Project guidelines and recommendations for using FRP in large OWTPs

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

18/04/2024 – Fibregy event - Madrid

Jean-Christophe Petiteau, BV M&O

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Gap Analysis

- Review of existing standards (part of it is on the right)
- Lack of composite rules specific to OWTP
- Especially lack of fatigue rules for FRP even in marine applications

- IEC 61400-1:2019 : Wind Turbines – Part 1: Design Requirements, October 2019.
- IEC 61400-2:2014/AC:2019-11 - Wind Turbines – Part 2: Small Wind Tubines, November 2019.
- IEC 61400-3-1:2009 : Wind Energy Generation Systems – Part 3-1: Design Requirements for Fixed Offshore Wind Turbines, February 2009.
- IEC 61400-3-2:2019 : Wind Energy Generation Systems – Part 3-2: Design Requirements for Floating Offshore Wind Turbines, April 2019.
- IEC 61400-5:2020 - Wind Energy Generation Systems – Part 5: Wind Turbine Blades, 16 June 2020.
- IEC 61400-6:2020 - Wind Energy Generation Systems – Part 6: Tower and Foundation Design Requirements, 12 June 2020.
- ISO 19901-7:2013 Petroleum and Natural Gas Industries - Specific Requirements for Offshore Structures - Part 7: Station Keeping Systems for Floating Offshore Structures and Mobile Offshore Units, May 2013.
- ISO 19904-1:2019 Petroleum and Natural Gas Industries - Floating Offshore Structures - Part 1: Ship-Shaped, Semi-Submersible, Spar and Shallow-Draught Cylindrical Structures, October 2015.

- BV - NI572 - Classification and Certification of Floating Offshore Wind Turbines, January 2019
- BV - NI594 - Design and Construction of Offshore Concrete Structures, February 2017.
- BV - NI603 - Current and Tidal Turbines, May 2015.
- BV - NI613 - Adhesive Joints and Patch Repair, May 2015.
- BV - NR500 - Rules for the Classification and the Certification of Yachts, June 2021.
- BV - NR493 - Classification of Mooring Systems for Permanent and Mobile Offshore Units, July 2021.
- BV - NR546 - Hull in Composite Materials and Plywood, Material Approval, Design Principles, Construction and Survey, November 2018.
- BV - NR578 - Rules for the Classification of Tension Leg Platforms (TLP), July 2012.
- BV - NR600 - Hull structure and arrangement for the classification of cargo ships less than 65 m and non cargo ships less than 90 m. Accessed 4 August 2021

- DNV Standard - DNV-ST-0119 - Floating Wind Turbine Structures, June 2021.
- DNV.GL Standard - DNVGL-ST-C501 Composite Components, September 2019.
- DNV Recommended Practice - DNV-RP-C205 - Environmental Conditions and Environmental Loads, September 2021.
- DNV Standard - DNV-ST-0437: Loads and Site Conditions for Wind Turbines, amended 11/2021 2016.
- DNV Recommended Practice - DNV-RP-0286 - Coupled Analysis of Floating Wind Turbines, October 2021.

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Project guideline overview

- No document exists at the moment
- Aim of the document is to have in one single document a good overview of all the aspect concerning the use of composite in OWTP
- Public document

1. Definitions, Symbols and abbreviations
2. Certification Procedure – methodology, certification requirements
3. Materials
4. Design Conditions and Load Cases
5. Structural Design Requirements
6. Safety factors
7. Stability
8. Fire safety
9. Inspection, Life Cycle considerations

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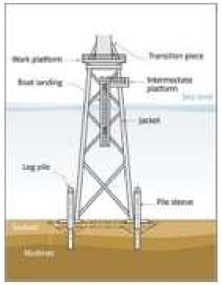
Certification Procedure

AIP and BDA

Technical feasibility of a concept; FEED Assessment of generic floaters



Component Certification

Standard commercial component used in large number

Prototype Certification

1st device of a new generation

Type Certification

Series of standard commercial system of common design and manufacture

Project Certification / Classification

Commercial farm of type-certified systems installed on a specific site

Addressed to Floater Designer

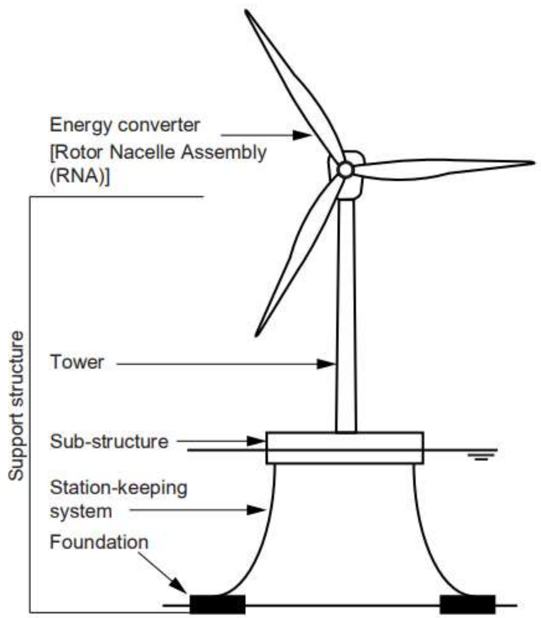
Addressed to Turbine OEM

Addressed to Project Developer

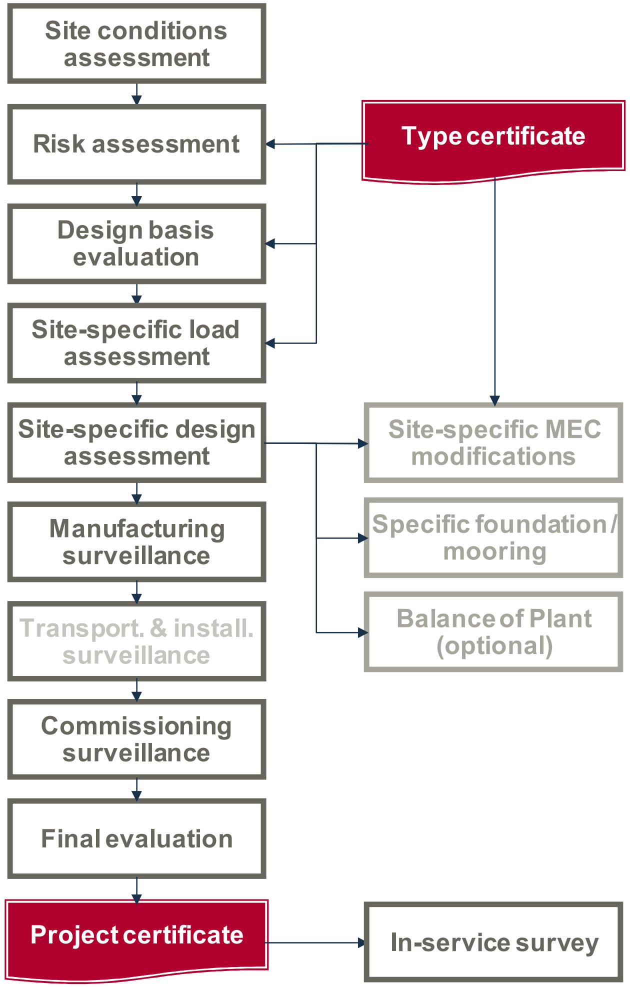
AIP: Approval in Principle
BDA: Basic Design Assessment

Certification Procedure

Project certification



Floating Offshore Wind Turbune (FOWT)



BV NR631 Certification Scheme for Marine Renewable Energy Technologies

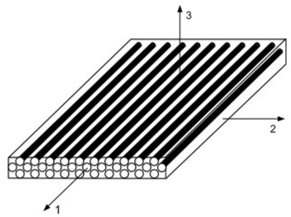
Materials

5.1. Composite panels → **Generalities concerning FRP**
- 5.1.1. Monolithic panels
- 5.1.2. Sandwich structures

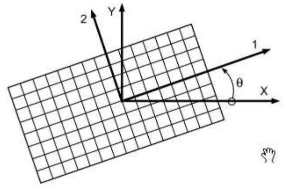
5.2. Constituents → **Values + classical considerations**
- 5.2.1. Fibres
- 5.2.2. Matrices
- 5.2.3. Cores

		Glass		Carbon	
		E	R	HS	IM(1)
Density ρ_f		2,57	2,52	1,79	1,75
Tensile in fibre direction	Poisson coefficient ν_f	0,238	0,20	0,30	0,32
	Young modulus E_{fl} (N/mm²)	73100	86000	238000	350000
	breaking strain (%)	3,8	4,0	1,5	1,3
	breaking stress (N/mm²)	2750	3450	3600	4500

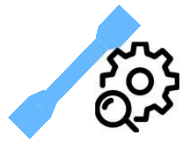
5.3. Individual layers characteristics → **Micromechanic reminder / law of mixture**
- 5.3.1. Fibre content, thickness and density
- 5.3.2. Determination of the ply's stiffness and strength
- 5.3.3. Rigidity and flexibility matrix



5.4. Laminate characteristics → **Classical laminate theory**
- 5.4.1. Rigidity in the laminate coordinate system
- 5.4.2. ABD Matrix and global behaviour of the laminate
- 5.4.3. Interlaminar shear behaviour



5.5. Tests to characterize materials → **Mandatory tensile and bending tests required for known materials (thermosets)**



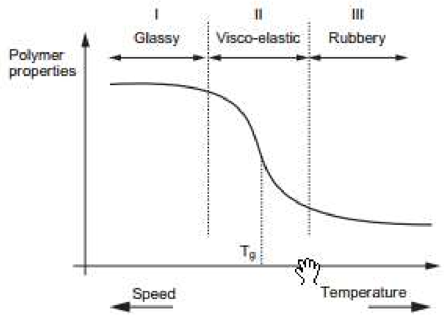
5.6. Specific attention points
- 5.6.1. Design using composite
- 5.6.2. Glass transition temperature Tg
- 5.6.3. Galvanic corrosion
- 5.6.4. Coating

Materials

5.6. Specific attention points

5.6.1. Design using composite

- Design to be adapted to the process considered
- Discussion between design office and manufacturer necessary from the beginning
- Defects and impacts consideration during manufacturing



5.6.2. Glass transition temperature Tg

- Operating temperature should be under Tg-20°C

5.6.3. Galvanic corrosion

- Special consideration for CFRP/metal couple => electric insulation

5.6.4. Coating

- Use may be considered to avoid/slow down water ingress

Design conditions and load cases

Design conditions and load cases

Environment conditions

Normal environment conditions

- Temperature
  - [-10; 30°C] (air)
  - [0; 30°C] (water)
- humidity up to 100%
- Solar radiation 1000 W/m²

Extreme conditions

- Temperature
  - [-15; 40°C] (air)
  - [-2; 35°C] (water)

Loads considered

- Fixed loads
  - Weigth
- Operating loads
  - Buoyancy
  - mooring, power cable loads
  - Ballast and liquid tanks loads…
- Environmental loads
  - **Wind**
  - **Temperature**
  - **Wave, current,…**
  - Snow and ice,
  - Reaction to loads
    - dynamic mooring
    - power cable loads
  - Tsunamis and earthquake loads
  - Lightning
- Accidental loads
  - Damaged conditions
  - Accidental flooding
  - Collision…

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Design conditions and load cases

DLC in line with IEC 61400-3

Design conditions :

- Power production
- Power production plus occurrence of fault
- Start up
- Normal shut down
- Emergency stop
- Parked (standing or idling)
- Parked and fault conditions
- Transport, assembly, maintenance and repair
- Power production in case of loss of mooring line
- Parked (standing or idling) in case of loss of mooring line

DLC	Design conditions	system conditions	Wind	Wave	Current	SF
1.1	Power production	Intact	Normal	Normal	Normal	N
1.2			Normal	Normal	-	F
1.3			Extreme (ETM)	Normal	Normal	N
1.4			Extreme (ECD)	Normal	Normal	N
1.5			Extreme (EWS)	Normal	Normal	N
1.6			Normal	Severe	Normal	N
2.1	Power production plus occurrence of fault	Normal control system fault or loss of electrical network or primary layer control function fault	Normal	Normal	Normal	N
2.2		Abnormal control system fault or secondary layer protection function related fault	Normal	Normal	Normal	A
2.3		External or internal electrical fault including loss of electrical network	Extreme (EOG)	Normal	Normal	A
2.4		Control system fault, electrical fault or loss of electrical network	Normal	Normal	-	F
2.5		Intact Low voltage ride through	Normal	Normal	Normal	N
2.6		Abnormal Fault of seastate limit protection system	Normal	Severe	Normal	A

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Structural design requirements

- 7.1. Ultimate load assessment → **Buckling, first ply failure**
    - 7.1.1. Design format method
    - 7.1.2. Buckling
- 7.5. Displacement/acceleration criteria
- 7.3. Fatigue design of composite structures
    - 7.3.1. Matrix and fibre stress
    - 7.3.2. Design S-N Curves
    - 7.3.3. CFL diagram
    - 7.3.4. Damage calculation
    - 7.3.5. Criteria
    - 7.3.6. Summary of the methodology
- 7.5. Modal analysis
- 7.5. Joints and connections
    - 7.5.1. Bolting → **Failure mechanisms description, specific design aspects and tightening of bolts**
    - 7.5.2. Bonding → **Specific design aspects of bonding**

Displacement/acceleration criteria / modal analysis

- **Acceleration of the nacelle**
  - to be limited to the maximum acceleration provided by the manufacturer of the rotor

- **Maximum displacement of the tower**
  - less than $1/150^{th}$ of the tower height

- **Eigen frequencies of the tower** of the wind turbine
  - different from 1P and 3P (frequency of the rotor and passage of the blades in front of the wind turbine)
  - Consideration of the added mass of water and the flexibility of the floater

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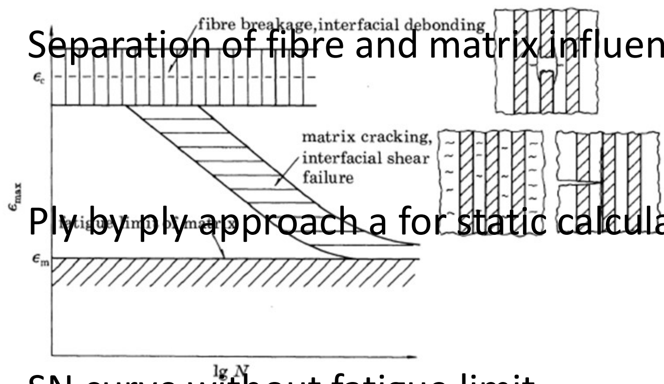
Fatigue behaviour of composite - Overview

Differences with metals

- A priori less prone to fatigue than metals
- More complex due to :
  - Orthotropicity of plies and difference of behaviour
    - Fibre breakage
    - Matrix cracking
  - Number of possible configuration considering layups and fibre content
- No consensus on a methodology
- No consensus on the existence of a fatigue limit (typical range of test 1➔10^6 cycles)

➔ Separation of fibre and matrix influence

➔ Ply by ply approach a for static calculation



➔ SN curve without fatigue limit for conservatism

Important influencing parameter

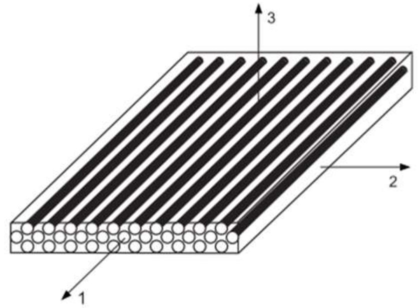
- Maximum stress σ_{max}
- Highly dependent on the load ratio ($R = \sigma_{min}/\sigma_{max}$)
- Sequence of loading
- Temperature / frequency dependence

➔ Use of Constant Fatigue Life (CFL) diagram to take into account R and σ_{max}

➔ Disregarded at this point but several type of cycles considered through Miner's sum

Equivalent fibre and matrix stress

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



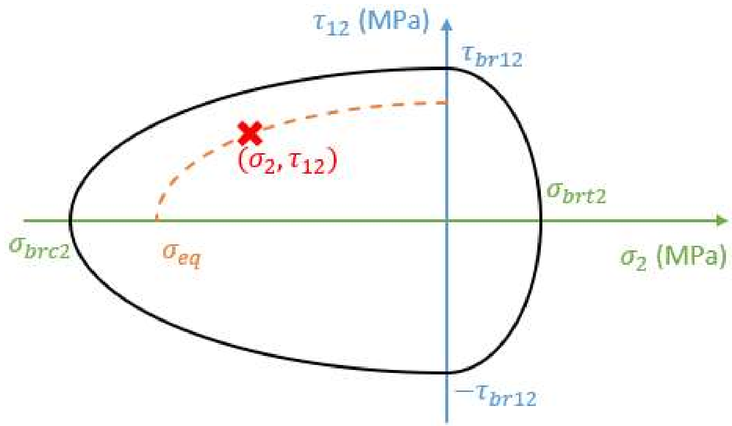
1 : Axis parallel to the fibre direction
2 : Axis perpendicular to the fibre direction
3 : Axis normal to the plane containing axes 1 and 2, leading to the direct reference axis system.

Fiber Equivalent stress

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

Matrix transverse equivalent stress

$$\sigma_{eq} = \sigma_2\sqrt{1 + \min\left(3, \left(\frac{f_2\tau_{12}}{\sigma_2}\right)^2\right)}, \text{ where } f_2 = \begin{cases} \frac{\sigma_{brt2}}{\tau_{br12}} & \text{if } \sigma_2 \geq 0 \\ \frac{\sigma_{brc2}}{\tau_{br12}} & \text{if } \sigma_2 < 0 \end{cases}$$

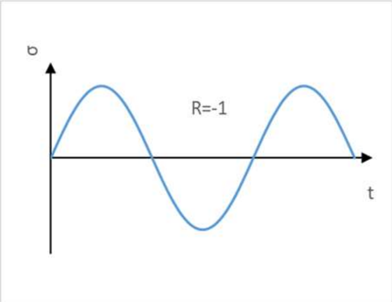


SN curve

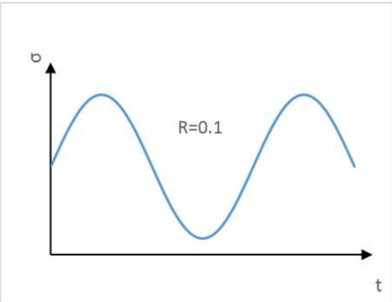
- Based on Basquin's model
- No fatigue limit
- Depend on static limit

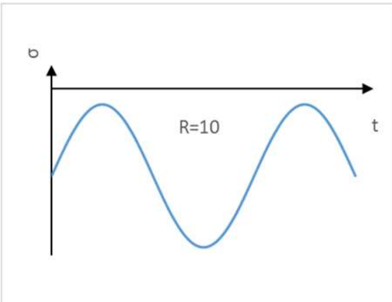
$$N_{R,i} = \left(\frac{\sigma_{max}}{\sigma_{br}}\right)^{-m}$$

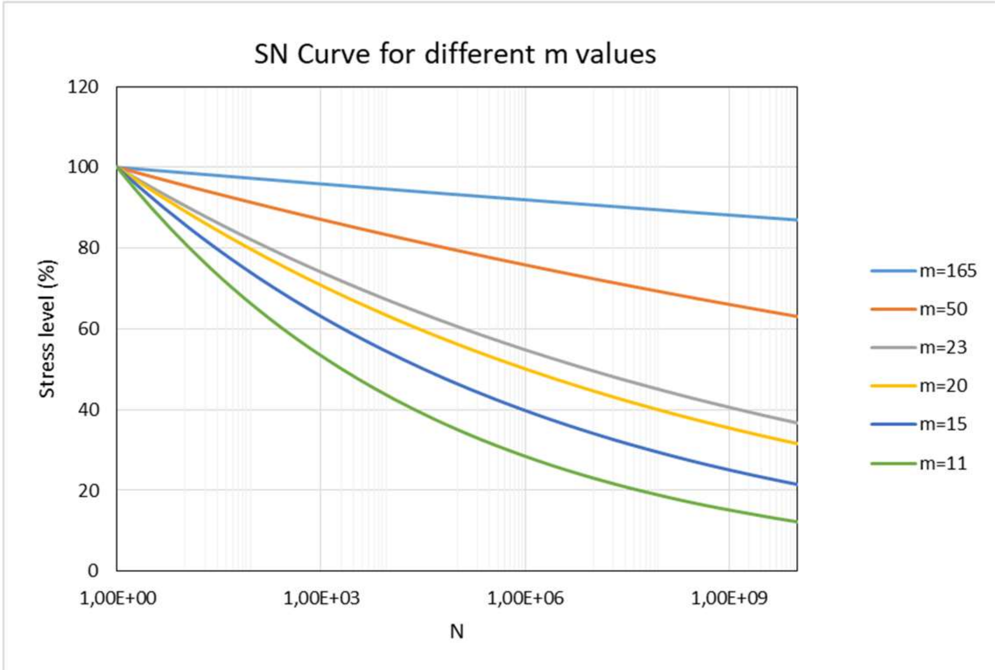
- Different slopes depending on R value



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

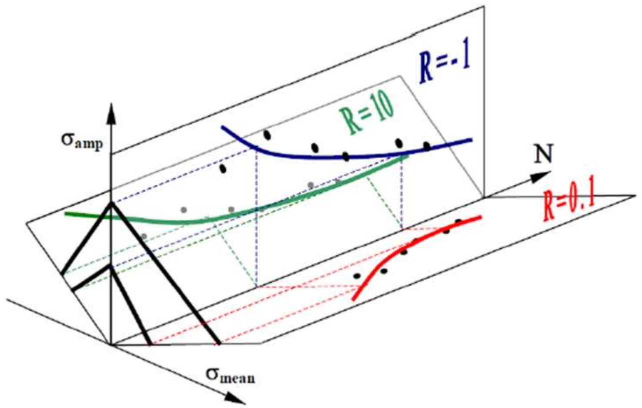


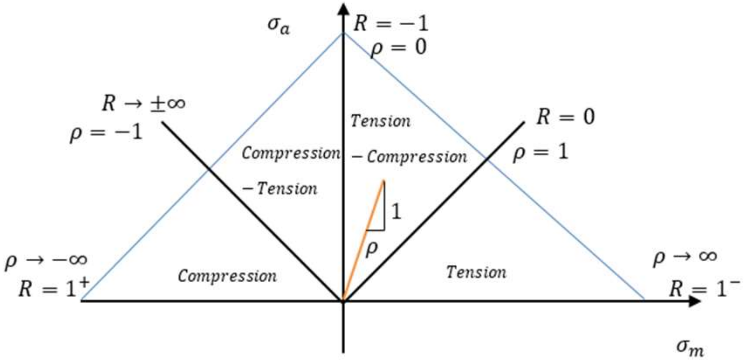




CFL diagram

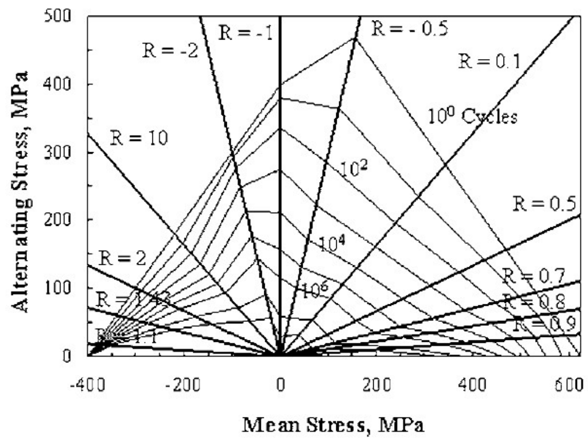
Construction of CFL diagram

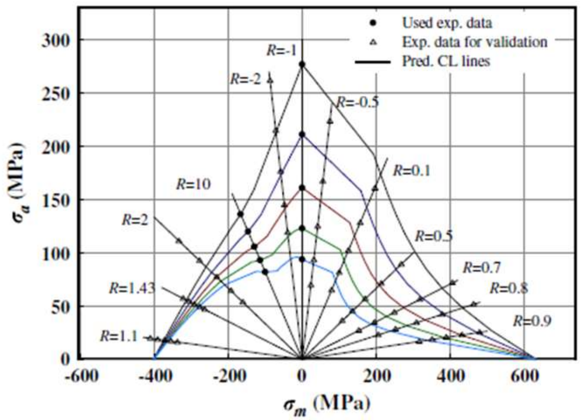


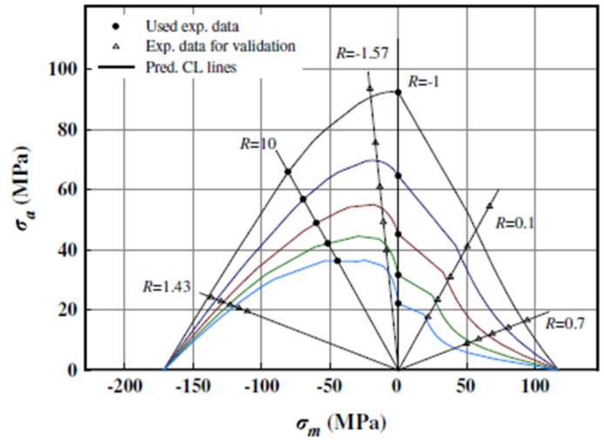


Typical CFL diagram

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







Sutherland & Mandell. (2005) https://doi.org/10.1115/1.2047589.

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

Equivalent fibre and matrix damage

- Calculation of damages for each contribution
- Miner's sum for each CFL diagram

$$D_{\sigma_1} = \sum_i \frac{n_{\sigma_1,i}}{N_{\sigma_1,i}}$$

$$D_{\sigma_{eq}} = \sum_i \frac{n_{\sigma_{eq},i}}{N_{\sigma_{eq},i}}$$

$$D_{\tau_{12}} = \sum_i \frac{n_{\tau_{12},i}}{N_{\tau_{12},i}}$$

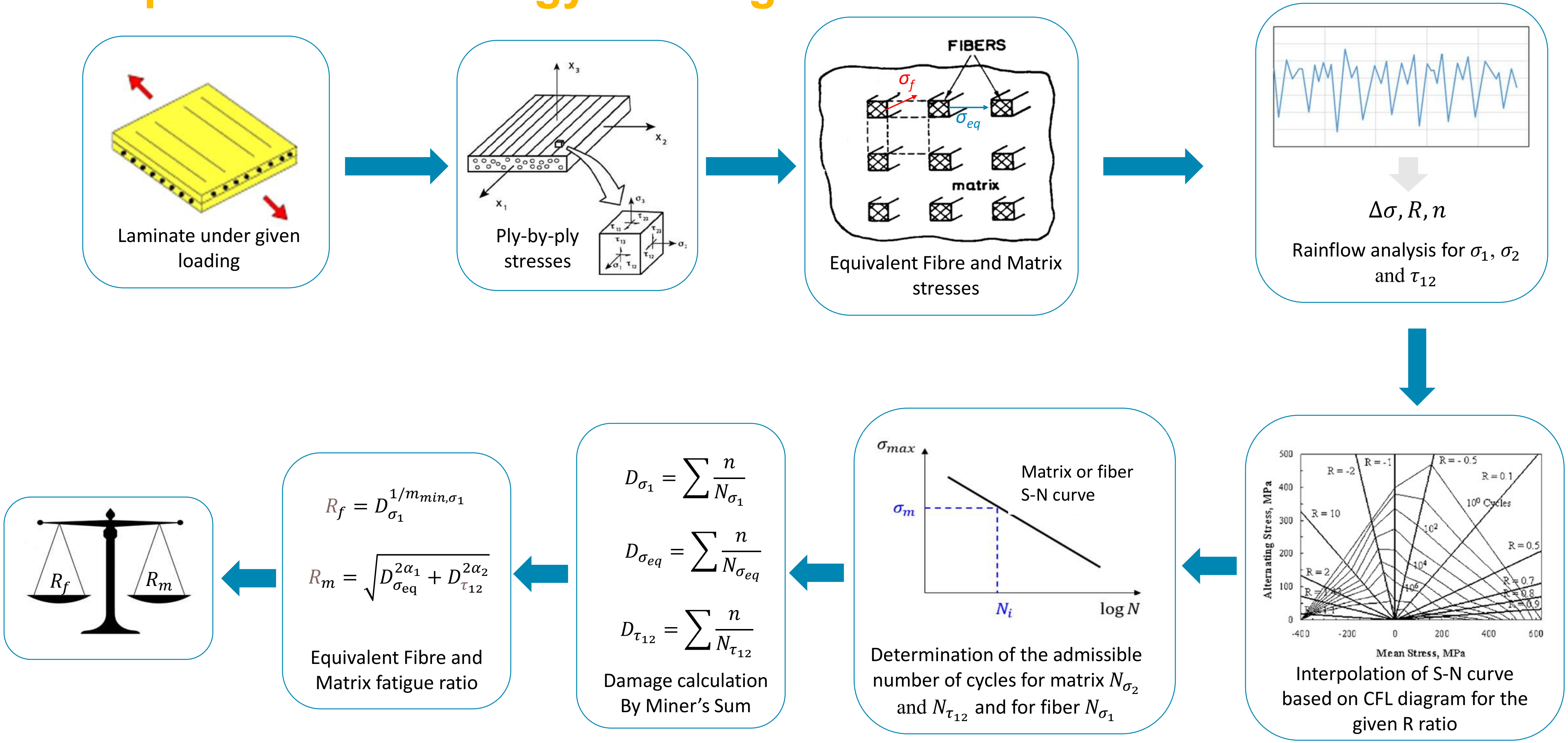
Fibre fatigue ratio

$$R_f = D_{\sigma_1}^{1/m_{min,\sigma_1}}$$

Matrix fatigue ratio

$$R_m = \sqrt{D_{\sigma_{eq}}^{2/m_{min,\sigma_{eq}}} + D_{\tau_{12}}^{2/m_{min,\tau_{12}}}}$$

Proposed methodology for fatigue



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Safety factors - LRFD

Loads

kind of loads	Normal (N)	Accidental (A)	Transport (T)	Fatigue (F)
fixed loads	1	1	1	1
operational loads	1.35	1.1	1.5	1
Environmental loads	1.35	1.1	1.5	1
Accidental loads	1.1	1.1	1.1	1
Favourable loads	0.9	0.9	0.9	1

From BV NI 572

Safety factors - LRFD

Material

Adapted from BV NR 546 and NR 600

Max stress

$$SF \geq C_V\, C_F\, C_R\, C_i$$

Combined stress

$$SF_{CS} \geq C_{CS}\, C_V\, C_F\, C_i$$

C_R (direction of stress)		
unidirectional (UD), bi-bias three-unidirectional fabric	Tensile or compressive stress parallel to the fibre	2.1
	Tensile or compressive stress perpendicular to the fibre	1.25
	Shear stress (in the ply and interlaminar)	1.6
Woven roving	Tensile or compressive stress parallel to the fibre	2.4
	Shear stress (in the ply and interlaminar)	1.8
mat	Tensile or compressive stress in the ply	2.0
	Shear stress (in the ply and interlaminar)	2.2

C_{CS} (combined stress)	
unidirectional (UD), bi-bias three-unidirectional fabric	1.7
otherwise	2.1

C_v (ageing)	
Monolithic in or under splash zone	1.2
Monolithic above splash zone	1.1
Core	1.1

C_i (loading speed)	
By default	1.0

C_f (process)	
prepregs	1.1
Infusion and vaccuum	1.15
Hand lay up	1.25
core	1.0

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Safety factors - WSD

Adapted from BV NR 546 and NR 600 and NI 572

Max stress

$$SF \geq C_V\ C_F\ C_R\ C_i\ C_l$$

Combined stress

$$SF_{CS} \geq C_{CS}\ C_V\ C_F\ C_i\ C_l$$

C_R (direction of stress)		
unidirectional (UD), bi-bias three-unidirectional fabric	Tensile or compressive stress parallel to the fibre	2.1
	Tensile or compressive stress perpendicular to the fibre	1.25
	Shear stress (in the ply and interlaminar)	1.6
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C_{CS} (combined stress)	
unidirectional (UD), bi-bias three-unidirectional fabric	1.7
otherwise	2.1

C_v (ageing)	
Monolithic in or under splash zone	1.2
Monolithic above splash zone	1.1
Core	1.1

C_i (loading speed)	
By default	1.0

C_f (process)	
prepregs	1.1
Infusion and vaccuum	1.15
Hand lay up	1.25
core	1.0

C_l (DLC Type)	
Normal load case	1.23
Accidental load case	1.0
Transport load case	1.36

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Stability

Intact stability is required

Damage stability not required for **unmanned FOWT** in case:

- there is no human life risk
- pollution and collision with neighbouring facilities are avoided.

#	Loading condition	Description	Environmental conditions		
			Wind	Current	Wave
1	Lightweight	Free floating	NA	NA	NA
2	Transit (3)	Free floating Transit draught	Expected during transit	Towing speed limit	Expected during transit
3.1	Installation	Free floating	Expected during transit	NA	NA
3.2		Partially installed mooring lines (1)			
4	Maintenance (2)	Moored Maintenance load	Specified limiting parameters	Specified limiting parameters	Specified limiting parameters
5.1	Operation	Maximum draught	Normal	Normal	Normal
5.2		Minimum draught	Normal	Normal	Normal
5.3		One mooring line failure	Normal	Normal	Normal
6.1	Parked	Maximum draught	Extreme	Extreme	Extreme
6.2		Minimum draught	Extreme	Extreme	Extreme
6.3		One mooring line failure	Extreme	Extreme	Extreme H_{S50}

NA: not applicable
The draught is the distance, in m, from the base line to the waterline, measured amidships.
The maximum draught is the deepest draught able to be observed during operation.
The minimum draught is the lightest draught able to be observed during operation.
(1) According to installation procedures.
(2) Required if specific loads are to be considered during maintenance (such as tools, transit containers...).
(3) In the special case of towing, the overturning moments should be calculated adequately and submitted for approval.

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Fire Safety

Fire safety is regulated by the International Convention for the Safety of Life At Sea (**SOLAS**)

➔ Due to the **absence of permanent personnel on-board**, fire safety can be addressed differently

FOWT fire safety requirements based on:

- **BV NI682** Certification of fixed offshore substations for renewable energy projects
- **DNVGL-SE-0077** Certification of Fire Protection Systems for Wind Turbines
- **IEC TS61400-30** Safety of wind turbine generators – General principles for design – Draft Technical Specification

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Fire Safety

Risk assessment

Objectives are to **minimize the risk of occurrence and escalation** of a hazardous event, **AND** to allow people on board during maintenance **to leave safely the floating platform** when a hazardous event happens.

The process of a risk assessment involves the following steps:

- **Hazards identification** (see Annex A of IEC TS 61400-30)
- **Risk evaluation**
  - The probability of occurrence of the hazard
  - The consequence of the hazard occurrence
- **Risk reduction**

  Mitigation measures and provision identified during the risk assessment are to be implemented accordingly in the design, construction, installation and testing

Fire Safety

Fire protections

- Passive fire protection
  - Insulation
  - Fire retardant coating or resin
- Active fire protection
  - Fire detector
  - Fixe and portable fire equipment

Emergency, escape and evacuation

- At least two independent exits
- Evacuation and escape routes shall be free of obstacles
- Evacuation time is to be tested and verified in the estimated time
- Permanent means of access are to comply ISO 14122

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Inspection and life cycle considerations

Maintenance should rely on :

- **Meteorological station**
- **Operational and structural conditions recording**
  - Displacement…
  - Strains…
- **Periodic inspections** at 3 levels:
  - Visual inspection
  - NDT
  - Continuous monitoring via sensors
- Periodicity to be agreed and reviewed each year
- Qualification of the maintenance team members

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

Appendixes

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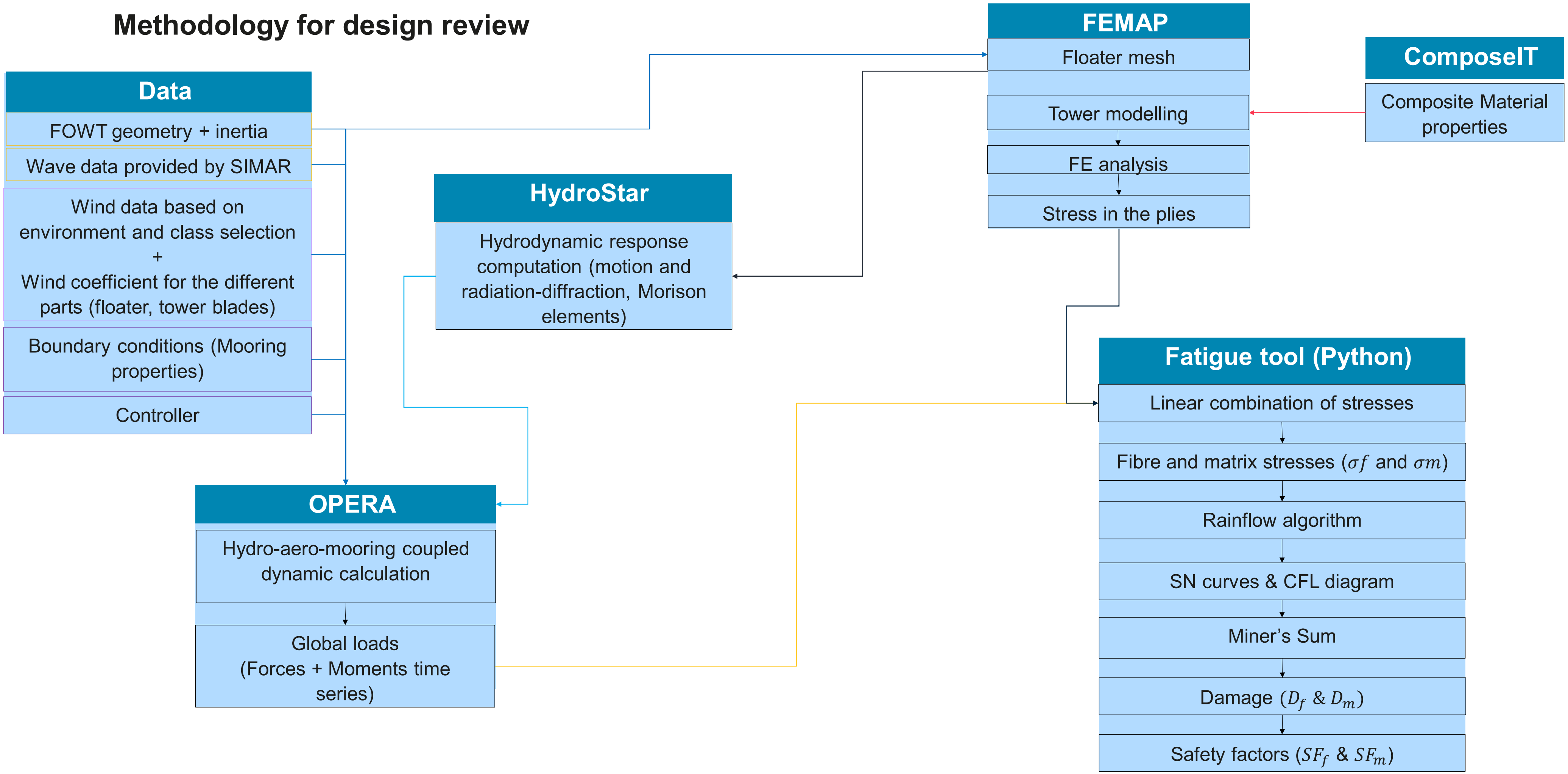
DESIGN OF THE FOWT TOWER IN COMPOSITE

Methodology for design review



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Thermoplastic resins

Literature review

- Advantages / Drawbacks

	Thermoset composite	Thermoplastic composite
Advantages	Low viscosity	Infinite shelf life
	Suitable for high temperature	Recyclable/reparable
	Low processing temperatures	Impact resistance
	Well-established properties	Chemical resistance
	Excellent bonding with fibres	No emissions
Drawbacks	Limited shelf life	High viscosity
	Difficult to manufacture thick composite parts	High manufacturing temperatures
	Non recyclable	Generally more expensive

Examples of industrial & research applications

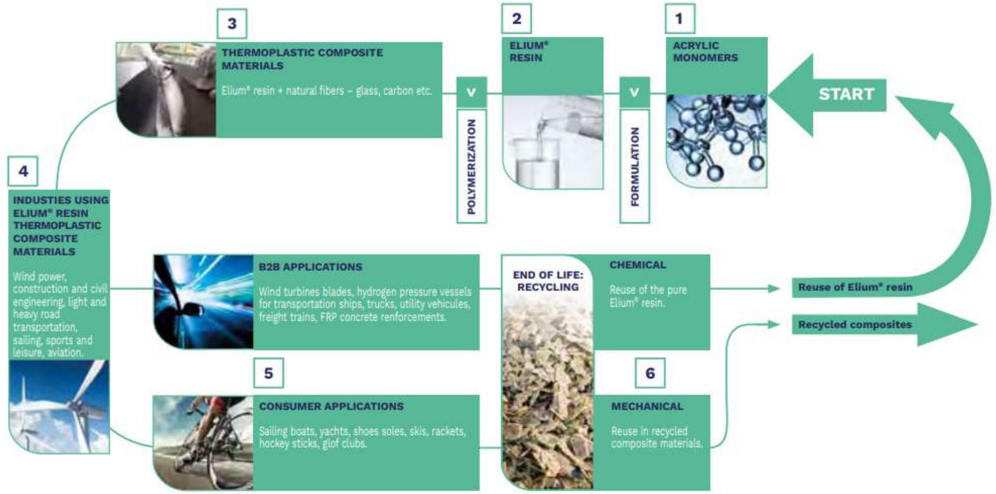
Monohull Mini 6.5 in 2017

Ocean Fifty Kraken, trimaran 50' in 2020

Class 40 Yemenja in 2022

NREL wind turbine blade

Recyclability



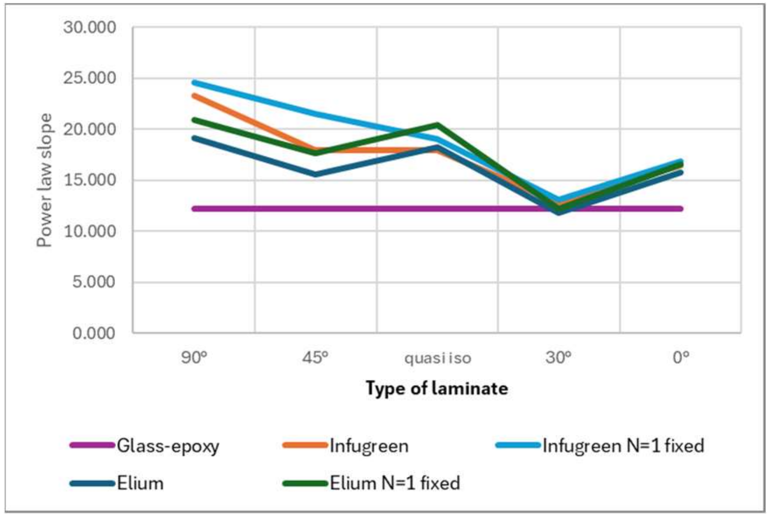
Comparison of results using Elium and Infugreen resins

Static

- Glass/Elium gives smaller strength than Glass/ epoxy resin
- Glass/ Infugreen leads to similar results as Glass/classical epoxy

Fatigue

- Glass/Elium and Glass/Infugreen seems to have same slope as Glass/ Epoxy based on power law fit
- The most critical aspect for the slope seems to be the shear behaviour



	Lay-up	Fibre Volume fraction (Vf)	Failure stress static	Theoretical failure stress Glass-epoxy last ply failure	difference with tests
Glass/Elium	[90]9S	55.85%	41.85	50.57	-17%
	Quasi-Isotropic [0°/+45°/90°/-45°]S	47.11%	313	365	-14%
	[±30°]8S	52.36%	346	352	-2%
	[0]6S	46.06 % *	939	954	-2%
Glass/Infugreen	[90]9S	52.47%	50	45.45	10%
	[±45]2S	57.99%	84	139	-40%
	[±30°]8S	49.69%	335	310	8%
	[0]6S	44.34 % *	978	921	6%

Recommendations for for finite element models

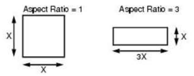
12.3. Recommendations for finite element models in composite materials

- 12.3.1. Basic hypothesis
- 12.3.2. Materials
- 12.3.3. Mesh and element types
- 12.3.4. Boundary conditions
- 12.3.5. Loading
- 12.3.6. Properties & Lay-up
- 12.3.7. Post Processing

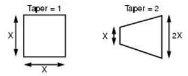
Criteria presentation
- **Tsai Hill criterion**
- **Tsai Wu criterion**
- **Hoffman criterion**
- **Hashin criterion**
- **Puck criterion**

Element size and shapes

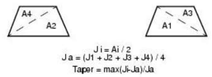
- Aspect ratio



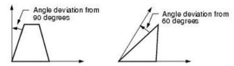
- Taper



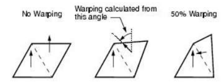
- Alternate taper



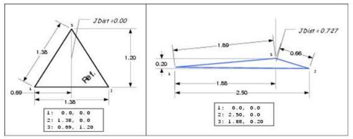
- Angles



- Warping



- Jacobian



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

THANK YOU FOR YOUR ATTENTION