



OC7 Project Phase II: Comparison of Global-to-Local Load Transfer Approaches in Floating Structures

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20 **Abstract.** Global-to-local load transfer remains a critical – yet largely unstandardized – step in the structural assessment of floating structures. This paper presents the results of package WP2.2 from the OC7 project Phase II, establishing a cross-industry benchmark for the workflows connecting global performance analysis (based on integrated loads analysis, ILA) and the local structural assessment (based on finite-element analysis, FEA). The study evaluates a spectrum of industry practices, including sequential approaches with the FEA following the ILA, fully integrated time-domain approaches with hydro-structural coupling, and simplified ILA-only approaches. Using the VoltturnUS-S reference semi-submersible, the models were first harmonized through mass/inertia, static, and modal verifications. Structural responses were then compared across three primary scenarios: topside-only excitation, irregular waves, and combined wind/wave loading. The results establish a structured comparison framework, highlighting how specific modelling choices and load transfer techniques directly influence confidence in design processes. The findings offer practical guidance to reduce uncertainty in "global-to-local" design workflows.

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1 Introduction

The Offshore Code Comparison Collaboration 7 (OC7) project is a large-scale international collaboration conducted under the International Energy Agency (IEA) Wind Technology Collaboration Programme (TCP) Task 56. Its objective is to
35 advance engineering-level, physics-based modelling tools and establish best practices for offshore energy systems (IEA Wind TCP, 2025).

Phase II of the OC7 project is structured into two work packages: WP2.1 (lead by the National Laboratory of the Rockies, not in scope of this paper) covering analysis of member-level loads within a floating substructure (Bergua et al., 2026), and
40 WP2.2 (lead by Ramboll, focus of this paper) dedicated to validation of the load transfer from global system-level simulations to detailed local structural models (further referred to as “global-to-local” load mapping). This process is critical for assessing structural integrity, especially in floating structures where uncertainties are greater. While global design and global performance analysis of floating systems has become a mature technology over the last years, moving from the global system level to local stress level design remains a challenge. The industry stakeholders are concerned about ensuring the consistency and reliability of this process and seek to enhance their understanding of it. WP2.2 aims to increase industry
45 confidence in the global-to-local analysis workflow by promoting consistency, clarity, and accuracy through shared modelling strategies and verification activities, using simulation data from participants to compare the different models and workflows in a joint effort.

With the primary focus on the accuracy of the different models, the numerical performance, robustness and efficiency are not evaluated in this study.

50 2 Participants and numerical models

A total of 23 academic and industrial partners participated in WP2.2 from Phase II of the OC7 project. Those actively contributing with results for comparison were, by alphabetical order, Akselos S.A. (*AKSE*), Bureau Veritas Marine and Offshore (*BVMO*), Centro Nacional de Energías Renovables (*CENER*), Centre Internacional de Mètodes Numèrics en Enginyeria together with Universidad Politécnica de Madrid (*CIMN*), DNV (*DNV*), Japan Marine United Corporation
55 together with Nihon Shipyard Co., Ltd. (*JMUC*), National Laboratory of the Rockies (*NLR*), PRINCIPIA (*PRI*) and Ramboll (*RAMB*). The participants contributed either with one, or – to address the impact of specific model variations and sensitivities – several numerical models, see Table 1 with further modelling details explained in this section below.



Table 1: Model categorization and approaches used (grey shading is used to visually emphasize differentiating modelling aspects).

Category	Model ID	Software	Hydrodynamic Pressure Origin	Load Application in FEA	Load/Pressure Extent		Viscous Drag Application in FEA	FEA Load Equilibration	Hull Structural Dynamics Captured?	Hull Struct. Damping ⁽⁴⁾
					Hydrostat.	Hydrodyn.				
Sequential ILA>FEA (QS)	AKSE1	OrcaFlex > Akselos RB-FEA	FD BEM (Reconstr.)	Step-by-Step (QS)	Inst. SWL	SWL	Line load distributed to nodes	Wetted Surface Distr. Load	No	-
	BVMO1	Opera > NASTRAN	FD BEM (Reconstr.)	Unit Loads/Response Superposition	SWL	SWL	Line load distributed to nodes	6DOF Nodal Supports	No	-
	CENER1	OrcaFlex > NASTRAN	FD BEM (Reconstr.)	Step-by-Step (QS)	Inst. SWL ⁽¹⁾	Inst. Surf. ⁽¹⁾	-	Inertia Relief ⁽²⁾	No	-
	DNV1	Sima > SESAM	TD Rankine (Calc.)	Step-by-Step (QS)	SWL	SWL	Line load distributed to nodes	6DOF Nodal Supports	No	-
	DNV2		FD BEM (Reconstr.)	Step-by-Step (QS)						
	DNV3		FD BEM (Reconstr.)	Unit Loads/Response Superposition						
	JMUC1	OrcaFlex > In-house	TD Rankine (Calc.)	Step-by-Step (QS)	Inst. SWL	Inst. Surf.	-	Wetted Surface Distr. Load ⁽²⁾	No	-
	NLR1	OrcaFlex > TRUST (WAMIT/ ANSYS)	FD BEM (Reconstr.)	Unit Loads/Response Superposition	SWL	SWL	-	Fairlead Springs ⁽²⁾	No	-
	RAMB2	OrcaFlex > ANSYS	GIS Generalized	Unit Loads/Response Superposition	SWL	SWL	Generalized Pressure	Inertia Relief	No	-
	RAMB3								Yes, in ILA ⁽³⁾	0%
RAMB6/7	Yes, in ILA ⁽³⁾								1% / 5%	
Integrated	CIMN1	Tdyn SeaFEM	TD FEM (Calc.)	Step-by-Step (Full Dynamic)	SWL	SWL	Line load distributed to nodes	n.a.	Yes, in TD FEA (One-way FSI)	1%
	CIMN2		TD FEM (Calc.) incl. Hydro-Elasticity		SWL	SWL			Yes, in TD FEA (Two-way FSI)	
	CIMN3		Inst. SWL		Inst. Surf.					
ILA with Beam FE	PR11	DeepLines Wind	n.a.	n.a.	Inst. Surf.	Inst. Surf.	n.a.	n.a.	Yes, in ILA	0%

60 Abbreviations used:
 BEM: Boundary Element Method, DOF: Degree-Of-Freedom, FD: Frequency-Domain, FE (FEA/FEM): Finite Element (Analysis/Method), FSI: Fluid-Structure Interaction, GIS: Global Influence Superposition, QS: Quasi-Static, SWL: Still Water Level, TD: Time-Domain

- 65 (1) Pressures set to zero above initial SWL.
 (2) Expected to be non-negligible as viscous drag is not transferred.
 (3) Mapped from ILA to QS FEA as inertia load.
 (4) in % of the critical damping at 1st fore-aft flexible eigenfrequency.

The applied numerical models can be categorized based on the general workflow and the level of integration between the global analysis (ILA) and the local structural assessment (FEA) into 3 main groups:

- 70 1. Sequential workflow, with separated global analysis (ILA) and structural FEA (i.e. loosely coupled link, indicated by “>” in Table 1).
 2. Integrated workflow, with global analysis and structural FEA running simultaneously (i.e. strongly coupled link).
 3. Simplified workflow, without shell element FEA, with basic structural assessment within the ILA using beam FEM.

75 The following paragraphs describe each modelling category, highlighting their similarities and specific differences to facilitate the interpretation of the results.



Category 1: Sequential Workflow

Models: *AKSEI*, *BVMO1*, *CENER1*, *DNV1/2/3*, *JMUCl*, *NLR1*, *RAMB2/3/6/7* (Bratbak et al., 2025; De Lauzon et al., 2013; Karch et al., 2024; Knezevic et al., 2022; Yim et al., 2026).

This category is used by most participants and appears to represent the current standard industry practice. It involves a sequential workflow where the ILA is conducted first, followed by the FEA.

In most models applied in this project, due to the quasi-static (QS) nature of the FEA, the structural dynamics of the hull are generally not captured in the obtained structural responses. One exception are the *RAMB3/6/7* models, where the global effect of hull flexibility is captured in the ILA and transferred to the QS FEA through inertia loads. In general, methods adopted for *DNV1/2*, *JMUCl* and *NLR1* would allow for consideration of structural dynamics via fully dynamic time-domain FEA, however this feature is not utilized in this project.

By separating the ILA and FEA, the “global-to-local” link in these models remains relatively loose and relies heavily on the quality of the load transfer (mapping) approach. A critical aspect of this process is the inclusion of all ILA load components; this is essential for maintaining load balance within the FEA. Any imbalances resulting from transfer inaccuracies must be equilibrated through support reactions, inertia relief, or other techniques. However, if a load component is neglected and the resulting imbalance is non-negligible, the equilibration will likely fail to reflect the physical nature of the missing load, ultimately distorting the calculated structural responses. In this regard, it should be noted that models *CENER1*, *JMUCl* and *NLR1* do not transfer viscous drag to the FEA, hence, the applied load equilibration technique might become relevant, see Table 1. For other models, the FEA equilibration technique is less relevant as the imbalance is either proved or expected to be negligible.

A major differentiator of the models in Category 1 is the way the hydrodynamic loads from the ILA are converted into pressures (i.e. where the applied pressures originate from). Here, three options exist, see Table 1:

- a) Pressures are obtained directly from the time-domain potential flow solution using the Rankine Source Method. (*DNV1* and *JMUCl*).
- b) Pressures or structural responses are reconstructed via linear superposition of hydrodynamic coefficients or the structural response to these, from the frequency-domain potential flow solution (BEM), scaled by the instantaneous motions and wave data from the ILA (*AKSEI*, *BVMO1*, *CENER1*, *DNV2/3* and *NLR1*).
- c) Pressures are reconstructed via linear superposition of generalized pressure distributions (uniform and gradient patterns) on hull segments, scaled by the instantaneous hydrodynamic loads acting on these segments in the ILA, i.e. following the global influence superposition (GIS) methodology (*RAMB2/3/6/7*).

Furthermore, the models differentiate in the way the pressures, together with other loads, are applied in FEA:

- a) Direct application of the instantaneous loads on the FE model, with subsequent FEA, in every time step of the analysis. (*AKSEI*, *CENER1*, *DNV1/2*, *JMUCl*).
- b) A set of unit load cases is solved in the FEA once, yielding unit structural responses. The full time-history of structural responses is obtained via linear superposition of unit responses, scaled by appropriate scaling



110 factors from the ILA. This method aligns well with the pressure reconstruction strategies (b, c) described
above. (*BVMO1, DNV3, NLR1, RAMB2/3/6/7*).

Category 2: Integrated Workflow

115 Models: *CIMN1, CIMN2, CIMN3* (García-Espinosa et al., 2023; Berdugo-Parada et al., 2024; Serván-Camas et al.,
2025; García-Espinosa et al., 2026).

In the models of this category a pure time-domain analysis approach is used, combining global response and
structural FEA. Hence, the “global-to-local” link in these models is inherently strong. The structural model includes
hull, tower, topside (i.e. rotor-nacelle assembly RNA) and mooring lines. The potential flow problem is solved
120 directly in the time-domain using the FEM on a fluid volumetric mesh. In the structural solver, a dynamic analysis
is performed in the time-domain, inherently capturing structural flexibility and structural dynamic effects. Because
the fluid and structural solvers are mathematically coupled at every time step, load equilibrium is inherently
satisfied without the need for artificial boundary conditions or inertia relief techniques.

The fluid-structure interaction is considered on two levels:

- 125 a) The hull is coupled as a rigid body to the hydrodynamic potential flow solution while elastic deformations
have no effect on the fluid pressure (one-way coupling). (*CIMN1*).
- b) The hull is modelled as an elastic body and coupled to the hydrodynamic potential flow solution through
generalized structural modes, using an enriched modal reduction approach. This enables a two-ways
coupling, with elastic deformation affecting the fluid potential field and vice versa. (*CIMN2/3*).

130 Category 3: Simplified Workflow, ILA with beam FEM

Model: *PRII* (Defoy et al., 2018; Quideau et al., 2025).

In this category, no external FEA model is used, and no load transfer from ILA to shell model FEA is done.
Consequently, the discussed concepts for pressure calculation/reconstruction, load equilibration, etc., are not
applicable. The “global-to-local” link is inherent but simplified in the way how “local” structural responses
135 (stresses) are obtained from the “global” responses/loads. The ILA model differentiates significantly from the
OrcaFlex reference model (see Sect. 6.1); the hull is modelled using skeleton beams, with potential flow multi-
bodies attached to them at appropriate locations. The beams are joined using rigid connections and their stiffnesses
are defined based on computer aided drafting (CAD) geometry to approximate the global structural flexible
behaviour. Hence, global structural dynamics are inherently captured within the ILA. The structural responses
140 (stresses) are derived from sectional beam loads (axial and bending) in a simplified way based on classical beam
theory. With that, only longitudinal stress components can be retrieved, and the accuracy is expected to be limited
around beam joints, i.e. no stresses are available inside the joints.



Disregarding the above toolchain categorization, the different models are further distinguished in Table 1 by the vertical
 145 extent of fluid pressure application. Most models (*BVMO1*, *DNV1/2/3*, *NLR1*, *RAMB2/3/6/7*, and *CIMN1/2*) follow a
 linearised approach, applying both hydrostatic and hydrodynamic pressure components up to the initial, undisplaced Still
 Water Level (SWL). For models based on Unit Loads/Responses, such linearization is inevitable.

In contrast, other models (especially those applying pressures step-by-step) can capture specific non-linear surface effects:

- Hydrostatic non-linearity: *AKSE1* applies hydrostatic pressures to the instantaneous SWL, considering roll, pitch
 150 and heave motions, and accounting for a physically more correct pressure distribution.
- Hydrostatic and hydrodynamic non-linearity: *CENER1*, *JMUC1*, *CIMN3* and *PR11* further extend fidelity by
 applying hydrodynamic pressures up to the instantaneous wave surface. While specific implementations vary (e.g.,
 applying only Froude-Krylov forces to the surface while keeping radiation/diffraction terms linear), these models
 generally aim to consider a physically more realistic pressure distribution than the linear models.

155 3 Reference model description

This study was performed using the VoltturnUS-S reference semi-submersible platform (Allen et al., 2020) with the IEA
 15 MW reference wind turbine (Gaertner et al., 2020), see Fig. 1.

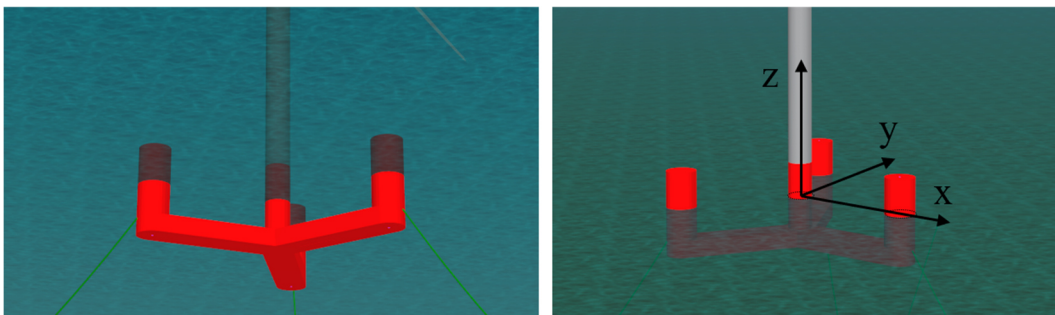


Figure 1: VoltturnUS-S semi-submersible platform

160 As in WP2.1 the structure was simplified by removing the horizontal braces that connected the top of the columns to the
 central tower. This was done to (1) simplify the distribution of load paths, making analytical verifications easier; and (2)
 create a more flexible structure where the effects of structural dynamics are more pronounced and easier to study. The
 mooring system is a steel chain catenary system consisting of 3 lines, attached to the offset at the top of pontoon level (7.0 m
 above baseline). The main particulars of the structure are compiled in Table 2.

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Table 2: Main particulars of VoltturnUS-S reference structure

Operating draft	[m]	20.00
Freeboard (to top of offset columns and to tower base)	[m]	15.00
Radial distance from central tower axis to offset column axis	[m]	51.75
Diameter of tower column	[m]	10.00



Diameter of offset columns	[m]	12.50
Length of pontoon (between central and offset column)	[m]	40.50
Width of pontoon	[m]	12.50
Height of pontoon	[m]	7.00
Floater mass (incl. ballast)	[t]	17,842
Tower mass	[t]	1,483
Rotor nacelle assembly (RNA) mass	[t]	950
Total mass	[t]	20,275
Total centre of gravity CoG-X (rel. to intersection of SWL and centre column)	[m]	0.330
Total centre of gravity CoG-Y (rel. to intersection of SWL and centre column)	[m]	0.005
Total centre of gravity CoG-Z (rel. to intersection of SWL and centre column)	[m]	-1.576
Total mass moment of inertia Ixx (rel. to CoG, axis aligned with global axis)	[tm ²]	4.404E+07
Total mass moment of inertia Iyy (rel. to CoG, axis aligned with global axis)	[tm ²]	4.393E+07
Total mass moment of inertia Izz (rel. to CoG, axis aligned with global axis)	[tm ²]	2.331E+07

4 Load case definition

170 The load cases considered are compiled in Table 3. The ultimate goal of this study was to assess the impact of the “global-to-local” (i.e. ILA-to-FEA) load transfer approach on the evaluated structural responses. Load cases (LC) 6.2/6.3 and 7.2/7.3 are of primary interest in this regard, comprising irregular wave excitation with and without RNA load. The other load cases primarily served to align and verify the models and improve understanding of the root causes for deviations between them while generally increasing model complexity within and across load case groups.

Table 3: Load cases definition

Load Case Group	Load Case	Description	Relevant Model	
1	Mass/Inertia Check	LC1.1	Mass/Inertia check	ILA / FEA
2	Static Checks	LC2.1	Const. RNA load, 6DOF supports, no gravity	FEA
		LC2.2	Gravity load, 6DOF supports	FEA
		LC2.3	Freely floating, linear stiffness in surge/sway/yaw	ILA / FEA
		LC2.4	Freely floating, with mooring	ILA / FEA
		LC2.5	Freely floating, with mooring, incl. current (0.8 m/s)	ILA / FEA
3	Natural Frequency Analyses	LC3.1	Modal analysis, unconstrained, substructure hull only	FEA
		LC3.2	Modal analysis, unconstrained, substructure hull + tower + RNA	FEA
		LC3.3	Modal analysis, floating in water, with mooring	ILA
		LC3.4	Free decay – Surge	ILA
		LC3.5	Free decay – Heave	ILA
		LC3.6	Free decay – Pitch	ILA
4	RNA Load only	LC4.1	Freely floating, with mooring, pre-computed time varying RNA load (no waves)	ILA / FEA
5	Regular Waves, H=1.96m, T=10s	LC5.1	Constrained at tower interface, no mooring, wave only	ILA / FEA
		LC5.2	Freely floating, with mooring, wave only	ILA / FEA
6	Irregular Waves, PM spectrum, Hs=1.0m, Tp=6.2s	LC6.1	Constrained at tower interface, no mooring, wave only	ILA / FEA
		LC6.2	Freely floating, with mooring, wave only	ILA / FEA
		LC6.3	Freely floating, with mooring, wave + RNA load	ILA / FEA
7	Irregular Waves, PM spectrum, Hs=11.0m, Tp=15.4s	LC7.1	Constrained at tower interface, no mooring, wave only	ILA / FEA
		LC7.2	Freely floating, with mooring, wave only	ILA / FEA
		LC7.3	Freely floating, with mooring, wave + RNA load	ILA / FEA

175 For models with a sequential workflow (Category 1), the load cases were evaluated in either FEA or ILA, or in both models with load transfer between them. Simulation durations in LC groups 4 and 5 were 600 s and 200 s respectively. For irregular wave LC groups 6 and 7 the simulation duration was 1200 s, allowing to assess both, the individual wave events and



statistics. Modelled water depth was 200 m. All environmental loads (waves, current, RNA load) were applied from the same direction (180 deg, i.e. towards negative x-direction, see Fig. 1). Wind drag was not considered. The RNA load was defined
180 by Ramboll as a pre-computed load time series applied along the rotor shaft axis, based on turbulent wind simulation (mean wind speed of 12 m/s, Class C turbulence intensity, vertical wind shear exponent of 0.14). This simplified RNA load approach was chosen to eliminate full rotor aerodynamics in the ILA as a potential source of discrepancy between participants' models.

5 Finite element (FE) models

185 5.1 Reference FE model

To better align the FE models used in the different toolchains, a reference structural model of the VoltturnUS-S semi-submersible was created at the start of the project, see Fig. 2. The structural layout, including plate thicknesses and internal stiffening, was based on minimum scantling requirements and created solely for educational purposes of this project and to maintain consistency across the participants, with no intention of fully complying with any structural rule requirements (i.e.
190 not to be used for a real engineering project).

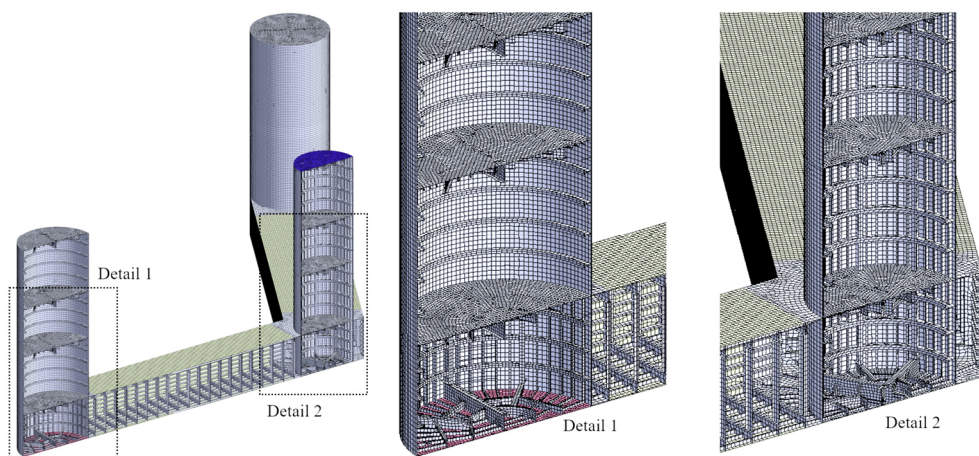


Figure 2: Reference FE model of the VoltturnUS-S semi-submersible

The original VoltturnUS-S semi-submersible design has ballast in columns and pontoons to achieve the required operating draft. While modelling of ballast is straightforward in global response analysis (ILA), its consideration in structural
195 assessments can be challenging. Some tools distribute the ballast mass to nodes of the FE mesh, while others model it as mass points connected to the FE mesh via springs, or as pressure distributions. The deviations in the evaluated structural responses introduced by the different modelling techniques can be difficult to isolate and assess and would require another dedicated study. Therefore, the global effect of ballast was replicated in this study in a simplified way by increasing the material density in different areas of the FE mesh.



200 The reference FE model consists of 420,672 shell elements (i.e. no 1D beam elements, nor solid elements) and only includes the hull. The tower and mooring lines are not modelled in FE and are applied as interface loads during ILA-to-FEA load transfer. The model is supported at the base of its three columns, constraining three DOFs (x, y, z) at column 1, two DOFs (y, z) at column 2, and one DOF (z) at column 3. The support conditions primarily affect the static analyses in LC2.1 and LC2.2; in the free-floating cases, the external loads should be in equilibrium, making FE support reactions negligible.

205 The reference FE model was created by Ramboll in ANSYS and shared with participants in various export formats, and as a CAD geometry file, to accommodate the different toolchains involved. In all toolchains using a sequential workflow (Category 1), the reference mesh definition could be adopted directly, or similar meshes could be created based on the CAD geometry. The integrated workflow (Category 2) applied in *CIMN* models, required a structural model that included the entire floating structure (hull, tower, RNA, and mooring lines), and therefore had to be extended accordingly. The simplified

210 workflow (Category 3) applied in *PRII* model, does not require a separate structural FEA model.

5.2 FE model alignment verification

The alignment of the applied FEA models was verified based on:

- mass/inertia check (LC1.1 in Table 3), which was performed by the participants during FE model creation and is not further detailed in this paper,
 - static FE analyses (LC2.1 and 2.2), and
 - modal FE analyses (LC3.1 and 3.2).
- 215

Since the *DNV1/2/3*, *CIMNE1/2/3* and *RAMB2/3/6/7* model variants are based on the same FE model, only one variant per participant was evaluated. The *PRII* model does not use a separate FEA model and was therefore not evaluated.

5.2.1 Static FE analyses

220 For the static FE analyses (LC2.1 and LC2.2) panel-averaged stress components are evaluated. Area-weighted averaging across the elements of one panel was performed to minimise the dependency of results on the mesh density, which differs between participants. Mesh sensitivity analysis was not the focus of the study. The evaluated panels are shown in Fig. 3.

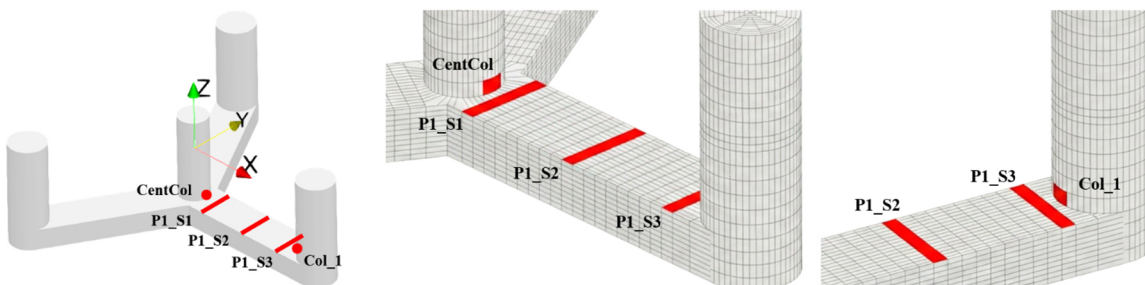
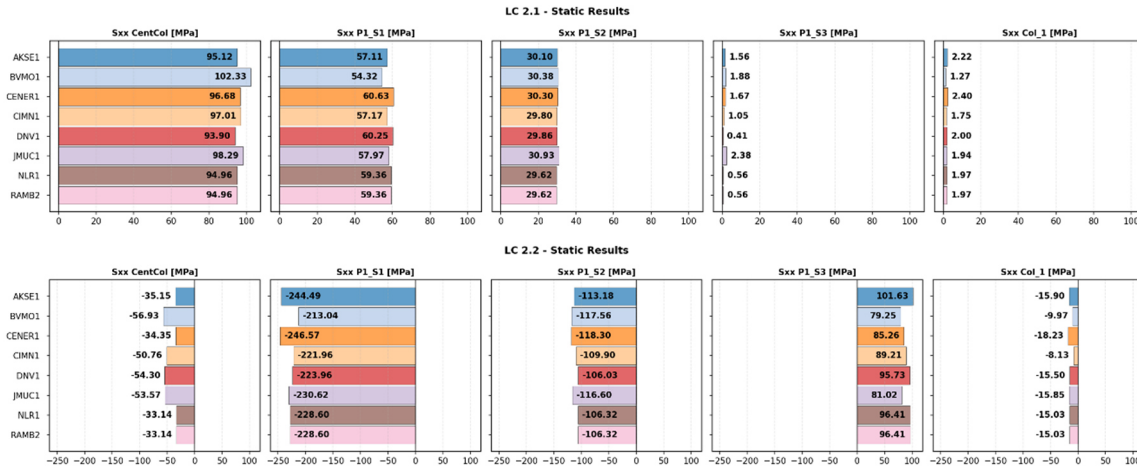


Figure 3: Panels definition for the evaluation of panel-averaged stress components (marked red)



225 The calculated stress components S_{xx} (in longitudinal pontoon/column direction) are shown in Fig. 4. Generally, good agreement is observed between the FE models. Any deviations may be due to potential misinterpretations of the definitions of boundary conditions, RNA load application or stress averaging. The alignment level is deemed acceptable moving forward.



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Figure 4: Comparison of panel-averaged stresses (S_{xx} component) for static load cases LC2.1 (RNA load only) and LC2.2 (gravity only)

5.2.2 Modal FE analyses

235 The results of modal FE analyses (LC3.1 and 3.2) are shown in Fig. 5. All FE models show very good agreement in the calculated natural frequencies.

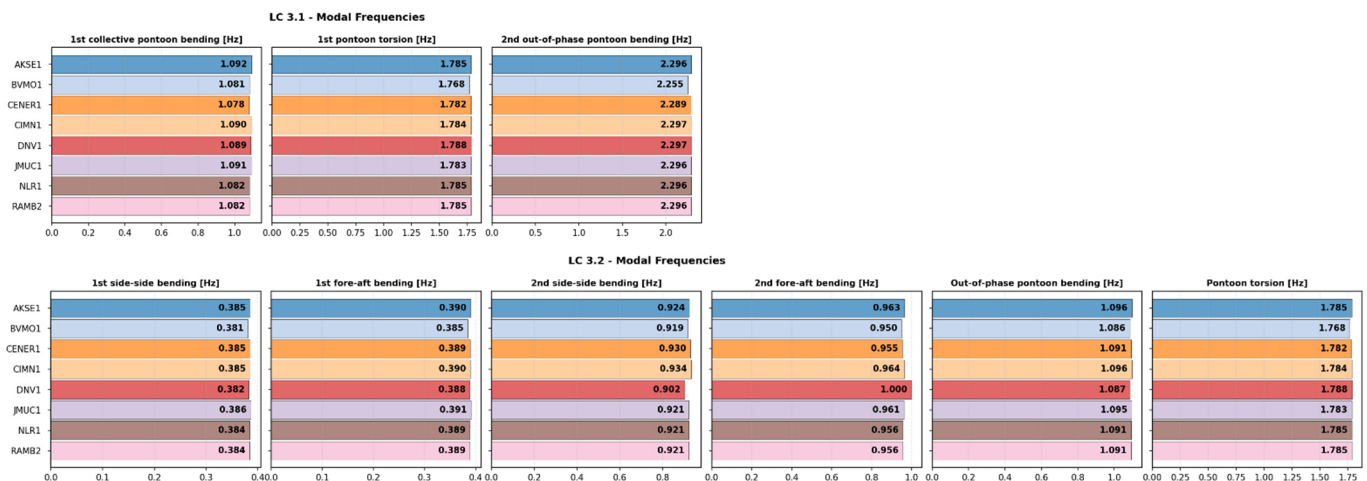


Figure 5: Comparison of eigenfrequencies from FE modal analyses (LC3.1: hull only, LC3.2: hull, tower and RNA)



6 Global response (ILA) models

240 6.1 Reference ILA model

To investigate the “global-to-local” (i.e. ILA-to-FEA) load transfer, it is important that the “global” basis (ILA) is well aligned between all participants. Therefore, at the start of the project Ramboll provided the project participants with a reference global response analysis (ILA) model in OrcaFlex software combined with model descriptions and parameter overviews. The modelling details aimed to suffice the common floating wind industry requirements and practices (e.g., hull hydrodynamics based on boundary element method (BEM), consideration of viscous drag, non-linear mooring, etc.) while at the same time being relatively simple to better align with capabilities of available load transfer approaches, allowing more institutions to participate (e.g. rigid hull, exclusion of ballast, exclusion of 2nd-order wave loads, etc.).

This reference model was used directly by most participants for their analyses. Where specific toolchains required a different ILA software (Opera, Sima, DeepLines Wind, SeaFEM), the respective models were created adopting (if possible) the OrcaFlex reference model features. Furthermore, some model variations were created by participants on purpose, to investigate specific modelling aspects (e.g. hull flexibility, pressure application extent, etc.).

For this project that largely focuses on the ILA-to-FEA load transfer, the (hydrodynamic) modelling of the hull in the ILA is of particular interest; mooring lines and tower/RNA modelling are less relevant, as these components are usually not included in the same FEA and considered only via respective interface loads.

In the OrcaFlex reference model the hull is modelled as a single rigid body. The 1st-order potential flow loads (radiation/diffraction) are reconstructed from frequency-domain coefficients obtained with BEM: radiation forces are calculated via the Cummins convolution integral, while wave excitation loads are applied via superposition of linear transfer functions. Hydrostatic stiffness is linearised about the initial (undisplaced) floating position. Viscous drag is modelled non-linearly using Morison elements, with drag forces integrated up to the instantaneous water surface using Wheeler stretching. 2nd-order wave loads are not considered. Mooring lines are modelled with finite elements (OrcaFlex line-objects). The tower was modelled as flexible beam and the RNA as a mass point with inertia and pre-computed load time series (see Sect. 4) applied to it in selected load cases (see Table 3). Wind drag was neglected.

6.2 Global model alignment verification

The alignment of the global response models was verified based on:

- static analyses in freely floating conditions (LC2.3, 2.4 and 2.5),
- global modal analyses (LC3.3), and
- free decay simulations (LC3.4, 3.5 and 3.6), c.f. Table 3.

For the comparison, two groups of models should be distinguished, where deviations are expected:

- 1) Models aimed to replicate same features as the OrcaFlex reference model (rigid hull): *AKSE1*, *BVMO1*, *CENER1*, *DNV1/2/3*, *JMUC1*, *NLR1*, *RAMB2*. In model *RAMB2*, the hull was divided into 14 segments and treated as a multi-



body system in the BEM solution. This is necessary for the global influence superposition (GIS) load transfer approach (Karch et al., 2024). However, since the segments are rigidly connected, the global performance behaviour is the same as that of the single body reference model.

2) Models with features modified on purpose, see also Table 1:

- 275
- *RAMB3/6/7*: Using the same hull segmentation as in *RAMB2*, but with flexible connections between segments whose stiffness was calibrated to achieve the same modal response (1st/2nd fore-aft/side-side bending) as the FEA model. Model variants differentiate in the amount of structural damping considered.
 - *CIMN1/2/3* and *PRII*: The integrated *CIMN* models and the simplified (ILA with beam FE) *PRII* model inherently capture hull flexibility and structural dynamic effects as well as hydrostatic/hydrodynamic non-linearities (only *CIMN3* and *PRII*).
- 280

Other sources of expected discrepancies are:

- Model *BVMO1* only considered one drag coefficient (*C_d*) for normal direction, whereas the OrcaFlex reference model considers individual coefficients for the horizontal and vertical directions for pontoons.
 - Reporting of rigid body motions in models with flexible hull. In models *RAMB3/6/7* and *PRII*, this relates to a point fixed on the central column (SWL level). In models *CIMN1/2/3*, however, rigid-body motions are extracted directly from the total displacement field using standard FEM procedures, mathematically separating the overall rigid-body movement from the elastic deformation of the hull.
- 285

6.2.1 Static analyses in freely floating conditions

Figure 6 shows the rigid body motions in static freely floating cases LC2.4 (without current) and LC2.5 (with current). While 290 no results for *DNV* model were available, other rigid hull models are generally well aligned. Here, *BVMO1* shows some deviations in both cases. Flexible hull models *RAMB3* (also representing *RAMB6/7*), *CIMN1* (also representing *CIMN2/3*) and *PRII* show some differences, likely related to the way rigid body motions are extracted, see explanations above.

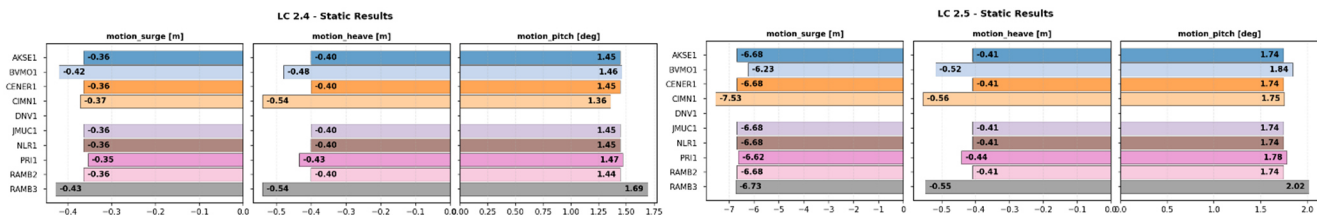
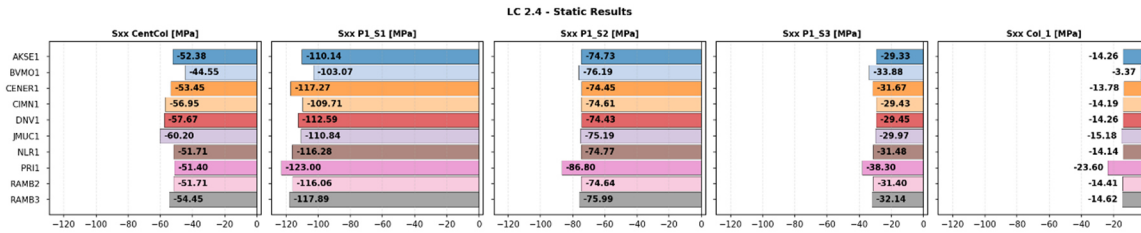


Figure 6: Comparison of rigid body motions in static freely floating cases LC2.4 (without current) and LC2.5 (with current)

295 In Fig. 7 panel-averaged stresses for LC2.4 are shown (LC2.5 is very similar). The results are generally consistent, showing similar deviations to those observed in LC2.2 (see Fig. 4). The deviations observed in the *BVMO1* model for motions are also reflected in the stresses. The beam-based model *PRII* shows deviations in stresses, especially in the pontoon (P1_S1/2/3, see Fig. 3), which are likely inherent in the structural model simplifications.



300 **Figure 7: Comparison of panel-averaged stresses (Sxx component) for static freely floating case LC2.4**

6.2.2 Global modal analyses

The results of global modal analysis (LC3.3) are shown in Fig. 8. All rigid hull models are very well aligned. The flexible hull models of *CIMN1* (also representing *CIMN2/3*) and *RAMB3* (also representing *RAMB6/7*) are well aligned, while *PRII* model deviates slightly, which is probably caused by simplifications of the beam-based structural model and/or differences in hydrodynamic added mass formulation.

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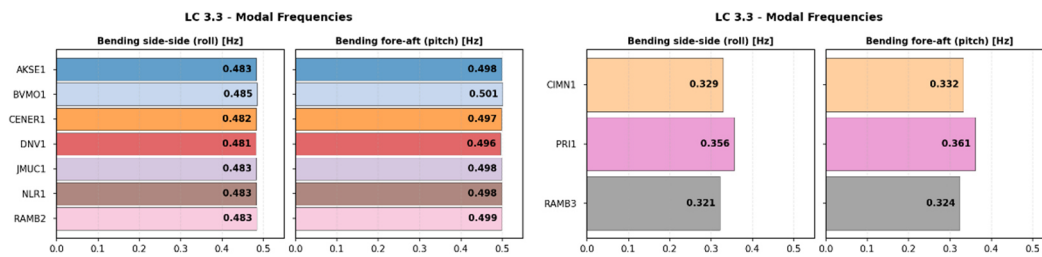


Figure 8: Comparison of 1st fore-aft/side-side bending eigenfrequencies from global modal analyses (LC3.3) for rigid (left) and flexible hull models (right)

6.2.3 Free decay simulations

In Fig. 9 the results of the free decay simulations are shown, i.e. time series (left), statistics (middle), and power spectral densities (PSD, right). The statistics plots show mean values, standard deviations (coloured boxes) and minimum and maximum values (dashed vertical black lines) for each model. The annotations for the mean (black) and standard deviation (blue) values show the ratio to *RAMB2* model, which should be treated as a reference only, for relative comparison. Rigid body natural frequencies of the floating system (dashed vertical lines) are included in the spectral density plots as reference, i.e. surge 0.007 Hz, pitch 0.036 Hz, heave 0.049 Hz (Allen et al., 2020).

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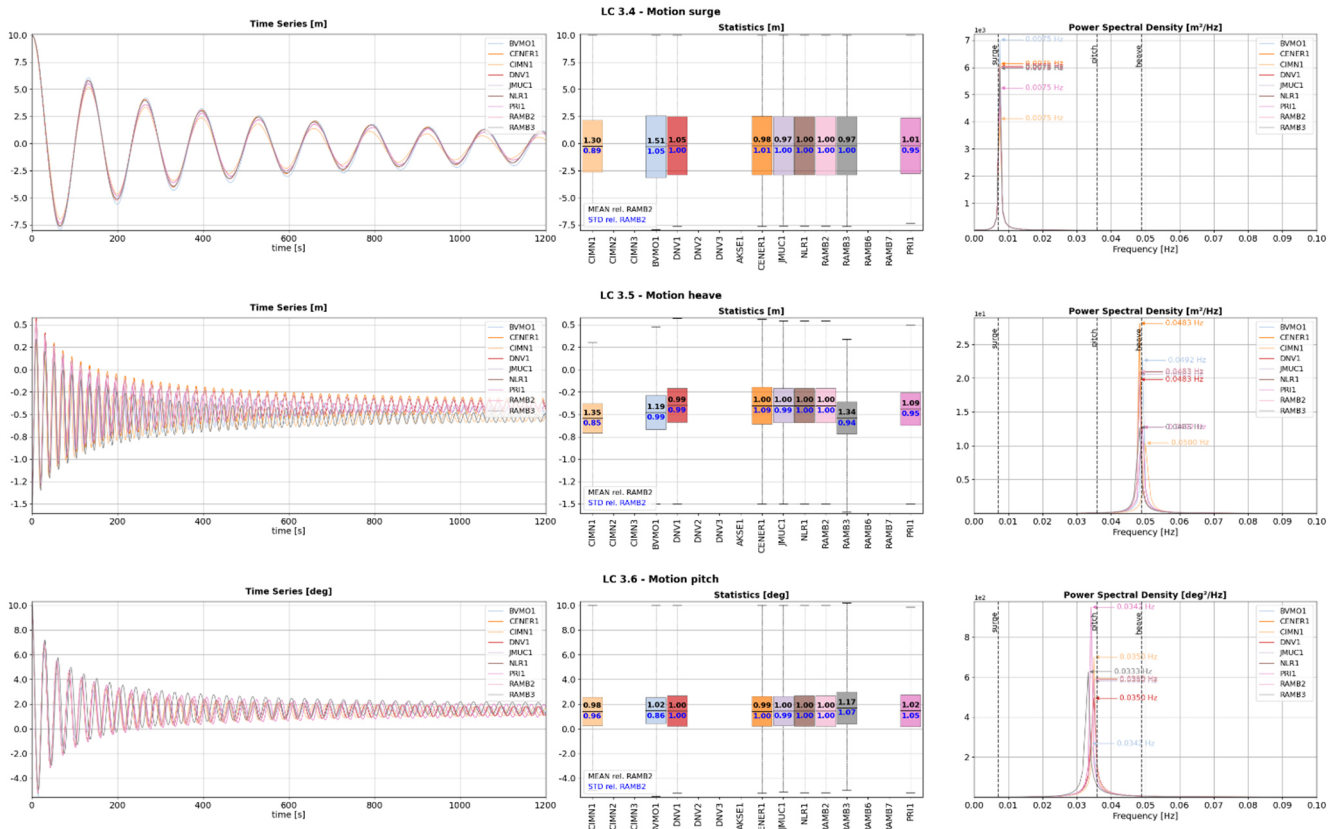


Figure 9: Free decay results for platform surge (LC3.4), heave (LC3.5) and pitch (LC3.6)

320 While no results for *AKSEL* model were available, other rigid hull models are generally well aligned. Here, *BVM01* indicates higher damping in pitch, reflected in smaller standard deviation (STD) value and lower PSD peak, which could be related to drag coefficient definition, see explanations above. Flexible hull models *RAMB3* (also representing *RAMB6/7*), *CIMN1* (also representing *CIMN2/3*) and *PR11* show slight deviations, probably related to the way how rigid body motions are reported (see explanations above) and – in case of *PR11* – potential implications of non-linear hydrostatics used in this model. While *RAMB3* and *PR11* indicate higher pitch amplitudes (STD values) for flexible models, *CIMN1* shows a distinct response trend.

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Overall, while there are some differences between the global response models, the alignment is deemed acceptable moving forward. However, it is expected that the global motion behaviour might deviate significantly in longer irregular wave simulations in load case groups LC6 and LC7 which are the focus of the following sections.

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7 Evaluation of numerical models

After ensuring sufficient alignment between the applied FEA and global analysis (ILA) models, the “global-to-local” (i.e. ILA-to-FEA) load transfer approaches are evaluated based on stress comparisons in load cases:

- LC4.1 (no wave, RNA load only),
- LC6.2/6.3 (irregular waves $H_s=1.0\text{m}$, with/without RNA load), and
- LC7.2/7.3 (irregular waves $H_s=11.0\text{m}$, with/without RNA load).

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Other load cases (LC5.1/5.2/6.1/7.1) from Table 3 were used for specific verifications and are not presented in this paper. The results are presented in a format similar to Fig. 9:

- time series plot on the left;
- statistics box plot in the middle, with annotations of mean values (black) and standard deviations (blue) expressed as ratios relative to the rigid-hull *RAMB2* model for comparison;
- power spectral density (PSD) plot on the right, including dashed lines indicating the natural rigid-body frequencies, the global flexible eigenfrequencies (fore-aft/side-side), and the peak frequency of the RNA load.

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To make the global performance simulations as consistent and comparable as possible the RNA load was specified through a pre-computed load time series applied on the rotor, see Fig. 10. The time series plot includes a 15-second zoom-in region (300 – 315 s).

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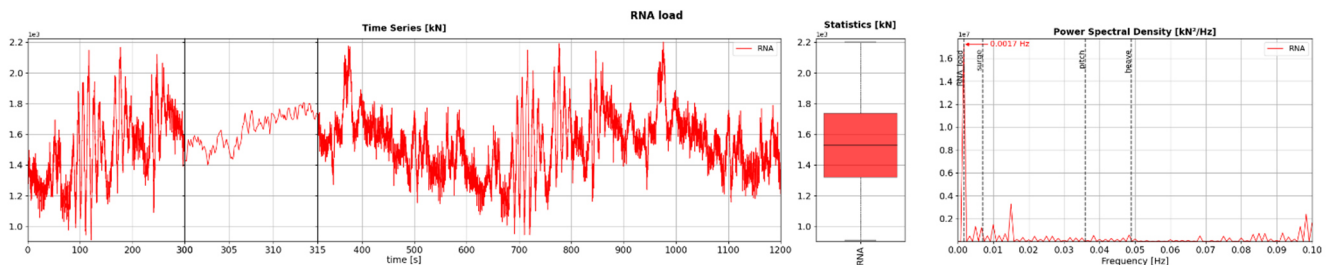


Figure 10: RNA load time series applied on the rotor in LC4.1, LC6.3 and LC7.3

Furthermore, the wave elevation time series (i.e. the amplitudes and phase shift angles of the irregular wave components) were specified as the input data for the load cases LC6.2/6.3 and LC7.2/7.3.

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Only the most relevant stress results are presented in the following sections. Further results, such as stresses on other panels, sectional loads and pressures, were evaluated and used to validate and support the derived conclusions.

7.1 Load case LC4.1 (no waves, RNA load only)

Figure 11 shows panel-averaged stress components S_{xx} (in longitudinal pontoon/column direction) for panels CentCol, P1_S1, P1_S3 and Col_1, see Fig. 3. As an additional information, fatigue damage indicators (FDIs) are included as red dots in the statistics plots. The FDIs are essentially damage ratios relative to the *RAMB2* model, which is used as the reference for comparison. Damage is calculated based on Rainflow counting of stress component time series, considering the S-N curve

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exponent of $m = 3$. The FDIs are intended solely as qualitative indicators of fatigue damage accumulated in the different models and do not represent a rule-compliant fatigue assessment.

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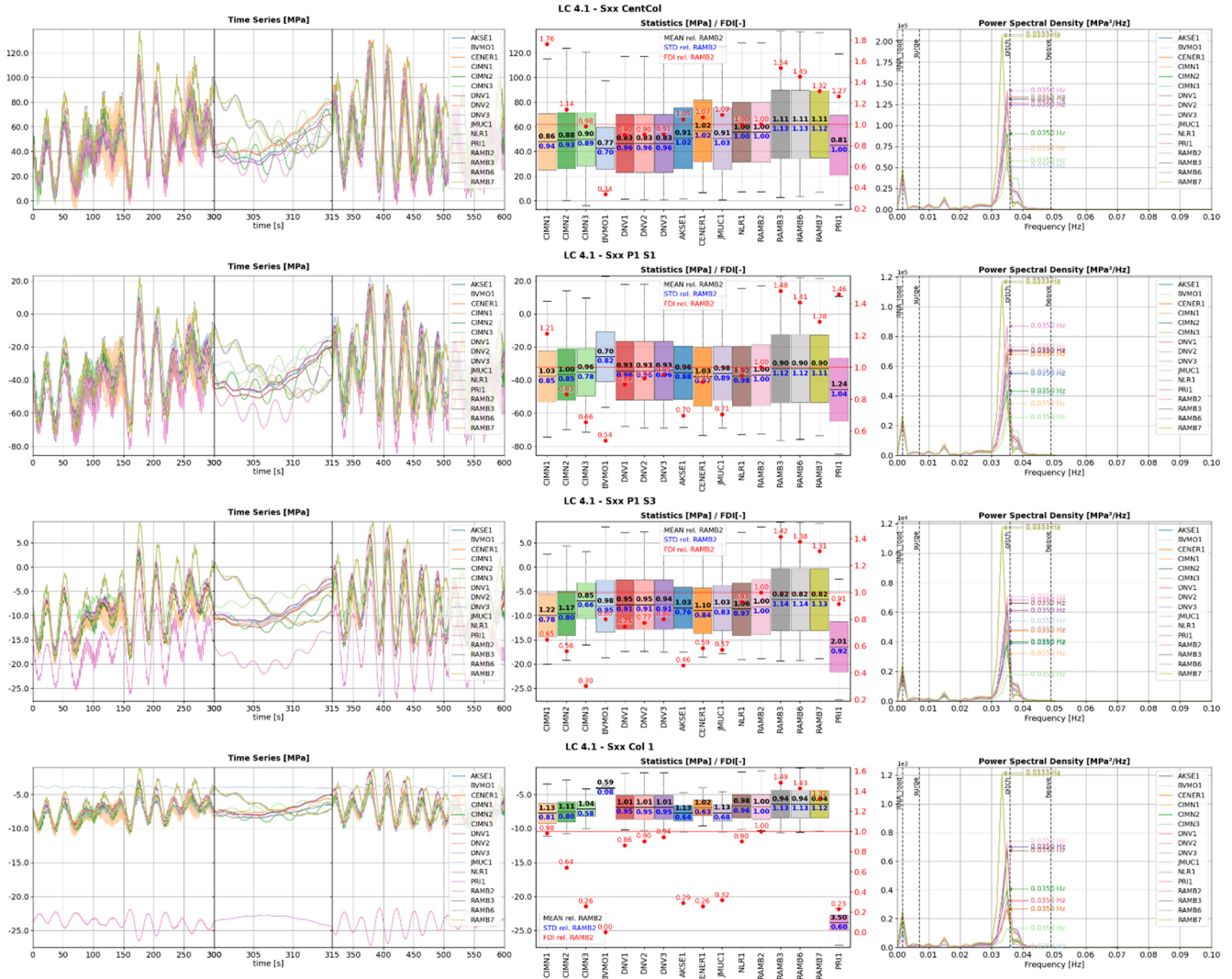


Figure 11: Comparison of panel-averaged stresses (Sxx component) for LC4.1 (no wave, RNA load only)

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The time series plots in Fig. 11 reveal discrepancies between the global analysis models discussed in Sect. 6.2. The models based on the OrcaFlex reference model form one cluster (see zoom-in region 300 – 315 s), with the other rigid hull models close by, except for *BVMO1*. All flexible hull models deviate from this cluster. The statistics plots show that most models are relatively well aligned. Those in the cluster in particular show good consistency in mean and STD values, and mostly in FDIs. The statistics of the flexible hull models *CIMN1/2/3* and *RAMB3/6/7* generally align quite well with these. The flexible hull *PR11* model aligns well on STD values while deviating on the mean values.

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By comparing *RAMB3/6/7* with *RAMB2*, it is evident that considering hull flexibility increases the STD values, particularly the FDIs. The amount of structural damping included in the *RAMB3/6/7* hull models (see Table 1) clearly impacts the FDIs. A comparison between the *CIMN1* and *CIMN2* models shows that considering two-way hydrodynamic coupling – where elastic deformations affect hydrodynamic pressures – accounts for the hydrodynamic damping caused by waves radiating by elastic displacements, leading to reduced FDIs and a potentially more realistic representation of energy dissipation mechanisms.

Furthermore, a significant reduction in FDI can be seen in panels P1_S1, P1_S3 and Col_1 of models *CIMN3*, *AKSE1*, *CENER1* and *JMUC1*. These models differ from similar ones in how hydrostatic pressures are applied in the FEA. While models such as *BVMO1*, *DNV1/2/3*, *NLR1*, *RAMB2/3/6/7* and *CIMN1/2* apply a linearised distribution, the models *CIMN3*, *AKSE1*, *CENER1* and *JMUC1* use a non-linear formulation. This leads to different load path distributions within the hull structure, see Fig. 12.

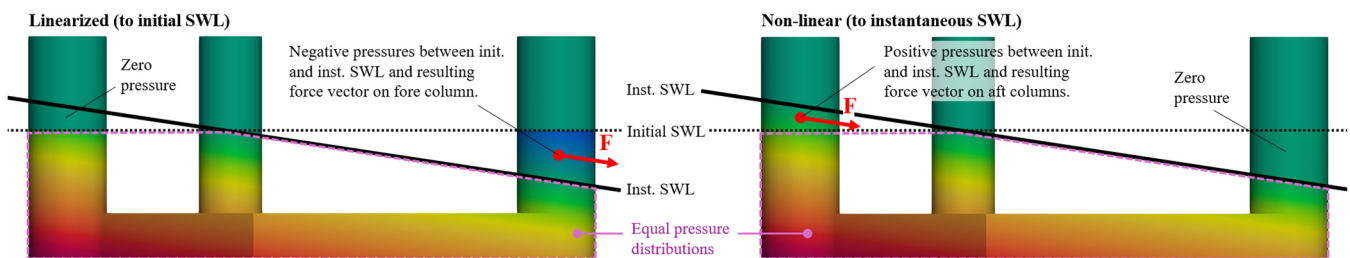
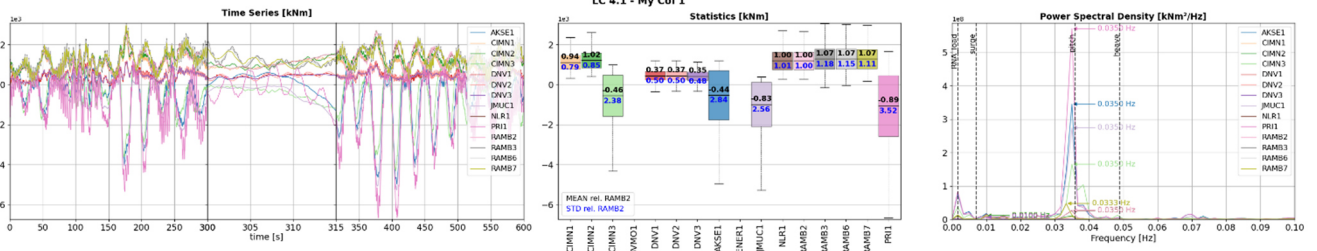


Figure 12: Impact of the linearization of hydrostatic pressures on the load paths distribution within the hull structure

In models with linearised distribution, the hydrostatic restoring moment is generated through negative pressures on the fore column. In models with non-linear distribution, however, it is generated through positive pressures on the aft columns. For LC4.1, the resulting force vector on the fore column is greater for models with a linearised distribution. This increases the sectional loads in the column base and throughout the pontoon sections, consequently increasing the panel-averaged stresses in the respective panels.

The *PRII* model uses a non-linear pressure formulation, and the deviations in stress statistics are likely partially related to this approach. However, the impact of the pressure formulation on the CentCol panel is unexpected; therefore, the remaining deviations are likely due to the simplifications of the beam-based structural model.

The impact of pressure formulation becomes very evident when looking at the sectional bending moments at the base of fore column (Col_1), see Fig. 13 (for *CENER1* and *BVMO1* no results were available).

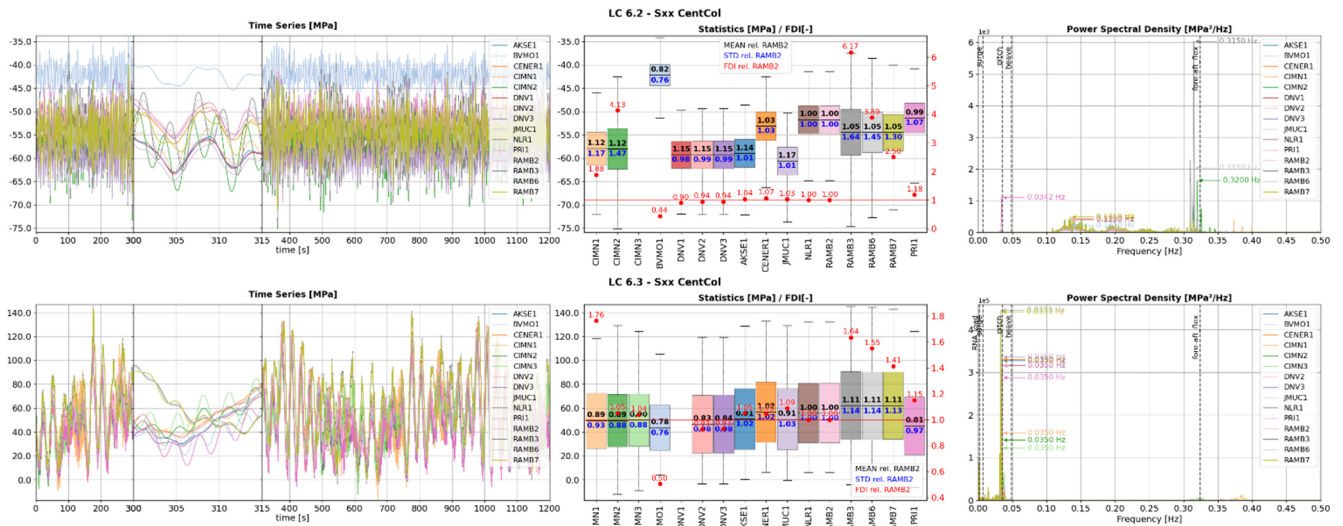


395 **Figure 13: Bending moment at the base of fore column (Col_1) for LC4.1 (no wave, RNA load only). The effect of non-linear formulation for hydrostatic pressures is evident in models *CIMN3*, *AKSE1*, *JMUC1* and *PRI1***

7.2 Load cases LC6.2/6.3 (irregular waves $H_s = 1.0$ m, with/without RNA load)

The panel-averaged stresses (S_{xx}) for the CentCol and P1_S3 panels are evaluated for load cases LC6.2 (without RNA load) and LC6.3 (with RNA load), with irregular waves and $H_s = 1.0$ m, on a case-by-case basis. This allows assessing the impact of the RNA loads directly. Evaluation of the other panels leads to similar conclusions regarding the overall behaviour of the different models and is therefore omitted.

Figure 14 shows the stresses in panel CentCol. Without an RNA load (LC6.2), the tower leans forward, resulting in compressive stresses and small, motion-induced fluctuations from the low wave amplitude seaway with $H_s = 1.0$ m. The stress spectrum is governed by wave excitation and, for flexible models *CIMN2* and *RAMB3/6*, exhibits distinct peaks around the 1st fore-aft bending mode. The RNA load (in LC6.3) leans the tower in opposite direction and results in tensile stresses with much more pronounced fluctuations (higher STD values). The stress spectrum shows much higher energy content and is dominated by RNA-induced pitch motions.

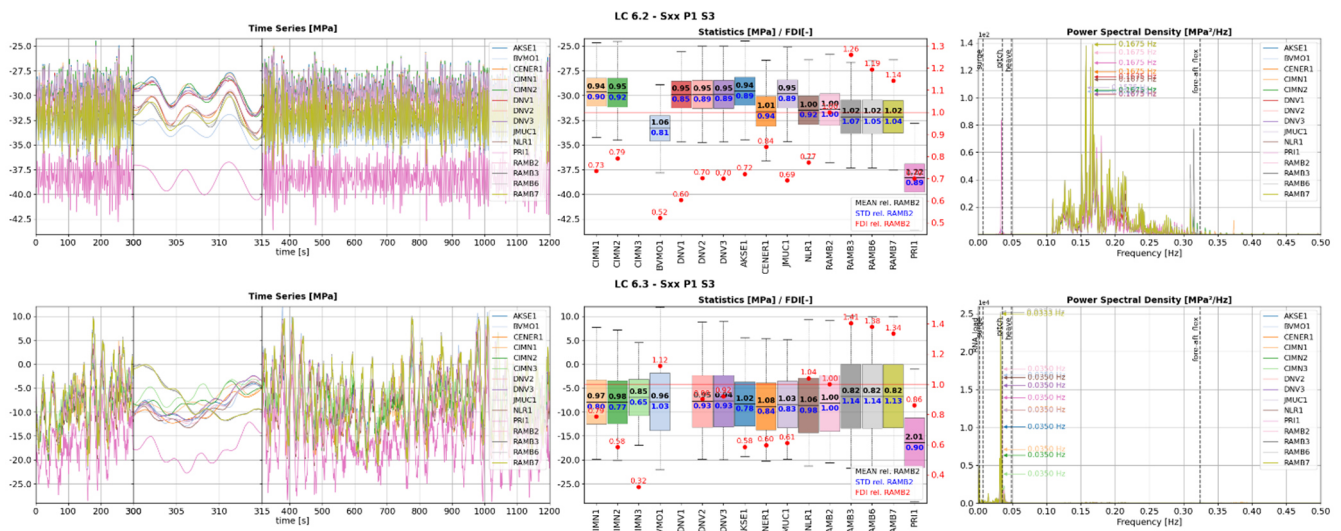


410 **Figure 14: Comparison of panel-averaged stresses (S_{xx} component) in panel CentCol for LC6.2 (without RNA load) and LC6.3 (with RNA load)**



While some differences (especially in mean values) exist, the overall agreement between the models is good. In particular, rigid body models show good agreement in STD and FDI values. Here, *BVMO1* deviates from the others. In LC6.2, the flexible models *RAMB3/6/7* and *CIMN1/2* show significantly higher STD values and especially FDIs compared to rigid body models. The *RAMB3* model without structural hull damping experiences excessive excitations at the 1st fore-aft bending mode, which reduce with the increased structural damping in *RAMB6/7* models but still being pronounced. The RNA load in LC6.3 stabilizes the structural response of the flexible models, making the results and conclusions very similar to those from LC4.1 (RNA only).

Figure 15 shows the stresses in panel P1_S3. Similarly to panel CentCol, the stress spectrum is dominated by wave excitation in LC6.2 and by RNA-induced pitch motions with a higher energy content in LC6.3. However, the excessive impact of the structural dynamic effects observed in the flexible models in panel CentCol is not seen in panel P1_S3. The impact of the non-linear pressure application (*CIMN3*, *AKSE1*, *CENER1*, *JMUC1* and *PR11*) on the calculated FDIs becomes pronounced in this panel (close to the fore column) in LC6.3, which aligns with the observations from LC4.1 (RNA only).



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Figure 15: Comparison of panel-averaged stresses (Sxx component) in panel P1_S3 for LC6.2 (without RNA load) and LC6.3 (with RNA load)

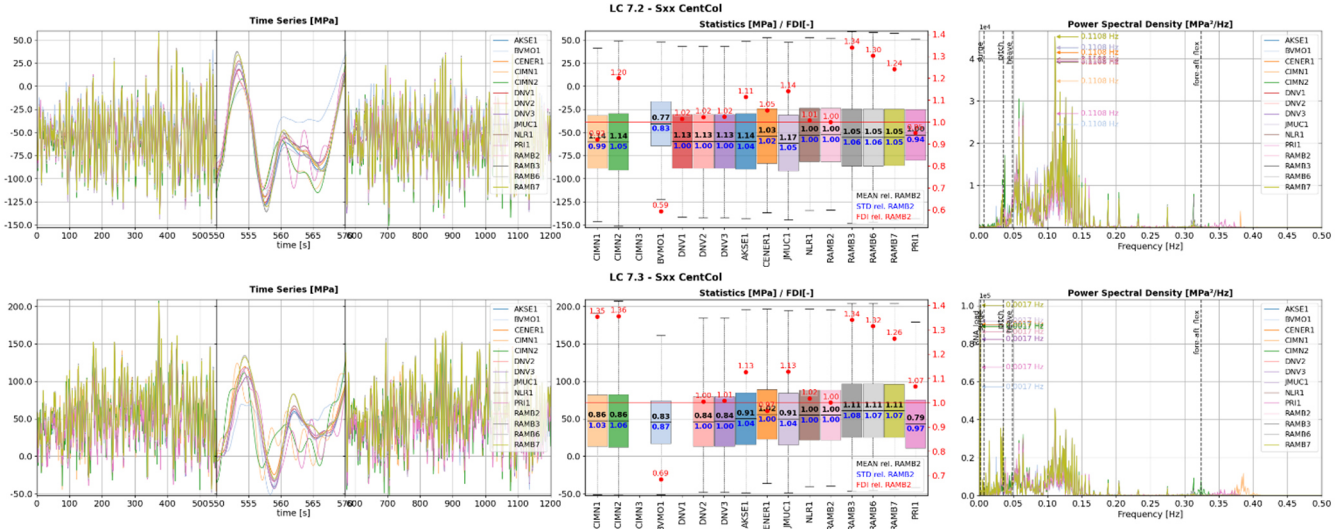
7.3 Load cases LC7.2/7.3 (irregular waves $H_s = 11.0$ m, with/without RNA load)

Similarly to Sect. 7.2, the evaluation of the panel-averaged stresses (Sxx) for load cases LC7.2 (without RNA load) and LC7.3 (with RNA load), with irregular waves with $H_s = 11.0$ m, is limited to the panels CentCol and P1_S3. Evaluation of other panels leads to similar conclusions and is therefore omitted.

Figure 16 shows the stresses in panel CentCol. Without an RNA load (LC7.2), the stress spectrum is completely governed by the high amplitude wave excitation and resulting floater pitch response, with small peaks around the 1st fore-aft bending mode appearing in flexible models. The low-frequency RNA load shifts the distribution in the power spectral density in



435 LC7.3 and highest peaks occur at the RNA load frequency and the pitch natural frequency. Still, the wave energy content is very pronounced.



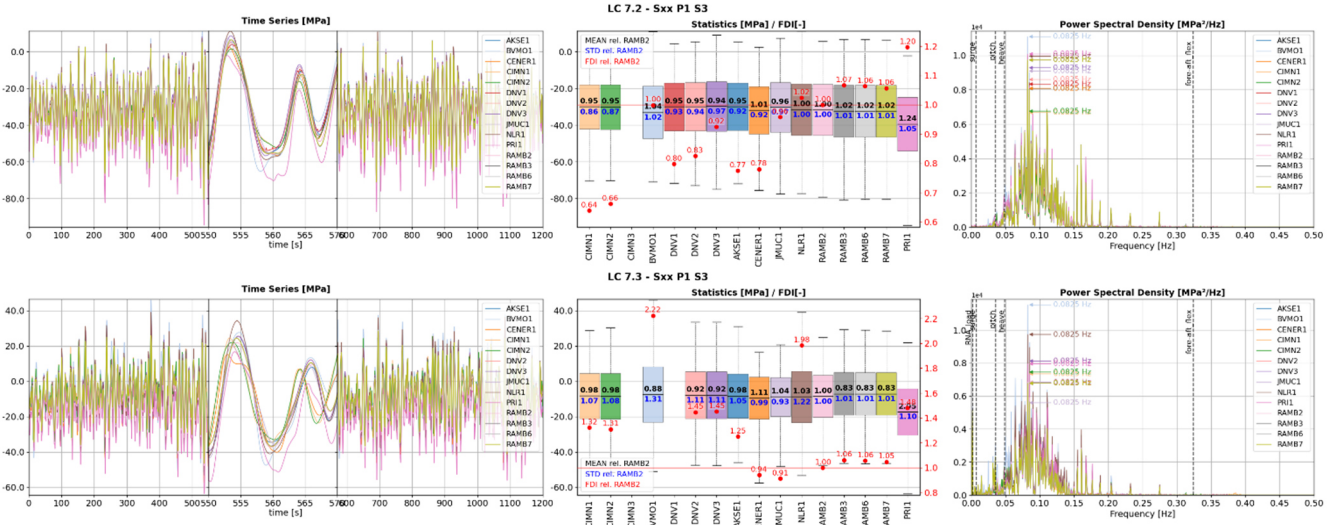
440 **Figure 16: Comparison of panel-averaged stresses (Sxx component) in panel CentCol for LC7.2 (without RNA load) and LC7.3 (with RNA load)**

The time series plots in Fig. 16 reveal a good overall agreement between most of the models. The time series for all rigid body models follow a very similar course, except for *BVMO1*. This is due to the weak alignment of its global analysis model, which is potentially caused by the deviating formulation of the drag coefficients. The flexible models are generally closer to the rigid body ones and are less scattered than in other LCs. This good agreement is also reflected in the statistics plots, with most mean and standard deviation (STD) values being relatively close. This indicates a good alignment between the global analysis models in terms of wave response. Most models compare very well on the applied hydrodynamic loads (radiation, diffraction and drag), which clearly govern the loads in LCs 7.2 and 7.3.

Rigid body motions dominate structural responses and structural dynamics, which makes the effect of hull flexibility less visible in time series and STD values. Nevertheless, the fatigue damage indicators (FDIs) highlight its importance; see the results for *CIMN1/2* and *RAMB3/6/7*. The FDIs of the flexible *PR11* model do not align with these models, which is probably due to the generally lower accuracy of the beam-based structural model.

The *AKSE1* and *JMUC1* models have higher FDI values than other rigid body models. This may be due to their non-linear treatment of hydrostatic pressures. However, this cannot be fully confirmed with the results for *CENER1* and *PR11*, which also treat pressures in a similar way, nor by *CIMN3*, for which no results were available.

455 The results for panel P1_S3 in Fig. 17 lead to similar overall observations. While the time series and the mean and STD value statistics are very well aligned, the FDIs show discrepancies that are, in some cases, significant, even among similar rigid body models (see *BVMO1*, *DNV2/3*, *NLR1* and *RAMB2*). These discrepancies cannot be explained by differences in the consideration of structural dynamics (*RAMB2* is similar to *RAMB3/6/7*) or hydrostatic pressure treatment.



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Figure 17: Comparison of panel-averaged stresses (Sxx component) in panel P1_S3 for LC7.2 (without RNA load) and LC7.3 (with RNA load)

8 Conclusions and further work recommendations

This work investigated a variety of models that approach the “global-to-local” (i.e. ILA-to-FEA) load transfer and structural assessment in different ways. The models differ in terms of their general workflows, methods for calculating and applying hydrostatic and hydrodynamic pressures, approaches to considering structural dynamic effects, etc. The purpose of this study was not to identify the best model in terms of accuracy, efficiency or performance. Also, the overall approach and results obtained in this study hardly allow the selection of the most accurate method, as no real reference exists (e.g. model test-based). Nevertheless, the following general conclusions can be drawn from the evaluation of the structural responses calculated with different models:

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- The accuracy of the global performance model is the most important factor. It is essential to create an accurate global performance model that adequately captures relevant global load effects to obtain accurate local structural responses.
- Structural dynamic effects contribute significantly to structural responses in some cases, making them important to capture. While the hull structure in this study was intentionally made very soft to better visualise these effects, it is expected that they will not be negligible for most real-world steel floating structures. Their contribution to fatigue in low Hs sea states appears to be particularly relevant. While different modelling approaches were employed to capture these effects – namely, structural reduced-order models based on generalized modes (*CIMNI/2/3*) and flexible multi-body ILA models (*RAMB3/6/7* and *PRII*) – they all proved effective, though showing some degree of scatter in the results.

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- Simplified structural models (such as the beam-based *PRII* model) expectedly yield less accurate results and cannot replace shell element FE models in resolving the “global-to-local” load transfer. However, their application may be justified in engineering practice at early conceptual design stage to increase efficiency and provide high-level identification of structural utilisation.
- 485 • Linearisation of pressures (i.e. application of pressures up to the initial undisplaced SWL) may affect the distribution of load paths within the structure and the calculated structural responses. The significance of this effect is expected to depend heavily on the shape of the hull, the location at which the structural responses are evaluated and the sea state (i.e. the resulting heave, roll and pitch motions). In this context, aligning the hydrostatic modelling (linear vs. non-linear) between the ILA and FEA models is advisable to maintain load balance after load transfer.
- 490 • Models based on unit loads/response superposition appear to manage the “global-to-local” load transfer well. While having some inherent restrictions (e.g. related to pressure linearization), they generally lead very similar results as the models solving the FEA step-by-step. Their application in engineering industry practice appears to be well justified, especially considering their usually substantial efficiency gains.

The study provided valuable insights into the “global-to-local” transfer of hydrostatic and hydrodynamic loads and
495 highlighted the importance of incorporating structural dynamics. However, as these dynamic effects are not yet fully proven, further verification and validation will be required as methodologies improve.

Most models used in this study were based on linear potential-flow solutions, evaluating hydrostatic and hydrodynamic pressures up to the initial undisplaced SWL. While the study successfully isolated the impact of this simplification for hydrostatic pressures, the effects of hydrodynamic non-linearities could not be entirely decoupled. Nevertheless, this
500 modelling aspect is relevant; as observed in WP2.1 (Bergua et al., 2026), incorporating non-linear Froude-Krylov corrections up to the instantaneous water level yielded more accurate results. Therefore, future work focused on transferring non-linear hydrodynamic effects to the FEA level is recommended, potentially benchmarking against Computational Fluid Dynamics (CFD).

Furthermore, for the sake of simplicity, the current models did not account for ballast. Considering ballast in structural
505 assessments is not straightforward and can be done in different ways, such as distributing the ballast mass to nodes of the FE mesh or by applying generalised pressure distributions. Studying the effect of different modelling techniques on the calculated local structural responses and their implications for structural design would be beneficial.

Data availability

The numerical models and results supporting this study are archived in the open-access Zenodo repository:

510 [\[LINK WILL BE ADDED IN FINAL PUBLICATION\]](#)



Author contributions

Michael Karch prepared the manuscript with support by Friedemann Borisade. The reference ILA model (OrcaFlex) and FE mesh (exported from ANSYS) were provided by Ramboll to the project participants together with additional model descriptions, parameter tables and reference results. Akselos supported in the initial CAD geometry model development. All
515 coauthors provided results and editorial changes.

Acknowledgments

This work was authored in part by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Critical Minerals and Energy Innovation Integrated Energy Systems Office. The views expressed in the article do not necessarily represent the
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