NATIONAL TECHNICAL UNIVERSITY of ATHENS (NTUA)

A comprehensive method for the structural design and verification of the INNWIND 10MW tri-spar floater

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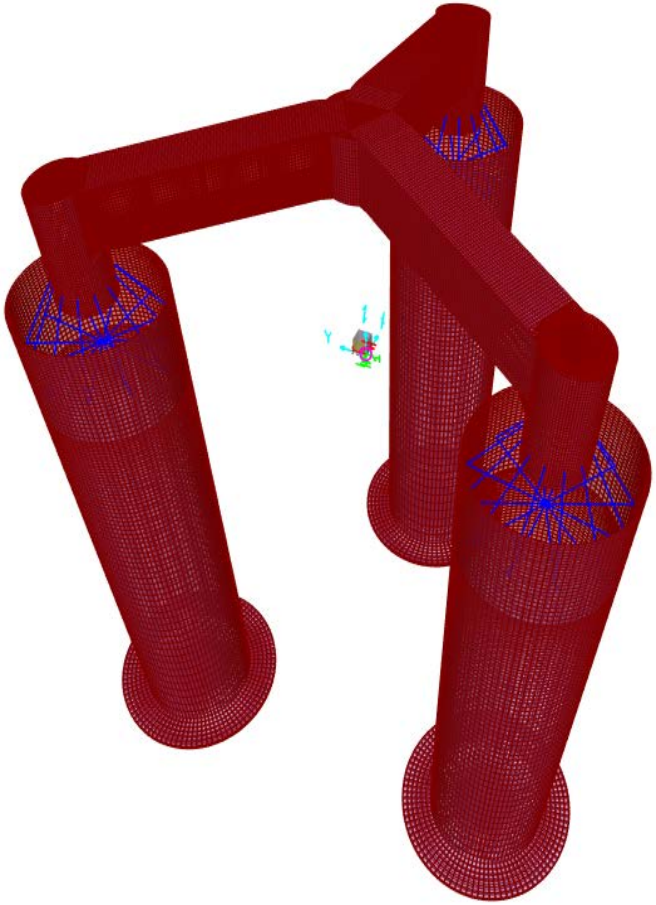
- Scope
- Numerical Tools
- Method for detailed design and verification
- INNWIND 10MW tri-spar concrete floater
- Conclusions

- Cost effective method for floater detailed design and verification
- 3D “complex” geometry (i.e. semi-submersible, tri-spar etc)
- Concrete!
- Account for ULS and FLS
- Environmental excitation (wind & wave/current)
- Realistic modeling
- Application: INNWIND 10MW tri-spar concrete floater

SAP2000: 3D FEM Solver

General purpose commercial software for analyzing any type of structures.

- Solution: Static, frequency domain and time domain
- Elements: Beam, shell thick, solid
- Design is fully integrated for both steel and concrete members, based on American or European standards



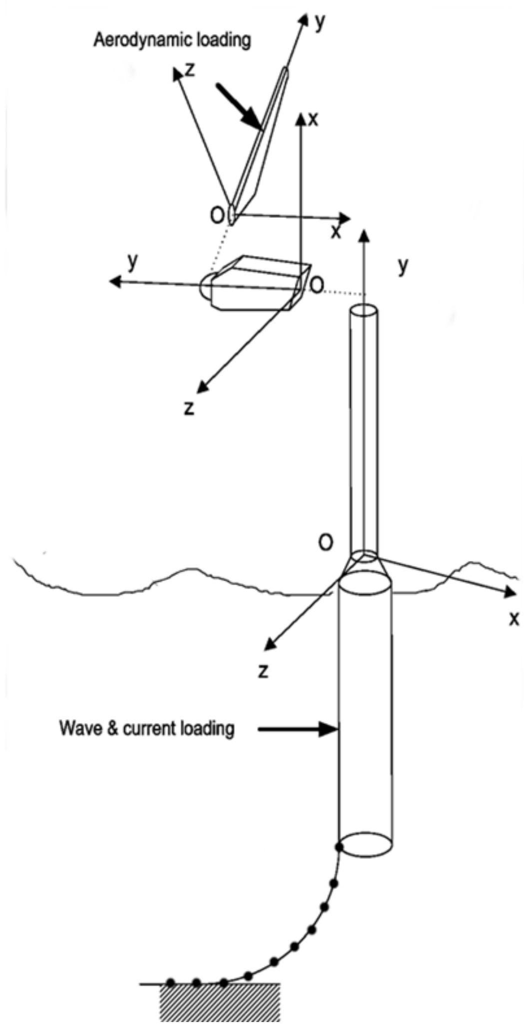
hGAST: hydro-servo-aero-elastic tool

General in-house simulation platform for analyzing the fully-coupled dynamic behavior of WT

Simulates all support structures

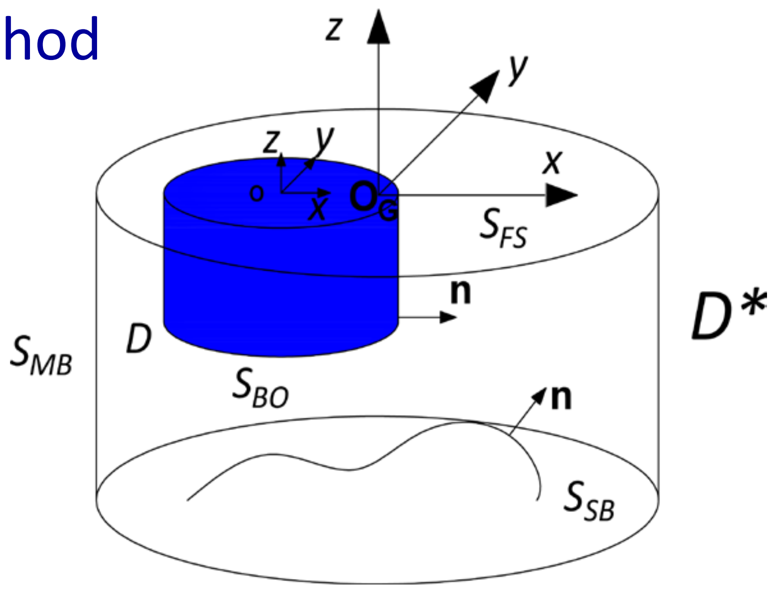
Modules

- Dynamics: Multi-body formulation
- Elasticity: beam theory
- Aerodynamics: BEM or Free wave
- Hydrodynamics: Potential theory or Morison's equation
- Moorings: dynamic modeling
- Control: variable speed/pitch
- Environmental Excitation according IEC



freFLOW: Hybrid integral equation method

General in-house hydrodynamic solver for analyzing and designing floating structures

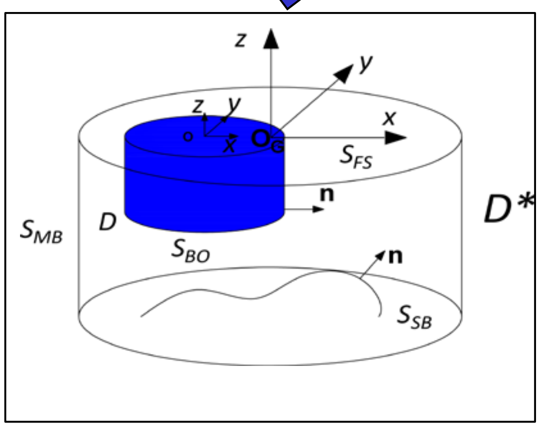


- Solution: 3D Laplace equation in frequency domain
- Method: BEM – indirect formulation with constant source distribution
- Radiation condition: Matching with Garrett's analytic solution
- Provides: Exciting loads, Added mass & damping coefficients, RAOs, total hydrodynamic loads and total hydrodynamic pressure

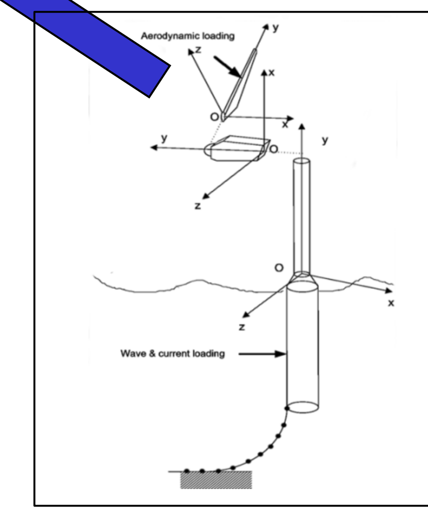
SAP2000

Pressure field on floater's wet surface

Tower base loading vector



freFLOW



hGAST

- Detailed Analysis in 3D FEM
  - ULS: static solution
  - FLS: frequency domain stochastic solution
- Input: Preliminary design
- Checking (stress level)
  - ULS: capacity ratios (max σ / material yield σ)
  - FLS: σ PSD → Time series → RFC → damage ratios (S-N curve data)

- hGAST (IEC DLCs)
  - ULS: maximum loading
  - FLS: lifetime PSD
- freFLOW

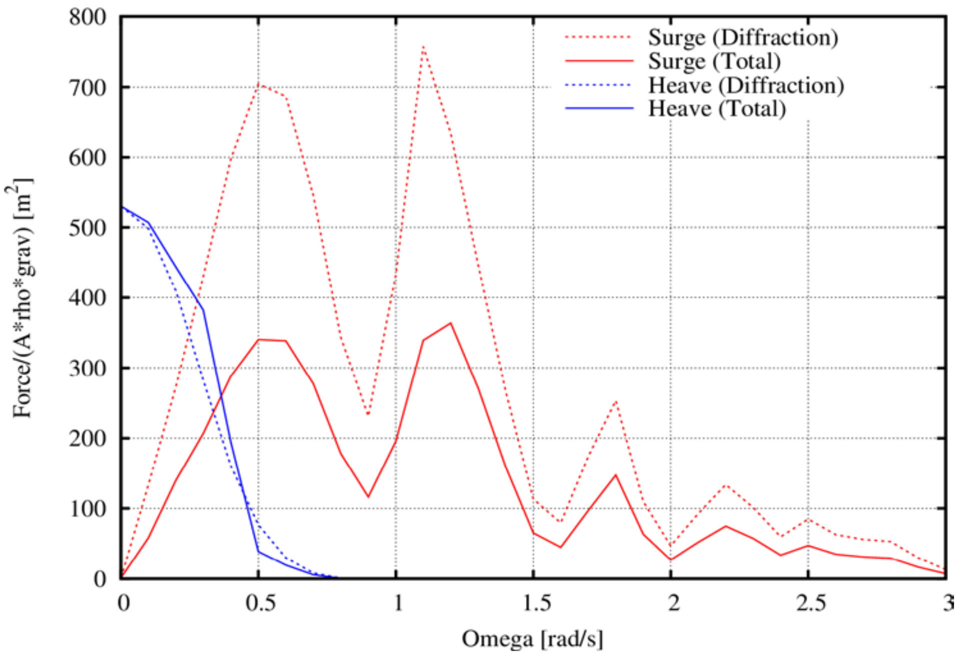
$$p_{PSD}(\mathbf{x},\omega) = [p(\mathbf{x},\omega)/A]^2\, S(\omega;T_p,H_s)$$

$$p_{\max}(\mathbf{x}) = 1.86 \cdot 2\sqrt{\int_0^\infty [p(\mathbf{x},\omega)/A]^2\, S(\omega;T_p,H_s)\, d\omega}$$

  - FLS: pressure PSD
  - ULS: max pressure
    - Simultaneously applied
    - Generating the max moment at critical points

(Realistic) Modeling

- SAP2000: Introduce the 6 rigid body motions (Stiffness Matrix)
- hGAST: simulations for the off-shore WT
- freFLO*W*: total pressure field (RAOs for floater & M_{WT}, C_{WT}, K_{WT})

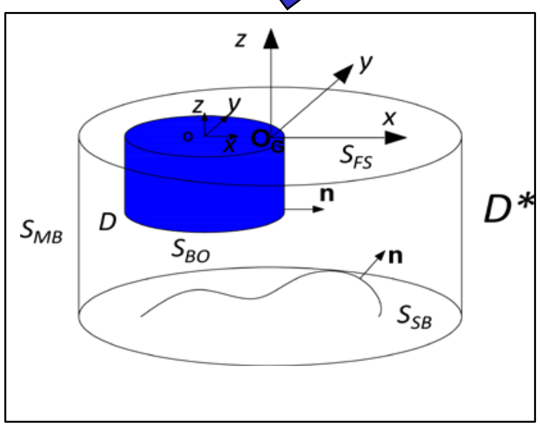


SAP2000

Capacity ratios (ULS)
Damage ratios (FLS)

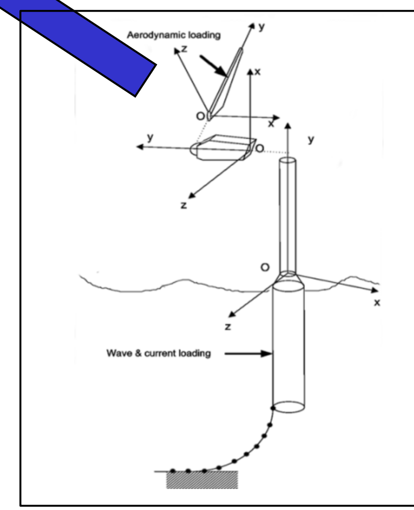
Pressure field on floater’s wet surface

Tower base loading vector



Additional M_{WT}, C_{WT}, K_{WT}

Hydrodynamic operators



freFLOW

hGAST

WT: DTU 10MW RWT

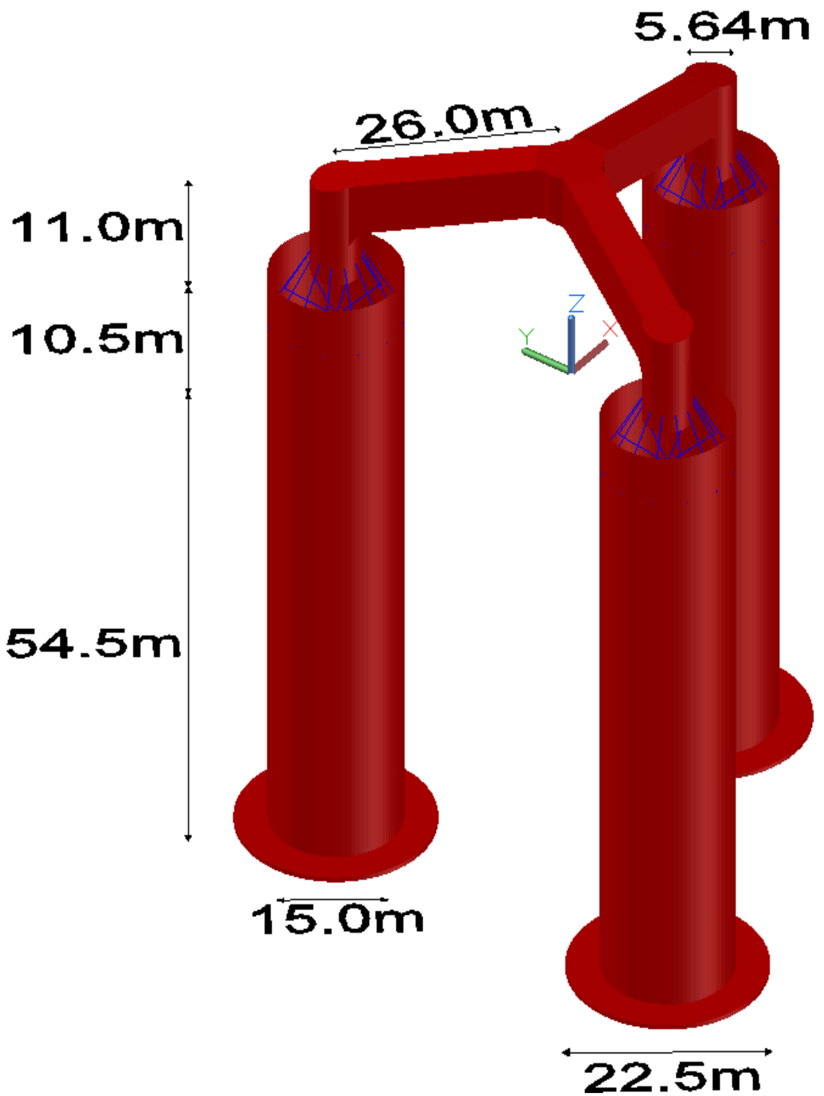
Rotor D : 178.3m
Hub Height : 119.0m
Tower base : 25.0m

Floater: tri-spar concrete

Concrete : 11478tn
Steel : 1138tn
Ballast : 15653tn
Total : 28268tn

Water Depth : 180m

Catenary mooring lines

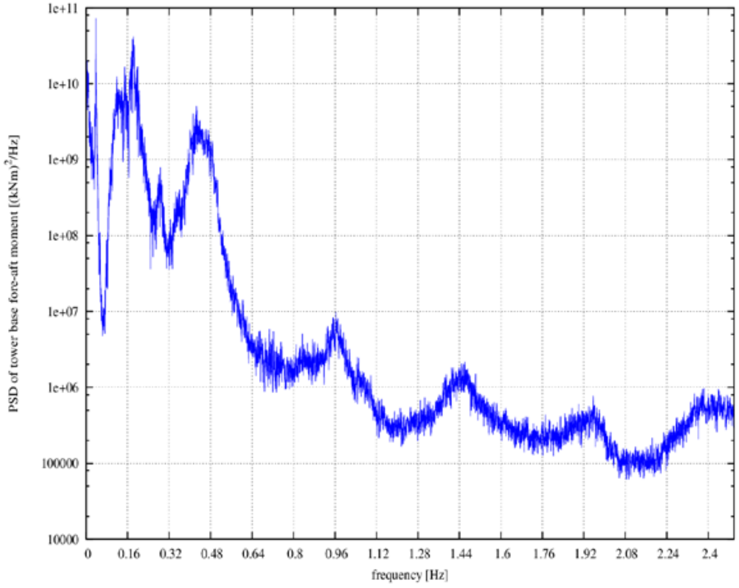


DLCs definition for time domain simulations

DLC	Wind	Wave	Seeds	Bins [m/s]	Yaw	Wave	SF
1.2	NTM	NSS	1	5, 7, 9, 11, 13, 15, 17, 21, 23, 25	0	0	
1.3	ETM	NSS	3	11, 25	0	0	1.35
1.6	NTM	ESS	3	11, 13, 17, 21, 25	0	0	1.35
6.1	EWM	SSS	3	41.8	0	0, 30	1.35
6.2	EWM	SSS	3	41.8	0,+/-30	=Yaw	1.10

Maximum tower base loading applied on the tri-spar floater (DLC1.6 at 13m/s, Hs=10.9m, Tp=14.8s. SF=1.3).

Fx [kN]	Fy [kN]	Fz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
7472	168	-9736	-5186	621000	3679



Lifetime PSD of tower base fore-aft moment, Weibull C=11/s, k=2.

Detailed design and verification

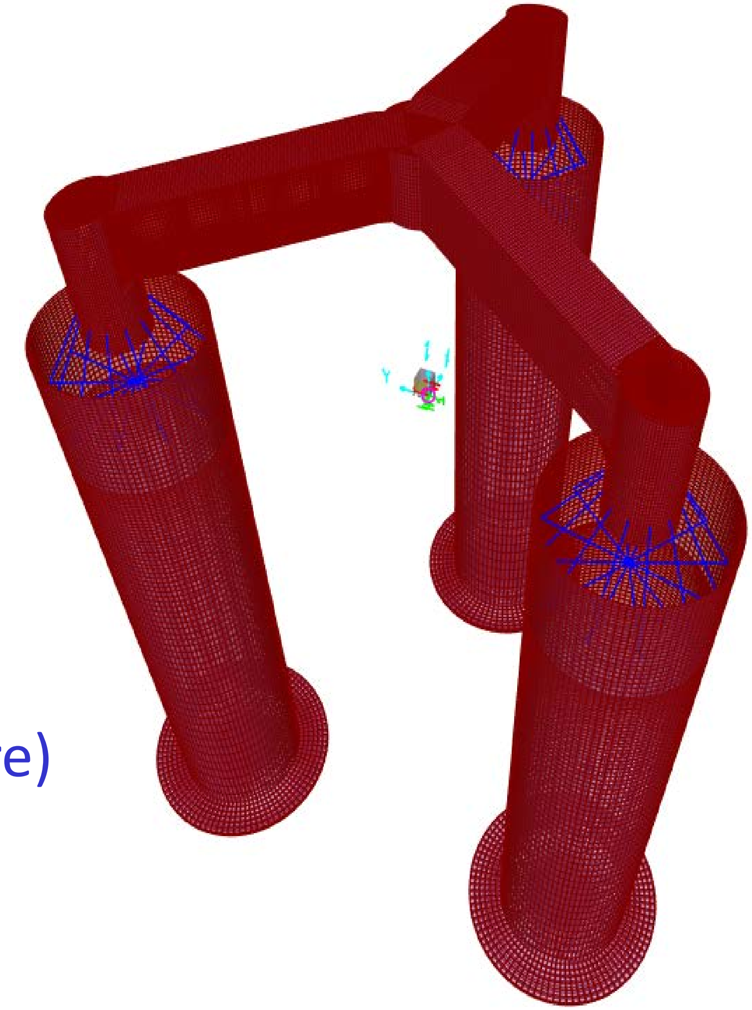
- Heave plates (HP): steel → concrete
- Concrete Column (CC): reinforcement
- Connection (steel legs-concrete columns)
- Steel Tripod

Materials:

- Steel : S450 , t=0.0564m
- Concrete : C50/60 , t=0.40m
- Rebar : Reinforcement

Reinforcement (DLC1.6 - max pressure)

- CC Vertical : Φ25/180
- CC Horizontal : Φ20/250
- HP Radial : double Φ36/65
- HP Horizontal : double Φ36/75

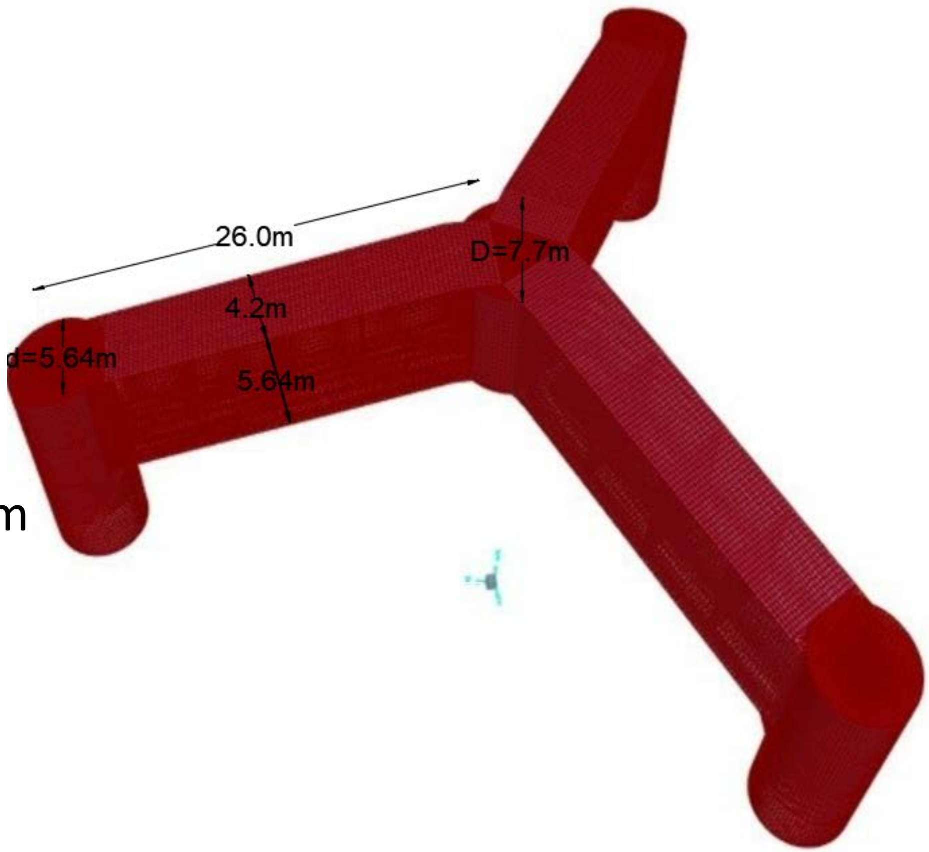


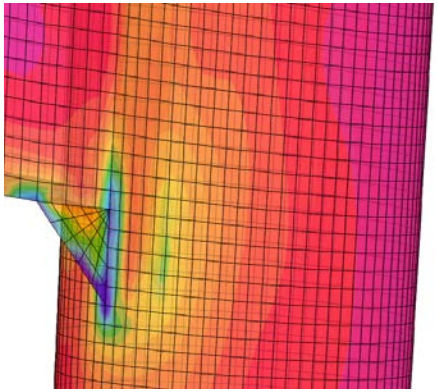
Tripod Design Modifications

Bracket width (5.64m → 4.62m)

Local reinforcements

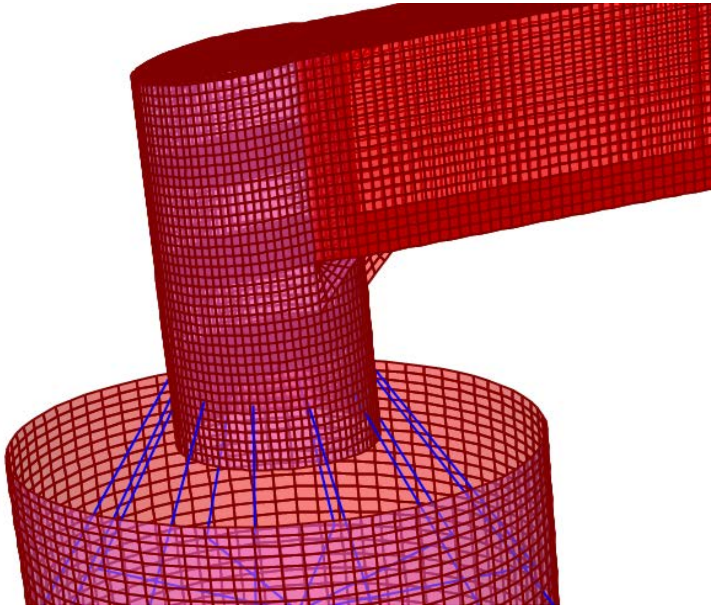
- Central cylinder : t=0.0564-0.175m
- Brackets : 3 diaphragms
- Legs : 4 diaphragms
- Legs : t-top =0.0564m
- t-bottom=0.175m
- gamma connection: triangular plate





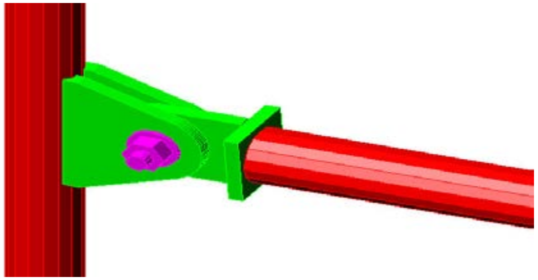
Steel – Concrete connection

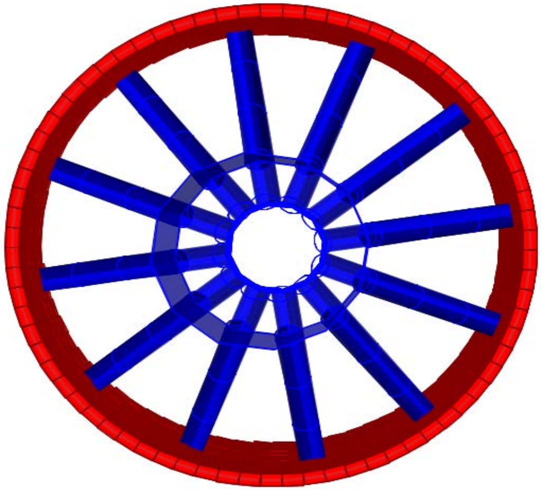
- 12 inclined steel rods (inclination =60°)
- 12 horizontal steel ties
- a steel ring



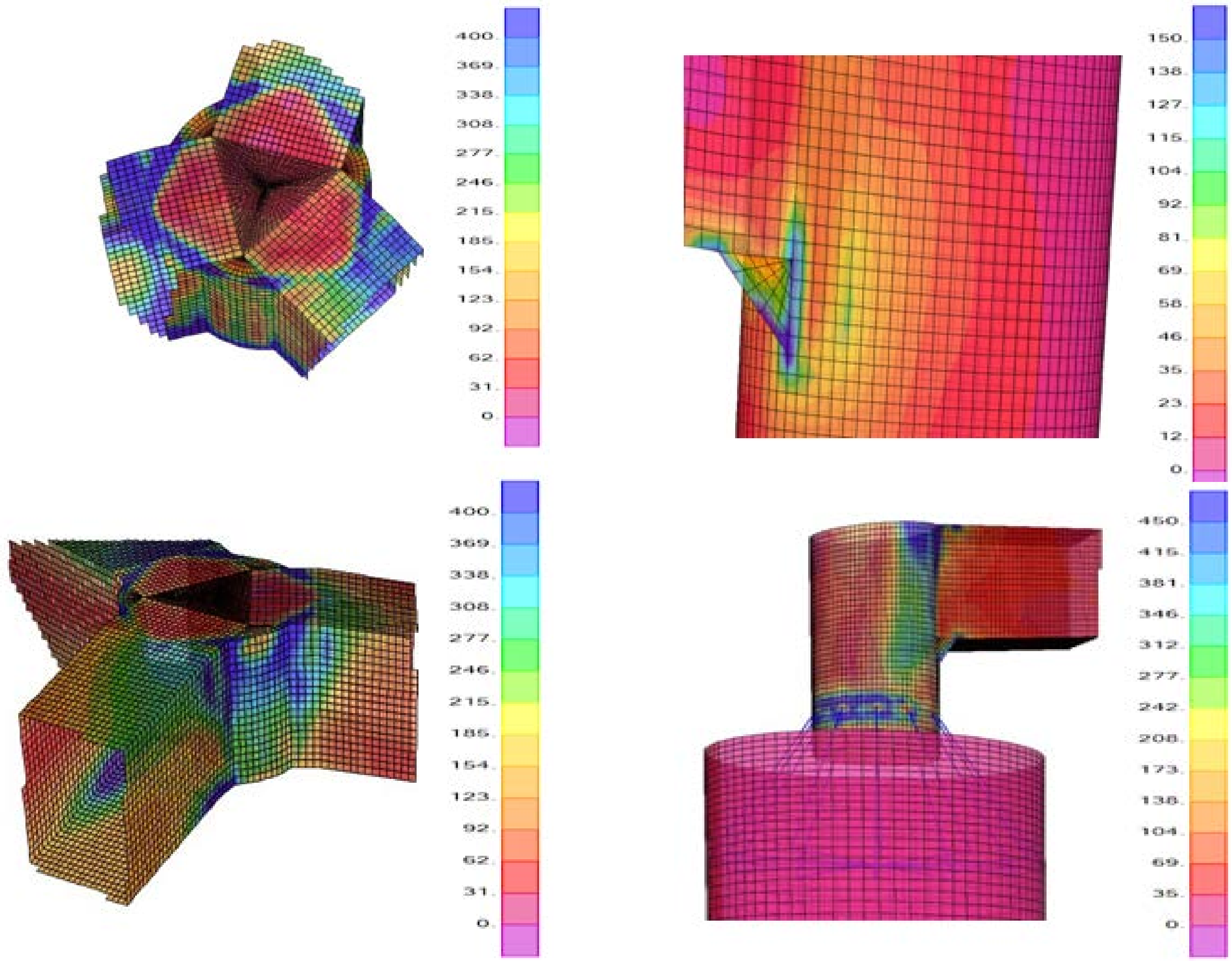
Rods - Ties

- D= 0.50m
- t = 0.02m
- Pinned connection





INNWIND 10MW tri-spar concrete floater



Critical points of tri-spar floater considered for ULS and FLS verification. Stress contours from ULS case II (max moment at gamma connection).

ULS verification: capacity ratios at critical positions (DLC1.6 at 13m/s, Hs=10.9m, Tp=14.8s)

Critical Position	Capacity ratios	
	I**	II
1. Central Cylinder -Horizontal Leg Connection	0.64	0.68
2. Horizontal Leg-Vertical Leg Connection	0.26	0.28
3. Vertical Leg –Inclined Rods Connection	0.64	**0.78**
4. Inclined Rods	0.46	0.54
5. Ties	0.08	0.09

FLS verification: 20 years damage ratios at critical positions.

Connection	S-N curve parameters			Damage
	Type	log(a)	m	Ratio
1. Central Cylinder – Horizontal Leg	B2	16.856	5	0.31
2. Horizontal Leg at inclination point	C	16.320	5	**0.93**
3. Horizontal Leg –Vertical Leg	B2	16.856	5	**0.86**

****I: max pressure, II: max moment at gamma- connection**

- A comprehensive method for floater detailed design and verification has been presented.
- The isolated floater is analyzed in 3D FEM solver, by performing static (ULS) and frequency domain (FLS) simulations
- WT loads: hydro-servo-aero-elastic tool (hGAST)
- Wave loads: frequency domain potential solver (freFLO*W*)
- Application on INNWIND 10MW tri-spar floater; the present designs seems to be FLS driven.

Outlook

- More design loops (mainly for FLS)
- Detailed modeling for mooring lines connection point
- Verification of the method vs fully coupled analysis

Thank you for your attention

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