A methodology for development of a digital twin ship

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Abstract. Recently, digital twin has emerged as an alternative technology to predict the structural integrity of ships and offshore structures with good accuracy in real time. An appropriate digital twin for this field of application should consider important aspects such as the harsh environmental conditions and load variations that are induced during the lifetime of the involved components. The behavior of mooring lines, risers and the floating unit compose a complex coupled system, which has to be modeled by the digital twin. A large amount of data can be collected by monitoring systems or inspections. This paper presents a methodology for developing a digital twin ship for a FPSO (Floating Production Storage and Offloading) capable of being coupled with external data and automatically run multiple numerical analyses. The proposed methodology employs a three-cargo tank length model in three dimensions via FEM (Finite Element Method) to receive information, solve the structural analyses and check the results for damage detection on hotspots of the model. This procedure can be applied in different approaches to help on ship operation by checking generated results for several conditions that can be considered with numerous variations of parameters and avoid excessive maintenance proceedings that may have a significant impact on operations.

Keywords: digital twin ship; floating unit structure; three-cargo tank; finite elements

1 Introduction

The offshore oil and gas exploitation industry expands according to the global demand for energy consumption. After ending of the concession period for the oilfield, the decommissioning phase of the installations and facilities or the lifespan extension must occur [1]. The decision between these two options is guided by different analyses in order to do not carry out early decommissioning, and, in case of option for continuing operations, the grant can be expanded by the national government agency after a series of inquiries. The practice of extending exploration of the oilfield requires the implementation of recommendations with risk assessment of the extension of lifetime study. Sometimes the replacement of operating platforms is mandatory, and conditions of the offshore structure are, in most of the cases, essential for the feasibility of the extension life cycle of the production platform, since it is necessary a balanced investment strategy combining costs and profit with the postponement of the decommissioning stage.

The general conception of a digital twin (digital replicas of physical assets) consists of three parts: the physical asset, the digital (or virtual) asset and connections between these two assets to update data coming from the physical system to the digital system, being possible to analyze and make results available to enable more precise prevention or maintenance actions in order to support operations of the physical asset. Over the past two decades, digital twins have been developed and applied with different goals in vessels from many sectors, including oil and gas industry (Danielsen-Haces [2], Grange [3], Bole et al. [4], Renzi et al. [5]) where they are usually called digital twin ships.

This work is restricted to the development of a digital twin ship for a FPSO that performs numerical models via FEM using time-series data as input for static linear structural analysis running in software Ansys Mechanical® and providing results through a DSS (Decision Support System).

2 Monitoring data

2.1 Performance scenarios

The development of a realistic and integrated global model with several systems, interpreting many variables at different stages of the lifecycle is one of the biggest challenges. It is convenient and essential to understand some considerations related to scenarios and needs of offshore platforms. There are important considerations, especially related to the pre-operational (engineering and design) and operations phase, leading to certain determining factors for finite element models created for digital twin ships:

Variable types: random (stochastic process) or predefined by monitoring system (deterministic process).

Frequency of execution: discrete (a single execution of the numerical analysis) or continuous (periodic execution of the numerical analysis).

Data set: single (set of information that represents an instant or condition) or multiple (several single sets).

Simulated time: real (reproduces real time) or predicted (try to evaluate a future event).

DSS response: instantaneous (if simulated time is real) or non-instantaneous (if simulated time is predicted).

For scenarios of operations phase, the variables obtained from the monitoring instrumentation representing an instant of time are expected to be submitted with a certain periodicity of time. Therefore, a single set of data should be regularly received for a structural analysis and, after each numerical simulation, an immediate recommendation from the DSS is required so that any action can be taken, if necessary. On the other hand, for scenarios of pre-operational phase, multiple sets of variables may be submitted for testing, one or more times. However, at this stage, ship management does not necessarily require an instantaneous result or recommendation. Regarding these particularities, Table 1 presents determining factors for the mathematical model (e.g.: finite element model) of a digital twin ship according to lifecycle phase

Table 1. Determining factors for finite element model of a digital twin ship according to lifecycle phase.

	Product lifecycle phase	
Determining factor	Pre-operational	Operations
Variable type	Random	Predefined
Frequency of execution	Discrete	Continuous
Data set	Multiple	Single
Simulated time	Predicted	Real
DSS response	Non-instantaneous	Instantaneous

2.2 Loads

The large amount of variables involved that cannot be estimated by deterministic processes makes designers define loads that represent hypothetical cases for the design of the vessel's structure. Some guides and rules (ABS [6], DNV [7]) address examples of structural loads based on statistical data and mathematical models expected during the ship lifecycle. In this work, the loads are divided into three categories:

Static loads: they can be easily determined (although there is variation in the components related to these loads, such as stored cargo and temperature). Some examples: self-weight (material, machinery and equipment); operational load and internal hydrostatic pressure (caused by stored volume); external hydrostatic pressure (caused by seawater); thermal effect, etc.

Dynamic loads: they are usually a consequence of disturbances due to variations in weather and vessel motion. Some examples: hull pressure (caused by waves); internal and external pressure (caused by slamming and sloshing effects); wind load; inertial loads (due to acceleration from vessel motion); forces from other systems (mooring lines, risers, turret), periodic forces from propulsion system, etc.

Exceptional or accidental loads: they are caused by occasional circumstances in the operational lifetime of vessels (such as stranding, collision and explosions), being more common only for ships more susceptible to impacts (such as icebreakers or military ships). Some examples: ice load; impact load; marine operation loads (during transport, launch, or docking).

The behavior of the sea can be more realistically represented by irregular wave models. Sea state is often described as the power spectrum density, obtained from the time history of the free-surface elevation and that can be interpreted as the decomposition of the irregular sea into a set of regular waves.

Irregular waves can be expressed by parameters of significant wave height (H_s), which is the average height of the highest one-third of all waves measured, and zero-crossing period (T_z), which is the average of the values of the wave periods (T_i). These two parameters can be obtained from sea level monitoring. According to Young [8], significant wave height can be calculated through wave energy spectral density, as presented by Equation 1.

$$H_s = \int F(f)\, df = 4\sqrt{\sigma^2} \tag{1}$$

where, $F(f)$ is the sea spectrum.

As described by Riva [9], in a range of 3 hours, the statistical properties of the sea state can be considered constant and the sea can be called stationary.

2.3 Inspection

Due to the aggressive environment that any offshore structure is exposed to corrosion over the years must be considered. In regards to this issue, some guides and standards are constantly published and revised (ABS [6], DNV [10]) to provide maintenance procedures and suggest corrosion rates according to the region of each structural element. Nominal Design Corrosion Values (NDVC) are recommended by ABS [6] for the design service life of 20 years. In addition, periodic inspections are performed in order to preserve the structural integrity of ships.

3 Methodology

In order to comply with all requirements presented in Section 2, a methodology based on the traditional steps of the Finite Element Method was created. However, by developing algorithms in MATLAB®, pre-processing and post-processing steps were modified with some substeps to receive information from coupled systems, update the FEM model, perform numerical simulation and, process results to provide an overview of the structural integrity on the DSS. Besides, to ensure the automatic work of the process, substeps were classified as varying or definitive. A varying substep stands out for a continuous data flow or information that can be changed or disregarded, allowing execution of multiple and periodic numerical analyses. A definitive substep is performed only once during the workflow, with most of the definitions unchanged during the process. It is important to highlight that all varying substeps are automatically performed by algorithms. A simplified overview of the methodology developed for the digital twin ship is shown in Figure 1 and better detailed in this section.

A1 - Coupled systems: pre-processing step starts with update of data collected from coupled systems, that can be results from other numerical analyses, metaocean conditions, sensors, inspection data, etc. They must provide time-series as input related to loads and inspection according to the performance scenario (as shown in Sections

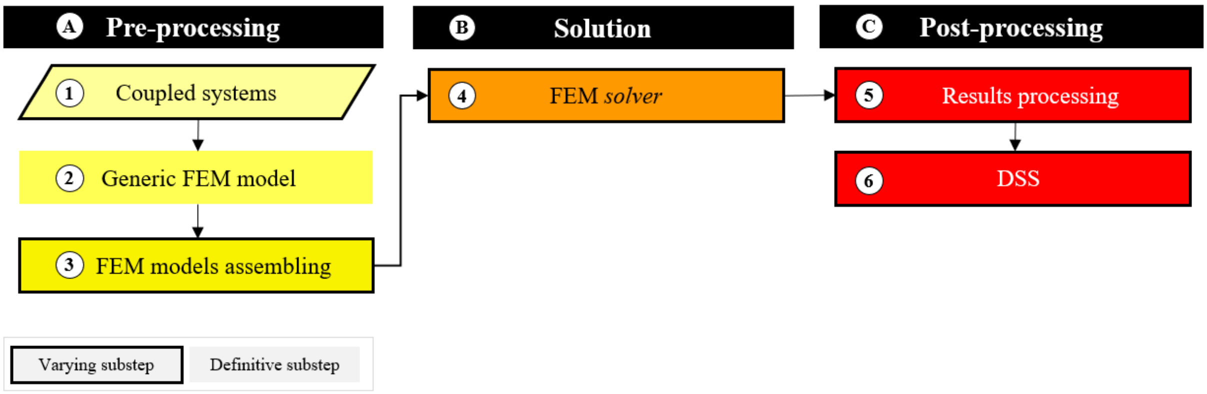


Figure 1. Flowchart of the simplified methodology to comply with digital twin requirements

2). In the case of using coupled hydrodynamic analysis, it must be previously processed. Significant wave height and zero-crossing period are calculated from time-series of sea elevation. These two parameters are used to obtain hydrodynamic hull pressure from phase angle that returns the maximum value of pressure. For other values, as accelerations and forces, for instance, the maximum resultant vector from time series is used to be conservative in the analysis.

A2 - Generic FEM model: a finite element model should be created with all needed boundary conditions to represent loads. If the thickness of plates and cross-sections of beams are intended to be considered by inspection data, these structural members must be modeled as shell and beam elements. Dummy values should be applied to any load or thickness that will be updated from coupled systems data. Then, the input file for the finite element model is generated and dummy values are replaced by unique codes. The defined model with a set of unique codes is called the generic FEM model.

A3 - FEM models assembling: every time coupled systems data is updated, algorithms use generic FEM model to update a set of codes and send single or multiple numerical analyses to the FEM solver.

C5 - Results processing: the results generated by FEM solver are processed and prepared to be used by the DSS.

C6 - DSS: algorithms use data from the previous substep to provide comprehensive interpretation structural integrity of asset based on different results from numerical analyses. Required results and structural members that are above to specified tolerance limits are plotted on software Gmsh (Geuzaine and Remacle [11]) and informed in a text file, allowing more accurate prevention or maintenance actions in the physical ship.

4 Application and results

A generic FEM model was created based on guidelines from ABS [6] that propose recommendations for the construction of a model of three cargo tanks with extension of two frames fore and aft of the two end bulkheads. All primary load-carrying members must be modeled and secondary structural members, which may affect the overall load distribution, also should be appropriately accounted for. The model is composed of 135,424 nodes from 136,117 shell and beam elements, thickness of plates and beams were adopted equals to $10mm$, material properties from structural steel (Young's modulus and Poisson's ratio are respectively $E = 200GPa$ and $\mu = 0.3$). Each tank has 25 meters in longitudinal direction (X-axis) and extension of the model by bulkheads adds up to 20 meters, in Figure 2 is shown isometric view of longitudinal section plane of finite element model and midship section.

The boundary conditions applied in the model are determined by longitudinal elements from fore end and aft end must be rigidly connected to the independent point defined by the centerline and the neutral axis of the section (see Figure 3). Shear forces must be represented by springs (one-dimensional elements having only axial stiffness). Horizontal springs must be connected to the deck and bottom, and vertical springs must be connected to side hull and longitudinal bulkheads. The second end of the springs must be fixed in all degrees of freedom (see

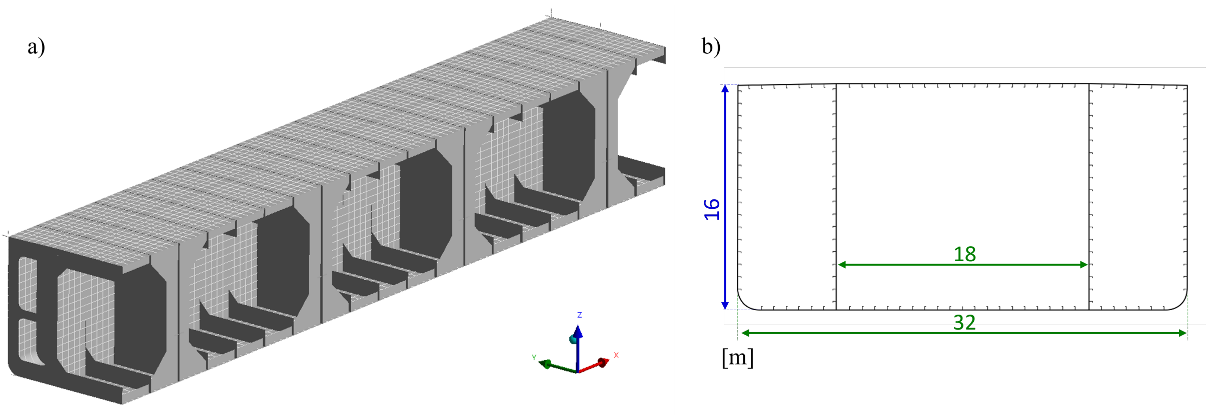


Figure 2. a) Isometric view of longitudinal section plane of finite element model; b) Midship section and dimensions

Figure 3).

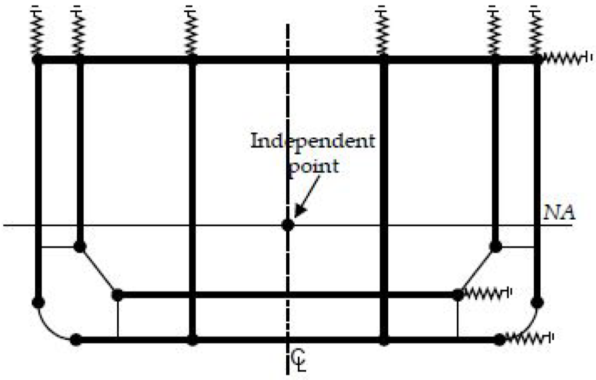


Figure 3. Spring constraints at model ends ABS [6]

Spring stiffness is equivalent to the support given to the considered end bulkhead by the cutout longitudinal structural members. The resulting cross-sectional of springs can be determined by Equation 2:

$$A = \left(\frac{1}{1+\nu}\right)\frac{A_s l}{l_{tk} n} \tag{2}$$

where, A is the cross-sectional area of the spring (represented by one-dimensional element), A_s is the shearing area of the connected individual structural element, μ is the Poisson's ratio of the material, l_{tk} is the length of cargo tank (between bulkheads of the middle tank), n is the number of nodal points to which the spring elements are applied to the connected structural member and l is length of the spring (usually adopted equals to 1m).

For learning purposes, three time-series of 20 minutes each were used to receive coupled systems data: metaocean conditions, storage levels and inspection; total time of data monitoring was 1 hour. Metaocean conditions were used by numerical analyses from software EDTools®(Malta [12]) and Orcaflex® to calculate time-series data of sea elevation (see Figure 4) and vessel acceleration. Besides, a mooring line system composed of nine lines was considered, top tension load on these mooring lines is also included by time-series data received from Orcaflex®. Hydrodynamic analysis were previously processed on WAMIT® (WAMIT [13]) (as mentioned in Section 3). Storage levels of tanks were defined constant in 70%.

To satisfy coupled systems, loads with dummy values were created for hydrostatic pressure, center of gravity and mass moment of inertia of volume of each tank; center of gravity, linear and angular acceleration of vessel.

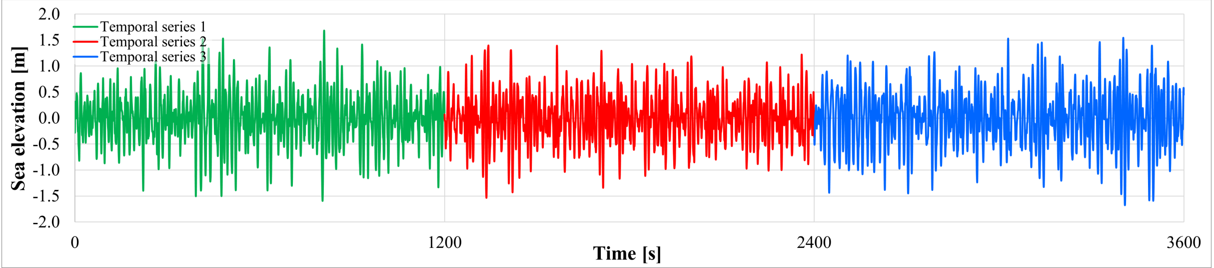


Figure 4. Sea elevation for 1 hour

Self-weight of the hull structure was considered in the analysis. In addition, the top tension load from mooring lines was simplified in a remote force to transfer effects to the model structure.

DSS tolerances values for two levels of alerts were created based on yield and tensile strength of steel according to ABS [14] as shown in Table 2.

Table 2. Alert levels and tolerance values created for DSS.

Tensile properties (ABS [14])		Coefficient	Alert level	Tolerance value
Yield strength [MPa]	235	0.7	1	165
Tensile strength [MPa]	400	0.45	2	180

A numerical simulation was performed for each time-series presented in Table 3 with average computing time of 2 minutes and 50 seconds using 4 cores by a computer that features an Intel® Xeon® E5-1650 v3 @ 3.50GHz, 64Gb RAM, 64-bit Windows OS.

Table 3. Result of significant wave height and zero-crossing period for each time-series.

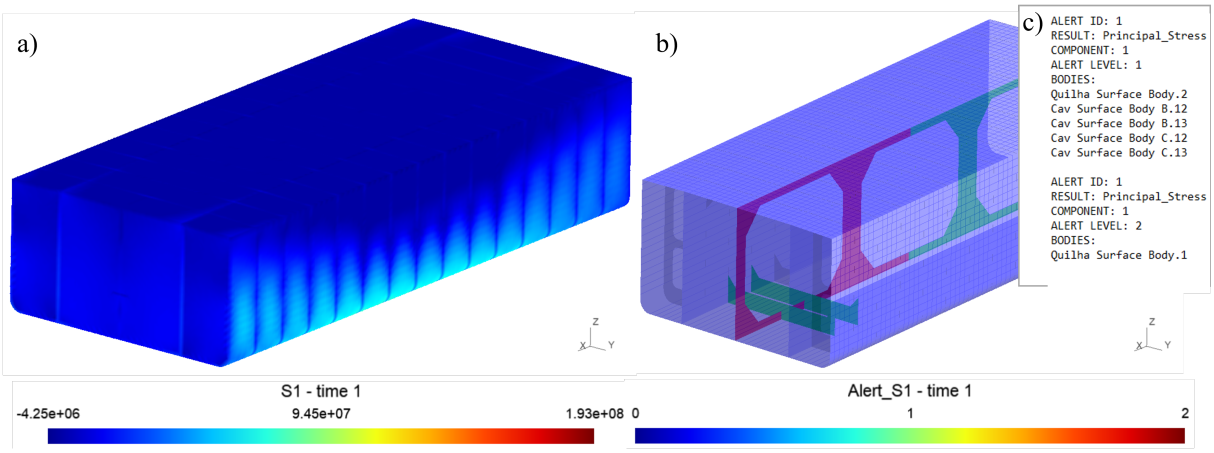
Time-series	1	2	3
H_s [m]	2.0	1.8	2.1
T_z [s]	9.7	9.9	10.9

Alert levels were reached only in the first time-series, DSS reported 6 structural members, one of them above alert level 2 (displayed in red color in Figure 5-b) and the others above alert level 1 (displayed in green color in Figure 5-b).

5 Conclusions

The methodology developed was demonstrated capable to quickly evaluate the structural integrity of a ship. Using a complex model for generic FEM, algorithms could constantly receive external data from coupled systems and automatically solve numerical analyses representing a time span. Even without stress results close to yield or tensile strength, lower tolerance values were assigned to alert levels, verifying the purpose of DSS and promptly providing alerts for decision-making to avoid failures. Another advantage noticed was the easy way to interact and check regions that would need further investigation. Loads related to ship motion, as accelerations, for instance, lead to significant effects in stress results.

Due to the lack of references in the literature, since it is a recent technology, this study should be considered as a first step for the development of digital twin ships focused on structural integrity based on numerical analysis via FEM. The algorithms implemented to the presented methodology are still being improved. Tests using more critical conditions, fatigue analysis based on external data or local analyses should be a step further to this work.



```
ALERT ID: 1
RESULT: Principal_Stress
COMPONENT: 1
ALERT LEVEL: 1
BODIES:
Quilha Surface Body.2
Cav Surface Body B.12
Cav Surface Body B.13
Cav Surface Body C.12
Cav Surface Body C.13

ALERT ID: 1
RESULT: Principal_Stress
COMPONENT: 1
ALERT LEVEL: 2
BODIES:
Quilha Surface Body.1
```

Figure 5. DSS results for time-series 1: a) Maximum principal stress plotted on Gmsh; b) Alert levels for structural members plotted on Gmsh; c) Text file informing structural members

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References

[1] ANP, 2019. Relatório anual de segurança operacional das atividades de exploração e produção de petróleo e gás natural - 2019. Technical report, Agência Nacional do Petróleo, Gás Natural e Biocombustíveis.
[2] Danielsen-Haces, A., 2018. Digital twin development: condition monitoring and simulation comparison for the revolt autonomous model ship. Master's thesis, Norwegian University of Science and Technology.
[3] Grange, E., 2018. A roadmap for adopting a digital lifecycle approach to offshore oil and gas production. *Offshore Technology Conference*, vol. , pp. 15.
[4] Bole, M., Powell, G., & Rousseau, E., 2017. Taking control of the digital twin.
[5] Renzi, D., Maniar, D., McNeill, S., & Del Vecchio, C., 2017. Developing a digital twin for floating production systems integrity management. *Offshore Technology Conference*, vol. , pp. 8.
[6] ABS, 2020. *Rules for building and classing - Floating production installations*. American Bureau of Shipping, USA.
[7] DNV, 2014. *Environmental conditions and environmental loads - DNV-RP-C205*. Det Norske Veritas, Norway.
[8] Young, I., 1999. Chapter 9 - ocean wave measurement. In *Wind Generated Ocean Waves*, volume 2 of *Elsevier Ocean Engineering Series*, pp. 227–254. Elsevier.
[9] Riva, I., 2004. Análise de fadiga em estruturas metálicas com ênfase em offshore. Master's thesis, UFRJ, Rio de Janeiro, RJ, Brasil.
[10] DNV, 2015. *Thickness diminution for mobile offshore units - DNVGL-CG-0172*. Det Norske Veritas, Norway.
[11] Geuzaine, C. & Remacle, J.-F., 2009. Gmsh: A 3-d finite element mesh generator with built-in pre- and post-processing facilities. *International Journal for Numerical Methods in Engineering*, vol. 79, n. 11, pp. 1309–1331.
[12] Malta, E. B., 2010. Métodos e processos para a análise experimental de sistemas oceânicos de produção de petróleo e gás. Master's thesis, Engenharia Naval e Oceânica da Escola Politécnica da USP.
[13] WAMIT, 2018. Wamit user manual 7.3. Technical report, WAMIT Inc.
[14] ABS, 2021. *Rules for Materials and Welding - Part 2*. American Bureau of Shipping, USA.