This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

Design and Fatigue Assessment methodologies of W2Power FRP towers

Pablo Ropero, EnerOcean
Joel Jurado, Compassis
Stéphane Paboeuf, Bureau Veritas

E-Lass – Las Palmas – 03/05/2023

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

W2Power technology design and development

Pablo Ropero, EnerOcean

Validation at sea

1:6 scale prototype

ENEROCEAN

- ✓ Lean R&D company based in **Málaga, Spain** (est.2007) and **Canary Islands**
- ✓ Specialised in **Marine Energy Engineering**
- ✓ Owner and developer of the **W2Power solution**
- ✓ **First** multiturbine floating solution to reach sea testing **in the world**
- ✓ Our industrial owners list comprises:
  - ENI **PLENITUDE** (main shareholder)
    Fully owned by ENI, one of the biggest energy companies in the world (32000 employees, active in 69 countries)
  - **GHENOVA** INGENIERÍA
    Biggest naval engineering company in Spain (>800 employees around the World)
  - **ISATI** ENGINEERING SOLUTIONS
    Leading engineering company with more than 100 engineers supporting wind turbine OEMs
  - **INRIGO** AS
    Norwegian O&G SME company
  - **1-TECH** BV
    Belgian energy consulting company

W2Power technology

✓ **Lightweight but large semi-sub**

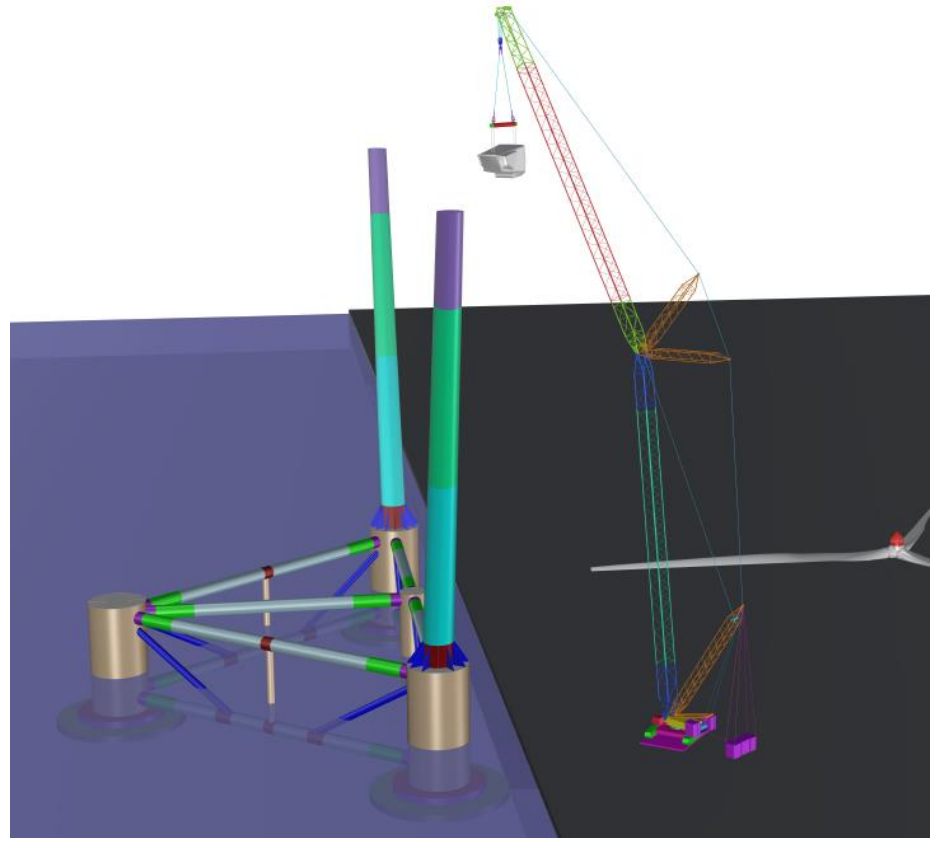
- Sea proven hydrodynamic stability
- Optimized steel weight per MW
- Smaller column volume, less draft

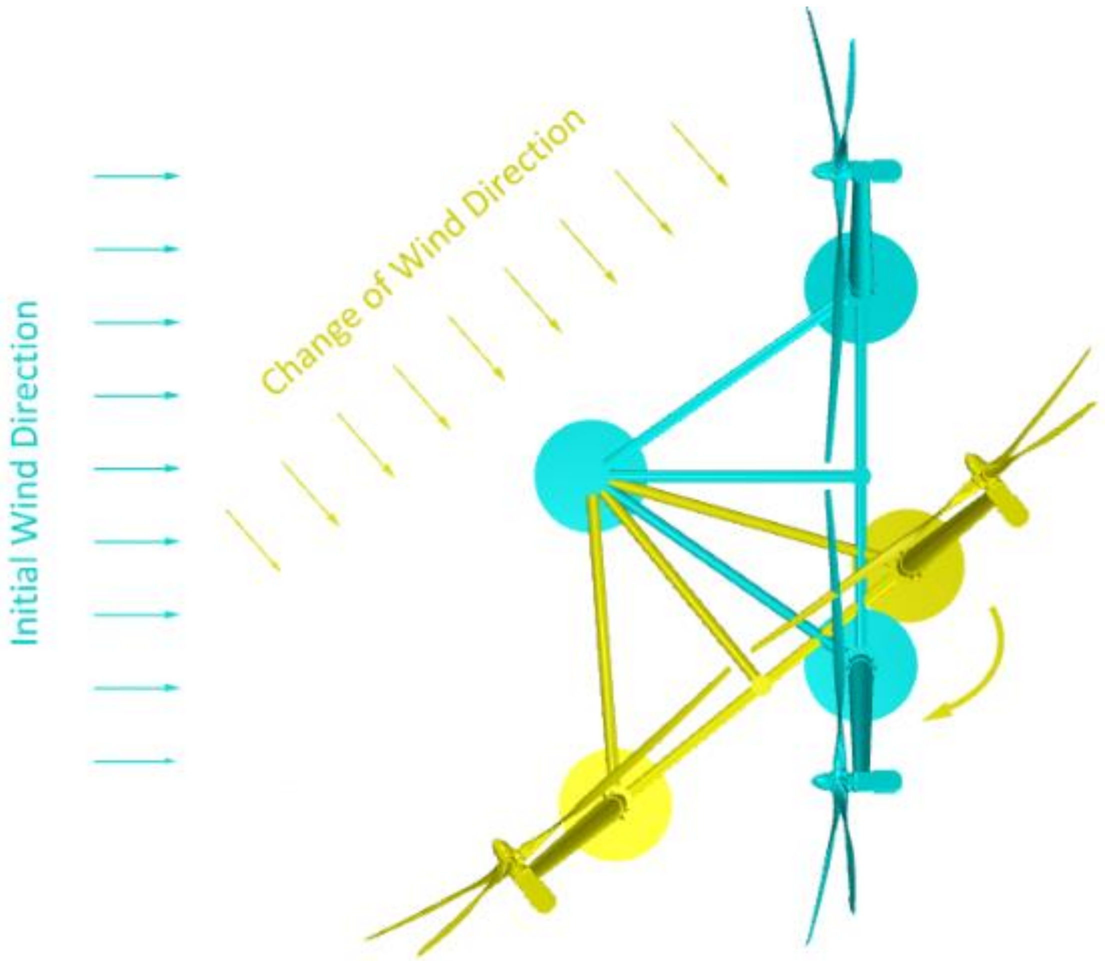
✓ **Smaller lighter turbines at a lower height**

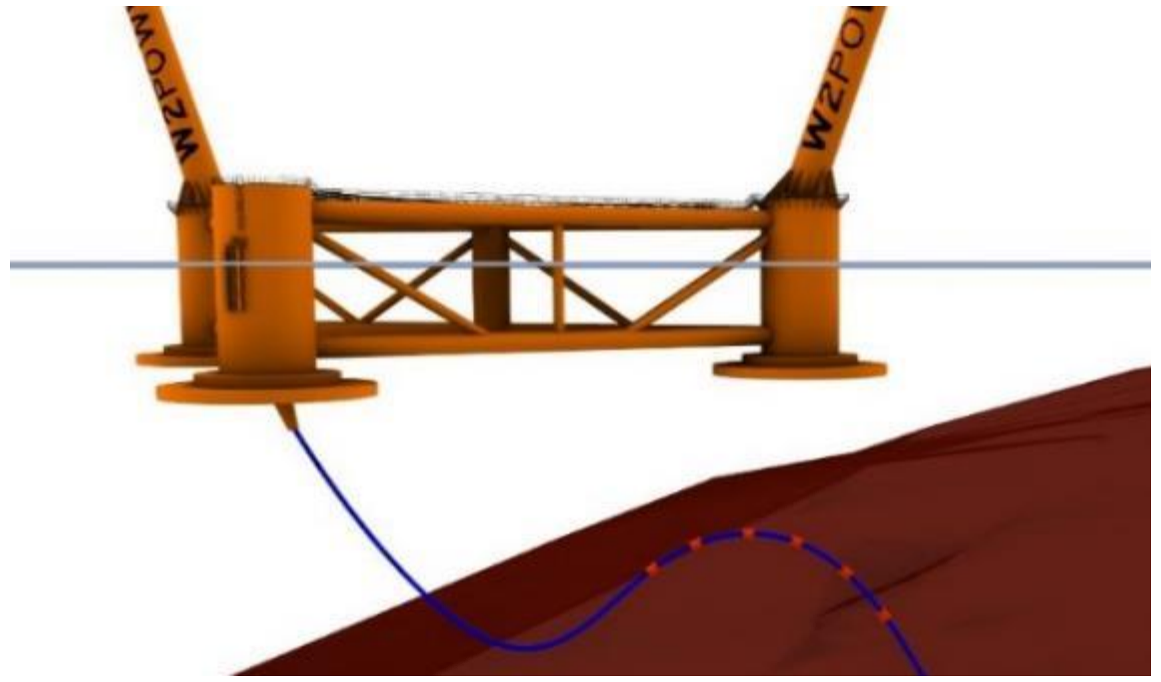
- Multiple vendors with proven models
- Cheaper assembly
- Lower OPEX (no advanced vessel needed)
- Lower CAPEX (less steel needed)

✓ **W2Power self-orientation**

- Proven at sea
- Allows closely spaced turbines
- Turbine yaw sub-systems not required
- Accurate even in low winds



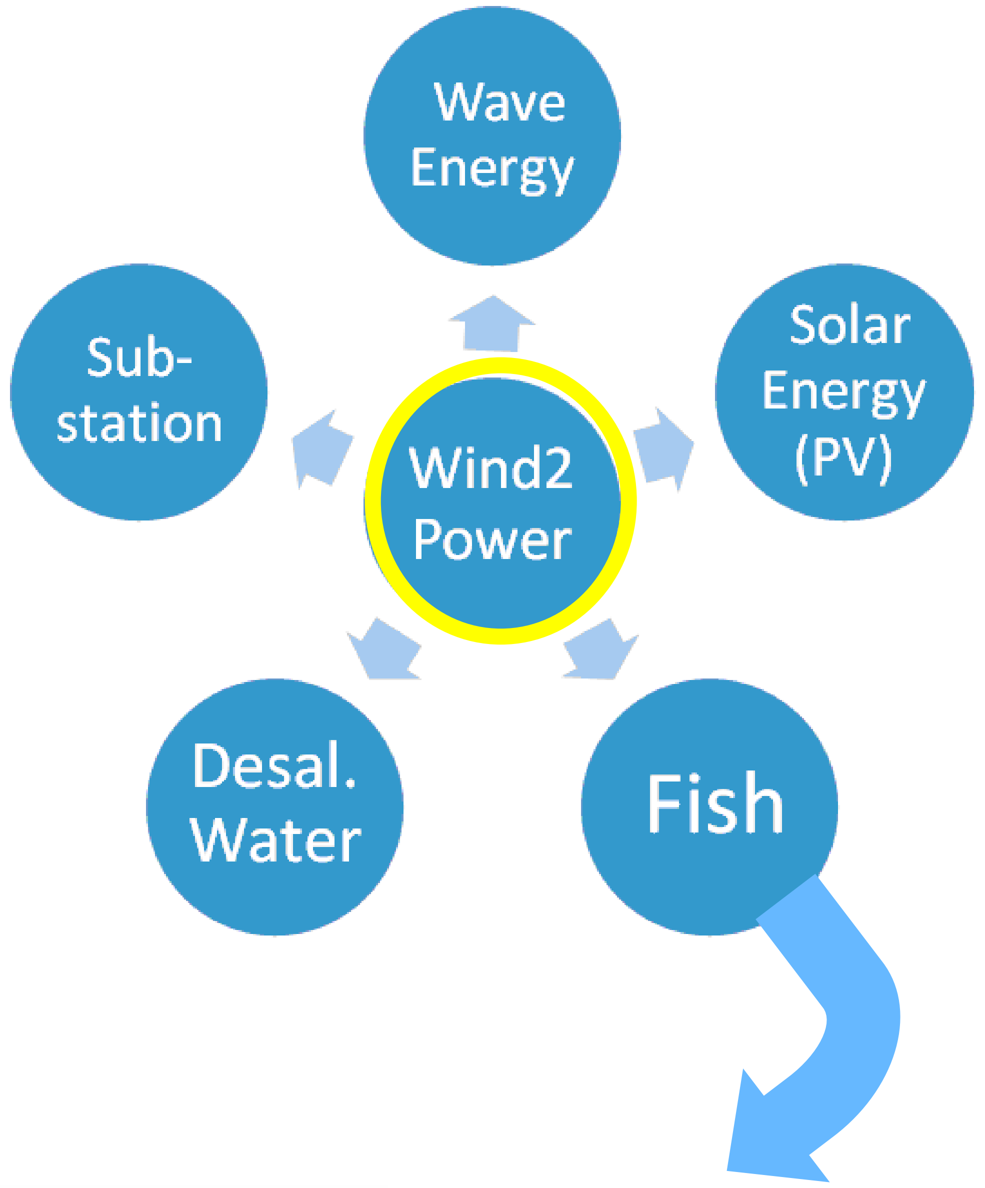




Multi-use capabilities: Example Fish farming

Fish cage protected by, and anchored to, platform. Unique to W2Power.
(no other suggested design can match its accessible moon-pool size)

Some multi-use capabilities:



140m circumferemce cage (adapted for 30 m depth)

can hold c.1250 tonnes *Salmo salar*

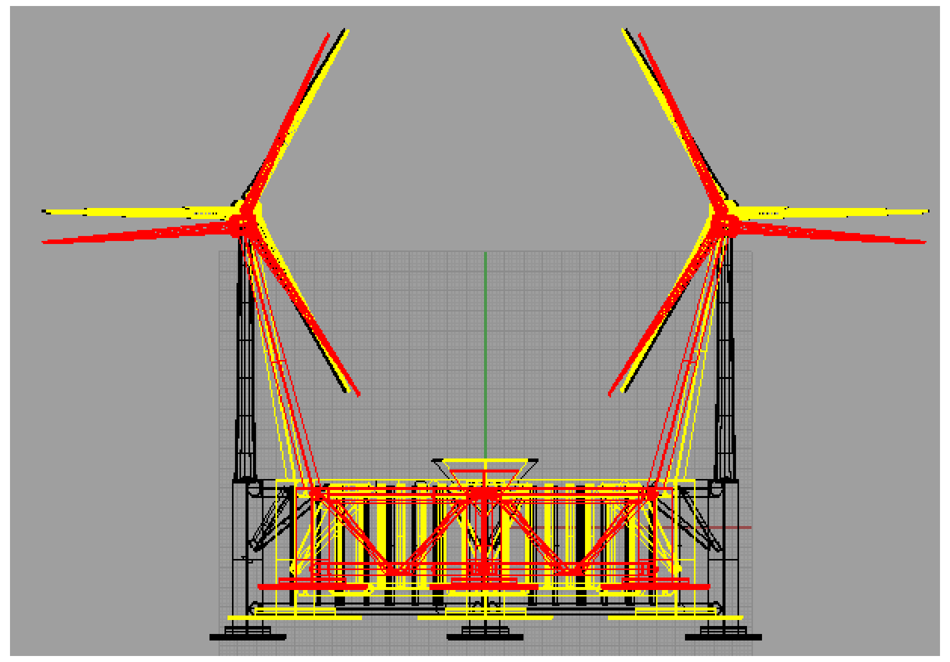
c.1500 tonnes *Seriola spp.*

FIBREGY

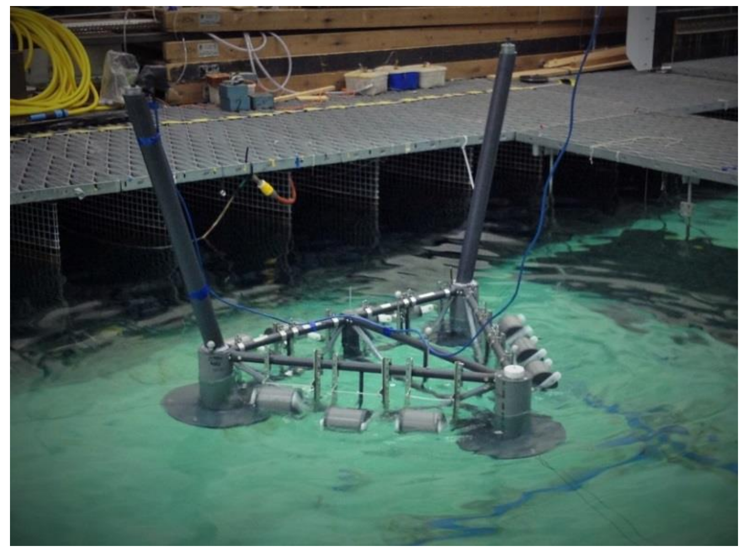
enerOCEAN

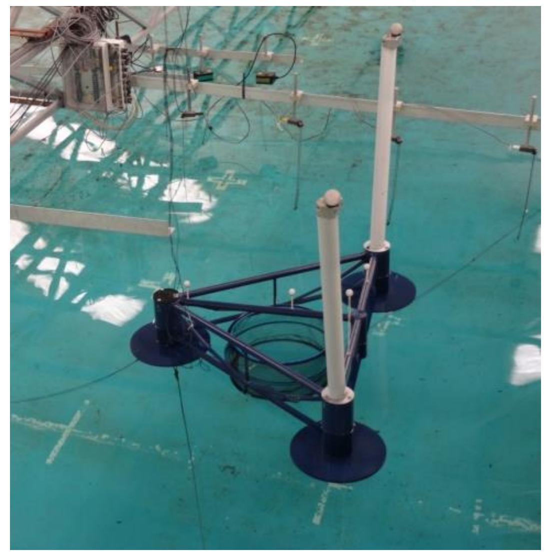
Systematic step by step development

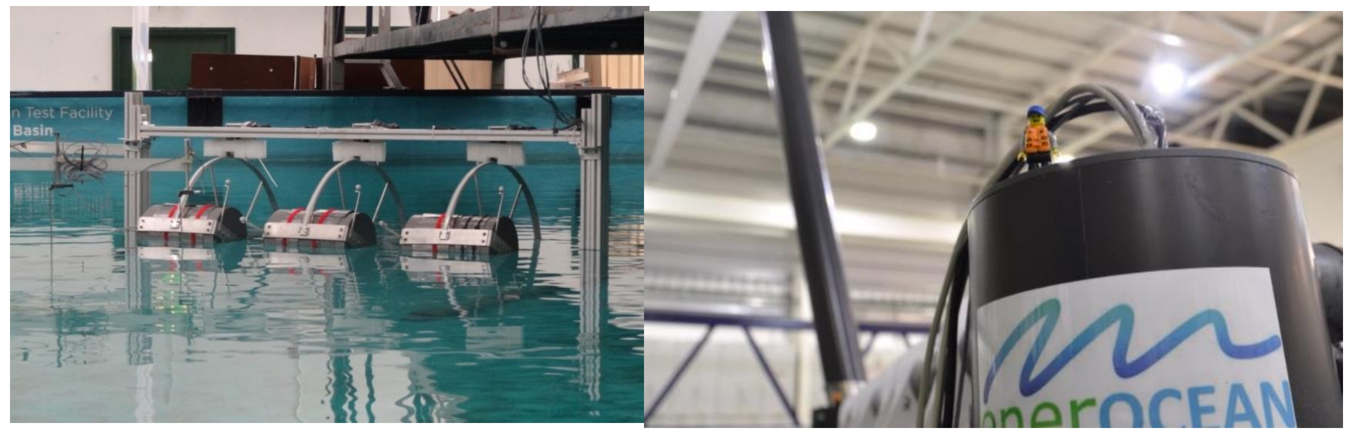
2009-12: Design evolution of W2P structure and components: from 2009 PATENT through multiple re-design cycles to **TRL3.**

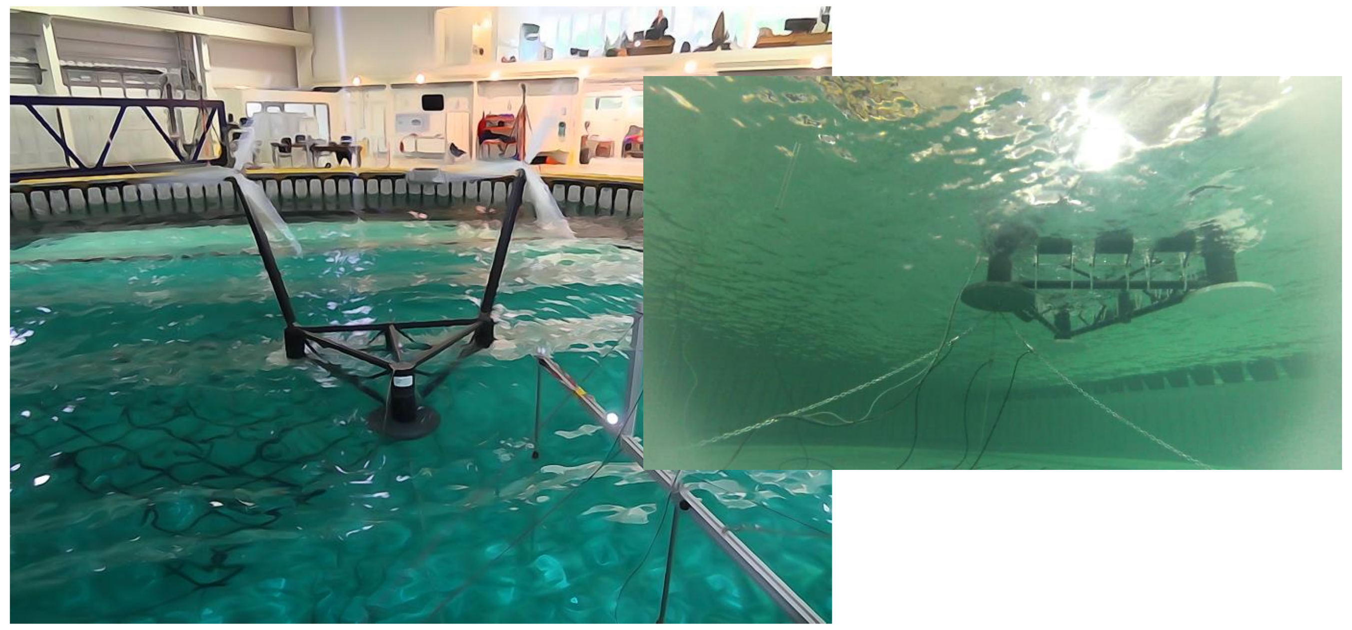


2012-15: 8 tank testing campaigns at the of the best European labs:
U. Edinburgh (UK), Marintek (NO), UC Cork (IE), U.Ed. FloWave (UK)



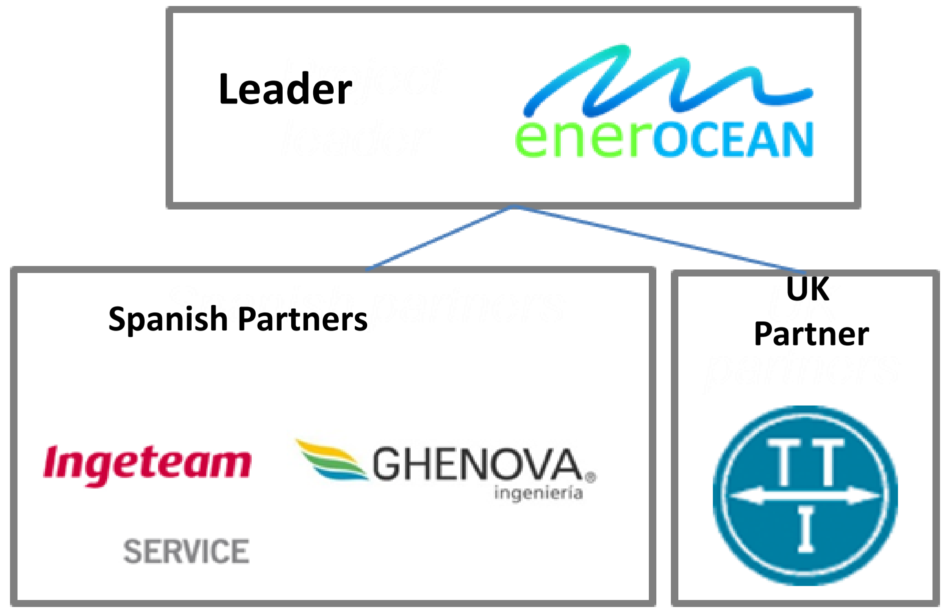






2016-19: Prototype Engineering and Open Sea testing completed:

Horizon 2020 project "WIP10+"



CDTI Centro para el Desarrollo Tecnológico Industrial

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

PlanE Plan Español para el Estímulo de la Economía y el Empleo

MARINET

Department for Business, Energy & Industrial Strategy

JUNTA DE ANDALUCIA

HORIZON 2020

European Commission

SEVENTH FRAMEWORK PROGRAMME

eurostars

CDTI Centro para el Desarrollo Tecnológico Industrial

W2POWER

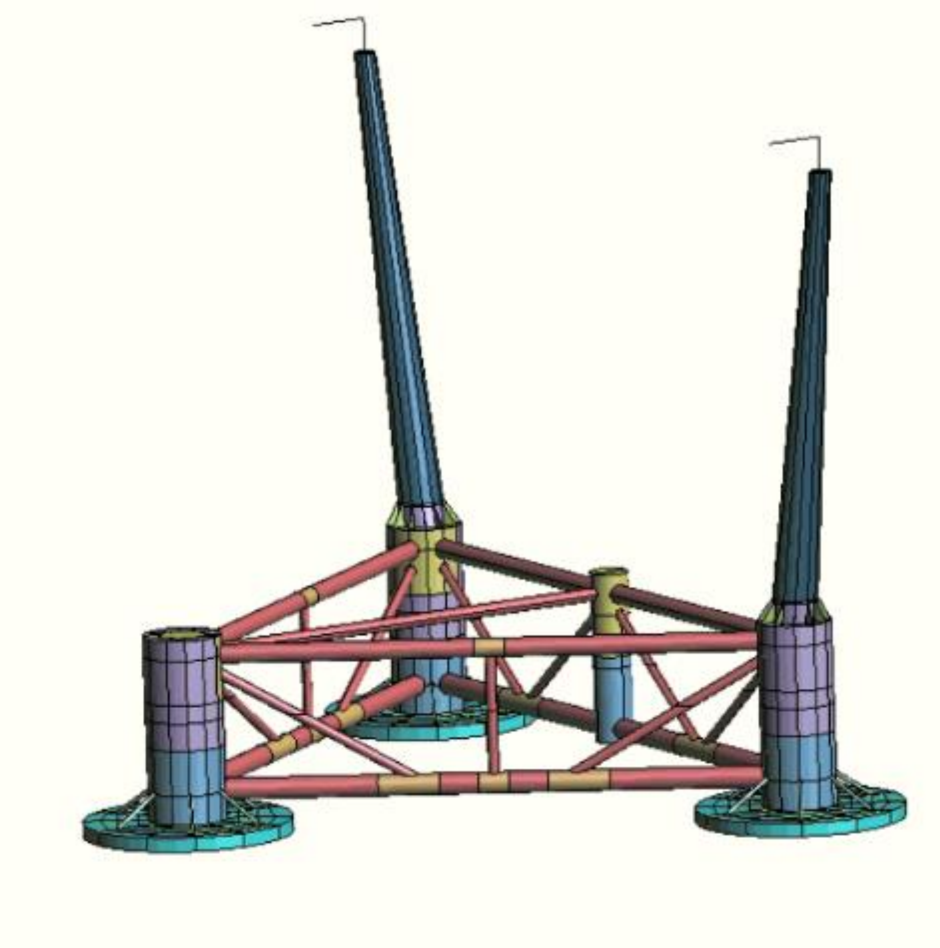
Design challenges

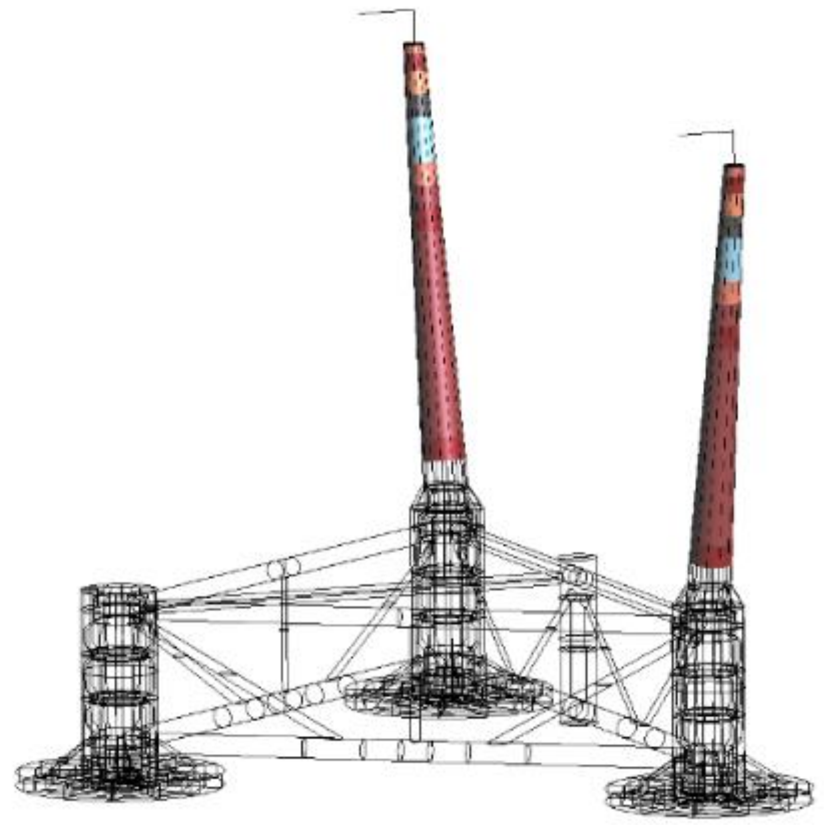
✓ **Steel-based design process based on:**

- CAE analysis
- Based on international standards
- Extensive experimental campaigns
- Cost-effectiveness and manufacturing perspective

✓ **FRP-based redesign implies new challenges**

- Lack of CAE tools
- Lack of specific standards
- Lack of experimental results
- Novel manufacturing and assembly methods





This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

Design of W2P prototype towers in FRP

Joel Jurado Granados, COMPASSIS

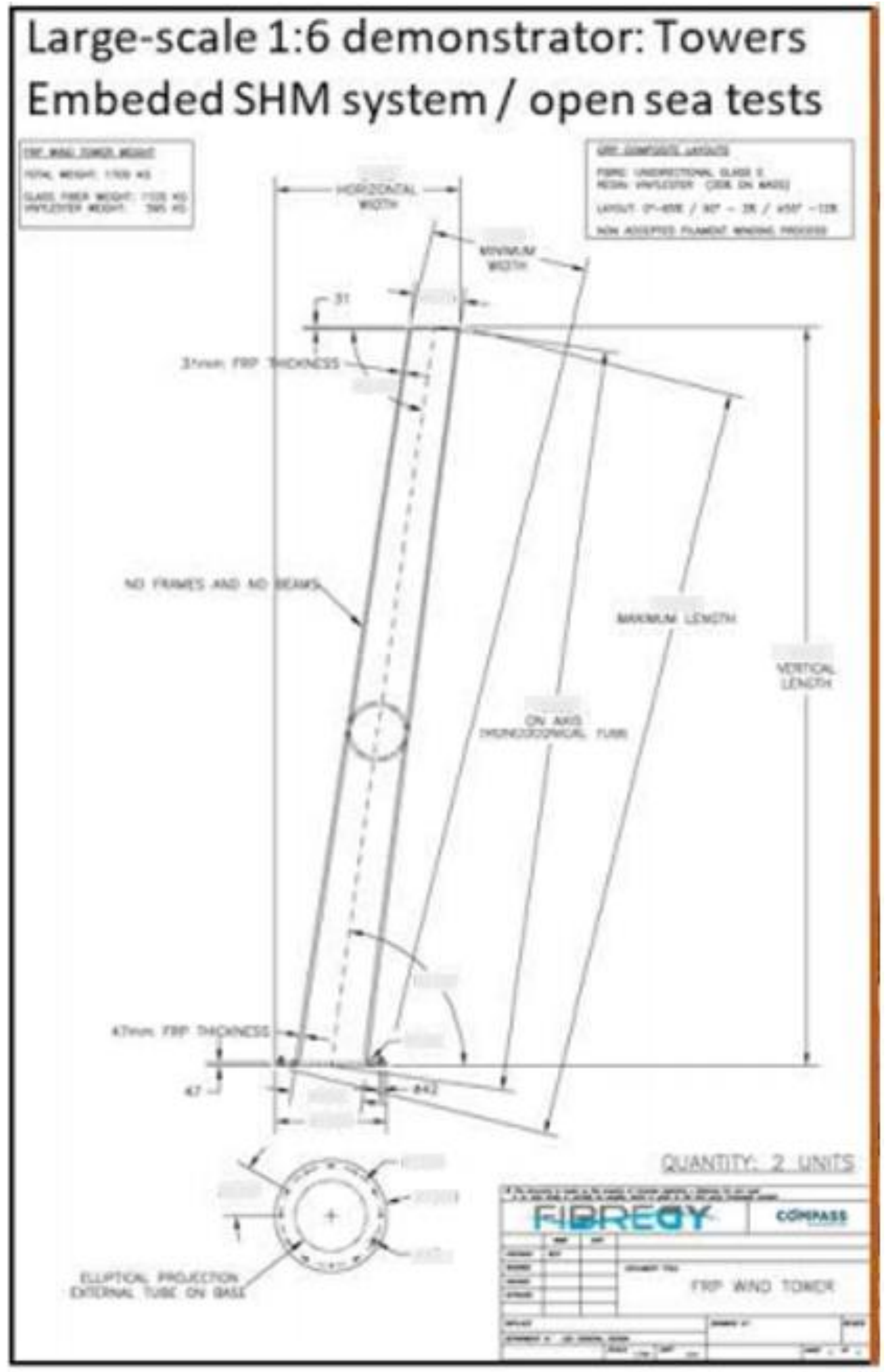
FIBREGY

COMPASS
www.compassis.com

CONTEXT: W2Power prototype

- Design of a new FRP tower to be installed in an existing offshore wind turbine steel prototype at scale 1/6.
- Design of a bolted-glued connection of the tower with the steel nacelle and platform.
- The review of the current guidelines exposed a lack of design rules for FRP towers of floating offshore wind turbines
    - IEC → It applies to small onshore wind turbines. Its major concern is regarding the rotor.
    - BV NI 572 DT R02 E: "does not cover top structure, i.e. tower, rotor, blades and nacelle design".

W2Power platform



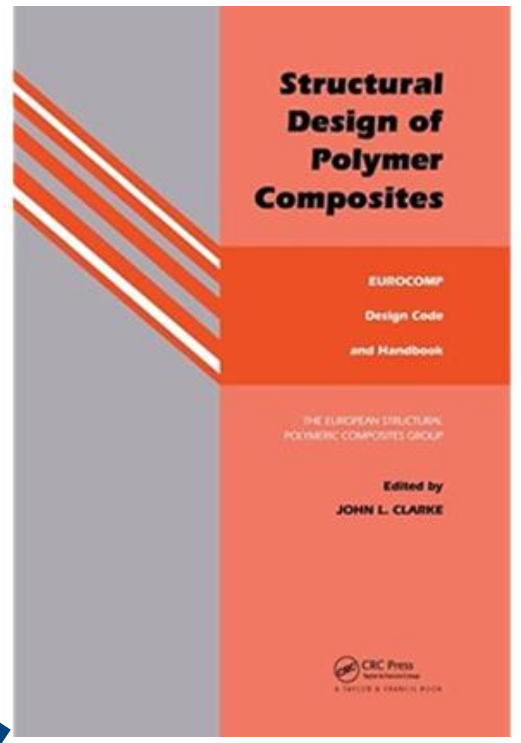
Design assessment procedure: W2P prototype

IEC 61400-2

International Electrotechnical Commission

Wind loads. Tower scantling.

W2Power platform



Eurocomp guidelines

Steel-FRP connection.

BUREAU VERITAS 1828

NI 572 DT R02 E, 2019

Sea state & Environmental conditions

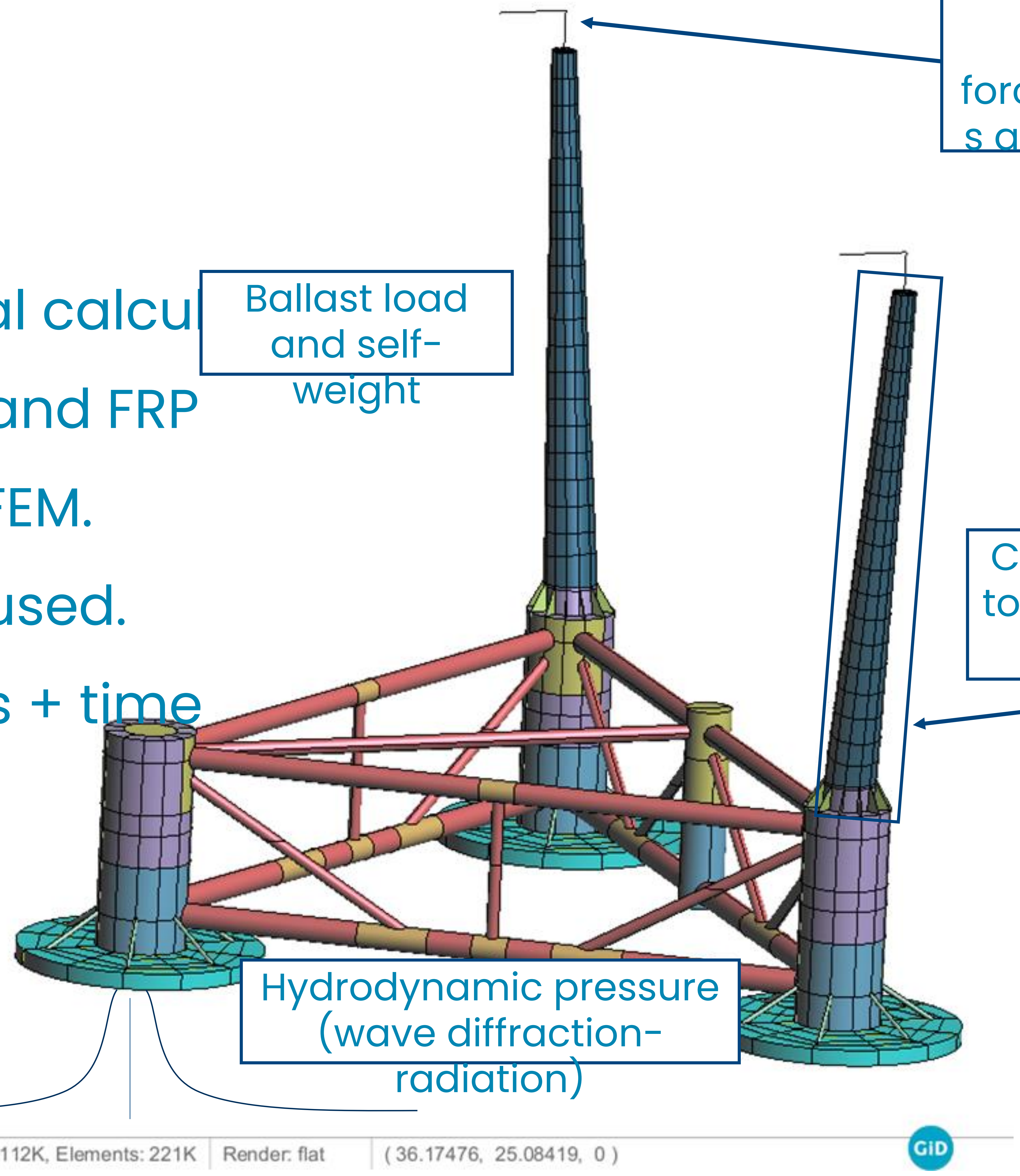
- Based on different rules and guidelines.
- Analytical approach, and verified by FE analysis.
- Loadcases based on wind-wave conditions:
  - Normal scenario (Ulimate & Fatigue).
  - Maximum thrust scenario.
  - Shutdown scenario.
  - Ultimate scenario.

FIBREGY

COMPASS
www.compassis.com

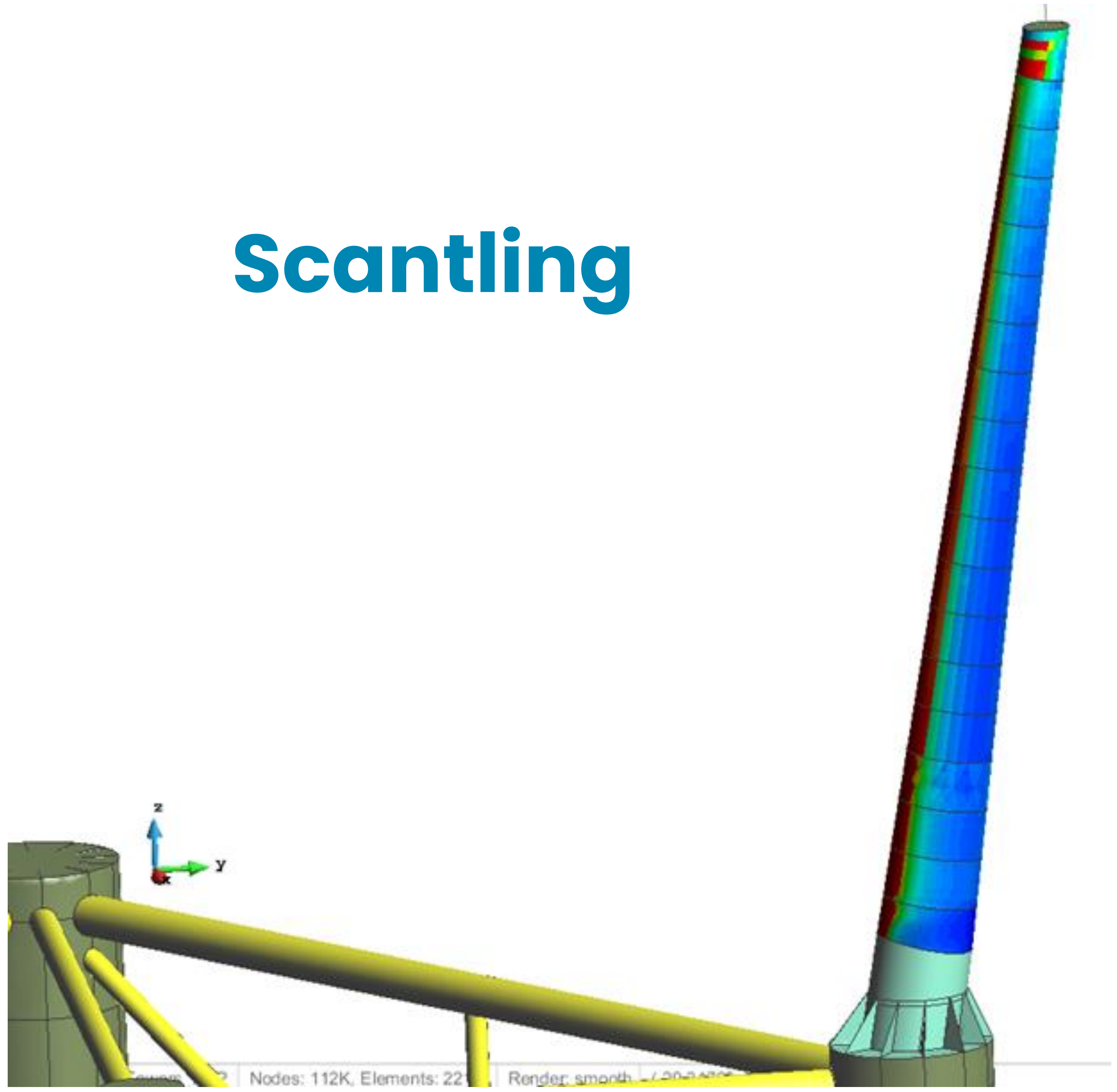
FEM analysis: W2P prototype

- Used for verifying the analytical calcul
- 3D FEM model of the platform and FRP towers: CompassIS’ Tdyn-SeaFEM.
- Beam and shell elements are used.
- Dynamic linear elastic analysis + time domain seakeeping analysis.

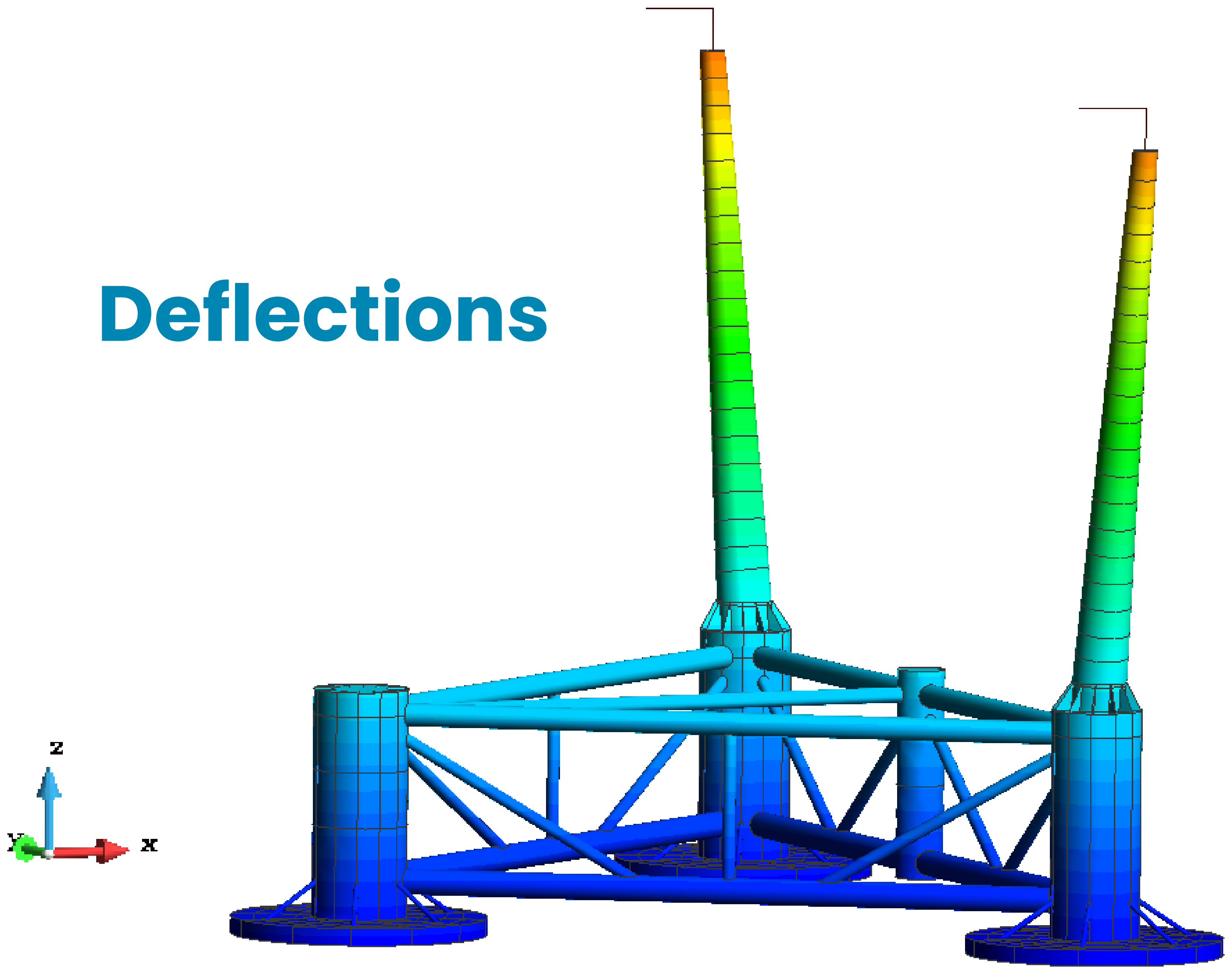


Verifications: W2P prototype

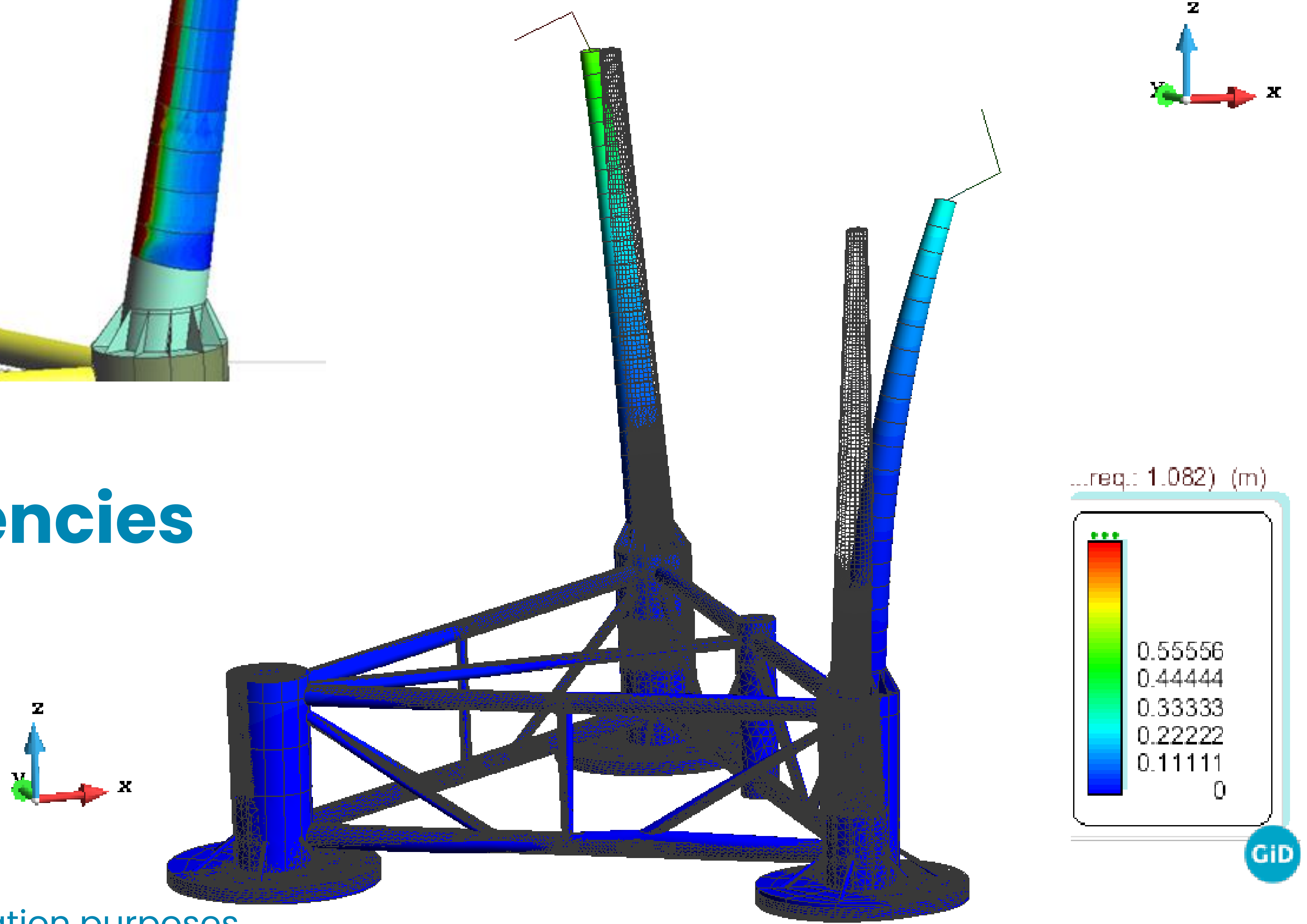
Scantling



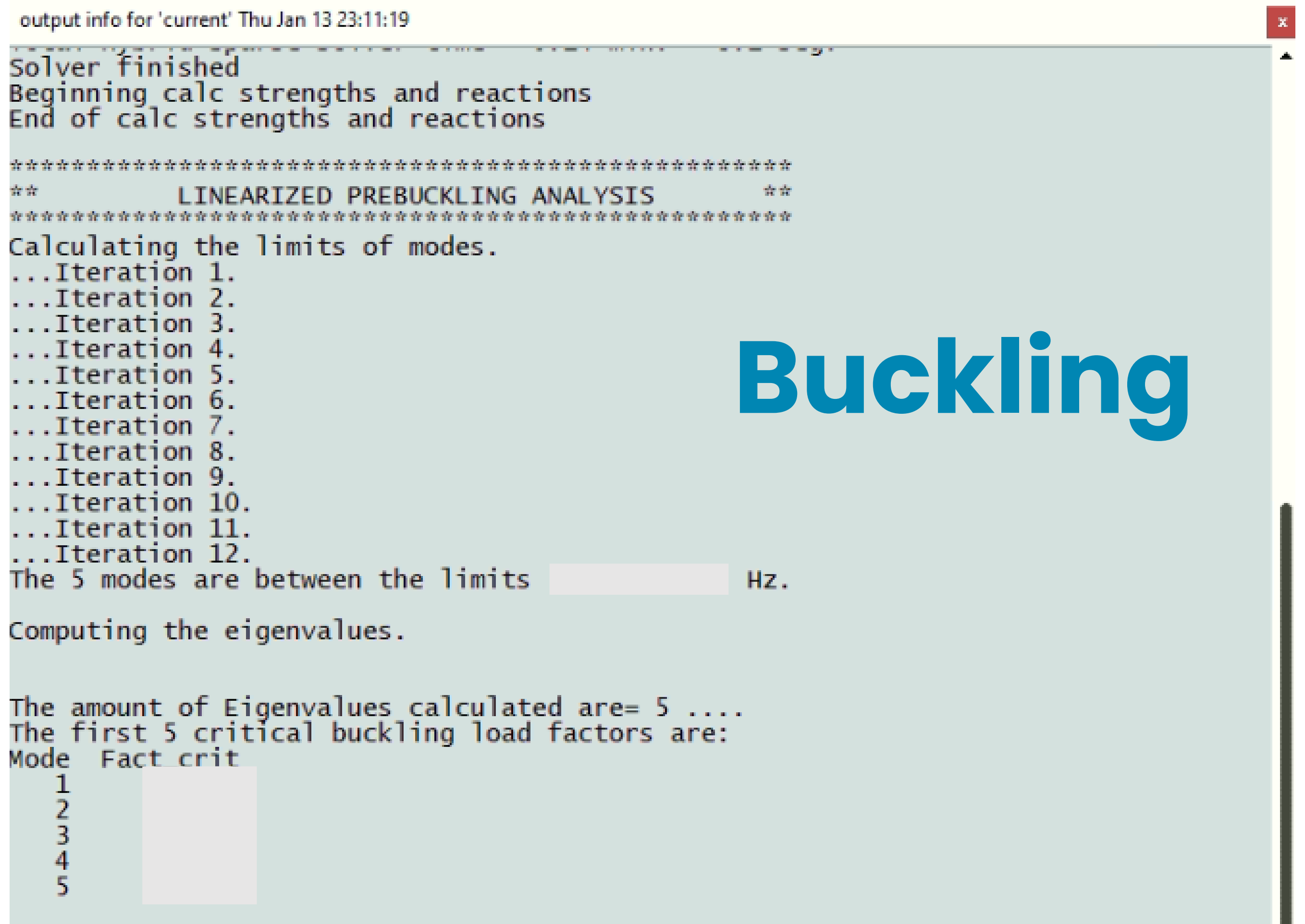
Deflections



Natural frequencies

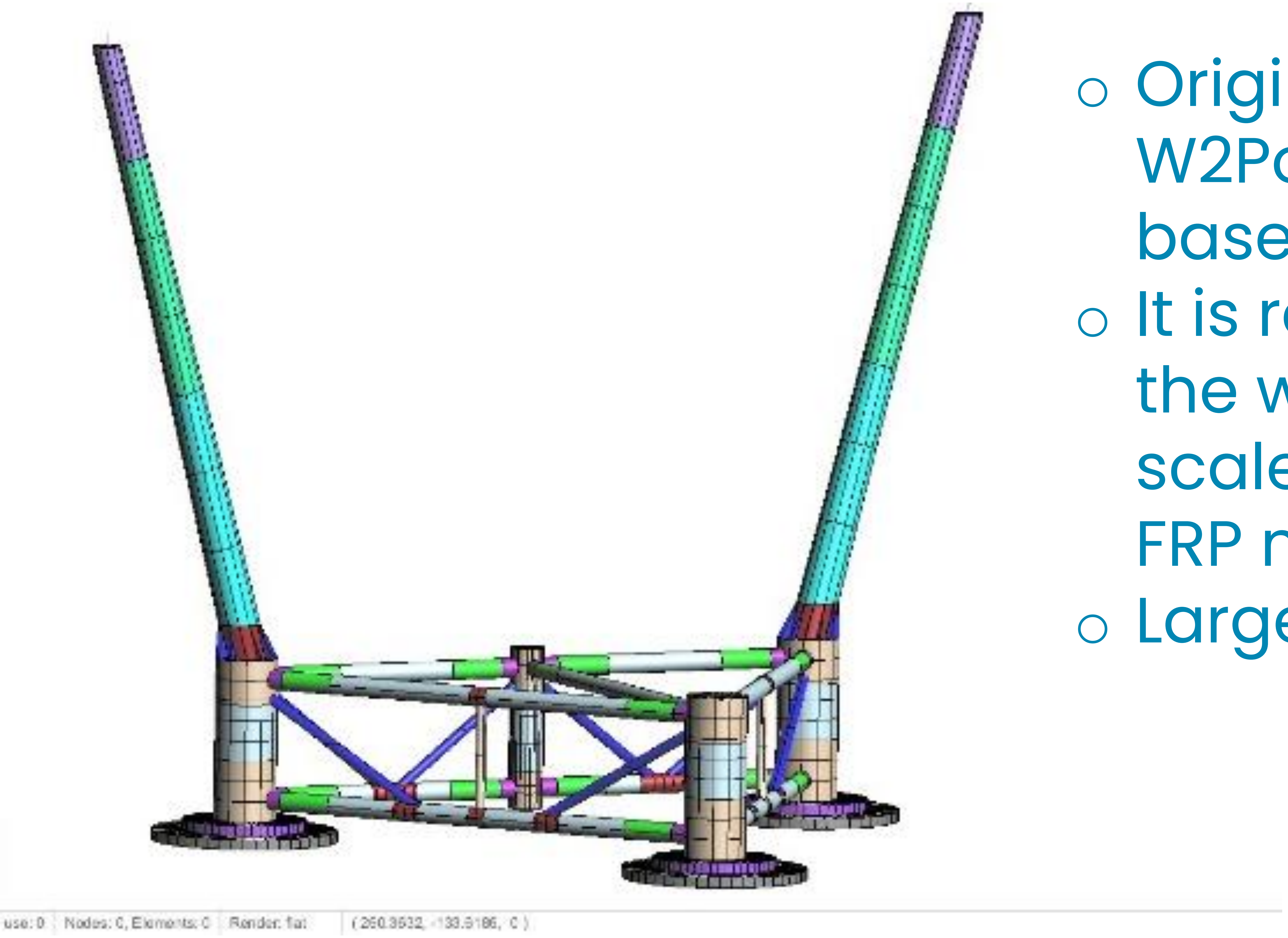


Buckling



Deformations amplified for visualization purposes

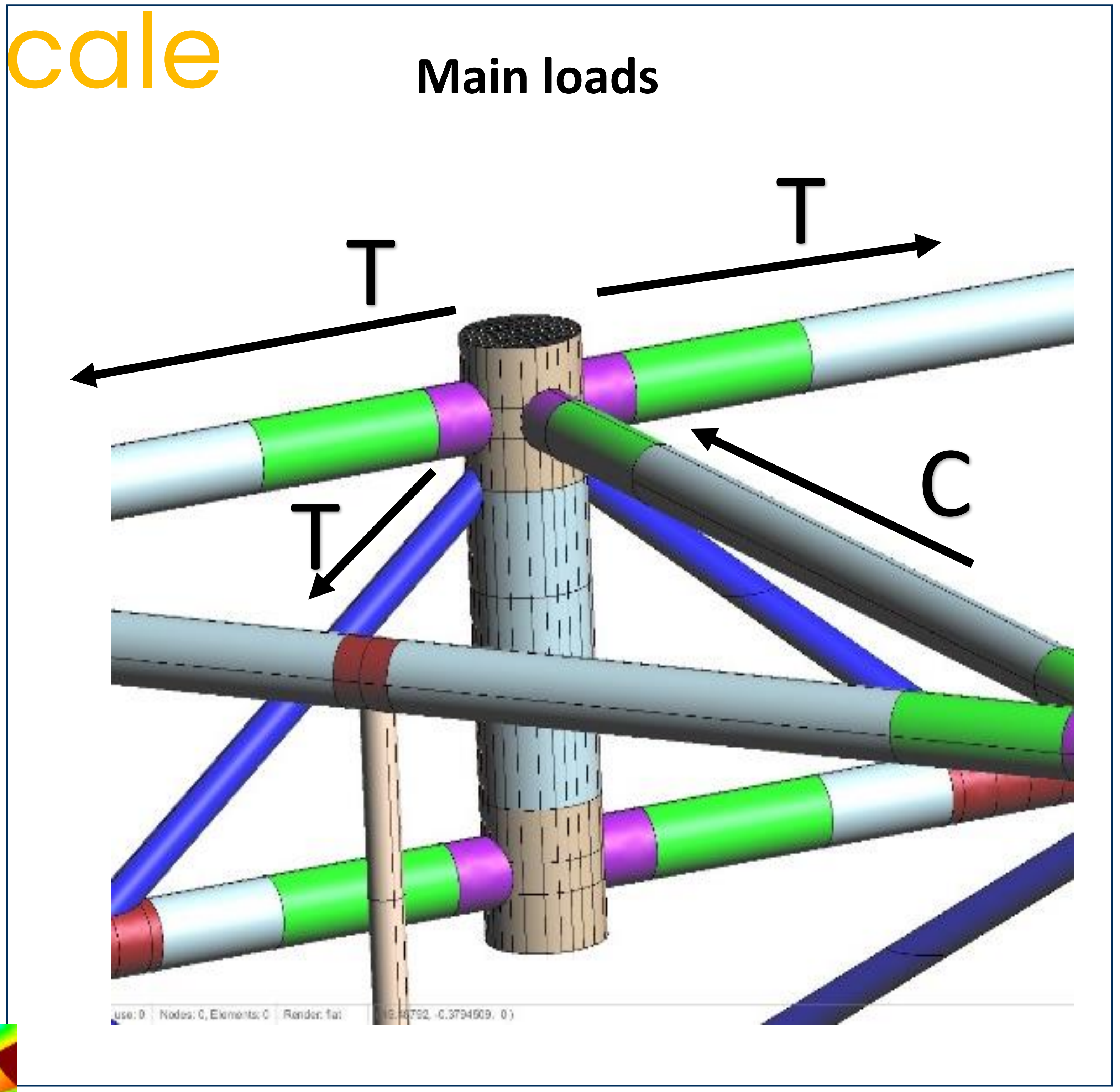
Context: W2P real-scale

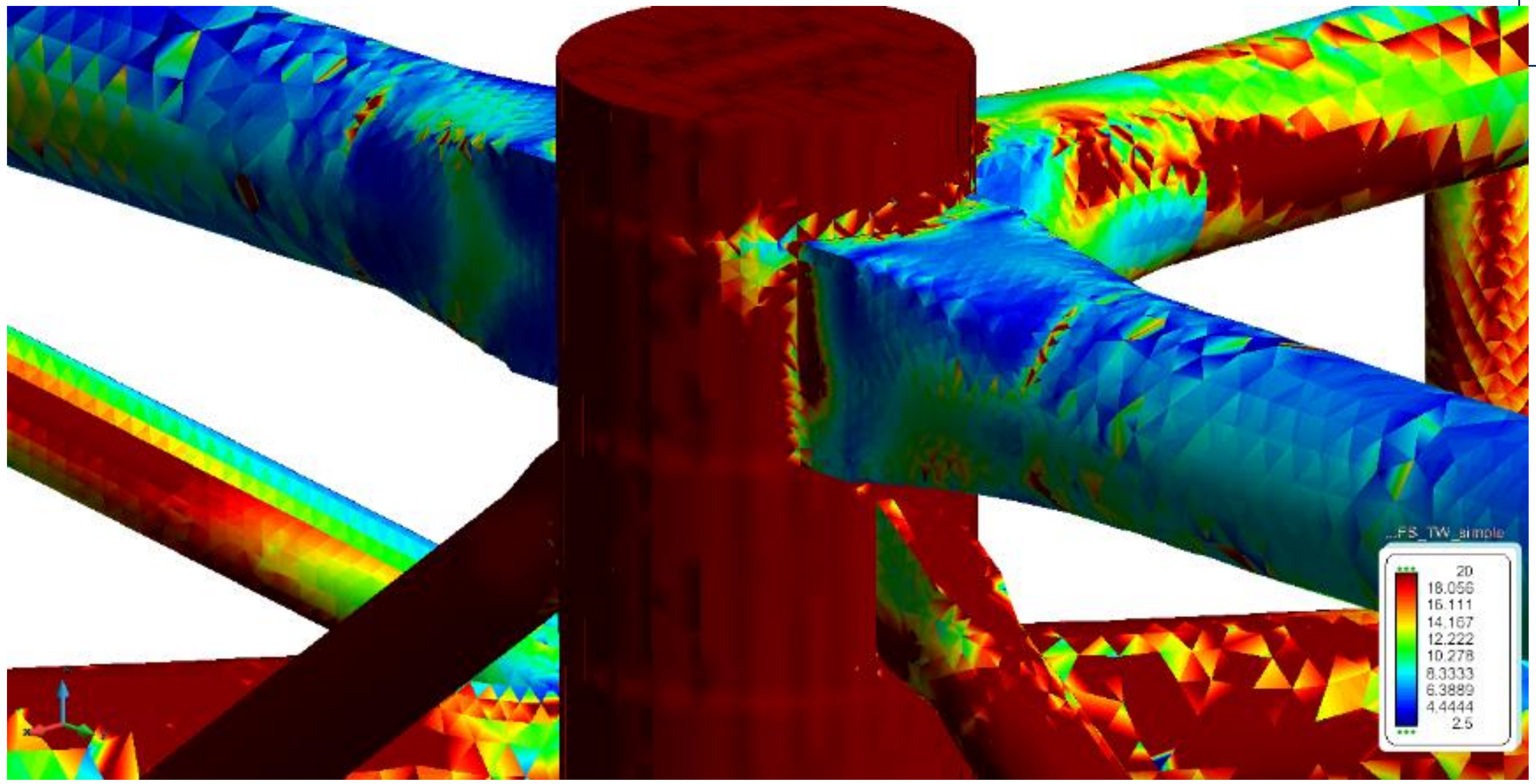


- Original design of the W2Power platform is based on steel.
- It is required a redesign of the whole W2Power real-scale platform, to include FRP materials.
- Large dimensions.

Study of structural performance: W2P real-scale

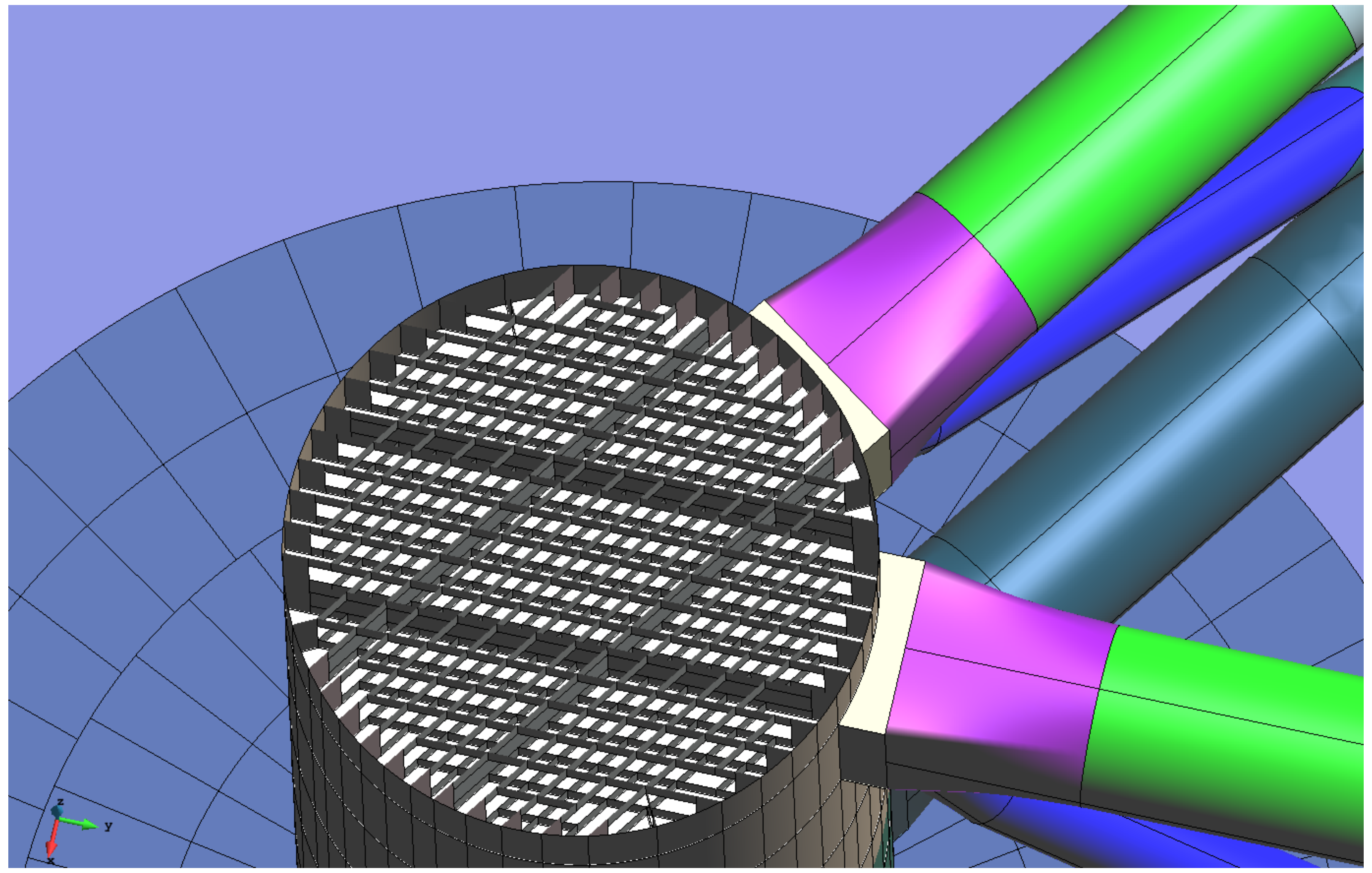
- Study of the structural performance of the whole W2Power platform.
- Different alternatives were studied.
- Each proposal was shared with the consortium, to analyze the pros and cons (from the point of view of manufacturing, performance, etc).
- Validation of the FRP W2P real-scale platform by using hydroelastic model.

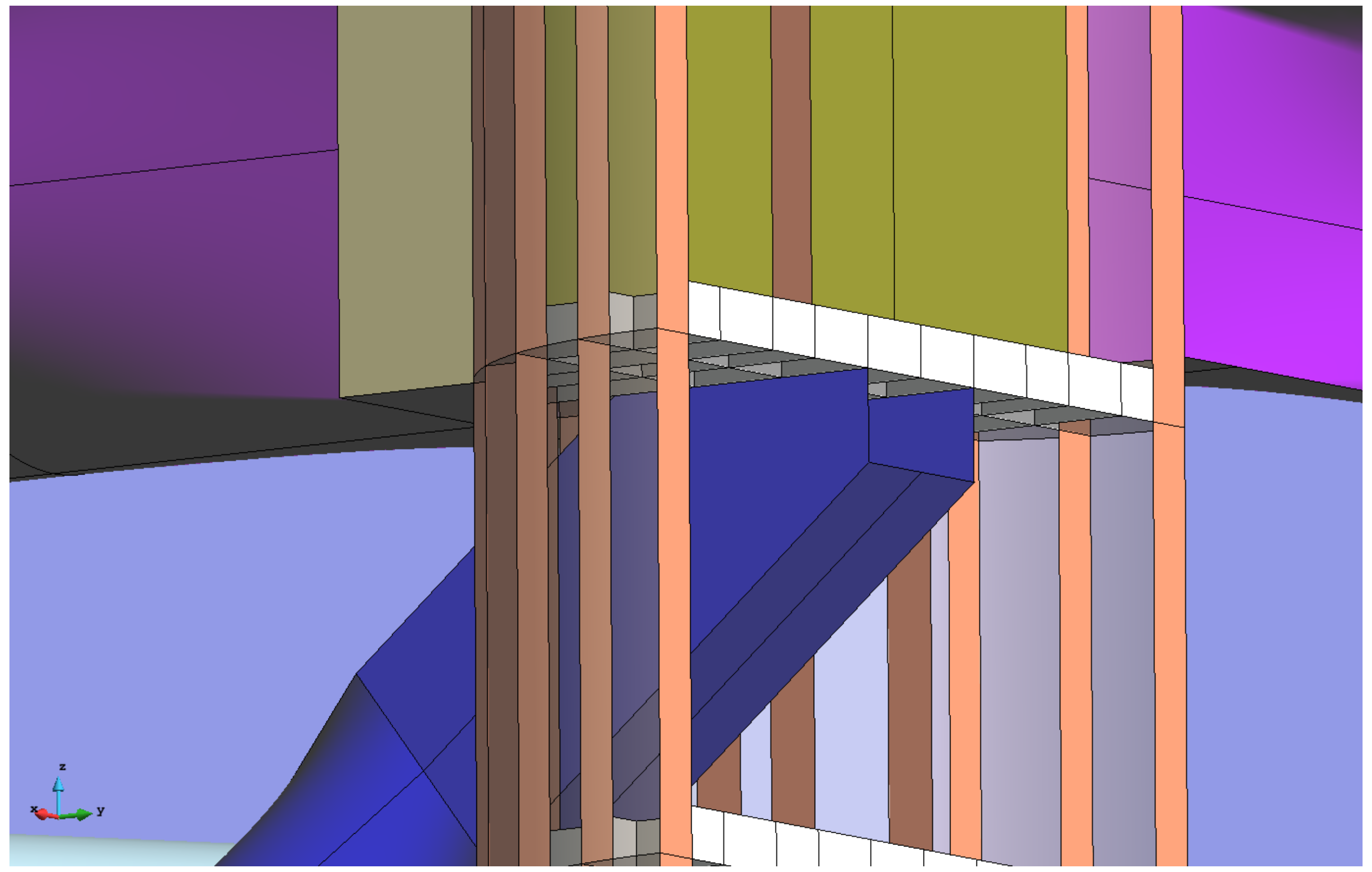
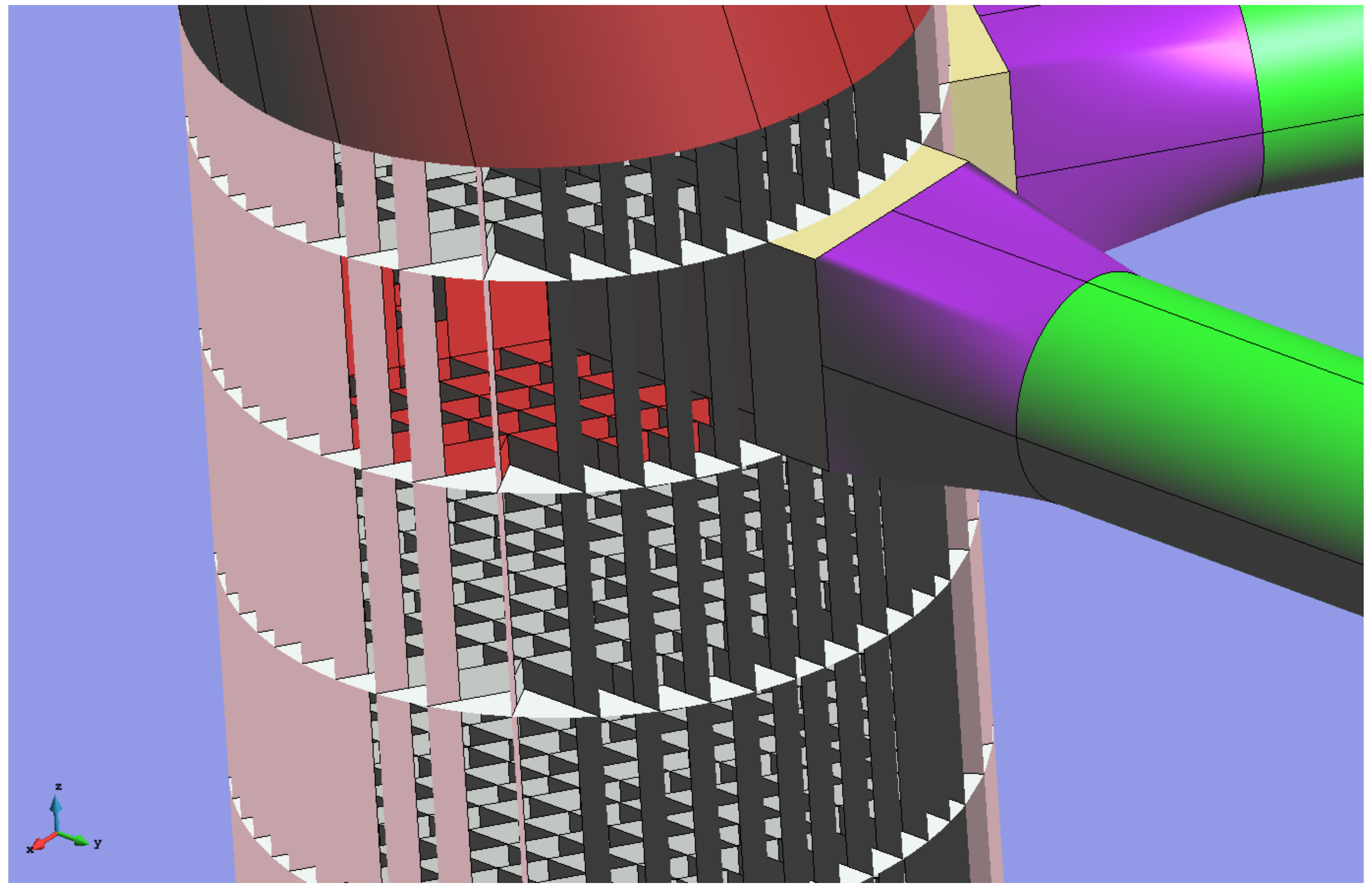
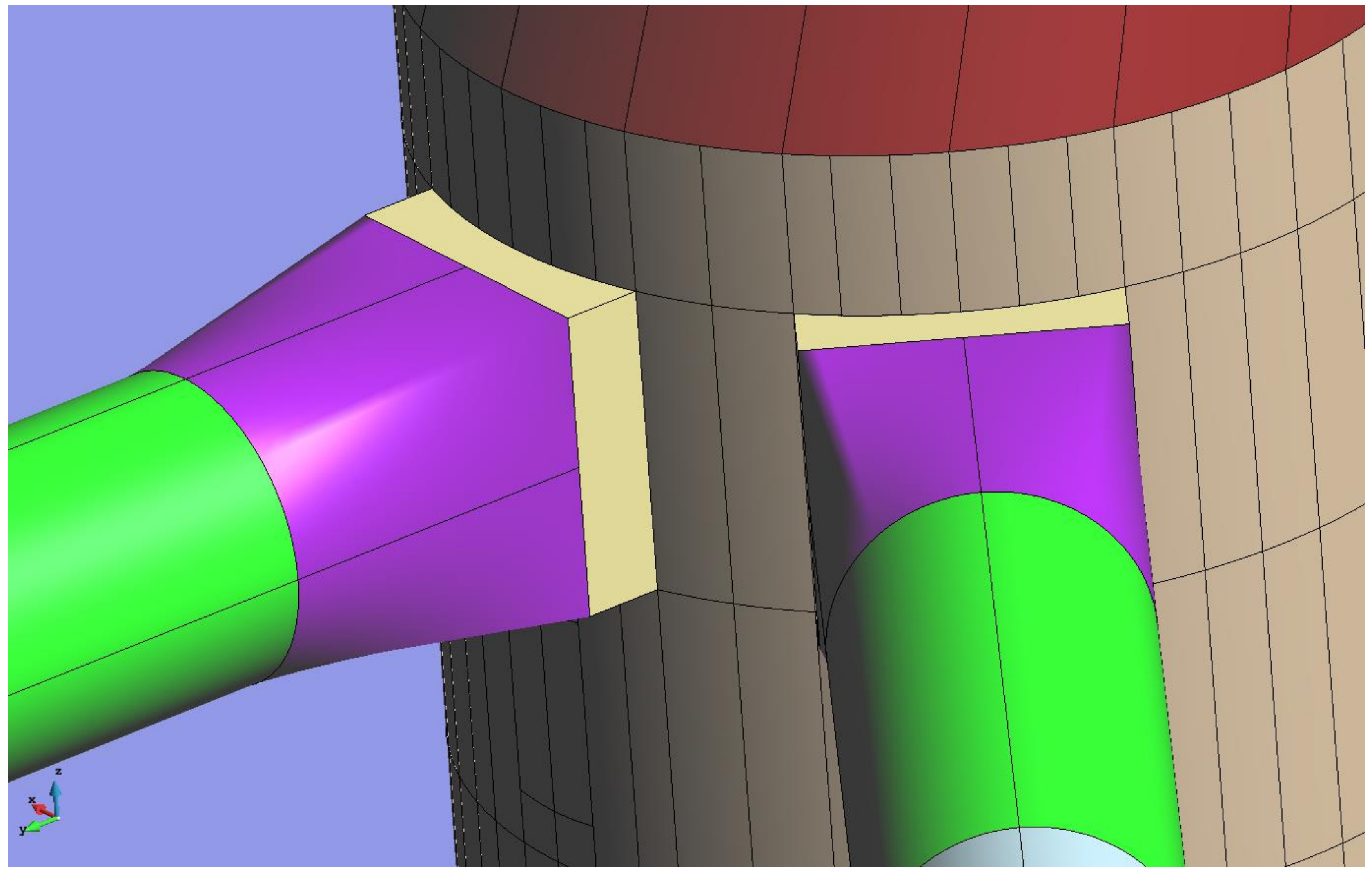




Proposals of structural solutions: W2P real-scale

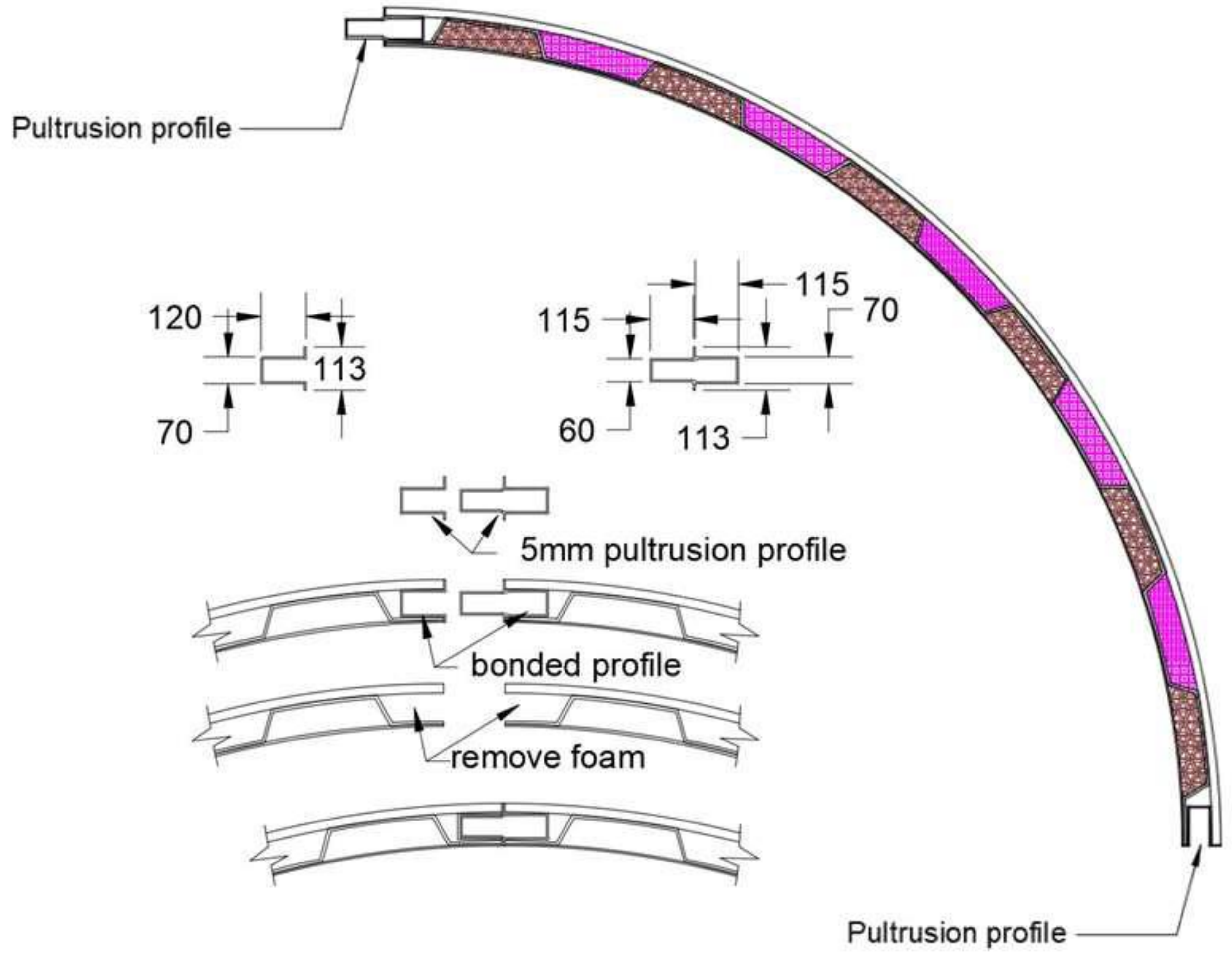
- Internal structure based on Cartesian distribution.
- Load transfer between elements were improved.
- Geometrical transitions were used for facilitate the manufacturing, as well as structural behavior.
- Geometric transitions were inspired on offshore industry, using flat panels.

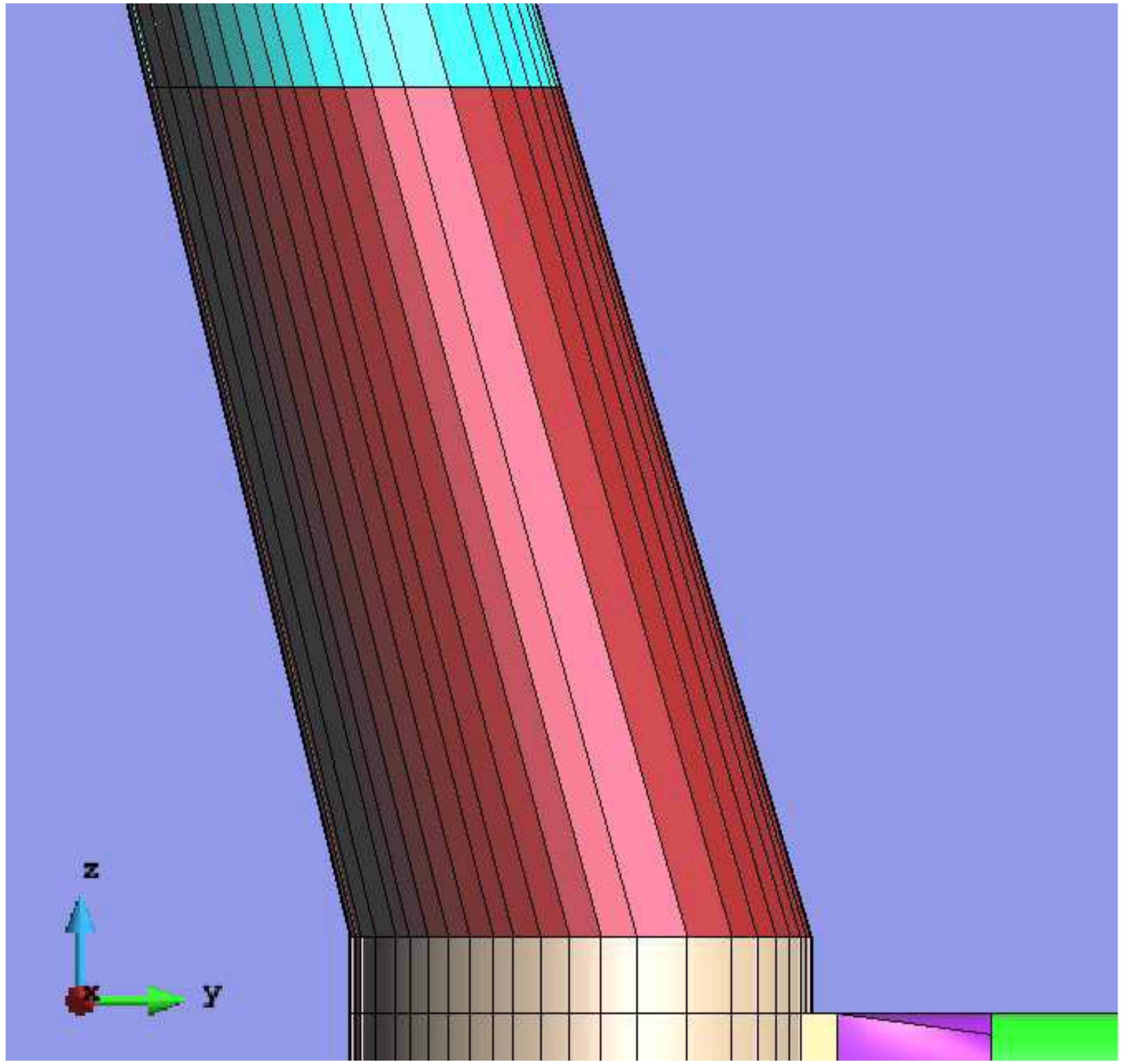


Proposals of structural solutions: W2P real-scale

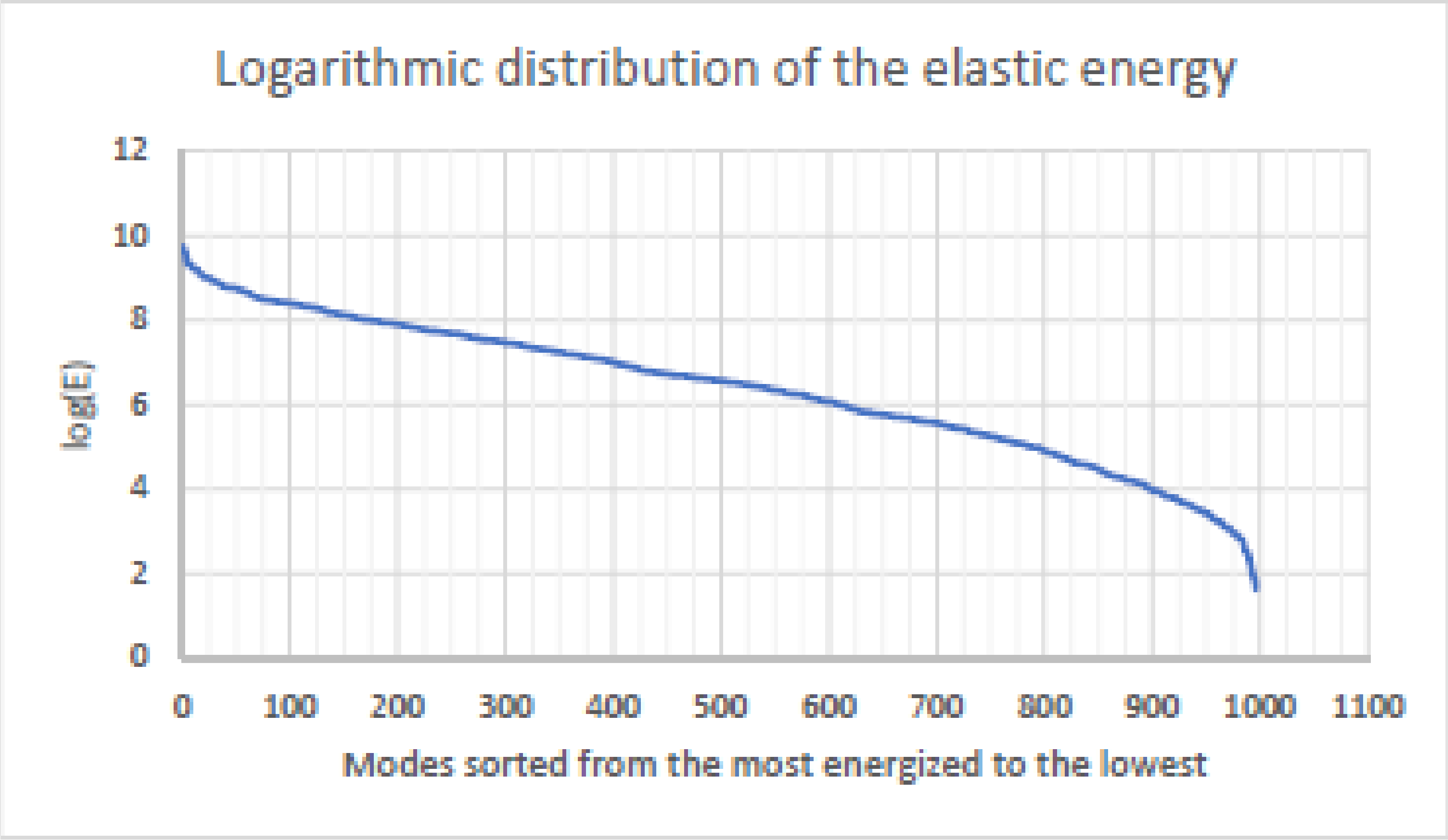
- Different approaches were developed, for improving the structural behavior of the tower.
- Conical transition between platform and tower.
- Development of sandwich like solutions for increase tower inertia.
  - New numerical solutions were required.



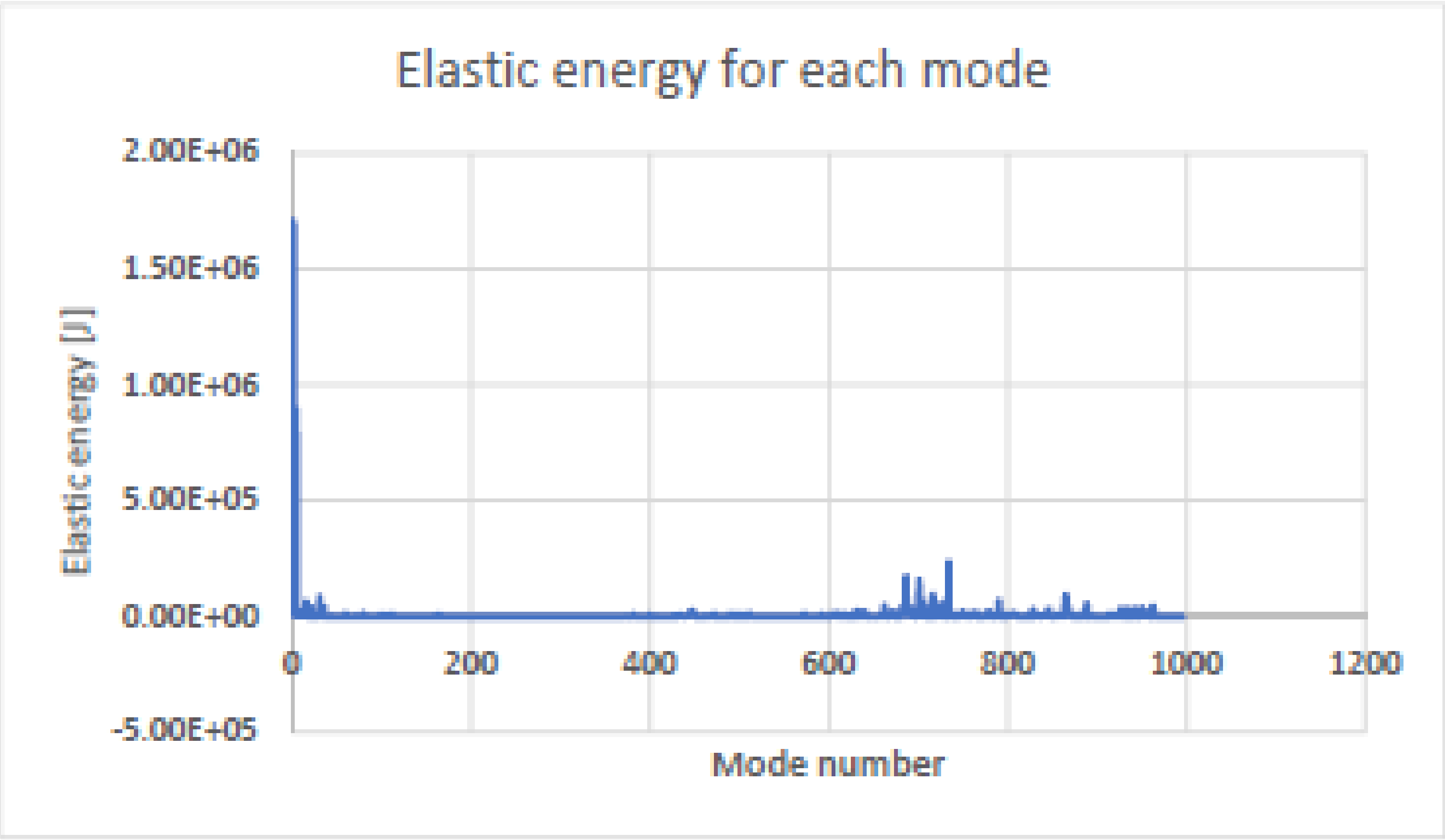


W2Power real scale analysis

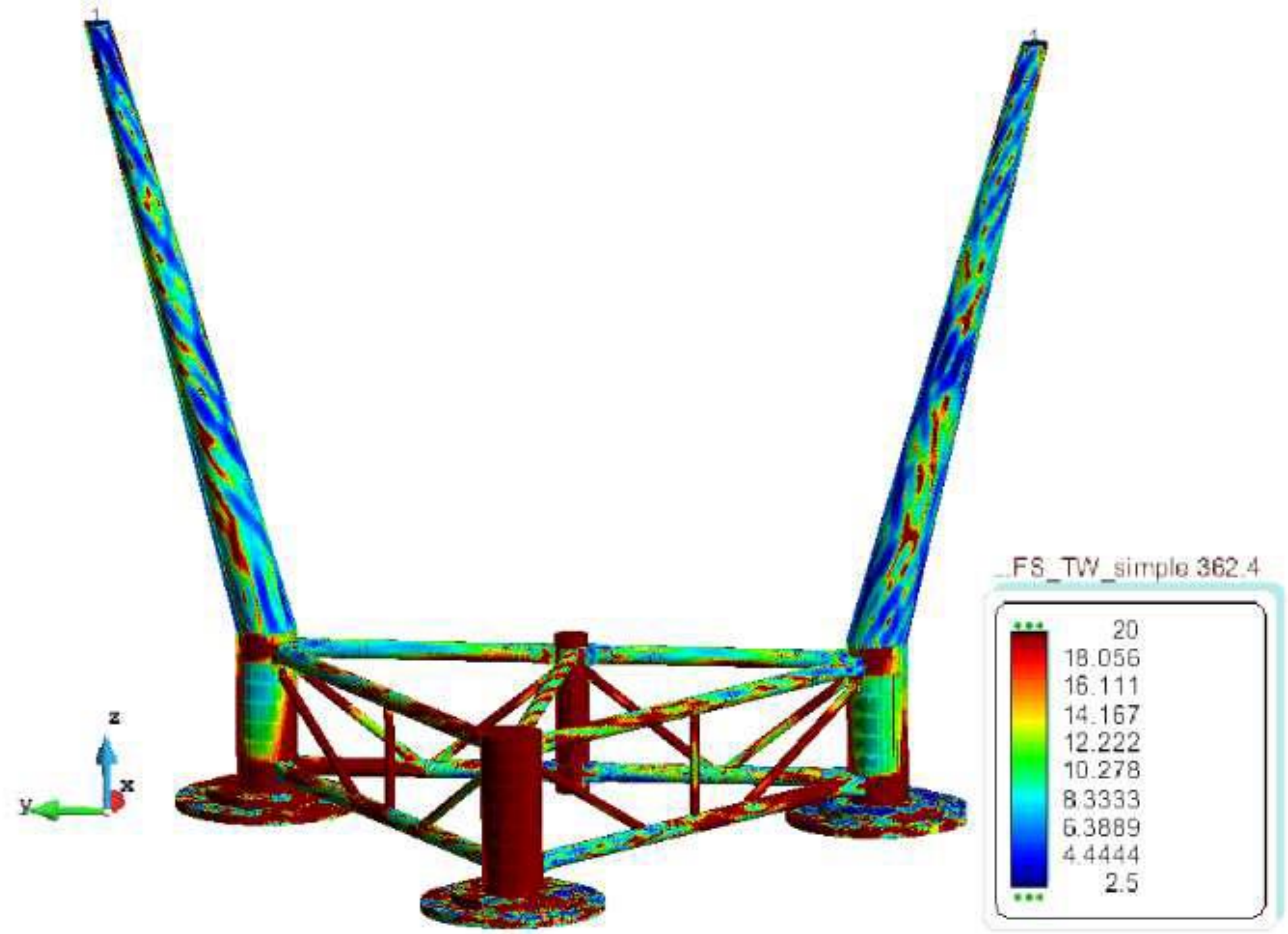
- A Model Order Reduction solution was developed by CIMNE to obtain the hydroelastic performance by reducing the computational cost.
- The hydroelastic model is used to assess the structural performance of the W2Power real-scale platform.
- The most energetic time-step is chosen as the critical step.

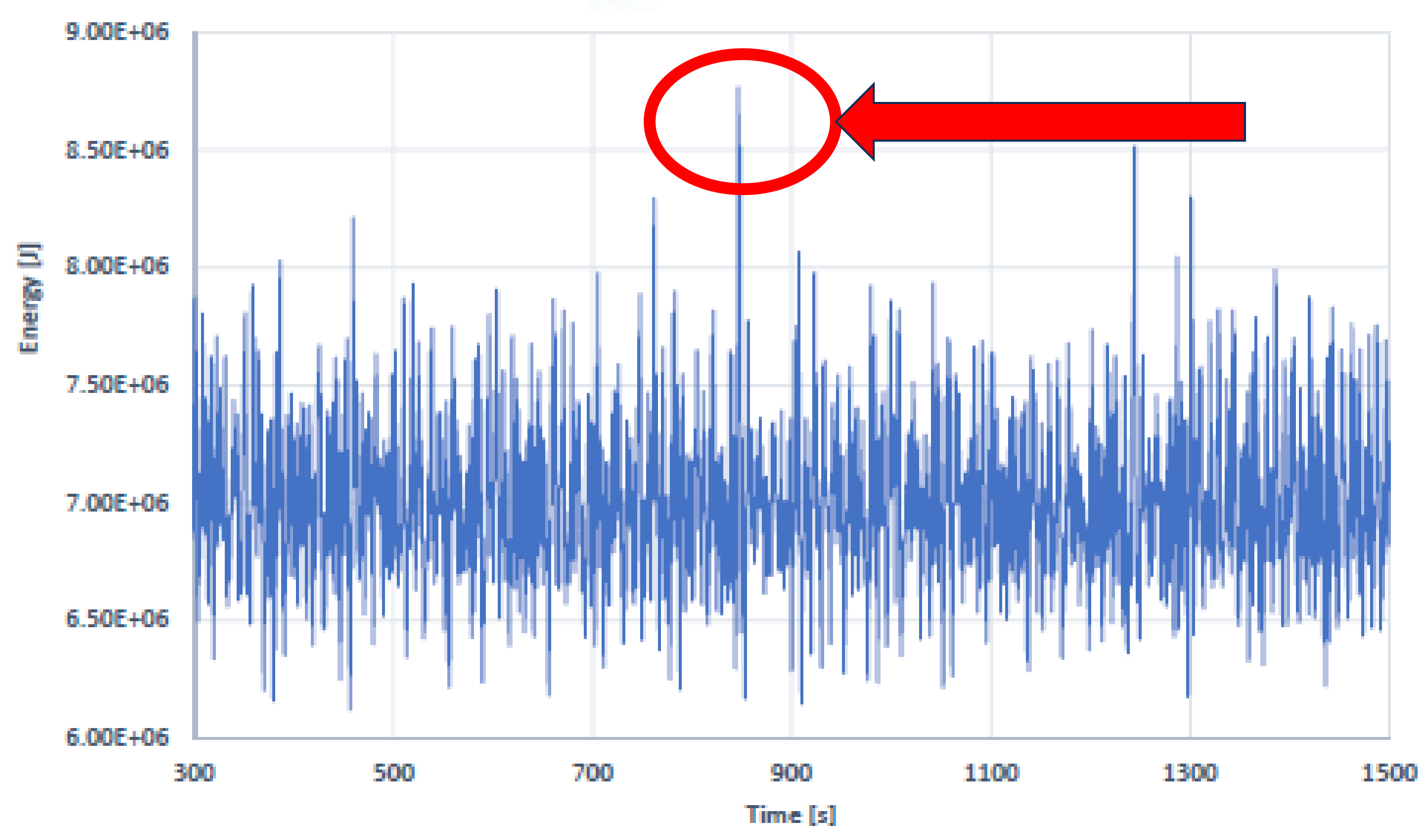


(a)



(b)





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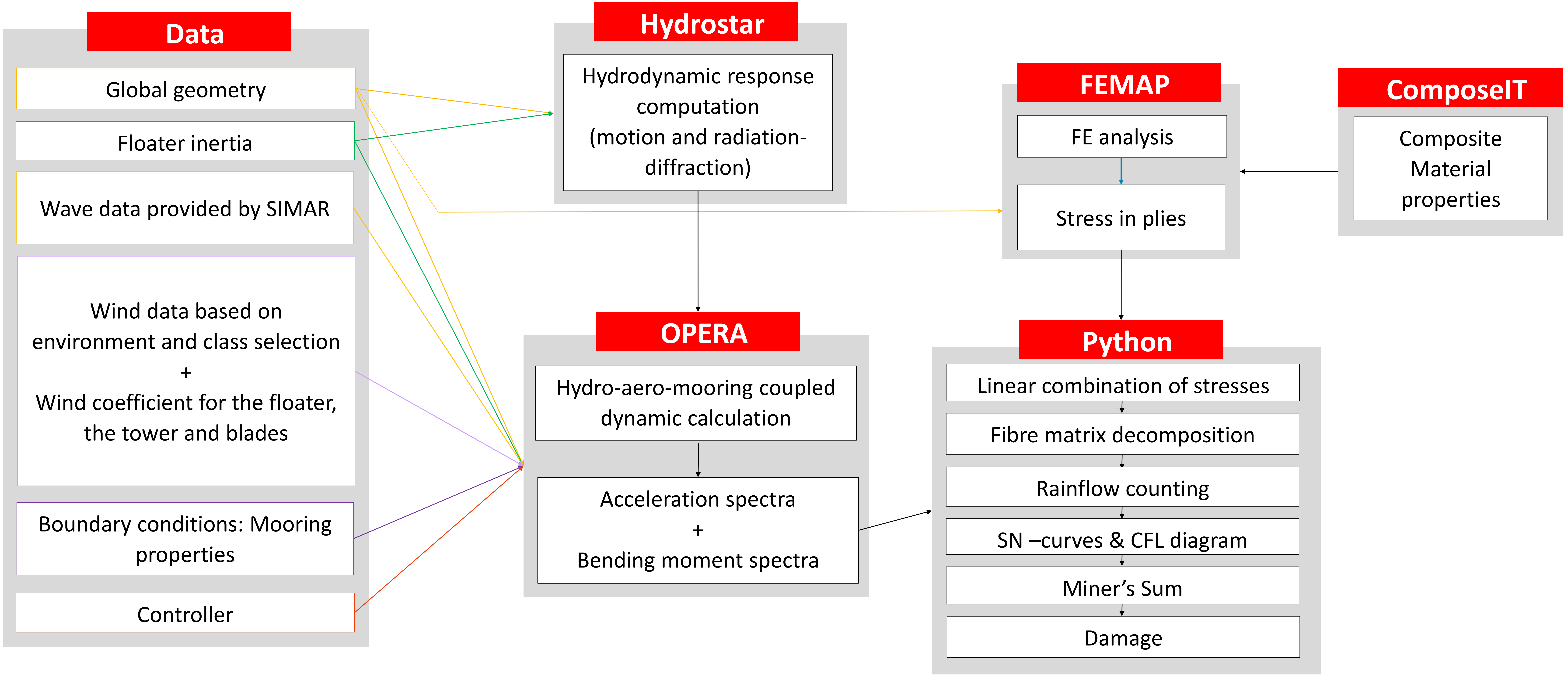
Fatigue assessment methodology for tower in composite materials

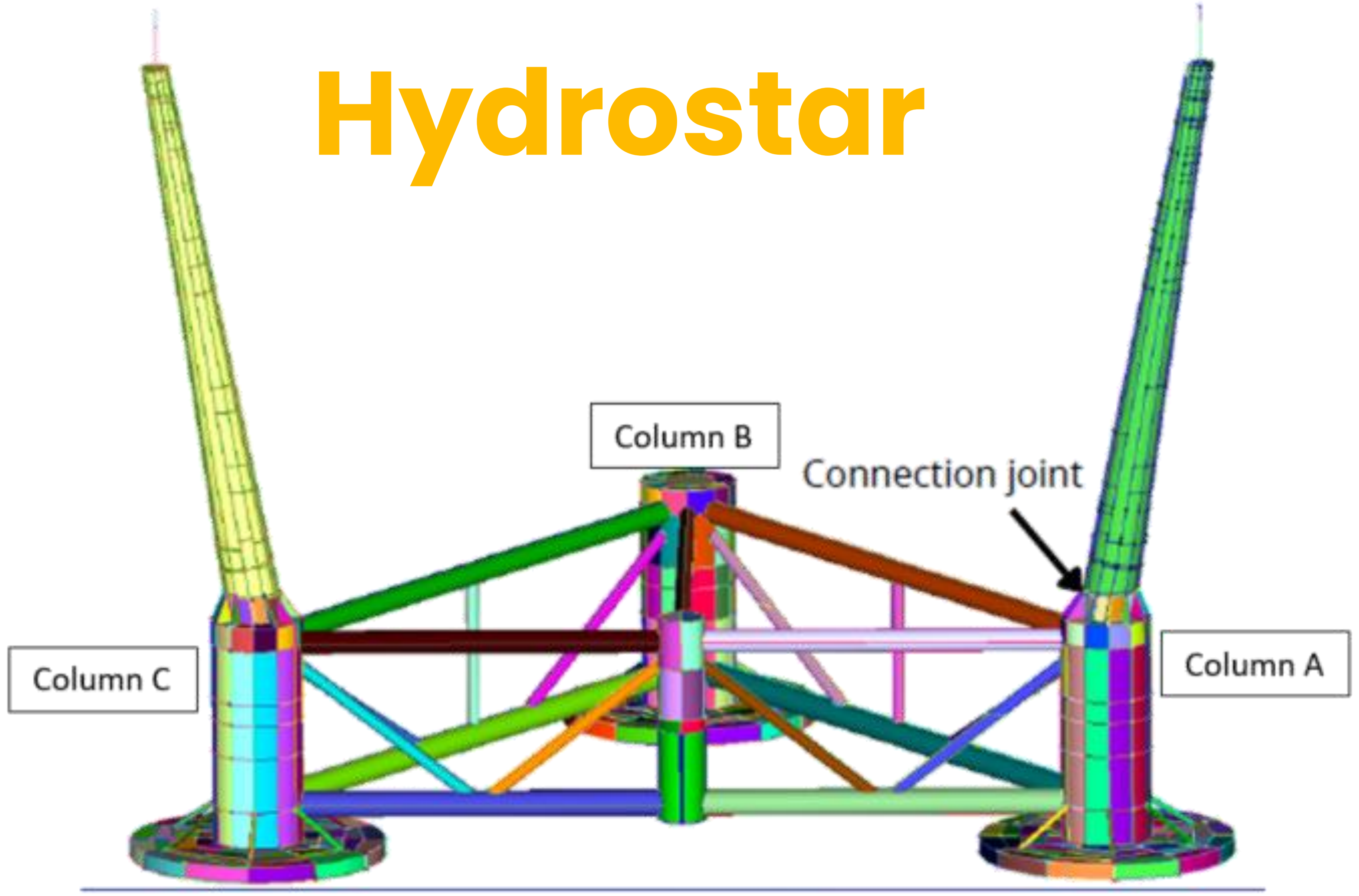
Stéphane Paboeuf, Bureau Veritas

FIBREGY

Fatigue assessment: Global methodology



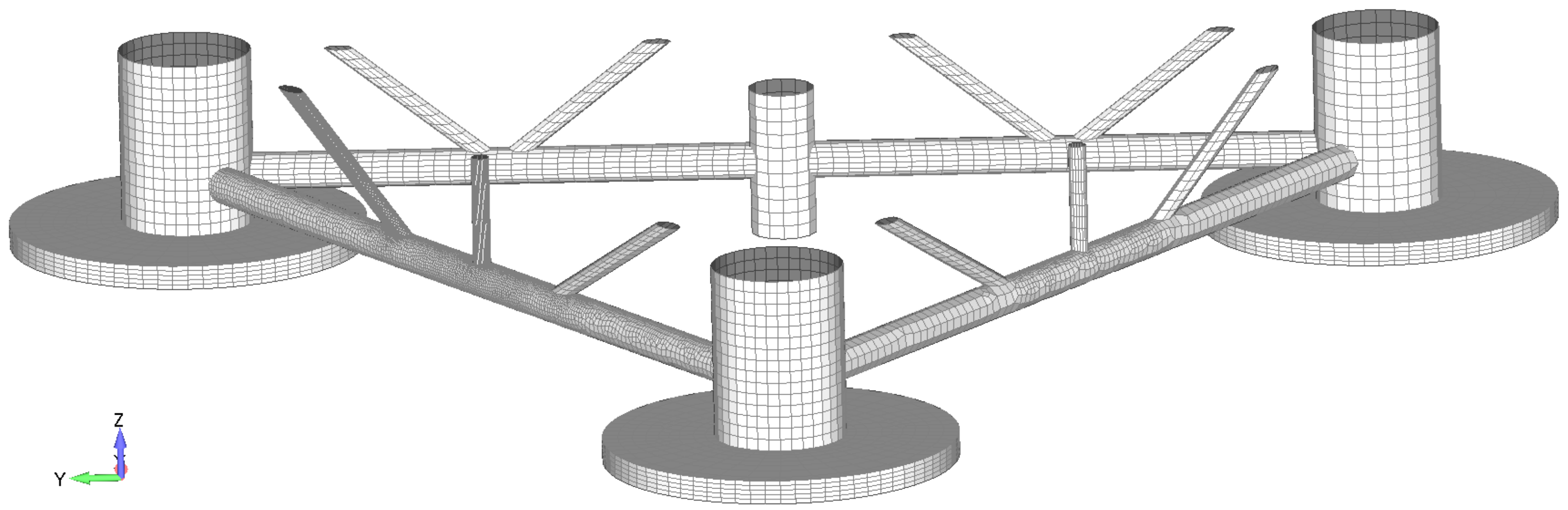
Hydrostar



Floater geometry

EXPORT

Up to the DRAFT Portion



HYDROSTAR meshing

CHECK THE QUALITY OF MESH

COMPUTE HYDRODYNAMIC RESPONSE ON FLOATER

HYDROSTAR hydrodynamic response of floater

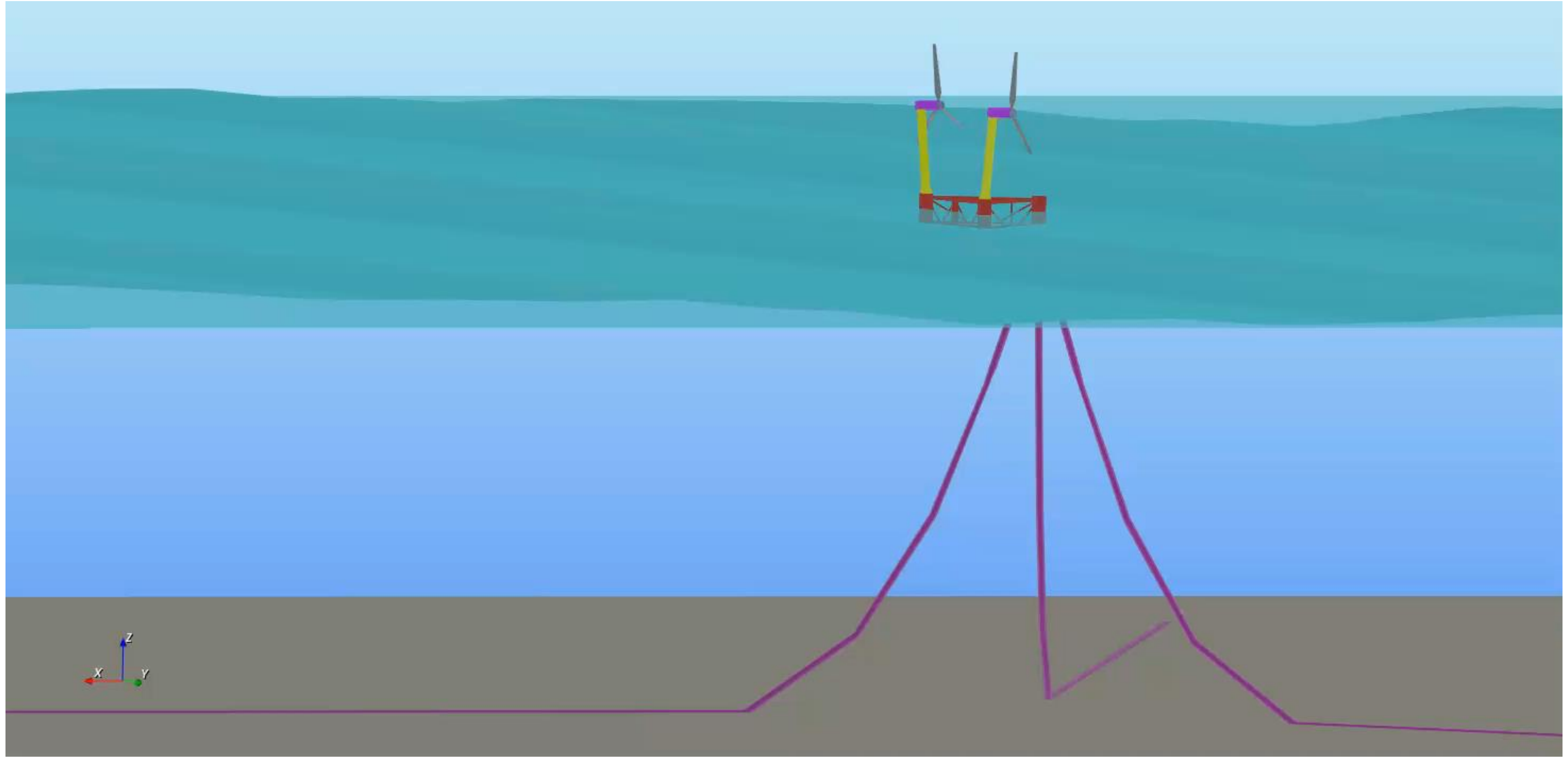
Export

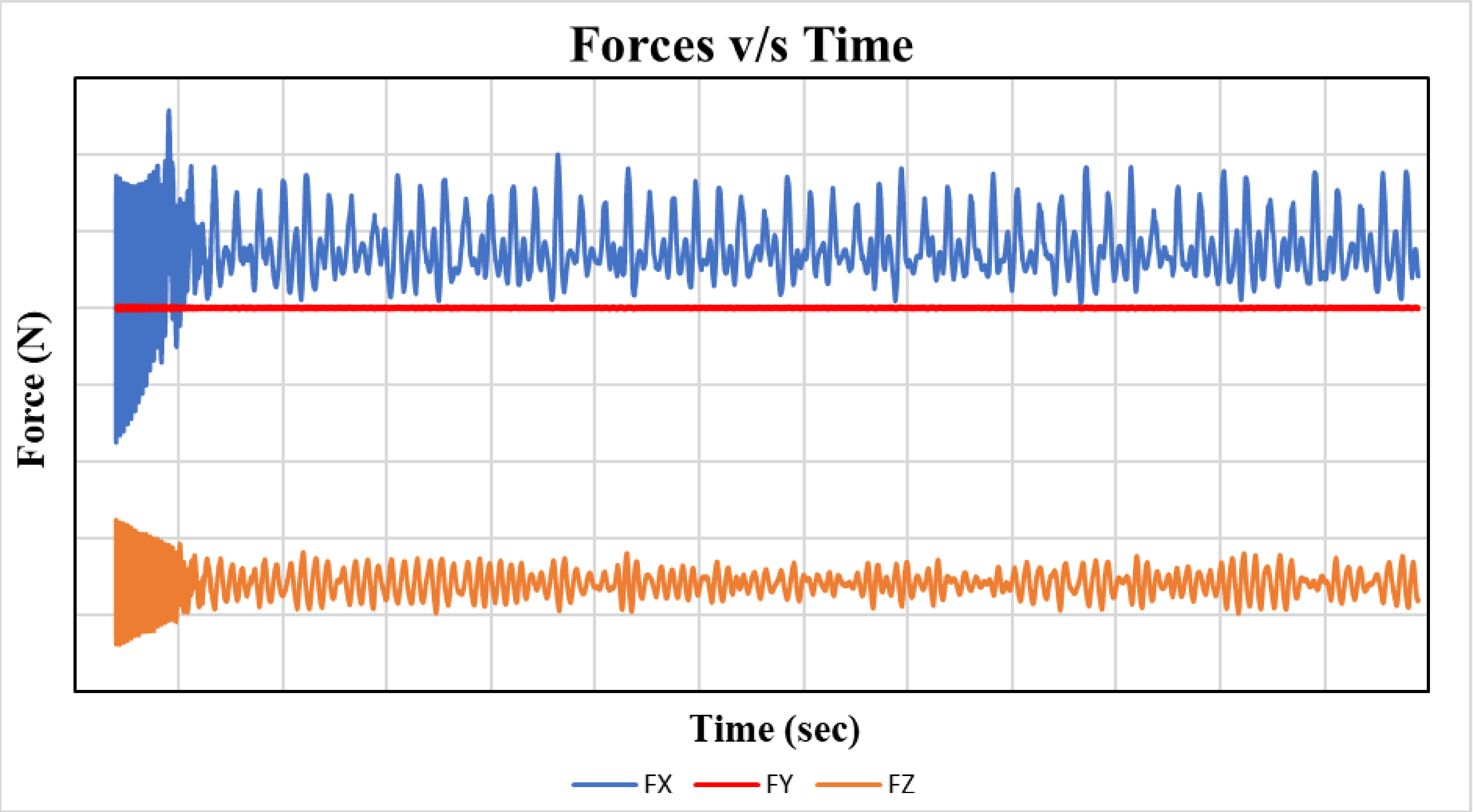
OPERA

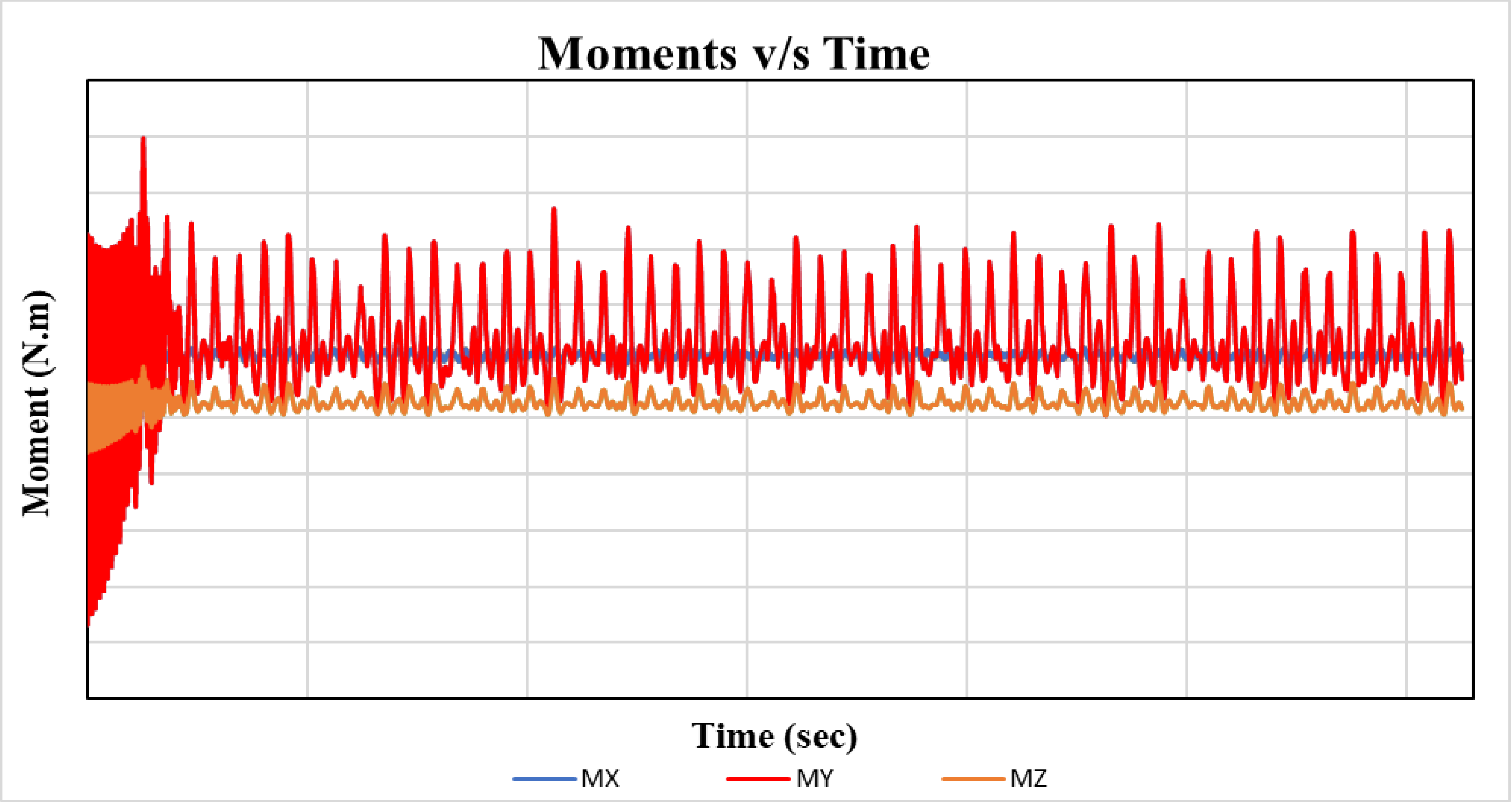
FIBREGY

Opera

- Global response of the structure
- Extraction of forces and moments at the base of the tower







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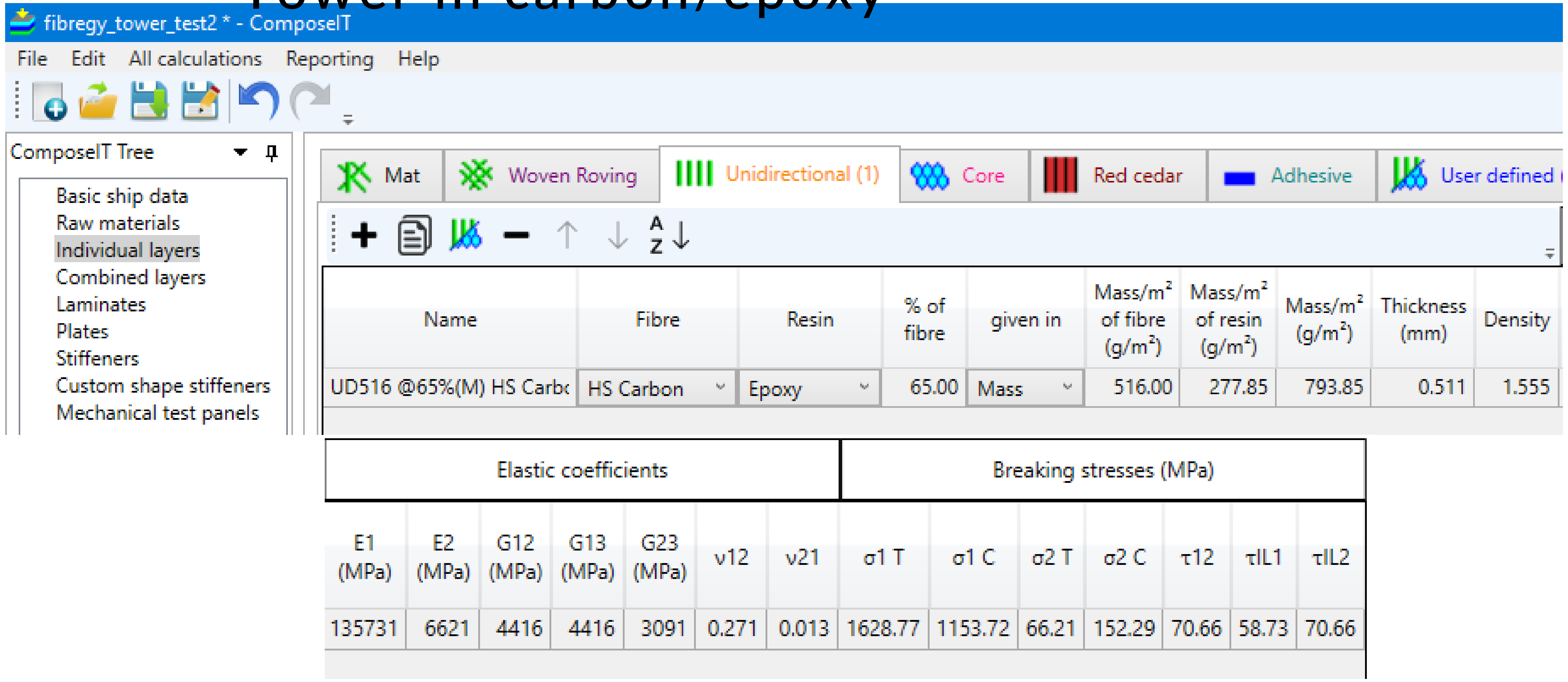
BUREAU VERITAS 1828

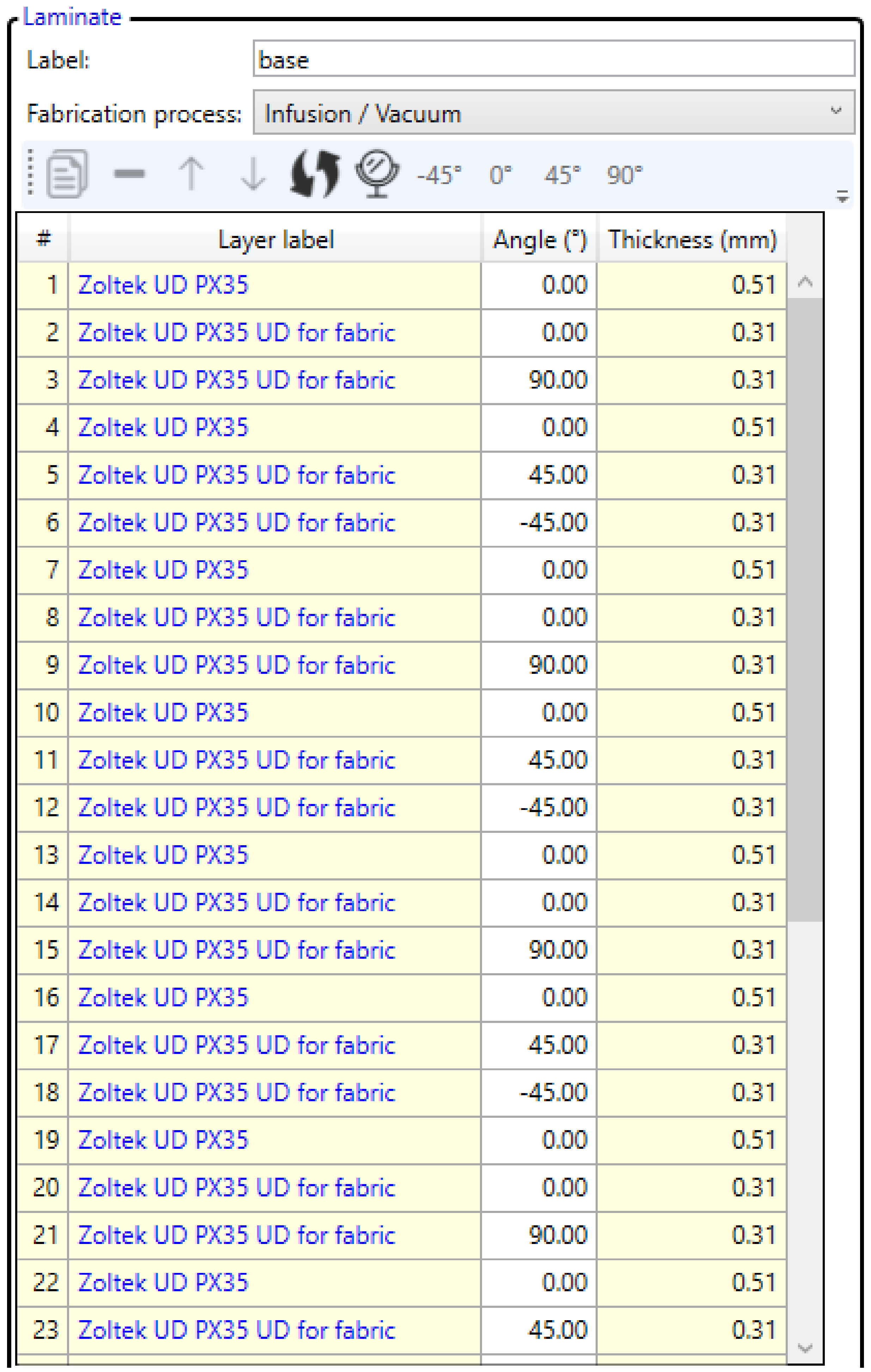
ComposeIT

- Individual layer characteristics based on material type and fibre ratio
  - Tower in carbon/epoxy



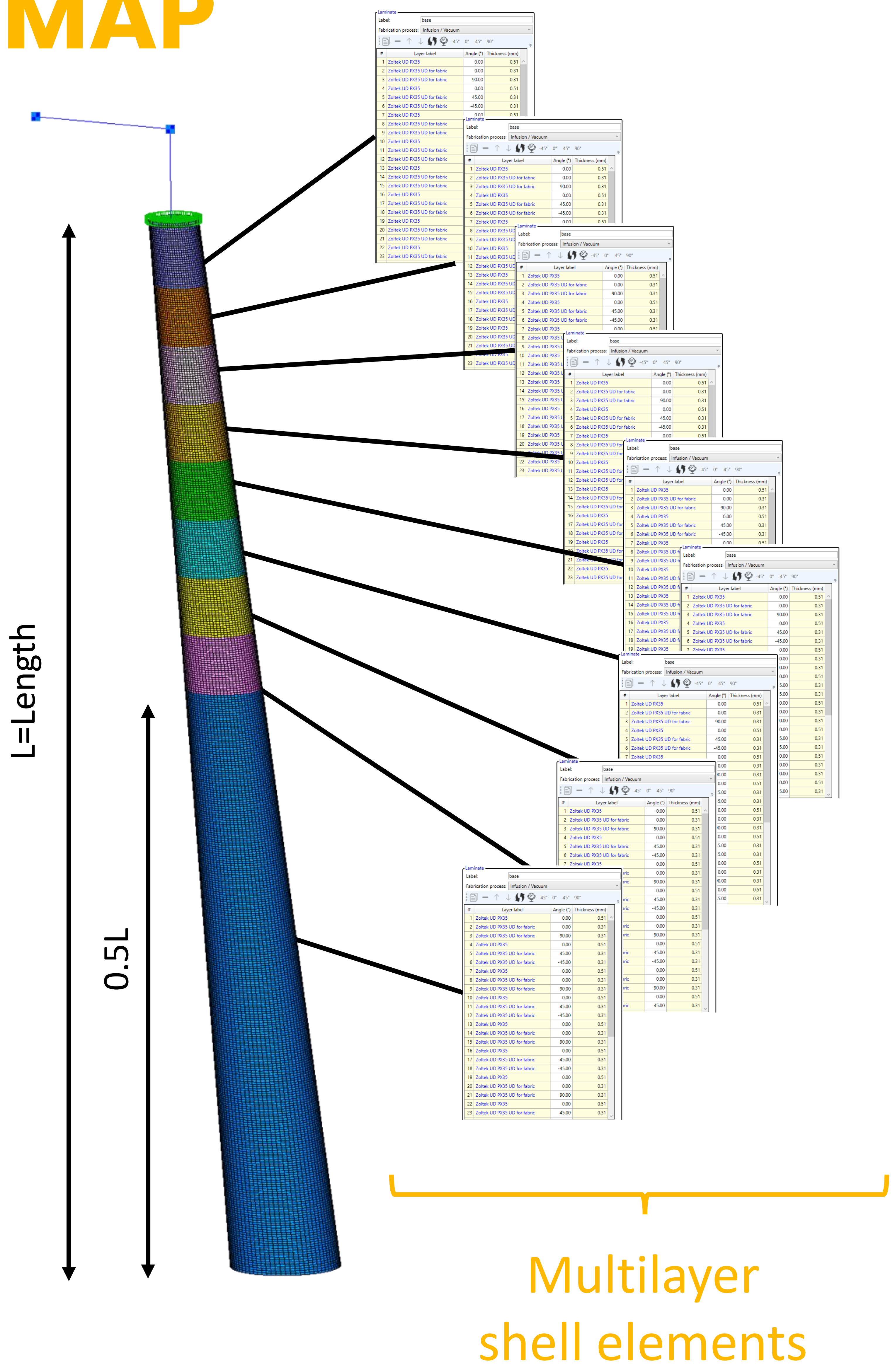
Name	Fibre	Resin	% of fibre	given in	Mass/m² of fibre (g/m²)	Mass/m² of resin (g/m²)	Mass/m² (g/m²)	Thickness (mm)	Density
UD516 @65%(M) HS Carbc	HS Carbon	Epoxy	65.00	Mass	516.00	277.85	793.85	0.511	1.555

Elastic coefficients							Breaking stresses (MPa)						
E1 (MPa)	E2 (MPa)	G12 (MPa)	G13 (MPa)	G23 (MPa)	ν12	ν21	σ1 T	σ1 C	σ2 T	σ2 C	τ12	τIL1	τIL2
135731	6621	4416	4416	3091	0.271	0.013	1628.77	1153.72	66.21	152.29	70.66	58.73	70.66

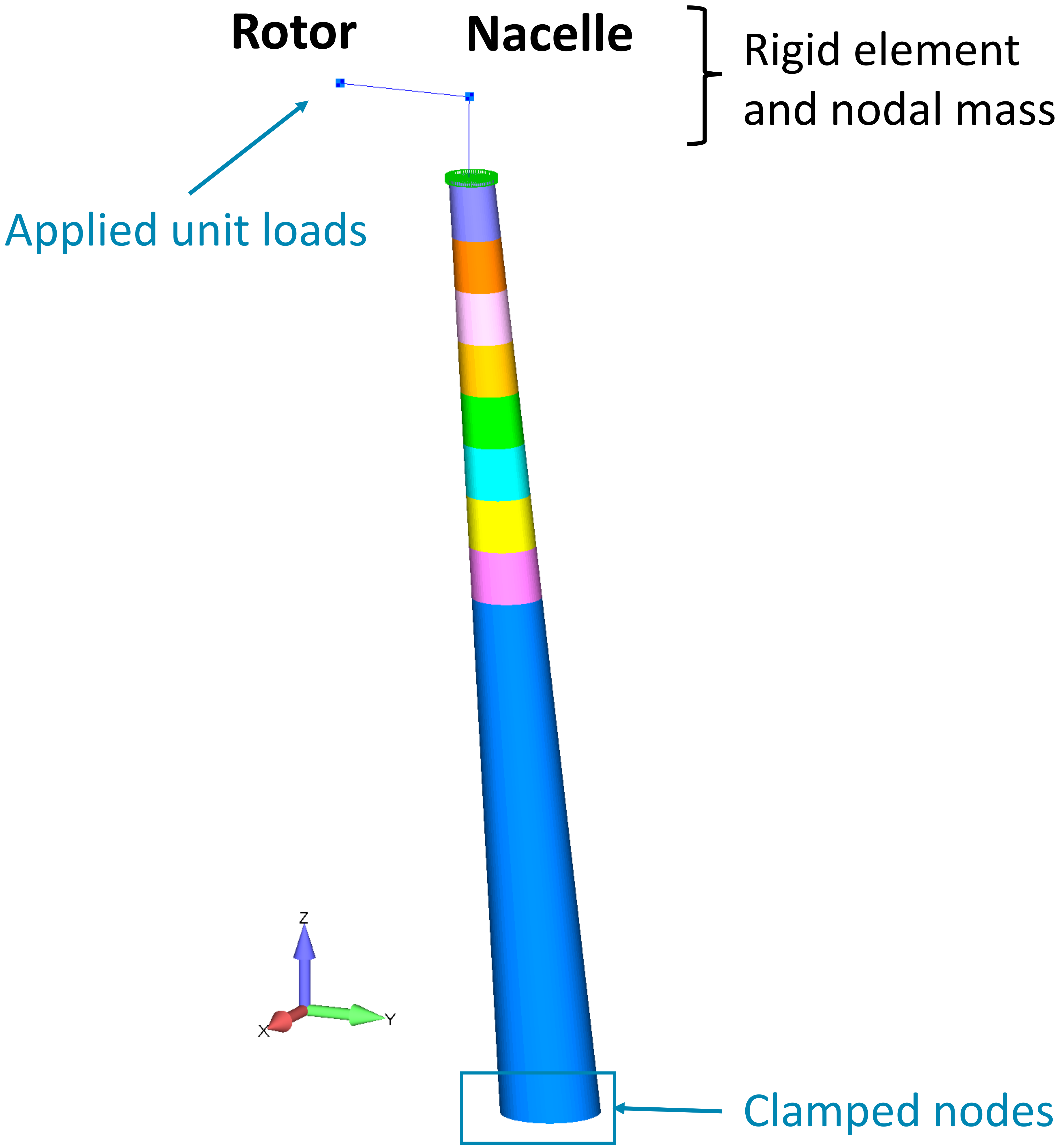


#	Layer label	Angle (°)	Thickness (mm)
1	Zoltek UD PX35	0.00	0.51
2	Zoltek UD PX35 UD for fabric	0.00	0.31
3	Zoltek UD PX35 UD for fabric	90.00	0.31
4	Zoltek UD PX35	0.00	0.51
5	Zoltek UD PX35 UD for fabric	45.00	0.31
6	Zoltek UD PX35 UD for fabric	-45.00	0.31
7	Zoltek UD PX35	0.00	0.51
8	Zoltek UD PX35 UD for fabric	0.00	0.31
9	Zoltek UD PX35 UD for fabric	90.00	0.31
10	Zoltek UD PX35	0.00	0.51
11	Zoltek UD PX35 UD for fabric	45.00	0.31
12	Zoltek UD PX35 UD for fabric	-45.00	0.31
13	Zoltek UD PX35	0.00	0.51
14	Zoltek UD PX35 UD for fabric	0.00	0.31
15	Zoltek UD PX35 UD for fabric	90.00	0.31
16	Zoltek UD PX35	0.00	0.51
17	Zoltek UD PX35 UD for fabric	45.00	0.31
18	Zoltek UD PX35 UD for fabric	-45.00	0.31
19	Zoltek UD PX35	0.00	0.51
20	Zoltek UD PX35 UD for fabric	0.00	0.31
21	Zoltek UD PX35 UD for fabric	90.00	0.31
22	Zoltek UD PX35	0.00	0.51
23	Zoltek UD PX35 UD for fabric	45.00	0.31

FEMAP

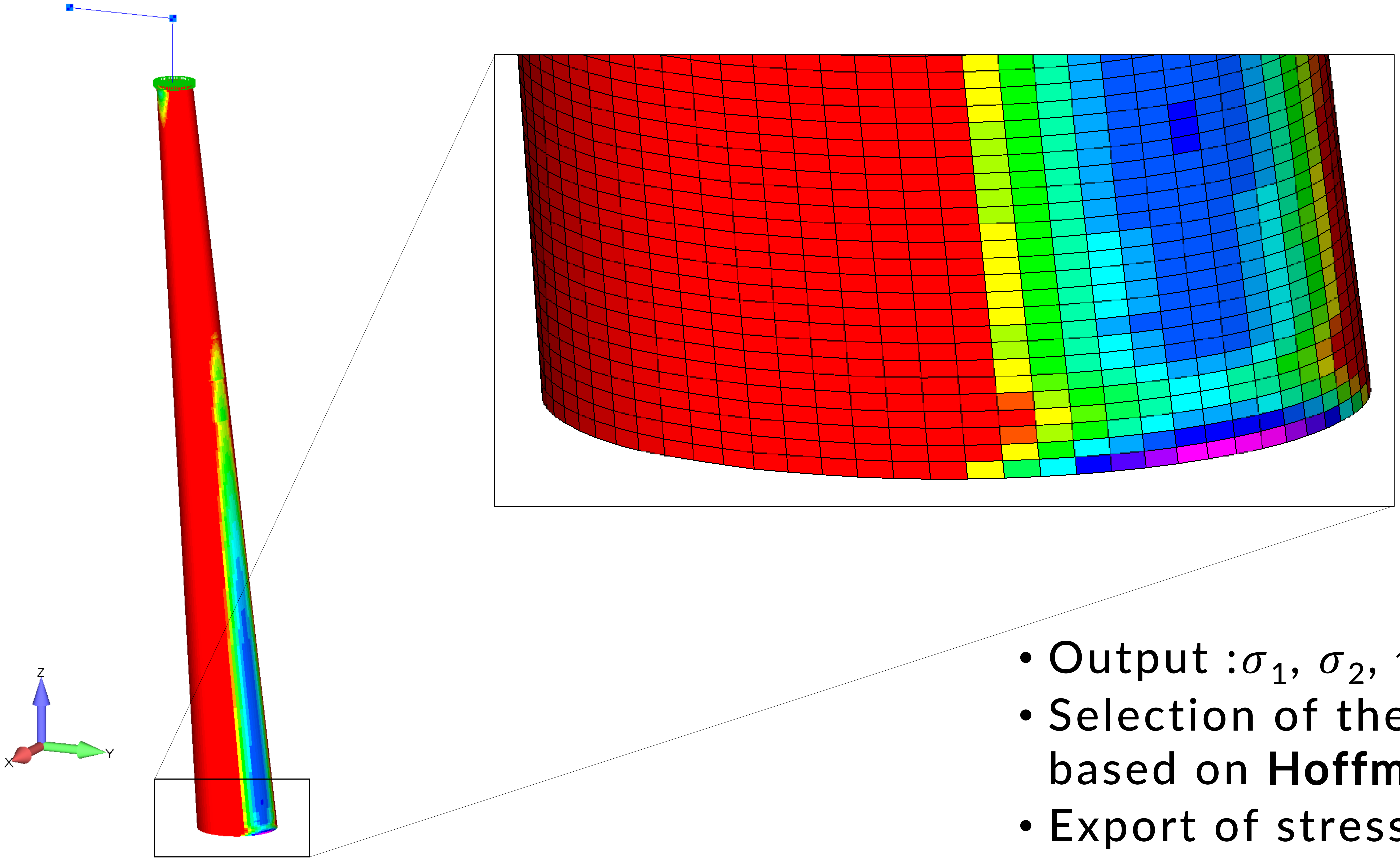


L=Length
0.5L
Multilayer
shell elements



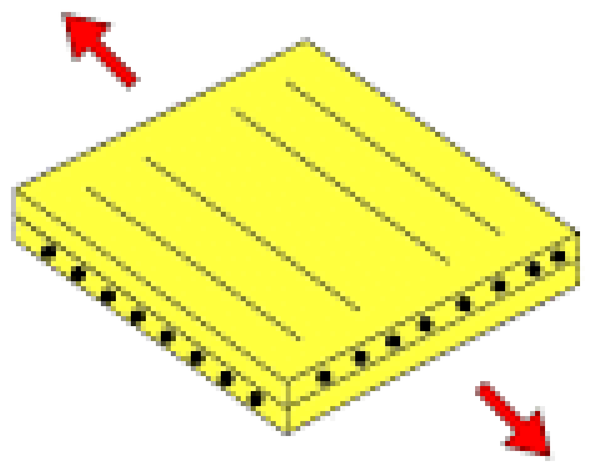
Rotor
Nacelle
Rigid element
and nodal mass
Applied unit loads
Clamped nodes
Z
Y
X

FEMAP/NASTRAN Analysis

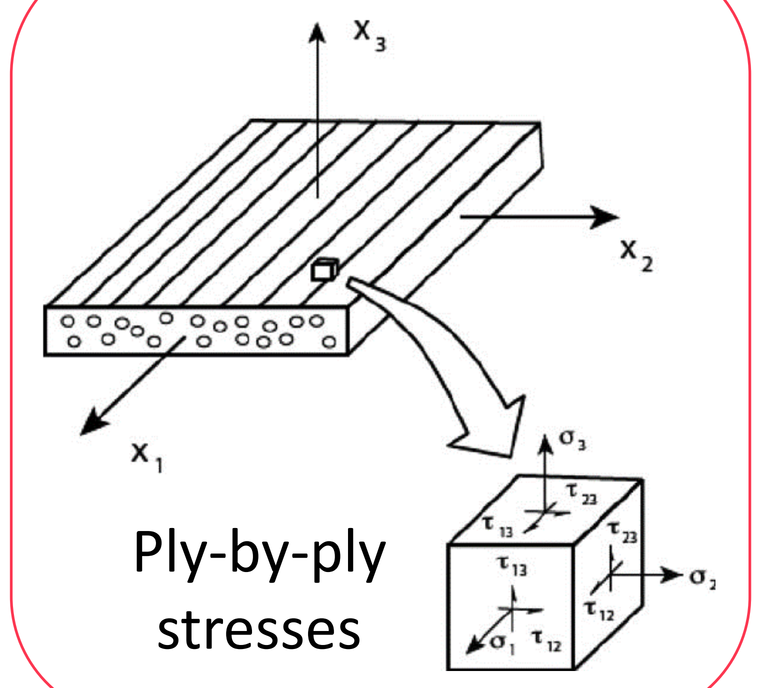


- Output :σ_1, σ_2, τ_{12} for each ply
- Selection of the critical element based on **Hoffman** criteria
- Export of stresses to Python

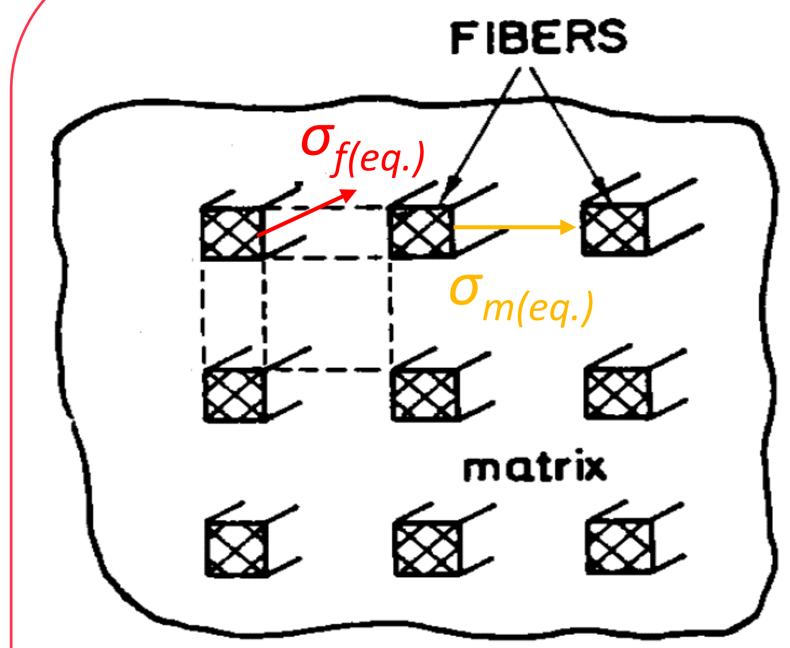
Proposed methodology for the fatigue



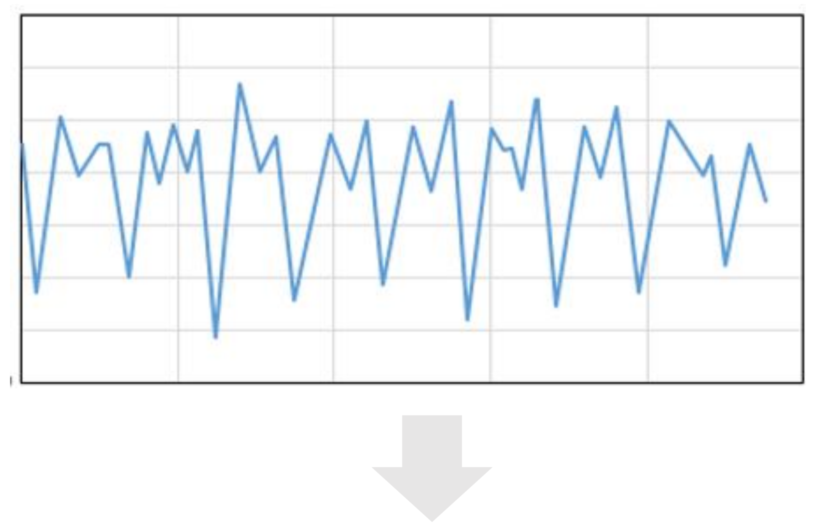
Laminate under given loading



Ply-by-ply stresses

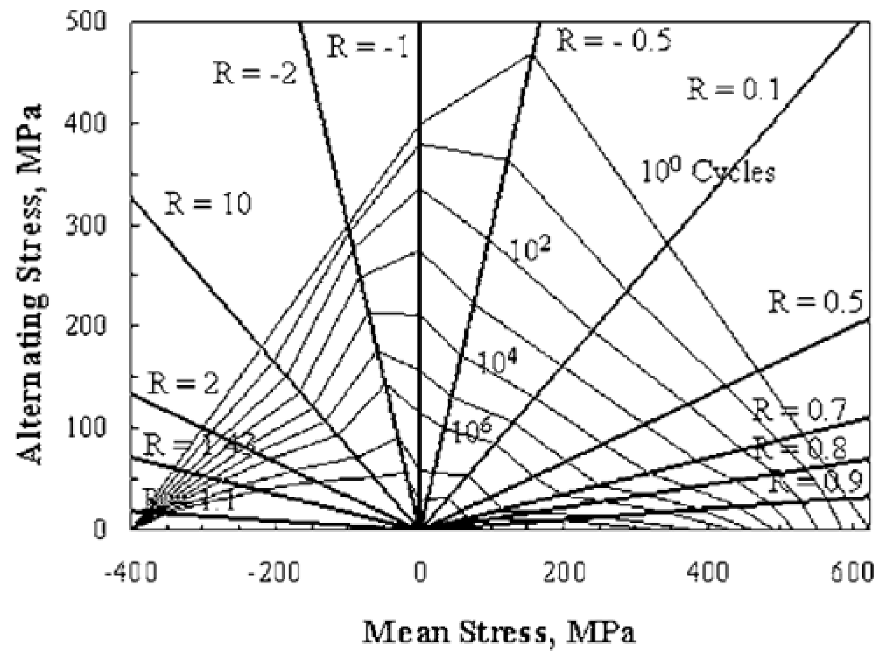


Equivalent Fibre and Matrix stresses

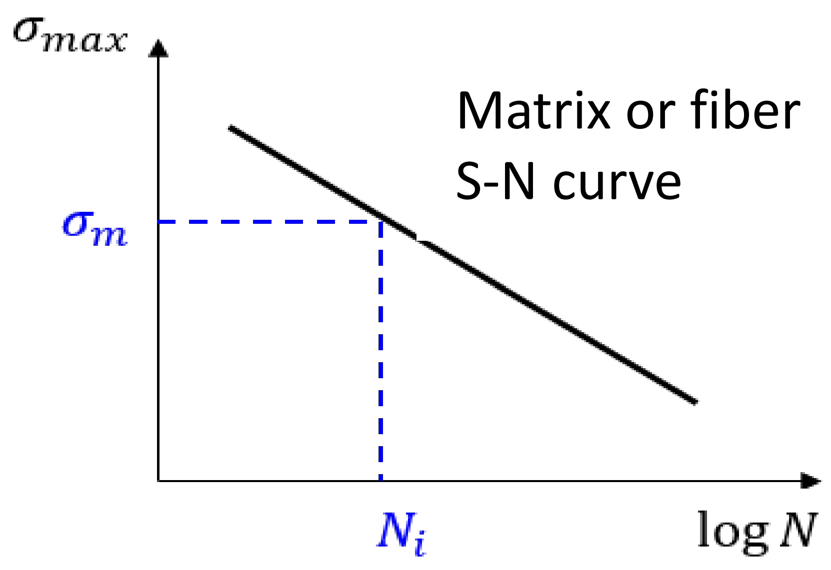


$\Delta\sigma, R, n$

Rainflow analysis for fiber and matrix



Interpolation of S-N curve based on CFL diagram

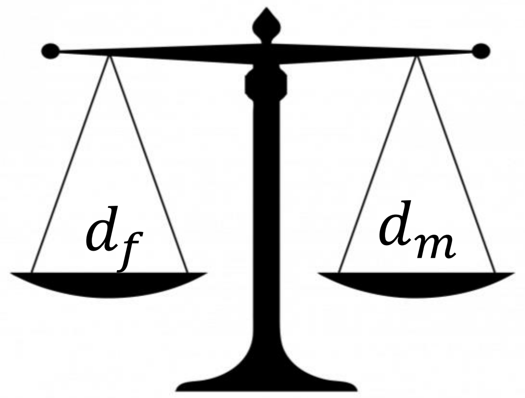


Determination of the admissible number of cycles for matrix N_m and for fiber N_f

$$d_f = \sum \frac{n}{N_f}$$

$$d_m = \sum \frac{n}{N_m}$$

Miner’s Sum



Conclusion

- Development of a **methodology for fatigue loads evaluation**
  - Based on BV existing tools
- Development of a **methodology for fatigue assessment**
  - Simple (S-N curve and Basquin's model) and based on static approach

- Results on the composite tower show **low damage**
  - Static safety factor > 30
  - Structure not optimised

- Fatigue methodology under validation

[1] MarTech2020 - *Analytical Approach for Global Fatigue of Composite-hull Vessels*, J.P. Tomy, L. Mouton, S. Paboeuf, A. Comer, A.K. Haldar, A. Portela

[2] EWTEC2021 - *Application of a ply-by-ply fatigue analysis methodology in the design of a full-scale tidal turbine blade*, S. Paboeuf, L. Mouton, JP Tomy, M. Arhant, N. Dumergue, P. Davies

[3] EWTEC21 - *Fatigue Design, Testing and Validation of a Prototype Tidal Turbine Blade Considering Realistic Environmental Loads*, L. Mouton, JP Tomy, S. Paboeuf, J. Valette, D. Caous

[4] OMAE2022 - *Fatigue Life Evaluation of a Tidal Turbine Blade: From Simulations using BEMT/FEM and CFD/FEM to Full-Scale Test*, S. Paboeuf , Meryem Guisser, Sébastien Loubeyre, Peter Davies, Maël Arhant, Nicolas Dumergue, Erwann Nicolas

[5] PRADS2022 - Fatigue assessment of composites parts for Marine Renewable Energy converters, JC Petiteau, S. Paboeuf

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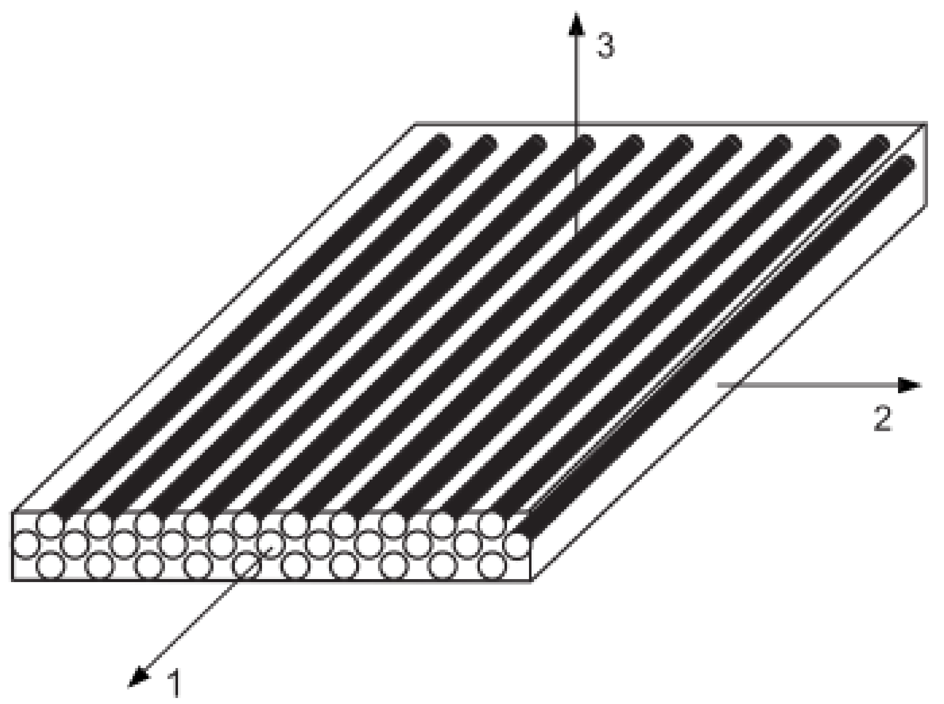
THANK YOU FOR YOUR ATTENTION

Equivalent fibre and matrix stress

- Separation of failure behaviour between matrix and fiber needed
- Fiber and matrix criterion for each **UD ply**



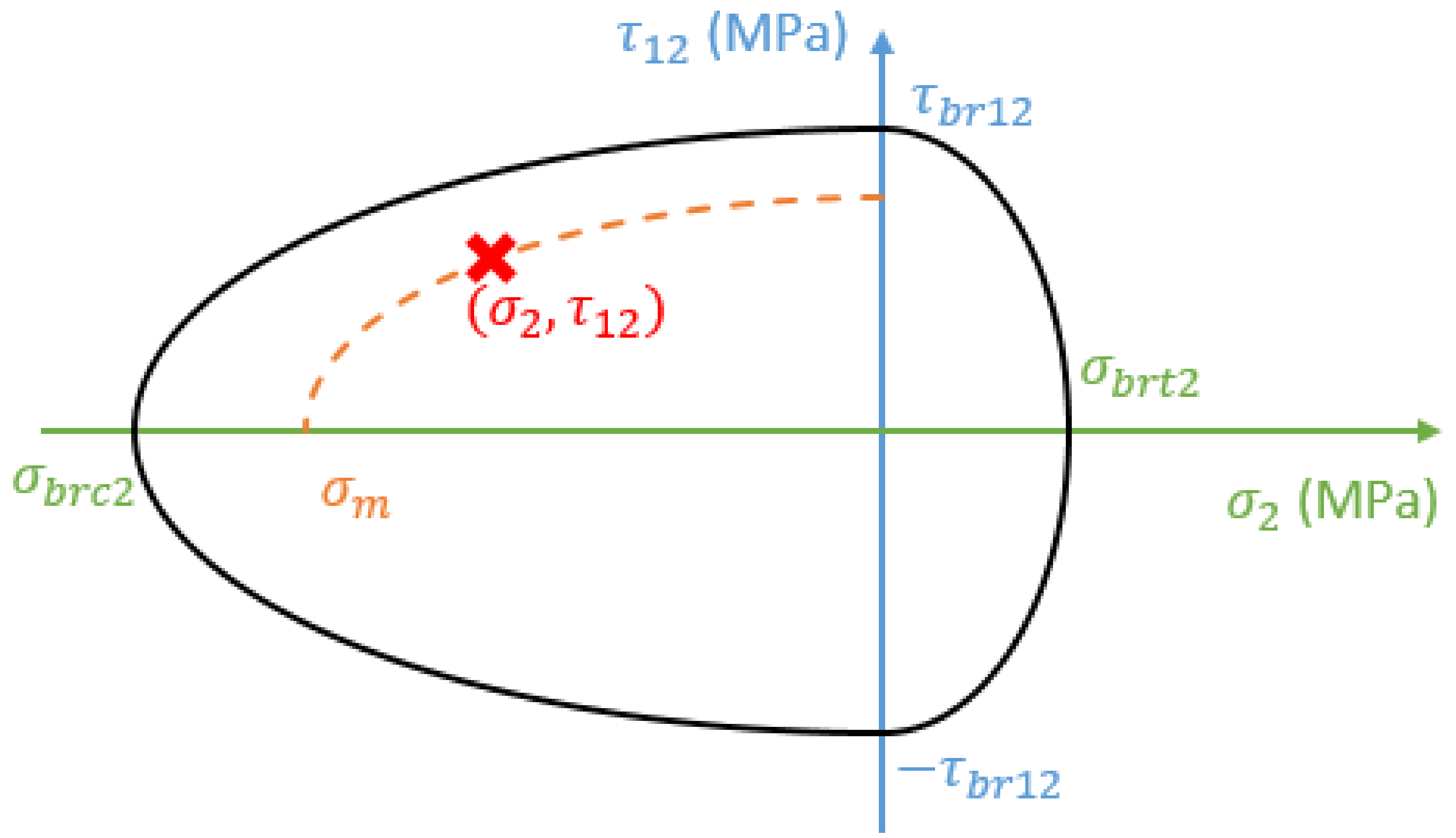
1 : Axis parallel to the fibre direction
2 : Axis perpendicular to the fibre direction
3 : Axis normal to the plane containing axes 1 and 2, leading to the direct reference axis system.

Fiber Equivalent stress

$$\sigma_{f(eq)} = \sigma_1$$

Matrix Equivalent stress

$$\sigma_m = \sqrt{\sigma_2^2 + (f_2\tau_{12})^2}, \text{ where } f_2 = \begin{cases} \dfrac{\sigma_{\mathrm{brt2}}}{\tau_{\mathrm{br12}}} & \text{if } \sigma_2 \geq 0 \\ \dfrac{\sigma_{\mathrm{brc2}}}{\tau_{\mathrm{br12}}} & \text{if } \sigma_2 < 0 \end{cases}$$

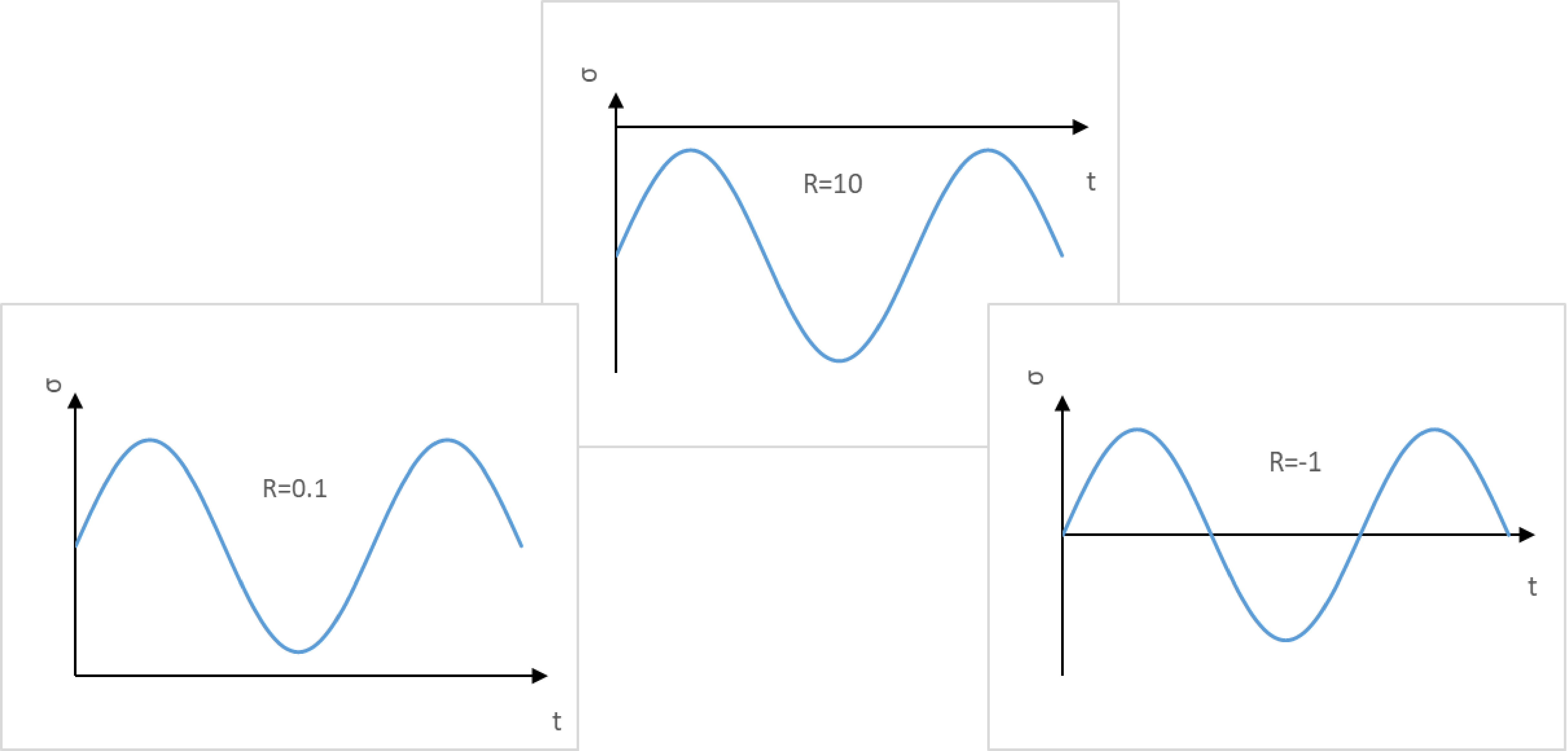


SN curve

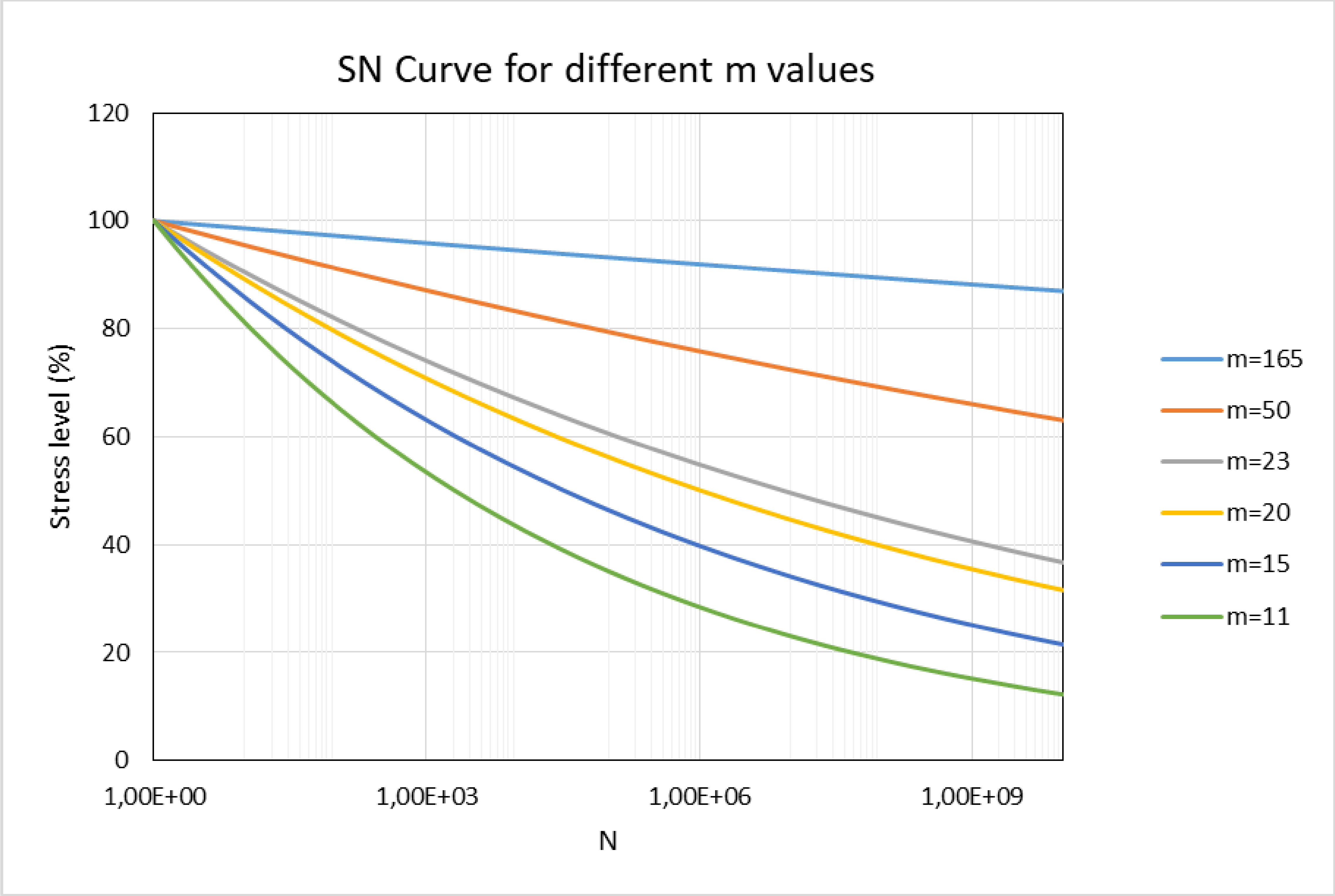
- Based on Basquin's model
- No fatigue limit
- Depend on static limit σ_{br}

- Different slopes depending on load ratio R value

$$R = \sigma_{min}/\sigma_{max}$$



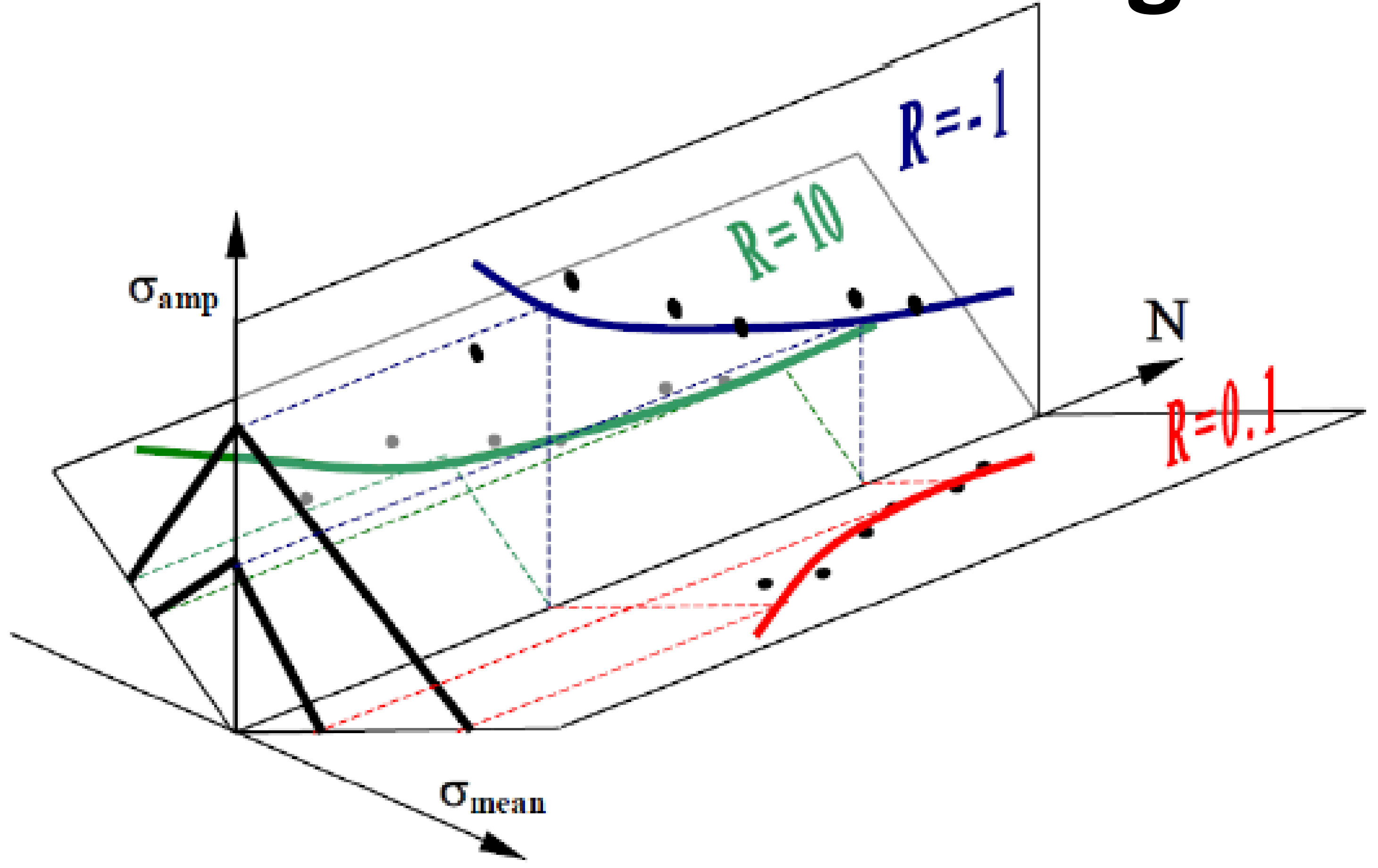
$$N_{R,i} = \left(\frac{\sigma_{max}}{\sigma_{br}}\right)^{-m}$$

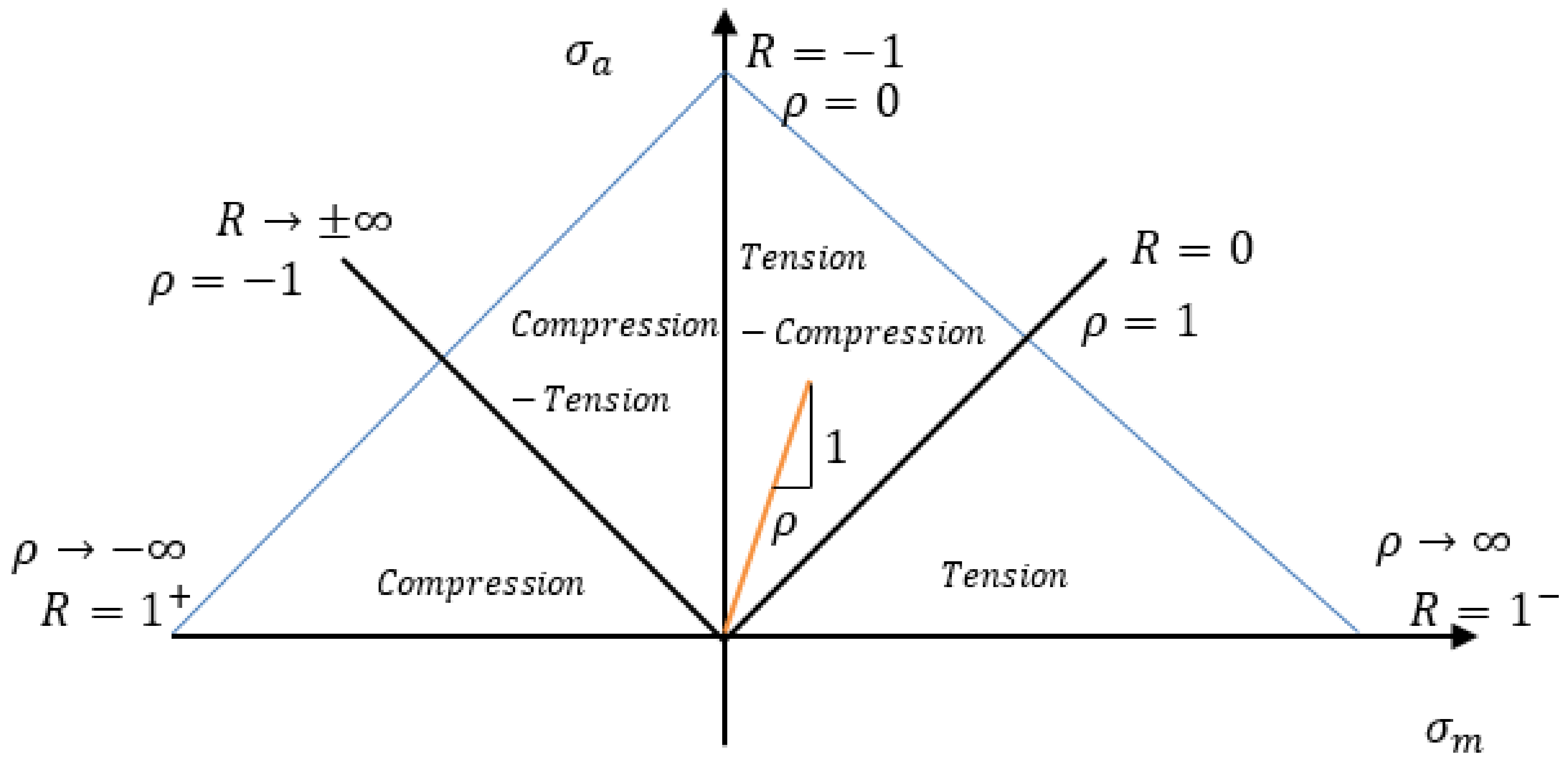


FIBREGY

CFL diagram

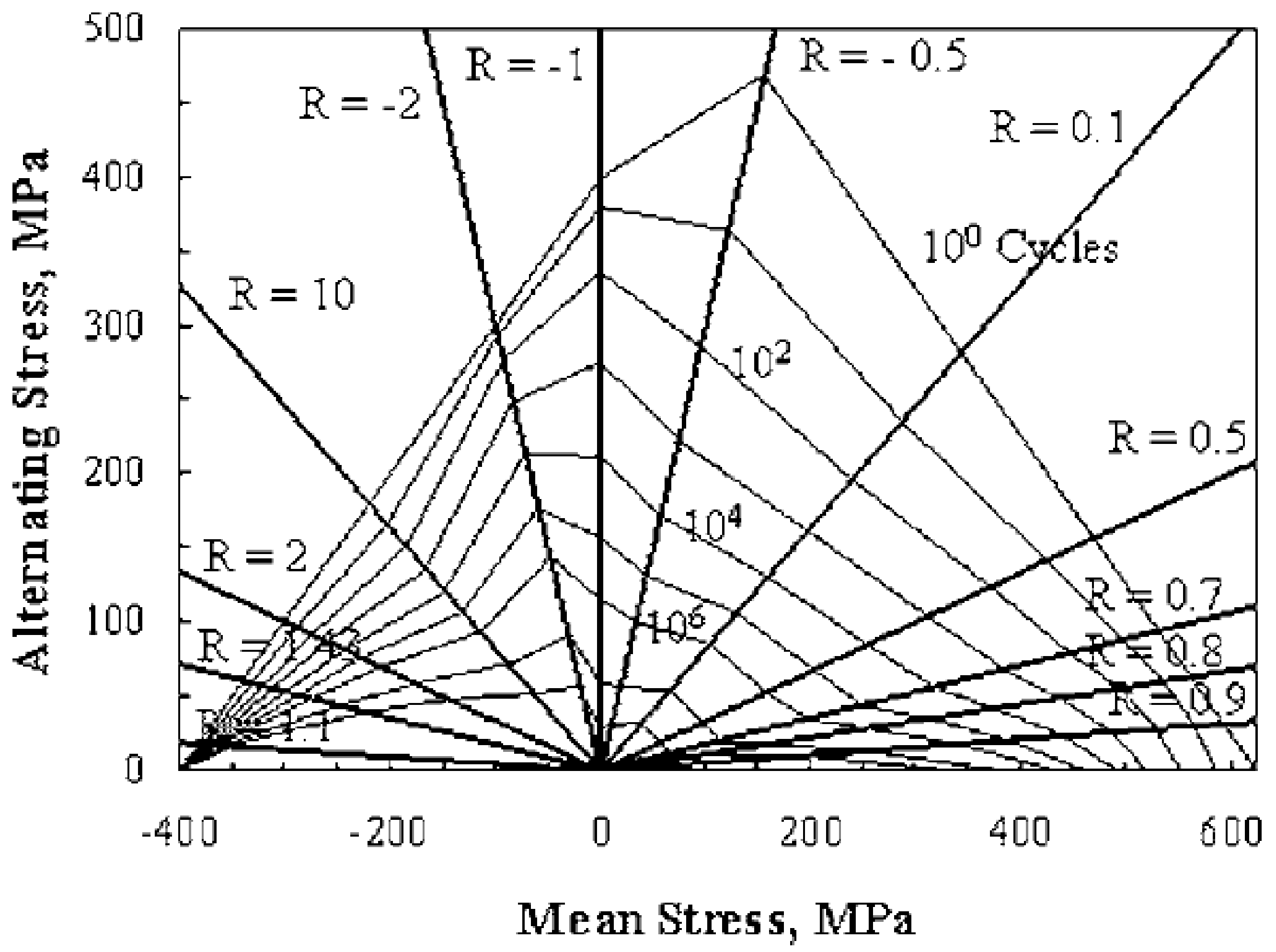
Construction of CFL diagram



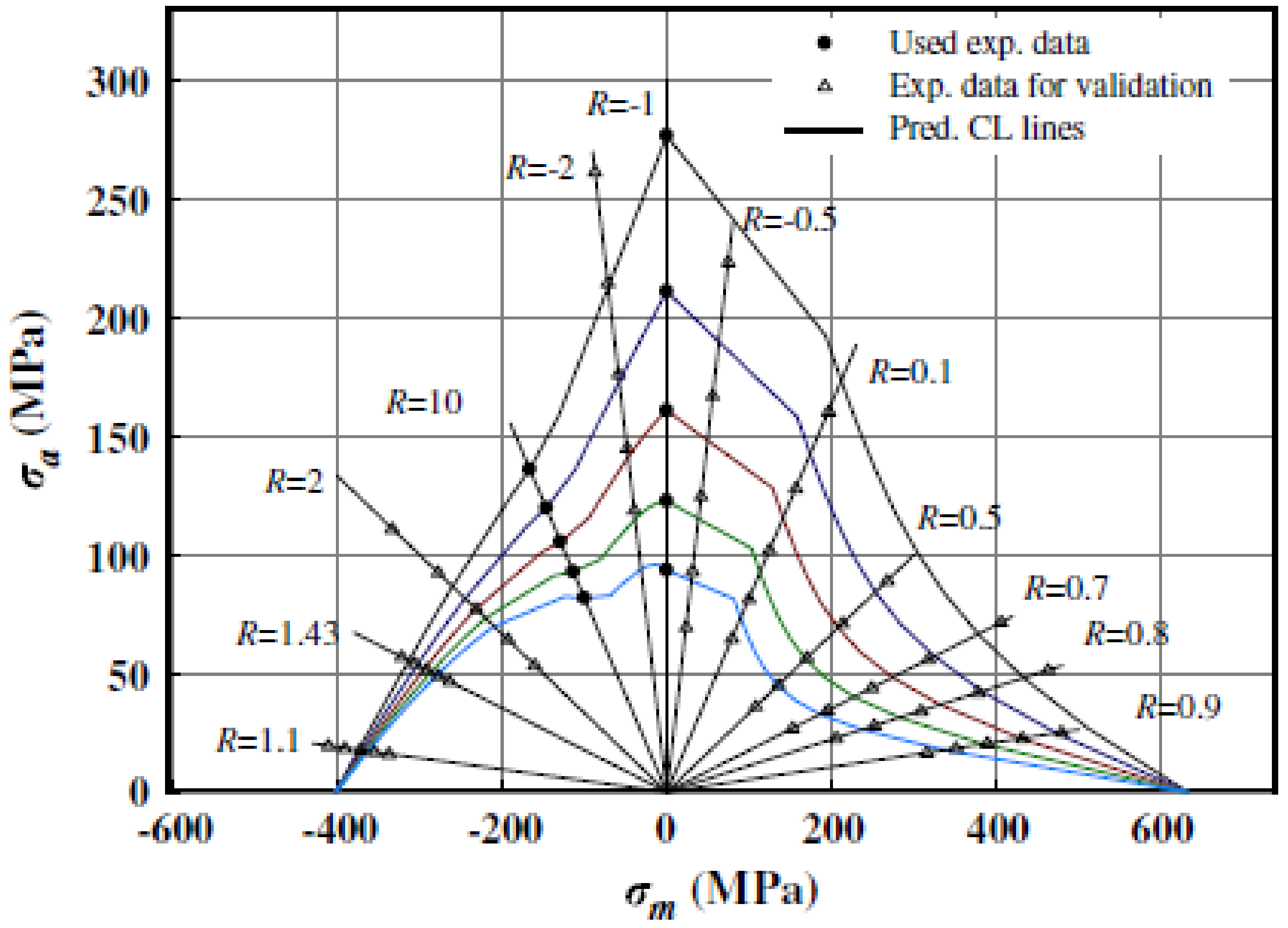


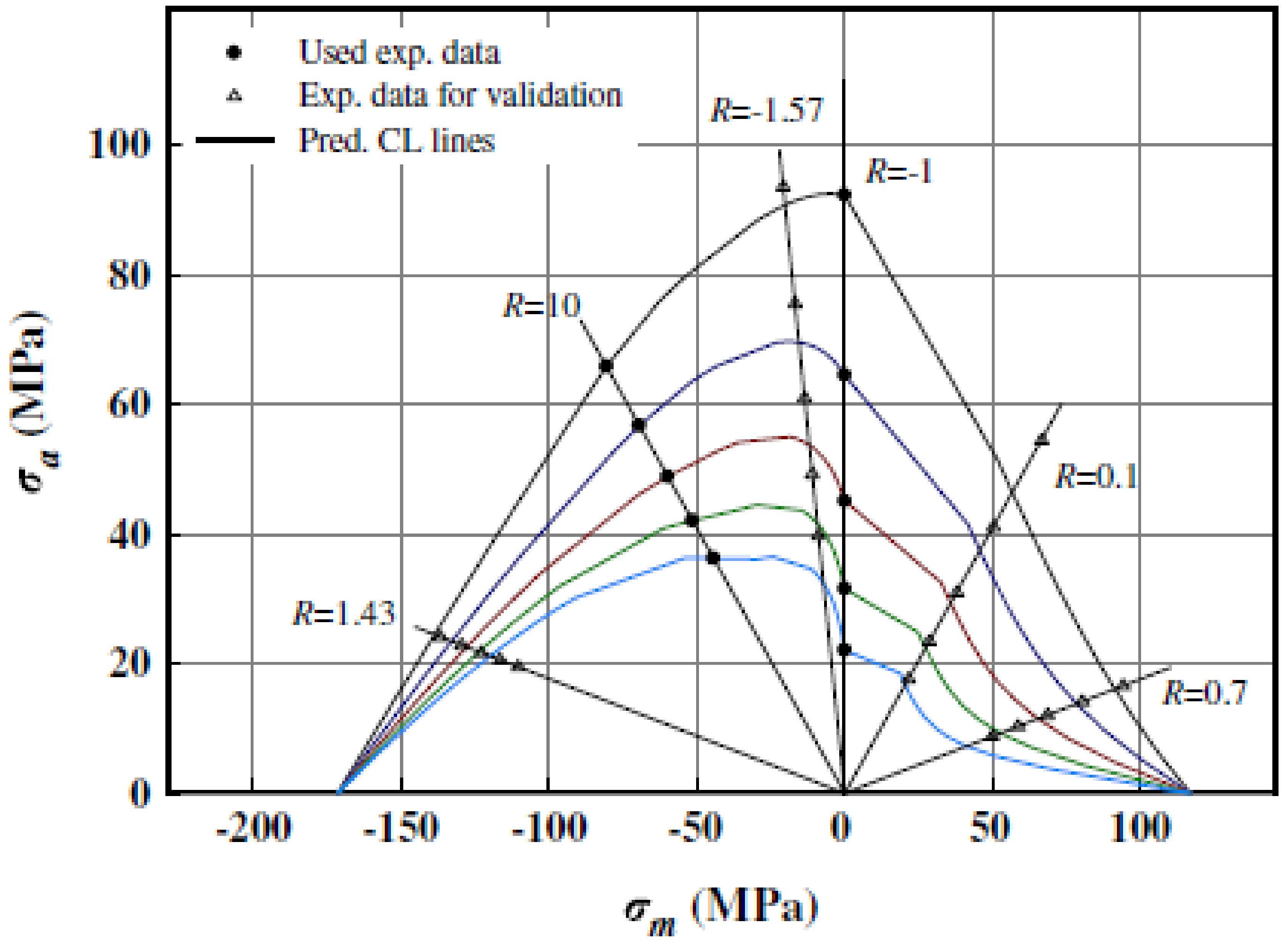
Typical CFL diagram

- Difference of behaviour between tensile and compressive cycle
- Linear Interpolation for other R values



- Results obtained through test





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Vassilopoulos (2010) https://doi.org/10.1016/j.ijfatigue.2010.03.013.