Development of a Structural Monitoring System for the Digital Twin of the Hull Structure of an Ore Carrier

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ABSTRACT

Ship structures are constantly subjected to wave loads and the excessive loads or repetitive loads increase a risk of failure. To avoid economic and environmental losses caused by the failure of ship structures, ship manoeuvring, maintenance, and design decisions are made so that the stress due to loads acting on the hull does not exceed the strength of the structure. However, because there is uncertainty in both the stress and the strength, there is the potential for safety and economics to be compromised. One solution to reduce the uncertainty is a digital twin that provides stress information at areas of interest in the ship structure in cyber space. In general, a digital twin is an integrated model that accurately reconstructs the state of a physical object based on sensing data measured in physical space and digital models that simulate the behavior of physical objects. Stress monitoring of the ship structure, including unmeasured parts, using the digital twin helps crews, shipping companies, and other stakeholders make rational decisions based on the situation. In this study, we developed a structural monitoring system for digital twins of ship structures with the aim of improving the safety and economic efficiency of ships. This system reconstructs and show the stress due to wave loads in a whole area of the hull structure. We developed a measurement module to obtain strain data from an interrogator of fiber optic sensors, an analysis module to calculate the stress at areas of interest based on the strain data and the Kalman filter, and a visualizing module with the graphical user interface (GUI) to show the stress of the hull structure, including the unmeasured parts. The analysis module also counts stress continuously and estimates the cumulative fatigue damage. These modules were integrated to form into the structural monitoring system for a digital twin. The structural monitoring system was implemented on an ore carrier in February 2023 and has been continuously operated without any serious troubles. In this paper, we introduce the modules with related technologies and the structural monitoring system with monitoring and operating data. This works is expected to provide valuable insights for building a digital twin for ship structures.

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INTRODUCTION

The volume of cargo transported by international shipping has been increasing steadily [1]. Given that maritime shipping supports over 80% of the world's trade volume [2], the safe operation of ships is a critical issue for the global economy. Ships are subjected to various loads throughout their life cycles, including wave-induced loads and buoyancy. Excessive loading or repeated cyclic loading can lead to fatigue damage and ultimately structural failure. Therefore, it is essential to ensure that operational decisions are made in such a way that the resulting structural stresses remain within the material strength limits of the ship structure. However, the wave loads considered at the design stage of ship structures inherently involve uncertainty due to the stochastic nature of ocean environments. As a result, there is a risk that irrational or overly conservative operational decisions may be made, potentially compromising both safety and economic efficiency.

One promising approach to mitigate such uncertainty is the application of digital twin technology. A digital twin is typically defined as an integrated virtual model that combines sensing data measured from a physical object with a numerical simulation model that predicts the behavior of the physical object. This integration enables accurate reproduction of the physical object's condition within the cyber space. In the context of ships, the use of a digital twin to monitor structural stress, including in areas where direct measurements are not feasible, provides valuable insights to the stakeholders like crews and shipping companies. Digital twin technology enables the stakeholders to make rational decisions based on real-time conditions.

In our previous research [3], we developed a structural health monitoring (SHM) system designed to enable the creation of a digital twin that reproduces the condition of the ship structure across its whole area. This system was applied through experiments using a towing tank and an elastic scale model ship. This study aims to improve both the safety and operational efficiency of ships by developing a SHM system for full-scale ships that supports digital twin implementation. In this study, an ore carrier was selected as the subject ship. The proposed system reconstructs the stress distribution over the entire ship hull caused by wave loading, based on strain data measured by sensors discretely installed on the ship structure. Sensing and analyzed data by the SHM system is visualized through a graphical user interface (GUI) for practical use.

The remainder of this paper presents the hardware and software architecture of the structural monitoring system, examples of data collected during operation, and the status of system operation. We anticipate that the findings and insights derived from this study will contribute significantly to the advancement of digital twin development for ship structures.

OVERVIEW OF MONITORING SYSTEM OF AN ORE CARRIER

In this study, we implemented a SHM system on a full-scale ship with the aim of enabling rational operational decision-making based on a digital twin of the ship's structure. The system is designed to reconstruct the stress distribution over the entire hull structure in order to assess the structural response under actual sea conditions.

Table 1 presents the principal particulars of the target ship, which is an ore carrier operating regularly between Japan and Australia. Figure 1 provides detailed information about the ship's structural configuration and the installation locations of the strain sensors. To measure the longitudinal strain induced by wave loading, a total of 16 fiber-optic strain sensors (Luna OS3155 [4]) were installed (Figure 2). These sensors were mounted in two locations each on the deck and bottom plating of four cargo holds, respectively, covering critical regions where bending stresses caused by the hull girder deformation are expected to be significant. The interrogator (HYPERION si255 [5]), which is used to acquire data from the fiber optic sensors, was installed in the engine control room located at the aft of the ship, as shown in Figure 3. The interrogator is wired to all of the fiber-optic sensors.

TABLE I Principal particulars of the subject ship.

Length overall	319.95 m
Breadth	55.0 m
Depth	24.3 m
draft	16.525 m
Deadweight tonnage	215,790 ton
Gross tonnage	122,790 ton
Service speed	14.5 knot

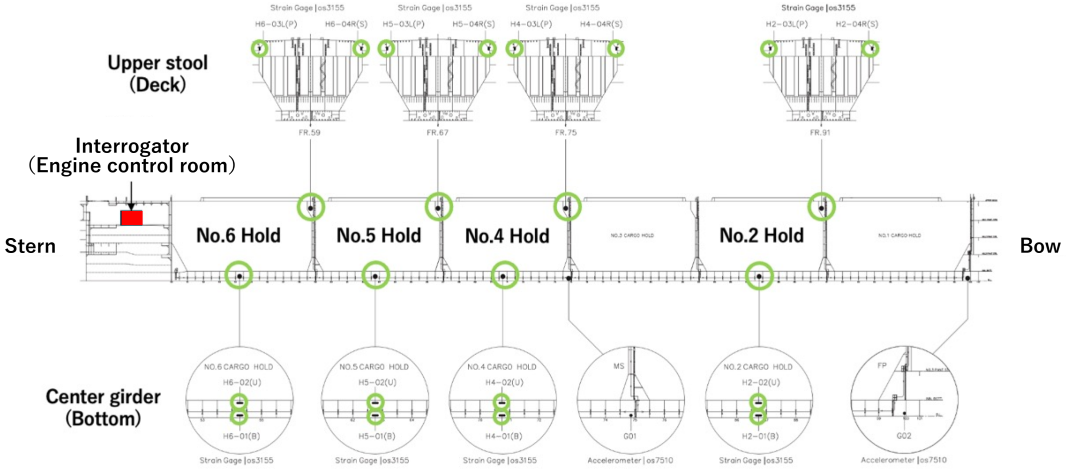


Figure 1. Positions of fiber-optic strain sensors and an interrogator on the subject ship.

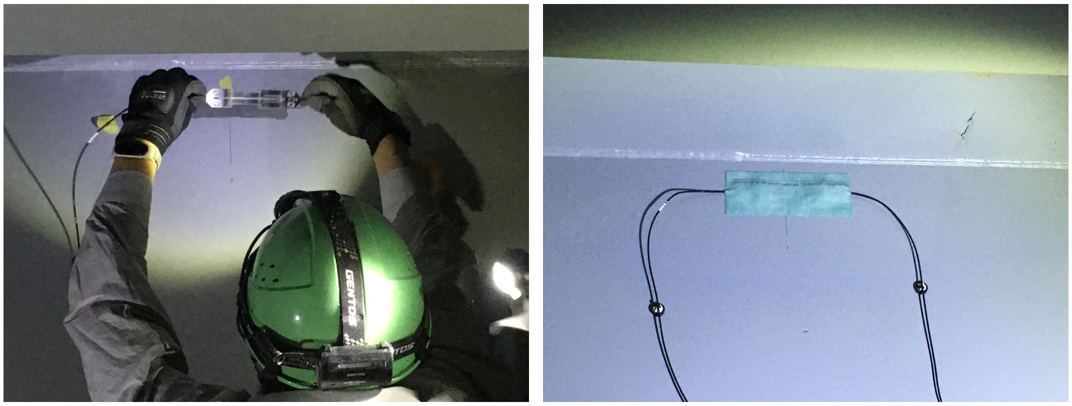

(a) (b)

Figure 2. Fiber-optic strain sensor on the center girder: (a) Installation of the sensor; (b) Installed sensor.

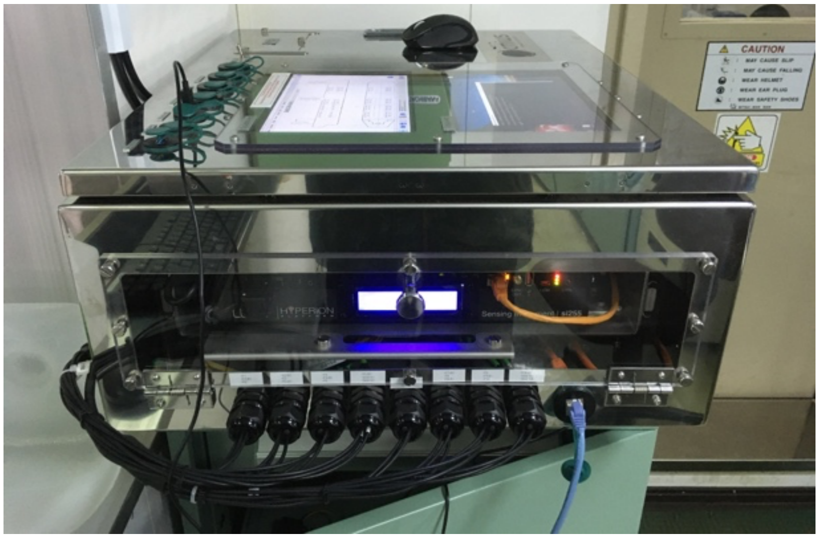


Figure 3. Interrogator of fiber-optic sensor in the engine control room of the subject ship.

STRUCTURAL HEALTH MONITORING SYSTEM FOR DIGITAL TWIN

The SHM system installed on the target ship consists of two core components, as illustrated in Figure 4: a sensing system that acquires data from onboard sensors, and an analysis system that reconstructs the structural state of the ship based on the sensing data. The sensing system is responsible for collecting data from strain, temperature, and acceleration sensors installed on the hull, and saving the measured data to onboard storage devices. These data are retrieved manually during port calls and shared with relevant stakeholders including researchers. In contrast, the analysis system processes the sensor data in real-time and consists of the following functional modules:

Measurement module: This module acquires raw signals of strain, temperature, and acceleration from sensors and interrogator. It then integrates these measurements into the SHM system, ensuring synchronized and consistent data input for subsequent analysis.

Structural response estimation module: In this module, the structural response of the hull is estimated based on a modal superposition method. Specifically, it assumes that the response can be expressed as a linear combination of the natural vibration modes of a finite element model that accounts for the weight distribution of the subject ship, as shown in Figure 5. These mode shapes (see Figure 6), derived via eigenvalue analysis, are used to reconstruct structural responses of the hull girder such as displacement, stress, and vertical bending moment across the entire hull. To estimate the amplitude of each modal component from the measured strain data, a Kalman filter is employed [6, 7].

Fatigue analysis module: Based on the reconstructed stress history, stress cycles are identified by the rain flow method [8] and then fatigue damage is estimated using Miner's linear damage rule, in conjunction with S–N (stress-number of cycles) curves. This allows for the assessment of fatigue life and structural integrity over extended periods of operation.

Visualization module: This module generates graphical outputs that are displayed via a GUI installed in the engine control room. The visualizations include:

- Time series graphs of the estimated stress.
- Distributions of vertical bending moments along the ship's longitudinal axis.
- Histograms of stress cycles.
- Time series of cumulative fatigue damage.

By integrating these modules, the analysis system enables real-time reconstruction of the stress distribution over the entire ship structure based on measured strain data by sensors. It also supports structural integrity monitoring through fatigue damage assessment, thereby facilitating proactive maintenance and safety assurance. The visualized outputs, presented on the GUI located in the engine control room, provide feedback directly to the crew, supporting rational decisions related to ship operation.

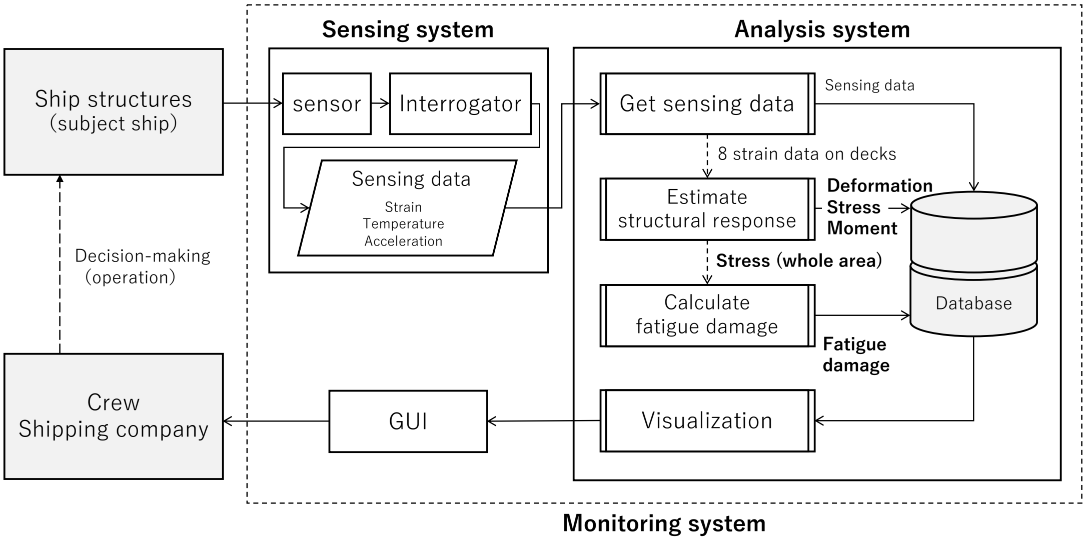


Figure 4. System architecture of the structural monitoring system of the subject ship.

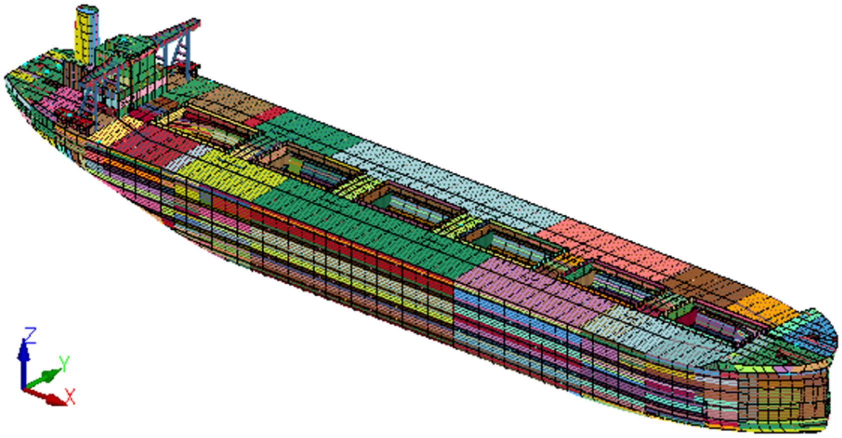
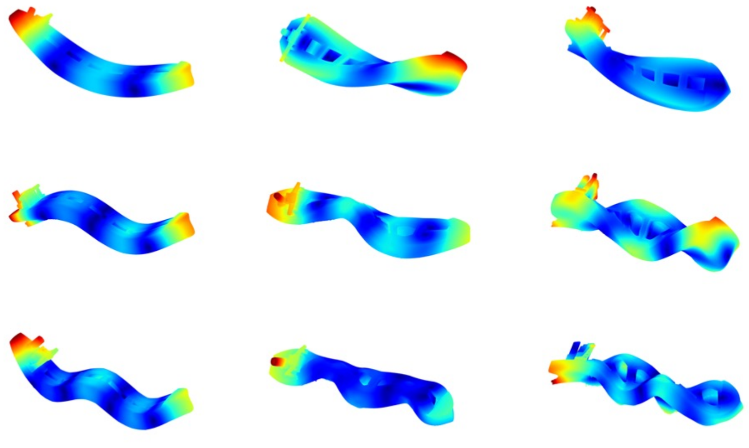


Figure 5. Finite element model of the subject ship.



(a) (b) (c)

Figure 6. Deformations of eigenmodes: (a) Vertical modes; (b) Horizontal modes; (c) Torsional modes.

RESULTS AND DISCUSSION

Figure 7 presents the strain signals acquired from eight sensors installed on the deck, after applying a band-pass filter to extract the strain components caused by wave-induced loads in the frequency range of 0.01–0.2 Hz. These filtered strain signals were then used as input for the structural response estimation method with Kalman filter, which reconstructs the structural response, including displacements and stresses, over the entire hull structure. Figure 8 compares the measured and estimated strain values at eight sensor locations on the center girder. It is important to note that the estimation was performed using only the strain data obtained from the deck sensors. The strain data collected from the center girder sensors were not used in the estimation process and were used for comparison purposes only. Although the estimated strain shows slightly larger amplitudes than the measured values, the two datasets show good qualitative agreement. The observed amplitude discrepancy can be attributed to local structural responses in the double bottom area, which are not fully captured by the global modal superposition approach used in the estimation method.

This monitoring system was installed on the subject ship on February 10, 2023, and remained operational for 691 days out of a total of 767 days until March 18, 2025—representing a system availability rate of 90.1%. Of the downtime, 8.8% was due to unexpected shutdowns caused by uninterruptible power supply (UPS) failures, while analysis system failures accounted for only 0.4% of the total downtime. These results clearly demonstrate the high operational stability and practical applicability of the proposed monitoring system for use on full-scale ships under real operational conditions.

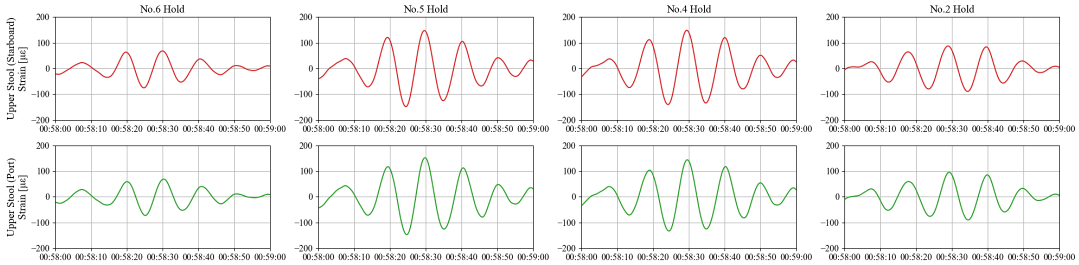


Figure 7. Measured strain data from fiber-optic strain sensors installed on the starboard and port sides of the deck of four cargo holds.

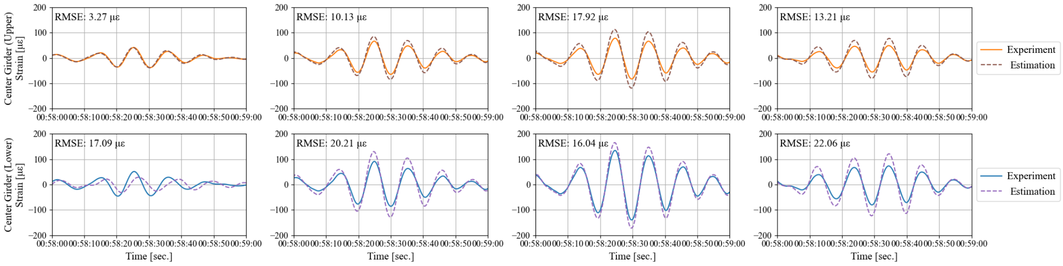


Figure 8. Measured and estimated strain data on the sensor positions of the center girders .

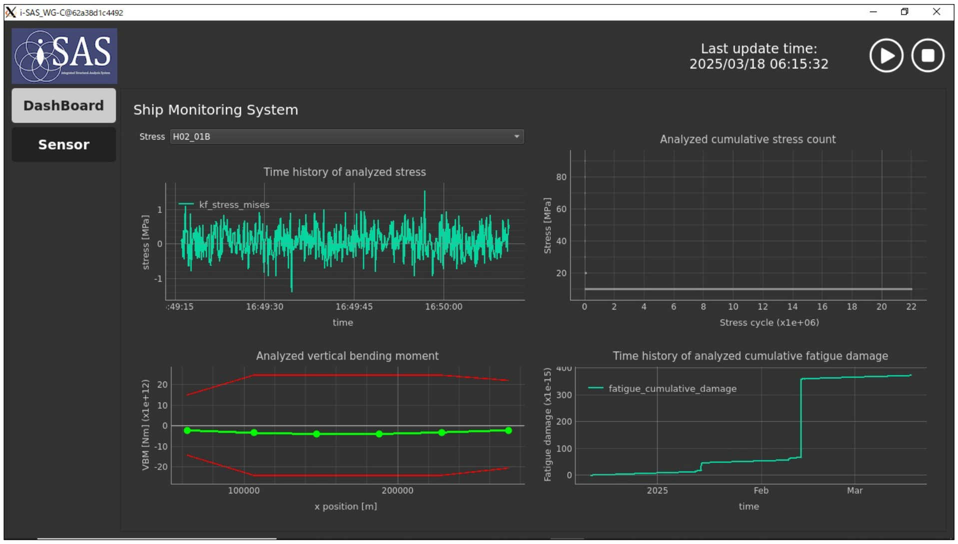


Figure 9. GUI of the structural monitoring system of the subject ship.

CONCLUDING REMARKS

In this study, a structural health monitoring system for the realization of a digital twin was developed and implemented on a full-scale ship. The system reconstructs the stress distribution across the entire hull structure in real time by integrating strain data obtained from sensors installed on the hull with a structural (finite element) model. The system aims to reduce uncertainty in operational decisions and help crew members in making rational decisions by providing real-time information on the structural integrity of the ship. Since its installation, the system has demonstrated stable performance, operating successfully for over 90% of the monitoring period, thereby confirming its practical applicability to full-scale ship operations. This work is expected to provide valuable insights for building a digital twin for ship structures.

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REFERENCES

1. UN Trade and Development (UNCTAD). 2024. “Review of Maritime Transport,”.
2. UNCTAD, “Review of Maritime Transport 2024”, https://unctad.org/publication/review-maritime-transport-2024.
3. Fujikubo, M., et al. 2024. “A digital twin for ship structures—R&D project in Japan,” Data-Centric Engineering, 5: e7.
4. LUNA Innovations, “OS3150/55 Optical Strain Gages,” https://lunainc.com/product/os315055.
5. LUNA Innovations, “HYPERION si255 Optical Sensing Instrument,” https://lunainc.com/product/hyperion-si255.
6. Perišić, N., et al. 2013. “Low-cost tower root fatigue load estimation for structural health monitoring of grouted connections in offshore wind turbines”, Key Engineering Materials , 569: 676-683.
7. Miyake, Y., et al. 2023. “Estimation of ship hull girder deformation and load by using sensors and numerical model”, Journal of The Japan Society of Naval Architects and Ocean Engineers, 37: 47-56.
8. Endo, T., et al. 1974. “Rain Flow Method, the proposal and the applications,” Bulletin of the Kyushu Institute of Technology, 28: 33-62.