1 Research background and current situation

Chinese marine engineering manufacturing industry has achieved great progress since the implementation of the national maritime strategy, *Towards Deep Blue*. Guangdong Province has also clearly proposed to actively develop the marine engineering equipment industry in *the 13th five-year plan* for the development of strategic emerging industries but restricted by severe material failure under complicated marine environment, especially in the South China Sea. Therefore, it is urgent to establish an intelligent evaluation and management system for the service performance of marine engineering equipment materials, so as to provide technical support for their safety service and life extension.

The rapid development of new generation of information technology in recent years makes the appliance of digital twin system in industries available. The digital twin system for engineering materials performance evaluation proposed in our project will extract physical model from huge amount of material service performance data, which is acquired from experiments under multiscale, multifield coupling and various failure conditions, and combine data mining and artificial intelligence to construct the digital simulation model for failure dynamics that builds the mapping between simulation and practical engineering materials and equipments. Taking the advantage of the iteration of on-site and real-time inspection data, our system will be able to improve simulated prediction model to obtain higher accuracy on the evaluation of service performance of materials. However, the system can’t be co

Due to the lack of data of service performance of complicated marine engineering material and inadequate research on its failure mechanism, the validation and optimization of the prediction model in the system can’t be executed, which are also affected by the deficiency of on-site inspection and the inability to assess the service performance of huge, full scale entity subsection, or scalable equipment.

Thus, our project plans to employ the resource contained in the national major science and technology infrastructure of the initiating unit, experiments of huge and full scale materials under complicated service conditions, software and hardware platform for simulation and safety assessment, and selects the marine engineering equipment as research material and develops detection system to inspect environmental load spectrum and service status by material-component-equipment multifield experiments and simulation. We expect to acquire data of service performance of equipment material under multifield coupling environment from various aspects, and extracts the failure mechanism and the influence of environmental factors on models, and connect the digital twin system for engineering materials performance evaluation with the prediction technology of life span. National and even worldwide frontier and difficult problems are expected to be solved by our project.

2 Scientific issues

For the development of the digital twin system for marine engineering materials performance evaluation, we need to reveal the scale-span association and the evolution law of the service performance of marine engineering materials under multi-field and multi-factor coupling environment, and solve the problems in scale domain, environmental domain and time domain and their coupling effect.



Scientific issues in scale domain (scale effect)

* **尺度域科学问题（即尺寸效应）**——目前实验室积累的海工钢实验数据多基于试片级样品的测试结果，但由于结构中成分和微观组织结构的不均匀性（如材料中的夹杂相、偏析、缺陷等）、及装备中的焊接部位、紧固和动连接部位等的异金属连接和缝隙结构等，试片级样品数据往往不能很好地预测结构/装备的服役行为，需揭示海工材料成分-组织结构-环境载荷-服役性能间的内在联系，建立海工用钢微观与宏观性能、小尺寸材料与大尺寸材料性能、材料与结构性能间的相关性。

At present, the experimental data of offshore steel accumulated in the laboratory are mostly based on the test results of the sample-level samples,

but due to the non-uniformity of the composition and microstructure of the structure (such as inclusion phase, segregation, defects, etc. in the material), and equipment The test piece-level sample data often does not predict the service behavior of the structure/equipment, and the composition of the marine material-organizational structure-environmental load is often not well predicted for the welded parts, fastening and moving joints. - The intrinsic link between service performance, establishing the correlation between microscopic and macroscopic properties of offshore steel, properties of small and large materials, and material and structural properties.

* **环境域科学问题（即环境耦合效应）——**海工装备不同部位服役于海洋大气区（盐雾环境、日光照射的老化效应和热效应）、浪溅区、潮差区、全浸区、海泥区等不同的海洋环境，同时受到自身结构载荷、加工残余应力、风载荷、浪涌载荷等复杂力学因素影响，还取决于其表面涂层防护体系及水下区阴极保护系统的工作状态。解决环境域科学问题在于揭示以上多场多环境因素环境载荷对工程材料服役行为的复杂非线性耦合作用机制与规律。
* Different parts of marine equipment are used in different marine environments such as the marine atmosphere (salt fog environment, aging effect and thermal effect of sunlight), wave splash zone, tidal zone, full immersion zone, sea mud zone, etc. The influence of complex mechanical factors such as machining residual stress, wind load and surge load
* depends on the surface coating protection system and the working state of the underwater protection system.
* Solving the problem of environmental domain science is to reveal the complex nonlinear coupling mechanism and law of the above-mentioned multi-field and multi-environmental environmental load on the service behavior of engineering materials.

Scientific issues in time domain (time effect)

* **时间域科学问题（即时间效应）**——围绕海工装备剩余寿命预测及延寿评价需求，需掌握复杂力化耦合环境下材料服役性能的经时非线性演化特性。其关键在于提炼实验室（加速）评价方法，并与现场服役数据对比验证其等效性，从而构建材料服役性能的经时演化模型，为依据短时间服役数据推演长期服役行为奠定基础。
* Focusing on the remaining life prediction and life extension evaluation requirements of offshore equipment, it is necessary to grasp the time-dependent nonlinear evolution characteristics of material service performance in complex and force-coupled environments. The key is to refine the laboratory (acceleration) evaluation method, and verify its equivalence with the on-site service data, so as to construct a time-dependent evolution model of material service performance, which lays a foundation for deriving long-term service behavior based on short-time service data.

3 Research content

1 Selection of research target

For the efficient construction of the digital twin system for engineering materials performance evaluation, a typical marine engineering equipment is required as research target among a great variety of marine engineering materials and equipments, which service under complicated environments and fail due to the coupling of sundry failure mechanisms.

The development of offshore wind energy is entering an accelerated status in China and Guangdong province plans to build 23 offshore wind farms with a total installed capacity of 66.85 million kilowatts by 2030. At present, most sites for wind power construction are located in the intertidal zone, in where the service environment is more demanding than the offshore platform and alternation of wetting and drying is more frequent on the surface of steel structure and the effect of surge and spray gets severer. The coupling effect of the unique wind load on the sea and the harsh corrosive environment makes the failure forms of marine engineering equipment materials more complex and diverse. At the meantime, the constructions of remote inspection on service status and real-time management system for risk assessment and maintaining decision are desperately required for the reason that the development of the Chinese offshore wind power gradually reaches toward the far sea. However, due to the short operating life of offshore wind power in China, a system that assesses the service performance and predicts life span of materials has not been formed for the lack of data of service performance of materials and accumulation of failure mechanism, comparing with other marine engineering equipment. Therefore, our project takes typical offshore wind equipment as research target, which is urgently needed and possesses inadequate accumulation of data of service performance, and conquers the key scientific issues in the evaluation of service performance of engineering materials, and constructs the digital twin system for material service performance of offshore wind equipment, and finally demonstrates their appliance.

2 Research content

1) Multiscale performance evaluation for offshore wind equipment under multi-field and multi-factor coupling environment

Our project takes typical offshore wind power metal materials, its structure (welding zone and connection sections), important equipment and its protection material as research targets, and collects multiple environmental load spectrums of marine atmosphere and seawater, unique wind load and wave load, and et cetera, and develops material-component-equipment multiscale (accelerated) evaluation experiment methods. The research on multiscale evaluation experiment and the accumulation of data from

开展 近工况 复杂力 化 耦合环境条件下 典型材料、结构 与装备服役性能 的多尺度 实验室评价研究 与数据积累，

明确 腐蚀-疲劳 耦合作用下 装备材料 失效机理 及各因素影响规律模型。

**2）海上风电装备材料服役性能的跨尺度建模仿真**

以多因素耦合条件下海上风电装备材料服役性能演化机理模型为基础，对海上风电装备材料服役行为进行多尺度数字建模仿真；通过各尺度模拟间关键参数的跨尺度传递及区域嵌套等方式，实现材料/结构环境损伤行为的跨尺度关联；结合仿真结果与前述多尺度实验数据的对比验证，修正仿真模型与参数，共同支撑对装备材料失效机理与规律的深入解析；同时，相应的机理模型与数据关联可以作为物理信息融合基础，支撑后续海上风电数字孪生系统的构建。

**3）海上风电装备服役载荷谱及健康状态实时监检测技术研发**

基于海上风电装备服役特点，开发适用于海洋环境的全固态环境因子监测传感器和基于多电极技术的腐蚀特征量监测传感器，并基于物联网技术，开展适用于大型海上风电装备服役和防护状态实时监测系统和设备研发，以获取海上风电装备服役中关键部件应力应变水平等服役状态数据、所处局域环境及其腐蚀性监测数据、及阴极保护等防护体系的工作状态数据，为海上风电装备健康状态评估及关键部件维护策略的选择与优化提供支撑。

**4）海上风电装备材料服役性能数字孪生原型系统开发**

基于海上风电装备材料服役性能的多尺度实验评价数据、数值仿真数据，同时收集相关服役失效案例，突破海上风电装备材料多源异构数据融合方法、全寿命周期评价模型以及关键材料失效溯源与寿命预测等关键技术，重点针对其中关键组成部分，建立“材料-构件-子系统-整机装备”数字孪生原型系统，实现对装备局域环境严酷性分级和关键部件风险等级划分，初步形成海上风电装备材料失效概率分析与寿命预测能力。

**5）****海上/风电/装备/服役性能/智能化/评价系统/技术集成与验证**

开展数字孪生原型系统和在线监检测系统与海上风电装备现有监控和运维系统的技术集成，利用数字孪生系统提供的相关数据、模型、方法及工具，实现对海上风电装备的安全评价。完成海上风电装备数字孪生评价系统的示范性应用，基于现场实时监测数据，迭代优化失效概率与寿命预测模型，最终形成一套集海上风电装备服役状态监测、服役安全性评估与预测、风险预警及防护决策建议功能为一体的实时智能化数字孪生评价系统。

2) Cross-scale modeling and simulation of service performance of offshore wind power equipment materials

Based on the evolution mechanism model of offshore wind power equipment service performance under multi-factor coupling conditions, the multi-scale digital modeling and simulation of the service behavior of offshore wind power equipment is carried out.

The cross-scale transmission and regional nesting of key parameters between simulations are simulated. To realize the cross-scale correlation of material/structural environmental damage behavior;

combined with the simulation results and the above-mentioned multi-scale experimental data, verify the simulation model and parameters, and jointly support the in-depth analysis of the failure mechanism and law of equipment materials; meanwhile, the corresponding mechanism model and data association can be used as the basis of physical information fusion to support the construction of the subsequent offshore wind power digital twinning system.

3) Research and development of real-time monitoring and detection technology for service load spectrum and health status of offshore wind power equipment

Based on the characteristics of offshore wind power equipment service, an all-solid-state environmental factor monitoring sensor suitable for marine environment and a corrosion characteristic quantity monitoring sensor based on multi-electrode technology are developed,

and based on the Internet of Things technology, real-time monitoring for service and protection status of large-scale offshore wind power equipment is carried out.

System and equipment research and development, to obtain the service status data such as the stress and strain level of key components in the service of offshore wind power equipment, the local environment and its corrosive monitoring data, and the working status data of the cathodic protection and other protection systems, for the offshore wind power equipment health Support for state assessment and selection and optimization of key component maintenance strategies.

4) Development of digital twin prototype system for service performance of the offshore wind power equipment

Multi-scale experimental evaluation data and numerical simulation data based on service performance of offshore wind power equipment, and collect relevant service failure cases, break through multi-source heterogeneous data fusion method of offshore wind power equipment materials, life cycle evaluation model and critical material failure traceability and life Key technologies such as forecasting,

focusing on key components, establish a digital material prototype system of “material-component-subsystem-machine equipment”, realize the rigorous classification of equipment local environment and the classification of risk components of key components, and initially form offshore wind power. Failure probability analysis and life prediction capability of equipment materials.

5) Offshore / Wind Power / Equipment / Service Performance / Intelligent / Evaluation System / Technology Integration and Verification

The digital integration of the digital twin prototype system and the online monitoring system with the existing monitoring and operation system of the offshore wind power equipment is carried out,

and the relevant data, models, methods and tools provided by the digital twin system are used to realize the safety evaluation of the offshore wind power equipment. The demonstration application of the digital wind power equipment evaluation system for offshore wind power equipment is completed.

Based on the on-site real-time monitoring data, the failure probability and life prediction model are iteratively optimized, and finally a set of offshore wind power equipment service status monitoring, service safety assessment and prediction, risk warning and The protection decision suggestion function is an integrated real-time intelligent digital health evaluation system.

5) Technical integration and validation of the intelligent performance evaluation system for offshore wind power equipment in service