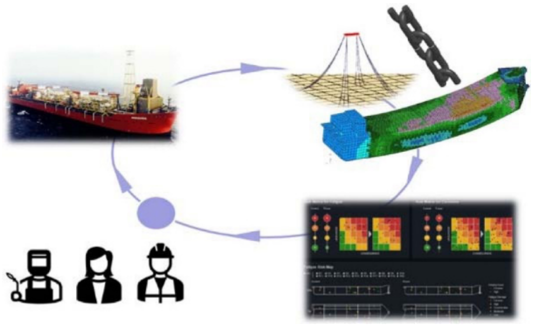
Development of Asset Integrity Management System Using Digital Twin for Large Floating Structures



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Digital twin reproduces individual products and processes in the digital space for the purpose of real-world applications such as design, production, control, and maintenance management. The practical use of digital twin is accelerating along with technological advances in machine learning, information and communications technology, computational capabilities, and sensors.

In light of social demands such as stable energy supply and realization of a decarbonized society, Mitsubishi Heavy Industries, Ltd. (MHI) is also working on the development of digital twins and asset integrity management services for large floating structures such as floating production, storage and offloading (FPSO) units. This report summarizes digital twin technology and presents a dashboard system for asset integrity management.

1. Introduction

For a slew of products, digital twin is a key technological theme getting increasing attention. The definition of digital twin and their enabling technologies have been discussed and are still being discussed at many international conferences and in academic journals. Envisioning Society 5.0, Japan has set out to create a human-centered society that can simultaneously bring economic growth and solutions to social issues, while each one of us can comfortably take an active role in society. Digital twin is positioned as a core concept therein(1)(2).

The "digital twin" is defined as an integrated multiphysics, multiscale, probabilistic simulation that uses the best available physical models, sensor updates, fleet history, etc.(3) or a model that seamlessly integrates the five dimensions of physical systems, digital systems, update engine, prediction engine, and optimization to support decision making throughout the lifecycle(4).

With reference to these definitions, in addition to the advancement of analysis and simulation technology and physical measurement technology, which are our core technologies, we have been working on the development of elemental technologies for digital twin such as machine learning (surrogate, dimension reduction, etc.) to reduce large-scale analysis models with over 1 million degrees of freedom and UQ (Uncertainty Quantification) to update analysis models using measurement data from actual machines, through joint research with universities with advanced technologies and in-house research and development(5)-(11).

One of the promising applications of digital twin is the asset integrity management in which the remaining useful life of a facility (asset) and its risks are assessed, and the operation and maintenance are streamlined based on the risk information. The asset integrity management requires not only the basic functions of remote monitoring such as collection/analysis of sensor data, but also the collection and management of various types of asset information. Such information typically pertains to modeling of asset failure physics and failure statistics, standardization of inspection data format, monitoring of spare parts/materials and their market availability, and developing of

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maintenance work database such as asset upgrading and preventive maintenance cost. The collected asset information is used to estimate the remaining useful life, risks and financial metrics (e.g., net present value, and internal rate of return) according to the operation and/or maintenance menu. Decision-making on operation and maintenance by the facility manager can thus be based on these objective metrics. Moreover, one of the keys to enabling the facility manager, operator or maintenance inspector to make appropriate decisions lies in the user interface technology, because it provides information necessary for task fulfillment by each user and can make it easier for the user to understand and process the information.

A type of facility for which asset integrity management with digital twins is in high demand is large floating structures such as FPSO units. When an unexpected failure occurs in such a structure, the consequences will become serious because of multiple factors such as the difficulty in evacuating or rescuing workers, impact on marine ecosystems, and prolonged work for recovery (lower availability). Floating structures are permanently fixed/installed in an allocated sea area for operation. Unlike ships, periodic docking for detailed inspection or repair is not possible. The obtainable inspection data and applicable repair methods are limited. While the structural integrity of floating structures is currently monitored mainly through inspection, the operators are hoping that the inspection workload will be reduced (in terms of frequency and coverage).

Under such circumstances, recommended practices (RP) are published regarding assurance of an asset or system digital twin in the maritime field[12]. When a digital twin is built as a means to provide the customer or third party (e.g., a classification society) with solid ground for a proposal by quantifying the damage of structural members or their potential risks, this can help to not only improve the efficiency of maintenance/operation, but also to accelerate the process of decision-making or consensus among the stakeholders.

This report presents the current development status of large floating structure digital twins and asset integrity management, whose aim is to improve the safety, reliability, availability and maintainability of large floating structures.

2. Digital twin of a large floating structure

A digital twin of a large floating structure contains information about the components such as the hull/floating structure, mooring system, and riser. This report presents the technologies that have been developed for the FPSO hull structure and mooring system[9]-[11].

2.1 Hull structure digital twin

(1) Concept of hull structure digital twin

Taking an FPSO hull structure as an example, **Figure 1** illustrates the concept of a large floating structure digital twin and the asset integrity management process. The workflow of this process is fourfold: (i) focus on the major failure modes of hull structure (i.e., fatigue and corrosion) and collect the relevant data from actual measurement and inspection data (e.g., stress, acceleration, plate thickness, visual inspection, repair history and loading conditions) and metocean data (e.g., wave height, direction and frequency); (ii) update the digital model, consisting of the whole ship finite element model and structural simulation results, with the actual measurements and metocean data to form a digital twin, and use it to predict the actual ship's state; (iii) use the dashboard to obtain current and future information about each of the structural members regarding the remaining useful life, risks, and risk-based optimal operation/maintenance menu; and (iv) have the proposed risk-based optimal menu subjected to a review by the FPSO operator based on their own insights, before planning and conducting the operation and maintenance of the actual unit.

This section gives three summaries: the assessment of stress and fatigue life based on the whole ship finite element model, the use of measurement data to correct the stress response spectrum, and the assessment of corrosion initiation and wastage.

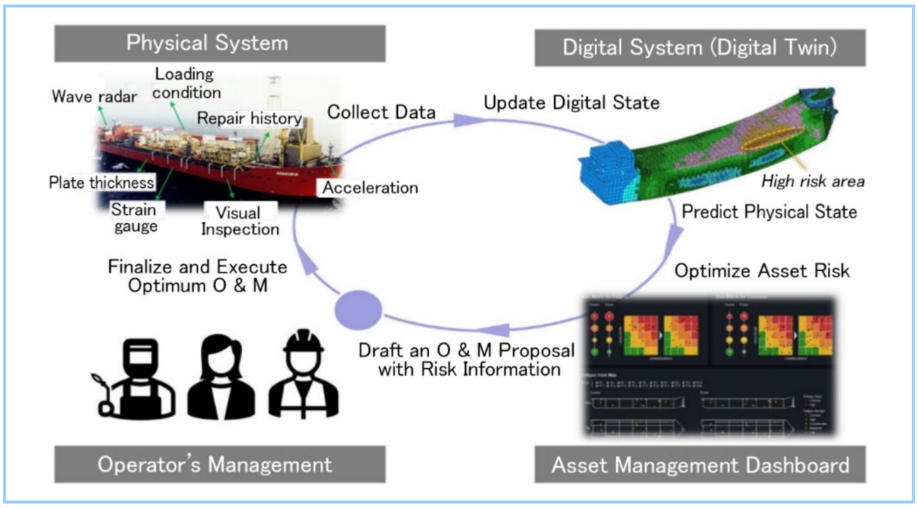

Figure 1 Conceptual representation of large floating structure digital twin and asset integrity management (in the case of a hull structure)

(2) Assessment of stress and fatigue life based on whole ship finite element model

As shown in **Figure 2**, a finite element model of whole ship was created, on which our direct load and structural analysis system called MHI-DILAM (DIrect Loading Analysis Method) was run for structural simulation[13]. Local structural members to be monitored on the dashboard were extracted.

For the extracted local structural members, their zooming models were created to calculate the response amplitude operators (stress RAOs) for fatigue reference stress. The stress RAO represents the stress amplitude generation factor for regular waves of arbitrary wave frequency ω, wave direction θ, and wave amplitude 1 (m). In this case study, the stress RAO was obtained by structural analysis under a total of 2880 wave conditions (20 wave frequency conditions, 12 wave direction conditions, and 12 conditions for 1 wave period). Generally, in the evaluation of stress response and fatigue in the field of ship and offshore structures, the stress response spectrum is calculated by combining the stress RAO with the wave spectrum, and the amount of fatigue damage, remaining useful life, and probability of failure are calculated from the spectral characteristics.

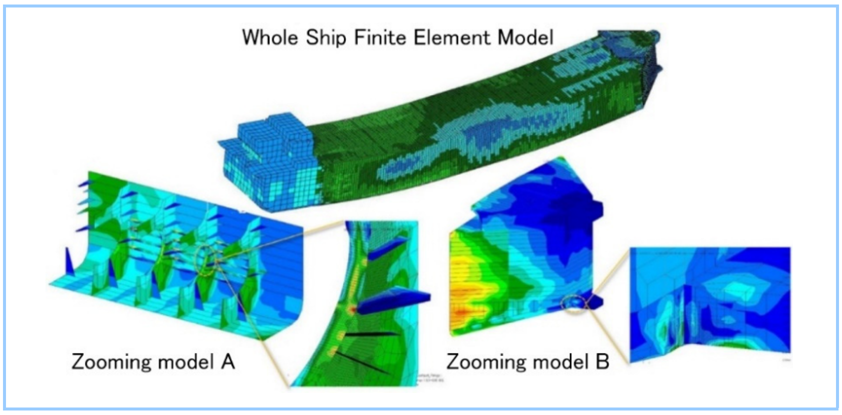

Figure 2 Hull structure digital model: example of whole ship finite element and zooming model and analysis results

(3) Use of measurement data to correct stress response spectrum

Estimates of the stress response spectrum calculated from the stress RAOs obtained by structural simulation and the wave spectra of real wave conditions capture most of the actual stress response behavior. On the other hand, this estimate includes uncertainties such as modeling errors in the analysis (response prediction assuming regular waves), discretization errors (element size, wave direction and wave frequency division width, etc.), and wave measurement errors. This may cause some discrepancy between the measured value of the stress response spectrum obtained based on the time history stress data from actual measurement and the estimated value, mainly in terms of the peak value and position of the spectrum.

Accurate life prediction based on stress measurement is preferable for high-risk structural members. However, when it comes to handling an actual unit, stress cannot be measured in some of these high-risk structural members because of the constraints on the number of measurement points and measurable locations (e.g., difficulty in making the inside of the oil tank explosion-proof or wiring therein).

Therefore, as shown in **Figure 3**, we considered correcting the estimated stress response by estimating the main part of the stress response behavior with the stress response spectrum calculated from the stress RAO and the wave spectrum, and then estimating the small discrepancy between the estimated and actual stress responses. Specifically, first, a surrogate is constructed by learning the relationship between the estimated value of the stress response spectrum, the amount of discrepancy from the measured value, and the wave conditions (wave height, direction, and period) using stress measurement data at several points measured on the upper deck, etc., which are relatively easy to measure. Then, the amount of deviation under arbitrary wave conditions is estimated from the constructed surrogate, and after correcting the estimated stress response spectrum of unmeasured members, it is reflected in the evaluation of remaining useful life and probability of failure. In this development, a Gaussian process regression model was adopted as the surrogate, because it can express the prediction uncertainty and allows flexible modeling according to the kernel function.

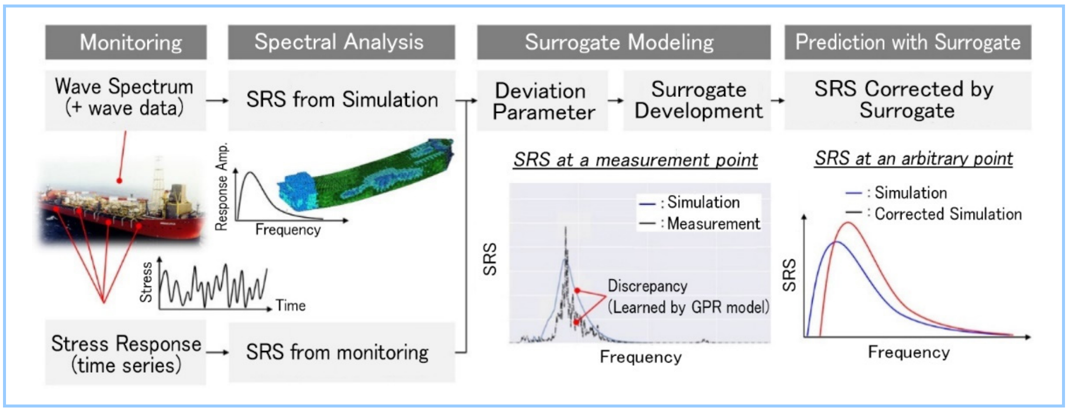

Figure 3 Learning and prediction of error of stress response spectrum using actual unit data and real metocean data

(4) Assessment of corrosion initiation and wastage

The initiation and growth of corrosion depend on various factors such as durability of surface coating, steel plate characteristics, temperature, humidity, oxygen, chloride and sulfur dioxide. As a result, the time of corrosion and the tendency of wall thinning vary depending on the tank contents (i.e., ballast water, oil), type of structural member, location within the member, and other factors.

At present, no physics simulation can predict the initiation of corrosion and the wastage in hull structures over a long period of time at a practical level of fidelity. Based on the previous studies[(14)-(16)], we decided to adopt Bayesian stochastic modeling in which corrosion statistics, obtained from a large number of marine vessels, are combined with corrosion measurement data from a marine vessel of interest. The corrosion initiation life is modeled by log-normal distribution, while the degree of corrosion progression is subject to exponential law.

Figure 4 shows an example of estimation and updating of corrosion initiation life using randomly generated virtual corrosion inspection data. First, the tank type and structural member to be evaluated are selected, the probability parameters (log mean and log standard deviation) of corrosion initiation life are extracted from the corrosion statistics of the target member, and a prior distribution is defined in which the uncertainty of the probability parameters is expressed as a probability distribution. Next, the prior distribution is updated based on Bayes' rule using the information on the presence or absence of corrosion obtained from periodic inspections every five years (in this estimation, it is assumed that 300 visual inspections are conducted) to obtain the posterior distribution. The obtained posterior distribution is then used to estimate the probability distribution of the corrosion initiation lifetime along with its uncertainty.

As shown in Figure 4, by using the periodic inspection data at the 5-year time point, a posterior distribution was obtained that reduced the uncertainty of the prior distribution. When estimating the cumulative distribution function using this posterior distribution, there is a divergence between the predicted mean value (red line) and the true value (blue line), especially in the region after the 5th year, and the variation of the prediction (green line) is large. On the other hand, when Bayesian updating is performed using inspection data accumulated over 25 years, the predicted range of the posterior distribution almost converges to a single point, and the prediction of the cumulative distribution function asymptotically approaches the true value over the entire time domain, confirming that the uncertainty in prediction is reduced.

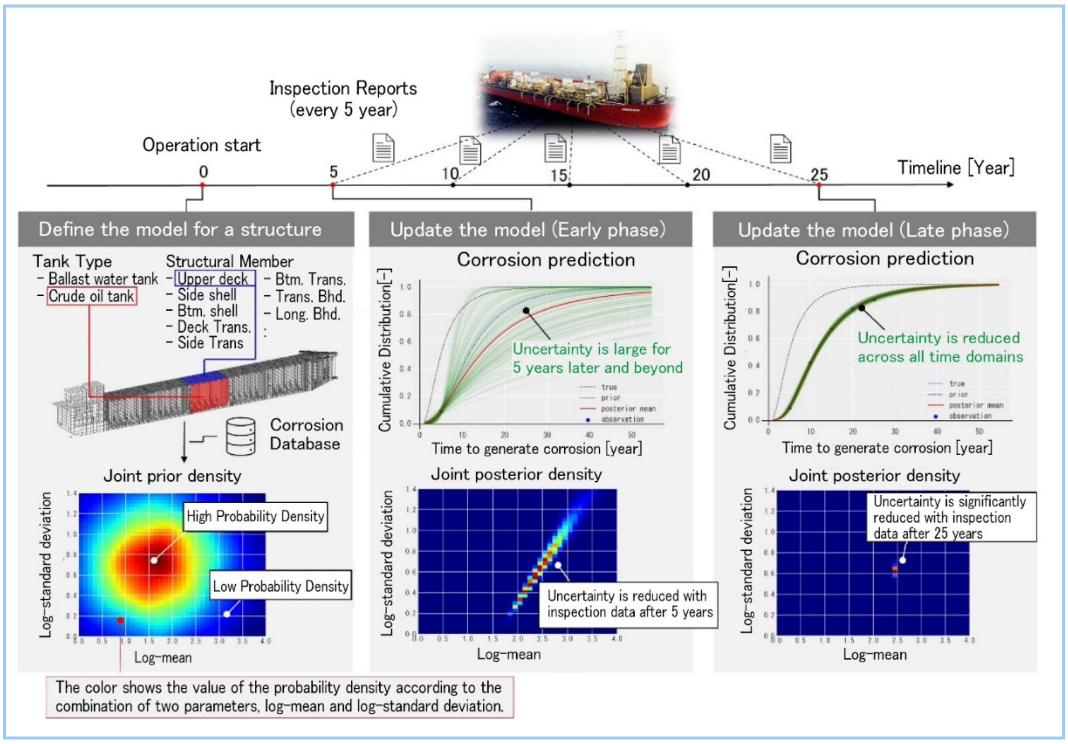

Figure 4 Probabilistic prediction of corrosion initiation life using corrosion statistics and inspection data

2.2 Mooring system digital twin

(1) Concept of mooring system digital twin

Mooring chains, which have a particularly higher failure rate, were chosen as the main subject of the assessment based on the statistics on mooring system accidents and discussions with FPSO operators. Holding workshops with classification societies, FPSO operators, mooring system vendors and others, we investigated the needs in the industry and technological challenges from the viewpoints of inspection method, automation/workload reduction and integrity management, before setting out to develop a conceptual digital twin framework and the technology. A mooring system digital twin and the asset integrity management were developed with the same concept as the hull structure in Figure 1. As shown in **Figure 5**, regarding the mooring system, the industry is in need of using physics simulation for mooring analysis and structural analysis as the chief means to perform the integrated assessment of various uncertainties (which are generated at multi-scales from 5-mm corrosion pits in mooring chains to 2,000-m mooring lines) and measurement data to improve the accuracy of remaining useful life assessment, which in turn decreases the lifecycle cost through reduced inspection workload and extended life.

This section gives three summaries: the prediction of mooring line tension by mooring analysis, the establishment of a standard inspection data template, and the stress prediction and life assessment by structural analysis.

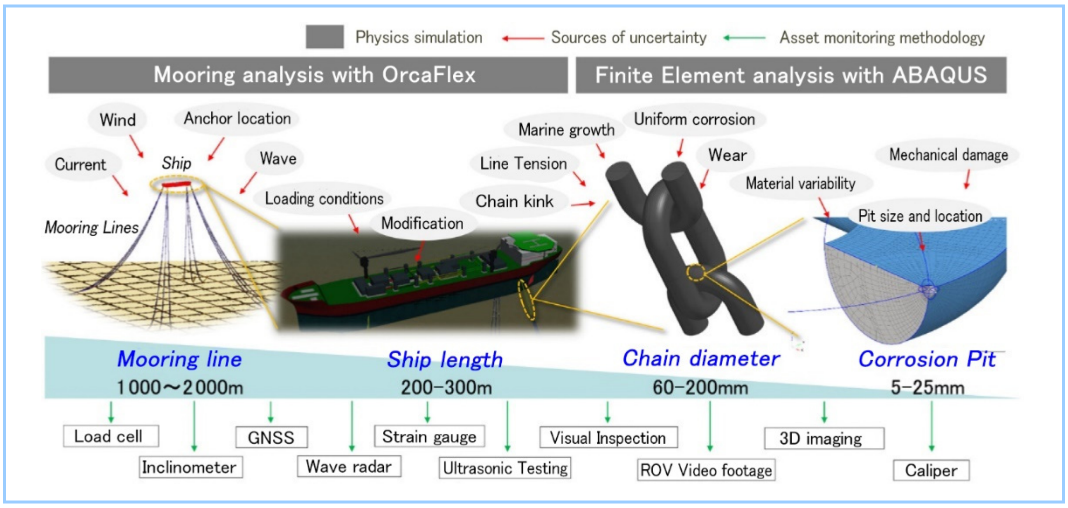

Figure 5 Conceptual diagram of physics models in mooring chain digital twin, sources of uncertainty, and asset measurement methodology

(2) Prediction of mooring line tension by mooring analysis

We set the mooring system specifications of a virtual FPSO (mooring type: multi-point catenary mooring, number of mooring lines: 12, and water depth: 1,200 m), and created an analysis model for OrcaFlex mooring analysis software (Figure 5, left).

This analysis model was used to perform time history response analysis in which the parameters are environmental conditions (wave height and direction, wind speed and direction, and flow velocity and direction). The outcome was a mooring line tension database, containing the position of an FPSO unit under arbitrary environmental conditions, time series data on the mooring line tension of each mooring line, and statistics. Incorporating this database into the mooring line tension prediction process makes it possible to predict mooring line tension in real time without performing time history response analysis, every time a prediction is made.

(3) Establishment of standard inspection data template

Updating a mooring system digital model requires a standard inspection data template that can be used in the digital model. A standard inspection data template was therefore created by extracting and organizing particularly important inspection items for integrity management from various inspection reports of multiple inspection companies owned by the classification societies. The template was further polished based on the feedback from FPSO operators and mooring system vendors, before the final version was established.

This template comprises a total of 36 items of information about chain ID, dimensions of major segments such as the interlink and the straight bar part, corrosion pit occurrence and so on. With these, the state of chains in an actual unit is represented.

(4) Stress prediction and life assessment by structural analysis

The time history of the mooring line tension obtained by mooring analysis and the standardized inspection data are used to assess the remaining useful life of a corroded chain, validity of static strength, and probability of failure. Based on the previous studies, we organized major influential factors in the fatigue life of a corroded chain, and enabled the assessment model to incorporate the residual stresses induced by the guaranteed load during chain production (approx. 70% of the minimum breaking load), stress range, average stress, corrosion wastage and corrosion pitting.

Figure 6 shows an example of finite element model of a pitted mooring chain and analysis results. The parameters therein are the location of a corrosion pit with a hemispherical shape (i.e., outer crown, inner bend, or straight bar part) and the size (by the depth of 5, 15 or 25 mm). The regression model that we built learned the relationship between the size of the corrosion pit and the stress concentration coefficient (i.e., the ratio of the maximum principal stress to the average stress on the side bar) at each of the representative locations. By combining with the concentration of stress caused by uniform wastage, the regression model assesses the stress in a corroded chain with a corrosion pit of an arbitrary size at a given location. Thus, a method for assessing the validity of static strength and fatigue life has been developed.

The information about the location of a corrosion pit, which is provided according to the standardized inspection data template, is just the indication of which one of the eight segments the pit is located in, as shown in the lower left part of Figure 6. No more detailed information is available. Therefore, if a corrosion pit is observed in Segment 3, the stress is assessed in such a way as to provide a sufficient margin of safety, considering the pit is located in the outer crown (top surface of a chain ring) with the highest stress generation.

In this development, a virtual FPSO was installed in a given sea area, and environmental conditions (wave height, wave direction, wind speed, wind direction, current direction) assumed in the sea area and time series data of corrosion conditions of each chain were generated by a simplified model and random numbers, and these were used to conduct a load-stress-strength evaluation of the mooring chain.

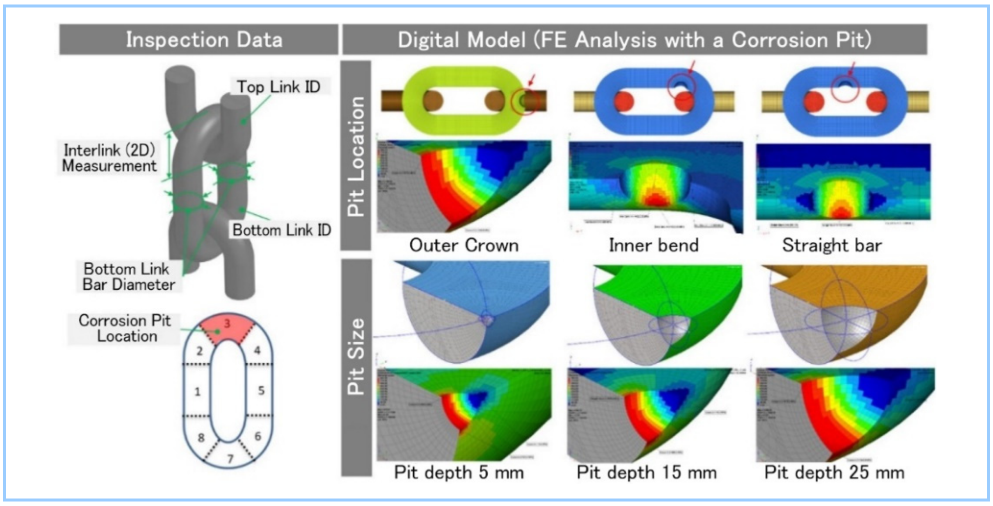

Figure 6 Standard inspection data template (left) and corroded chain digital models (right)

3. Asset integrity management dashboard

With regard to asset management, the outline, principles, terminology, requirements and application guidelines are standardized as the ISO 55000 series[(17)-(19)]. The application cases in facility maintenance management have been reported mainly for aging infrastructures. In accord with the concepts of international standards, we have also developed a dashboard to help manage the asset integrity, which provides objectivity and a solid base for decision-making.

3.1 Risk-informed decision-making

The asset integrity management system is designed to help the FPSO operator with decision-making, by efficiently aggregating, visualizing and analyzing heterogeneous data in different formats. These data include sensor data such as environmental data (e.g., wave height, direction and frequency) and actual measurement data (e.g., stress, acceleration and plate thickness), inspection data containing facility specifications, analysis models, tables, texts and images, and computation results regarding the remaining useful life of structural members, probability of failure and failure risks. This section describes specific examples of decision support methods and evaluation criteria.

(1) Risk-informed decision-making

For the optimization of asset information-based operation and maintenance, we have decided to introduce risk-informed decision-making in which the optimal solution based on the objective risk indicator (obtained by the probability of failure multiplied by the failure consequence) is considered together with the FPSO operator's insight. By using a quantitative index such as risk as a criterion for judgment, maintenance rationalization can be systematically promoted while maintaining objectivity and accountability. In addition, the policy was to flexibly adopt other decision-making criteria (e.g., reliability) in response to customer needs and business environment.

(2) Failure consequence

The failure consequence of each of the structural members is rated (by assigning a score of from 1 to 5 points) from four perspectives: safety, environment, productivity and breakdown maintenance cost. For example, damage to the outer plate of an oil tank poses a significant degree of damage impact from environmental stand point, because of the concern that it may lead to an oil spill into the sea. In risk assessment, the degree of damage consequence can be estimated by selecting a single indicator with the highest concern among the four perspectives, or using the weighted average of multiple indicators.

3.2 Dashboard system

In designing a dashboard system, we first focused on its expected use cases and considered a user interface through which the data necessary for decision-making is organized to show the indicators and information necessary to take various decisions for asset integrity management.

The system is expected to be used in (a) daily operation for collection of data for waves, stress, acceleration and such, ship-to-shore communications, and automation/workload reduction of the assessment of remaining useful life and risk; (b) periodic inspection for determination of the necessity of additional examinations/parts replacement, digital model updating, and planning of medium to long-term maintenance based on the updated model; (c) unplanned failure events as a support tool to make a decision (regarding whether to perform immediate repair or monitor until the next inspection) and consider additional inspection items; and (d) examinations after exposure to severe loading (e.g., due to a storm), for example, the assessment of the state of high-risk components, crack propagation analysis, and consideration of additional inspection items.

Furthermore, in order to have the capability to flexibly respond to the requests from users, our dashboard system is enabled to run in two types of environments: on-premise and public cloud (Microsoft Azure). The functions such as risk computation and communications were verified in these environments.

(1) Dashboard overview

Depending on an asset of interest (e.g., hull, mooring or riser), the dashboard handles information for asset integrity management and presents the following seven WEB pages: Insight, Maintenance, Risk Analysis, Monitoring, Damage Event, Report, and Information.

“Insight,” which is shown on the main page, enables the check of key performance indicators (KPIs) such as locations of risk components and their quantities, and daily accumulation of fatigue damage. “Monitoring” provides the time series charts of archived data on environment and measurements of actual units, temporal change in the degree of fatigue damage, and so on. In “Risk Analysis”, the individual structural members can be checked in detail in terms of the current status and future life, and probability of failure. For those requiring more detailed information, “Report” gives an access to the inspection reports and data. “Maintenance” can confirm or review the risk-based optimal work plan in comparison with the original inspection/replacement plan. This report summarizes some representative pages (i.e., “Insight” and “Risk Analysis”) because of space limitations.

(2) Dashboard screen for hull structure and mooring system

Figure 7 gives the pages of “Insight” and “Risk Analysis” for a hull structure. Shown at the top of the “Insight” page are KPIs for asset integrity, such as current and future fatigue damage and the number of evaluation items where corrosion damage exceeded the threshold. Others include metocean data (i.e., wave direction, frequency and height) over a certain period of time, the accumulation history of fatigue damage in representative evaluation points, spatial distribution of fatigue damage and corrosion damage for representative components, and recommended action list for maintenance. Displaying such information helps to give a rough understanding of overall situation of asset integrity.

Selecting “Risk Analysis” on the side menu leads to the overall risk of asset integrity, as well as detailed integrity assessment results such as summaries of individual structural members, remaining useful life, and probability of failure. The “Overview” tab shows Pareto charts of current and future risks, and fatigue and corrosion damage risk matrices, whereby high-risk structural members can be identified. After the identification, moving to the individual tabs for damage modes such as fatigue enables the collection of information about the assessed locations of the high-risk structural members, time series prediction of the degree of fatigue damage, probability of failure, damage risk and recommended maintenance action.

Figure 7 Example of asset integrity management dashboard: hull structure

Figure 8 shows the "Risk Analysis" page for a mooring system. In "Risk Analysis", different tabs were created for "Overview" and individual mooring lines (tabs of 1 to 12 in the figure). "Overview" helps to have temporal/spatial understanding of the damage status of all mooring lines, by presenting each line's current and future fatigue damage, number of chains exceeding the thresholds that has been set for fatigue damage and static strength, and spatial distribution of damage (with the degree of damage on the y-axis and the depth of water on the x-axis).

After looking through the overall status, the tabs for individual mooring lines can be selected as needed to understand the asset conditions in detail. Therein, relevant information such as time series prediction of the degree of fatigue damage, probability of failure, failure risk, and recommended maintenance action can be obtained for all chains of the selected mooring line. If chain inspection data are available, the damage conditions can also be viewed based on 2D mapping of the severity of corrosion wastage with the corresponding gradations of colors, and the locations of corrosion pits, which promotes an understanding of the status.

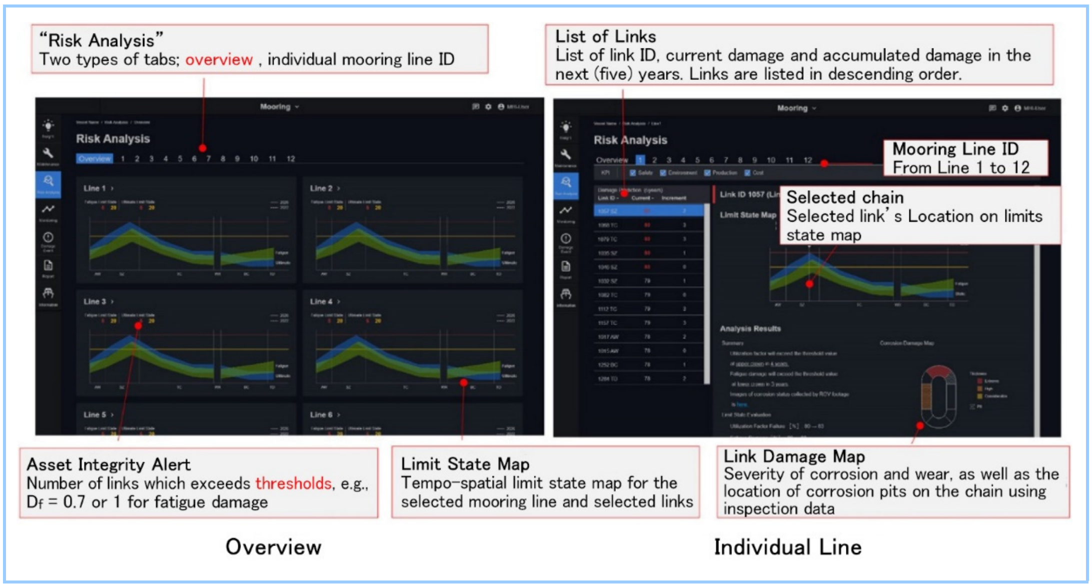

Figure 8 Example of asset integrity management dashboard: mooring system

4. Conclusion

This report presents the current status of the development of large floating structure digital twin and the dashboard system to support asset integrity management with digital twin. The introduction of these technologies that we have developed will create multifaceted value including prevention of unplanned outages, life extension of aging facilities, minimization of the need for maintenance, facilitation of investment in upgrading appropriate facilities, and reduction of asset lifecycle cost. It can therefore be expected to reduce the economic burden when shifting to a sustainable energy system.

The concept of our digital twin and dashboard system are versatile and can be applied to the asset integrity management of wide-ranging products including mechanical and electrical components. Looking forward, we will customize the logic and interface flexibly according to the product or customer's business environment/problems, thereby offering our technologies to many customers.

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