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Enhanced Methodology For Structural Load Analysis For Concrete Floating Offshore Wind Turbine Substructures

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OUR HISTORY

- Founded 1962 by Dr.techn.Olav Olsen.
- From October 2020 part of Artelia Group.
- 150 employees (Olav Olsen) - Artelia Group 8900 employees worldwide.
- Offices at Lysaker, Trondheim, Ålesund and Bergen, Norway.
- Structural and marine consulting company.
- Participates regularly in research and development projects.

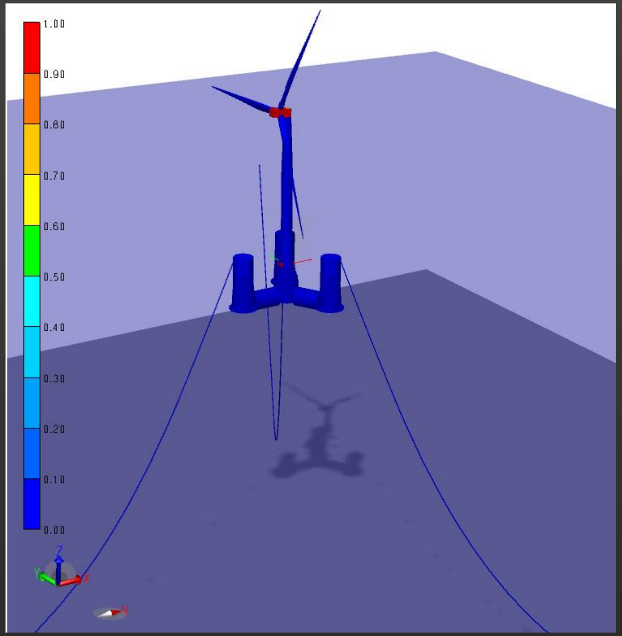
Floating wind pioneering since 2004

- Significant involvement in all Hywind projects.
- Developed OO-Star Wind Floater from 2010.
- IP rights for OO-Star Wind Floater acquired by Bouygues Travaux Publics. (BYTP) in 2022. We are now supporting BYTP in the further development of OO-Star.

Dr.techn. Olav Olsen

Capabilities Offshore wind

- Substructures.
  - Bottom fixed and floating.
  - Steel and concrete.
  - Concept development.
  - Design and analysis (ShellDesign).
  - Geotechnics.
- Mooring and anchors.
  - System configuration.
  - System design.
  - Geotechnics.
- Installation.
  - Method development.
  - Installation concepts.
- Fully coupled simulations.
  - SIMA.
  - Orcaflex.
  - Bladed.
  - 3DFloat.
  - Deeplines.
- Cost models.
  - Fabrication and installation.
    - Substructure.
    - Mooring.
    - Anchors.
- Computational Fluid Dynamics (CFD).



CONTENTS

- Background.
- Motivation.
- Sectional body modelling for integrated load analyses (ILA).
- Generation of hydrodynamic pressures from integrated load analyses for substructure design.
- Screening of critical time intervals for ULS/ALS/SLS concrete substructure design.

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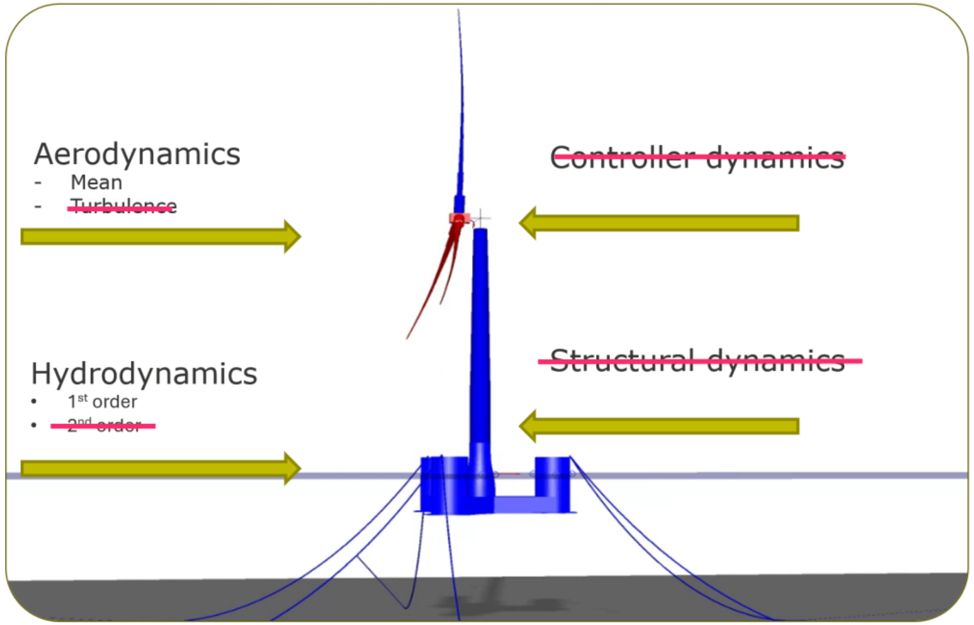
BACKGROUND – OIL AND GAS TO FOWT

> Traditional FD analysis approaches applied for substructures in O&G do not capture all relevant load effects for FOWTs.
  - Aerodynamics.
  - Controller dynamics.
  - Structural dynamics.
  - Hydrodynamic 2nd order loads.
  - No coupled effects.

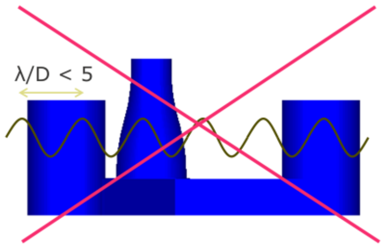


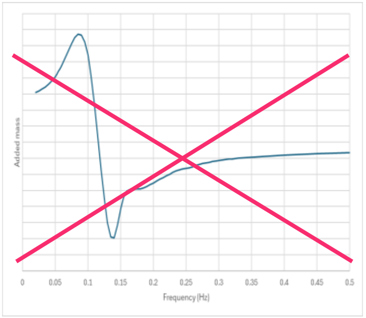
> Integrated load analyses (ILA) are required.

BACKGROUND – ILA OF FOWT

> Substructure as flexible beam elements assigned with Morison load formulation typical approach for FOWT substructure design.

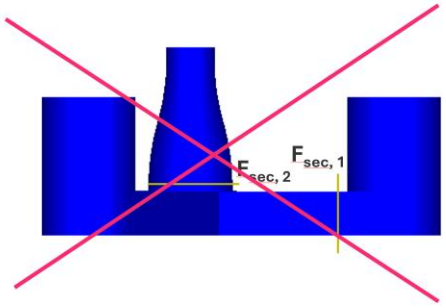
- Pros:
  - Extraction of substructure sectional loads.
  - Representation of substructure flexibility.
  - Stretching of wave potential to instantaneous free surface possible.
- Cons:
  - Only valid for long waves (relative to structure), 1st and 2nd order diffraction loads not represented.
  - Constant added mass (and radiation damping), i.e. tuning of sectional added mass required and dependent on sea state.





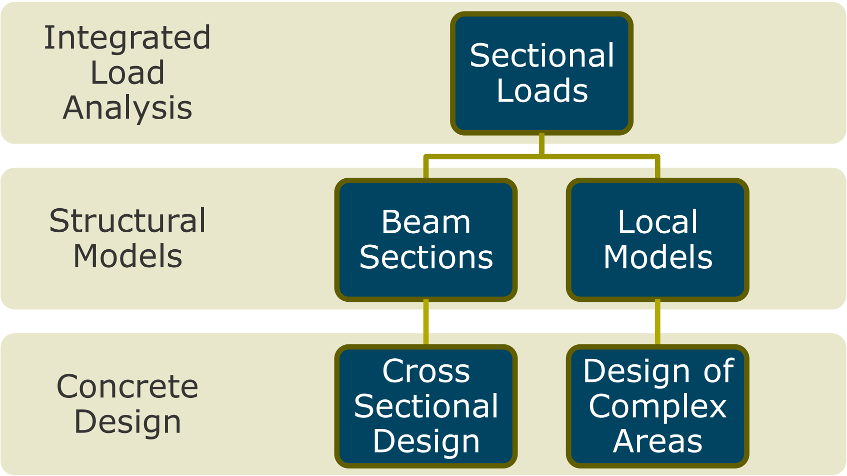
> Substructure as rigid potential theory body for FOWT mooring/power cable/tower design.

- Pros:
  - Not restricted to long waves.
  - Frequency dependent added mass/radiation damping.
  - Hydrodynamic mean and slowly varying loads included through QTFs.
- Cons:
  - Extraction of substructure sectional loads not possible.
  - Corrections for rigid substructure typically needed.
  - Integration of wave potential limited to mean sea level.

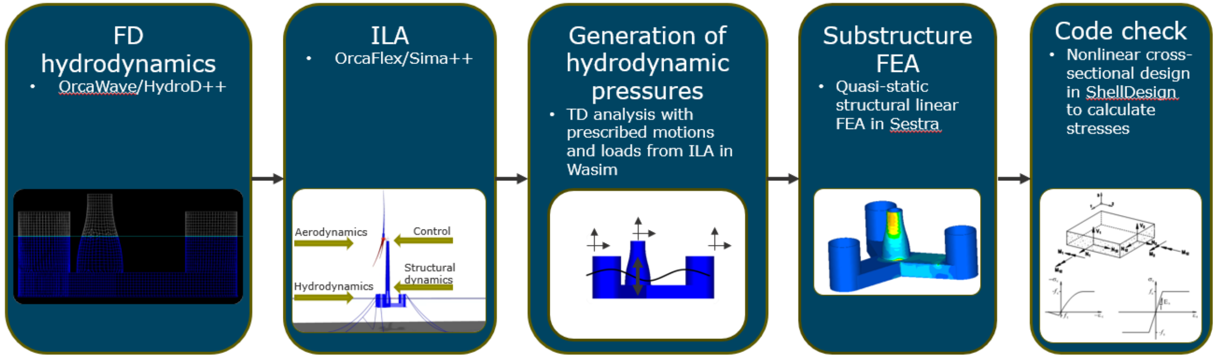


BACKGROUND – CONCRETE SUBSTRUCTURE DESIGN OF FOWT

- Sectional loads from ILA.
  - Cross sectional design based on beam sections.
  - Design of complex areas based on local FEA.
  - Correction required if beam representation in ILA is not representative for the structural member.
  - Complete load distribution not established.



- Procedure to capture complete load distribution:
  - Generation of hydrodynamic pressures from ILA through TD potential theory in Wasim.
  - FE analysis in Sestra.
  - Distribution of loads from ILA calculated for the entire substructure and used for shell cross-sectional design in ShellDesign accounting for nonlinear material behaviour.



MOTIVATION

Main motivation

- Can more accurate and efficient design workflows for concrete substructures be established?
  - Suggested: Screening of critical time intervals and validation of substructure responses from generation of hydrodynamic pressures through ILA sectional body model.

Bonus motivation

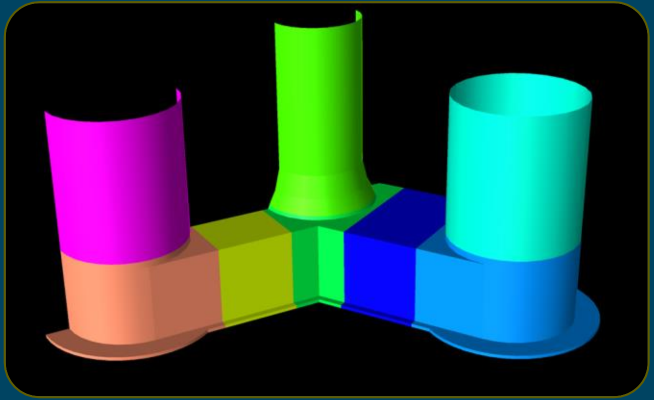
- Can a single ILA model for both substructure, mooring/power cable, and tower design be established?
  - Suggested: ILA sectional body model.

Sectional body modelling for ILA

ILA SECTIONAL BODY MODEL - OVERVIEW

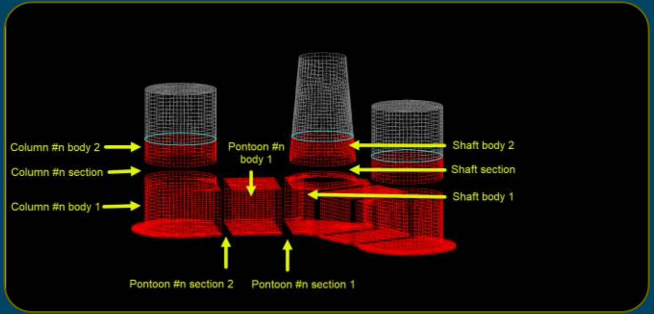
Mesh generation

- Sectional body mesh generation
- E.g. GeniE.



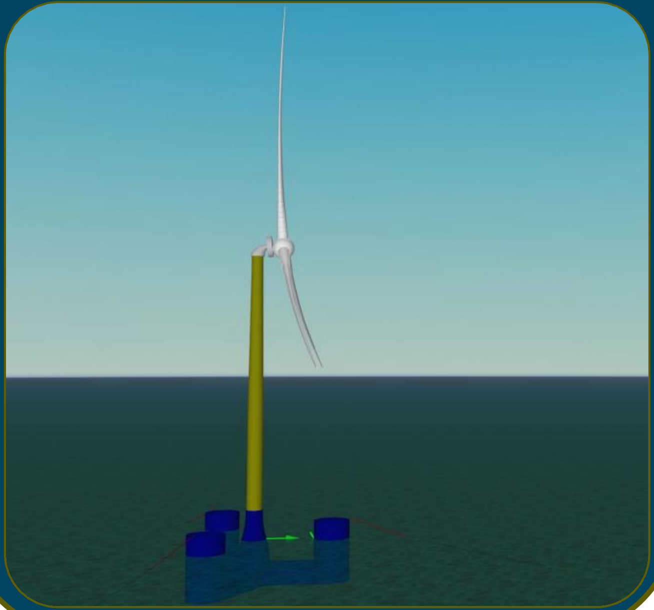
FD multibody potential theory analysis

- Establish 1st order wave load transfer functions, added mass and radiation damping for each sectional body.
- OrcaWave.



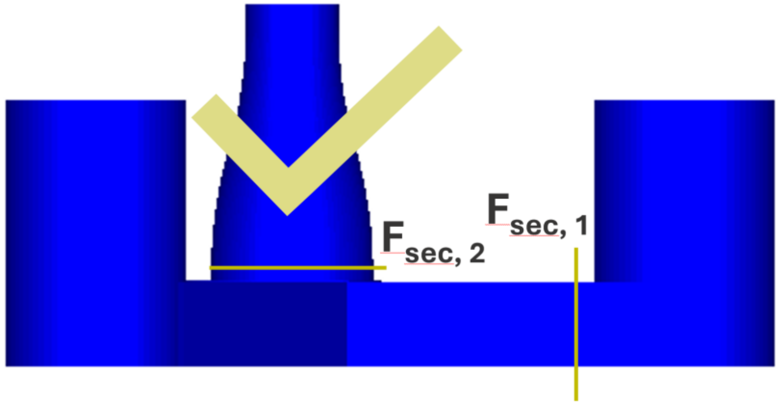
TD integrated load analysis

- Establish global responses, e.g. substructure sectional loads.
- OrcaFlex.



ILA SECTIONAL BODY MODEL – PROS & CONS

- Pros:
  - Extraction of substructure sectional loads.
  - Representation of substructure flexibility.
  - Not restricted to long waves.
  - Frequency dependent added mass/radiation damping.
  - Hydrodynamic mean and slowly varying loads included through QTFs.



- Cons:
  - Integration of wave potential limited to still water level.
  - More computationally demanding with increased number of bodies.

- Pros from both beam model and single body.

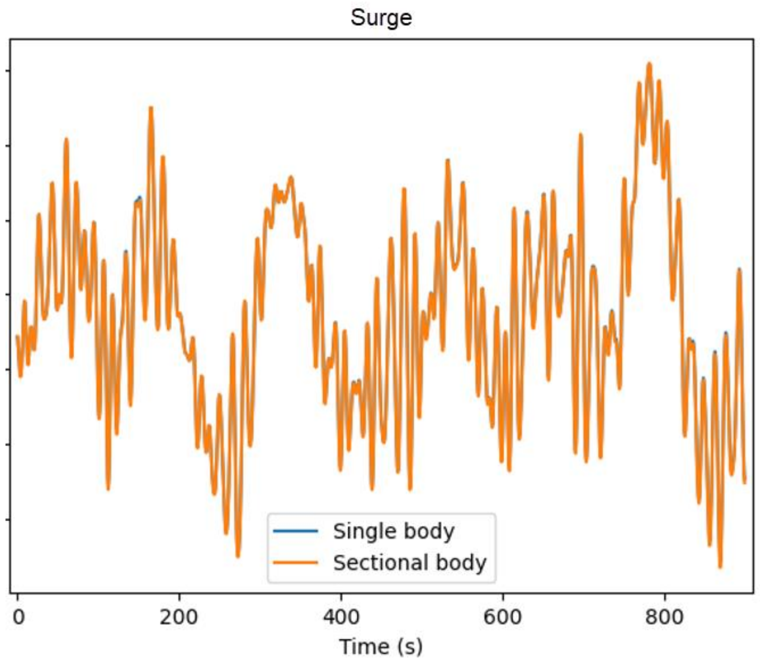
ILA MODELS HYDRODYNAMIC RESPONSE COMPARISON

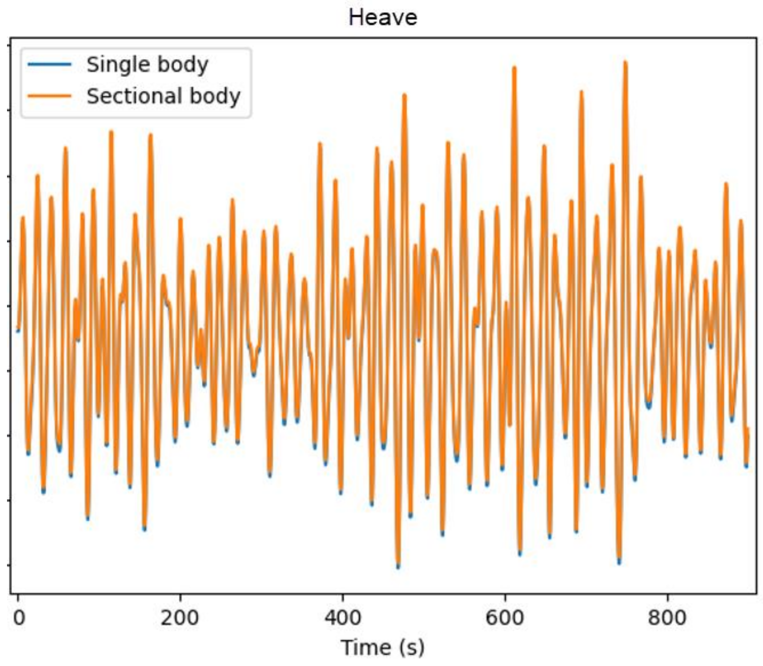
- Substructure single body model.
  - 1st and 2nd order hydrodynamic loads from FD potential theory solver.
  - Frequency dependent added mass.
  - Single body connected to mooring/tower.

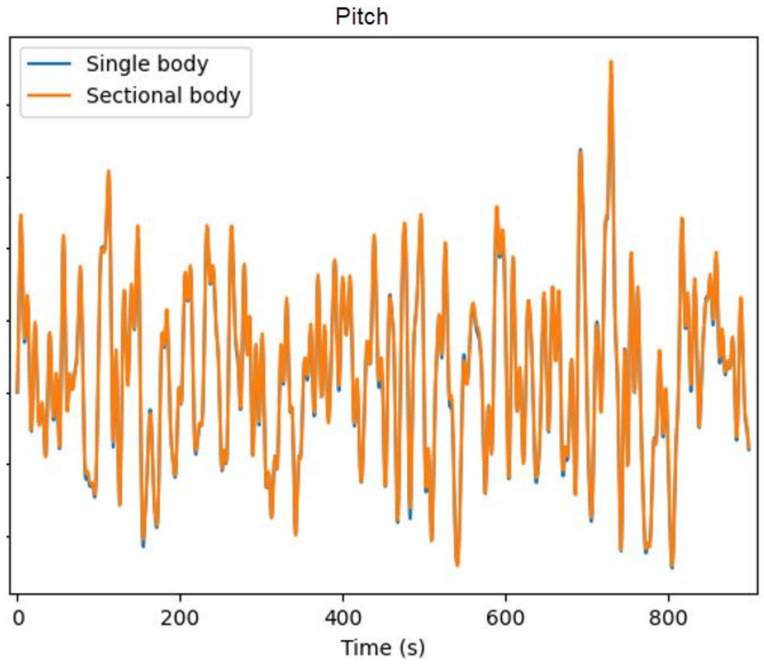
- Substructure sectional body model.
  - 1st and 2nd order hydrodynamic loads from FD potential theory solver.
  - Frequency dependent added mass.
  - Multiple sectional bodies rigidly connected.
  - Relevant bodies rigidly connected to mooring/tower.
  - Note: underlying beam model possible, introducing substructure flexibility.

IRREGULAR WAVE RESPONSE

> Rigid body motion

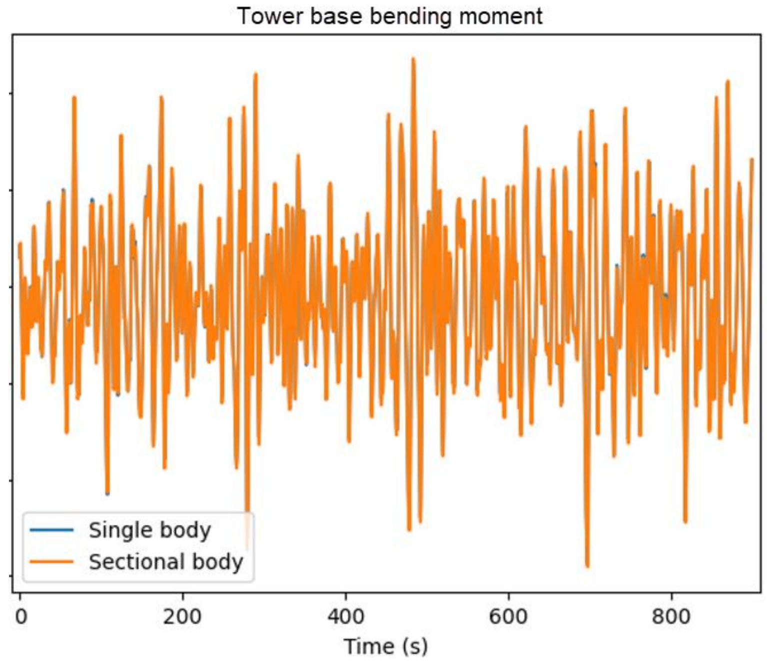


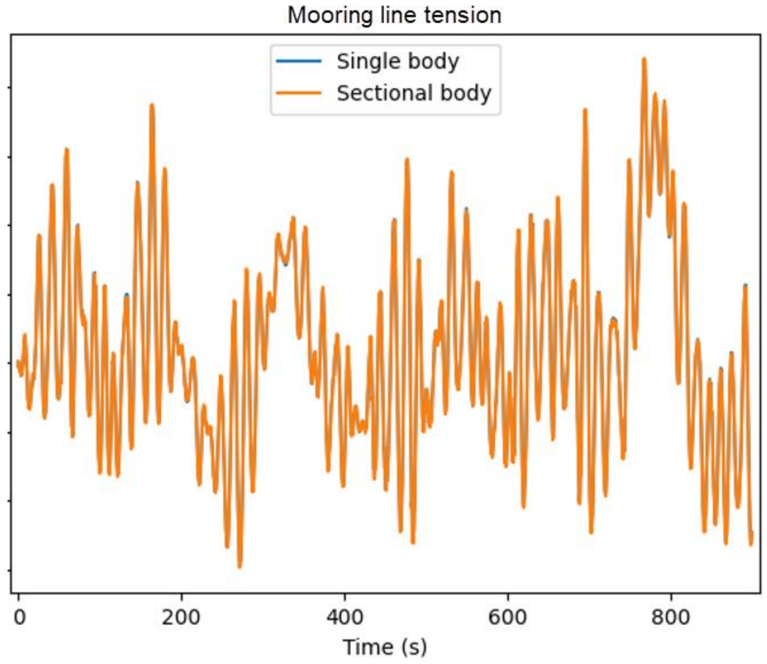




IRREGULAR WAVE RESPONSE

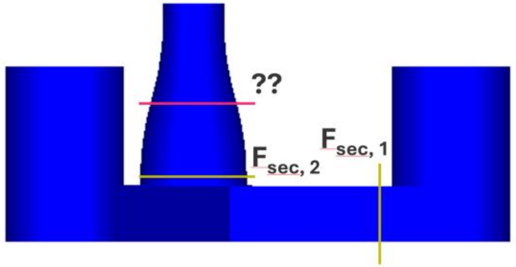
> Tower and mooring loads





CONCLUSION

- Sectional body model produces the same responses as the traditional single body model.
- Sectional body improvements:
  - Extraction of substructure sectional loads from potential theory ILA model.
  - Frequency dependent added mass/radiation damping.
  - A single ILA model can be used for estimation of tower, substructure, and mooring loads.
  - Distributed hydrodynamic loading – to what extent depends on number of sectional bodies.
  - Substructure flexibility possible with underlying beam model.
- Sectional body limitations:
  - Direct pressure integration required for quadratic load calculation in FD solver, which is more prone to convergence than control surface methods.
    - Converged 2nd order potential solution very computationally demanding.
    - Remedy is to perform QTF calculation for single body in FD and lump the loads to centre shaft in ILA model – equivalent to how QTFs are included in traditional single body ILA models.
  - Increased ILA simulation time compared to single body.
  - Sectional loads available at limited sections, depends on number of sectional bodies.



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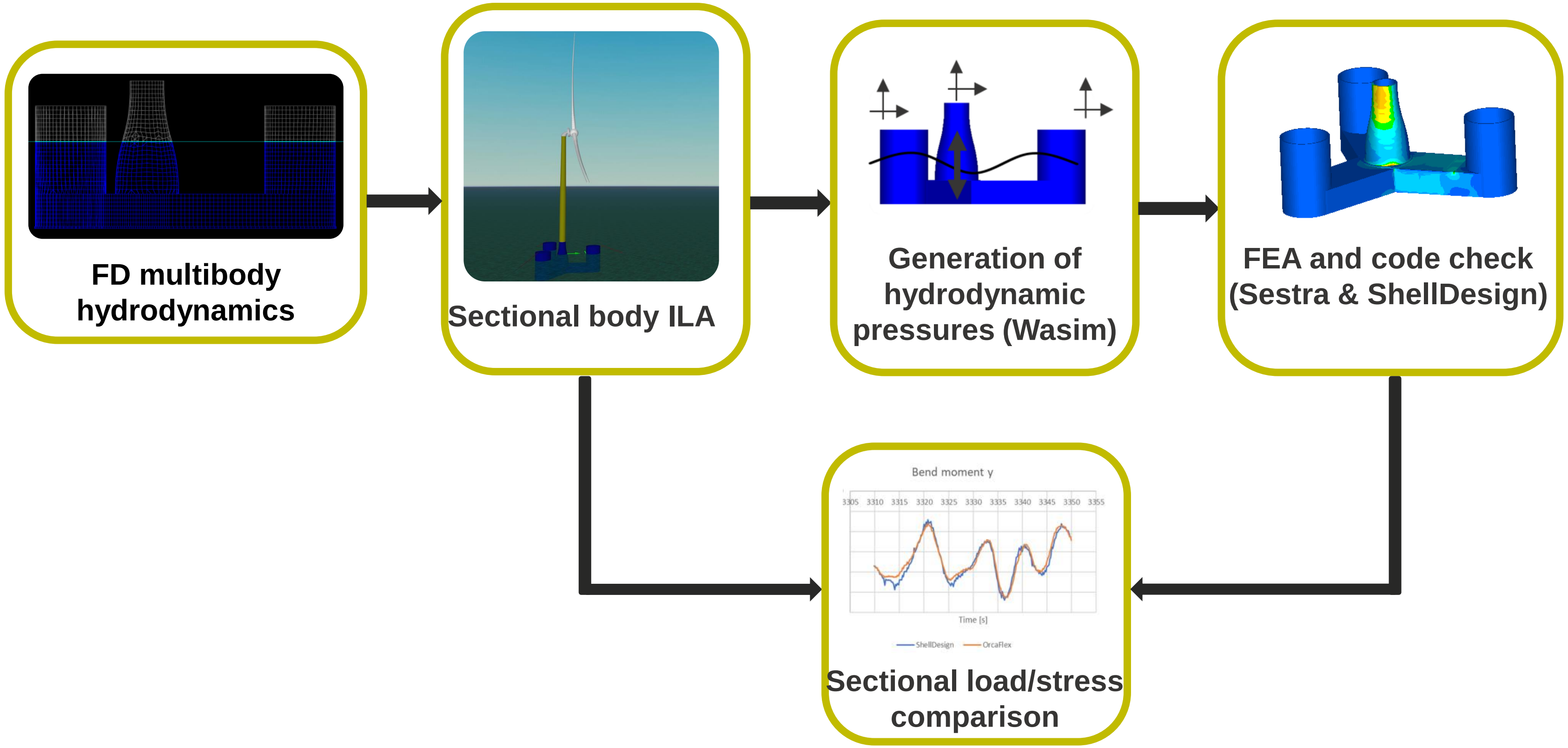
GENERATION OF HYDRODYNAMIC PRESSURES FROM ILA FOR SUBSTRUCTURE DESIGN

APPROACH OVERVIEW

- Sectional body ILA model to verify substructure sectional responses in *DNV Time Domain Direct Load Generation method*
- Some intermediate steps not indicated (e.g. transformation from ILA sectional loads to shell sectional loads, screening of critical time intervals for input to time domain substructure design)



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GENERATION OF HYDRODYNAMIC PRESSURES - PROS & CONS

- Pros:
  - Load effects included in ILA are combined with linear hydrodynamic pressure distribution over substructure.
  - Characteristic load situations can be analysed, which may reduce conservatism.

- Cons:
  - Some load effects must be excluded in ILA to ensure consistency in generation of hydrodynamic pressures.
    - To avoid out-of-balance forces in quasi-static FEA.
  - Computationally demanding.
    - Response reconstruction methods, such as the one proposed by DNV, are expected to significantly improve this.

SIMPLIFICATIONS ILA MODEL

- To ensure consistency with linear Wasim:
  - No 2nd order hydrodynamic loads.
  - Wave kinematics at global origin used to ensure identical wave kinematics.
  - No substructure current load.
  - No substructure wind load.

- Note: excluding 2nd order hydrodynamic loads, substructure current loads and substructure wind loads affect design loads.
  - Mainly substructure parts affected by mooring line loads.
  - Partly substructure parts where roll/pitch motion is important.

- Note: Morison elements are included in ILA but excluded in Wasim here. This can cause out-of-balance loads and affect design loads.
  - Morison elements can be included in Wasim.

METHOD VERIFICATION – IRREGULAR WAVES

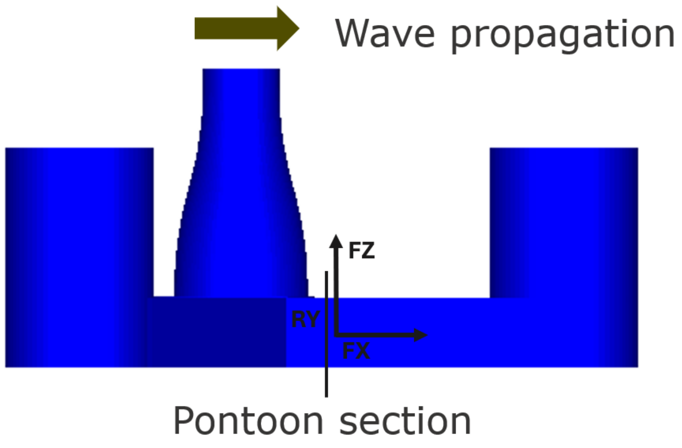
> Pontoon sectional load comparison.
  - ILA.
  - Wasim.
  - ShellDesign.

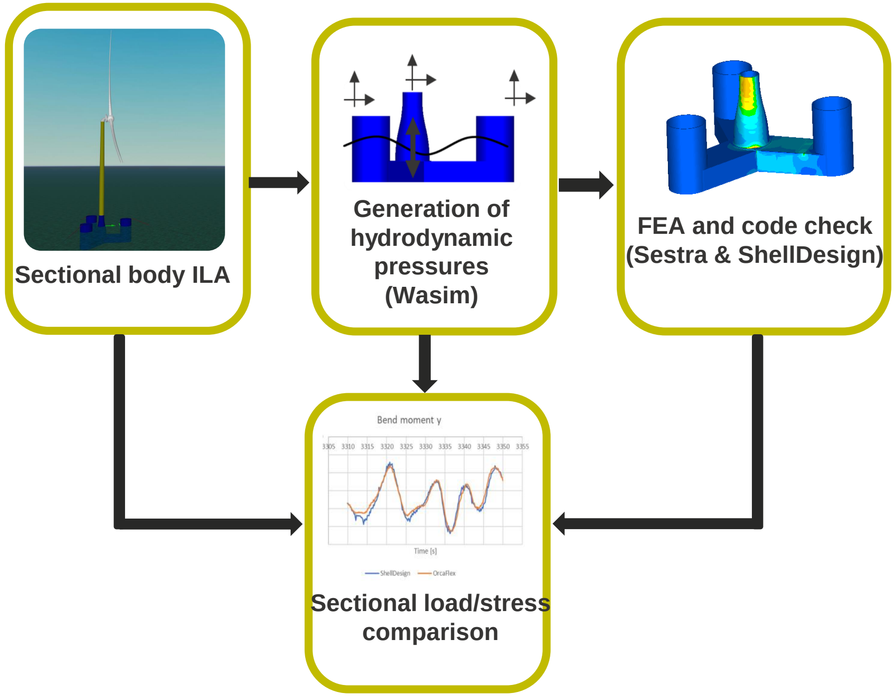
> Independent time domain linear Wasim analyses:
  - Only wave input from ILA.

> Dependent time domain linear Wasim analyses:
  - Wave, motion and load input from ILA.

> ESS - irregular sea state.

> No wind.





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METHOD VERIFICATION – IRREGULAR WAVES

Independent analyses

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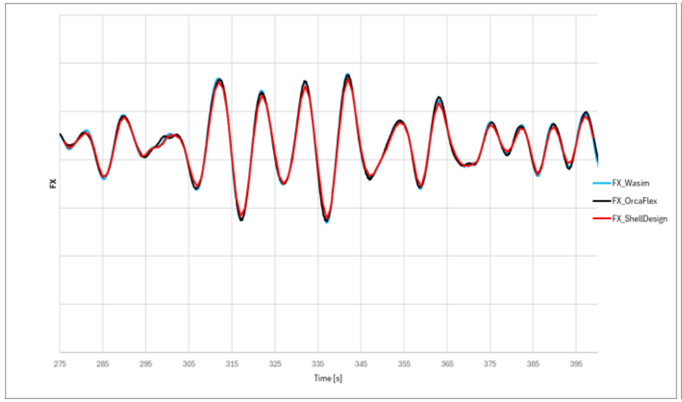

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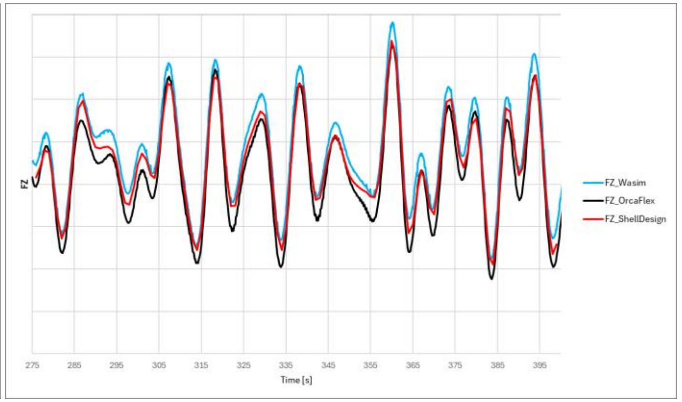

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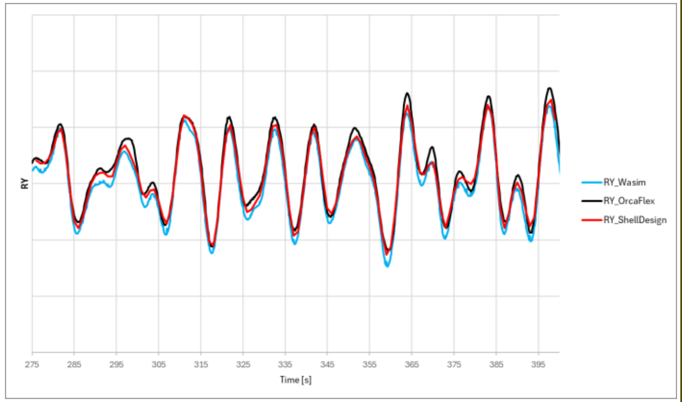
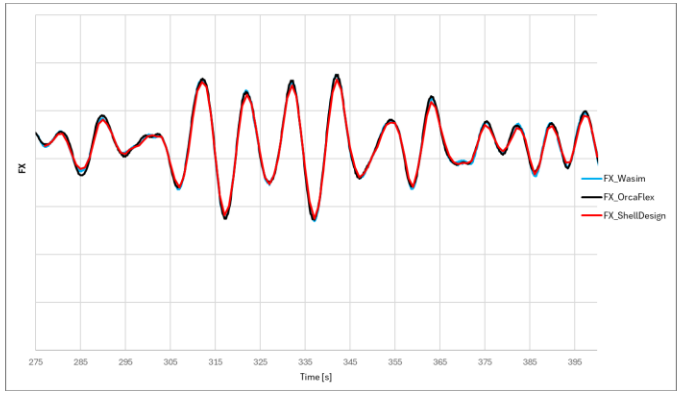


Dependent analyses

FX



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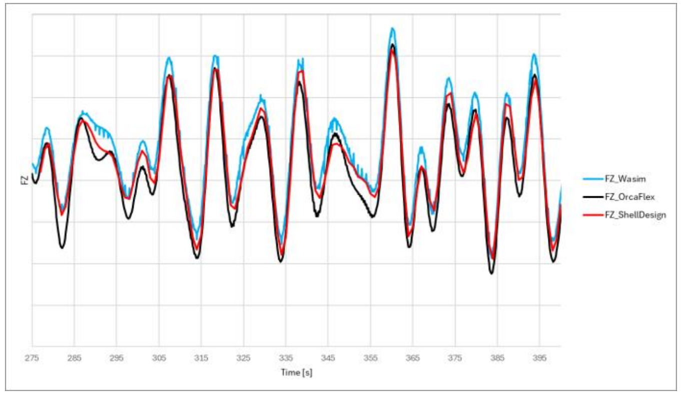

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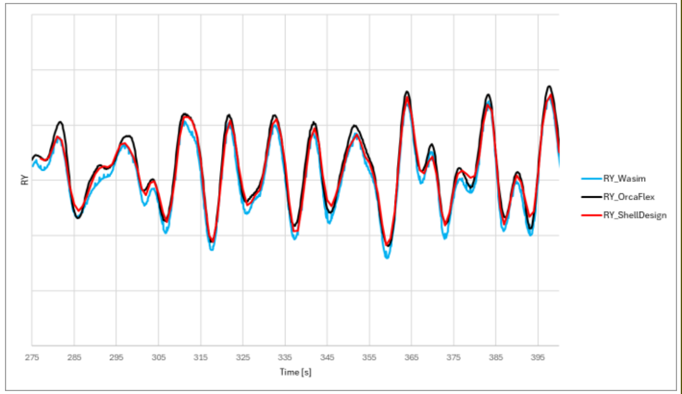


Note: OrcaFlex results are the same in “independent” and “dependent analyses”. Only Wasim and ShellDesign loads are altered.

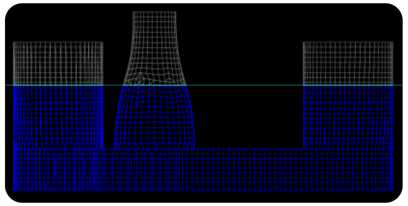
CONCLUSION

- Sectional loads are reasonably reproduced at different steps in the design workflow.
  - But some deviations remain to be solved.

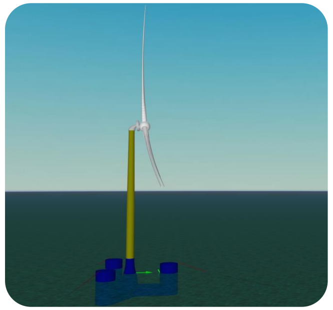
- Hydrodynamic pressure generation (Wasim), FEA (Sestra), and code check (ShellDesign) must be limited to critical time intervals due to computational effort.
  - Presented method currently limited to ULS/ALS/SLS.
  - Response reconstruction methods expected to significantly reduce computational effort of hydrodynamic pressure generation (Wasim) and FEA (Sestra).

SCREENING OF CRITICAL TIME INTERVALS FOR ULS/ALS/SLS CONCRETE SUBSTRUCTURE DESIGN.

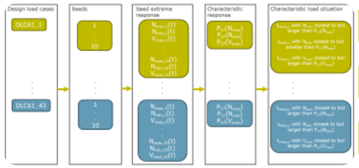
OVERALL APPROACH OVERVIEW



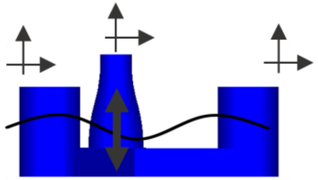
FD multibody hydrodynamics



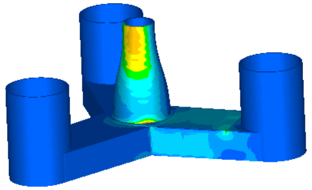
Sectional body ILA



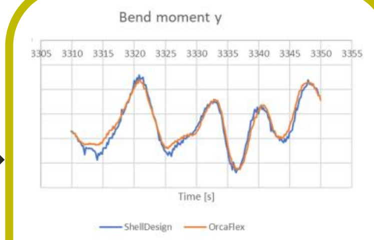
Screening of critical time intervals



Generation of hydrodynamic pressures (Wasim)

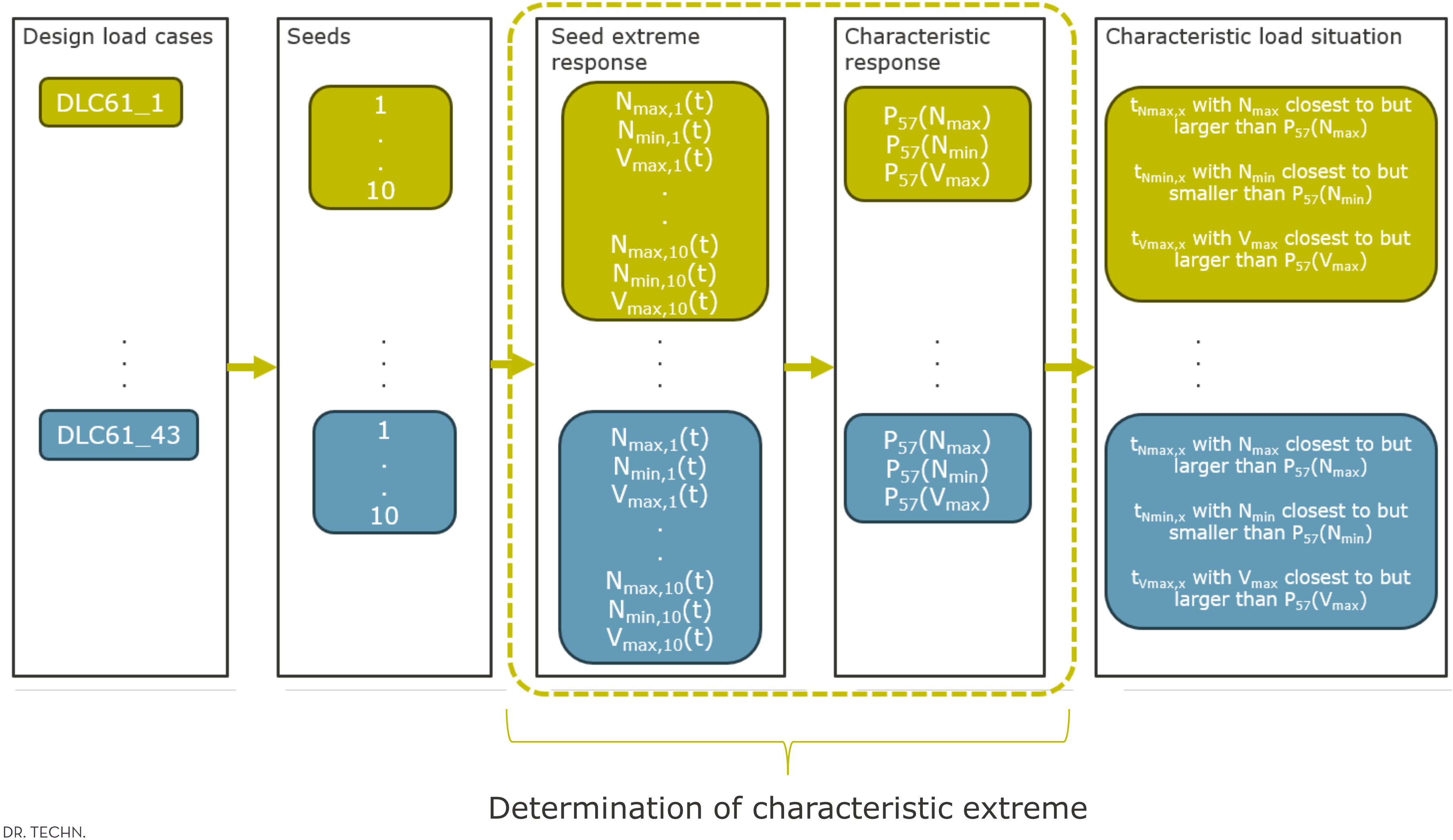


FEA and code check (Sestra & ShellDesign)

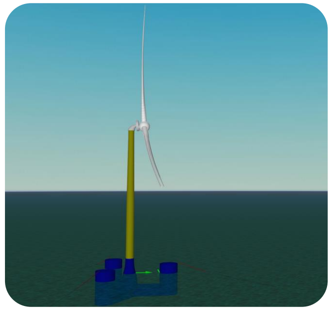


Sectional load/stress comparison

SCREENING OVERVIEW



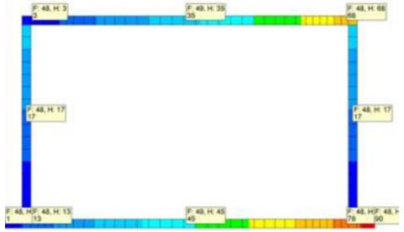
DETERMINATION OF CHARACTERISTIC EXTREME



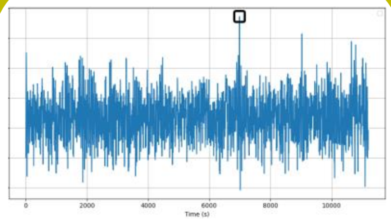
ILA beam section load time series

Local shell section response time series — Transformation matrix — Global beam force time series

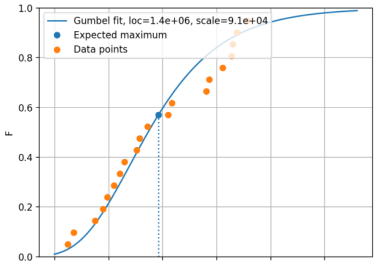
$$\begin{bmatrix} N_1(t_0) & \cdots & N_1(t_n) \\ N_2(t_0) & & N_2(t_n) \\ N_{12}(t_0) & & N_{12}(t_n) \\ M_1(t_0) & & M_1(t_n) \\ M_2(t_0) & & M_2(t_n) \\ M_{12}(t_0) & & M_{12}(t_n) \\ V_1(t_0) & & V_1(t_n) \\ V_2(t_0) & & V_2(t_n) \end{bmatrix} = \begin{bmatrix} K_{N,N_1} & \cdots & K_{M_z,N_1} \\ \vdots & \ddots & \vdots \\ K_{N,V_2} & \cdots & K_{M_z,V_2} \end{bmatrix} \cdot \begin{bmatrix} N(t_0) & \cdots & N(t_n) \\ V_y(t_0) & & V_y(t_n) \\ V_z(t_0) & & V_z(t_n) \\ T(t_0) & & T(t_n) \\ M_y(t_0) & & M_y(t_n) \\ M_z(t_0) & & M_z(t_n) \end{bmatrix}$$



Transformation ILA beam section loads to shell section loads

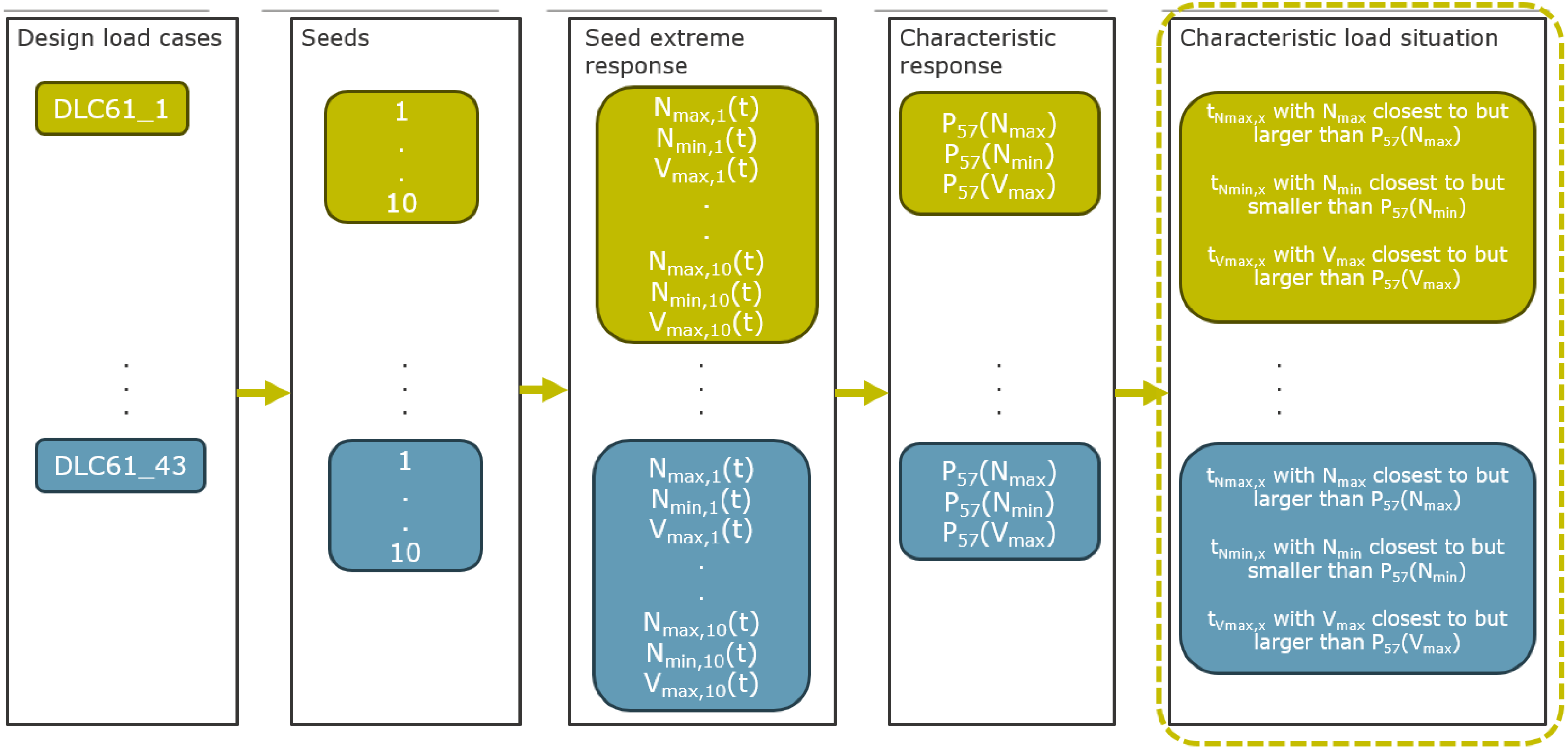


Extraction of stress seed extremes

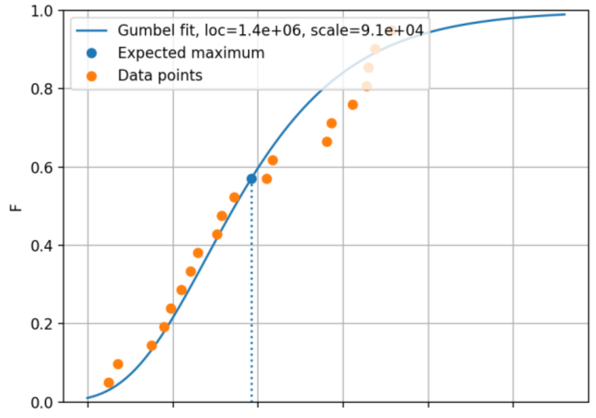


Determine characteristic extremes

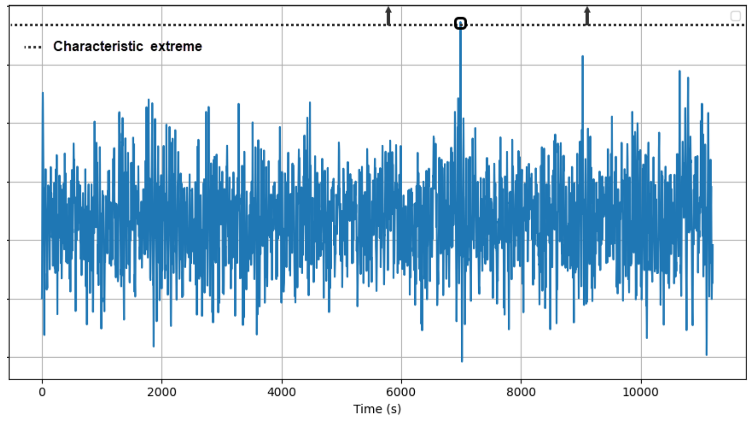
SCREENING OVERVIEW



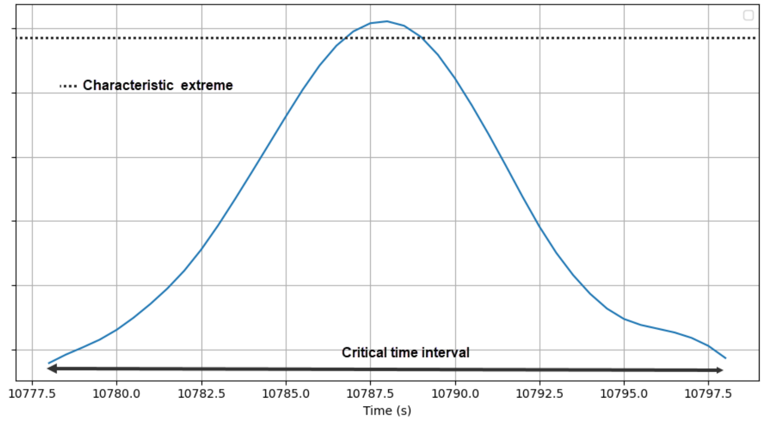
DETERMINATION OF CHARACTERISTIC LOAD SITUATION



Characteristic extreme



Characteristic load situation identified



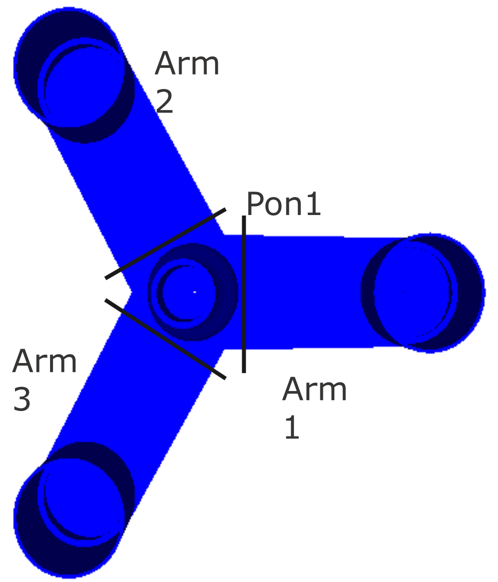
Critical time interval determined.

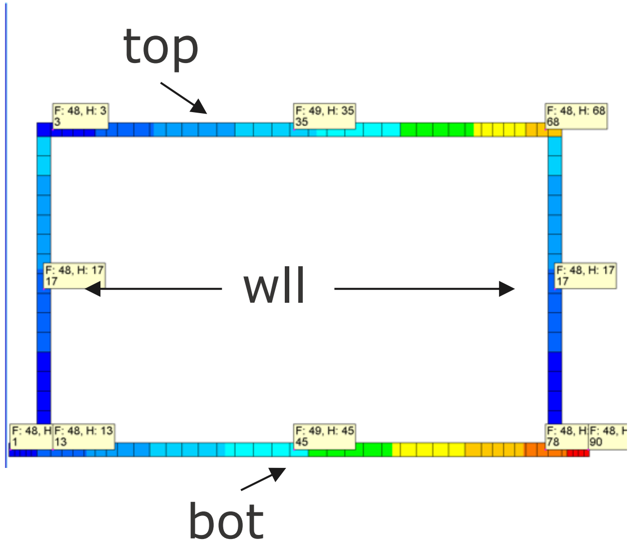
> Contour methods can be applied to ensure selected time interval is representative.

RESULTING CHARACTERISTIC LOAD SITUATION

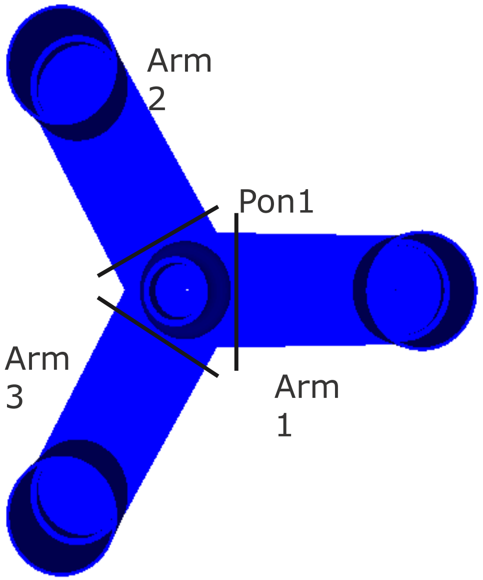
- 1 load situation per N_Max, N_Min, V_Max for each structural part.
  - Example pontoon section.

Screening parameter	Structural part	Arm	DLC	Seed	Time step
N_max	Pon1_bot	Arm1	DLC61_22	2	1031.4
N_max	Pon1_top	Arm1	DLC61_40	6	5325.6
N_max	Pon1_wll	Arm1	DLC61_31	8	9127
N_min	Pon1_bot	Arm1	DLC61_40	1	1795.6
N_min	Pon1_top	Arm1	DLC61_22	6	6061
N_min	Pon1_wll	Arm1	DLC61_22	2	1376
V_max	Pon1_bot	Arm1	DLC61_1	10	5451.2
V_max	Pon1_top	Arm3	DLC61_25	3	1741.4
V_max	Pon1_wll	Arm2	DLC61_43	8	2112.8

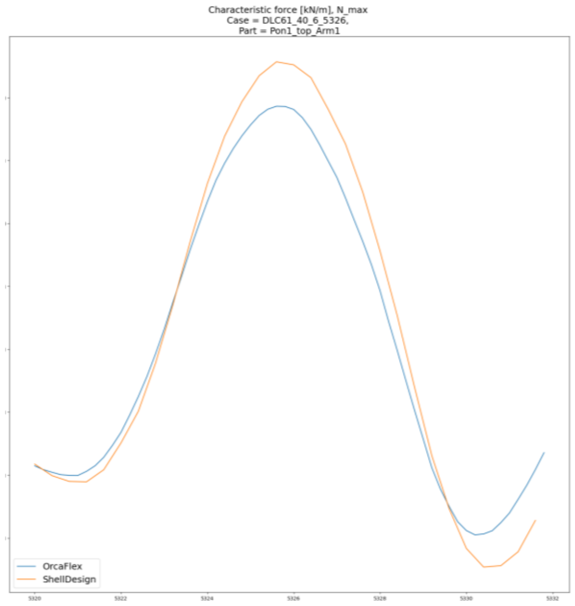


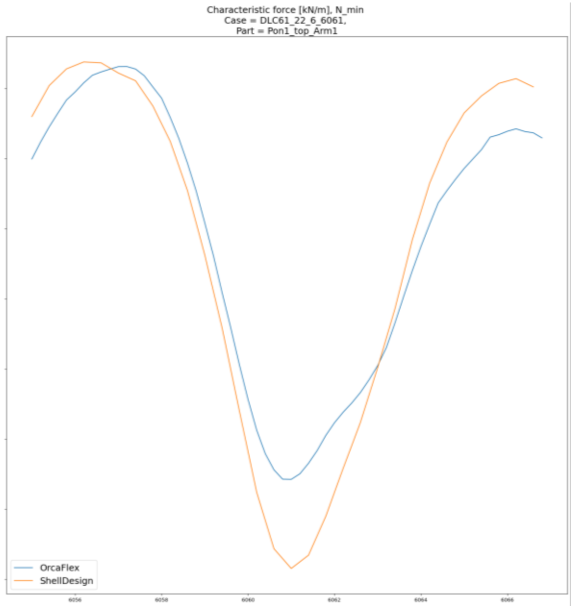


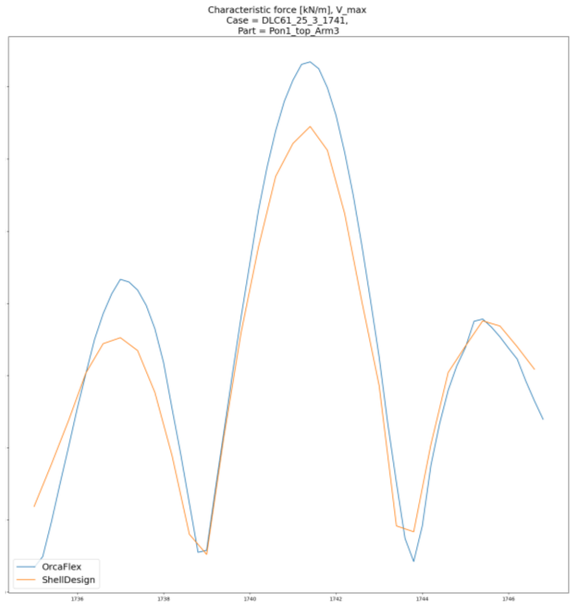
RESULTING CHARACTERISTIC LOAD SITUATION

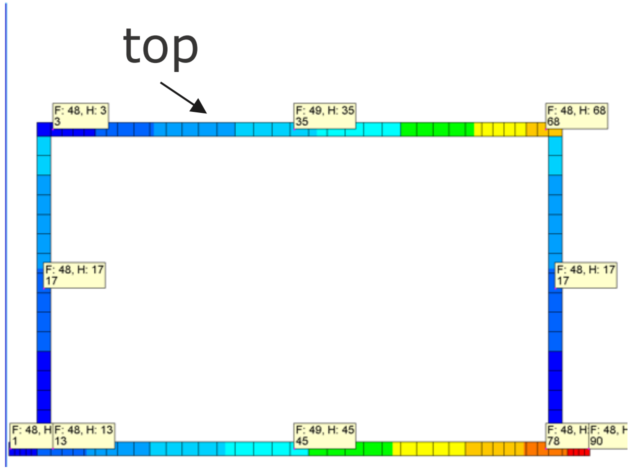


- Characteristic extremes not reproduced exactly.
- Expected due to non-negligible out-of-balance loads in quasi-static FEA.
  - Exclusion of Morison elements in Wasim possible reason.





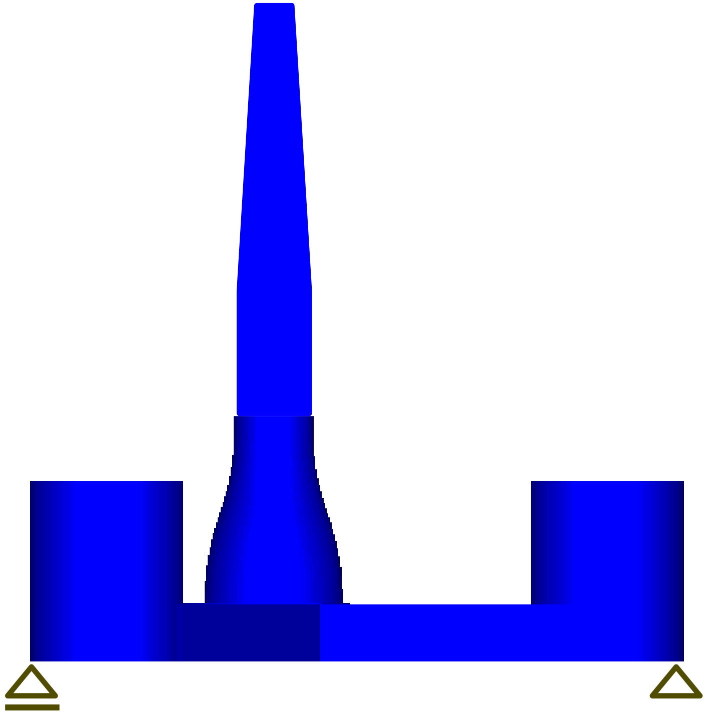




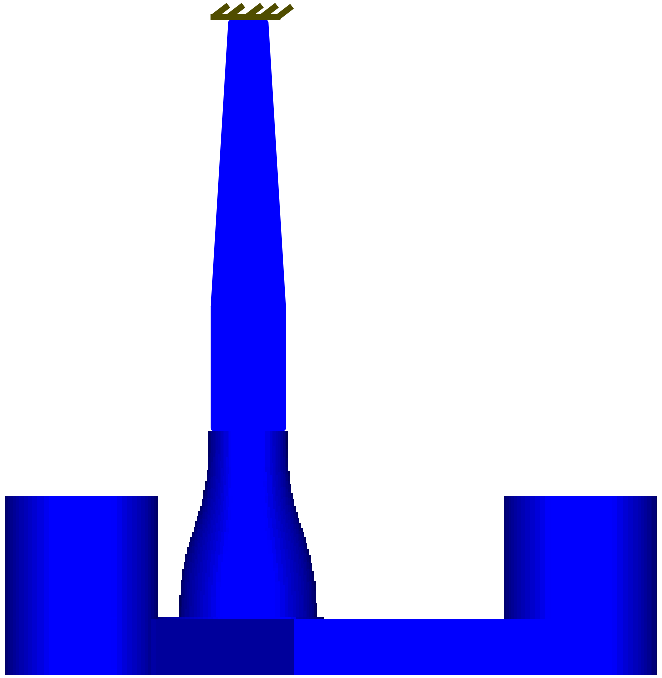
BOUNDARY CONDITION SENSITIVITY QUASI-STATIC LINEAR FEA

- Two boundary conditions evaluated for FEA.
  - BC1: Pinned at corner columns (keel).
  - BC2: Fixed in all DOFs at top of tower.

BC1

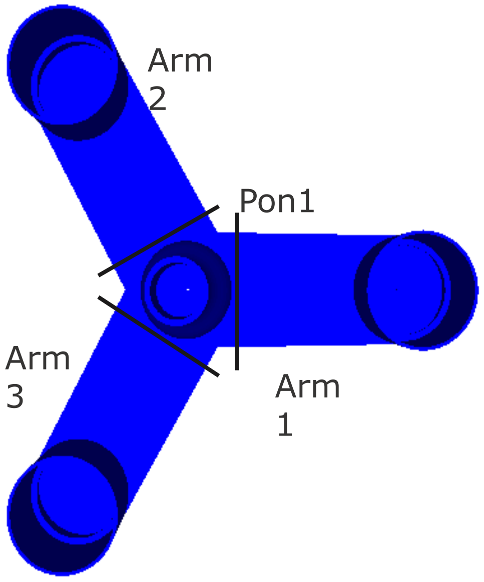


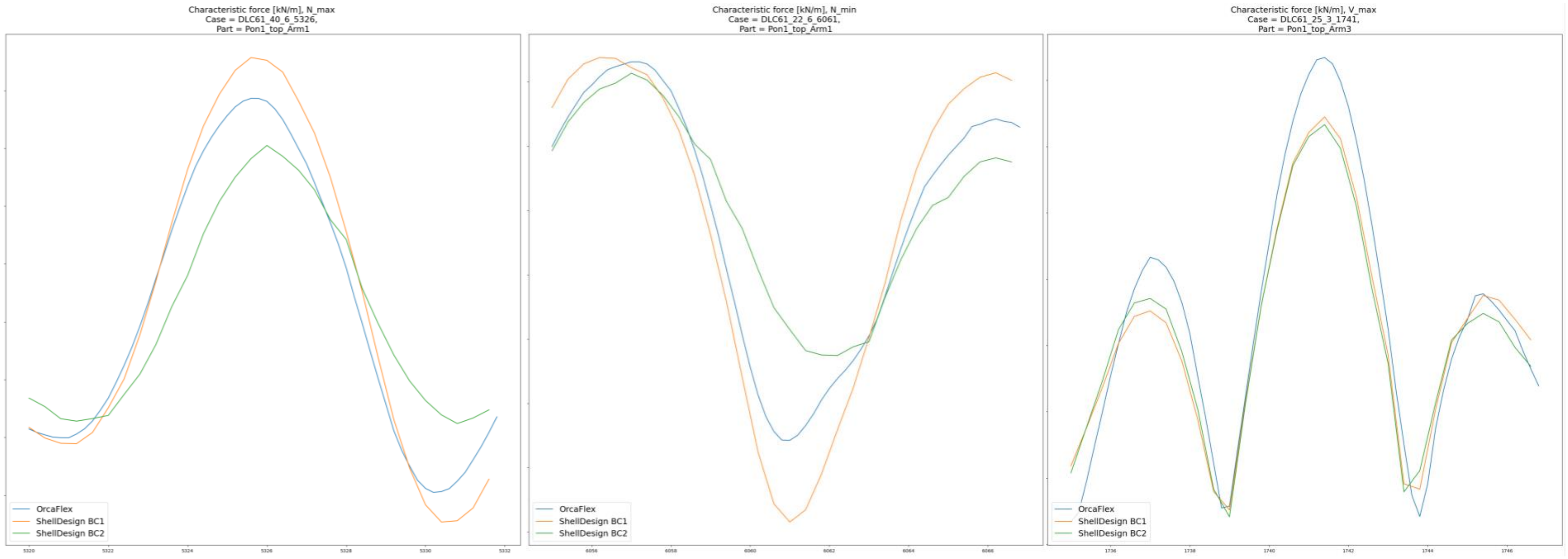
BC2

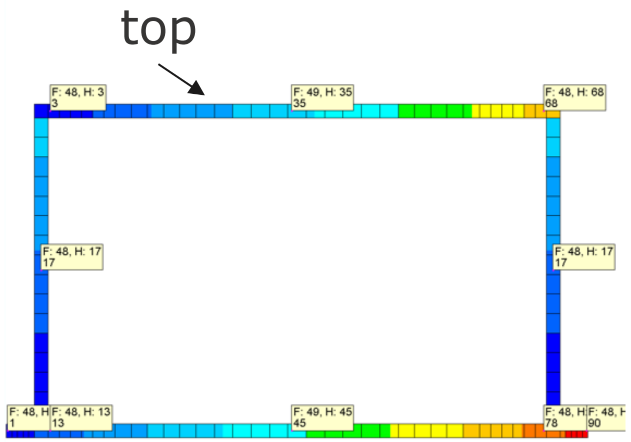


BOUNDARY CONDITION SENSITIVITY

- Responses sensitive to BC.
- For design, evaluation of BC can be made based on:
  - Most accurate compared to ILA.
  - Most conservative compared to ILA.







CONCLUSION

- Critical load situations can effectively be identified to ensure computational effort of time domain concrete substructure ULS/ALS/SLS design is acceptable.

- Stresses are not identical in ShellDesign-ILA.
  - Expected due to non-negligible out-of-balance loads.
  - Morison load formulation to be included in Wasim.
  - Comparison sectional loads ShellDesign-ILA valuable for evaluation of impact of out-of-balance forces.

- Structural response in Sestra is dependent on the applied boundary conditions.
  - Different boundary conditions are required for different structral parts.

Main conclusions and future work

MAIN CONCLUSIONS AND FUTURE/ONGOING WORK

- Efficient workflow including screening and verification is suggested for substructure concrete design.
  - Currently limited to ULS/ALS/SLS.
- Improvement of ILA workflow as single model can be applied for substructure/tower/mooring loads.

Further/ongoing work:

- Testing of the more efficient response reconstruction methods and include modules for FLS design in time domain substructure design workflow.
- Include Morison load formulation in Wasim to assess importance of viscous loads and their effect on out-of-balance loads in quasi-static FEA.
- Evaluation of importance of neglected effects in time domain substructure design workflow, ref. slide 19.

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