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A digital twin model within the framework of a digital healthcare engineering system for aging containership hull structures

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ABSTRACT

Digital Healthcare Engineering (DHE) offers a proactive approach to improving the safety, longevity, and sustainability of aging ships and offshore structures operating in harsh and remote environments. The DHE framework is composed of five interconnected modules: (1) on-site monitoring and digitalization of structural health parameters, (2) transmission of collected data to land-based analytics centers via low Earth orbit (LEO) satellites, (3) advanced analytics and simulations through digital twin technology, (4) AI-driven diagnostics with automated maintenance recommendations, and (5) predictive health analysis for future maintenance planning. This paper focuses on the development of a digital twin model used for data analytics and simulations within the DHE system, specifically for aging containership hull structures. A case study involving an as-built 22,000 TEU containership is presented to demonstrate the digital twin's effectiveness, where on-site monitoring of parameters such as ocean wave profiles and in-service damage (e.g. corrosion wastage) is integrated with the land-based analytics system.

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Digital healthcare engineering (DHE); aging ships and offshore structures; harsh and remote environments; digital twins; AI-driven diagnostics

1. Introduction

As ships and offshore structures age, they undergo age-related degradation (i.e. in-service damage), such as corrosion wastage, fatigue cracking, and mechanical denting. Additionally, their operation in harsh and remote oceanic environments often exposes them to hazardous conditions, further increasing the risks to their structural integrity. For the lifetime healthcare of ship hull structures – particularly in autonomous ships and advanced vessels, such as those powered by small modular reactors (SMRs) – the maritime industry employs a range of strategies, including: (a) designing robust hull structures, (b) conducting regular hull inspections on an annual or biennial basis, (c) performing dry-docking with comprehensive inspections every five years, (d) monitoring stress through strain gauges, (e) carrying out risk assessments, and (f) utilizing weather hindcast data to enhance navigation safety. However, managing the structural integrity of aging ships remains a significant challenge due to their large size, complex geometry, long inspection intervals, and the numerous unpredictable factors arising from volatile, uncertain, complex, and ambiguous (VUCA) environment and operational conditions (Paik 2020; Bai and Paik 2024). Additionally, the remote locations in which ships often operate make access for inspections and repairs more difficult.

With the advent of the fourth industrial revolution, rapid advancements in digital and communication technologies present an opportunity to enhance the lifetime healthcare, longevity, and sustainability of aging ship hull structures. The concept of Digital Healthcare Engineering (DHE), proposed by the second author of this paper (Paik 2023, 2024), provides an advanced approach for efficiently managing structural health by leveraging digital and communication technologies. Unlike traditional Structural Health Monitoring (SHM), DHE focuses on real-time digitalization of critical health information through Digital Twin (DT) technologies to ensure structural safety and facilitate informed decision-making for the lifetime healthcare of engineered structures (Figure 1).

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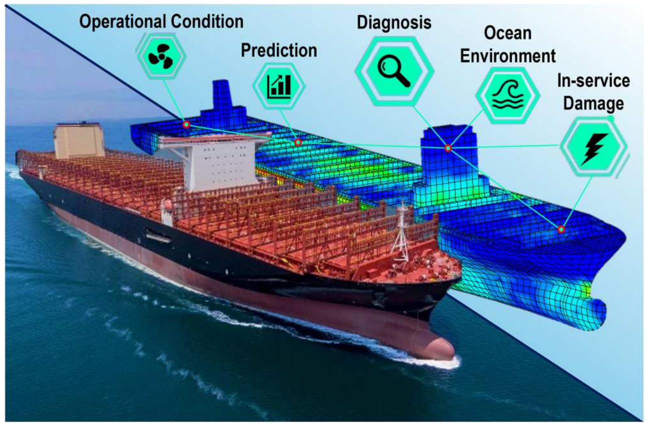


Figure 1. Schematic example of the DHE system for aging containerships in rough weather conditions (This figure is available in colour online).

In recent years, DTs have garnered significant attention across various industries, including aerospace, automotive, and manufacturing. However, the maritime sector remains a step behind in adopting these technologies, as noted by Mauro and Kana (2023). While numerous researchers and institutions have explored and developed DT technologies for maritime applications, their application in the industry remains in the early stages. Recent literature reviews (Taylor et al. 2020; Chen et al. 2021; Fonseca and Gaspar 2021; Giering and Dyck 2021; Assani et al. 2022; Ferreno-Gonzalez et al. 2023; Mauro and Kana 2023) have provided systematic insights into the digitalization of marine structures. These reviews cover various aspects of digitalization, such as design, construction, propulsion, structure, and navigation. However, there remains a gap in the literature specifically focusing on the digitalization of ship hull structures for their lifetime healthcare. Addressing this gap, Sindi et al. (2024) have provided an in-depth review of recent technological advancements and feasibility analyses concerning the digitalization of aging ships and offshore structures for their lifetime healthcare. Building on their work, subsequent studies have reviewed the application of DHE systems to offshore pipelines (Mohammad Fadzil et al. 2024), jacket-type offshore wind turbines (Xie et al. 2025), and even to the healthcare of seafarers and offshore personnel (Cui et al. 2025).

Several research articles have introduced concepts and methodologies for the digitalization of ship structural health monitoring. For instance, Anyfantis (2021) proposed two digital health monitoring models for ships: a finite element analysis (FEA) optimization model and an artificial neural networks (ANNs) model. Han et al. (2021) suggested a digital health monitoring and decision support framework based on real-time risk assessment. Cheng et al. (2022) introduced a digital twin concept for ships that estimates structural health conditions using health parameters measured by wave radars, motion reference units (MRU), accelerometers, and strain gauges. VanDerHorn et al. (2022) developed a digital health monitoring system for fatigue damage, which utilizes fatigue analysis models instead of sensor-based measurement data. Despite these advancements, existing frameworks for ship digitalization remain in early development or are limited to addressing specific issues, such as fatigue damage (VanDerHorn et al. 2022). Furthermore, most digital healthcare models rely on estimated health parameters derived from ocean wave hindcasting, neural networks, or mathematical prediction models, rather than real-time measurement data, primarily due to high costs and technical limitations.

This paper introduces a DHE framework specifically designed for the lifetime healthcare of aging containerships. The proposed DHE system encompasses the entire healthcare process through five key modules: (1) on-site monitoring and digitalization of structural health parameters, (2) transmission of collected data to land-based analytics centers via low Earth orbit (LEO) satellites, (3) advanced analytics and simulations through digital twin technology, (4) artificial intelligence (AI)-driven diagnostics with automated maintenance recommendations, and (5) predictive health analysis for future maintenance planning. The aim of the present paper is to introduce the DHE system and develop the DT model for the third module, demonstrated through an illustrative example using an as-built 22,000 TEU containership. Section 2 introduces the proposed DHE system and each of its modules. Sections 3 and 4 detail the development of the DT model and the illustrative example for data analytics and simulations, respectively. Concluding remarks and future works are discussed in Section 5.

Figure 2. Lifetime healthcare processes for human bodies and engineered structures (Paik 2022) (This figure is available in colour online).

2. Framework of the proposed DHE system for aging containerships in rough weather conditions

Human bodies and engineered structures share several similarities in terms of lifetime healthcare, as illustrated in Figure 2 (Paik 2022), particularly in the assessment and management of their health conditions as both experience age-related deterioration over time. Just as human bodies require regular and appropriate healthcare to prevent illness and promote longevity, engineered structures require continuous health monitoring, diagnosis, remedial actions, and predictive assessments of future conditions to ensure structural safety and prevent accidents that could lead to catastrophic consequences, such as casualties, property damage, and marine pollution (Paik 2020, 2022; Bai and Paik 2024). Building on these principles, the DHE system employs a framework consisting of five key modules, as described in the previous section. The core processes and technologies of each module are briefly introduced in this section. Figure 3 illustrates the proposed DHE system framework.

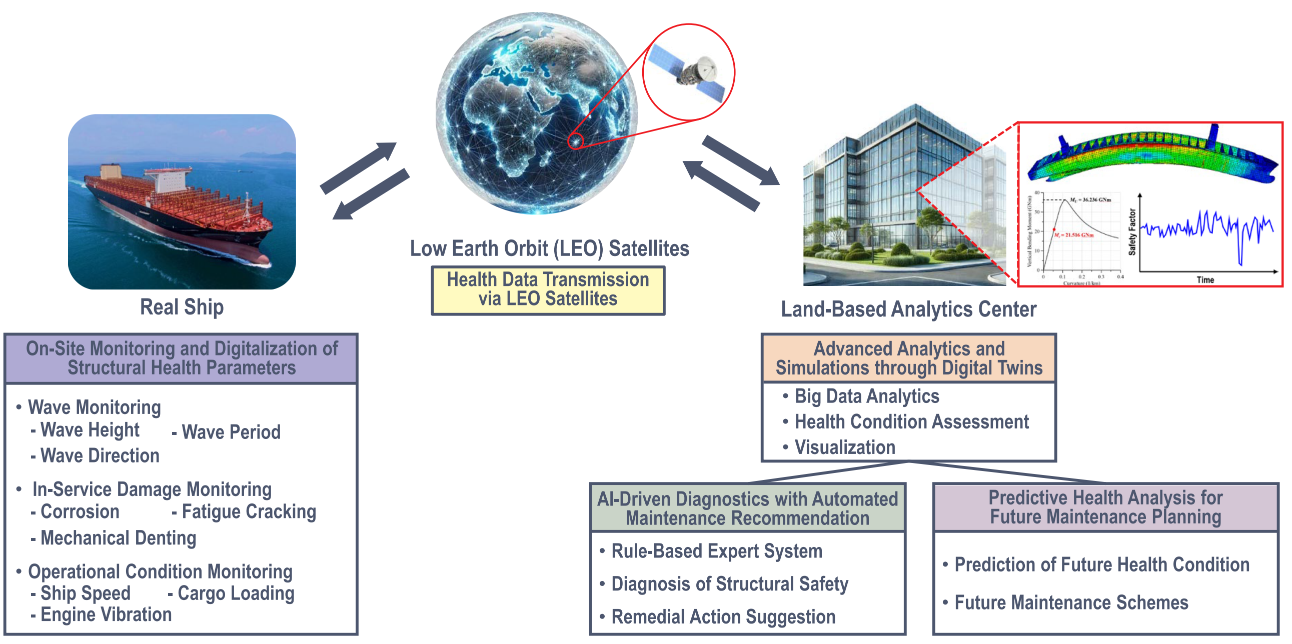


Figure 3. Framework of the proposed DHE system for aging containerships in rough weather conditions (This figure is available in colour online).

2.1 Module 1: on-site monitoring and digitalization of structural health parameters

The structural health of ship hulls is affected by various factors, including ocean environmental conditions (e.g. waves), in-service damage (e.g. corrosion, fatigue cracking, and mechanical denting), and operational conditions (e.g. ship speed, cargo loading conditions, and engine vibration). These key health parameters are continuously monitored in real-time using in-situ instruments within the DHE framework. The health parameters include:

- Ocean environmental conditions
  - Wave height
  - Wave period
  - Wave direction
- In-service damages
  - Location, depth, and extent of pits for corrosion wastage
  - Location and length of fatigue cracking
  - Location, depth, and extent of mechanical denting
- Operational conditions
  - Ship speed
  - Cargo loading conditions
  - Engine vibration

Various methods are available for accurately measuring wave parameters, including X-band radar, wave buoys, air gap sensors, acoustic wave and current profilers, and satellite-based observation (Sindi et al. 2024). Among these, X-band radar is particularly suitable for ships due to its relatively lower cost and remote sensing capabilities, which enable wave monitoring even on moving vessels. However, monitoring in-service damage with real-time sensors poses challenges, as sensor accuracy significantly diminishes when the damage occurs outside the sensor's immediate range, and it is prohibitively expensive to install and maintain sensors across the entire hull structure. Therefore, the authors propose monitoring in-service damage through visual or close-up inspections, supported by portable devices (e.g. ultrasonic sensors and tablet computers) on a more frequent schedule – daily, weekly, monthly, or quarterly – rather than the traditional annual or biannual basis. In conjunction with these measurements, operational conditions can be recorded or measured using voyage data recorders (VDRs), integrated automation systems (IASs), and vibration sensors. Figure 4 shows X-band wave radar and portable ultrasonic sensor for on-site monitoring of ocean environmental conditions and in-service damage (Lund et al. 2015).

2.2 Module 2: transmission of collected data to land-based analytics centres via LEO satellites

Data transmission is a key module within the proposed DHE system, facilitated by modern technologies. Health data measured onboard is logged and recorded in data loggers. This recorded data can then be transmitted to a land-based data analytics center via LEO satellites, such as Starlink, which provides a reliable solution for maintaining internet connectivity on vessels operating in remote areas. Notably, Mitsui O.S.K. Lines (MOL), one of the world's largest shipping companies, has already installed Starlink antennas on its vessels and successfully tested internet connectivity, as shown in Figure 5.

2.3 Module 3: advanced analytics and simulations through digital twin technology

The transmitted data must be analyzed to compute ocean environmental loads and the residual strength of the structures. These analyzed health parameters are then utilized for real-time health condition assessments through computer simulations using predefined computational models. Through this process, a digital twin model is developed, acting as a virtual

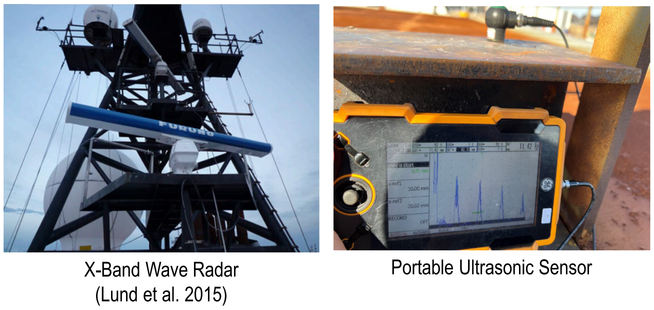


Figure 4. Instruments for on-site monitoring of ocean environmental conditions and in-service damages: X-band wave radar (left) and portable ultrasonic sensor (right) (This figure is available in colour online).

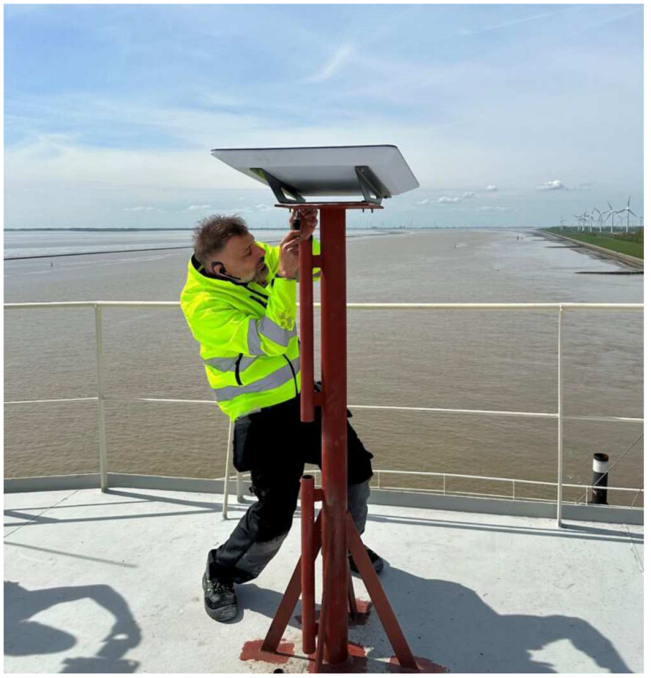


Figure 5. Starlink antenna being installed on an MOL vessel (Magli 2023) (This figure is available in colour online).

representation of the physical asset. With significant advancements in computing technologies and analysis methods, powerful computational tools are now available for the digitalization of ships. Hydrodynamic analysis using CFD (computational fluid dynamics) software is particularly useful for calculating the ocean environmental loads acting on ships, while nonlinear finite element analysis (NLFEA) is highly effective for evaluating the residual strength of hull structures. The outcomes from hydrodynamic analysis and NLFEA are then visualized as color-coded contours and plots, providing a clear representation of time-variant changes in the loads and their effects on the hull structures. In the proposed DHE system, the digital twin model is created using MAESTRO software (MAESTRO 2025) for load analysis and NLFEA. This software utilizes ALPS/ULSAP (2025) for calculating the buckling and ultimate strength of plates and stiffened panels, and ALPS/HULL (2025) for analyzing the progressive ultimate strength behavior of hull girders. Additionally, commercial software for hydrodynamic analysis and NLFEA has been integrated. Further details are provided in Section 3.

2.4 Module 4: AI-driven diagnostics with automated maintenance recommendations

A local structural member and hull girder structures can fail as a result of progressive collapse due to a loss of stiffness and strength of structural members caused by yielding, buckling, and fracture (Paik 2018, 2020, 2022). To prevent catastrophic failure of ship hull structures, precise diagnosis and proper remedial actions (e.g. repair or renewal of structural parts) are required. In the proposed DHE system, the health condition of ship hull structures will be diagnosed in real-time using the results of computer simulations, with automated maintenance recommendations. However, conducting real-time diagnostics and identifying appropriate remedial actions for a large number of structural components on a ship is highly challenging for humans to manage continuously, 24 h a day, seven days a week. Therefore, it is essential to use AI techniques for prompt diagnosis and maintenance recommendations. Among various AI techniques, a rule-based expert system (Bernat and Gil 2013; Nuhu et al. 2021) may be appropriate for a prototype of the DHE system due to the need for conservative and definite judgement criteria in structural safety assessment. In subsequent stages, advanced AI techniques such as deep neural networks (DNNs) will be introduced to further enhance Module 4.

Figure 6 outlines the procedure of AI-driven diagnostics with automated maintenance recommendations based on the rule-based expert system. Once the DT simulations are conducted, the results are then fed into the expert system. An inference engine within the expert system then applies if–then logic rules to determine appropriate diagnoses and recommend corresponding remedial actions. A knowledge base, which includes

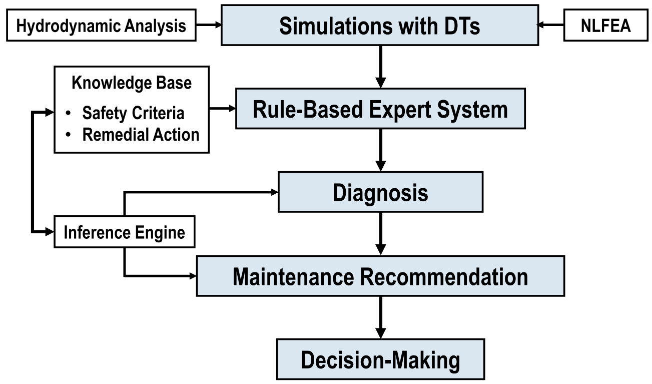


Figure 6. Procedure of AI-driven diagnostics with automated maintenance recommendations based on the rule-based expert system (This figure is available in colour online).

safety criteria and a list of remedial actions, is a crucial component, providing the necessary information from human experts to the inference engine. In the proposed DHE system, the diagnosis of the structural health condition is primarily conducted using a safety factor, as defined in Equation (1) (Paik 2018). This safety factor was chosen because it is widely employed in serviceability limit state (SLS) and ultimate limit state (ULS) analysis and design of ships and offshore structures. In the AI-driven diagnostic process, the fatigue limit state (FLS) with fatigue cracking and the accidental limit state (ALS) with accidental damage are also considered (Paik 2018, 2020, 2022; Bai and Paik 2024). Fatigue cracking and accidental damage (e.g. mechanical denting) serve as damage parameters that impact both the serviceability limit state (SLS) and ultimate limit state (ULS) within the digital twins for NLFEA. It is worth noting that other key performance indicators (KPIs), such as the Component Health Index (CHI) or Remaining Service Life (RSL), can also be integrated into the DHE system according to user requirements.

$$\eta = \frac{C}{D} > \eta_{cr} \tag{1}$$

where C is the maximum load-carrying capacity (i.e. ultimate strength), D is the applied loads, η is the safety factor, and η_{cr} is the critical safety factor predefined by classification societies or operators for ensuring the structural safety. η should always be greater than η_{cr} to ensure the safety of the target structures.

Maintenance and remedial action schemes for repair or renewal of structural parts can be prepared with reference to the automated maintenance recommendations provided by the DHE system. Classification societies provide useful guidance for the maintenance and repair of defects and damage on the hull structures (ABS 2017; DNV 2021; IACS 2021; LR 2022). Minor damage can be addressed with temporary onboard repairs or at repair facilities once the ship reaches port, while major damage which significantly affects structural integrity should be promptly and thoroughly repaired with proper treatment. Table 1 summarizes typical causes and remedial actions for in-service damage on ship hull structures.

2.5 Module 5: predictive health analysis for future maintenance planning

Predicting future health conditions allows for early detection of structural defects and more effective planning of maintenance schemes, thereby minimizing downtime costs. The accumulated data of in-service

Table 1. Typical causes and remedial actions for in-service damage on ship hull structures (Paik 2022).

In-service damage	Cause	Remedial action
Corrosion wastage	• Inadequate type of corrosion protection • Insufficient coating or protection system • Corrosive environment	• Renewal with higher structural capacity • Recoating • Repair by welding
Fatigue cracking	• Stress concentration • Cyclic loads • Poor workmanship in welding • Vibration	• Renewal with higher structural capacity • Reinforcement with additional structural members • Smooth transition in geometry • Change of natural frequency • Post-weld treatment (e.g. burr grinding and ultrasonic impact treatment)
Mechanical denting	• Impact loads • Insufficient strength • Poor operation	• Renewal with higher structural capacity • Reinforcement with additional structural members

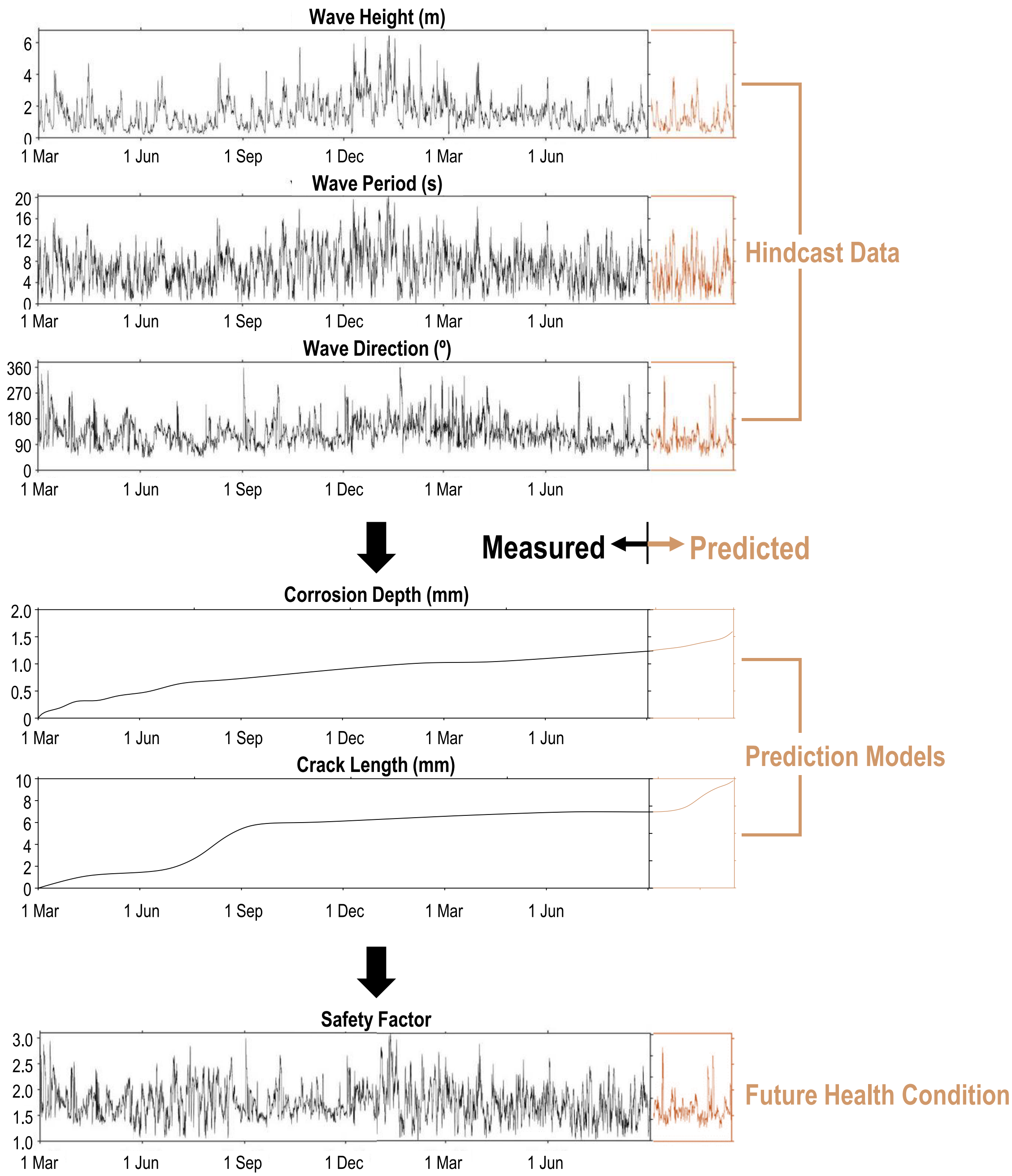


Figure 7. Illustrative example of predictive health analysis (This figure is available in colour online).

damage, measured through the first module, will be instrumental in developing time-variant prediction models, while hindcasting data can be utilized to predict wave parameters. Advanced techniques for predicting time-variant corrosion damage and fatigue crack propagation are available in Paik (2018, 2022) and the review by Sindi et al. (2024). Finally, future health conditions can be estimated by using predictive data on both ocean environmental conditions and in-service damage, as depicted in Figure 7. Comprehensive details will be provided in a subsequent paper dedicated to Module 5.

2.6 Integration and automation of the DHE modules

Upon the complete development of each module, the key components of the DHE system are seamlessly integrated and automated to function as a unified framework. Through Modules 1–5, the structural health of aging ships is continuously monitored, assessed, and managed in real-time, enabling proactive maintenance and enhancing overall safety. Figure 8 illustrates the integrated DHE system, highlighting the specific tools and methods employed in each module.

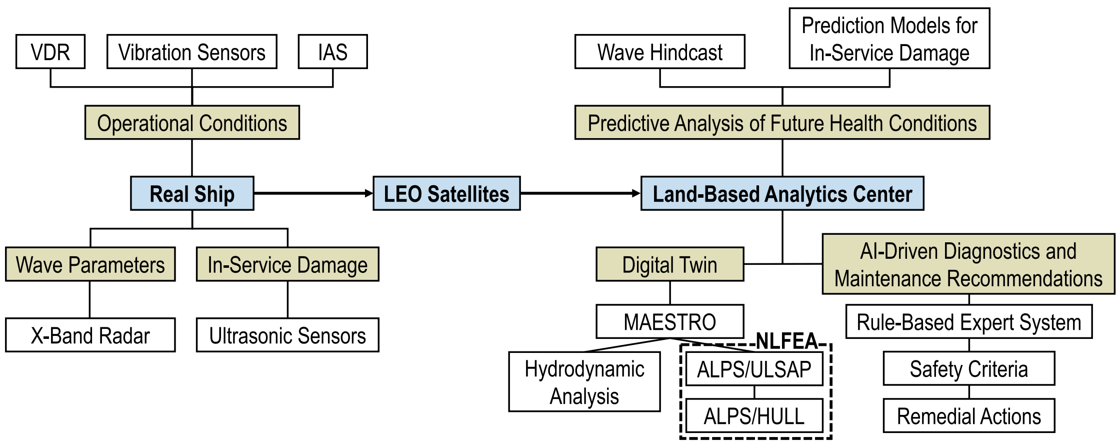


Figure 8. Integrated DHE system with specific tools and methods to be employed (This figure is available in colour online).

3. Development of the DT model within the DHE system

In the proposed DHE system, a DT model is a crucial component, serving as a virtual representation of the real ship. The DT model can be developed and visualized through a combination of hydrodynamic analysis and NLFEA. This model enables real-time health monitoring and simulation of the ship hull structures, providing essential health information for maintaining structural integrity. In this study, the MAESTRO software (MAESTRO 2025) with ALPS/ULSAP (2025) and ALPS/HULL (2025) is employed to perform hydrodynamic analysis and NLFEA within the DHE framework. The detailed methodologies for hydrodynamic analysis and NLFEA, as implemented in MAESTRO, are discussed in Sections 3.1 and 3.2, respectively.

3.1 Hydrodynamic analysis

Calculating hull girder loads requires accounting for their components, including vertical bending moments, horizontal bending moments, torsional moments, and shearing forces across the hull structure (Hughes and Paik 2010). These loads comprise both still water loads, governed by cargo loading conditions, and wave-induced loads generated by sea waves.

Wave-induced loads, along with the resulting hull girder loads, must be calculated and applied to the digital twin model for accurate health condition assessment. The MAESTRO software (MAESTRO 2025) provides powerful tools for calculating the loads acting on ship hulls, with CFD simulations and NLFEA for a single case scenario typically completed in under 5 min. Hydrostatics with load

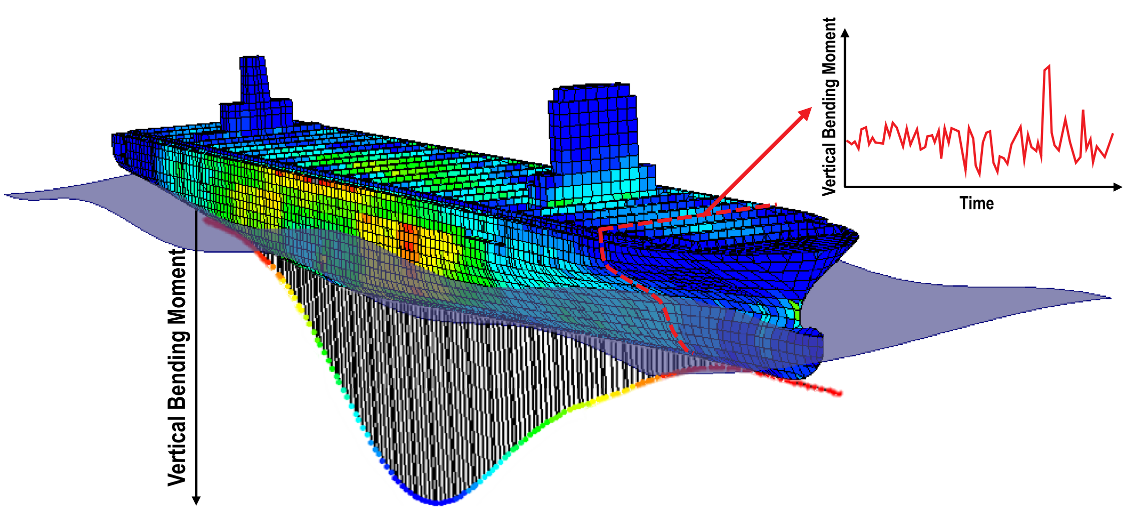


Figure 9. A containership model for hydrodynamic analysis within MAESTRO (This figure is available in colour online).

balancing is used for load analysis in still water or quasi-static wave conditions, while the MAESTRO-Wave module provides hydrodynamic motion and load analysis based on three-dimensional potential theory. This allows for both hydrodynamic wave analysis and load balancing. Additionally, boundary conditions for the ship models are automatically applied in MAESTRO according to the load balancing process (Ma et al. 2014; Kim and Paik 2017). Figure 9 illustrates a containership model used for hydrodynamic analysis within MAESTRO.

3.2 NLFEA

3.2.1 Ultimate strength analysis of plates and stiffened panels

Ultimate strength is fundamental to the structural analysis, design, and subsequent health condition assessment of ship hull structures. In this context, the analysis of buckling and ultimate strength in plates and stiffened panels – essential structural components of ships – is of critical importance.

ALPS/ULSAP (2025) is a specialized computational tool for analyzing the buckling and ultimate strength of plates and stiffened panels under various combined loads, including longitudinal axial compression/tension, transverse axial compression/tension, edge shear, and lateral pressure. It provides accurate and efficient calculations based on the theories outlined in Paik (2018). The software also incorporates initial imperfections from welding fabrication, such as initial deflections, residual stresses, and softening in the heat-affected zone (HAZ), treating them as key parameters in the analysis. Additionally, the effects of in-service damage, such as corrosion wastage, fatigue cracking, and mechanical denting, are considered in assessing the buckling and ultimate strength of plates and stiffened panels.

For the ultimate strength analysis of plates, a membrane stress-based method is applied. A plate is considered to have reached its ultimate strength if plasticity occurs at any of three possible locations for initial plastic yield: the corners, the longitudinal mid-edges, or the transverse mid-edges, as illustrated in Figure 10 (Paik et al. 2011a, 2011b; Paik 2018). Membrane stresses within the plate are computed by solving the nonlinear governing differential equations of the elastic large-deflection plate theory. Yielding is assessed using the von Mises yield criterion, which is defined as follows:

$$\left(\frac{\sigma_{x\,\max}}{\sigma_Y}\right)^2 - \left(\frac{\sigma_{x\,\max}}{\sigma_Y}\right)\left(\frac{\sigma_{y\,\max}}{\sigma_Y}\right) + \left(\frac{\sigma_{y\,\max}}{\sigma_Y}\right)^2 + \left(\frac{\tau_{av}}{\tau_Y}\right)^2 = 1 \quad (2)$$

where $\sigma_{x\,\max}$ and $\sigma_{y\,\max}$ are the maximum membrane stresses in the x (longitudinal) and y (transverse) directions, respectively. τ_{av} is the average shear stress, and the subscript Y refers to the yield stress.

For the ultimate strength analysis of stiffened panels, the possible collapse modes are classified into six types (Paik 2018): Mode I – overall collapse, Mode II – plate collapse without distinct failure of stiffener, Mode III – beam-column collapse, Mode IV – collapse by local web buckling of stiffener, Mode V – collapse by flexural-torsional buckling of stiffener (also known as tripping), and Mode VI – gross yielding.

The analysis considers various load combinations relevant to these collapse modes, including uniaxial compressive loads and combined in-plane loads, with or without lateral pressure. The true ultimate strength of a stiffened panel is determined by the minimum value among six ultimate strengths, including gross yielding (Mode VI) as the upper limit, corresponding to each collapse mode, as illustrated in Figure 11. When calculating the residual ultimate strength of

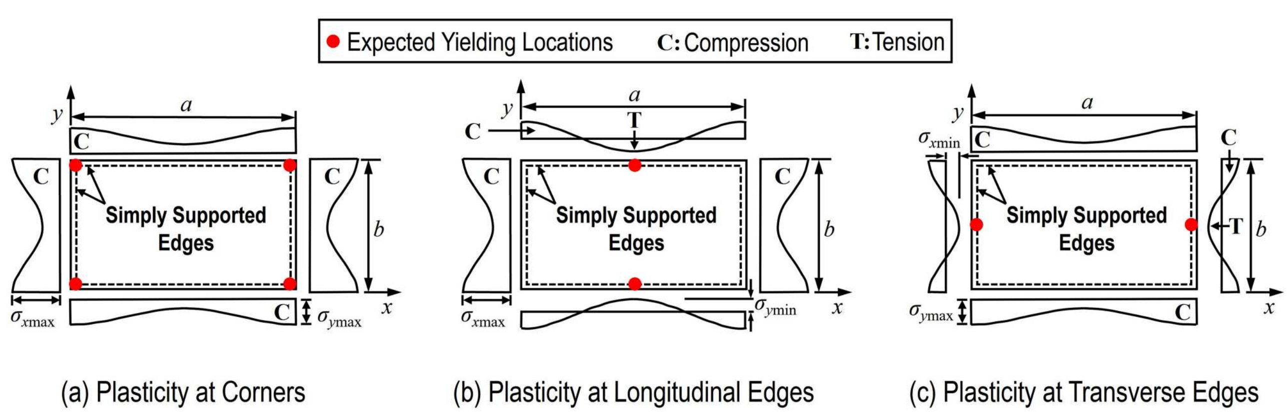


Figure 10. Three possible locations for the initial plastic yield at the edges under combined loads (Paik 2018) (This figure is available in colour online).

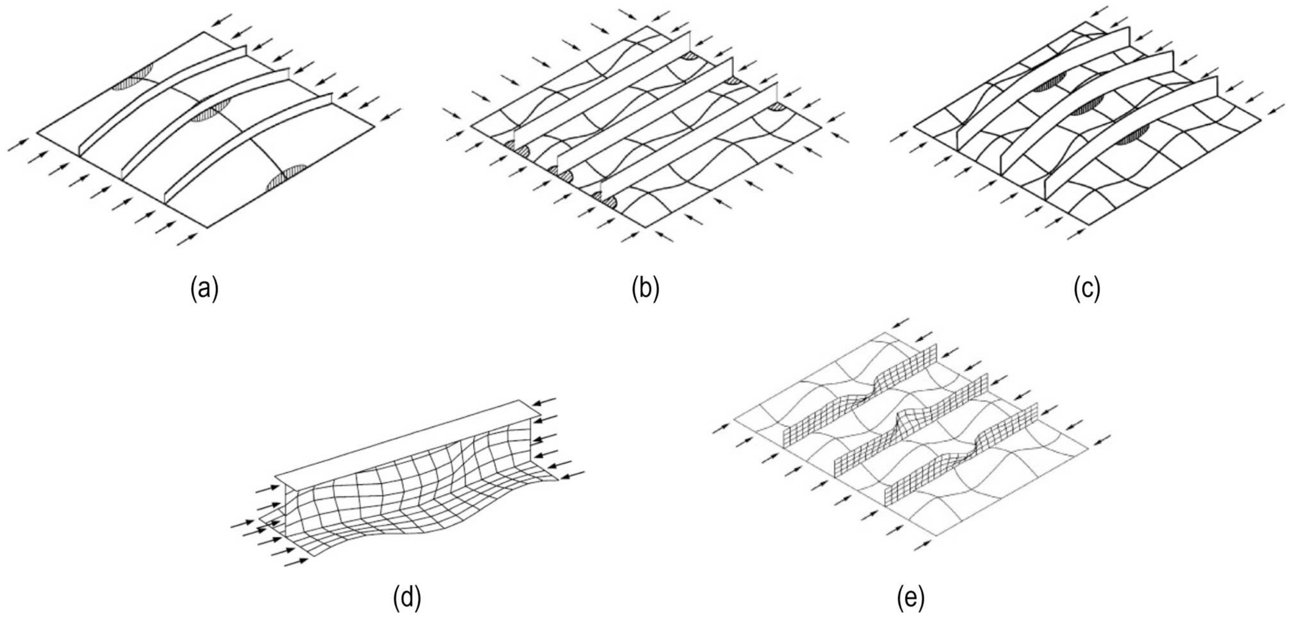


Figure 11. Collapse modes of stiffened panels (Paik 2018): (a) Mode I – overall collapse; (b) Mode II – plate collapse without distinct failure of stiffener; (c) Mode III – beam-column collapse; (d) mode IV – collapse by local web buckling of stiffener; (e) Mode V – collapse by flexural-torsional buckling of stiffener (also known as tripping) (Paik 2018) (This figure is available in colour online).

aged structures, the remaining thickness of structural members is used to account for uniform corrosion, while a strength reduction factor is applied to account for the effects of localized corrosion (pitting), cracks, and dents. A detailed explanation of the ultimate strength analysis of plates and stiffened panels can be found in Paik (2018, 2022).

3.2.2 Ultimate strength analysis of hull girder structures

The collapse of hull girder structures represents the most catastrophic type of failure, resulting in the ship breaking into two, which can lead to significant casualties, property damage, and marine pollution. Consequently, continuous monitoring of the ultimate hull girder strength of aging ships is essential, necessitating accurate and efficient analysis methods. Ultimate strength analysis of hull girder structures is more complex than that of plates and stiffened panels, as it requires progressive collapse analysis of the entire hull structures with intricate geometries. ALPS/HULL (2025), based on the intelligent supersize finite element method (ISFEM), is a highly accurate and efficient computational tool for conducting ultimate hull girder strength analysis (Paik 2018, 2022). It performs progressive collapse analysis of a ship's hull under combined vertical bending, horizontal bending, shearing force, and torsional moment. Additionally, ALPS/HULL accounts for fabrication-related initial imperfections and in-service damage as influential parameters in the analysis.

Both ALPS/ULSAP and ALPS/HULL offer significant advantages for the development of digital twin models due to their computational efficiency in ultimate strength analysis. These tools are seamlessly integrated within the MAESTRO software, enhancing the digitalization process for ship structures. Figure 12 presents the NLFEA results for a containership model, performed using ALPS/ULSAP and ALPS/HULL within MAESTRO.

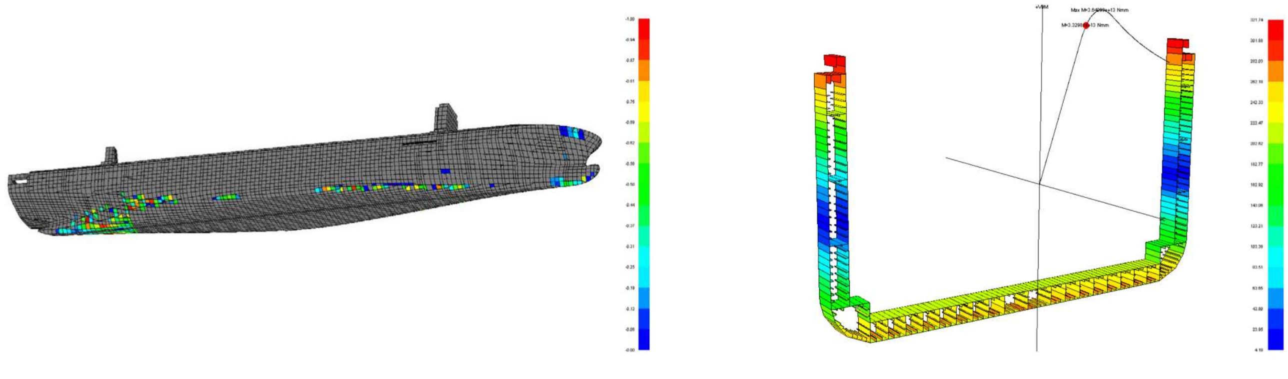
3.3 Validation of hydrodynamic analysis and NLFEA modules within MAESTRO

The hydrodynamic analysis and NLFEA modules within MAESTRO have been extensively validated in the literature, including studies by Paik et al. (2011a, 2011b), Ma et al. (2014, 2015), Paik (2018, 2020, 2022), and Lee and Paik (2020). Selected validation data are presented in this section as examples. Figure 13 displays the validation results for the hydrodynamic analysis as documented in the manual of MAESTRO (2025), while Figure 14 shows the validation results for ALPS/ULSAP and ALPS/HULL (Paik 2018; Paik et al. 2011b).

4. Illustrative example: an as-built 22,000 TEU containership

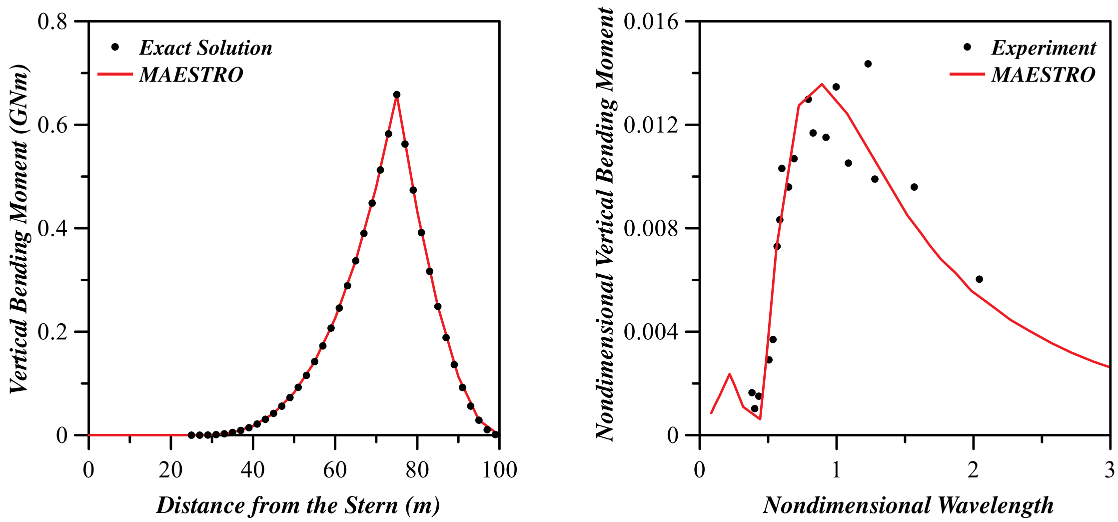
4.1 Digital twin model

An as-built 22,000 TEU containership model was developed as an illustrative example of the digital twin model



(a) ALPS/ULSAP (b) ALPS/HULL

Figure 12. Colour-coded NLFEA results for a three-dimensional containership model obtained using ALPS/ULSAP and ALPS/HULL within MAESTRO (This figure is available in colour online).



(a) Vertical Bending Moment Distribution (b) Response Amplitude Operator

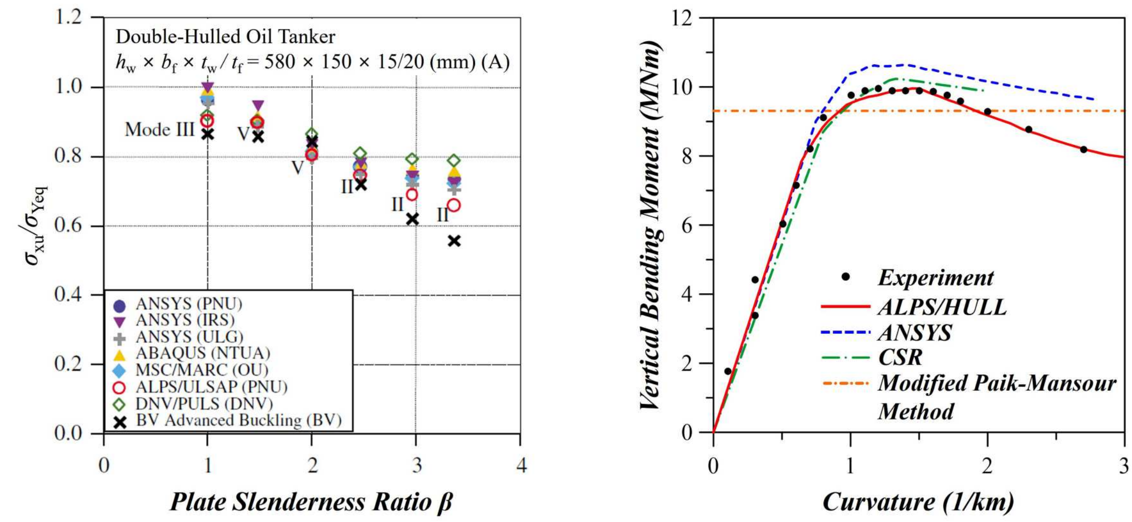
Figure 13. Validation of the hydrodynamic analysis using MAESTRO (MAESTRO 2025) (This figure is available in colour online).

within the proposed DHE system, as shown in Figure 15. The principal dimensions of the containership are summarized in Table 2, and the model assumes a full load condition. The MAESTRO software was employed to create the three-dimensional model and perform both hydrodynamic analysis and NLFEA for the digital twin, as detailed in the previous section.

4.2 Application of the digital twin enabled by real-time monitoring data of structural health parameters

Within the DHE system, wave profiles (e.g. wave heights, wave periods, and wave angles) will be measured on-site in real-time, while in-service damage (e.g. corrosion wastage, fatigue cracking, and mechanical denting) will be measured on-site at regular intervals, typically daily, weekly, or monthly. These health parameters will be transmitted immediately after measurement to a land-based data analytics center for hydrodynamic analysis and NLFEA. However, in the present study, it is assumed that these health parameters are transmitted to the data analytics center, as the focus is solely on the digital twin model within Module 3 for illustrative purposes, specifically for data analytics and simulations.

The digital twin was implemented for an as-built 22,000 TEU containership operating in the North Atlantic Ocean. Wave parameters, including significant wave height, peak wave period, and wave direction, are assumed to be measured on-site using an X-band wave radar, while in-service damage – such as corrosion wastage, fatigue cracking, and mechanical denting – is measured on-site by seafarers using ultrasonic sensors



(a) ALPS/ULSAP (Paik 2018) (b) ALPS/HULL (Paik et al. 2011b)

Figure 14. Validation of the ALPS/ULSAP and ALPS/HULL modules within MAESTRO (This figure is available in colour online).

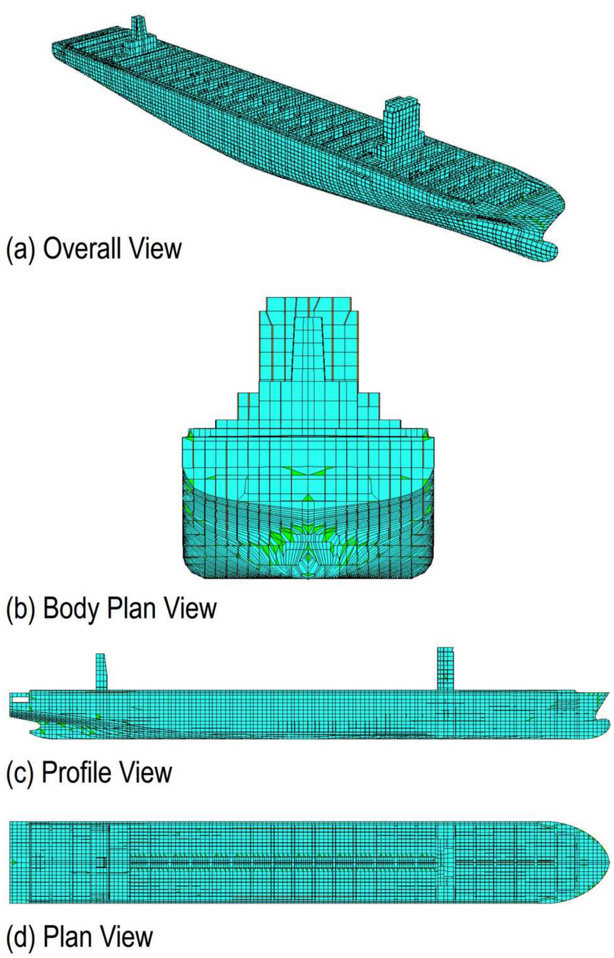


Figure 15. Three-dimensional digital twin model of the as-built 22,000 TEU containership (This figure is available in colour online).

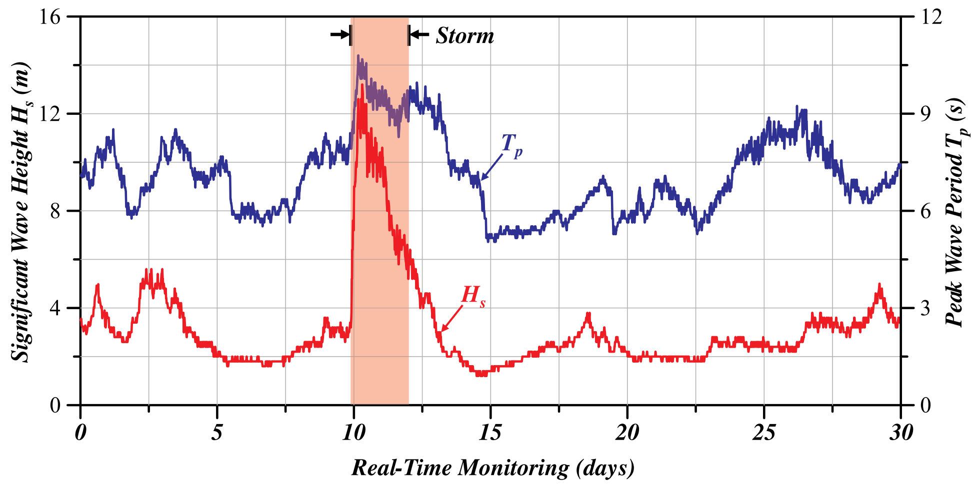
and devices with tablet computer assistance. The measured health parameters are then assumed to be transmitted in real-time to our land-based analytics center. Figure 16 illustrates the wave parameters measured and transmitted during real-time monitoring.

The structural health conditions of all hull girder sections between transverse frames and stiffened panels from stern to bow were evaluated using the safety factor defined in Equation (1), based on the results of hydrodynamic analysis and NLFEA. However, as a representative example, 27 hull girder sections and 10 stiffened panels were selected to illustrate the real-time structural health assessment in this paper, as shown in Figure 17.

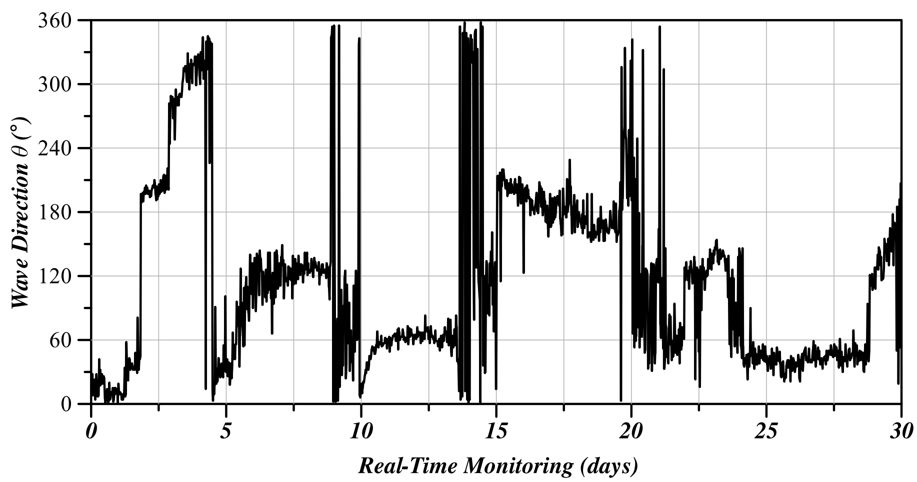
In this study, the illustrative simulations were conducted over a period of 30 days. In a real DHE system, however, these simulations would continue throughout the ship's entire lifetime. Figure 18 illustrates the real-time variations in the safety factor for the selected hull girder sections under vertical bending moments, focusing on values below 5.0. The safety factors fluctuated

Table 2. Principal dimensions of the as-built 22,000 TEU containership model.

Parameter	Dimension
Length between perpendiculars (L_{BP})	413.0 m
Breadth (B)	58.6 m
Depth (D)	35.1 m
Scantling draught (d_s)	16.5 m
Design draught (d_d)	14.5 m
Block coefficient (C_b)	0.61
Waterplane coefficient (C_{wp})	0.78
Design speed	24.0 knot



(a)



(b)

Figure 16. Real-time monitoring data of wave parameters: (a) significant wave height and peak wave period, (b) wave direction (This figure is available in colour online).

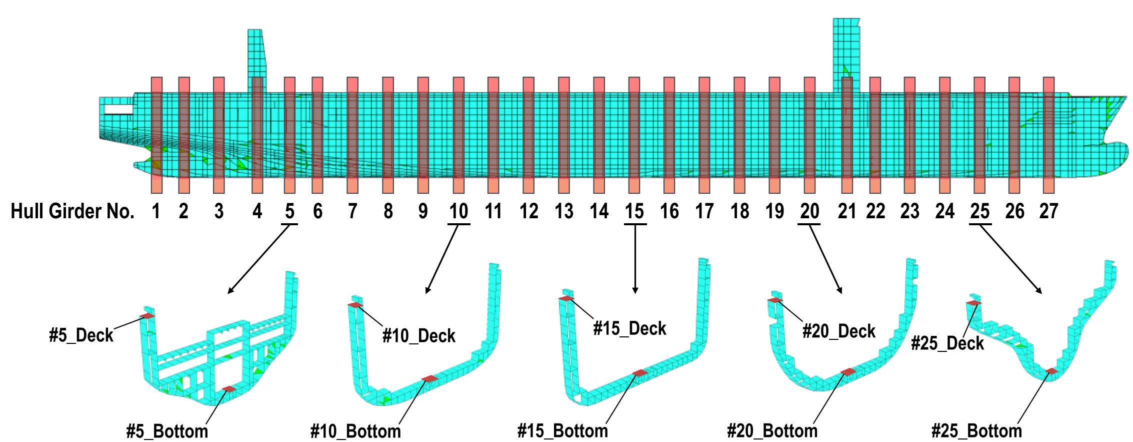


Figure 17. Selected stiffened panels and hull girder sections for the illustrative example of real-time structural health assessment (This figure is available in colour online).

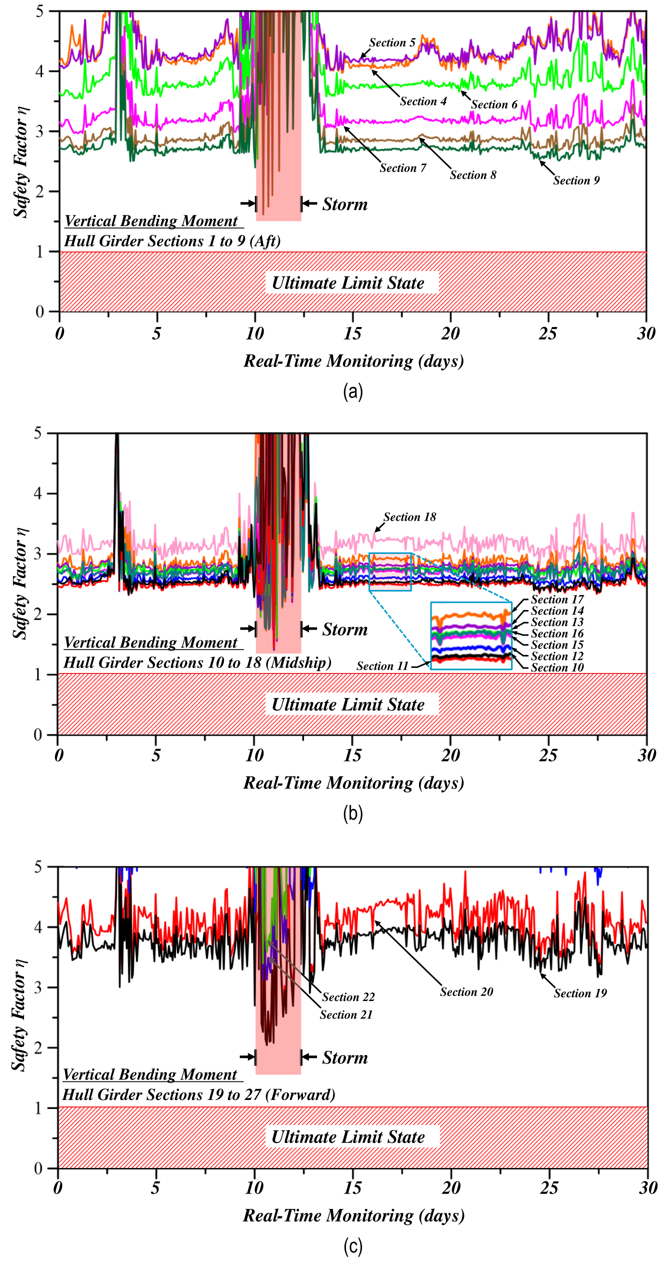


Figure 18. Changes in safety factors for the hull girder structures under vertical bending moments during the real-time monitoring: (a) sections 1–9 (aft), (b) sections 10–18 (midship), (c) sections 19–27 (forward) (This figure is available in colour online).

throughout the real-time monitoring period, with minimum values observed during the storm (between days 10 and 12), when significant wave height and peak wave period increased drastically. Relatively lower safety factors were observed in the midship region (Figure 18b), whereas several hull girder sections (1, 2, 3, 23, 24, 25, 26, and 27) located at the aft and forward sections of the ship were excluded from the plots (Figures 18a and c), as their safety factors exceeded 5.0. This variation is likely due to the higher distribution of vertical bending moments typically occurring in the midship region of vessels.

Figure 19 illustrates the real-time variations in the safety factor for selected stiffened panels under combined in-plane loads and lateral pressure throughout the monitoring period. The lowest safety factor values occurred during the storm (between days 10 and 12), mirroring the observations for hull girder structures. Safety factors for stiffened panels in the midship region were notably lower than those in the aft and forward regions. The computation time for wave load analysis and NLFEA was approximately 22.2 s per quasi-static wave case, indicating that it is feasible to update the health condition of ship hull structures at least every 5 min ($22.2 \times 12 = 266.4$ s), even when considering twelve phase angles per wave simulation.

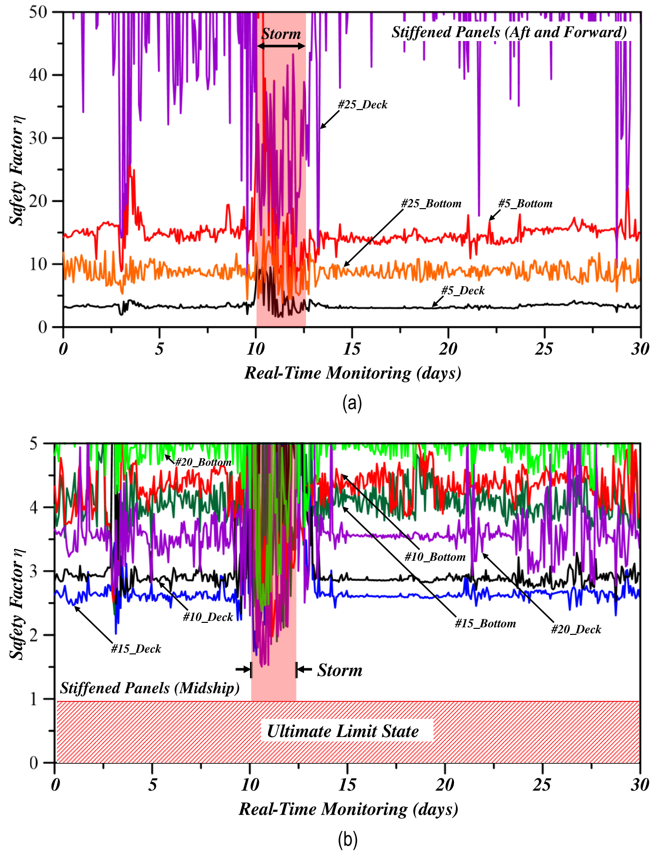


Figure 19. Changes in safety factors for the stiffened panels subjected to combined in-plane loads with lateral pressure during the real-time monitoring: (a) stiffened panels located at the aft and forward sections of the ship, (b) stiffened panels located at the midship sections (This figure is available in colour online).

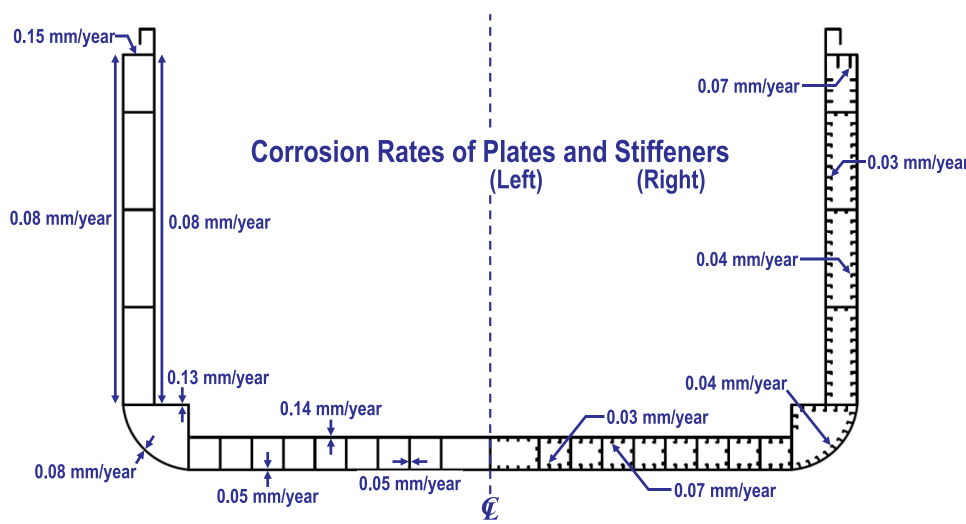
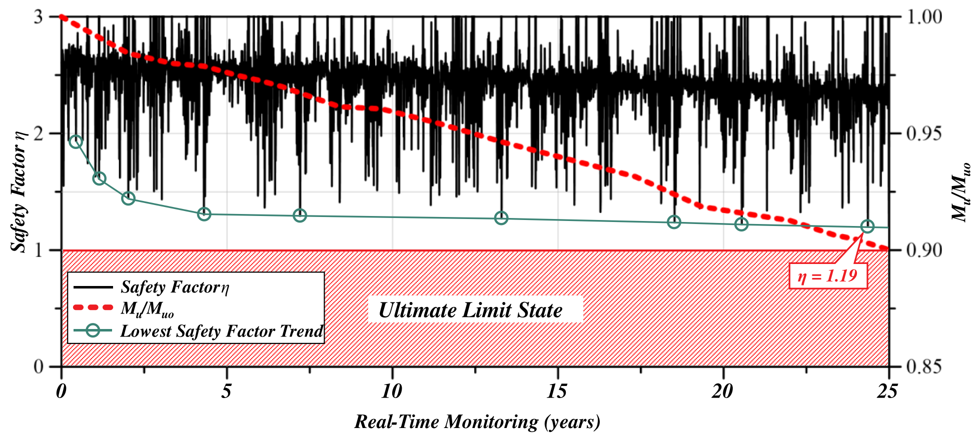


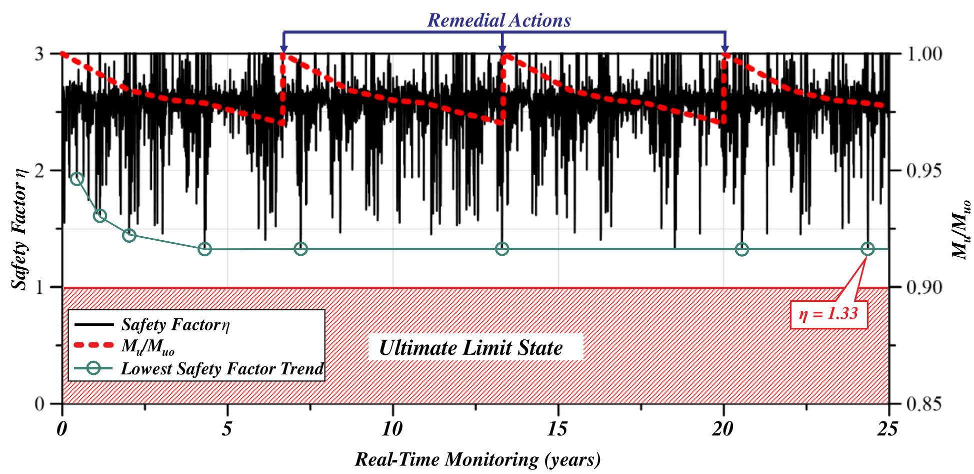
Figure 20. Corrosion rates for each longitudinal strength member in the selected midship section (This figure is available in colour online).

4.3 Long-term degradation of structural health conditions and lifetime healthcare of ship hull structures using the DHE system

Over a 30-day period, the progression of in-service damage is expected to be minimal, and its impact on the structural safety factor or health conditions may be negligible. Therefore, to demonstrate the effects of in-service damage more effectively, simulations should be conducted over a much longer timeframe. For this purpose, a 25-year period is analyzed with a focus on uniform corrosion wastage, assuming that corrosion is measured on-site at weekly intervals. For the present illustrative



(a)



(b)

Figure 21. Changes in safety factors for the midship section under vertical bending moments over 25 years of operation in the North Atlantic Ocean: (a) without remedial actions, (b) with timely repair (This figure is available in colour online).

study, however, uniform corrosion rates defined by Paik (2018, 2022) are used to simulate corrosion wastage as if it were being measured on-site and transmitted to our land-based data analytics center for NLFEA.

This section analyzes the long-term degradation in the structural health of ship hulls, comparing scenarios with and without timely remedial actions facilitated by the DHE system. For illustration, hull girder section 15 (the midship section) in Figure 17 was selected as a case study. In this scenario, the target ship is assumed to operate in the North Atlantic Ocean, with historical wave profile data sourced from buoy 41,048 in the National Oceanic and Atmospheric Administration (NOAA) database. Figure 20 shows the corrosion rates for each longitudinal strength member within the selected midship section.

Figure 21 illustrates the changes in safety factor and residual ultimate strength ratio (M_u/M_{uo}), both with and without timely remedial actions, over a 25-year operational period in the North Atlantic Ocean. Herein, M_u and M_{uo} are the ultimate strength of damaged and intact hull structures. When remedial actions were not taken (Figure 21a), the residual ultimate strength ratio gradually declined, reaching approximately 90% of the ultimate strength of the intact structures. Given that classification society rules typically require the hull girder strength of an aging ship to remain above 90% of the initial state of new building, reaching this threshold at the 25-year mark suggests a potentially unsafe condition. The safety factor also decreased, reaching as low as 1.19, which poses a significant risk of local structural failures; indeed, several stiffened panels at the bottom experienced collapse, resulting in a substantial reduction in residual ultimate strength during the monitoring period. In practice, the safety factor may be even lower, as this case study accounts only for corrosion damage.

In contrast, when remedial actions were implemented (Figure 21b), no gradual decrease in safety factor over time was observed, with values consistently remaining above 1.3. Proactive safety measures, including real-time health monitoring and timely remedial actions facilitated by the DHE system, are effective in maintaining aging ships and extending their operational longevity, potentially to 50 years rather than the current standard of 25 years.

5. Concluding remarks and future works

This paper presents a digital twin (DT) model within a Digital Healthcare Engineering (DHE) system designed for the lifetime structural healthcare of aging containerships operating under rough weather conditions. The proposed DHE system consists of five modules, each introduced in Section 2. Section 3 details the DT modelling used for hydrodynamic analysis and nonlinear finite element analysis (NLFEA), while Section 4 provides illustrative examples using an as-built 22,000 TEU containership as a case study.

The DT model developed in this study enables real-time assessment and management of structural health, with the ability to generate safety factors for both local components and the global hull structure. These factors are calculated based on health parameters, including ocean environmental conditions and in-service damage. The model's output can be utilized for structural health diagnostics, where AI techniques enhance the efficiency and accuracy of the process. Given the computation times achieved in the study, it is concluded that the ship hull structure's health can be updated at least every five minutes using MSESTRO software, ensuring a highly responsive and accurate monitoring system.

Compared to traditional industry practices, such as periodic inspections and limited hull stress monitoring using a small number of strain gauges, the DHE system offers a more comprehensive, efficient, and proactive approach to structural healthcare. Its key advantages include real-time monitoring using data from onboard sensors, precise health assessments across the entire hull, accelerated decision-making supported by AI, and predictive health analysis to guide future maintenance. These features contribute not only to safer operations but also to enhanced maintenance and repair, reduced downtime costs, and potential lifespan extensions for aging vessels. Although this study focused on containerships, the DHE system could be adapted to other vessel types with modifications tailored to their specific operational and structural characteristics.

The proposed DHE system is currently under development. Future research tasks to advance the system include the following: (1) configuring onboard health parameter monitoring (e.g. wave profiles and in-service damage) using sensors and devices; (2) establishing a reliable data transmission system via LEO satellites; (3) developing predictive health analysis software to support maintenance planning; (4) integrating and automating key modules for streamlined operations; and (5) verifying the prototype DHE system through physical testing on an actual ship.

With these enhancements, the DHE system has the potential to become a transformative solution for the maritime industry, promoting safety, operational efficiency, and structural longevity across diverse vessel types, including autonomous ships and high-value vessels such as SMR-powered ships.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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