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THE TRUE DIGITAL TWIN CONCEPT FOR FATIGUE RE-ASSESSMENT OF MARINE STRUCTURES

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ABSTRACT

The paper presents a true digital twin concept, which is a general and novel methodology that significantly improves the fatigue prediction models of existing marine structures. The actual structural condition of existing marine platforms can often change after several years in operation due to degradation mechanisms and/or other structural changes. It is within this context, the true digital twin concept has been developed and the general idea is to create a coupling between the digital twin and measurements. The measurements are performed by Structural Health Monitoring Systems (SHMS). This coupling facilitates a direct performance evaluation of the digital twin against measurements and most importantly creates the basis for improving the performance of the digital twin to accurately capture the actual condition of the structure, and thus become a true digital twin. The full concept of creating a true digital twin encompass novel advanced analysis methods ranging from linear system identification, expansion processes, Bayesian FE model updating, wave load calibration, quantification of uncertainties from measured data, and Risk- and Reliability Based Inspection Planning (RBI) analysis, [1]. This paper presents the first 3 levels for establishing a true digital twin. The levels are illustrated by 3 case stories.

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1 INTRODUCTION

In the North Sea alone, more than 600 offshore structures have exceeded or will in the near future exceed their original design lifetime. The industry is facing extensive investments to upgrade or reinforce the existing infrastructure, to maintain the present oil and gas production in the future. The alternative for many installations is to consider decommissioning of outdated production facilities and consequently facing potential significant reduction in the oil and gas production. In order to choose the most optimal direction for the future development, the decision-makers need thorough insight into the actual condition of their installations to establish a solution which facilitates economic profitability, environmental protection and human safety. To secure a satisfactory evaluation of the future solution strategy, it is essential for the decision-makers to possess reliable prediction models of their assets. In this context, the question arises, whether the existing models actually provide a sound and reliable prediction of the present condition. The condition for an offshore platform may have changed multiple times during the operational life due to natural occurring degradation mechanism's and/or other structural changes like new platform extensions, increase in topside masses, etc. During the lifetime of the structure, the prediction model therefore has to be modified to reflect the actual conditions of the structure. A digital twin model is essen-

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FIGURE 1. Exemplification of measurement equipment in a structural health monitoring system.

tial for safe operation of any Structural Integrity Management (SIM) program. The digital twin reflects the current conditions of the structure and provides valuable knowledge about the expected future behavior of the structure.

1.1 Digital twin performance

A major question emerges in this context of how good does the digital twin actually perform, and what is the level of uncertainty associated with the digital twin? To provide sufficient information to answer this question, it is necessary to create a coupling between the real conditions and the digital twin. Founded in this demand, the industry has initiated several joint industry projects regarding development of methods for performance evaluation of digital twins, reference is made to e.g. [1], [2], [3].
Ramboll is recognized to be first mover within the field of developing a methodology to facilitate a coupling between the real conditions and their digital twins. The real conditions are in this context identified by means of SHMS, which in general provide information about the actual environmental loads and the corresponding structural response. A typical configuration of a permanent monitoring system is illustrated in Fig. 1.
Throughout the past 15 years Ramboll has developed novel methods for assessing the real/measured uncertainties associated with design and analysis of platforms. The concept of the Ramboll digital twin differentiates from other digital twin concepts by the introduced advanced methods for model updating, quantification of model uncertainties and the direct link to Risk- and Reliability Based Inspection planning (RBI). The validity of the methods has been verified on a large number of projects for offshore structures. These technologies have recently been compiled into a State-of-the-Art in-house software, called SIMA, (Structural Integrity MAnager). The SIMA software enables a direct coupling between a given structural monitoring system and the digital twin, in a simple and sound interface. This provides the basis for an uncertainty assessment of the digital twin, regardless of which Finite Element (FE) software is preferred, e.g. ROSAP, SACS, SESAM, other. The SIMA software is in the current paper illustrated by means of digital twins prepared for the Ramboll in-house FE software ROSAP, [4].

1.2 The true digital twin

The SIMA software package provide an interface for observation and detection of inconsistencies between the digital twin and the real/measured conditions, cf. Fig. 2. The software furthermore possesses facilities for improving the performance of the digital twins, enabling the creation of the true digital twin in

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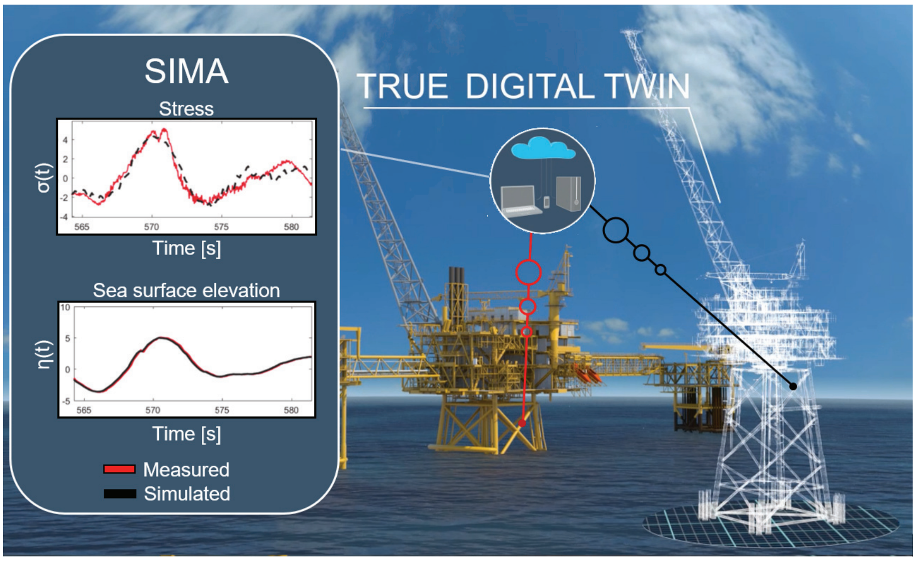

FIGURE 2. SIMA - Time domain performance evaluation of a true digital twin.

general. It has been decided to use the term "true" to introduce a clear distinction between the original and the updated digital twin. The improvement methodology in use is fully general and can be applied for all structural analysis disciplines. In the development of a true digital twin, it is obviously essential to consider the cost and benefits of approaching a true digital twin, which is tailored to a specific purpose. This is necessary as the monitoring system consisting of a number of sensors is the cost driving factor when developing a true digital twin. It is always recommended to develop the true digital twin in stages or levels (Levels 1 - 5), as presented in the below, where each level is followed by a Decision Gate (DG) to be passed before activating the next level of improvement as required in the individual cases and hence controlling the associated costs.

Level 1 (DG-1) - Screening and diagnostics
Level 2 (DG-2) - FE model updating
Level 3 (DG-3) - Wave load calibration
Level 4 (DG-4) - Quantification of uncertainties
Level 5 - Accumulated fatigue monitoring

The purpose of the current paper is to clarify the concept of the true digital twin and how it potentially improves the basis for re-assessment of existing structures. The concept is illustrated by presentation of three examples of application representing the first three levels in the development of a true digital twin. For a more detailed description of the methods and the theories adopted reference is made to [1].

2 Digital twin - Screening and diagnostics (DG-1)

Before deciding on the strategy for any digital twin updates and improvements, it is essential to evaluate the performance of the existing digital twin by studying its ability to predict the actual structural behavior. This knowledge enables for a diagnosis to be drawn and creates the basis for deciding whether to continue to the next level or not, i.e. DG-1 has to be passed. The following section provides an elaboration of the screening phase clarifying the methodology by an example for a simple tripod type platform, see Fig. 3. The screening is generally based on a correlation study of the dynamic response, hence the objec-

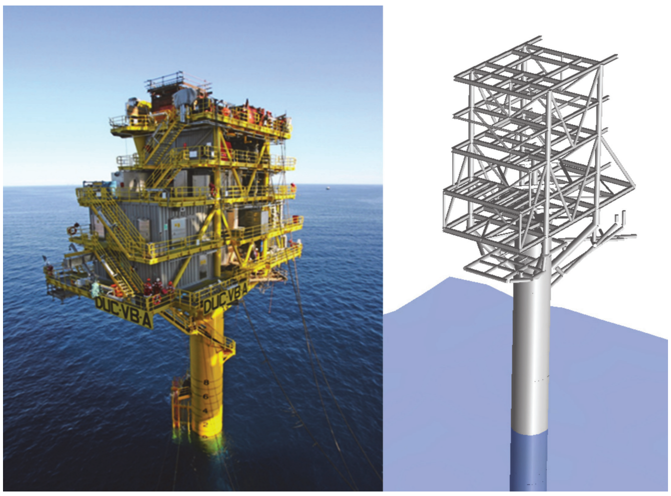

FIGURE 3. Satellite platform of tripod type structure.

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tive is to correlate the dynamic behavior of the digital twin with the measured condition of the platform. To facilitate for a quick and cost effective screening phase, it is crucial that the measurement sensor set-up is kept sufficiently simple in order to minimize analysis costs.
The strategy adopted in this first screening phase therefore focuses on a simple measurement set-up which, within a very limited measurement period, provides sufficient information of the real structural behavior. A quick "fingerprint" of the structure is generated based on the measurements in terms of identification of the modal parameters, i.e. natural frequencies, mode shapes and the associated damping parameters for the real structure. The fingerprint of the structure can typically be generated from measurements from only 2 accelerometers in the two horizontal directions at 2 locations on the platform, e.g. at the Cellar Deck of the platform at two locations. By means of this simple sensor set-up and very few hours of measurement, i.e. the measurements could be performed on a 1-day measurement survey with portable equipment (non-permanent equipment), it is possible to assess the performance of the digital twin and evaluate (DG-1), if it is required to proceed to the next Level 2 or not.

2.1 Results

The data sampled during the offshore campaign is post-processed by the SIMA software, which contains several signal processing toolboxes and facilitates a complete identification of the modal parameters for the given structure. The software enables a direct comparison of the modal parameters identified from the measurements with the modal parameters for the digital twin counterpart.

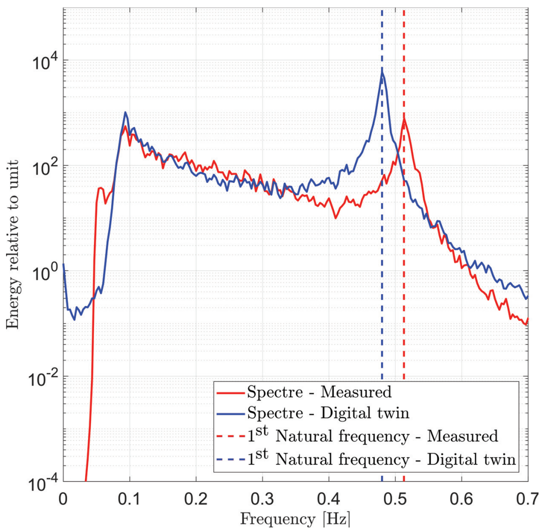

FIGURE 4. 1^{st} natural frequency: Comparison between measured and predicted spectra before updating(north-south dir.).

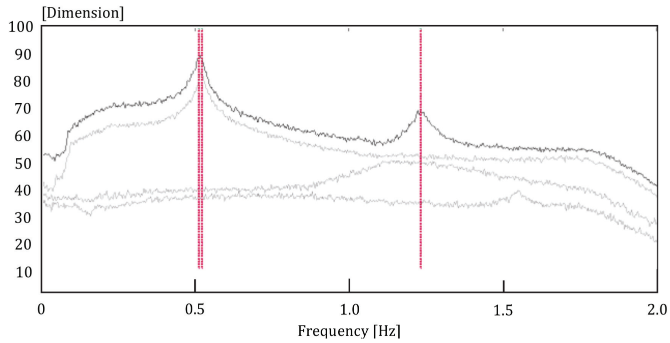

FIGURE 5. Stabilization diagram for linear system identification by Stochastic Sub-space Identification (SSI) method, red marker - stable mode identification.

Employing this methodology for the particular case, it is observed that the spectra are not coinciding, cf. Fig. 4. The peak values, marked by the stipulated lines, indicate that there is a difference between the measured and the FE model natural frequencies. The real modal parameters is identified by the linear system identification toolbox integrated in the SIMA software. The real modal parameters are in this case estimated by the Stochastic Sub-space Identification (SSI) method, as indicated in Fig. 5. From the performed Level 1 analysis it can be concluded, that the modal parameters for the platform are not accurately represented by the digital twin. Based on this observation, it is possible to make the diagnosis; that the parameters effecting on the modal parameters, typical stiffness and mass representation for the digital twin need to be updated. For this case it is therefore recommendable to proceed to Level 2 to perform a FE model updating of the digital twin.

3 True Digital Twin - FE model updating (DG-2)

Level 2 (DG-2) is related to the first step in generating a true digital twin of the real-world counterpart. It is exemplified by means of a second case story for a platform structure as illustrated in Fig. 6. The platform consists of a Topside structure supported at one end by a concrete shaft and at the other end by a 4-legged steel lattice tower structure. The installed full Structural Health Monitoring System (SHMS) consists of several types of load and response measuring sensors, however for illustration purposes of Level 2 only the accelerometers are presented, cf. Fig. 7.
The resulting spectra from the Level 1 analysis on this platform is presented in Fig. 8. It is noticed, that the spectre of the accelerometer in the north-south direction captures two natural frequencies, marked by the stipulated lines in Fig. 8. The first and second natural frequency are well represented by the digital twin, whereas the third natural frequency deviate significantly. All performed analysis indicated that FE model updating was required

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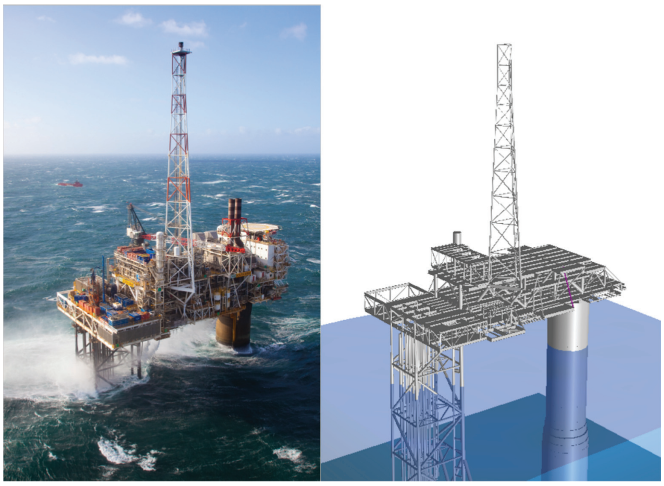

FIGURE 6. Offshore platform with Topside supported by a concrete shaft and a four-legged steel lattice tower structure.

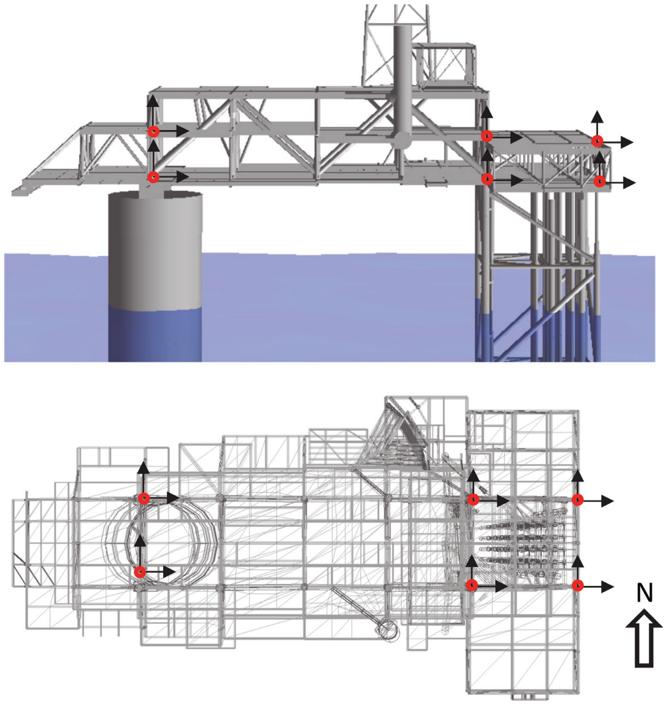

FIGURE 7. Location and orientation of the accelerometers, platform directions.

to proceed to Level 2 for generating a true digital twin, i.e. FE model updating to measured modal parameters.

3.1 FE model updating

The updating of the structural behavior aims at minimizing the discrepancy between the modal parameters of the digital twin and the real structure. The entire process related to updating of the structural behavior of the digital twin is facilitated by the SIMA software package. The updating process initially perform an identification of the modal parameters of the real structure. This is facilitated by the integrated toolbox for system identification. A number of methods are available such as e.g. Stochastic Subspace Identification (SSI) in the SIMA software package, [1]. The toolbox identifies the natural frequencies and associated mode shapes along with the damping properties for the current conditions of the real structure. The identified modal parameters are employed as the target for the digital twin model updating.

The next phase of updating the digital twin is accomplished by the Bayesian-based FE model updating toolbox integrated in the SIMA software package. A theoretical elaboration of the SSI and the Bayesian-based FE model updating method is not the scope of the present paper, [1].

However, the model updating process is generally formulated as an optimization problem, where the governing variables are all the parameters, which impacts on the modal parameters; typically it could be mass and stiffness parameters of the digital twin, but all parameters have to be identified. An example of changes to e.g. masses is presented in Fig. 9. In Fig. 10 an example of typical parameters to be considered is presented in terms of re-

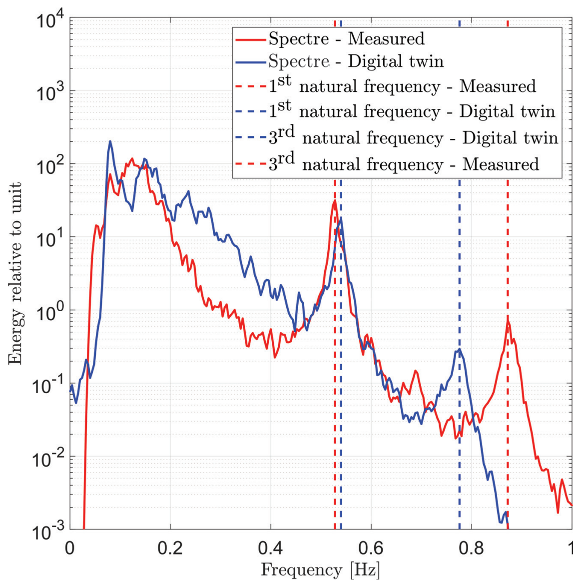

FIGURE 8. Comparison between measured and predicted spectra before updating (north-south dir.).

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sults from an initial sensitivity analysis, which forms the basis for the final updating process. The objective of the model updating is generally to identify the set of mass and stiffness parameters of the digital twin, which minimizes the discrepancy between the predicted and measured modal parameters. This entails that the optimization problem is aiming at minimizing the discrepancy of the natural frequencies and the mode shapes in combination. In this context, the discrepancy is thus a measure of the deviation between the respective natural frequencies of interest and the discrepancy of the associated mode shapes, which are quantified by the Modal Assurance Criterion number (MAC). A MAC value of 1.0 represent optimal correlation between the measured and the predicted mode shapes. Thus, the term true digital twin of the structural response is in this case achieved when the modal parameters of the digital twin becomes a sufficient approximation of the real-world counterpart.

3.2 Results of the FE model updating

In the present case the target of the model updating was an optimal representation of the three lowest natural frequencies and their respective mode shapes. The mode shapes are illustrated in Fig. 11, where the red lines are a representation of the measured mode shapes of the real structure and the blue lines are representing the mode shapes from the updated FE model. Fig. 11 present the mode shapes after updating. With the defined target at hand, the next step is to define the governing parameters for the FE model updating problem.

For the presented case, the local joint flexibilities (joint stiffness's) for all nodes in the model, the Young's modulus of the concrete shaft, the Young's modulus of the steel members and the mass and the Center of Gravity (COG) for all topside masses, are chosen as the variable parameters impacting on the modal parameters. Observations made during the model updating process showed that the optimization problem was less governed by the global stiffness and the local joint flexibilities of the structure, whereas the mass and the location of COG for the topside masses governed the problem for this specific case story.

Fig. 9 illustrates the initial location of the COG of the topside masses and the final location of the COG after the model updating. An example of detailed results from a FEM updating is presented in Fig. 12. The updated mass and stiffness representation of the digital twin, secures an accurate prediction of the mode shapes and the respective natural frequencies, as illustrated in Fig. 11 and 13. Especially the prediction of the third natural frequency and the respective mode shape is significantly improved by the updated digital twin. The MAC for the third mode shape (torsion) is increased from 0.89 to 0.97. The updated stiffness and mass representation for the digital twin induces a sufficiently accurate prediction of the real-world mode shapes and the respective natural frequencies, hence a true digital twin for the structural behavior is obtained. Updating of the FE model

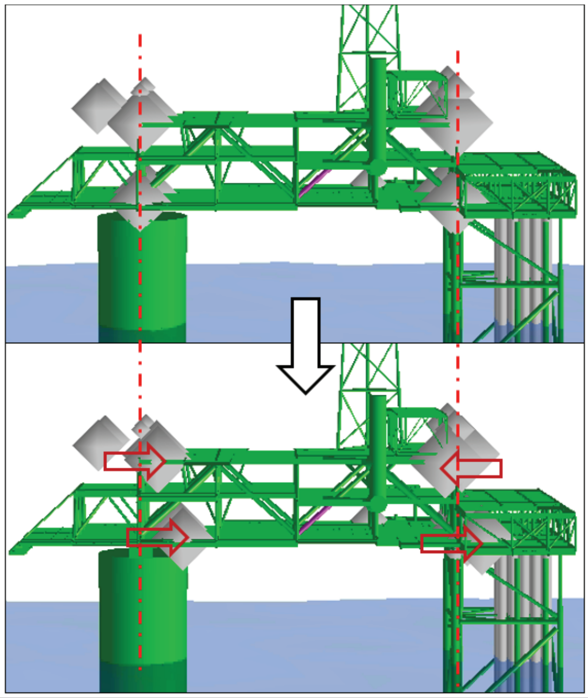

FIGURE 9. Location of mass appurtenances, before and after the updating to the modal parameters.

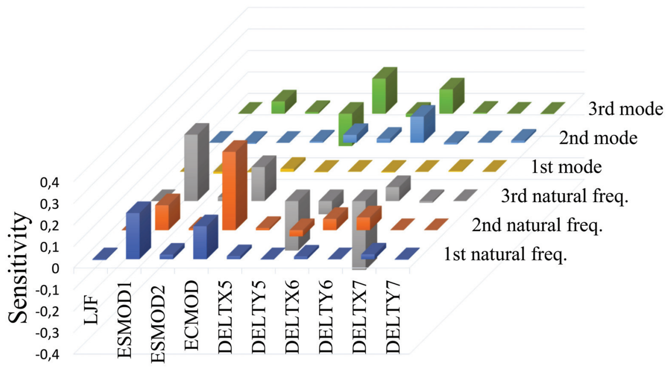

FIGURE 10. Example of results from sensitivity analysis forming the basis for the following FE model updating process.

to the measured modal parameters secures that the static and dynamic characteristics of the real structure is represented correctly in the prediction model. This for example secures that the distribution of the force and stress flow in the structure is correct represented, and consequently the location of the most critical hot spots can also be correctly identified. However, updating to the modal parameters does not secure that the wave load modelling is correct.

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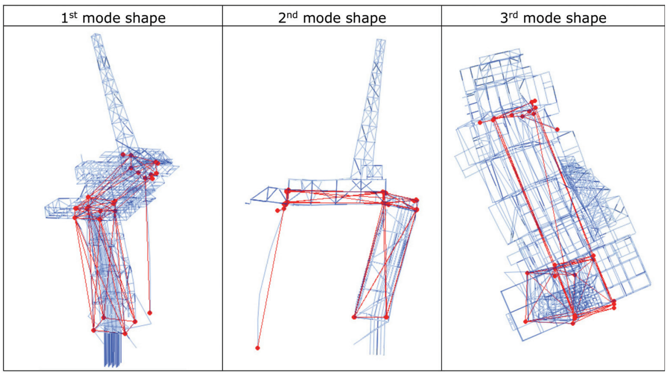

FIGURE 11. Updated mode shapes. True digital twin (Blue: FE model mode shapes) and the real-world counterpart (Red: measured mode shapes).

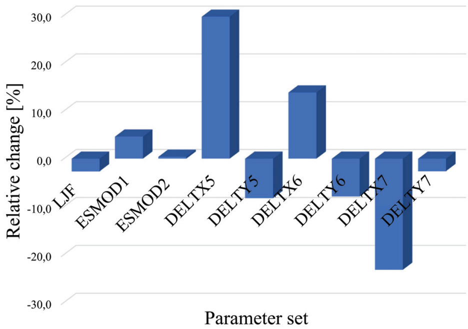

FIGURE 12. Example of results from a FEM updating, where the change in each parameter is presented as a percentage of the initial value.

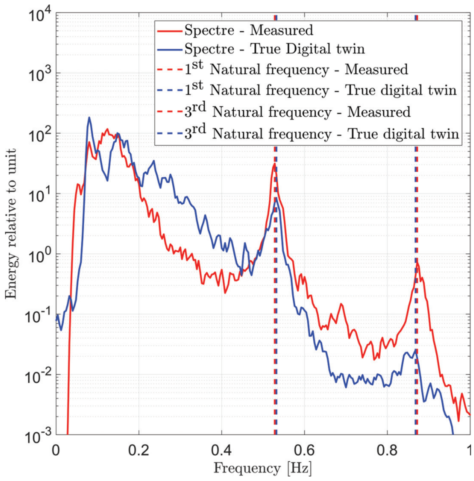

FIGURE 13. Measured and predicted spectre after updating (north-south dir.).

The decision to continue with Level 3 (DG-3) is depending on whether it is judged that wave load calibration is required or not. Wave load calibration typically removes conservatism in the adopted wave load models and hence facilitates for life time extension.

4 True digital twin - Wave load calibration (DG-3)

The previous sections elaborated upon the processes associated with establishing a true digital twin for the structural behavior of a given marine structure, securing the best possible representation of the real structural behavior. The true digital twin can be utilized in all types of structural analyses for the current structural conditions, and in relation to fatigue re-assessment of ageing structures the true digital twin is obviously the key technology for securing the most reliable fatigue prediction.

In the introduction to this paper, the performance and validity of any digital twin is questioned. In continuation to this question, the performance of the true digital twin is not solely related to its ability to accurately represent the structural static and dynamic characteristics, but also the load modelling part is of equal concern when evaluating the performance of the digital twin for fatigue prediction for a given structure. Thus, to achieve a true digital twin for fatigue re-assessment purposes, it is essential that also the wave load modelling are accurately representing the real conditions.

Typically, adopting wave load modelling parameters from codes and standards relevant for the specific structure will yield conservative fatigue predictions. The decision to go for Level 3 is then dependent on, whether there is a need for removing conservatism in the prediction models and hence facilitating for lifetime extension or not.

To illustrate the process related to evaluating and optimizing a wave load model used for fatigue life estimation of a given structure, the result from wave load calibration of a 8-legged jacket is presented. The structure is illustrated in Fig. 14 along with its digital twin. For this project the structural monitoring system was installed to provide a real-time assessment of the structural behavior and furthermore create the possibility for optimizing the digital twin with respect to wave load modelling.

The structural and environmental conditions of the platform are monitored by a permanent structural monitoring system, consisting of 4 tri-axial accelerometers installed at the topside level and 24 strain gauges installed at 6 bracing members in the splash zone, see Fig. 15. In additional duplicate strain gauges was installed at selected locations for assessment of measurement uncertainties (applicable for Level 4). The accelerometers are installed to generate the true digital twin representing the structural static and dynamic characteristics. The strain gauges are installed to provide valuable information both for local member response in the splash zone, but also for the global platform response. In addition to this the structure is equipped with 3 wave

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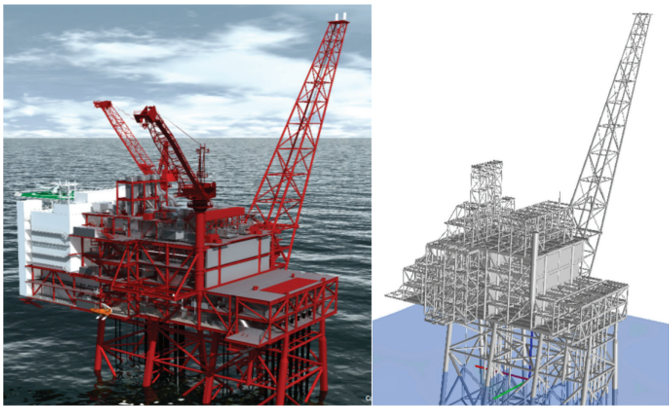

FIGURE 14. Oil and gas platform, 8-legged jacket.

TABLE 1. True digital twin, structural model and wave load model.

Structural model	
True digital twin	
Fatigue prediction method	
Transient fatigue analysis	
Wave theory	
Irregular waves (1^{st} and 5^{th} order)	
Sea representation	
Sea surface elevation, mean wave direction, wave spreading	
Calibration parameters	
C_d and C_m	
Calibration format	
Stress history	

radars, providing measurement of the sea surface elevation and thus sampling information about the sea state conditions.

The digital twin, is as mentioned, established to provide real time information about the fatigue damage accumulation in all elements and nodes of the structure based on measurements from only a limited amount of sensors, [1]. In the current case this is achieved by employing the measured sea surface elevation and the associated measured wave direction as direct input to the wave load modelling for the real-time simulation. The analysis is performed by transient fatigue analysis, where the wave loading is modelled by irregular waves, cf. basic model properties in Tab. 1. The next step is to investigate and possibly improve the performance of the selected wave load modelling.

With the strain gauges installed on bracing members in the splash zone, it is possible to evaluate the real-time performance of the true digital twin. In this performance evaluation, it is assumed that the evaluation of a finite number of reference measurement locations (6 selected bracing members) provides sufficient information about the performance of the true digital twin in the splash zone. In the current case, the performance is evaluated by means of members which are dominated by local wave loading, as illustrated in Fig. 15, i.e. in-plane-bending and out-of-plane bending. It shall be noted that also global platform behavior is covered both by the local strain gauge measurements and by the global displacement measurements from the 4 tri-axial accelerometers. If it can be verified that the true digital twin provides an accurate estimation of the stress state in the reference measurement points, it is assumed that the prediction is accurately estimated in all parts of the structure. It has been verified by laboratory scaled model experiments that this is a valid assumption, [1].

To illustrate the performance of the real-time true digital twin, the measured and predicted stress state is compared in Fig. 15, before any wave load calibration. The comparison is exemplified by strain gauge (SG) No. 2D and strain gauge No. 4B. By visual inspection it is observed that the true digital twin provides a good representation of the real time stress state in the splash zone.

The actual performance evaluation of the fatigue prediction of the true digital twin, must however be evaluated for a longer period of time e.g. 3-12 months or even longer depending on the conditions. The historical representation of the stress state is identified by means of Rain Flow Counting (RFC) of the continuously measured and predicted stress state, as exemplified in Fig. 15. Inspection of the stress history curves in the current case reveals that the true digital twin slightly overestimate the stress state. Hence the true digital twin predicts slightly higher stress ranges ($\Delta\sigma$) for each RFC bin size. This tendency is observed for all the measurement points, indicating that the true digital twin overestimates the actual measured fatigue damage, not only in the measurement points, but for elements and joints in the entire structure.

Assuming, that the true digital twin provides the best possible representation of the structural response, it is only possible to improve the fatigue prediction of the true digital twin by calibrating the wave load model against measured sea state conditions. In general terms, the idea of calibrating a load model to measured sea state conditions is defined as an optimization problem, where relevant load parameters are selected as the governing variable in the optimization of the load model. The objective of the calibration is to minimize the discrepancy between the measured and the predicted response by calibrating the wave load modelling part of the FE analysis.

For the current case the wave load calibration was performed by the SIMA software, which has an integrated wave load calibra-

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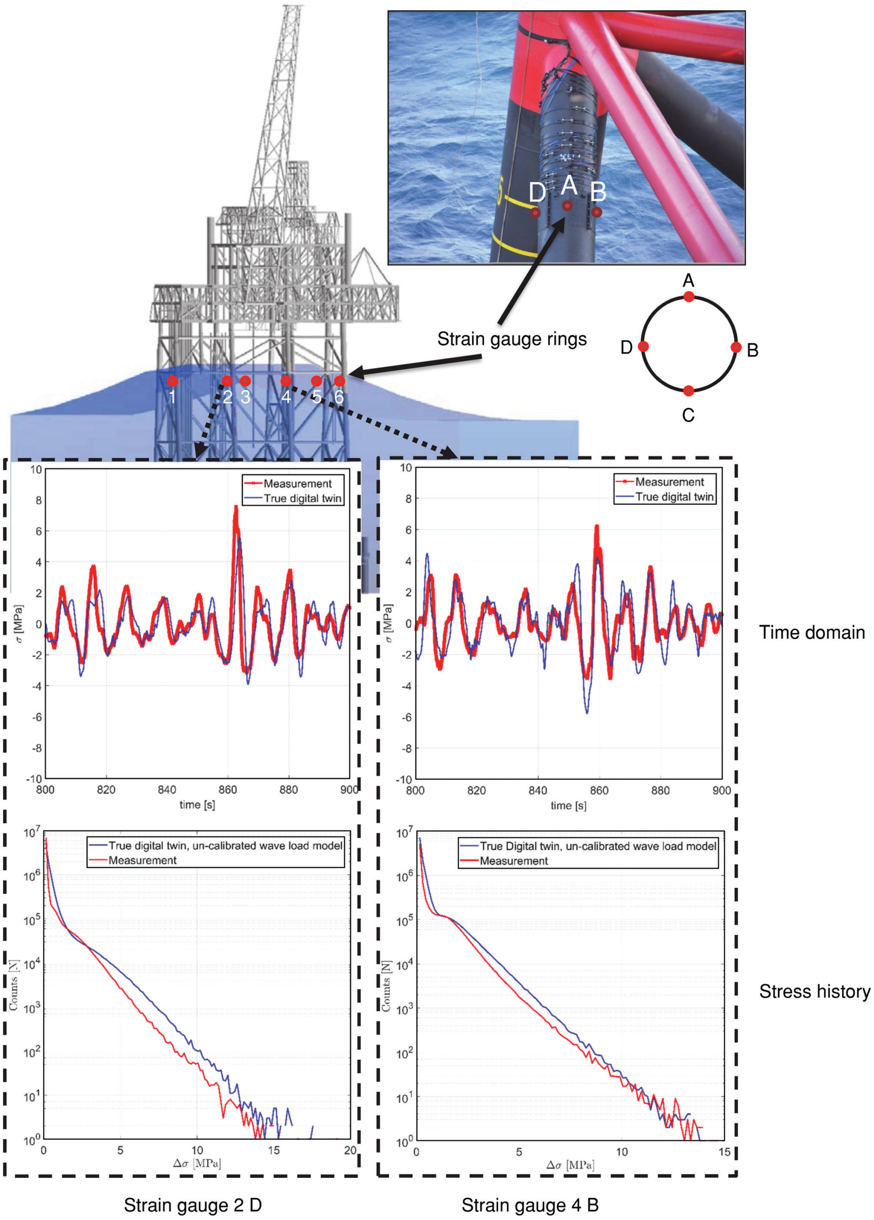

FIGURE 15. Time domain and historical representation of the normal stresses, as monitored in strain gauge No. 2 D and 4 B, un-calibrated wave load model.

tion toolbox. In this case, it was chosen to use the global hydrodynamic parameters in terms of Cd and Cm, representing the drag and inertia term of the Morison equation. The target of the wave load calibration therefore is to identify the set of hydrodynamic parameters, which provide a minimum discrepancy between the measured and predicted stress history curves. For the current case, the wave loading was calibrated for a period of approximately 1 year, using all available measurement points. The target for the calibration was thus 24 (6 braces x 4 SG) measured stress history curves.

Performing a wave load calibration, based on approximately 1 year's data, is indeed a Big Data problem, as each 1 hour of measurement needs to be represented by the associated 1 hour of prediction, i.e. a continuous 1:1 prediction in the time domain for 1 year measurement data with a down sampled frequency of 20Hz (sampling frequency 128Hz). Due to the iterative nature of

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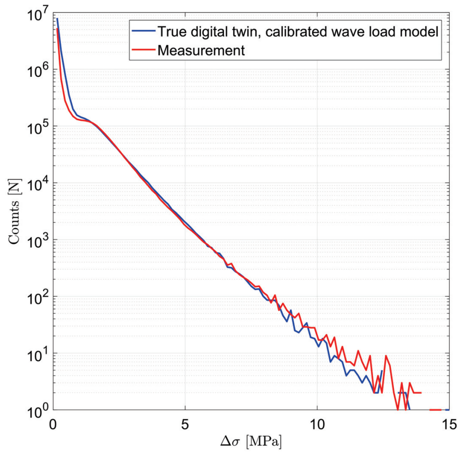

FIGURE 16. Stress history after wave load calibration - strain gauge 4 B.

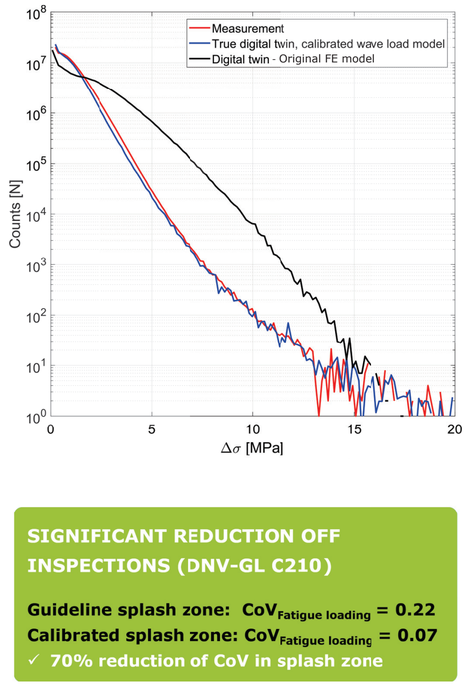

FIGURE 17. Example of reduction of uncertainties (CoV) after execution of Level 1 to Level 4. Bias is calibrated to 1.0.

the calibration process, it demands for extensive computational resources to perform a wave load calibration. A solution to the challenge can only be achieved through the use of High Performance Computing (HPC), in terms of advanced cloud computing set-ups. High performance cloud computing is an integrated part of the wave load calibration toolbox used in the SIMA software.

4.1 Results of the wave load calibration

Calibration of the wave load model, is as mentioned defined as an optimization problem, where the objective is to minimize the discrepancy between the curves representing the measured stress history and the predicted stress history, computed for a specific set of hydrodynamic parameters. Thus, the optimal fit between the stress history curves represents the optimal set of hydrodynamic parameters. The result of the wave load calibration of the current case is illustrated in Fig. 16, which represents 1 out of the 24 resulting stress history curves, after the wave load calibration. Comparing these with the original curves illustrated in Fig. 15 it can be observed that the discrepancy is reduced significantly for the calibrated set of hydrodynamic parameters, removing conservatisms in the wave load prediction.
As the wave load calibration can be performed as a continuous on-line calibration process while gradually obtaining more and more data from the measurements, the progress in the fitting procedure can be followed by observing the asymptotic approach to the optimal set of values for the load parameters.
At this Level 3 of the generation of the true digital twin the prediction models have been improved for prediction of the real fatigue damage. However, the question after Level 3 still remains on how much the models really have improved? A decision (DG-3) has to be made whether to continue to Level 4 or not.

5 Brief - Level 4

At Level 4 the question of how much the prediction models have improved can be answered in terms of quantification of the uncertainties of the updated prediction model performance against measurements. The benefit from continuing to Level 4 is typically only relevant for operators which have requirements for reduction of cost for inspection planning activities. In case the inspection planning is based on Risk- and Reliability based Inspection Planning (RBI) methods, the model uncertainties can be quantified in terms of Bias (typically calibrated to 1.0) and CoV values. The assessment of the uncertainties shall be consistent with the RBI approach as adopted by the operator. The effect of a reduction of the uncertainties of the prediction model in term of reduced CoV values are a reduction in the number of hot spots to be inspected and an increase in the time periods required in between inspections, i.e. a reduction in the numbers of surveys to be performed in the lifetime of the structure. A reduction in the uncertainties typically results in significant reduction of cost for inspections, and in some cases structures have been verified to be inspection free in the remaining lifetime of the structure, i.e. considerably reduction of OPEX costs. This is exemplified in Fig. 17, where the wave load model of the true digital twin has been calibrated against measurements. The calibration of the wave load results in a significant reduction of the uncertainty associated to the fatigue model.

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6 Brief - Level 5

After Level 3 (DG-3) and/or Level 4 (DG-4) a decision can further be made whether to proceed to Level 5. In Level 5 it can be considered to continue monitoring after the updating of the prediction models has been performed. A continuation of the measurements beyond the measurement period required for the actual updating activities (Level 1 to Level 3/4), facilitates for continuous monitoring of the actual accumulated fatigue damage in all elements and joints (hot spots) of the structure. Typically only the accelerometers are required for the continuation of the measurement, i.e. measurements from strain gauges are not required once the prediction models has been updated. On e.g. a bi-yearly basis the fatigue damage can be updated. The advantage of the continuous fatigue monitoring is that the structure is only "punished" by the fatigue damage actually occurring, i.e. any conservatisms in the future load description from codes and standards is gradually removed resulting in even longer lifetime extension. A more detailed description of the Level 4 and 5 will be presented in future papers.

7 Discussion

The previous sections dealt with development of the true digital twin concept for prediction of fatigue damage to marine structures. The concept has the potential to improve the lifetime prediction when reassessing existing structures, as it creates the desirable coupling between the prediction model and the actual condition of the structure. It is therefore suggested to distinguish between a digital twin, which is the initial model employed to represent the actual structural conditions and a true digital twin, where the initial model is updated to represent both the real static and dynamic characteristics of the structure (modal parameters) and the wave loading.

The true digital twin concept, is the only concept providing full insight to the performance of a given prediction model and providing a general methodology to improve its performance. It is obvious, that the costs associated with establishment of a true digital twin increase with the increase in the level of analysis required (Level 1-5). Level 1 and Level 2 can in most cases be performed based on short term measurements from e.g. a 1-day measurement survey with portable equipment, whereas Level 3, Level 4 and Level 5 requires for a permanent installation of a full SHMS set-up.

8 Conclusion

The paper presents a novel approach for evaluation and improvement of the performance of digital twins, employed in the fatigue life prediction of marine structures. The approach is named the true digital twin concept, where the term "true" marks a distinction between a digital twin and a digital twin optimized to capture the real condition of the structure more accurately.

The paper provides an elaboration of the process of establishing the true digital twin by means of 3 case studies, which cover the phases related to the initial performance evaluation of the digital twin (Level 1), the methodology employed for obtaining a true digital twin representing the static and dynamic characteristic (modal parameters) of the real structure (Level 2) and finally the method related to wave load calibration of a true digital twin (Level 3). Each level of analysis is followed by a Decision Gate (DG), at which it is evaluated and decided whether it is required to proceed to the next level or not. The benefit of the introduction of the decision gates is for cost optimization of the process. It can be concluded that the true digital twin concept facilitates for accurate prediction models for fatigue estimation of marine structures. The concept has the potential to increase the fatigue life of existing structures, which are updated to more accurately represent the real structural and environmental conditions for a given marine structure. Most projects performed in the past by Ramboll Oil & Gas have passed the Levels 1-4. A few projects is still ongoing on Level 5.

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