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Approaches and Challenges in FEED and Detailed Design Process of Floating Substructures

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Abstract. In the FEED or detailed design phases, the floating foundation designers have to deal with complex structural design aspects and meet certification or class requirements for structural verifications, such as yield and buckling checks as well as fatigue checks for steel structures. The designer faces several challenges during the structural verification process, starting with the accurate definition of the complex external load state with the simultaneous action of aerodynamic, hydrostatic and hydrodynamic loads, inertia and mooring loads, followed by the processing and handling of very large load case tables required for the analysis of floating wind turbines, down to time efficient post-processing of the analysis results compatible with typical commercial project schedules. The paper discusses some of the currently existing and applied methodologies on how the structural checks are typically performed in these circumstances, and addresses their advantages and shortcomings. In addition, a new Global Influence Superposition (GIS) methodology that has been developed by Ramboll is presented, which is able to address many of the existing challenges in an efficient manner.

1. Motivation

In recent years, there has been a significant increase in the number of floating offshore wind concepts attempting to achieve higher Technical Readiness Levels. When entering the FEED (Front-End Engineering) or detailed design phase, which is typically associated with a certification process, the requirements, e.g. on the scope of analyses, accuracy of numerical models and methods, consideration of relevant physical effects, etc., increase significantly. Available methods and analysis approaches from bottom-fixed wind turbines or O&G industry cannot be directly transferred to floating wind turbines. Limited budgets and tight schedules by which the designers are constrained in typical commercial projects dictated the need for a fast and efficient design approach. A quick look at existing methodologies currently applied in the industry reveals that few, if any, provide the required level of accuracy and/or efficiency to serve commercial projects. With an increasing number of floating offshore wind concepts now moving from the conceptual design phases towards certification, the absence of a holistic and efficient structural analysis approach that at the same time satisfies the requirements for accuracy and fidelity is becoming a major challenge in the industry. Such an approach should fulfil the following requirements:

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- It must be sufficiently *accurate* for more detailed design levels. Relevant physical effects should be properly considered without having the need to make (too) conservative assumptions, thus allowing for optimized structural designs.
- It must be *accepted* by Certification or Class. It must therefore be able to provide all the results that are required to comply with the requirements set out in the relevant Rules and Standards.
- It must be *efficient* and robust, enabling quick design iterations within the typical timeframes required for commercial projects.
- Ideally, it must be *flexible*, i.e. applicable for different substructure types (semi-submersibles, SPAR, TLP, etc.) or materials (steel/concrete). The flexibility of the approach would allow it to be widely applied, contributing to the objective of gaining acceptance by Certification or Class and contributing to a smooth approval process.

In practice, to be sufficiently accurate and acceptable for FEED or detailed design, the approach must handle a very large set of Design Load Cases (DLCs), analyzed in coupled time domain simulations, with typically millions of time steps being analyzed [1]. The ULS/ALS verifications should be carried out in accordance with the state of the art, for the entire structure, and it is often difficult to justify focusing on just a few supposedly critical areas. The FLS analyses must be performed for a very large number (thousands) of fatigue hot-spots, working on fine FE meshes and performing analyses in the time domain.

2. Common Challenges in a Typical Structural Analysis Process

The analysis process of a floating offshore wind turbine typically starts with the global response or Integrated Loads Analysis (ILA) using software like OpenFAST, OrcaFlex, Sima or Bladed. The floating system is represented here by a coupled aero-servo-hydro-elastic model and includes the wind turbine, the controller, the substructure and the mooring system. Handling the large number of DLCs is no longer a challenge for ILA, given the possibilities of cloud computing. However, the floating substructure is typically represented in a simplified way as a rigid radiation/diffraction body or a simplified Morison beam model, which is sufficient for global response analysis but hardly suitable for structural checks at FEED or detailed design level [2]. The ILA results do not include information on the distribution of hydrostatic and hydrodynamic pressures on the hull and – as there is no accurate structural model – do not include accurate stresses in the substructure. For that reason, the stresses are typically calculated in a subsequent step, using an accurate structural model (typically shell-type FE elements) and general FEA software.

All the loads contributing to the state of dynamic force equilibrium must be transferred from the ILA model to the structural FE model. For some of the load components, such as mooring line loads, tower or turbine interface loads, acceleration loads, the load transfer is evident. Other load components, such as hydrostatic and hydrodynamic pressure loads, are not directly available from the ILA results and must be reconstructed and "mapped" from the hydrodynamic ILA model to the elements of the structural FE model.

When a radiation/diffraction hydrodynamic model is used in the ILA, the reconstruction of radiation and diffraction pressures requires a fairly complex mathematical process but is relatively straight forward in theory [3]. In practice, however, an efficient implementation of this process is challenging considering the number of timesteps to be processed. For other pressure components, such as pressures due to non-linear viscous drag or 2^{nd}-order wave loads, or when a simplified hydrodynamic model with Morison beam elements is used in the ILA, a physically correct pressure representation is generally not obvious. In practice, applied pressure distributions are often based on experience and are relatively arbitrary.

Another problematic area associated with pressure mapping relates to tank loads. In the ILA, tank contents are typically represented by mass points. Similarly, in the structural FEA model, the tank mass is often distributed and attached to the relevant nodes as mass points. This modelling approach appears to be oversimplified and ignores the physical aspects of the tank contents being a fluid rather than a solid body. A representation of the gravity and inertia loads by pressure distributions would be more accurate.

In the structural FE analysis itself one challenge relates again to the very large number of time steps to be analysed, leading to long calculation times and difficult data handling. The other more significant one lies in the post-processing of this very large amount of FE results. This includes e.g.:

- For ULS/ALS:
  - Calculation of seed average stresses to be used as characteristic values following DLC-specific averaging procedures defined by Standards.
  - Evaluation of the highest stresses for yield checks across the structure, e.g. by compiling an "envelope" stress solution in which the highest stresses from all time steps are included.
  - Implementation of rule-based buckling checks (e.g. for shell buckling or buckling of plated structures), incl. definition of critical load combinations (e.g. critical stress and pressure components).
- For FLS:
  - Definition of hot-spots incl. paths for stress extrapolation, S-N curve details, etc.
  - Implementation of FLS checks following the procedures defined by the Rules, including advanced methods such as multi-directional fatigue analysis.
- Identification of design driving DLCs to facilitate the design process.

Given the sheer volume of data, designers must rely on sophisticated and very flexible tools to automate post-processing. However, tools that fully meet the above requirements are not a matter of course, encouraging designers to develop in-house solutions.

In general, it can be concluded that the biggest common challenge in the design process is the ability to handle a very large number of time steps in an efficient and accurate manner.

3. Review of Possible Approaches

There are currently many different approaches to dealing with the challenges described above. Many approaches are concept specific and use simplifications that are only acceptable for that specific floater concept, but not in general. Hence, there is currently little technological convergence in this area, which in practice leads to a more difficult certification process and a high level of uncertainty in the design, which is at best too conservative and at worst unsafe. Some selected approaches, without claiming to be exhaustive, are presented in the following paragraphs.

3.1. Approach #1 – Design Based on Cross-Sectional Loads

In this approach, the substructure model in the global response analysis (ILA) is composed in such a way that it allows to obtain some internal forces (cross-sectional loads) in the hull. The general idea is that the knowledge of the internal forces will help to identify the most critical time steps within the ILA simulations. This eliminates the need to process millions of time steps in load mapping, FE calculations and post-processing for the ULS/ALS analyses. The substructure model can consist of beam elements (Morison elements) only [4] or be a segmented radiation/diffraction model, where the different segments are connected to a beam skeleton [5].

The *advantages* of this method are:

- Early knowledge of internal loads, even if only indicative, is very useful for initial structural sizing. It can be used in the beginning of the structural design process to define, based on hand calculations, the initial structural layout, wall thickness and cross-sections.
- The number of calculations for ULS is drastically limited. Load mapping and FE calculations are only performed for a limited number of selected critical time instances. This allows post-processing to be carried out manually using conventional tools, without the need for special tools that allow automated bulk processing.

- The elasticity of the model introduced through the beam elements allows for the consideration of structural dynamics, such as resonance effects, of the substructure hull.

However, this approach also has significant *drawbacks*:

- It is not very flexible, i.e. applicable to any type of hull geometry. While the use of Morison elements or skeleton beams is well suited for lattice-type structures, it can be difficult to apply to large volume structures.
- In practice, for most geometries, it is very difficult to calculate the internal forces accurately, mainly due to the following reasons:
  - The structures are often complex, especially in the area of connections of main elements (e.g. pontoon-to-column connections), with complex deformation behavior that is difficult to sufficiently approximate with standard beam elements. Correct modelling of the structural stiffness in these areas is very important, especially in statically overdetermined beam models. This problem can be solved by modelling these connections with super-elements (which is practiced for example in the design of bottom-fixed jacket foundations), but super-elements are often not available in the current global response analysis programs for floating substructures.
  - Another problem relates to the modelling of the hydrostatic loads on the hull segments (i.e. each individual beam or radiation/diffraction body segment), including variable hydrostatic stiffness loads due to heave, roll and pitch motion. Usually, these loads are calculated by multiplying the 3x3 hydrostatic stiffness matrix by the 3x1 displacement vector. In the segmented models, there are interfaces between the segments where there is no hydrostatic pressure acting on them. This fact requires consideration of additional coupled terms in the hydrostatic stiffness matrix (e.g. x-force due to z-displacement), which becomes a 6x3 matrix. In practice, this hydrostatic problem is not addressed in a typical ILA model [6]. The impact of the hydrostatic loads on the calculated internal forces can be significant.
- Critical time instances for further FE-based ULS analysis are typically identified based on cross-sectional loads at selected locations (e.g. tower interface, hull sections, etc.). Ensuring that time instances with highest loads at these selected locations correlate with the overall design driving load conditions for the entire structure is difficult to facilitate in practice.
- For the FLS analysis, the internal force time series are then often fed into local FE models for subsequent hot-spot analysis. Correctly accounting for external hydrostatic, hydrodynamic and tank pressures in these local models can be challenging (see also discussion on Approach #3).

3.2. Approach #2 – FE Analysis in Every Time Step

The idea is to perform the load and pressure mapping and the FE analysis for *every* time step of the global response analysis. To make this task manageable, the following measures are usually taken:

- Computational power is increased through cloud computing, parallel processing, etc.
- Each individual analysis is accelerated by reducing the FEA effort. This is usually achieved by reducing the size of the FE model (coarser meshes). Less common in floating wind industry, but generally possible, is the use of alternative solver algorithms, such as Reduced Basis FEA (RB-FEA) [3].

The *advantages* of this method are:

- Accurate load modelling including global and local influences is achieved by performing load and pressure mapping at each time step. It is important to note that *all* loads that contribute to the state of dynamic load equilibrium in the global response analysis should be transferred to the structural analysis model. Neglecting load components leads to unbalanced loads and distorted calculated stresses resulting from support reactions or artificial correction loads (e.g. inertia relief). Therefore, load balance, support reactions and correction loads should be carefully monitored during the analysis process.

- Calculation of stresses in the FE model in *all* time steps guarantees that all stress peaks are captured in the ULS/ALS analyses. Furthermore, it provides the required time series of stresses for the FLS analyses.
- The method is very flexible, i.e. applicable to any type of hull geometry.
- Some tool chains that follow this approach are able to perform not only quasi-static but also dynamic structural analysis, ensuring that the effects of hull resonance are taken into account.

The *disadvantages* are:

- Speed-up of the FE analyses is often achieved by using relatively coarse meshes in the global FE model. This becomes a necessity for the computational feasibility of the approach. For FEED or detailed design projects with the required high level of accuracy, such FE models may not be sufficient. Especially for FLS, where the size of FE elements near fatigue hot-spots is defined by Standards, a reduction of the total number of elements would mean that only a very limited number of hot-spots can be considered, which is again insufficient at these detailed levels. On the other hand, the use of local sub-models with higher mesh resolution leads to an increased FEA effort and compromises the feasibility and the holistic principle of the approach.
- Despite cloud and parallel computing, the computation time, required storage capacity and the associated costs are usually significant.

3.3. Approach #3 – Influence-Matrix-Based FE Analysis Using Local FE Models

In this approach, the computational effort for load mapping and FE analysis is reduced by applying unit loads on local FE models. The substructure model in the global response analyses is composed in the same way as in Approach #1, using beam elements and allowing for extraction of internal forces. In FEA, only *local* models are analysed, e.g. a local model of the column-pontoon connection in a semi-submersible. Instead of mapping the loads from the ILA model to the FE model at each timestep (as done in Approach #2), only a small number of Unit Load Cases (ULCs) are analysed in FE, which include unit forces and moments applied at the interfaces of the local model to the rest of the structure. From each ULC analysis, stress components (stress tensors) are extracted and combined into a matrix called the *Influence Matrix* (IM). This approach is therefore called the *IM-based approach*. The time series of internal forces and moments are then extracted from the beams in the ILA model at the positions corresponding to the FE model interfaces. The resulting load vectors are combined into a load matrix, which is then multiplied by the stress IM to obtain time series of the stress components in each element at all time steps.

The *advantages* of this method are:

- Stress calculation is very efficient, as it is reduced to a matrix multiplication.
- Large FE meshes with fine discretization can be managed to meet the requirements on the accuracy of stress calculation defined in the Standards (e.g. for FLS).
- Structural dynamics are taken into account with this approach to a certain extent, as the associated loads are included in the beam cross-sectional loads of the ILA model.

The *disadvantages* of this method are:

- Same as those in Approach #1, related to the use of beams in the global response analyses (applicable only to certain types of substructures, internal forces may be inaccurate).
- The load modelling can be oversimplified as only interface loads are considered. In the ILA, all loads acting on the local part of the structure are in dynamic equilibrium. The load components contributing to this equilibrium are the cross-sectional loads at the interfaces, but also local loads such as hydrostatic and hydrodynamic loads, inertia loads (resulting from the mass of the local model), tank loads, etc. These local loads are mostly ignored in this approach, which has two negative effects on the calculated stresses: 1) there will be unbalanced loads in the FE analysis (after scaling and superposition of the ULCs), leading to

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support reactions or requiring correction loads (e.g. inertia relief) that are likely to be unrealistic, and 2) local loads are often relevant for local stress states, e.g. local pressures can contribute significantly to the bending stresses in the outer plates and are important to consider for fatigue hot-spots in these areas.

- The approach is not holistic, but requires multiple local FE models, which can be difficult to handle efficiently in the design process. In addition, modelling inaccuracies at the boundaries of the local FE models must be taken into account.

4. Global Influence Superposition Methodology

After dealing with the different approaches (mostly variations of the above in Sections 3.1 to 3.3) in many projects and understanding their advantages and drawbacks in engineering application, a new Global Influence Superposition (GIS) methodology has been developed at Ramboll. The methodology takes advantage of the very effective stress calculation of the IM-based Approach #3 but applies this approach to a *global* FE model, taking into account *all* load components that contribute to the state of dynamic load equilibrium. In the following sections, the main principles of the methodology are explained. Ramboll has recently been selected by Fred. Olsen 1848 as independent engineering consultant to support the next design phase of their BRUNEL floating foundation, see Figure 1, which is used in the following sections to illustrate the application of the methodology.

4.1. Global Response Analysis Model for GIS

An important feature of the global response analysis model for GIS is a relatively fine subdivision of the hull into a number of segments, each modelled as a separate radiation/diffraction body, see Figure 2. The hydrodynamic loads on the segments are calculated separately using the potential BIEM theory [7] and taking into account the hydrodynamic interaction of the segments.

Figure 1. BRUNEL floating foundation by Fred. Olsen 1848.

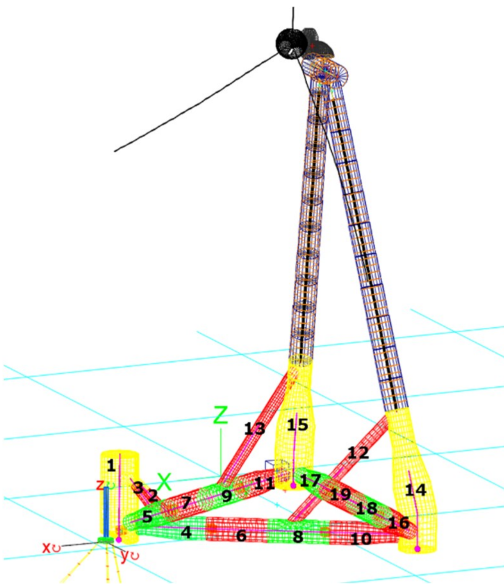

Figure 2. Global response analysis model with subdivision of the hull into 19 segments.

As a result of the global response analysis, the integrated hydrodynamic loads (wave radiation and diffraction loads, 2^{nd}-order wave loads, drag loads) on each hull segment are available separately, providing an understanding of how they are distributed over the hull. In contrast, for a single body model only the total integrated hydrodynamic load on the entire hull would be available from the analysis results.

The hull segments can be either rigidly connected to each other or to flexible skeleton beams, depending on whether the consideration of the structural dynamics is relevant or not. The cross-sectional properties of the beams should be calibrated with modal analysis results obtained from a shell FE model, to ensure that the important structural eigenmodes are adequately captured in the global response analysis. It should be noted that the skeleton beams are only used to reproduce the global stiffness of the hull, they are not used to calculate section loads for the reasons explained in Section 3.1.

4.2. IM-Based Load and Pressure Mapping

All the loads contributing to the state of dynamic force equilibrium in the global response analysis must be transferred from the ILA model to the structural FE model (load and pressure mapping). In the Approach #2 described above, the loads are transferred for the *individual* time steps. In each time step, pressure fields, e.g. for the wave diffraction forces, are reconstructed and applied to the FE model. This load mapping technique is referred to as Direct Load Mapping (DLM).

The GIS method uses a different, IM-based load mapping technique where the hydrodynamic pressures are reconstructed segment-wise and in a simplified manner, approximating the pressure distribution obtained by the Direct Load Mapping. More details on this simplified IM-based pressure reconstruction are provided below. The accuracy of this approximation increases as the hull segmentation becomes finer in the ILA model. With the segmentation shown in Figure 2, a high accuracy is achieved.

As outlined in Section 3.3, the stresses in an IM-based method are calculated by multiplying the stress influence matrix (IM) by the load matrix or, more generally, by a matrix of scaling factors for the unit loads. An important aspect is that these scaling factors can be easily obtained from the ILA results without significant numerical effort. In contrast to the Approach #3, in the GIS method, the stress IM is calculated using a global hull model in FE, with a sufficiently fine mesh discretization. The Unit Load Cases (ULCs) used to derive the stress IM, include all relevant load components required to reconstruct the state of dynamic load equilibrium of the global response analysis at each time step:

- ULCs for concentrated loads (mooring loads, tower or turbine interface loads)
- ULCs for acceleration loads (gravity, inertia loads due to rigid and flexible body accelerations)
- ULCs for pressure loads (hydrostatic, hydrodynamic pressures, tank loads)

Each of these load components is represented by either one or more ULCs. The (integrated) loads in the respective ULCs multiplied by the respective unit load scaling factors must equal the load component that is represented. Consequently, the sum of all ULCs, scaled by their unit load scaling factors and superposed, must be in equilibrium for the global FE model at each time step, as is the case for the loads in the global response analysis.

Keeping track of this load balance is important in both steps of the load mapping process: when the loads are extracted from the global response analysis, and when the unit load scaling factors are calculated. Only by maintaining the load balance is it possible to ensure that the stresses are calculated accurately, i.e. that there are no unbalanced support reactions in the FE model, nor massive load corrections (i.e. inertia relief) applied.

The concentrated loads and the rigid body acceleration loads can be easily represented by ULCs, i.e. the definition of ULCs for these loads is evident. The pressure loads, in particular the hydrodynamic pressures, are more complex. In the GIS methodology, the complex distribution of the hydrodynamic pressures is approximated as follows:

- The hydrodynamic model of the substructure in the global response analysis model is divided into relatively small segments, see Figure 2.
- The hydrodynamic pressure patterns on each individual segment are described by the superposition of one *uniform* pressure field and several *gradient* pressure fields (up to 6, depending on the geometry), referred to as Unit Pressures.

In a simple load state, it may be sufficient to approximate the hydrodynamic pressures on a single segment by a linear pressure field. This linear field is represented as a linear combination (i.e. superposition) of three unit pressure fields where the pressure increases linearly with a gradient of 1 in the directions of the three axes of the reference coordinate system (*gradient* pressure fields) and one field where the pressure is constant at 1 (*uniform* pressure field). By assigning scaling factors to these four unit pressure fields, any linear pressure field can be represented as a linear combination of these four fields. The four scaling factors can be derived from the three components of the force vector acting on the segment and considering one integration constant that follows e.g. from the pressure at one point on the segment. Both, the resulting force (three degrees of freedom) and the value for determining the integration constant (one further degree of freedom) are obtained from the ILA results.

If the load state acting on the considered segment is more complex and cannot be described in the selected reference coordinate system by a resultant force vector (three degrees of freedom) alone, but requires additional degrees of freedom (resultant moments), then additional unit pressure fields are introduced. These pressure fields must be linearly independent of the previous ones and their integration must produce moments with respect to the chosen reference coordinate system. These pressures are also referred to as *gradient* unit pressures in the terminology used.

The exact formulation of the unit pressure fields should be based on the physical description of the load component considered and can be individually adapted to it.

Figure 3 shows an example, where four gradient unit pressure fields are used to represent the hydrodynamic loads on a hull segment, each resulting in an integrated load in predominantly one degree of freedom (DOF) in the selected reference coordinate system. Due to the cylindrical shape, there are no hydrodynamic loads in DOFs 1 and 4, so the four gradient pressure fields, scaled with appropriate load scaling factors, are sufficient to represent any load state.

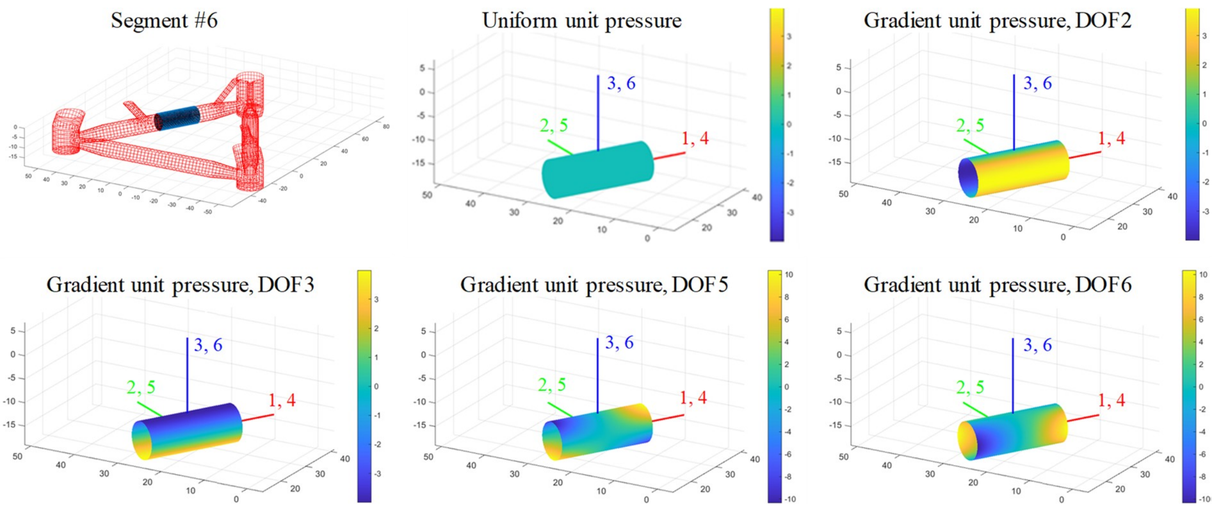

Figure 3. Definition of the Unit Pressure fields for the representation of hydrodynamic wave loads on hull segment #6 (example)

The *uniform* pressure field, for the example in Figure 3, gives an integrated load that is zero, so it does not contribute to the integrated hydrodynamic load on the segment. However, this pressure field is required to replicate a physically realistic pressure distribution across the hull. The load scaling factor for the uniform pressure field is found by calculating the instantaneous *mean* diffraction pressure (mean value over all panels of the segment) at each time step of the global response analysis. The calculation is based on the *mean* values of the diffraction pressure RAOs from the radiation/diffraction analysis and requires only little numerical effort.

A quality measure for the physically realistic approximation of the hydrodynamic pressures in the GIS method is that the pressure patterns on the whole hull derived from the scaling and superposition of the ULCs are similar to the Direct Load Mapping at each time step of the global response analysis. This has been successfully demonstrated in verification studies, see example in Figure 4, where the pressure distribution from GIS is nearly identical to that from DLM, with only minor discontinuities at the boundaries of the hull segments (one example is marked with black rectangle).

The *gradient* pressure fields can be used to represent not only the 1st-order wave diffraction loads, but also other hydrodynamic load components, such as wave radiation loads, non-linear viscous drag and 2nd-order wave loads.

Figure 4. Example comparison of combined wave diffraction, viscous drag and 2nd-order wave pressures reconstructed by DLM (left) and GIS methodology (right). Only minor discontinuities at the boundaries of the hull segments can be seen in GIS (example marked with rectangle).

The tank contents are modelled in the global response analysis by mass points with inertia attached to the substructure. In this way, time series of static and dynamic loads (due to acceleration and roll/pitch motion) acting on each tank are available and used as unit load scaling factors. In the structural analysis, the tank loads are represented by internal pressures. The distribution of the static tank pressures is evident. For the dynamic tank loads, similar to the wave pressures (Figure 3), 6 *gradient* unit pressure fields are used to represent the 3 forces and 3 moments acting on the tank. In this way, tank loads are modelled in a much more physically realistic way than, for example, by using masses lumped to the FE nodes.

The structural dynamic loads (i.e. internal modes of the substructure) can be considered within the GIS method as long as the elasticity of the structure is considered in the global response analysis, e.g. by attaching the radiation/diffraction segments of the hull to a beam skeleton. Due to the structural dynamic effects, all segments will have different accelerations that deviate from the rigid-body accelerations. In order to transfer the associated inertia loads to the structural FE model, additional ULCs are composed where unit accelerations are applied only to those elements of the FE model that belong to the hull segment considered. The load scaling factors for these ULCs are the actual accelerations of the respective hull segment obtained from the global response analysis.

4.3. Model and Result Examples

In Figure 5 examples of the global FE meshes for ULS and FLS are shown that have been processed with the GIS method.

Some examples of post-processing results are shown in Figure 6. The “envelope” von Mises stress solution (a) visualises the maximum stresses from all time steps of all DLCs. The plot of the governing DLCs (b) identifies the design load cases resulting in highest stresses, which is very helpful in the design process. Rule-based buckling checks, e.g. shell buckling (c), are performed on a reliable basis of the most critical compressive stress components calculated with the GIS methodology. Fatigue damages in over 6000 hot-spots (d) are calculated based on the global FE model and full stress time series derived from global response analysis.

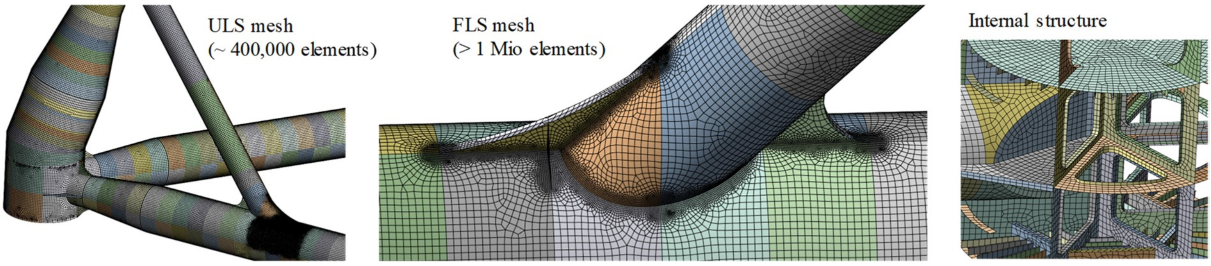

Figure 5. Examples of the FE meshes processed with the GIS method.

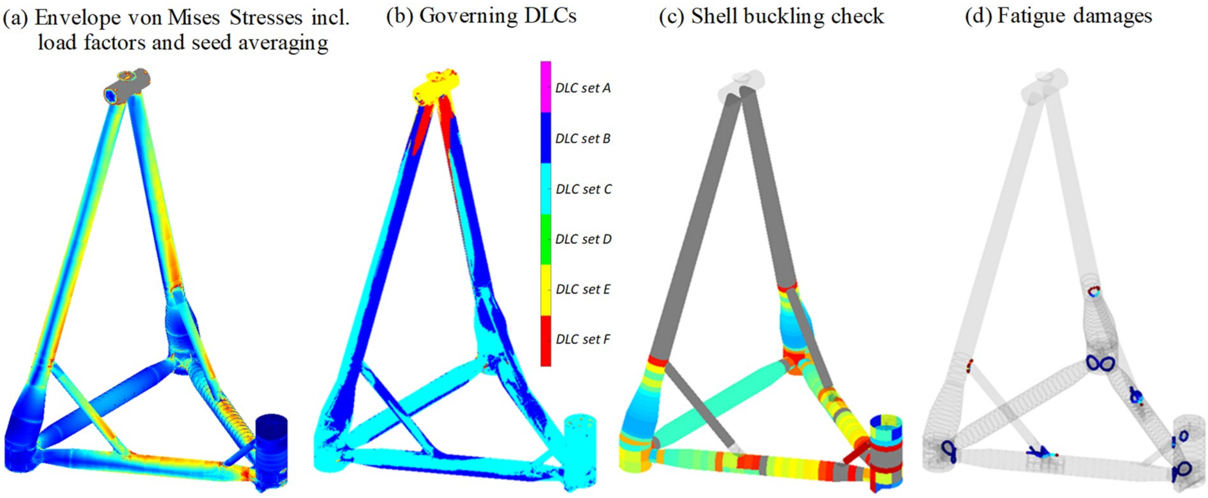

Figure 6. Examples from the post-processing based on GIS method.

5. Conclusions

In the design process of floating substructures on FEED and detailed design levels the key challenge was identified in the efficient handling of a very large number of time steps throughout the entire analysis process including global response analysis, load mapping and detailed structural FE analyses and verifications according to Standards, especially following the requirements for FLS. In the currently existing and applied structural design approaches there is only little technological convergence. Many of them are limited to specific substructure concepts, applying individual simplifications only acceptable for a specific design.

Selected structural design approaches were presented with their advantages and shortcomings: the Approach #1 using cross-sectional loads obtained directly from the ILA model, the Approach #2 based on Direct Load Mapping and FE analysis in every time step, as well as the IM-based Approach #3 using on local FE models. All approaches were found to have drawbacks that make them not well suited for use in FEED and detailed design projects, as they do not provide the required level of accuracy and/or efficiency.

A new Global Influence Superposition (GIS) method developed by Ramboll was presented, which works with stress influence matrices on the global FE model and considers all load components contributing to state of dynamic load equilibrium, including pressure loads being represented segment-wise by unit pressure fields. The method can be applied to any type of hull geometry and is able to address many of the challenges in an efficient manner. It has been successfully demonstrated and verified in a commercial project.

Acknowledgments
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References

[1] Kvittem M I and Moan T 2015 Time domain analysis procedures for fatigue assessment of a semi-submersible wind turbine *Marine Structures* 40. 38-59
[2] Cordle A and Jonkman J 2011 State of the art in floating wind turbine design tools *Proceedings of the Twenty-first (2011) International Offshore and Polar Engineering Conference*
[3] Knezevic D, Pinguet R, Martin B, Peterson J, Podskarbi M, Price S and Vallaghe S 2022 Validation of a Fully Integrated Numerical Simulation Method to Assess Structural Integrity on a Flexible Model of FOWT Using RB-FEA *Proceedings of the ASME 4th International Offshore Wind Technical Conference* V001T01A021
[4] Thomsen J B, Bergua R, Jonkman J, Robertson A, Mendoza N, Brown C, Galinos C, Stiesdal H 2021 Modeling the TetraSpar Floating Offshore Wind Turbine Foundation as a Flexible Structure in OrcaFlex and OpenFAST *Energies*, 14, 7866
[5] Engebretsen E, Haslum H and Aagaard O 2020 Distributed Potential Theory and its Application for Spar-Type Floating Offshore Wind Turbines *Proceedings of the ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering* (*Offshore Technology* vol 1) V001T01A062
[6] Guignier L, Courbois A, Mariani R, and Choisnet T 2016 Multibody Modelling of Floating Offshore Wind Turbine Foundation for Global Loads Analysis *Proceedings of the 26th International Ocean and Polar Engineering Conference*
[7] Lee C-H 1988 Numerical methods for boundary integral equations in wave body interactions PhD Thesis MIT