 2) Primer in mild to medium corrosive environments
Coating B	Two-component high build, epoxy polyamide/amine paint, which cures to an abrasion and corrosion resistant coating.	Severe corrosive environments where an abrasive resistant coating is needed. Splash and immersion zones
Coating C	Two-component, high build epoxy phenalkamine paint, which combines relatively high-volume solids content with a short drying time.	Primer in mild to medium corrosive environments

SEM



Left to right:

- **Figure 6:** Micrographs of the coating/substrate interface of coatings A, B, and C (DFT~350µm) with a view field of 160µm, working distance of 15mm, and magnification of 2230X
- **Figure 7:** Cross sectional micrographs of pores observed in coatings A, B, and C (DFT>1000µm) with 160µm view field, working distance 15mm, and 2230X magnification
- **Figure 8:** Cross sectional micrographs of pore/defect density in coatings with a view field of 640µm, working distance of 15mm, and magnification of 550X.

Solvent loss kinetics

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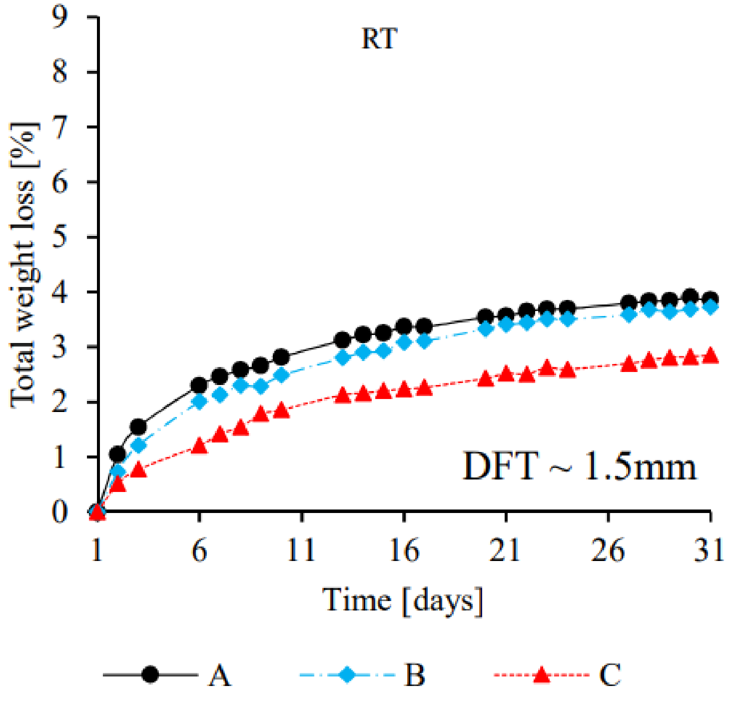

Figure 9: Cumulative weight loss of thick films subjected to cure schedule 1.

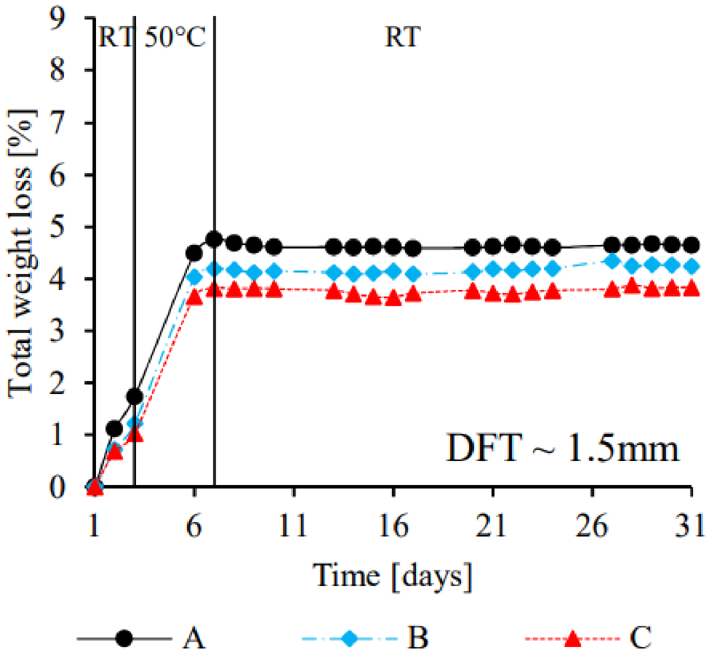

Figure 10: Cumulative weight loss of thick films subjected to cure schedule 2.

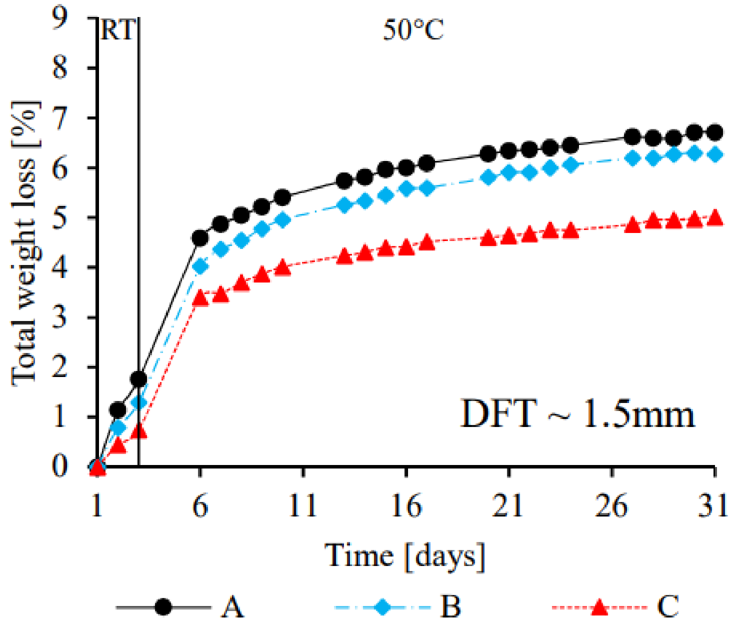

Figure 11: Cumulative weight loss of thick films subjected to cure schedule 3.

DMA

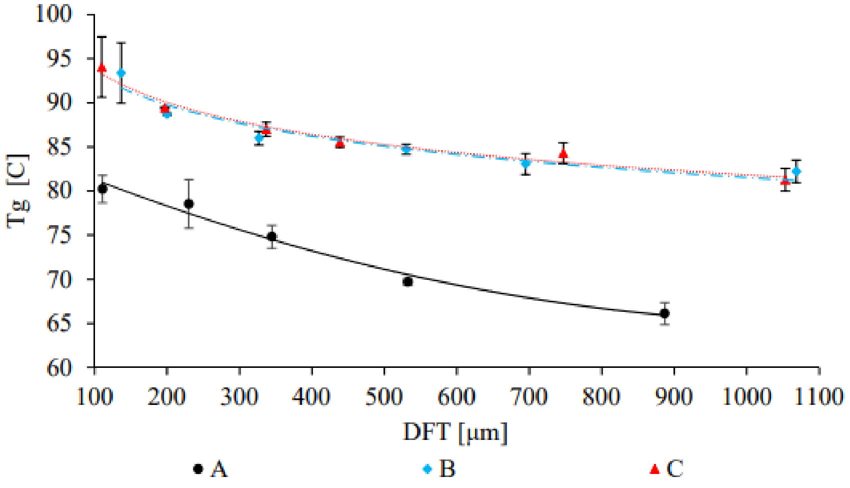

Figure 12: Glass transition temperature dependence on coating thickness for all supported coatings

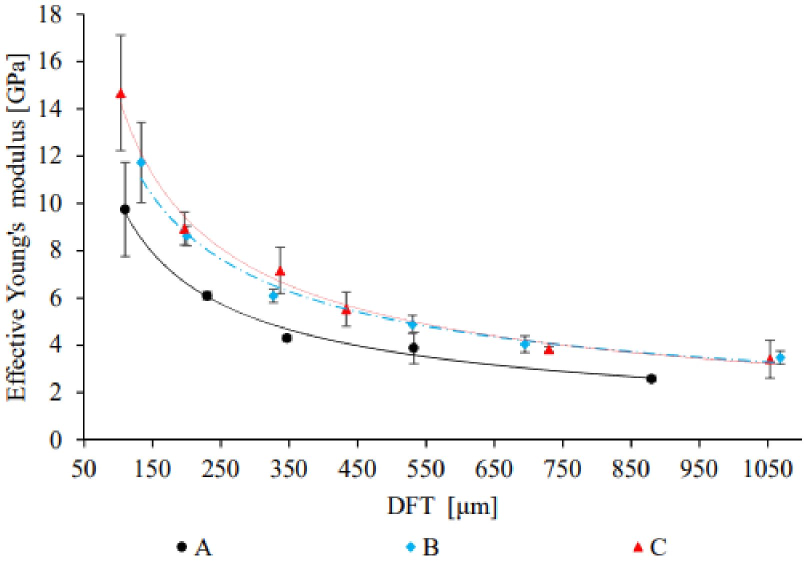

Figure 13: Variation of Young's modulus of the coatings with coating thickness at RT

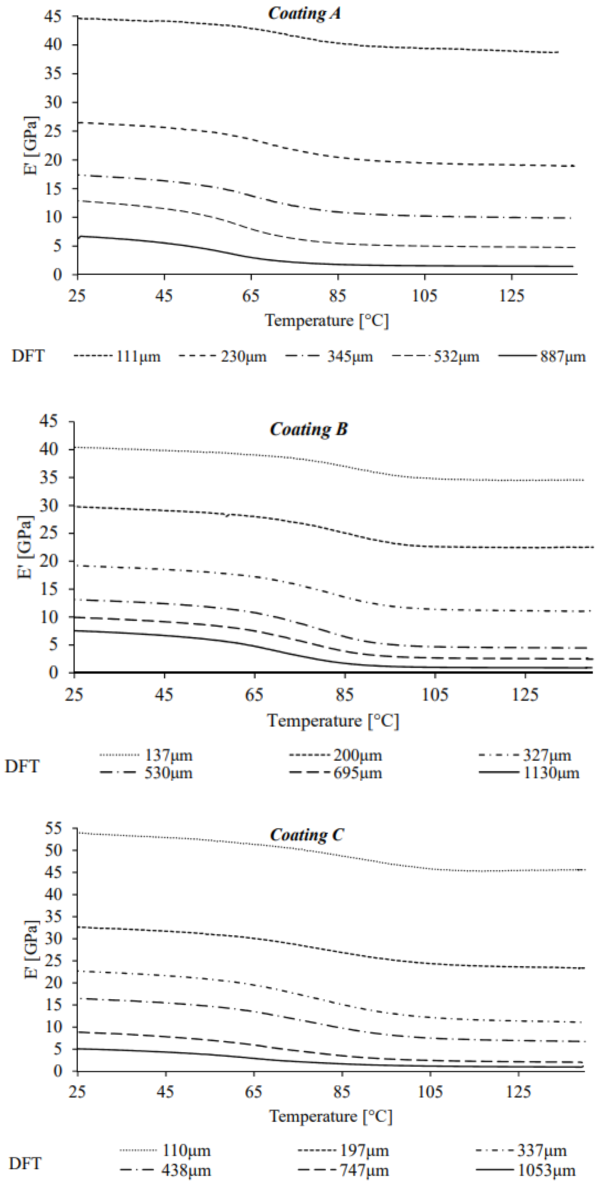

Figure 14: Variation of the storage modulus with coating thickness

Cantilever Beam Method

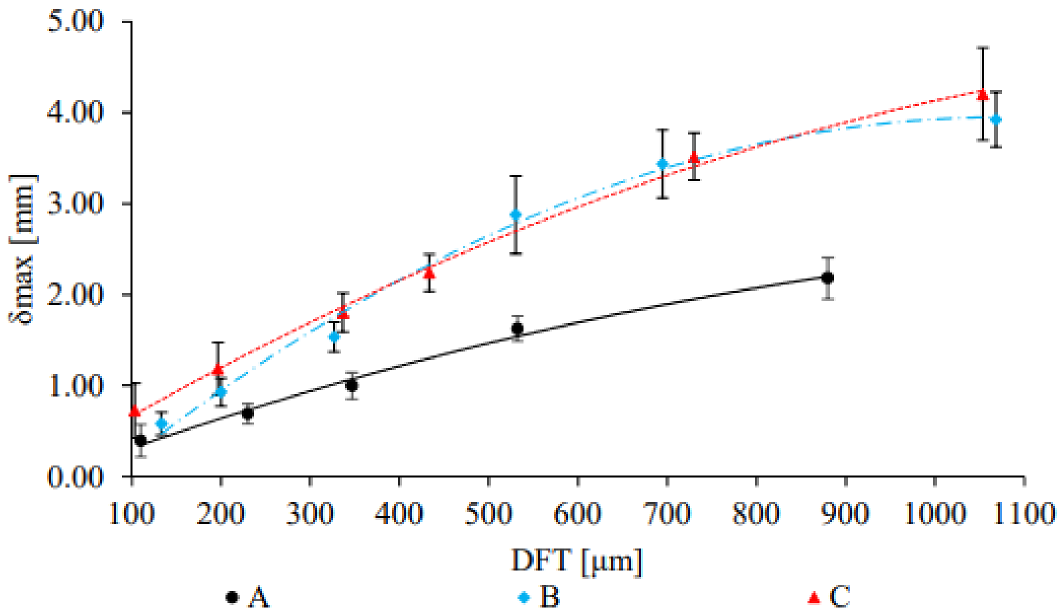

Figure 15: Maximum deflection of the bi-layer beams

Main Findings

- The mechanical and physical properties of the marine coatings were found to be dependent on coating thickness.
- The storage modulus of the coatings decreases with an increase in coating thickness. This was found to be due to increasing solvent retention, porosity and stiffness associated with an increase in coating thickness.
- Retained solvent acts as a plasticiser reducing the tensile strength of the material and the glass transition temperature.
- The rate of evaporation of the solvent also has a relevant effect on the mechanical response of the material; fast solvent loss rates were found to be associated with lower internal stress development.
- Ultimately, it has been found that it is possible to design more reliable and predictable coating systems by a judicious manipulation of the paint formulation, and control of the dry film thickness and post-cure schedule. A proper understanding of the stress development of organic coatings and the influencing factors is invaluable for not only offshore wind farms but also any structure where long-term corrosion protection (over 25 years) is required with minimal maintenance.

Protective Coatings: What have we learned?

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Lack of relationship between test data and in service data

- Studies comparing field data and laboratory data have shown that the assessment confirms that a complete assessment of the performance of offshore wind turbine coatings requires consideration of both laboratory and field data.

Consideration of the effect of dynamic loads

- A complete assessment of the performance of protective coatings needs to consider the complexities of the structures. Such as the effect of dynamic loads on coating aging and degradation.

Lack of historic in-service data

- Unlike Oil & Gas, Offshore wind is a relatively new field so currently there isn't enough data to predict behaviours.

Protective Coatings: What have we learned?

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Experience indicates shorter coating lifetime than the 20 years designed life for offshore wind turbines

- Coating lifetime is highly dependent on workmanship during coating application and structure installation, as well as corrosivity of the environment.

Effect of Cathodic Protection systems

- Although carbon steel corrodes mainly uniformly, CP failures due to unforeseen factors and unfavourable conditions may lead to accelerated localised corrosion.
- Challenges with external cathodic protection (CP) of tall steel structures under extreme tidal loads

The need to see "the big picture"

- Corrosion models with inputs from: real service corrosion rates, mechanical properties of coatings, and historical data, are necessary in order to control and mitigate risks of fatigue and corrosion failure.

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Thank you for your time.

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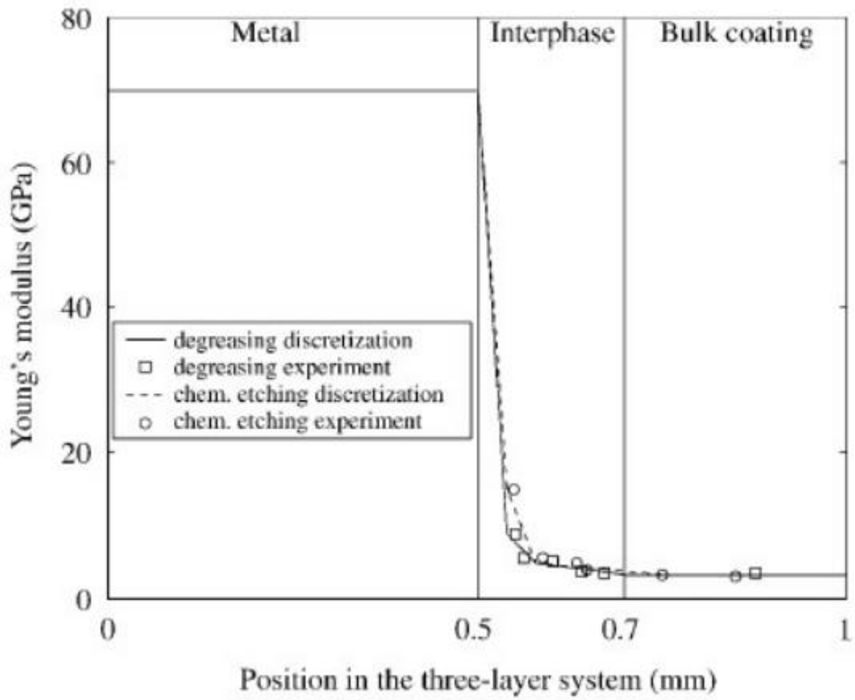

Figure 3.11 Variation of the Young's modulus as a function of the position in the three-layer system [98].

Mechanical Characterization of Protective Coatings for Offshore Wind Turbines

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- Pass/fail tests do not tend provide a property or parameter that can be related to well-known mechanical properties or be used to model the behaviour of the films.
- Efforts must be made to propose test methods for the determination of the mechanical properties of supported coatings and evaluate the different factors affecting the mechanical performance of coating.
- Due to the viscoelastic nature of coatings, any improvements or contributions in the field of coating's mechanical properties will involve dynamic mechanical analysis (DMA).