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# Development, engineering, production and life cycle management of improved FIBRE-based material solutions for the structure and functional components of large offshore wind enerGY and tidal power platforms

## D4.7 (WP4): Project guidelines and recommendations for using FRP in large OWTPs

Responsible Partner: BV

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| | | | | |
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# 1. INTRODUCTION

The objective of the task 4.7 is to produce project guidelines for the design of composite parts used for Floating Offshore Platforms and more precisely to Floating Offshore Wind Turbine Platform (FOWT). It is important to note that another guideline that focuses on the manufacturing of such parts is written in the context of the Fibregy project. This will be the object of the deliverable D5.4. As the manufacturing and design of Composite materials are highly intricated, both guidelines must be taken into consideration from a design point of view.

As shown in the deliverable D4.6 of Fibregy, there is no standard or Rules that consider fully the use of composite materials in the context of large FOWT platforms. The aim of this document is to introduce the methodology to be followed for the assessment of a structure in composite. The classical design process for a floating offshore wind turbine is summarized in the following figure.

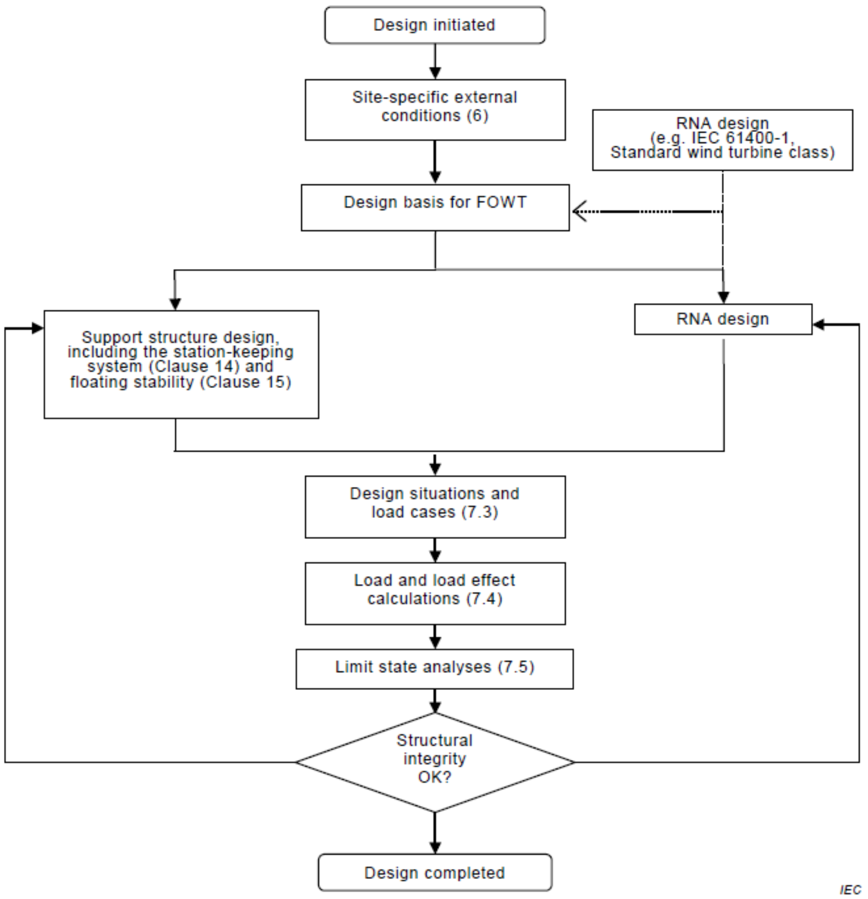


Figure 1 – Design process for a floating offshore wind turbine (FOWT) (extracted from [18])

The different aspects of the assessment of this design are developed in the following parts:

- the certification procedure in part 4
- the FRP materials characteristics, stress criterion and specificities are presented in part 5
- the loads and design load cases (DLC) usually used for floating offshore platform are described in part 6
- the structural design requirements in static and fatigue for the materials and the connection are presented in part 7 and the associated safety factor in part 8. This part is linked to the material criteria defined in the part 5 and the DLC of the part 6.

- the specific problematics are presented in the following parts:
    - Stability of the platform in part 9
    - Fire safety in part 10
    - Inspection and maintenance in part 11

In addition, the methodology that was used to check the design of the tower of the W2power platform is presented in appendix as well as thermoplastic resin characteristics.

# 2. REFERENCES

[1] BV - NI572 - Classification and Certification of Floating Offshore Wind Turbines, January 2019
[2] BV - NI594 - Design and Construction of Offshore Concrete Structures, February 2017.
[3] BV - NI525 - Risk-based qualification of new technology – Methodological guidelines, April 2020
[4] BV - NI603 - Current and Tidal Turbines, May 2015.
[5] BV - NI613 - Adhesive Joints and Patch Repair, May 2015.
[6] BV - NI631 - Certification Scheme for Marine Renewable Energy Technologies, January 2024.
[7] BV - NI691 - Environmental conditions, loads and induced responses of marine units, December 2022
[8] BV – NI682 - Certification of fixed offshore substations for renewable energy projects, April 2022
[9] BV - NR500 - Rules for the Classification and the Certification of Yachts, June 2021.
[10] BV - NR493 - Classification of Mooring Systems for Permanent and Mobile Offshore Units, July 2021.
[11] BV - NR546 - Hull in Composite, Plywood, and High Density Polyethylene Materials. 2022.
[12] BV - NR578 - Rules for the Classification of Tension Leg Platforms (TLP), July 2012.
[13] 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
[14] IEC 61400-1:2019 : Wind Turbines – Part 1: Design Requirements, October 2019.
[15] IEC 61400-2:2014/AC:2019-11 - Wind Turbines – Part 2: Small Wind Turbines, November 2019.
[16] IEC 61400-22, Wind turbines - Part 22: Conformity testing and certification, May 2010
[17] IEC 61400-3-1:2019 : Wind Energy Generation Systems – Part 3-1: Design Requirements for Fixed Offshore Wind Turbines, April 2019.
[18] IEC 61400-3-2:2019 : Wind Energy Generation Systems – Part 3-2: Design Requirements for Floating Offshore Wind Turbines, April 2019.
[19] IEC 61400-5:2020 - Wind Energy Generation Systems – Part 5: Wind Turbine Blades, 16 June 2020.
[20] IEC 61400-6:2020 - Wind Energy Generation Systems – Part 6: Tower and Foundation Design Requirements, 12 June 2020.
[21] IEC TS 61400-30 – Safety of wind turbine generators – General principles for design – Draft Technical Specification, September 2022
[22] ISO 31010 Risk management – Risk assessment techniques, [3]2019
[23] 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.
[24] 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.
[25] ISO 14122 Safety of machinery — Permanent means of access to machinery — Part 1: Choice of fixed means and general requirements of access, 2016
[26] DNV Standard - DNV-ST-0119 - Floating Wind Turbine Structures, June 2021.
[27] DNV.GL Standard - DNVGL-ST-C501 Composite Components, September 2019.
[28] DNV Recommended Practice - DNV-RP-C205 - Environmental Conditions and Environmental Loads, September 2021.
[29] DNV Standard - DNV-ST-0437: Loads and Site Conditions for Wind Turbines', amended 11/2021 2016.
[30] DNV Recommended Practice - DNV-RP-0286 - Coupled Analysis of Floating Wind Turbines, October 2021.
[31] DNVGL Service Specification - DNVGL-SE-0077 – Certification of Fire Protection Systems for Wind Turbines, March 2015
[32] Kawai, M, and N Itoh. 'A Failure-Mode Based Anisomorphic Constant Life Diagram for a Unidirectional Carbon/Epoxy Laminate under off-Axis Fatigue Loading at Room Temperature'. Journal of Composite Materials 48, no. 5 (1 March 2014): 571–92. https://doi.org/10.1177/0021998313476324.
[33] Sutherland, Herbert J., and John F. Mandell. 'Optimized Constant-Life Diagram for the Analysis of Fiberglass Composites Used in Wind Turbine Blades'. Journal of Solar Energy Engineering 127,

no. 4 (1 November 2005): 563–69. https://doi.org/10.1115/1.2047589.https://doi.org/10.1115/1.2047589.
[34] Post, N, S Case, and J Lesko. 'Modeling the Variable Amplitude Fatigue of Composite Materials: A Review and Evaluation of the State of the Art for Spectrum Loading'. International Journal of Fatigue 30, no. 12 (December 2008): 2064–86. https://doi.org/10.1016/j.ijfatigue.2008.07.002.
[35] ComposeIT, Bureau Veritas Marine & Offshore, "Bureau Veritas Software," 2020. [Online]. Available: https://marine-offshore.bureauveritas.com/software
[36] IMO SOLAS - International Convention for the Safety of Life at Sea
[37] IMO MSC.1/Circular.1574 - Interim Guidelines for Use of Fibre Reinforced Plastic (FRP) Elements Within Ship Structures: Fire Safety Issues
[38] IMO FTP Code - International code for application of fire test procedures
[39] IMO FSS Code – International code for fire safety systems
[40] Elium® Product Selector, 02-2022, Arkema
[41] SR Infugreen 810 Green Epoxy for injection and Infusion, Technical Datasheet, SICOMIN, 01/03/2017
[42] Fibregy D2.2 (WP2 Task 2.4) – Fatigue performance of composite Materials, 24/05/2023
[43] Clarke, John. 1996. 'Structural Design of Polymer Composites - Eurocomp'.
[44] DNV-RP-0584 - Marine Composites: Design, development and operation of floating solar photovoltaic systems, Det Norske Veritas, 2021.
[45] DNV-ST-0126 - Support structures for wind turbines, Det Norske Veritas, 2021.
[46] DNV-ST-0164 - Tidal Turbines, Det Norske Veritas, 2015.
[47] DNV-SE-0439 - Certification of condition monitoring, Det Norske Veritas, 2016.
[48] DNV-ST-0438 - Control Performance, Richard Pemberton, John Summerscales and protection systems for wind turbines, Det Norske Veritas, 2016.Jasper Graham-Jones, 2019
[49] ISO 20816-3: Mechanical vibration: Measurement and evaluation of machine vibration (Part 3: Industrial machinery with a power rating above 15kW and operating speeds between 120 r/min and 30000 r/min). 2022
[50] ISO 10816-21: Mechanical vibration: Evaluation of machine vibration by measurements on non-rotating parts (Part 21: Horizontal axis wind turbines with gearbox). 2015
[51] ISO 20816-1: Mechanical vibration: Measurement and evaluation of machine General Guidelines. 2016
[52] ISO 13374-1: Condition monitoring and diagnostics of machines: Data processing, communication and presentation (Part 1: General guidelines). 2003
[53] ISO 13379-1: Condition monitoring and diagnostics of machines - Data interpretation and diagnostics techniques - Part 1: General Guidelines, 2012
[54] ISO 13379-2: Condition monitoring and diagnostics of machines - Data interpretation and diagnostics techniques – Part 2: Data-driven applications. 2015
[55] ISO 16079-1 Condition monitoring and diagnostics of wind turbines - Part 1: General guidelines
[56] ISO 16079-2 Condition monitoring and diagnostics of wind turbines - Part 2: Monitoring the drivetrain
[57] Pathak, Pharindra. 2022. 'Master Thesis: Fatigue Methodology of Floating Offshore Wind Turbine Platform & Tower in Composite Materials'. Université de Liège, Liège, Belgique. https://matheo.uliege.be/handle/2268.2/16557.
[58] Al-Ghuwaidi, Abdulelah. 2023. 'Master Thesis: Fatigue Analysis of Floating Offshore Wind Turbine Tower in Composite Material'. Université de Liège, Liège, Belgique. https://matheo.uliege.be/handle/2268.2/19333.
[59] IECRE OD 502 Project Certification Scheme, edition 1.0, October 2018 https://iecre.org//dyn/www/f?p=107:570:::::P570_DOCUMENT_FILE_ID:3181975
[60] Marine Composites: Design and Performance, Richard Pemberton, John Summerscales and Jasper Graham-Jones, 2019
[61] Fibregy D2.2 (WP2 Task 2.4) – Fatigue performance of composite Materials, 24/05/2023
[62] Clarke, John. 1996. 'Structural Design of Polymer Composites - Eurocomp'.
[63] Marine Composites: Design and Performance, Richard Pemberton, John Summerscales and Jasper Graham-Jones, 2019
[64] ZEBRA project, https://www.lmwindpower.com/en/stories-and-press/stories/news-from-lm-places/zebra-project-launched
[65] NREL project, https://www.nrel.gov/wind/assets/pdfs/engineering-wkshp2022-8-3-murray.pdf
[66] NREL project, https://www.nrel.gov/manufacturing/comet-wind-blade-resin.html

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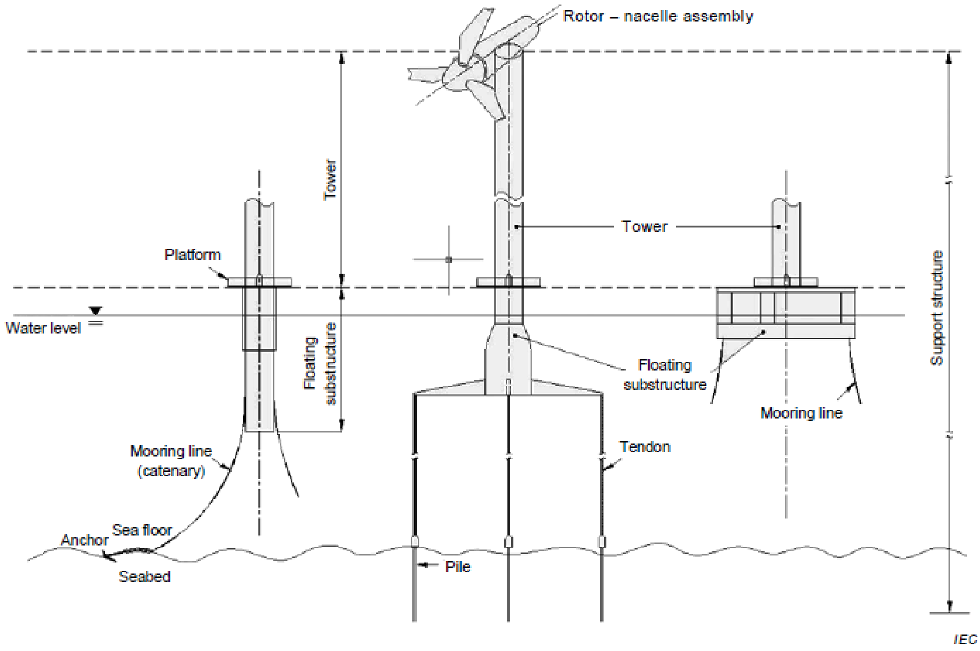
# 3. Definitions, Symbols and abbreviations

## 3.1. Definitions

In the following figure are presented the different parts of the floating substructure.




From left to right: Spar, TLP, and Semi.

Figure 2 - Parts of a floating offshore wind turbine (FOWT) (extracted from [18])

Fatigue: Process of deterioration of a structure subjected to fluctuating stresses, going through several stages from the initial "crack-free" state to a "failure" state.

Fatigue damage ratio: Ratio of the number of applied stress cycles and the corresponding number of stress cycles to failure at constant stress range (by use of S-N curve).

Fatigue life: Total time corresponding to the number of stress cycles required to cause fatigue failure of the component. The fatigue life is generally expressed in terms of number of years.

Fatigue limit: Stress range for which the fatigue strength under constant amplitude loading corresponds to a number of cycles large enough to be considered as infinite by a design code.

Miner's sum: Summation of individual fatigue damage ratios caused by each stress cycle or stress range block according to the Palmgren-Miner rule.

Palmgren-Miner rule: Method for estimating fatigue life under variable amplitude loading from the constant amplitude S-N curve. Often referred to as Miner's Sum.

S-N curve: Graphical presentation of the dependence of the number of stress cycles to failure (N) on the applied constant stress range ΔS, also known as Wöhler curve.

Stress cycle: A part of a stress history containing a stress maximum and a stress minimum. Stress history: A time-based presentation of a fluctuating stress for either the total life or a certain period of time.

Stress range: The difference between the maximum and minimum stresses in a stress cycle.

Stress ratio: Ratio of minimum to maximum stress values in a stress cycle

## 3.2. Abbreviations

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In this document the following abbreviated terms are used:

- ALS: Accidental Limit State
- CFRP: Carbon Fibre Reinforced Plastic
- FLS: Fatigue Limit State
- FMEA: Failure Mode and Effects Analysis
- FMECA: Failure Mode Effects and Criticality Analysis
- FOWT: Floating Offshore Wind Turbine
- FRP: Fibre Reinforce Plastics
- GFRP: Glass Fibre Reinforced Plastic
- HAZID: Hazard dentification
- IACS: International Association of Classification Societies
- IMO: International Maritime Organization
- LRFD: Load and Resistance Factor Design
- MEC: Marine Energy Converter
- MRE: Marine Renewable Energies
- OEM: Original Equipment Manufacturer
- OWTP: Offshore Wind and Tidal Platform
- RCS: Recognized Classification Society
- RNA: Rotor-Nacelle Assembly
- ULS: Ultimate Limit State
- WSD: Working Stress Design

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# 4. Certification Procedure – methodology, certification requirements

The present section outlines four certification procedures, corresponding to different stages of development of Marine Energy Converters (MEC), see [6]:

- Approval in Principle (AIP) and Basic Design Assessment (BDA)
- prototype certification
- component certification
- type certification
- project certification or asset classification

FOWT are considered as part of these Marine Energy Converters (MEC), with additional maturity.
Preliminarily of these 4 stages, an Approval in Principle (AIP), that is not a certification, can be performed to confirm that the outline project does not present any contradiction either with the state of art or with applicable rules.

On the whole, the guiding principles, objectives, scopes and applications of these certification procedures are very similar to other sectors. A summary of the application context for each certification procedure is presented in Figure 3.

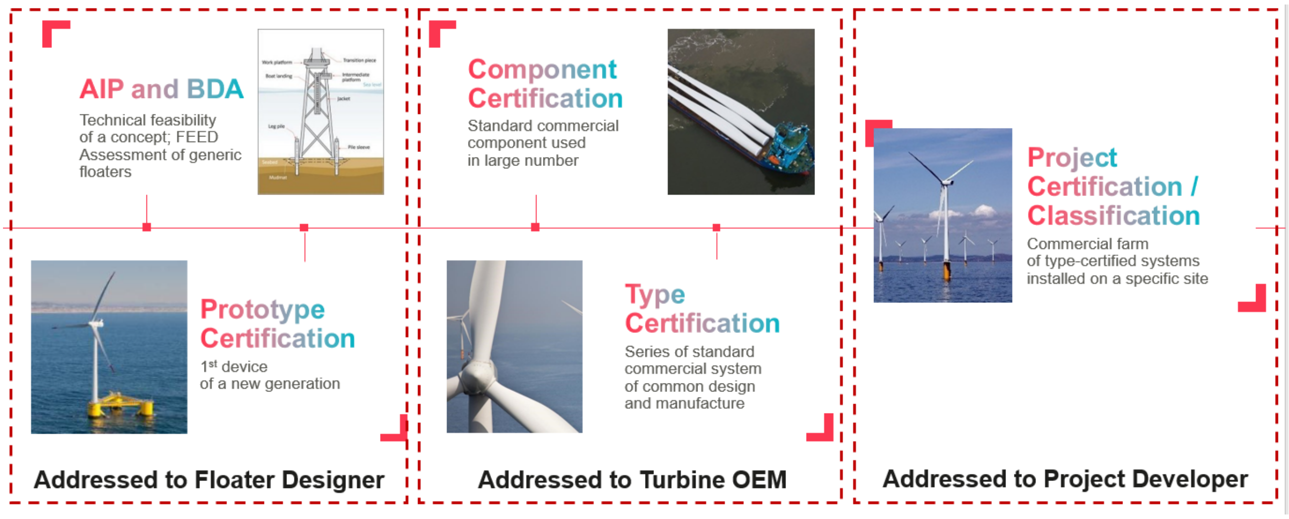


Figure 3 – Typical certification scheme, see NI631 [6]

## 4.1. Approval in Principle and Basic Design Assesment

As preliminary verification procedures, typically for an innovative and novel designs, Approval in Principle (AIP) or Basic Design Assessments may be performed.
Their purpose is to confirm that the design is feasible, achievable, and contains no technological showstoppers or contradiction with applicable rules and that may prevent the design from being matured.
AIP and BDA may follow different steps of design maturity, including:

- Feasibility study
- Conceptual design

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- So-called basic design

## 4.2. Prototype certification

The purpose of prototype certification is to verify the structural integrity of the first MEC of a new generation, before the prototype can be installed and tested at sea. The general plausibility and safety of the MEC design is assessed, with focus on specific risk areas.
Prototype certification addresses a MEC that is not yet ready for series manufacture, at a specific site and for a limited period. The certification body will evaluate that the prototype is safe during the specified period. As the design might still encounter large evolutions, type certification is not yet recommended.
The validity period of the prototype certification is maximum 3 years.

## 4.3. Component certification

The purpose of component certification is to confirm that a major component of a specific type, such as a Turbine, a gearbox or a blade, is designed, documented and manufactured in conformity with design assumptions, specific standards and other technical requirements.
Component certification addresses MEC components that are likely to be used in multiple projects. In such cases, a specific component certification can avoid the repetition of design evaluations for each project, as long as the external conditions are not more severe than those specified in the Component Certificate.
The validity period of the component certification is 5 years.

## 4.4. Type certification

The purpose of type certification is to confirm that the MEC type is designed, documented and manufactured in conformity with design assumptions, specific standards and other technical requirements. Demonstration by the applying party that it is possible to install, operate and maintain the MEC in accordance with the design documentation is required.
Type certification applies to a series of MECs of common design and manufacture. The Type Certificate covers the “generic part” of a standard commercial MEC i.e. the Rotor Nacelle Assembly (RNA) for FOWT. Note: The Tower used to be type certified for onshore wind turbine and possibly offshore bottom fixed, but for FOWT, the design is often site-specific and is part of the review of site-specific parts of the project certification.
Within type certification, conformity of the MEC is checked according to specified environmental conditions, corresponding to a certain load envelope. Consequently, type certification can avoid the repetition of the certification process for each project, as long as the external conditions are not more severe than those specified in the Type Certificate. In addition, type certification considers the same modules as component certification, but applied to the complete MEC. As such, components that are already certified are easily integrated into the type certification process.
The validity period of the type certification is 5 years.

## 4.5. Project certification

The purpose of project certification is to evaluate whether a specific MEC farm, including type-certified units and possibly other auxiliary installations, is designed and built in conformity with the external (environmental, electrical and soil) conditions at the intended location, and in conformity with applicable standards, construction and electrical codes and other relevant site-specific requirements.

The procedure covers the whole lifecycle of the project, including manufacturing, transportation, installation, commissioning, operation and maintenance, with the exception of decommissioning. Requirements for decommissioning are usually specified by local regulations and are thus project specific.

Project certification addresses "site-specific parts" of MECs optimized for every site based on external conditions, such as foundations or mooring systems, and possibly other installations.

The project certification scheme for FOWT may be based on:

- The IECRE OD 502 operational document [59] (previously IEC 61400-22 standard for wind turbines [16])
- Other project certification, e.g. NI631 project certification scheme defining Bureau Veritas adaptations of IECRE OD 502 to consider for the particular MRE requirements.
- Asset classification, e.g. Bureau Veritas classification scheme, first dedicated to the floater and moorings.

Project certification schemes typically follow a modular approach, with mandatory and optional modules which are listed and described below.

Modules of project certification are illustrated on Figure 4. An individual evaluation report and a conformity statement will be issued for each validated module of the certification scheme. Then, a Project Certificate, attesting to the conformity and correctness of all the modules, will be issued by the certification body at the end of the whole procedure, along with the final evaluation report. Delivery of the Project Certificate is subject to the completion of all the mandatory modules.

The validity period of the Project Certificate will be defined on a case-by-case basis with the certification body, aiming at covering the lifetime of the MEC farm. The Project Certificate validity is subject to the periodic inspections' outcomes (interval to be adapted to maintenance activities frequency when possible), and the annual review of monitoring, operation, maintenance and repair reports provided by the project operator.

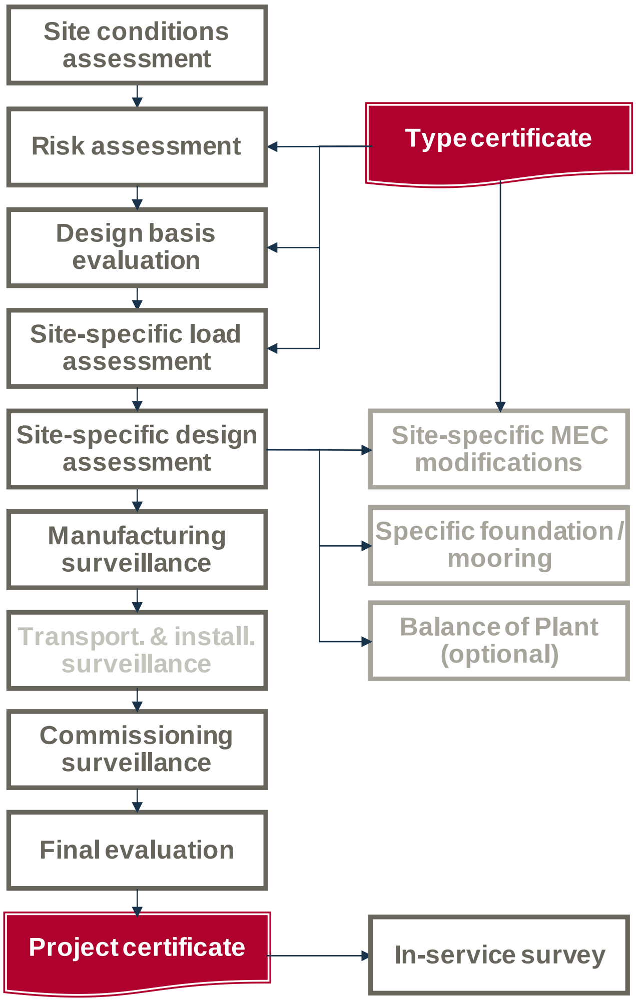


Figure 4 – Project certification scheme

### 4.5.1. Site-conditions assessment

The purpose of the site conditions assessment module is to examine whether the environmental (current, waves, etc.), electrical and soil (geotechnical and earthquake) properties at a site conform to the parameter values defined in the design documentation.

The certification body will evaluate that relevant reports properly document the external conditions as well as the data acquisition, the applied statistical methods and the design parameters for the external conditions.

### 4.5.2. Risk assessment (optional)

The risk assessment module aims at identifying systematically hazards associated with hazardous situations (collision or climatic extremes for instance), their possible causes and effects induced on asset integrity, personal safety and environment. HAZard IDentification (HAZID) or equivalent risk assessment method may support the implementation of this study.

If a risk assessment was already conducted during prototype or type certification, the present module can be a simple update, including project specificities such as interactions between different MECs, operational hazards, etc.

Appropriate prevention and mitigation measures shall be identified and deployed by the party applying for certification, to ensure safety of the MEC.

The certification body will review the risk assessment submitted by the applying party, ensuring that the selected methodology has been correctly implemented and that no major hazards remain unaddressed.

### 4.5.3. Design basis evaluation

The purpose of the design basis evaluation module is to examine that the design basis, sometimes referred to as basis of design, is properly documented by the applying party and sufficient for a safe design of the project. The design basis shall identify all requirements, assumptions and methodologies, which are essential for the design and the design documentation, including:

- existing codes and standards
- design parameters, assumptions, methodologies and principles
- other requirements, e.g. for manufacture and commissioning as well as for operation and maintenance.

For novel and innovative technologies, above mentioned codes and standards may not be sufficient or fully applicable. This currently is the case for FOWT floaters made of composite materials.
In such case, additional requirements or deviations from these codes and standards are required. This may be based on a risk-based methodology for the definition of the reference set of certification requirements. The methodology is developed in the last section of this paper "Definition of the reference set of standards". Based on results from the risk assessment module, the qualification process detailed in NI525 "Risk Based Qualification of New Technology – Methodological Guidelines" [3] is recommended to address MRE subsystems that are not fully covered by existing codes and standards.

### 4.5.4. Site-specific load assessment

The site-specific load assessment module aims at verifying the site-specific loads and load effects on the complete MEC structure.
This module includes:

- site-specific load calculations review based on measured environmental conditions
- assessment of any difference between the site-specific loads and the design load envelope assumed for the type certification, if any
- further load analyses performed by the applying party, when relevant.
- Independent analyses are typically performed by the certification body for verification purpose.

For FOWT, this module is typically called Integrated Load Analysis.

### 4.5.5. Site-specific design assessment

The site-specific design assessment module aims at reviewing the MEC design with regard to the site-specific loads previously assessed:

- type-certified design: design review is only required if design modifications have been made compared to the Type Certificate, or if the design load envelope is exceeded.
- foundations/mooring systems: site-specific design of foundations or mooring and anchoring systems is evaluated for compliance with the structural standards listed in the design basis. Independent analyses may be performed by the certification body for verification purpose.
- (optional) other site-specific installations: this optional module can include all additional site-specific equipment to be certified as part of the project certification, such as the Balance of Plant.

The exact scope of the evaluation will be agreed between the applying party and the certification body, depending on the specific installations to be certified.

### 4.5.6. Manufacturing surveillance

As part of the manufacturing surveillance, the quality system of the manufacturer (ISO 9001 or equivalent) will be evaluated by the certification body and manufacturing inspections are to be planned. Manufacturing surveillance will ensure that the intended quality requirements are met for the specific project, for the generic part as well as for the site-specific foundations or mooring systems and other installation.

Inspection planning is to be based on random sampling; the sampling rate being defined per component based on a criticality analysis.

### 4.5.7. Transportation and installation surveillance

It should be noted that transportation and installation phases are not covered by the certification procedure carried out by the certification body. Marine operations should be surveyed by an appropriate third party (e.g. a marine warranty surveyor on behalf of the insurance company) on the basis of a documented program comprising conditions for handling, lifting, etc.

However, project-specific transportation and installation procedures and reports shall be provided to the certification body for information. In addition, attendance of a surveyor during transportation and installation will be decided at the convenience of the certification body, in order to ensure that the structure and systems are in apparent good condition after transportation or installation stages, without visible damage.

### 4.5.8. Commissioning surveillance

The commissioning of the Project will be surveyed by the certification body, on the basis of an agreed program, to ensure that the procedures described in the commissioning manual are correctly and fully implemented.

### 4.5.9. Final evaluation

The purpose of final evaluation is to provide documentation of all the findings required for the evaluation of the elements leading to the Project Certificate.

The final evaluation report issued by the certification body consists of:

- reference list of all supporting product and project documentation provided by the applying party for the project certificate
- report of all conformity statements issued by the certification body for the project certification modules for outstanding issues.

### 4.5.10. In-service survey

To maintain the validity of the Project Certificate, the certification body will ensure that operation and maintenance activities are performed according to the requirements described in the respective manuals provided by the applying party.

Periodic inspections will be planned, the interval being agreed on a case-by-case basis with the certification body. When possible, periodic inspections will occur during onshore maintenance activities.

Monitoring, maintenance and repair reports will be presented to the certification body annually. At the convenience of the certification body, additional tests and site inspections may be required to maintain the validity of the certificate.

Classification scheme proposed by maritime Classification Societies such as Bureau Veritas typically include a more prescriptive in-service survey scheme, based on mandatory inspections of the unit.

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# 5. Materials

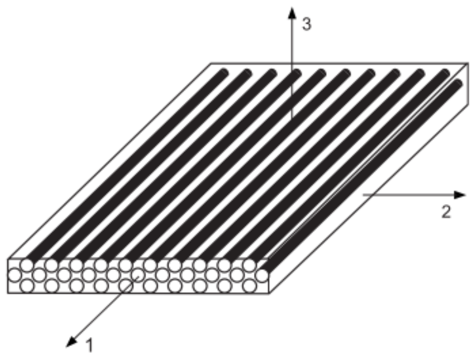
This section presents Fibre-reinforced plastics (FRP), also described as composite materials, which are the only materials considered directly in these project guidelines. The following subsections introduce the constituent of the FRP and the ways to determine the characteristics of the laminate in order to use and to check the design of the structure. As indicated in deliverable D4.6 of Fibregy, the case of composite materials for FOWT platform is usually not considered in rules and standards.
This section is mostly based on the BV NR546 Rules [11] and the results of D2.2 [42].

## 5.1. Composite panels

Composite panels usually used are of two kinds: monolithic panels and sandwich panels.

### 5.1.1. Monolithic panels

A monolithic panel referred also as laminate is a stacking of several individual layers named plies. Those plies are made of a matrix (resin) that is reinforced by fibres. The reinforcements are usually used in the form of unidirectional layers that can be stitched together to make multiaxial non crimped fabrics or woven in order to make woven roving. The mechanical properties of the ply are orthotropic with a big difference depending on the direction considered. They also have a strong dependence on their constituent materials. Depending on the constituent of one ply and on the direction of the fibre used, the mechanical characteristics of the ply can change a lot. Furthermore, the characteristics that can be obtained for the monolithic panels are highly dependent on the stacking sequence and the associated angle of these plies can be adapted to the desired use.




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.

Figure 5 – Composite ply orthogonal axes

### 5.1.2. Sandwich structures

The use of sandwiches structures is common in several industries. Sandwich panels consist of skins usually made of monolithic panels bonded to a Core material. The aim of doing this is to obtain a structure with a large bending stiffness by increasing the thickness of the panel. The core will undergo mostly shear stress and the tension-compression due to the bending will be sustain by the skins made of FRP. The point is to use lighter material than FRP in order to obtain a structure that would be stiffer than monolithic FRP part for a similar weight.

## 5.2. Constituents

The different constituents of composite plies are detailed in the following subsections.

### 5.2.1. Fibres

The main fibres type that are used are:

- Glass fibre with the classical E type and the seldom used R type.
- Carbon fibre with different grades: High strength (HS), intermediate Modulus (IM) or High Modulus (HM)
- Para-aramid

The fibres are used in the form of fabrics that are usually:

- Unidirectional (UD)
- Woven rovings (WR)
- Chopped strand mats (CSM)

Mechanical characteristics of the fibre can be found for example in [11]. They are given in the following table.

Table 1 – Fibre Mechanical characteristics (from [11])

| Fibre | | Glass | | Carbon | | | Para-aramid |
|---|---|---|---|---|---|---|---|
| Type | | E | R | HS | IM | HM | |
| Density $\rho_f$ | | 2.57 | 2.52 | 1.79 | 1.75 | 1.88 | 1.45 |
| Tensile in fibre direction | Poisson Coefficient $\nu_f$ | 0.238 | 0.2 | 0.3 | 0.32 | 0.35 | 0.38 |
| | Young Modulus $E_{f0°}$ (MPa) | 73100 | 86000 | 238000 | 350000 | 410000 | 129000 |
| | Breaking strain (%) | 3.8 | 4.0 | 1.5 | 1.3 | 0.6 | 2.2 |
| | Breaking stress (MPa) | 2750 | 3450 | 3600 | 4500 | 4700 | 2850 |
| Tensile normal to fibre direction | Poisson Coefficient $\nu_f$ | 0.238 | 0.20 | 0.02 | 0.01 | 0.01 | 0.015 |
| | Young Modulus $E_{f90°}$ (MPa) | 73100 | 86000 | 15000 | 10000 | 13800 | 5400 |
| | Breaking strain (%) | 2.4 | 2.4 | 0.9 | 0.7 | 0.45 | 0.7 |
| | Breaking stress (MPa) | 1750 | 2000 | 135 | 70 | 60 | 40 |
| Compression in fibre direction | Breaking strain (%) | 2.4 | 2.4 | 0.9 | 0.6 | 0.45 | 0.4 |
| | Breaking stress (MPa) | 1750 | 2000 | 2140 | 2100 | 1850 | 500 |
| Shear | Modulus $G_f$ (MPa) | 30000 | 34600 | 50000 | 35000 | 27000 | 12000 |
| | Breaking strain (%) | 5.6 | 5.6 | 2.4 | 3.0 | 3.8 | 4.0 |
| | Breaking stress (MPa) | 1700 | 1950 | 1200 | 1100 | 1000 | 500 |

### 5.2.2. Matrices

The main matrices that are used are thermoset resin:

- Epoxy
- Polyester
- Vinylester

Mechanical characteristics of these resins can be found for example in [11]. They are given in the following table.

Table 2 – Thermoset matrix mechanical characteristics (from [11])

| Matrix | Polyester | Vinylester | Epoxy |
|---|---|---|---|
| Density $\rho_r$ | 1.2 | 1.1 | 1.25 |
| Poisson Coefficient $\nu_r$ | 0.38 | 0.26 | 0.39 |
| Glass transition temperature Tg (°C) | Around 60°C | Around 100°C | Between 80 and 150°C |

| | | | |
|---|---|---|---|
| Tensile Young Modulus $E_r$ (MPa) | 3550 | 3350 | 3100 |
| Tensile or Compression Breaking stress (MPa) | 55 | 75 | 75 |
| Tensile or Compression Breaking strain (%) | 1.8 | 2.2 | 2.5 |
| Shear Modulus $G$ (MPa) | 1350 | 1400 | 1500 |
| Shear Breaking stress (MPa) | Around 50 | Around 65 | Around 80 |
| Shear breaking strain (%) | 3.8 | 3.7 | 5.0 |

Even if thermosets are classically used in marine industry and that they are defined in Rules/standards, new types of resins are more and more used. For example, thermoplastic resins have some specific properties that can be useful especially when considering the recyclability of the material. In Appendix, a brief bibliographic study is performed that describes those specificities.

In the Fibregy project, two different resins were used:

- SR Infugreen 810 that is an epoxy resin made using about 38% of carbon of plant origin,
- Elium 188XO resin that is based on a thermoplastic acrylic resin that is supposed to be processed in a similar way than epoxy.

The values given by the technical datasheet [40] and [41] are shown in the following table.

Table 3 – Fibregy matrixes mechanical characteristics

| Matrix | Elium | SR InfuGreen 810 |
|---|---|---|
| Density $\rho_r$ | 1.178 | - |
| Poisson Coefficient $\nu_r$ | - | - |
| Glass transition temperature Tg (°C) | Around 98°C | Above 63°C |
| Tensile Young Modulus $E_r$ (MPa) | 3000 | 2600 |
| Tensile or Compression Breaking stress (MPa) | 54 | 52 |
| Tensile or Compression Breaking strain (%) | 2.5 | 3.2 |
| Shear Modulus $G$ (MPa) | - | - |
| Shear Breaking stress (MPa) | - | 41 |
| Shear breaking strain (%) | - | - |

Those values depend on the cure cycle and can vary.

The appendix presents a comparison between the results in static and fatigue obtained with Elium® and Infugreen resin laminates and the theoretical data obtained for epoxy resin laminates.

### 5.2.3. Cores

Typical cores used in composite materials are:

- Foam core:
  - Linear or crosslinked PVC (Polyvinyl Chloride) foam
  - PU (Polyurethane) foam
  - SAN (Styrene Acrylo Nitrile) Foam
  - PET (Polyethylene Terephthalate) foam
  - PMI (Polymethacrylimide) foam
- Balsa core
- Meta Aramid or Thermoplastics Honeycombs

The typical characteristics of those foams and honeycomb structures can be found in [11] for example.

## 5.3. Individual layers characteristics

The scantling check of a laminate is made at the level of the individual layer (ply) and is often referred as ply-by-ply approach. Each ply should sustain the stresses computed taking into the safety factor defined in §8. In order to compute the stresses acting in each ply, the mechanical characteristics of the plies have to be determined as well as the laminate characteristics (this will be given in §5.4).
The characteristics of the laminate are determined based on the characteristics of the constituents and using a mixing law.

### 5.3.1. Fibre content, thickness and density

One of the main parameters used for the calculation of the ply is the fibre content or fibre ratio that can be expressed in term of volume $V_f$ or mass $M_f$. It is the amount of fibre in the ply generally expressed in percent. For example, the fibre mass content is given by the ratio between the mass of fibre over the individual layer mass. In the same way, the resin content or resin ratio ($V_r$or $M_r$) can be determined. These ratios are linked using the resin and fibre densities. They depend on the process used to manufacture the laminate and are generally given by the manufacturer.
Usually, reinforcement fabrics are characterized by the areal weight $P_f$ that is the mass per square meter of dry reinforcement.
Based on the fibre content and the fibre areal weight, the theoretical thickness $t$ of the ply can be obtained:

$$t = \frac{P_f}{V_f\, \rho_f}$$

And the density of one ply can be determined using the following formula:

$$\rho = \rho_f\, V_f + \left(1 - V_f\right)\rho_r$$

### 5.3.2. Determination of the ply's stiffness and strength

Based on the type of ply (UD, woven roving or mat), and knowing the fibre content and the characteristics of the constituent, one can determine the theoretical stiffnesses and the strength of the obtained ply. Ply characteristics are assumed to be orthotropic and thus the following parameters need to be determined:

- In-plane longitudinal characteristics:
  - Stiffness $E_1$

- Poisson Coefficients $\nu_{12}$ and $\nu_{13}$
- Tensile and compressive strengths $\sigma_{brt1}$ and $\sigma_{brc1}$

- In-plane transverse characteristics:
  - Stiffness $E_2$
  - Poisson Coefficient $\nu_{23}$
  - Tensile and compressive strengths $\sigma_{brt2}$ and $\sigma_{brc2}$
- In-plane shear characteristics:
  - Stiffness $G_{12}$
  - Shear strengths $\tau_{br12}$
- Out-of-plane (interlaminar) shear characteristics:
  - Stiffnesses $G_{13}$ and $G_{23}$
  - Interlaminar shear strengths $\tau_{IL1}$ and $\tau_{IL2}$

The determination is based on various rules of mixture. For more information, the reader can refer to [11].

### 5.3.3. Rigidity and flexibility matrix

Based on the previous stiffnesses and Poison Coefficients, the in-plane rigidity and flexibility matrix ($\bar{R}$ and $\bar{S}$) that link the stresses and the deformations vectors in the ply coordinate system can be computed as:

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix} = \bar{R}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix} = \begin{bmatrix}\bar{R}_{11} & \bar{R}_{12} & 0\\ \bar{R}_{12} & \bar{R}_{22} & 0\\ 0 & 0 & \bar{R}_{33}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix} \quad \text{Eq. 1}$$

And

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix} = \bar{S}\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix} \quad \text{Eq. 2}$$

With:

$$\bar{R}_{11} = \frac{E_1}{1-\nu_{12}\nu_{21}} \qquad \bar{R}_{22} = \frac{E_2}{1-\nu_{12}\nu_{21}} \qquad \bar{R}_{12} = \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} \qquad \bar{R}_{33} = G_{12}$$

## 5.4. Laminate characteristics

The laminate characteristics are determined based on the characteristics of the different plies and their orientation in the laminate global axis.

### 5.4.1. Rigidity in the laminate coordinate system

In order to compute the global laminate characteristics, it is necessary to obtain the rigidity matrix $[R]_k$ for each ply $k$ in the laminate coordinate system. This is done using a rotation matrix:

$$[R]_k = T[R]_k T'^{-1} \quad \text{Eq. 3}$$

With

$$T = \begin{bmatrix}\cos^2\theta & \sin^2\theta & -2\cos\theta\sin\theta\\ \sin^2\theta & \cos^2\theta & 2\cos\theta\sin\theta\\ \cos\theta\sin\theta & -\cos\theta\sin\theta & \cos^2\theta-\sin^2\theta\end{bmatrix} \qquad T' = \begin{bmatrix}\cos^2\theta & \sin^2\theta & -\cos\theta\sin\theta\\ \sin^2\theta & \cos^2\theta & \cos\theta\sin\theta\\ 2\cos\theta\sin\theta & -2\cos\theta\sin\theta & \cos^2\theta-\sin^2\theta\end{bmatrix}$$

Where $\theta$ is the angle between the ply coordinate system and the laminate coordinate system.

The flexibility matrix $[S]_k$for each ply $k$ in the laminate coordinate system is obtained in a similar way:

$$[S]_k = T'[S]_k T^{-1}$$

The laminate characteristics also depend on the position of the ply in the stacking sequence. For this, the $Z_k$ and $Z_{k-1}$ distance are defined. These correspond to the distances between the medium plane of the laminate and respectively the top and bottom interface of the ply.

$$Z_k = -\frac{t}{2} + \sum_{1}^{k} t_i \qquad Z_{k-1} = -\frac{t}{2} + \sum_{1}^{k-1} t_i$$

Where $t$ is the total thickness of the laminate and $t_k$ is the thickness of the ply $k$.

### 5.4.2. ABD Matrix and global behaviour of the laminate

Based on the previous definitions, it is possible to obtain the global rigidity matrix (also known as ABD matrix). This is used to link the deformation of the laminate and the force and moments applied on it.

$$\begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ K_x \\ K_y \\ K_{xy} \end{bmatrix} = \begin{bmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{bmatrix}^{-1} \cdot \begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} \qquad \text{Eq. 4}$$

Where:

$$A_{ij} = \sum_{1}^{n} [R_{ij}]_k . t_k \qquad B_{ij} = \frac{1}{2}\sum_{1}^{n} [R_{ij}]_k . (Z_k^2 - Z_{k-1}^2) \qquad D_{ij} = \frac{1}{3}\sum_{1}^{n} [R_{ij}]_k . (Z_k^3 - Z_{k-1}^3)$$

$N_x$, $N_y$, $N_{xy}$ are the forces applied to the laminate respectively in direction x, y and the shear load. In the same way, $M_x$, $M_y$ are the bending moments applied to the laminate respectively along direction y and x and $M_{xy}$ is the torque along direction x and y. All these loads are presented in Figure 6.

$\varepsilon_x^0$, $\varepsilon_y^0$, $\gamma_{xy}^0$ are the strains in the direction x and y and the shear strain at the median plane of the plane. $K_x$, $K_y$ are the curved deformation of laminate median plane around respectively y and x axis and $K_{xy}$ is the twist deformation of laminate median plane around x and y axis.

Basically, A part of the matrix links in-plane deformations to the in-plane forces, the D part links the angular deformation and the moment applied to the laminates. And the B part is used for the coupling of the in-plane deformations to the moments. The B part will be zero in case of symmetric laminate.

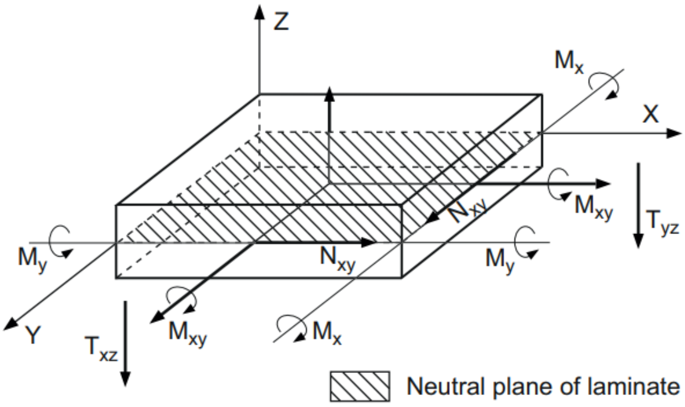



Figure 6 – Application of forces and moments (from [11])

In order to apply the ply-by-ply analysis of the laminate, it is necessary to determine the stresses in each layer. For this, based on the Eq. 4, it is possible to obtain the global laminate strains based on the loads applied to the laminate. Then based on the following equation, it is possible to obtain the strains for each ply in the laminate coordinate system:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}_k = \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \frac{Z_k + Z_{k-1}}{2} \quad \text{Eq. 5}$$

It is then possible express the strain in the ply coordinate system using the rotation matrix:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix}_k = T'^{-1} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}_k \quad \text{Eq. 6}$$

Using then the Eq. 1, it is possible to obtain the in-plane stress components for each of the ply. Then comparing the stresses obtained to the strength of the materials and considering the safety factor, it is possible to check all the ply to determine if the laminate is able to sustain the loads applied.

### 5.4.3. Interlaminar shear behaviour

Similar kind of approach can be used to determine the out-of-plane behaviour and mostly the interlaminar shear behaviour. These stresses are induced by the shear forces $T_{XZ}$ et $T_{YZ}$ presented in Figure 6. For more information, reader can refer to BV NR546 Rules [11].

## 5.5. Tests to characterize materials

For materials such as metals, the properties of the materials are known before assembly. On the contrary, for composite structure, the material itself is processed at the same time than the whole structure. For this reason, it is important to characterize the material when produced. For this, a test panel is to be produced and mechanical and physico-chemical tests must be performed on those panels. The material has to be representative of the construction:

- The same raw materials must be used with the same fibre content.
- The same process and curing cycle are considered. Depending on the process and curing cycle the properties can change a lot as the fibre and void content can be different for example.

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

- The lay-up (number and orientation of layers) should be representative of what is used in the real structure.

The list of tests that must be performed are presented in the following table.

Table 4 – Mechanical tests (from [11])

| Panels | Test-types – standards | Quantity of test pieces | Size of test pieces in mm |
|---|---|---|---|
| Monolithic | Tensile test: ISO 527 | 5 in lengthwise direction of panel<br>5 in crosswise direction of panel<br>2 test pieces for calibration | Length: 400<br>Width:<br>• 25 where t<25<br>• 30 where 25<t<30<br>• 35 where 30<t<35, etc… |
| | 3-points bending test: ISO 14125 | 5 in lengthwise direction of panel<br>5 in crosswise direction of panel<br>2 test pieces for calibration | Length: 200<br>Width:<br>• 25 where t<25<br>• 30 where 25<t<30<br>• 35 where 30<t<35, etc… |
| | Measurement of density: ISO 1183<br>Fibre content in weight: ISO 1172 or ASTMD3171 | 4 samples | 30x30 |
| Sandwich | 3-points bending test: ISO 14125 | 5 in lengthwise direction of panel<br>5 in crosswise direction of panel<br>2 test pieces for calibration | Length: 1000<br>Width: 2.t |
| | For both skins:<br>Tensile test: ISO 527 | 5 in lengthwise direction of panel<br>5 in crosswise direction of panel<br>2 test pieces for calibration | Length: 200<br>Width:<br>• 25 where t<25<br>• 30 where 25<t<30<br>• 35 where 30<t<35, etc… |
| | For both skins:<br>Measurement of density: ISO 1183<br>Fibre content in weight: ISO 1172 or ASTMD3171 | 4 samples | 30x30 |

In addition to these tests, it is also important to check the fatigue characteristics of the materials as required by IEC 61400-5 [19]:

- S-N curve for at least 4 consecutive decades at 0° and 90°. Representative ratio R shall be tested (typically 0.1, 10, -1)

## 5.6. Specific attention points

### 5.6.1. Design using composite

FRP material characteristics depends a lot on the manufacturing process. The manufacturing process used will also change the geometry possibilities and the joining strategy that can be used with the pieces obtained.

For example, pieces of revolution are usually not done using an infusion process. This can be realized, as in the Fibregy project for the mast of wind turbine, by creating 2 half part that are joined together. Another way to do it is to use filament winding that is a good process for this type of geometry but that is not as versatile as infusion in terms of geometry that can be used. However, one limitation of filament winding is the angle of fibre that can be used: fibre parallel to the axis is generally not possible and a minimum angle is necessary. Pultrusion can be used as well for cylindrical shapes. However, the fibre will be mainly aligned to the axis of the cylinder. This can result in a poor behaviour in shear. This also can be problematic if you want to bolt those parts.

This example shows that usually a design using composite materials should consider is a trade-off between:

- Manufacturing process and its inherent costs
- Design specificities due to composite manufacturing process
- Weight saving
- Materials that can be used
- ...

It is then important to consider all these effects from the start of the project. It is then advised to have discussions between the manufacturer and the design office from the beginning to build a good design of the composite structure. In general, the replacement of steel or other metallic materials by FRP without any other consideration does not lead to an efficient result.

In addition to those points, it should be noted that Composite parts are sensible to defects and impacts especially for the case of Carbon Fibre Reinforced Plastics (CFRP). It is then important to avoid any risk of impact. In order to avoid defects, if metallic parts are in contact with composite components, the edges of the metallic parts have to be rounded. In order to avoid localized damage in the composite parts, it is also important to avoid "hard spots" and sudden changes in structural strength and stiffness. For example, it is advised that for sandwich panel a smooth transition is designed from a sandwich part in the middle of the panel to a monolithic part on the edges that will be the junction to other parts.

### 5.6.2. Glass transition temperature $T_g$

The glass transition temperature of the matrix is an important characteristic of FRP material. Above this temperature, the mechanical characteristics of the material change a lot. In particular, the modulus of the matrix can be divided by more than 10. It is then important to make sure that the temperature of the material during operational conditions will sufficiently lower than the Glass transition temperature of the resin to avoid any damage. Usually, the temperature of the material should be under $T_g - 20°C$ when the Glass transition temperature Onset E is determined using Dynamic Mechanical Analysis (DMA).

### 5.6.3. Galvanic corrosion

CFRP are electrically conductive. When this type of composite materials is in contact with metal, galvanic corrosion can occur: As Carbon fibres are electrochemically very noble, the most part of the metals in contact will corrode. This phenomenon needs an electrolyte and oxygen to occur. Because the sea water acts as an electrolyte, this phenomenon can be encountered in FOWT. In order to avoid this phenomenon, the electrical connection between the CFRP and the metal must be cut. In order to do this Glass fibre plies can be used or other electrical insulation.

### 5.6.4. Coating

FRP materials are generally slightly porous. This induces that water ingress is susceptible to occur for immersed part or part in contact with water. As this changes the mechanical performance of the material, it is important to use coating on the material to protect it. It can be used as a protection against marine growth as biofouling can affect the shape and integrity of a structure. This accumulation and attack of organisms can lead to alteration of submerged surfaces and large increase in weight and drag of structure.

# 6. Design Conditions and Load Cases

In the following section are presented the loads acting on FOWT platform and the load cases to be considered. These are based on the conditions obtained in IEC 61400-3 series [17][18], DNV-ST-119 [26] and BV NI572 [1].

## 6.1. Environmental conditions

The typical environmental conditions that may be considered for FOWT platforms are the following in case no site data is given:

- Normal environmental conditions
  - Air temperature range within [-10; 30°C]
  - Water temperature range within [0; 30°C]
  - Relative humidity of up to 100%
  - Solar radiation intensity of 1000W/m$^2$
- Extreme environmental conditions
  - Air temperature range within [-15; 40°C]
  - Water temperature range within [-2; 35°C]
- Other site conditions such as salinity and marine growth is also to be considered in the design of the FOWT.
- Wind and wave environmental conditions are defined in the §6.2

## 6.2. Loads

In the following subsections are presented the loads that need to be considered in the design of FOWT platforms and some specific environmental loads such as wind, waves and current are also described.

### 6.2.1. Loads considered in the design of FOWT

The loads that need to be considered for FOWT platforms are:

- Fixed (or permanent) loads
  - weight of the structure and associated inertia
  - Weight of the permanent ballast
  - Weight of permanent liquids
- Operating loads
  - buoyancy,
  - mooring loads,
  - power cable loads,
  - ballast loads,
  - liquid tanks loads
  - impact and dynamic loads due to normal operation,
  - Wake loads from neighbouring FOWTs
  - etc...
- Environmental loads

  - Main environment loads
    - Wind loads,
    - Temperature
    - Wave, current, tidal and marine growth loads
  - Snow and ice,
  - Reaction to loads
    - dynamic mooring
    - power cable loads
  - Tsunamis and earthquake loads
  - Lightning
- accidental loads
  - hydrostatic pressure in damaged conditions
  - accidental flooding
  - collision with vessels
  - fire and explosions
  - electrical fault

For the environmental loads, wind, waves and current need to be considered simultaneously as they can have a significant effect especially in fatigue analysis. Several load cases are proposed in the section 6.3 to consider this.

### 6.2.2. Wind loads

#### 6.2.2.1. Main conditions considered

Wind loads are loads due to the action of the wind on the structure:

- Wind acting on the rotor of the turbine,
- Wind acting on tower and the floater of the FOWT.

The wind loads are determined based on the specific site where the FOWT platform is installed. It is mainly dependant on the height of the point considered, the average wind speed at the site location and the gust effect that can be faced  Different conditions of wind are considered for the design of FOWT. The main conditions are:

- Normal wind conditions that are encountered frequently during the service life of the FOWT having a 1-year return period,
- Extreme wind conditions having a 50-year return period. Several subcases are defined for the extreme wind conditions:
  - Extreme Wind speed Model (EWM)
  - Extreme Operating Gust (EOG)
  - Extreme Turbulence Model (ETM)
  - Extreme Direction Change (EDC)
  - Extreme Coherent gust with Direction change (ECD)
  - Extreme Wind Shear (EWS)

The definitions of all these phenomena may be found in IEC 61400-1 [14] or NI572 [1].

#### 6.2.2.2. Wind loads: specificities for FOWT

The 10-minute mean wind speed $U_{10}$ is usually considered in conjunction with the standard deviation $\sigma_u$. However, for natural periods that can be more than 200 seconds which can appear for compliant mooring especially in deep waters, this representation is insufficient and conversion to larger averaging times will be necessary. Power spectral density models for wind and sea state loads are preconized and reader is referred to DNV-RP-C205 [28]. Attention is to be paid to low frequency range. The representation of the wind in this range has to be adequate.

The Extreme Operating Gust EOG (generally based on duration period of 10.5 seconds) is not adequate for the design of FOWT. However, for the design of the tower, the EOF still needs to be considered as it could prove relevant. Gust events should be considered with durations longer than 10.5 seconds and should be selected based on the natural periods of the FOWT (typically in the range 10 to 100 sec).

### 6.2.3. Waves

Wave conditions as for wind are site specific and are generally described using:

- Significant wave height $H_S$
- Spectral Peak period $T_P$
- Wave heading
- Wave spectrum

Three different waves conditions should be considered:

- Normal wave that corresponds to the wave height encountered under normal wind conditions
- Severe wave that corresponds to the maximum wave height encountered under normal wind conditions with a return period of 50 years. This corresponds to the maximum operating wave height.
- Extreme wave that corresponds to the maximum wave height encountered with a return period of 1 year and 50 years (respectively $H_{S,1}$ and $H_{S,50}$). Depending on the load case considered, either $H_{S,1}$ or $H_{S,50}$ is to be taken into account.

Breaking waves (spilling, plunging and surging) should also be considered based on the sea floor slope encountered.

For waves, stationary waves conditions with constant significant wave height and peak period are assumed to prevail. A two-peaked power spectrum model such as Torsethaugen's is advised in DNV-ST-119 for FOWT.

The behaviour of FOWT platforms might be more induced by waves than by wind. Load cases considering waves should be taken carefully based on this remark.

### 6.2.4. Current

For the current, both sub surface current (due to tides storm surge) and near surface current (due to wind) are considered. Two different conditions are generally considered:

- Normal Current that can be based on the mean speed value due to tidal current and on the normal wind conditions.

- Extreme Current that corresponds to the maximum current encountered with a return period of 1 year and 50 years usually co-directional with the waves. As for the waves, the value to be used depend on the load case considered.

## 6.3. Load cases

### 6.3.1. Definitions

#### 6.3.1.1. Category of load cases

Different categories of load cases are to be analysed for the design of a FOWT:

- Normal load cases (N)
- Accidental load cases (A)
- Transit, Installation and maintenance load cases (T)
- Fatigue load cases (F)

The safety factors associated with the load cases will be different for each category of load cases. The safety factors will be defined in section 8. The letter between parentheses will be used in the following as an abbreviation of each category and the associated safety factor to be considered.

#### 6.3.1.2. Design conditions

Different design conditions are considered when analysing a FOWT. Those design conditions refer to different aspects of the service life of the structure with different associated loads and load cases

1. Power production
2. Power production plus occurrence of fault
3. Start up
4. Normal Shut down
5. Emergency stop
6. Parked (standing still or idling)
7. Parked and fault conditions
8. Transport, assembly maintenance and repair
9. Power production for floating structure
10. Parked (standing still or idling) for floating structure

### 6.3.2. Design load cases (DLC)

For each of these categories, the loading cases to be analysed are defined in the following table. This table is given for information. Some of the line can be similar in terms of loads but slight difference can be observed in terms of the return period considered for example. Reader can refer to IEC61400-3 series ([17][18]) for more information.

Table 5 – Design load cases for FOWT platform

| 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<br>Low voltage ride through | Normal | Normal | Normal | N |
| 2.6 | | Abnormal<br>Fault of sea state limit protection system | Normal | Severe | Normal | A |
| 3.1 | Start up | Intact | Normal | Normal | - | F |

| | | | | | | |
|---|---|---|---|---|---|---|
| 3.2 | | Intact | Extreme (EOG) | Normal | Normal | N |
| 3.3 | | Intact | Extreme (EDC) | Normal | Normal | N |
| 4.1 | Normal shut down | Intact | Normal | Normal | - | F |
| 4.2 | | Intact | Extreme (EOG) | Normal | Normal | N |
| 4.3 | | Intact | Normal | Severe | Normal | N |
| 5.1 | emergency stop | Intact | Normal | Normal | Normal | N |
| 6.1 | Parked (standing or idling) | Intact | Extreme (EWM) | Extreme | Extreme | N |
| 6.2 | | Intact | Extreme (EWM) | Extreme | Extreme | A |
| 6.3 | | Intact | Extreme (EWM) | Extreme | Extreme | N |
| 6.4 | | Intact | Normal | Normal | - | F |
| 7.1 | Parked and fault conditions | | Extreme (EWM) | Extreme | Extreme | A |
| 7.2 | | | Normal | Normal | - | F |
| 8.1 | Transport, assembly, maintenance and repair | Extreme conditions that may be encountered for Transport Assembly and Maintenance bases on the design assumptions | | | | T |
| 8.2 | | | Extreme (EWM) | Extreme | Extreme | A |
| 8.3 | | | Normal | Normal | - | F |
| 8.4 | | Extreme fatigue conditions that may be encountered for Transport Assembly and Maintenance bases on the design assumptions | | | | F |

| | | | | | | |
|---|---|---|---|---|---|---|
| 9.1 | Power production in case of loss of mooring line | transient condition between intact and redundancy check condition | Normal | Normal | Normal | A |
| 9.2 | | Redundancy check condition | Normal | Normal | Normal | A |
| 9.3 | | leakage (damage stability) | Normal | Normal | Normal | A |
| 10.1 | Parked (standing or idling) in case of loss of mooring line | transient condition between intact and redundancy check condition | Extreme (EWM) | Extreme | Extreme | A |
| 10.2 | | Redundancy check condition | Extreme (EWM) | Extreme | Extreme | A |
| 10.3 | | leakage (damage stability) | Extreme (EWM) | Extreme | Extreme | A |

## 6.4. Remarks on loads and loads cases simulations

FOWT rigid body motions have long natural period and low damping. Hence, care should be taken for initial conditions on simulations and the duration of the simulations. For fatigue loading, unclosed cycles (partial cycles) may play an important role. Using a Rainflow-counting algorithm, those cycles can be disregarded or on the contrary counted as one cycle and artificially increase the damage calculated.
It is important to note that it may be possible that the use of composites material will tend to increase the natural periods of the FOWT structural degrees of freedom (e.g. tower fore aft, or floater elastic modes), as the stiffness is supposed to decrease and may increase this type of behaviour.

# 7. Structural Design Requirements

As already explained in §5, the materials properties depend on the process used to build the structure. These characteristics need to be considered for the structural assessment of the structure that is presented below. Usually, theoretical characteristics are used and during the production a panel test is produced to check that the obtained characteristics are above the theoretical characteristics considered. The methodology used for the assessment of the tower of the W2Power platform studied in Fibregy is presented in §12.1.

## 7.1. Ultimate load assessment

The ultimate load assessment of the composite parts must be performed against buckling and first ply failure of the laminate. For the strength criterion, it is based on a ply-by-ply approach of the laminate as described in §5. The maximum stresses are obtained from the calculations of the FOWT submitted to the load cases of §6.3. The safety factor that should be considered are proposed in §8. If a finite element model is used, guidelines presented in §12.3 must be considered.

### 7.1.1. Design format method

The criteria for the assessment of a given design verification (e.g. hull scantlings) are based on one of the following design format methods with corresponding acceptance criteria:

- Working stress design (WSD) method, also known as the permissible or allowable stress method
- Load and resistance factor design (LRFD) method, also known as Partial Safety Factor (PSF) method

The criteria are detailed for First ply failure hereafter.

| | WSD format | LRFD format |
|---|---|---|
| General format | Maximum stress criteria in each ply: $$\sigma_1 < \frac{\sigma_{br1}}{SF}, \sigma_2 < \frac{\sigma_{br2}}{SF}, \tau_{12} < \frac{\tau_{br12}}{SF},$$ $$\tau_{IL1} < \frac{\tau_{brIL1}}{SF}, \tau_{IL2} < \frac{\tau_{brIL2}}{SF}$$ $\sigma_1, \sigma_2, \tau_{12}, \tau_{IL2}, \tau_{IL2}$: Stress (respectively in plane stress 1 and 2, in plane shear stress, interlaminar shear stress in direction 1 and 2) $\sigma_{br1}, \sigma_{br2}, \tau_{br12}, \tau_{brIL2}, \tau_{brIL2}$: resistances (respectively in plane strength 1 and 2, in plane shear strength, interlaminar shear strength in direction 1 and 2) $SF$: Permissible utilisation factor. The utilisation factor accounts for uncertainties in loads and structural capacity | Maximum stress criteria in each ply: $$\sigma_1 < \frac{\sigma_{br1}}{SF}, \sigma_2 < \frac{\sigma_{br2}}{SF}, \tau_{12} < \frac{\tau_{br12}}{SF},$$ $$\tau_{IL1} < \frac{\tau_{brIL1}}{SF}, \tau_{IL2} < \frac{\tau_{brIL2}}{SF}$$ $\sigma_1, \sigma_2, \tau_{12}, \tau_{IL2}, \tau_{IL2}$: Stress (respectively in plane stress 1 and 2, in plane shear stress, interlaminar shear stress in direction 1 and 2) $\sigma_{br1}, \sigma_{br2}, \tau_{br12}, \tau_{brIL2}, \tau_{brIL2}$: resistances (respectively in plane strength 1 and 2, in plane shear strength, interlaminar shear strength in direction 1 and 2) $SF$: Permissible utilisation factor. The utilisation factor accounts for uncertainties in loads and structural capacity |

| | | |
|---|---|---|
| | Combined stress criterion in each ply: $$SF_{CS} < SF_{CSiapp}$$ $SF_{CSiapp}$ is the margin of the Hoffman criteria computed based on the in-plane stresses $(\sigma_1, \sigma_2, \tau_{12})$ see part 8.1.2 $SF_{CS}$: Permissible utilisation factor. | Combined stress criterion in each ply: $$SF_{CS} < SF_{CSiapp}$$ $SF_{CSiapp}$ is the margin of the Hoffman criteria computed based on the in-plane stresses $(\sigma_1, \sigma_2, \tau_{12})$ see part 8.1.2 $SF_{CS}$: Permissible utilisation factor. |
| Calculated stresses | No factors applied: the considered stress is the calculated stress from the FEA. | Load safety factors applied to obtain the calculated stress (shown above), as follows: $$\sigma = \sigma\left(\sum_i \gamma_f \, \mathrm{F_i}\right)$$ The stresses are used in the above max stress criteria and combined stress criterion $\gamma_f$: DLC dependent load safety factors, as defined in §8. $\mathrm{F_i}$: calculated loads for load category i. $\sigma(\ )$: calculated stress from the FEA. |

### 7.1.2. Buckling

For buckling, the following modifications are to be used:

- The calculated stress is to be replaced by a buckling utilisation factor.
- The allowable stress is to be replaced by 1.0.

## 7.2. Displacement/acceleration criteria

The acceleration of the RNA obtained during the calculation must be consistent with the maximum acceleration provided by the manufacturer of the rotor. The displacement of the nacelle must also be limited. As a guidance, the maximum deflection of the tower should be less than $1/150^{th}$ of the tower height.

Sufficient clearance between the blades and the tower is to be assessed to avoid any interaction between those components.

## 7.3. Fatigue design of composite structures

The fatigue assessment of a laminate is carried out by calculating the damage ratio of both fibres and matrix for each layer of the laminate.

### 7.3.1. Matrix and fibre stress

#### 7.3.1.1. Ply by ply stress decomposition

As for the static calculation, a ply-by-ply analysis is to be considered in this methodology. The theory for this type of analysis is explained in NR546 BV Rules for Composite Materials [11] sec 6. This enables to determine the local stress state $\boldsymbol{\sigma} = [\sigma_1, \sigma_2, \tau_{12}]$ in each layer. The direction 1, 2, 3 are described in the Figure 5 and the different terms are:

- $\sigma_1$: the stress in the fibre direction
- $\sigma_2$: the stress in the direction perpendicular to the fibre
- $\tau_{12}$: the in-plane shear stress

#### 7.3.1.2. Determination of equivalent stress for matrix and fibre

The fatigue behaviour in the fibre and in the matrix are assumed to be different. Equivalent fibre and matrix stresses $\sigma_f$ and $\sigma_{eq}$ are defined in order to apply the methodology on both constituents of the composite material. In the case of the matrix, it is needed to consider both the shear and transverse stresses that act simultaneously and possibly with different frequencies but that interact with each other. Thus, an equivalent matrix transverse stress is computed as well as the shear stress

##### Equivalent fibre stress

In the fibre-dominated L-direction, the equivalent stress is taken equal to the stress along direction 1. That is to say, the effects of $\sigma_2$ and $\tau_{12}$ are ignored for the fibre equivalent stress:

$$\sigma_f = \sigma_1 \qquad \text{Eq. 7}$$

##### Equivalent transverse matrix stress

The equivalent matrix stress which accounts for both the transverse stress and the in-plane shear effects is defined as:

$$\sigma_{eq} = \sigma_2\sqrt{1 + \min\left(3, \left(\frac{f_2\tau_{12}}{\sigma_2}\right)^2\right)}, \quad \text{where } f_2 = \begin{cases} \frac{\sigma_{\text{brt2}}}{\tau_{\text{br12}}} & \text{if } \sigma_2 \geq 0 \\ \frac{\sigma_{\text{brc2}}}{\tau_{\text{br12}}} & \text{if } \sigma_2 < 0 \end{cases} \qquad \text{Eq. 8}$$

Where:

- $\sigma_{\text{brt2}}$ is the theoretical breaking stress in tension in the transverse direction
- $\sigma_{\text{brc2}}$ is the theoretical breaking stress in compression in the transverse direction
- $\tau_{\text{br2}}$ is the theoretical in-plane shear breaking stress

This formulation is based on the use of a failure envelope that is defined by two different ellipses, corresponding to the left and right halves respectively in the plane $(\sigma_2, \tau_{12})$.

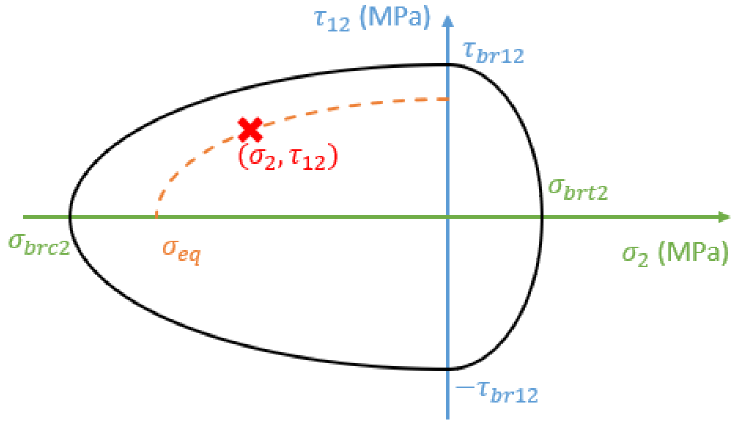



Figure 7 – Failure envelope in matrix

### 7.3.2. Design S-N Curves

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The design methodology described in this guideline is based on the use of design S-N curves. The S-N curves to be considered is dependent on the stress cycle history that will be described in the following subsection. The formulation and the values to be considered are then presented.

#### 7.3.2.1. Stress Cycles

The main parameter that has influence on the S-N curves to be used for the fatigue assessment of composite is the amplitude ratio $R$:

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

Where:

- $\sigma_{min}$ is the minimum stress of the cyclic loading considered
- $\sigma_{max}$ is the maximum stress of the cyclic loading considered

Different stress ratios stress cycles are presented in the Figure 8.

Other values used in the following of this document are presented here:

- $\sigma_m = \frac{\sigma_{max}+\sigma_{min}}{2}$ is the mean stress during the cycle
- $\sigma_a = \frac{\sigma_{max}-\sigma_{min}}{2}$ is the alternate stress during the cycle

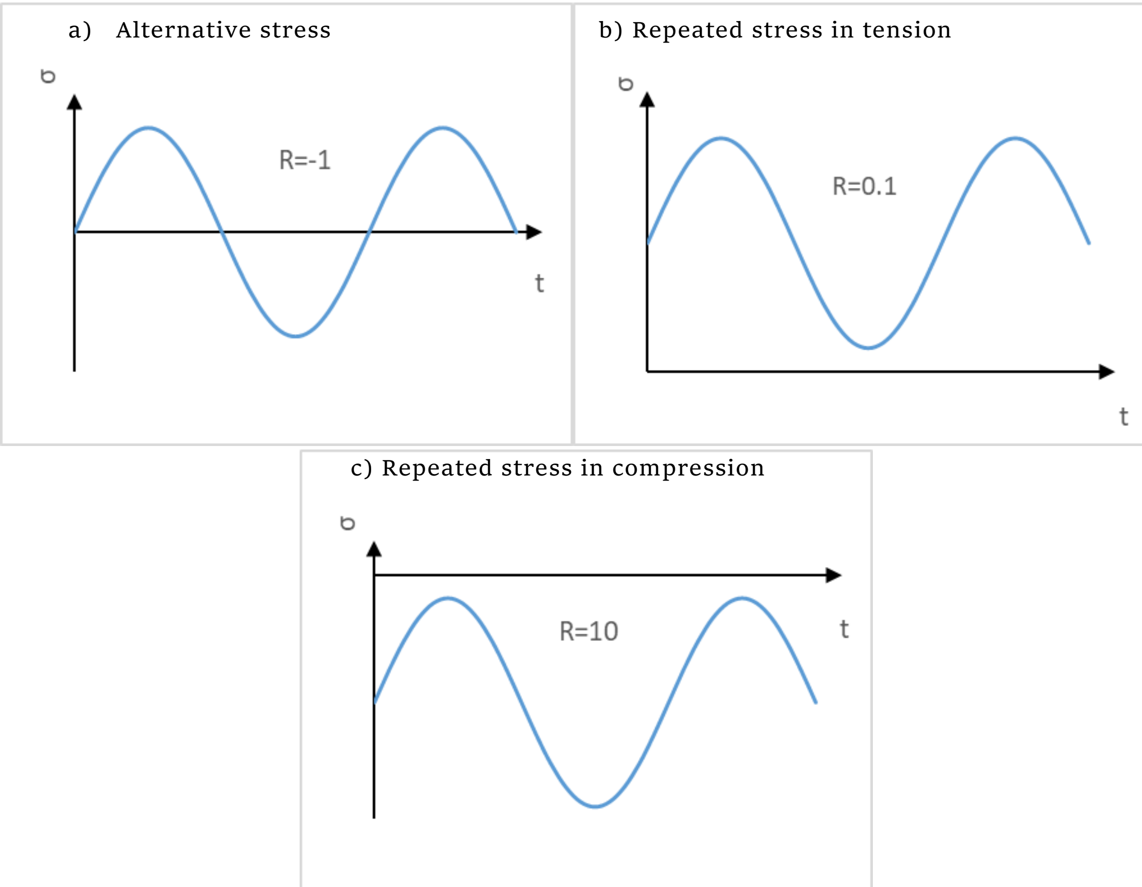


Figure 8 – Stress ratio

#### 7.3.2.2. Formulation

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For each individual layer and for matrix and fibre, the number of cycles to failure for a specific stress level is defined by the following equation:

$$N_{R,i} = \sigma_i^{-m}$$

Where:

- $\sigma_i = |\sigma_a|/\sigma_{br}$ is the alternate stress level *i.e.* the ratio of the alternate stress (See 7.3.3) to the theoretical breaking stress. The breaking stress to be considered depends on the amplitude ratio $R$:
  - $\sigma_{br} = \frac{\sigma_{brt}}{2}(1 - R)$, when $\frac{\sigma_{brc}}{\sigma_{brt}} \leq R < 1$,
  - $\sigma_{br} = \frac{\sigma_{brc}}{2}\frac{(1-R)}{R}$, otherwise
- $\sigma_{brt}$ and $\sigma_{brc}$ are respectively the tension and compression theoretical breaking stress in static. $\sigma_{brc}$ is to be considered as a negative value as it is a compressive stress.
- $m$ is the coefficient giving the slope of the S-N curve according to §7.3.2.2.

The relation gives a linear S-N curve in a log-log graph as shown in Figure 9.

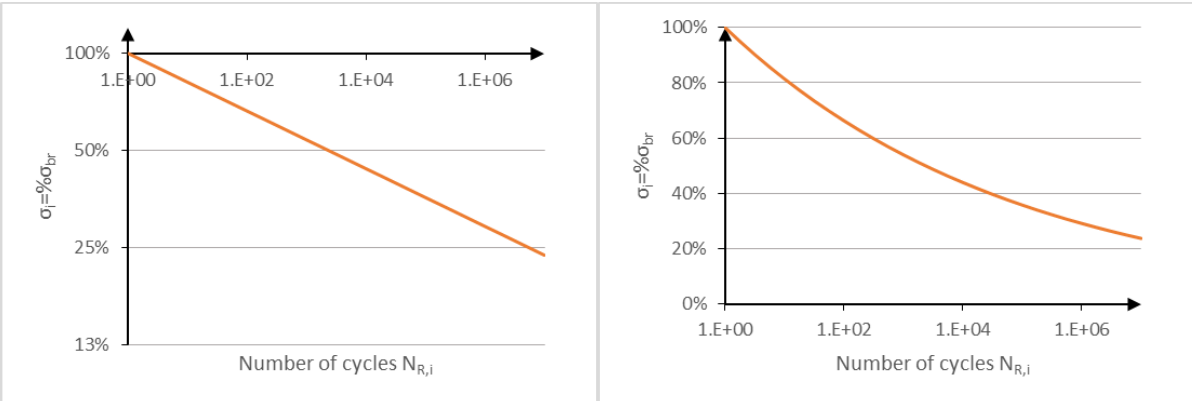


Figure 9 – Example of S-N curve (log-log graph on the left and semi-log graph on the right)

#### 7.3.2.3. *m* Coefficient values

The values of coefficient $m$ presented in the Table 6 are given for information. These values are determined based on the values of NI603 fitting them with the Basquin's model for number of cycles ranging from 1 to $10^6$ Cycles. These values depend mainly on the R ratio and on the type of material used. In order to obtain these values, fatigue life behaviour of the matrix is to be obtained from fatigue tests of UD [90°] laminates. For these laminates, the fatigue behaviour is dominated by matrix cracking and fibre-matrix debonding. Similarly, the fatigue life behaviour of the fibres is obtained from the fatigue tests of UD [0°] laminates. For such laminates, the fatigue loads would lead finally to the failure of the fibres.

For these tests, if the composite material experiences, during its fatigue life:

- Constant cycles at a given ratio $R$, tests are advised to be performed at this ratio
- Variable tension-tension cycles ($0 < R < 1$), tests are advised to be performed at $R = 0.1$
- Variable compression-Compression cycles ($R > 1$), tests are advised to be performed at $R = 10$
- Variable alternative stress, it is recommended that at least 3 R ratio are tested:
  - $R = 0.1$
  - $R = 10$
  - $R = \sigma_{brc}/\sigma_{brt}$

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For the determination of the allowable number of cycles, for a given R ratio that is not determined, the value should be determined according to the §7.3.3.

Table 6 – Coefficient ***m***

| | | | Glass | | | Carbon | | |
|---|---|---|---|---|---|---|---|---|
| | | R | Polyester | Vinylester | Epoxy | Polyester | Vinylester | Epoxy |
| UD | parallel to fibres | -1 | 11.2 | 16.6 | 14.6 | 11.2 | 16.6 | 22.9* |
| | | 0.1 | 10.3 | 13.3 | 12.2 | 13.3 | 76.4 | 20.2* |
| | | 10 | 16.6 | 38.6 | 25.5 | 13.3 | 76.4 | 50.3* |
| | perpendicular to fibres | -1 | 11.2 | 16.6 | 14.6 | ND | ND | 10.9* |
| | | 0.1 | 10.3 | 13.3 | 12.2 | ND | ND | 15.0* |
| | | 10 | 16.6 | 38.6 | 25.5 | ND | ND | 165* |

ND = Not Defined

The values are determined from NI603 except values with *

*: values determined based on the work from Kawai [32]

## 7.3.3. CFL diagram

### 7.3.3.1. Generalities on CFL diagram

The determination of the allowable number of cycles for a given R ratio is based on the use of Constant Fatigue Life (CFL) diagram. On this graph, each line corresponds to an identical or constant fatigue life given for different R ratios tested on a $(\sigma_m, \sigma_a)$ plane.

In order to build a CFL diagram, S-N curves are taken at various ratios. For a set of number of cycles (for example each decade), the corresponding stress is retrieved and plotted on the CFL diagram, see Figure 10. An example of Constant Fatigue Life diagram is given at Figure 11.

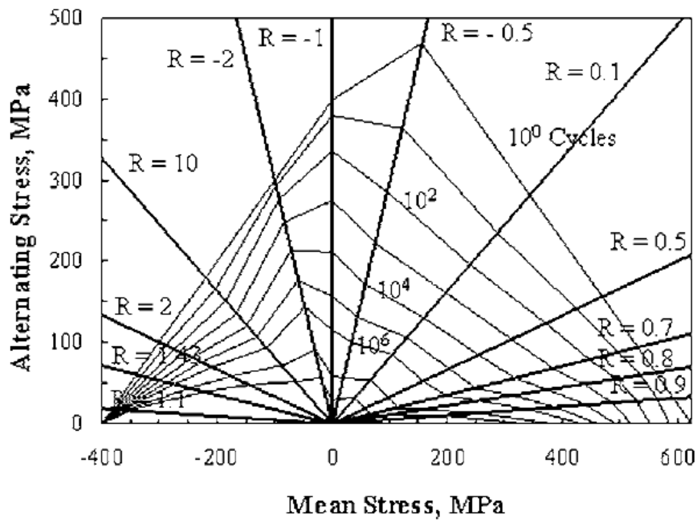


Figure 10 – Typical CFL Diagram for wind turbine applications (from [33])

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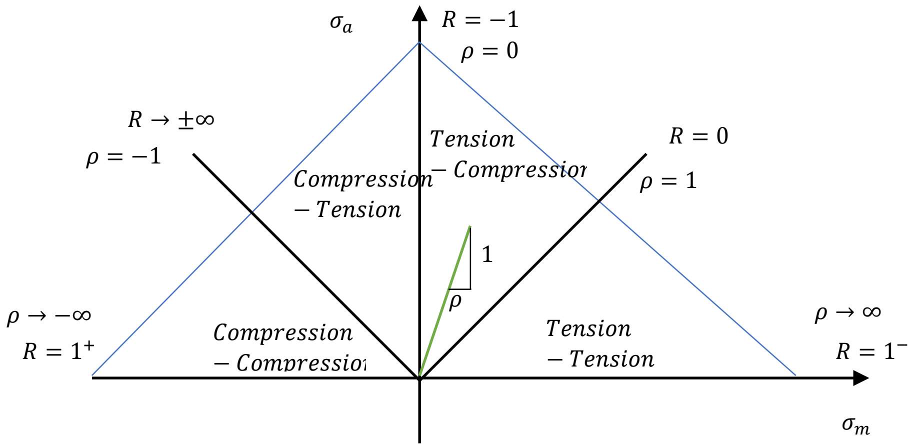


Figure 11 – Typical CFL Diagram

#### 7.3.3.2. Interpolation of results in CFL diagram

Knowing the values at two stress ratios ($R_1$ and $R_3$ respectively), the mean stress and stress amplitude corresponding to the same number of cycles (same fatigue damage state) for an intermediate ratio $R_2$ can be obtained by linear interpolation as illustrated in Figure 12.

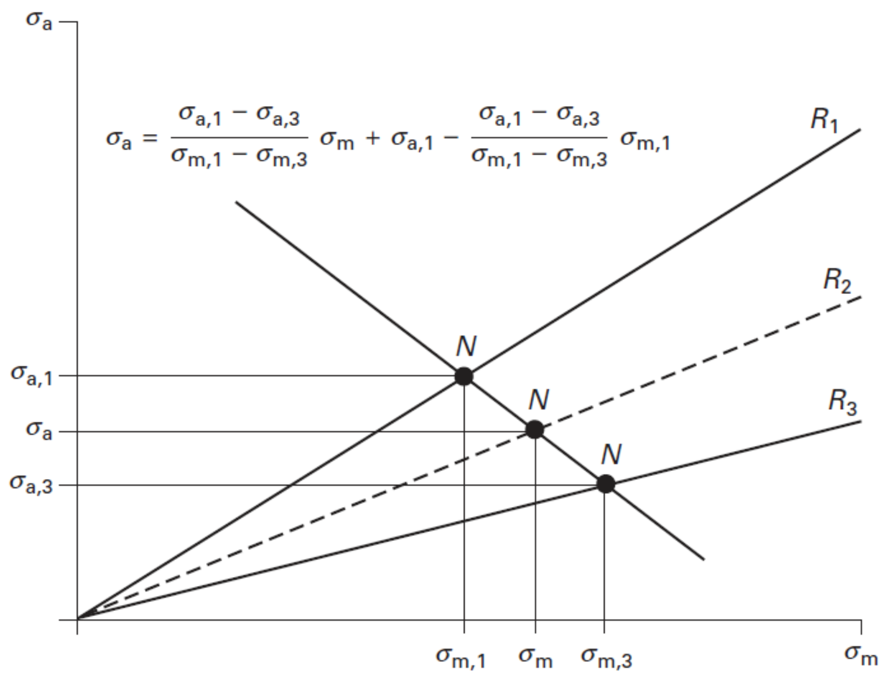


Figure 12 – Illustration of the linear interpolation method [34]

The stress amplitude ($\sigma_a$) for the intermediate ratio, can be derived as:

$$\sigma_a = \frac{\sigma_{a_1}(\rho_1 - \rho_3)}{(\rho_1 - \rho)\frac{\sigma_{a_1}}{\sigma_{a_3}} + (\rho - \rho_3)} \quad \text{Eq. 9}$$

Where $\rho_i$ is the alternate stress ratio, defined as the ratio of the stress amplitude to the mean stress.

$$\rho_i = \frac{1 + R_i}{1 - R_i} \quad \text{Eq. 10}$$

Based on the interpolated S-N curve, the number of allowable stress cycles is to be determined.

#### 7.3.3.3. Construction of the CFL diagram to be used for the methodology

For the fatigue methodology presented in this document, 3 CFLs diagram need to be constructed:

- CFL diagram for $\sigma_1$ stress
- CFL diagram for $\sigma_{eq}$ stress
- CFL diagram for $\tau_{12}$ stress

For the $\sigma_1$ and $\sigma_{eq}$ CFLs, it is necessary to have the breaking stresses from tension and compression static tests as well as the SN curves (especially $m$ coefficient values) for all tested $R$ ratio on respectively [0°] and [90°] samples.

Based on those values, the CFL diagram for $\tau_{12}$ stress is determined. First, it is important to note that for shear CFL the right and left part must be symmetrical as this is just the direction of the shear that is modified. In order to construct this CFL graph, the following values are considered:

- the shear strength (used both for positive and negative values)
- the m coefficients used for $\sigma_{eq}$ stress for any alternate stress ratio ρ in compression ($\rho < 0$)
- the symmetrical part is built by taking the m coefficients used for $\sigma_{eq}$ stress for any alternate stress ratio ρ in compression ($\rho < 0$) and applying it for the tension with an associated alternate stress ratio equal to $-\rho$

### 7.3.4. Damages calculation

The fatigue assessment of a structure is based on the cumulative damage principle. The Miner's sum is used to calculate the total damage ratios for each CFL diagram::

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

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

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

Where:

$N_i$ are the calculated allowable numbers of cycles for each type of stress cycles

$n_i$ are the referenced numbers of cycles for each type of stress cycles

### 7.3.5. Criterias for the fiber and the matrix

The fatigue factors $R_f$ and $R_m$ for fibre and matrix are then calculated considering that:

- The fibre ratio is only due to the $\sigma_1$ component of stress
- The matrix ratio is linked to the damage in shear and in the transverse direction ($\tau_{12}$ and $\sigma_2$)

It follows that:

$$R_f = D_{\sigma_1}^{\alpha_1}$$

$$R_m = \sqrt{D_{\sigma_{eq}}^{2\alpha_{eq}} + D_{\tau_{12}}^{2\alpha_{12}}}$$

With $\alpha_1$, $\alpha_{eq}$ and $\alpha_{12}$ respectively equal to $1/m_{min,\sigma_1}$, $1/m_{min,\sigma_{eq}}$ and $1/m_{min,\tau_{12}}$, where $m_{min,\sigma_1}$, $m_{min,\sigma_{eq}}$ and $m_{min,\tau_{12}}$ are the minimum slope values of respectively the CFL diagram for $\sigma_1$ stress, for $\sigma_{eq}$ stress and for $\tau_{12}$ stress

The fatigue factors are to comply with the following formulas:

$$R_f \leq \frac{1}{SF_f}$$
$$R_m \leq \frac{1}{SF_m}$$

The safety factor $SF_f$ and $SF_m$ are to be defined on a case-by-case basis.

### 7.3.6. Summary of the methodology

The procedure for evaluation of fatigue life is enumerated below. Figure 13 illustrates a graphical summary of the procedure.

1) For any given composite laminate, calculate the ply-by-ply stresses ($\sigma_1$, $\sigma_2$ and $\tau_{12}$) for the fatigue cycle using macromechanical laminate analysis tools, for example, ComposeIT [35] or a Finite Element Model.
2) Calculate the fibre and matrix stresses for each case.
   - $\sigma_f = \sigma_1$
   - $\sigma_{eq} = \sigma_2\sqrt{1 + \min\left(3, \left(\frac{f_2\tau_{12}}{\sigma_2}\right)^2\right)}$, where $f_2 = \begin{cases} \frac{\sigma_{brt2}}{\tau_{br12}} & \text{if } \sigma_2 \geq 0 \\ \frac{\sigma_{brc2}}{\tau_{br12}} & \text{if } \sigma_2 < 0 \end{cases}$
3) Fatigue of matrix:
   - Get the R ratio used in the cycle ($R = \frac{\sigma_{min}}{\sigma_{max}}$)
   - Get the number of cycles $N_i$ from S-N curves for the known ratios and interpolate the results for the actual ratio
   - Procedure is done both for $\sigma\_eq$ and $\tau_{12}$
4) Fatigue of fibres: the same procedure than for matrix is used based on fibre S-N curve
5) Determination of the damage for each CFL diagram separately using Palmgren-Miner rule:

$$D_{\sigma_1} = \sum_i \frac{n_{\sigma_1,i}}{N_{\sigma_1,i}}$$
$$D_{\sigma_{eq}} = \sum_i \frac{n_{\sigma_{eq},i}}{N_{\sigma_{eq},i}}$$
$$D_{\tau_{12}} = \sum_i \frac{n_{\tau_{12},i}}{N_{\tau_{12},i}}$$

6) Determination of the damage for the fibre and matrix

$$R_f = D_{\sigma_1}^{\alpha_1}$$
$$R_m = \sqrt{D_{\sigma_{eq}}^{2\alpha_{eq}} + D_{\tau_{12}}^{2\alpha_{12}}}$$

7) The following criteria is to be fulfilled:
   - $\max(R_m\, SF_m; R_f\, SF_f) \leq 1$

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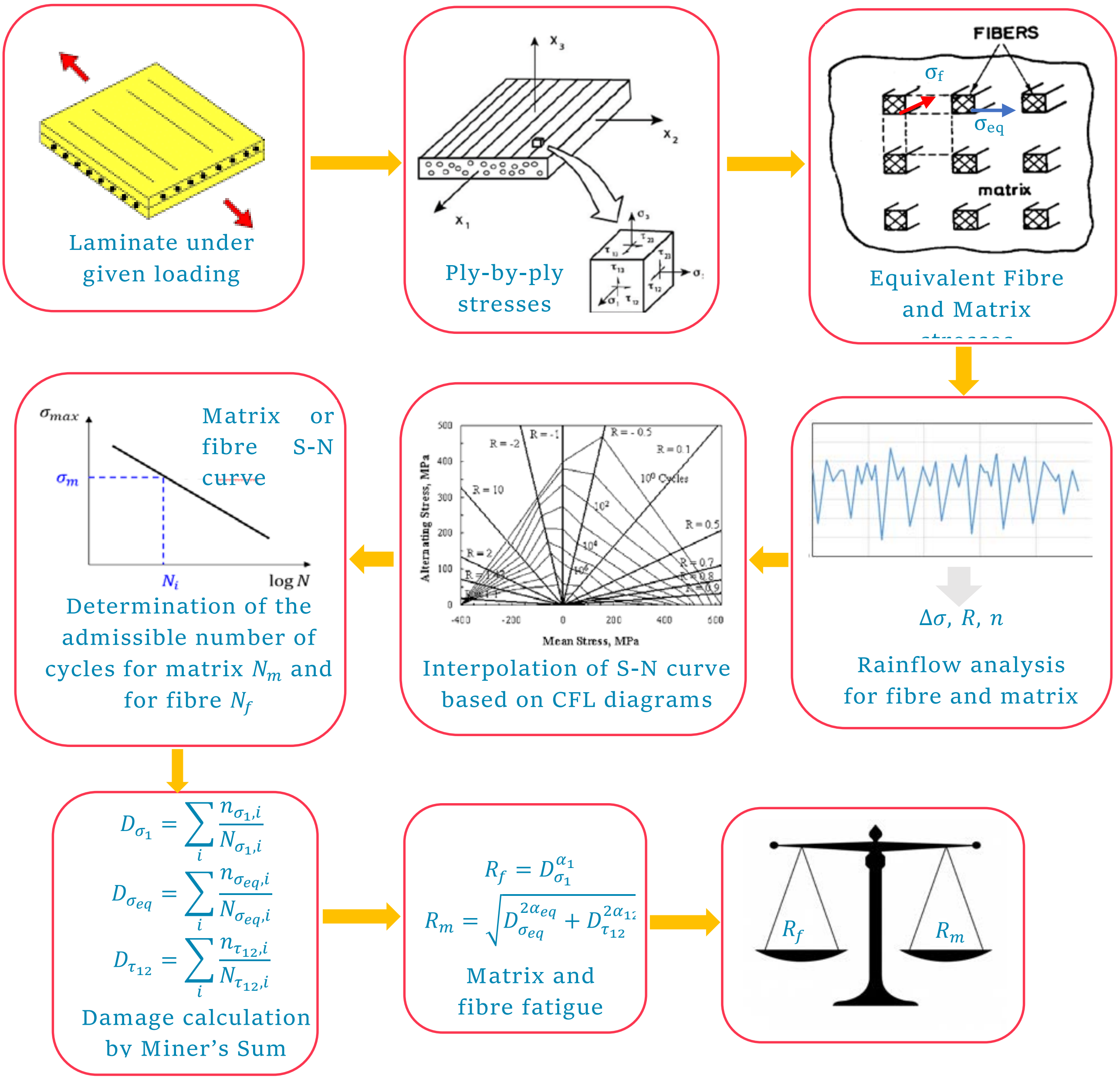


Figure 13 – Procedure for fatigue life evaluation using UD S-N curves

## 7.4. Modal analysis

In addition to the previous considerations, it also important to verify that no problem of resonance will occur during the lifetime of the platform. The first eigen mode of the global structure must be determined and compared to the range of frequency experienced on the platform. For example, it is important that the eigen frequencies of the tower of the wind turbine are not excited by the rotation frequency of the rotor (often called 1p) or the frequency of passage of the blades in front of the wind turbine tower (as generally 3 blades are used this implies that this is 3 times the frequency of the rotor (thus often called 3p)). The best approach to deal with those frequencies is to ensure that the first eigen frequency of the tower is superior to 1p and 3p. However, in some cases, it is not possible and the first eigen frequency of the tower is in between 1p and 3p. The calculation of the eigen frequencies is to be performed taking into account the flexibility of the floater as well as the fluid structure interaction with the floater, i.e. the water added mass of the floater that depends on the frequency and type of displacement.

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## 7.5. Joints and connections

Joints and connections between composites parts and other parts (either composite or metallic) are usually critical in the design of industrial applications. Stiffness changes can occur at these junctions leading to stress concentrations. Care should be given to the design of these parts.
For junction made by overlamination, shear transfer between the different part must be assessed (See [11] for more details for example). A sufficient overlap length must be used. A ratio between overlap length and thickness of more than 30 is generally considered or a 25mm length as shown in the following figure.

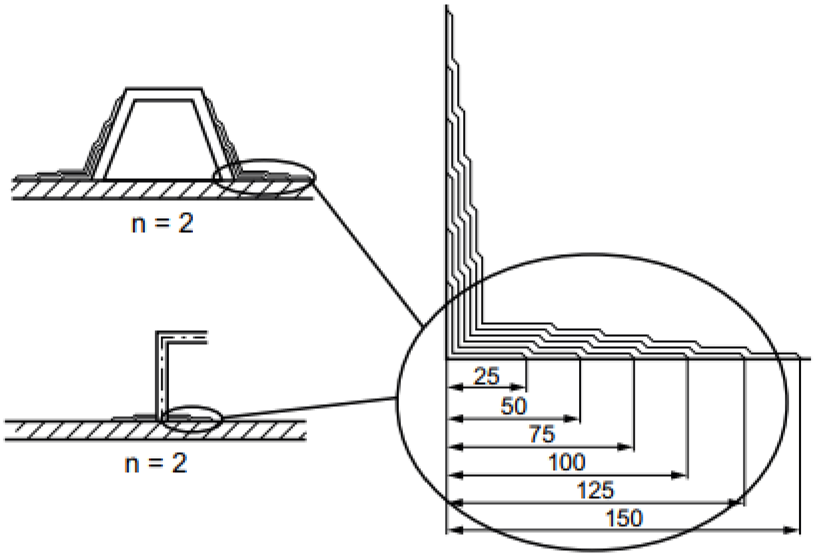


Figure 14 – Overlap of stiffener (extract from [11])

Bolting and bonding are further detailed in the following subsections.

### 7.5.1. Bolting

#### 7.5.1.1. Failure mechanisms

Bolting is a classical solution that can be used to connect composite parts especially with metal parts. It is simple and well-known technic. However, it induces stress concentration in the composite. It has to be considered that due to certain properties of the FRP materials, some specificities arise. Due to low out of plane compressive strength and interlaminar shear strength, tension induced by the tightening torque of the bolts must be limited. This induced the fact that unlike for steel the shear load transfer between part is not done by friction. The shear load is then transferred through bearing pressure. Due to orthotropicity of the material, several kinds of failure can occur such as:

- Net section failure
- Bearing failure
- Shear out failure
- Bolt shear failure

The first three mechanisms are presented in the Figure 15 with respectively the subscripts (a), (b) and (c). All these failure typologies must be considered in the design of the bolted connection.

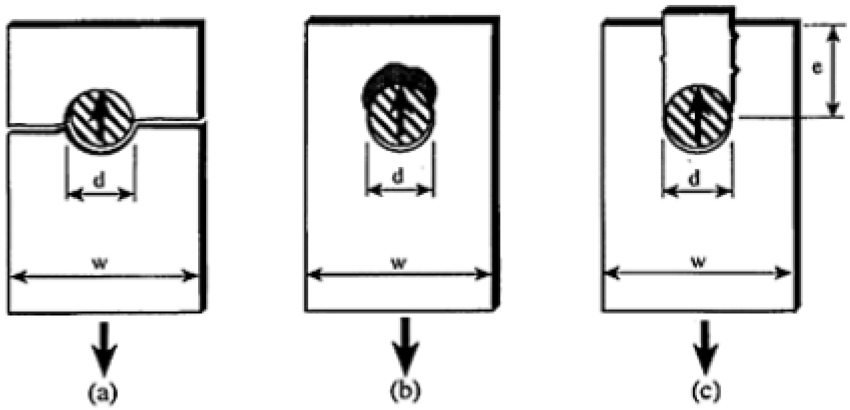


Figure 15 – Failure mechanisms (extract from [43])

### 7.5.1.2. Design aspects

In the design point of view, the designer must pay attention to the following points:

- Galvanic corrosion that can occur in this type of connection (See §5.6.3).
- Remove all sharp angles in metallic parts in contact with composites in order to avoid any damage of the composite.
- Use of large washers in order to spread the compressive stress is mandatory.
- Using a laminate with only UD plies oriented in the same direction would lead to a premature failure. Using a quasi iso laminate in the area surrounding the bolt is preferable. As a minimum, it is advised to distribute the direction of fibres using at least 12.5% of the plies in the laminate in the four directions (0°, 90° 45°, -45).

For more information on the design of the bolting of composite part, one can refer to Eurocomp Design Code [43].

### 7.5.1.3. Tightening of bolts

Bolts are to be tightened to a pre-set torque. Bolts are to be tightened as much as possible without damaging the composite part joined.

In order to achieve this goal, 2 criteria are to be verified:

- Interlaminar shear stress on the edges on the washer
- Out-of-plane compression under the washer

Interlaminar shear stress on the edges on the washer is to be under the interlaminar shear strength of the laminate times the safety factor:

$$\tau_{brIL}\, SF > \frac{F}{\pi\, t\, D_{e,w}}$$

Where:

- $F$ is the tension force in the bolt
- $D_{e,w}$ is the external diameter of the washer used
- $t$ is the thickness of the composite part to be bolted
- $\tau_{brIL}$ is the minimum interlaminar breaking strength of the plies used in the laminate
- $SF$ is the safety coefficient used in the analysis (See §8)

Compression stress under the washer surface is to be under the compressive strength of the laminate in the thickness direction times the safety factor.

$$\sigma_{brc3}\, SF > \frac{4F}{\pi\, D_{e,w}^2}$$

Where:

- $\sigma_{brc3}$ is the minimum out-of-plane compressive strength of the plies used in the laminate. As a default $\sigma_{brc3}$ can be taken equal to the transverse compressive strength $\sigma_{brc2}$ of a Unidirectional (UD) ply with the same resin and fibre used,
- $D_{i,w}$ is the internal diameter of the washer used.

The link between the tightening torque and the tension force in the bolt can be computed using the Kellerman and Klein Formula:

$$F = \frac{T}{(0.161\, p + 0.583\, \mu_t D_t + 0.5\, \mu_h D_h)}$$

Where:

- $T$ is the tightening torque of the bolt,
- $p$ is the thread pitch,
- $D_t$ is the diameter of the head contact (see following figure),
- $D_h$ is the diameter of the thread contact (see following figure),
- $\mu_t$ is friction coefficient in the threads,
- $\mu_h$ is friction coefficient under the head of the bolt,
- $\tau_{brIL}$ is the minimum interlaminar breaking strength of the plies used in the laminate,
- $SF$ is the safety coefficient used in the analysis (See §8).

The tool accuracy must be taken into account in the calculation of the Force induced by the tightening torque in order to consider the maximum force applied to the composite.

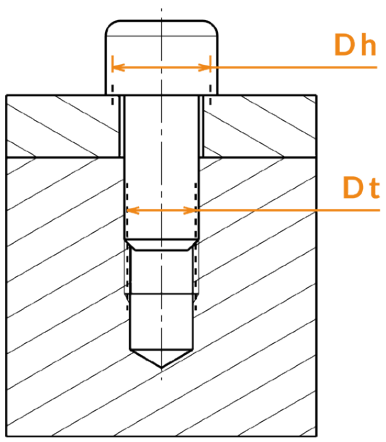


Figure 16 – Diameters used for the determination of the tightening torque

### 7.5.2. Bonding

Bonding is an interesting process for joining composites parts. Indeed, in comparison to bolting, it allows to avoid stress concentrations. However, the design of this type of joint must be made carefully considering a lot of different aspects:

- The bonded joints should be as much as possible transfer the loads from one part to the other by shear as the peel is usually critical for this type of joints (see Figure 17 for peel modes on bonded joints). The calculation of the bonded joints must take into account the fact that singularities appear at the edges of the bonded joints.
- Geometry of the joints and particularly to the edges (see Figure 18)
- Chemical compatibility between the adhesive and the substrates must be checked
- Protection of the joints from UV and water should be used or ageing due to these phenomena should be considered.
- Mechanical properties of the adhesive can change on the in-service temperature range. This must be taken into account for the design. Special attention must be paid to the Glass transition temperature (See also §5.6.2).
- Quality of the manufacturing of the joints:
    - Surface preparation of the substrates
    - Experience of bonders
    - Positioning
    - ...

For more information on the bonding of materials, one can refer to BV NI613 [5] for example.

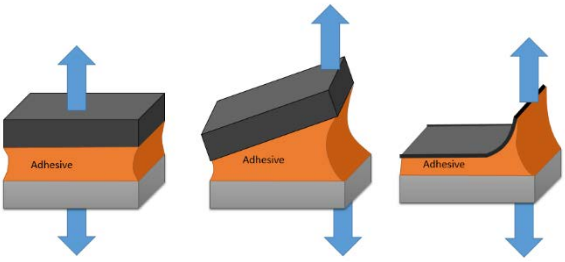


Figure 17 – Illustration of peel modes of loading range from uniform peel to various peel (cleavage) and finally local peel

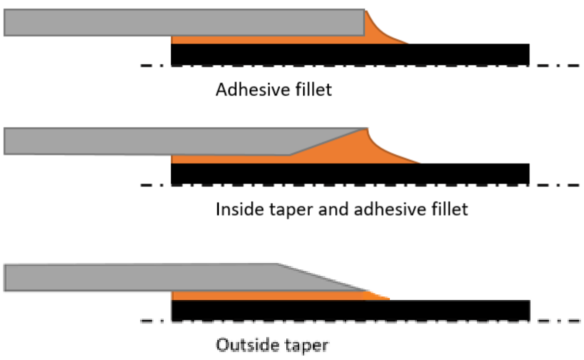


Figure 18 – Typical bonding edges

# 8. Safety factors

The safety factors that need to be considered for the design of the FOWT platforms in composite are given in the following. Two different approaches can be considered:

- LRFD (Load and Resistance Factor Design) that needs partial safety factors for both the materials resistance and the load. Increased loads and reduced strength are considered in this case to check the design
- WSD (working stress design) requires only one safety factor that covers all those uncertainties.

While LRFD offer the flexibility to split the different type of uncertainties, it should be noted that applying a LRFD methodology may not be possible for simultaneous loads processes, i.e. hydro-aero-servo-mooring loads for a FOWT floater.

The safety factors have to be used in conjunction with the chosen method and cannot be mixed. The safety factors given in here are derived from IEC 61400, BV NR546 and BV NI572.

## 8.1. LRFD

### 8.1.1. Loads

The safety factor $\gamma_f$ that must be considered for loads using the LRFD approach is given in the following tables

Table 7 – Load safety factor using LRFD method (values extracted from [1])

| 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 |

### 8.1.2. Material

The safety factor for composite materials (BV NR546) using a combined stress criterion is given by:

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

And for the maximum stress criterion:

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

Where:

- $C_{CS}$ is the partial safety factor for combined stresses in the individual layers of the laminates
  - 1.7 for unidirectional tape, bi-bias, three-unidirectional fabric
  - 2.1 for other type of layers

- $C_R$ is the partial safety factor taking into account the type of stress in the individual layers of the laminates:

| | | |
|---|---|---|
| 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 |

And the values for the core

| | | |
|---|---|---|
| Tensile or compressive stress | General case | 2.1 |
| Shear stress | General case | 2.5 |

- $C_V$ is the partial safety factor taking into account the ageing effect on the laminates:
  - 1.2 for monolithic laminates or face skin in or under the splash zone
  - 1.1 for monolithic laminates or face skin above the splash zone
  - 1.1 for sandwich core materials
- $C_F$ is the partial safety factor taking into account the fabrication process and the reproducibility of the fabrication, directly linked to the mechanical characteristics of the laminates
  - 1.1 for prepregs
  - 1.15 for infusion and vacuum
  - 1.25 for hand lay up
  - 1.0 for core materials
- $C_i$ is the partial safety factor taking into account the type of loads (sea pressure, dynamic sea pressure or internal pressure). As a default a value of 1.0 will be considered for FOWT design.

For the combined stress criterion, the minimum safety factor is to fulfil the following equation:

$$SF_{CS} < SF_{CSiapp}$$

where $SF_{CSiapp}$ is the margin of the Hoffman criteria:

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$$SF_{CSiapp}^2 . a + SF_{CSiapp} . b = 1$$

With

$$a = \frac{\sigma_1^2}{|\sigma_{brc1}\sigma_{brt1}|} + \frac{\sigma_2^2}{|\sigma_{brc2}\sigma_{brt2}|} - \frac{\sigma_1\sigma_2}{|\sigma_{brc1}\sigma_{brt1}|} + \frac{\tau_{12}^2}{\tau_{br12}^2}$$

$$b = \frac{\sigma_1(|\sigma_{brc1}| - |\sigma_{brt1}|)}{|\sigma_{brc1}\sigma_{brt1}|} + \frac{\sigma_2(|\sigma_{brc1}| - |\sigma_{brt1}|)}{|\sigma_{brc2}\sigma_{brt2}|}$$

The value of $SF_{CSiapp}$ is then calculated as follow:

$$SF_{CSiapp} = \frac{-b + \sqrt{b^2 + 4a}}{2a}$$

Also, the safety factor used for composite materials (BV NR546) is given by:

$$SF_B \geq C_{Buck}\, C_V\, C_F\, C_i$$

With $C_{Buck}$ the partial safety coefficient for laminate panel buckling taken equal to 1.45.

## 8.2. WSD

For WSD, using a combined stress criterion, safety factor is given by:

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

for the maximum stress criterion:

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

And for buckling as:

$$SF_B \geq C_{Buck} C_V\, C_F\, C_i\, C_l$$

With $C_l$ the partial safety factor based on the load case:

- 1.23 for Normal Load case
- 1.0 for Accidental load case
- 1.36 for Transport load case
- 1.0 for Fatigue load case

All other coefficients are as defined in the previous subsection.

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# 9. Stability

Intact stability is applicable to both manned and unmanned FOWT. However, damage stability is not required for unmanned FOWT in case there is no human life risk and that pollution and collision with neighbouring facilities are avoided.

In the following part the loads and prescription for stability in BV NI572 [1] is further detailed.

The load to be considered for the stability criteria are:

- Environmental conditions (wind, wave, ice, etc…)
- Operating loads on RNA
- Power cable and mooring lines as weights
- Failure of active ballast system

For the wind load, the force acting on the tower and substructure to be considered is determined by:

$$F_{wind} = \frac{1}{2}\rho_{air}\sum(C_S C_H \cos\theta\, V_{wind}^2)$$

With :

- $\rho_{air} = 1.222\ kg/m^3$ air specific mass
- $C_S$ the shape coefficient (given in Table 8)
- $C_H$ the height coefficient (given in Table 9)
- $S$ the projected area of the member considered
- $V_{wind}$ Wind speed at the considered elevation

This force is considered as a steady state load.

Table 8 – Shape coefficient (extracted from [1])

| Shape of the structural element | $C_S$ |
|---|---|
| Spherical | 0,40 |
| Cylindrical | 0,50 |
| Large flat surface | 1,00 |
| Exposed beams and girders under deck | 1,30 |
| Small part | 1,40 |
| Isolated shapes (crane, beam...) | 1,50 |
| Clustered deckhouses or similar structures | 1,10 |

Table 9 – Height coefficient (extracted from [1])

| Height above sea level of the structural member exposed to wind, in m | $C_H$ |
|---|---|
| 0 - 15,3 | 1,00 |
| 15,3 - 30,5 | 1,10 |
| 30,5 - 46,0 | 1,20 |
| 46,0 - 61,0 | 1,30 |
| 61,0 - 76,0 | 1,37 |
| 76,0 - 91,5 | 1,43 |
| 91,5 - 106,5 | 1,48 |
| 106,5 - 122,0 | 1,52 |
| 122,0 - 137,0 | 1,56 |
| 137,0 - 152,5 | 1,60 |
| 152,5 - 167,5 | 1,63 |
| 167,5 - 183,0 | 1,67 |
| 183,0 - 198,0 | 1,70 |

In the same way, the thrust force on the rotor is given by:

$$F_{wind} = \frac{1}{2}\rho_{air} C_T S_b V_{hub}^2$$

With:

- $C_T$: Thrust coefficient
- $S_b$: Swept area of the blades, in $m^2$

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- $V_{hub}$ : wind speed at hub height, in m/s

The stability calculations load cases are presented in Table 10. However, if tension of mooring lines or tendons provide stability of the structure, the restoring moment of those system is to be considered. Taking into account the damage of one mooring line is also necessary for stability assessment.

Table 10 – Stability load cases (extracted from [1])

| # | Loading condition | Description | Environmental conditions | | |
|---|---|---|---|---|---|
| | | | Wind | Current | Wave |
| 1 | Lightweight | Free floating | NA | NA | NA |
| 2 | Transit (3) | Free floating<br>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<br>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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# 10. Fire Safety

## 10.1. Introduction

For the fire safety, a particular attention is to be paid to elements made in FRP (Fire Reinforcement Plastic). Indeed, in case of fire or high temperature exposition, the mechanical properties of composite materials decrease significantly above 100°C, leading to a loss of load bearing capabilities of the structure. Moreover, composite materials are combustibles and generate toxic smokes that can compromise the safety of on-board personnel.

Fire safety is clearly regulated by the International Convention for the Safety of Life At Sea (SOLAS) [36] issued by the International Maritime Organisation (IMO) and required for passenger ships and cargo ships on international voyages. Requirements of this convention limit the use of composite materials even if a new guideline MSC.1/Circ.1574 [37] has been recently issued and allows the installation of FRP elements on-board of SOLAS vessels. However, the fire safety of floating offshore wind turbine (FOWT) made in composite materials can be addressed differently due to the absence of permanent personnel on-board. Indeed, personnel is only on-board of FOWT during the installation and maintenance phases with a low frequency of presence.

BV note NI572 [1] for the certification of FOWT does not have any requirements concerning fire safety. However, BV note NI682 [8] for the certification of fixed offshore substation and DNVGL-SE-0077 [31] can be used as basis for defining FOWT fire safety requirements as well as IEC TS 61400-30 [21].

## 10.2. Risk assessment

In case of composite construction, a risk assessment is required to demonstrate that the following safety objectives are achieved:

- Minimizing the risk of occurrence and escalation of a hazardous event,
- Allowing people on board during maintenance to leave safely the floating platform when a hazardous event happens.

The risk assessment is to be carried out using recognized risk analysis techniques and is to cover fire scenarios in all spaces where a fire cannot be excluded. FMEA/FMECA or HAZID type analysis can be used for this purpose. Guidance on those techniques can be found in ISO 31010 [22] or in NI 525 Appendix 1 [3]. For each scenario, the means of escape for persons located on or inside the FOWT is to be considered and it is to be shown that the escape routes will remain available long enough for those persons to escape.

The risk assessment is to take into account the active or passive fire protection measures provided all along the escape routes.

The process of a risk assessment involves the following steps:

- Identifying the hazard,
- Evaluating the risk,
- Introducing preventive and protective measures to reduce or eliminate the risk.

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### 10.2.1. Hazards identification

Hazards identification is to take into account the following:

- Operations to be performed by the FOWT,
- Tasks to be performed by the personnel,
- Mechanisms or functions of the FOWT,
- Materials used,
- Environment of the FOWT.

A list of significant hazards is given in Annex A of IEC TS 61400-30 [21].

### 10.2.2. Risk evaluation

Risk is to be evaluated for each identified hazard by determining:

a) the probability of occurrence of the hazard, taking into account:
   - accidental historical or statistical data,
   - how often persons are exposed to the hazard.

b) the consequence of the hazard occurrence, taking into account:
   - the severity of injuries or damage to health,
   - the number of affected persons,
   - the extent of the damage to the environment,
   - the cost of the damage to the asset.

Risk evaluation is to be carried out to determine if risk reduction is required. If risk reduction is required, then appropriate protective measures is to be selected and applied.

### 10.2.3. Risk reduction

The mitigation measures and provisions identified during the risk assessment are to be implemented accordingly in the design, construction, installation and testing of the FOWT.

## 10.3. Fire protections

### 10.3.1. Passive fire protection

a) Insulation

Fire insulation is to meet safety requirements of the International Code for Application of Fire Test Procedures (FTP) Code [38] or other standard deemed acceptable by the Society.

b) Fire retardant coating or resin

Fire retardant coatings and resins are to meet safety requirements of the International Code for Application of Fire Test Procedures (FTP) Code [38] or other standard deemed acceptable by the Society.

c) Other passive fire protections are to be justified to the Society.

### 10.3.2. Active fire protection

a) Fire detector

The selection of detectors is to comply with the requirement of Fire Safety Systems (FSS) code chapter 9 [39] which specify components of fire detection and alarm systems, requirements for their interconnection and installation and the performance, testing and servicing of parts or of complete systems.

Fire alarm systems, optical and acoustic, are to be installed in all hazard areas for FOWT on-board personnel:

- Working areas,
- Fixed fire extinguishing areas,
- Escape routes.

b) Fixe and Portable fire equipment

Fixed fire extinguishing systems and portable fire equipment are to be provided in line with the outcomes of the risk assessment. Some of these systems or equipment may not be needed if the result of the risk assessment is satisfactory. Firefighting systems are to meet safety requirement of the FSS Code [39] or other standard deemed acceptable by the Society.

c) Other active fire protections are to be justified to the Society.

## 10.4. Emergency, escape and evacuation

Evacuation and escape might be necessary in case of emergency. In case of fire, Available Safe Egress Time (ASET) shall exceed the Required Safe Egress Time (RSET). ASET is the amount of time from fire ignition to the development of untenable conditions; and RSET is the amount of time, measured from fire ignition that required for the last person to evacuate to a place of safety or place of temporally safety.
For the Required Safe Egress Time (RSET), the following shall be considered:

- $t_{detection}$: is the time between the beginning of the fire (usually the time zero of a time dependent design fire) until the fire detection. It depends on the fire detection elements and their location.
- $t_{alarm}$: is the time between the detection and alerting the exposed person, including searching and alerting colleagues in the danger zone.
- $t_{reaction}$: is the time from the triggering alert until the beginning of the preparation, the time that a person needs to realize what is happening and what to do.
- $t_{preparation}$: is the time from get dressed in personal protective equipment and prepare any equipment necessary to escape/evacuate. The time shall be measured through physical demonstration.
- $t_{evacuation/escape}$: is the time between the first person begins to evacuate/escape and until the last person reaches the place of safety or temporarily safety. The time shall be measured through physical demonstration.

The FOWT shall have at least two exits independent to each other. The evacuation and escape routes shall be free of obstacles. Lighting of the evacuation and escape routes shall be designed in accordance with IEC61400 [21].

The efficiency of the evacuation and escape strategy shall be verified by means of testing to verify that personnel are able to exit the FOWT from any location at which they might be working within the estimated times using the prescribed route for each scenario.

Permanent means of access are to be provided for each enclosed space and are to comply with ISO 14122 [25] series or with other standards deemed acceptable by the Society. National requirements are to be considered in the design.

# 11. Inspection, Life Cycle considerations

According to the standards [1][4] and [44] to [48], the maintenance and inspection test plan for Offshore Wind and Tidal Platforms (OWTP) should address at least the following concepts:

- a meteorological station shall record at least the following parameters to evaluate the structural condition of the platform:
    - wind speed,
    - wind direction,
    - precipitation,
    - temperature,
    - humidity,
    - salinity,
    - waves,
    - current
- Parameters such as operational, and structural conditions should be considered in the inspection and maintenance plan. The parameters of interest for operational conditions are usually referred to as rotational speed, pitch angle, power, while the parameters for the structural conditions are strain, stress, acceleration, gyros, and so on.
- The main structural components, drive train, generator, electrical installations, protection systems, among others components of the OWTP shall be inspected. It should be pointed out that splash zone and submerged zones of Floating Offshore Wind and Tidal Turbines shall be inspected as part of a maintenance plan. A programme for inspection and monitoring of wind and tidal farms shall be defined and implemented by the maintenance team taking into account:
    - Tests of the inspection;
    - Sampling Rate for data acquisition;
    - The periodicity of inspections might be annually, monthly, or daily depending on the case-scenario. As a general rule, the time interval for inspections of critical items should not exceed one year while, the inspection of less critical items might be executed at longer time intervals.
    - Qualification of the personnel for installation and follow-up of the inspections.
- The above-mentioned program shall be reviewed annually by the Classification Society involved in the maintenance activities.
- The periodic inspections can be carried out at three different levels:
    1. Visual inspection: Traditional visual inspections shall be carried out by specialized technicians, while underwater inspections might be executed by either remotely operated vehicles (ROV) or divers capable to perform inspection and maintenance activities in submerged areas. Cleaning of the surface may be necessary prior to the inspection.
    2. Non-destructive and destructive tests: The list of non-destructive tests that shall be executed for the inspection and maintenance of OWTPs is related to fatigue, deformations, bolt tension, corrosion, marine growth, grouted connections, cracks, and scour failures, among others.
    3. Condition-based monitoring (CBM). The main function a CBM system is to carry out continuous monitoring activities for detection and quantification of damage in structural components. In

particular, the technique analyses the data provided by an array of sensors to monitor the condition of components such as bearings, gearbox, and generator in real time.

- Particular attention must be paid to the corrosion protection of structural components such as foundation, mooring systems, support structure, nacelle, among others. The methods frequently used for corrosion protection are cathodic protection, corrosion protective coatings, and corrosion resistant materials.

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# 12. APPENDIXES

## 12.1. Thermoplastic resin

### 12.1.1. Introduction

The number of thermoplastic matrix polymer is increasing and two main families of materials can be distinguished: (1) the low-cost thermoplastic polymers which include Polypropylene (PP), Polyethylene (PE), and the family of Polyamides (PA 6, PA 6.6, PA 11, PA 12) and other high-performance polymers such as PEEK, PolyEtherKetoneKetone (PEKK), Poly-phenylene Sulfide (PPS), Polyetherimide, and Polycarbonates (PC). Also, a new thermoplastic acrylic resin called Elium® has been added to the market recently and was developed by Arkema. Contrary to other thermoplastic matrix, this resin has the main advantage to be infusible in a similar way to thermoset composite parts. It is also worth citing the Anionic Polyamide 6 (A-PA6) resin and the CBT (butylene terephthalate) from Cyclics™ that can also be infused.

The main advantages and drawbacks of thermoset and thermoplastics composites are reminded in the Table 11.

Table 11 – Thermoset composite vs thermoplastic composite [60]

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

### 12.1.2. Examples of industrial & research applications

Several examples of industrial & research applications using thermoplastic resins are presented in this section.

#### 12.1.2.1. Sailing boats

Several sailing boats have been produced with thermoplastics resin in the past 5 years:

- ECO Yachts designed and built a sailing boat of 12m length, EcoRacer30, with Elium® resin.
- Lalou Multi manufactured 3 boats with thermoplastic resin (see Figure 19):
  - Monohull Mini 6.5 in 2017 (A)
  - Ocean Fifty Kraken, trimaran 50’ in 2020 (B)
  - Class 40 Yemenja in 2022 (C)
- Beneteau First 44E (14.65m) is the first mass-produced sailboat built with Elium® thermoplastic resin.
- Sun Fast 30 One Design (10.4m) designed by VPLP and produced by Jeanneau is a sailboat using Elium® thermoplastic resin.

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Figure 19 – Lalou Multi boats manufactured using thermoplastic resin

### 12.1.2.2. ZEBRA (Zero wastE Blade ReseArch) project

ZEBRA project, led by IRT Jules Verne (French Technical Research Institute), aims to demonstrate the technical, economic and environmental relevance of thermoplastic wind turbine blades on a full-scale, with an eco-design approach to facilitate recycling.

A blade, measuring 77m in length, was made by LM Wind Power's blade plant using Arkema's thermoplastic liquid resin Elium® and high-performance glass fabrics from Owens Corning, Figure 20.

Figure 20 – LM Wind Power blade [64]

### 12.1.2.3. NREL thermoplastic blade

NREL produced 2 wind turbine blades using thermoplastic resin Elium®, 9m and 13m in length. Largest one has been tested in static and in fatigue given similar or better results than blade produced with epoxy resin, see Figure 21.

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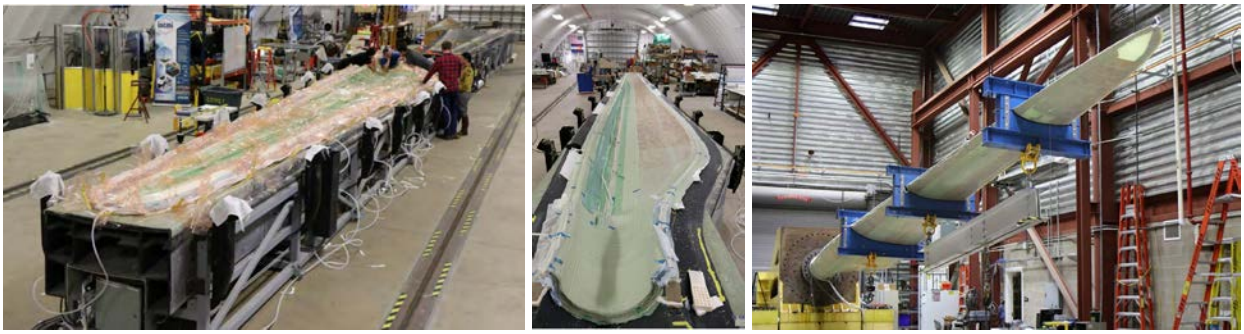

Figure 21 – Manufacturing, static and fatigue testing of 13m length blade [65] [66]

The NREL project found that the process and material demonstrated potential for:

- Recyclability: The Elium® thermoplastic blades exhibit the potential to be recycled, reducing both landfill waste and disposal costs.
- Thermal welding: Materials can be thermally joined, enabling the manufacture of potentially stronger and lighter blades.
- On-site manufacturing: Blades can be built on-site, allowing for the development of larger blades at greatly reduced transportation costs.
- Ease of repair: Unlike epoxy blades that necessitate traditional grinding repairs, thermoplastics can be reheated at just the point of repair and reshaped.
- Marine energy applications: Thermoplastic material performs better than traditional materials in seawater, making this material a game changer for marine energy applications.
- Reducing the equipment capital costs associated with blade production by up to 30%
- Decreasing the critical cycle time during production by up to 20%.

### 12.1.3. Comparison between Elium® and Infugreen resin

In the WP2 of static and fatigue tests have been performed by ULIM using Elium® and Infugreen resins. The results obtained are given in D2.2 [61]. In this appendix is presented the work of comparison of those results with other fatigue results obtained for Glass fibre composites. Two kinds of comparison are made:

- Static values
- Fatigue values

#### 12.1.3.1. Static values

In the tests performed and presented in D2.2, some static tests have been performed. The value obtained for the different configurations (Elium/Infugreen, 0°, 90°, ±45°, ±30°, quasi-iso), are compared to results obtained by theoretical calculations using ComposeIT and Glass-Epoxy composite hypothesis.

Two different calculations have been performed. The first one corresponds to the average stress at which first ply failure occurs. In the second calculation, if a ply fails in shear or due to transverse stress the shear and transverse stiffness of those plies are divided by 2 in order to get an idea of how the stresses are redistributed between the plies taking into account the non-linearities of the material for those stresses. Until this point no failure of the ply is considered. In a second step, if the redistribution of stress does not lead to a complete failure of the laminate, the plies that fails in shear or due to transverse stress the shear and transverse stiffness of those plies are divided by 10 and are considered as failed. This is done iteratively by changing the stiffness of each ply using user-defined materials of ComposeIT. It enables to compute two failure stresses. The results obtained are presented in the table below. It should be noted that for each laminate the same volume fibre content as in the experiment is used.

Table 12 – Failure stress for each laminate configuration from tests and theoretical results for glass-epoxy equivalent

| | Lay-up | Fibre Volume fraction ($V_f$) | Failure stress static | Theoretical failure stress Glass-epoxy First ply failure | difference with tests | Theoretical failure stress Glass-epoxy last ply failure | difference with tests |
|---|---|---|---|---|---|---|---|
| Glass/Elium | $[90]_{9S}$ | 55.85% | 41.85 | 50.57 | -17% | 50.57 | -17% |
| | $[\pm45]_{2S}$ | 60.91% | 108 | 132 | -18% | 150 | -28% |
| | Quasi-Isotropic $[0°/+45°/90°/-45°]_S$ | 47.11% | 313 | 96 | 226% | 365 | -14% |
| | $[\pm30°]_{8S}$ | 52.36% | 346 | 284 | 22% | 352 | -2% |
| | $[0]_{6S}$ | 46.06 % * | 939 | 954 | -2% | 954 | -2% |
| Glass/Infugreen | $[90]_{9S}$ | 52.47% | 50 | 45.45 | 10% | 45.45 | 10% |
| | $[\pm45]_{2S}$ | 57.99% | 84 | 123 | -32% | 139 | -40% |
| | Quasi-Isotropic $[0°/+45°/90°/-45°]_S$ | 55.60% | 341 | 113 | 202% | 429 | -21% |
| | $[\pm30°]_{8S}$ | 49.69% | 335 | 252 | 33% | 310 | 8% |
| | $[0]_{6S}$ | 44.34 % * | 978 | 921 | 6% | 921 | 6% |

From results obtained in Table 12, it appears that with the theoretical results, it is important to consider the redistribution of stress to obtain more realistic values for the final failure. There is still a big difference obtained for test performed at ±45° that may be due to the presence of edge effect in the test because of the limited width of the sample. Anyway, when considering the Elium resin, it seems to give results with a slightly smaller strength than for Epoxy resin with a magnitude of approximately 5 to 15%. On the contrary, Infugreen resin seems to give results that are a bit better (nearly 5 to 10%) than for the glass epoxy case. It should be noted that the values considered in ComposeIT/BV NR546 are considered conservative. Thus, Infugreen resin can be considered to have similar properties to classical Epoxy resin in terms of static mechanical characteristics.

#### 12.1.3.2. Fatigue values

Results obtained in D2.2 have been fitted using a power law formulation (Basquin's Model: see §7.3.2.2) and a logarithm model:

$$\sigma_i = \beta - \alpha \log N$$

Where $\sigma_i$ is the ratio of stress given in §7.3.2.2, $\alpha$ is the material parameter that defines the slope of the SN-curve, $\beta$ is the parameter giving the initial ratio for N=1 and $N$ is the number of cycles. The $\beta$ coefficient is considered equal to 1 when using this type of model These two types of models are the simplest ones that are used when considering SN-curves for composite materials. The fit performed were done using a least square difference criterion. For the two kind of models, two types of fit have been made. For the first case, the curve is fitted by modifying the coefficients $\alpha$ and $\beta$ (slope + initial value) for the logarithm model. For the second case, $\beta$ is considered equal to one. The same kind of approach is considered for the power law formulation. On the following figure is presented the results obtained with the two methods.

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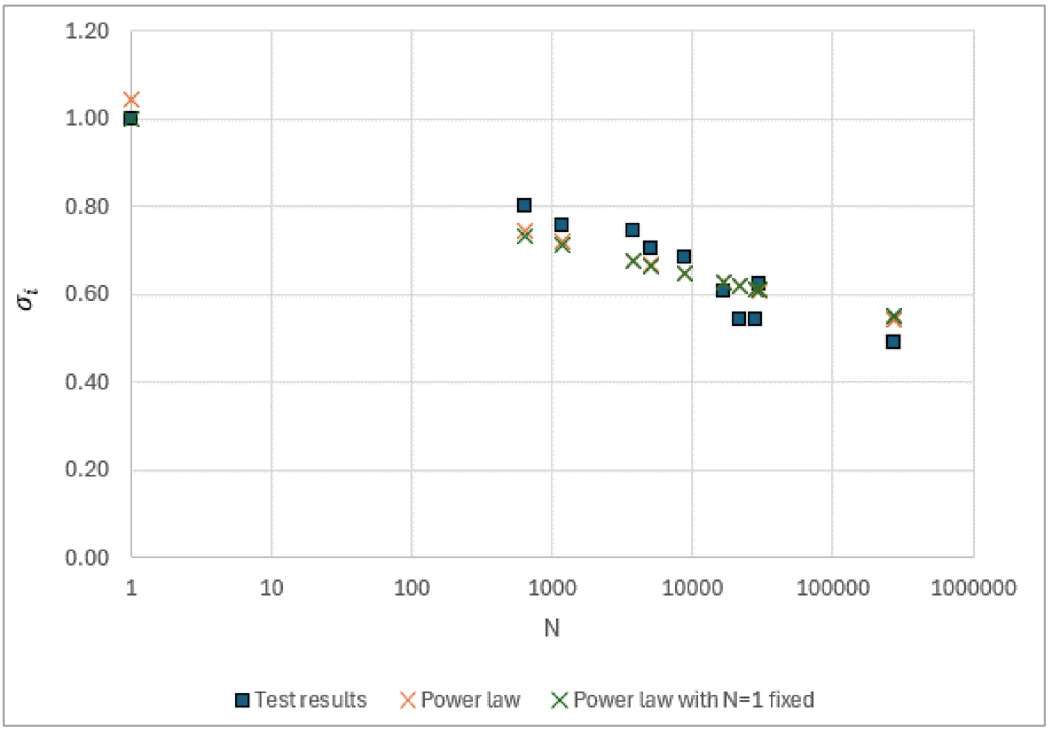


Figure 22 – Test results obtained for Glass-Elium composite oriented at 90°and the fitted results

In the Figure 23, the slope coefficients obtained for both formulations are presented and compared to the slope coefficients that are in the BV NI603 for the logarithmic formulation and in the §7.3.2.3 for the power law. For the power law formulation, the higher the coefficient the less the slope of the SN curve whereas for the logarithmic formulation the higher the coefficient the higher the slope of the SN curve. The smaller the slope of the S N curve, the better is the material fatigue behaviour. For Elium and Infugreen, the obtained slopes are smaller or equal to the one prescribed. Hence, those resins seem to react in a similar way than the epoxy.  From the curves it can be also pointed out that the slopes are generally smaller in the fibre direction than in the transverse direction. Considering the cases 0°, 90°, ±45° and ±30° it proves that for those material the more critical aspect that drive the slope of the SN curve is the in-plane shear stress. It should be noted however that for the ±30°, that shows the higher ratio of use between shear and transverse stress, a fatigue limit appears around $10^5$ cycles. However, this phenomenon is not captured by the two formulations used in this study.

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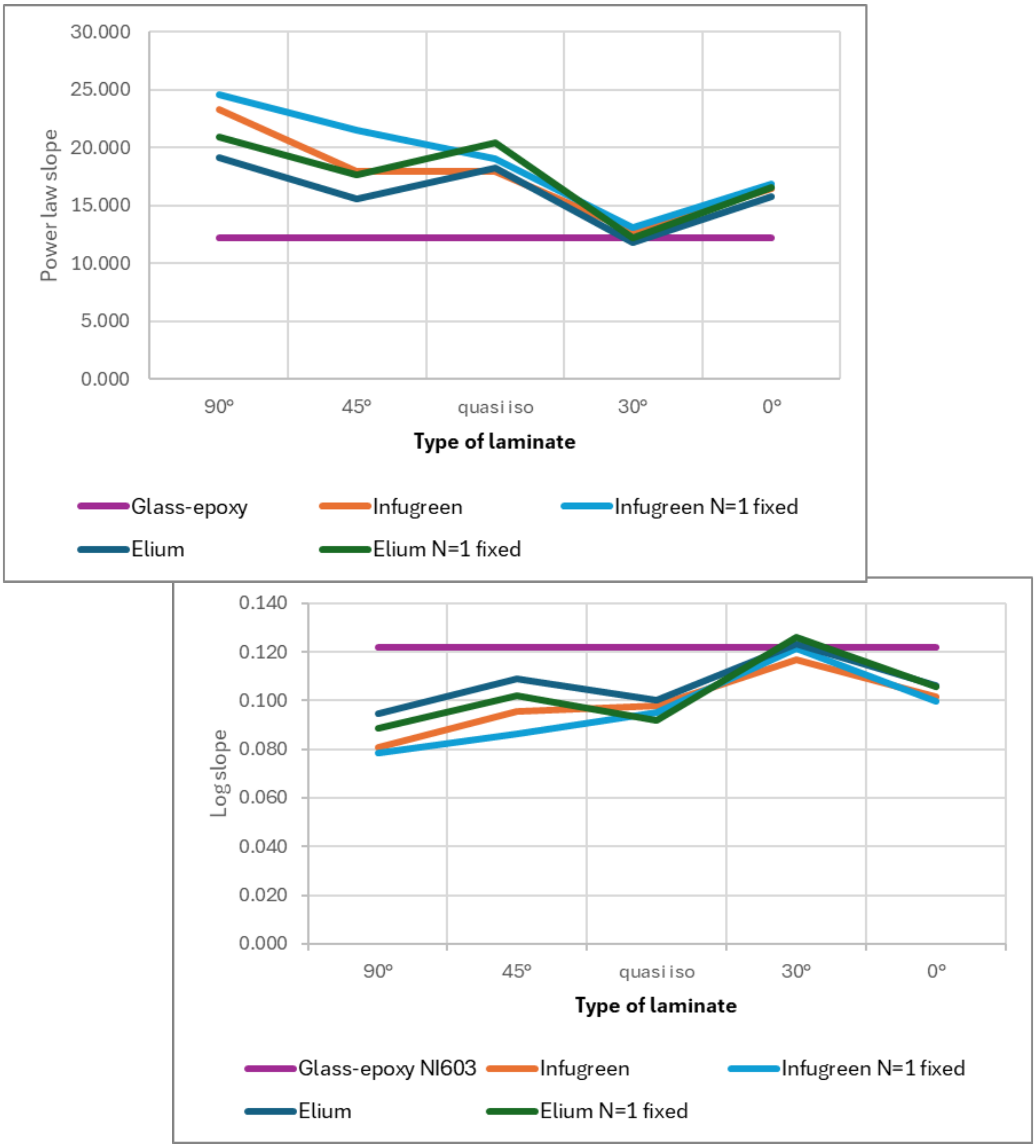


Figure 23 – Slope coefficients obtained for the power law (top) and logarithmic (down) formulations.

### 12.1.4. Recyclability

The main advantage of thermoplastic resin is their recyclability. Figure 24 shows the life cycle of Elium® thermoplastic resin from the formulation up to the end of life. Two types of recycling are possible: Chemical or mechanical.

Chemical recycling consists of separating the resin and the fibre reinforcement. The properties of Elium® and thermoplastic allow resins to be de-polymerized using a thermolysis process. once separated, the original monomer of the resin can be reused to create a new resin in a closed-loop recycling process. Mechanical recycling consists of grinding, heating and blending the composite laminate and to transform the obtained material for deposition, extrusion or compression processes.

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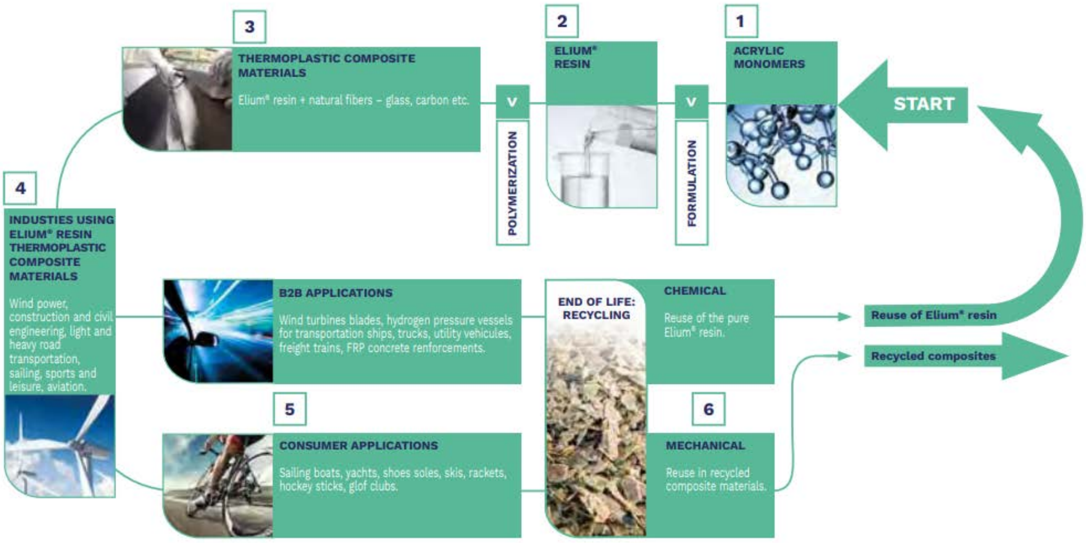


Figure 24 – Life cycle of Elium® thermoplastic resin

### 12.1.5. Conclusion

Thermoplastic resin such Elium® offers certain advantages particularly for recycling, by facilitating fibre/resin separation. Mechanical resistance in static and in fatigue seems close to epoxy resin but the durability in marine environment remains to be demonstrated. Additionally, manufacturing capability was not investigated in this study. Even if some applications have already been carried out, production at industrial scale is to be validated.

## 12.2. Methodology of design review for FOWT tower in fatigue

In the context of the WP4 of Fibregy, the design assessment of the tower used for the W2 Power platform has been performed. The methodology and the tools used are briefly presented in this appendix. For more details, on this work, the reader can refer to the master thesis of Pharindra Pathak and Abdulelah Al Ghuwaidi [57] and [58].

### 12.2.1. Presentation of the methodology

#### 12.2.1.1. Global overview

The methodology and its alternative are presented as flowcharts in the following figures. The procedure used is based on the following steps:

1 Computation of the hydrodynamic response of the floater using HYDROSTAR software
2 Computation of the global structural response of the floater by performing Hydro-aero-mooring coupled dynamic calculation using OPERA software
3 Characteristics of composite parts are determined using ComposeIT
4 Computation of stress in composite parts using Finite element software FEMAP or analytical formulas.
5 Determination of the fatigue life using the fatigue methodology presented in §7.3.

The software used are presented in the following part.

#### 12.2.1.2. Software used

In HydroStar, wave-body interactions in three dimensions using 3D diffraction/radiation potential theory can be explored. It incorporates multi-body interactions, forwarding speed effects, and fluid motion dynamics in tanks. All structures, whether in deep or finite depth waters, will be evaluated for wave loads, motions, accelerations, relative motions, and wave elevation in the first and second order.

OPERA is a digital and independent tool built by BV teams that support design verification and certification of floating units. It is a static and dynamic solver which uses the knowledge of multi-physics: hydrodynamic, aerodynamic, and mooring, along with hydrodynamic couplings. It offers a fully integrated modelling solution that includes all floating wind turbine components, from defining mooring system to turbine blades.

ComposeIT is a software tool developed by BUREAU VERITAS that allows the detailed strength analysis of composite panels and stiffeners. With ComposeIT, individual layers, combined layers, laminates, plates, stiffeners (standard or custom shapes), and loads on these structural elements can be defined.

FEMAP (Finite Element Modelling And Postprocessing) is an engineering analysis program that creates finite element models for complex engineering problems ("preprocessing") and displays the results ("post processing"). The Finite element method is used to determine the behaviour of components, assemblies, or systems under a set of boundary conditions. As part of the design process, it is typically used to reduce the cost of prototyping and testing, evaluate different designs and materials, and optimize the structural design. The calculations are performed using the solver NASTRAN.(Siemens Digital Industries Software).

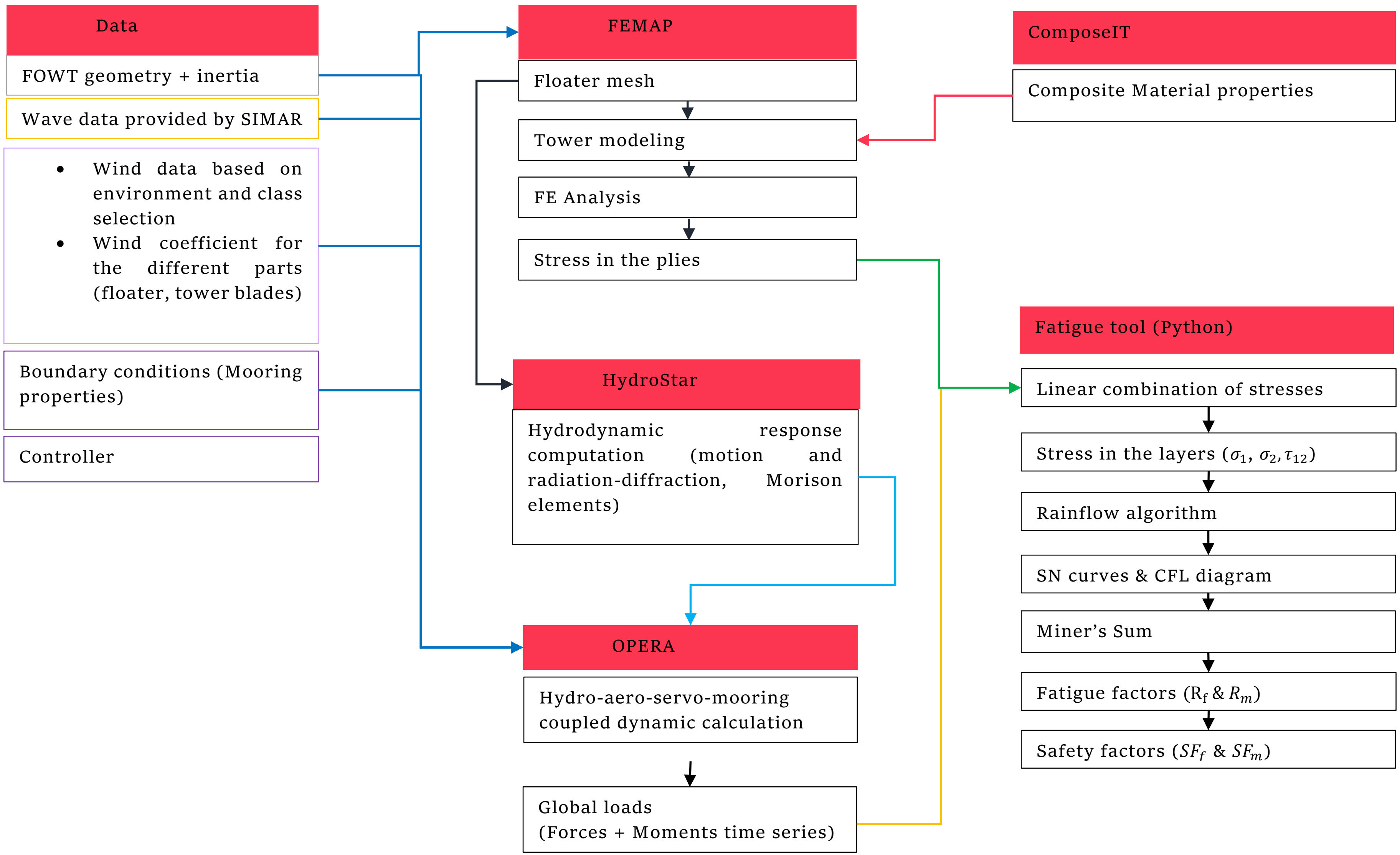


Figure 25 – Methodology of design review for FOWT tower

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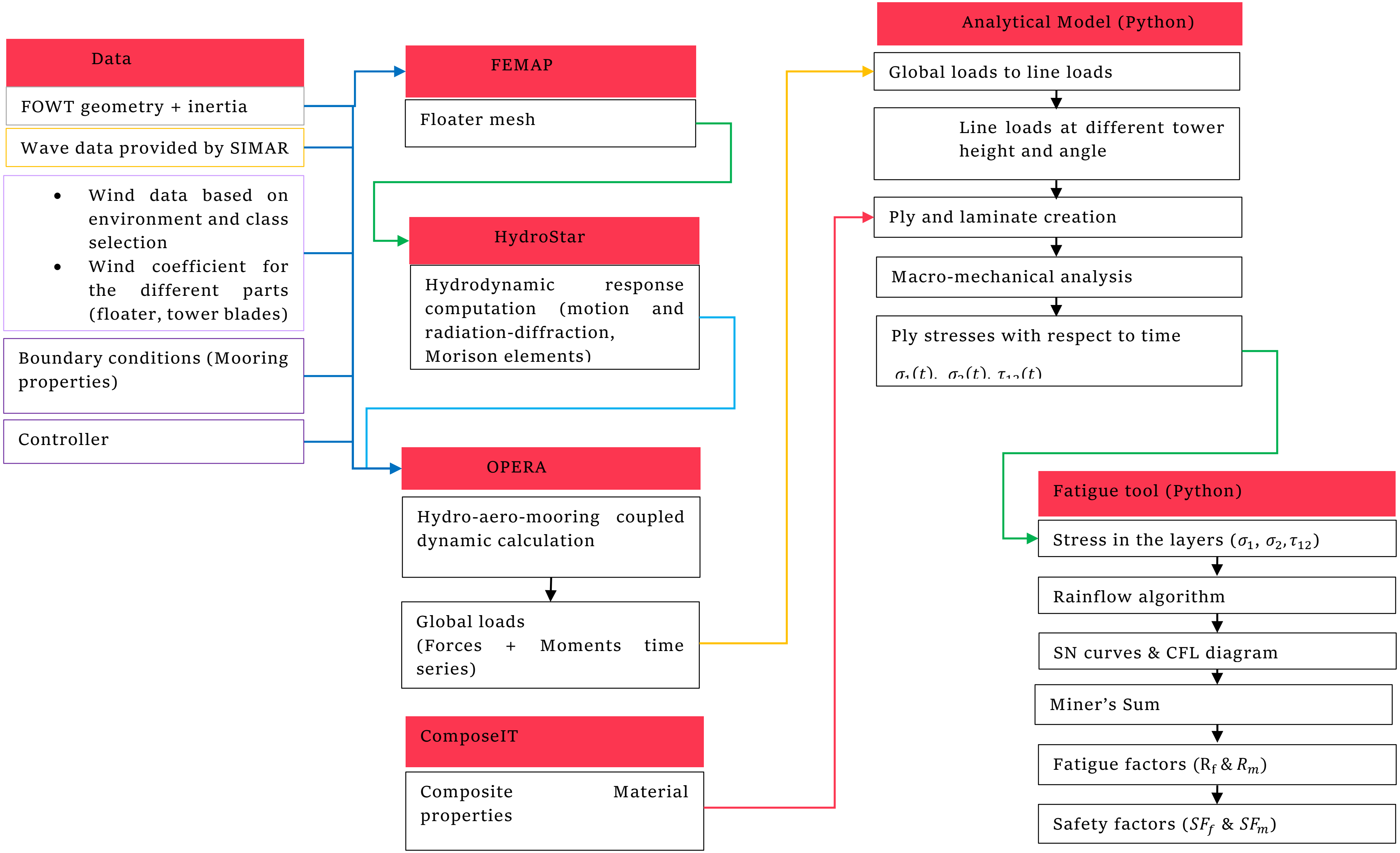


Figure 26 – Alternative Methodology of design review for FOWT tower

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### 12.2.2. Steps description

The different steps of the methodology are presented in the following subsections.

#### 12.2.2.1. Data

The data needed to perform the calculation are:

- FOWT geometry and its associated material and masses
- Material characteristics (see §12.2.2.5 for composite material properties)
- Loads conditions:
  - Loads Cases
  - Wind:
    - Data based on environment and class selection (wind speed for the different conditions…)
    - Lift and Drag coefficient for the different parts (floater, tower blades)
  - Waves: data provided by simar (Spectrum with period and wave height, heading…)
  - Current
- Boundary conditions:
  - Mooring properties (type and length of lines, footprint…)
  - Seabed topology
- Controller that will change actively the behaviour depending on the environmental conditions.

#### 12.2.2.2. Hydrodynamic response calculation using Hydrostar

To evaluate the hydrodynamic response of the platform, HydroStar software is used. It calculates loads and motions of ships and floating units using diffraction and radiation first order problem and the Quadratic Transfer Function (QTF) second order low frequency wave loads.

Figure 27 shows the flowchart of the steps followed in HydroStar to compute the loads and motions of the FOWT.

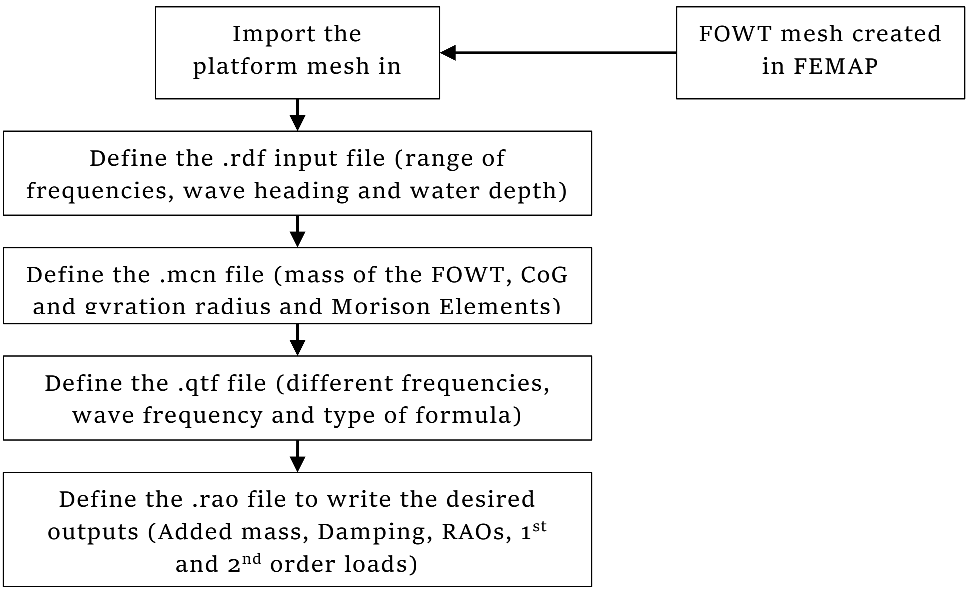


Figure 27 – Hydrostar flowchart

Offshore structures like FOWT platforms are made of thin structures that connects large structures. These thin structures have low response under diffraction-radiation loads in case of thin structures with respect to the wavelength, Morison equation is used instead of radiation-diffraction approach. To accurately model the platform, the braces are removed and for the motions input file in HydroStar they are added as Morison elements.

Radiation and diffraction module computes the radiation and diffraction components in terms of added mass, and the first order wave loads. The output file from this module is an input to mechanical module.

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The mechanical module computes the FOWT's platform motions. In the mechanical input file, we need to define the FOWT's mass, Centre of Gravity (CoG), radius of gyrations and Morison elements.

The second order potential is solved using the full QTF calculation. HydroStar gives the option of choosing the formulation either near field or middle field. First order waves and motions need to be evaluated for the near field formulation.

After performing the simulations, the transfer functions module in HydroStar is used to construct some outputs including Response Amplitude Operators (RAOs), added mass, damping matrices and wave diffraction loads (1st order loads), drift loads and QTFs low and high frequency.

The output from HydroStar will be used as inputs for the global response of the FOWT in OPERA software.

#### 12.2.2.3. Hydro-aero-mooring coupled dynamics using OPERA

To assess the global response of the FOWT under environmental loads (i.e. wind, waves, current), BV software OPERA is used. IN OPERA the different parts and associated data need to be defined:

- Site
  - Water depth (a uniform seabed has been considered)
  - Seabed anchor positions
- Floater
  - Initial position of the floater
  - Position of the fairleads
  - CoG, mass and inertia matrix
  - Hydrodynamic characteristics from Hydrostar (added mass, radiation damping, hydrostatics, 1$^{st}$ order motions and loads, 2$^{nd}$ order load.
  - Area and drag coefficient for wind
  - Morison elements in the same way than for Hydrostar
  - Heave plates elements
- Mooring line
  - Length
  - Diameter
  - Mechanical properties in air and fluid
- Turbine
  - Position and inclination of the tower
  - Tower length, linear mass and stiffnesses (bending shear, axial and torsion)
  - Blade characteristics (in the case of this analysis only the mass of the blade was considered)
  - Mass of nacelle and Cog
- Environment
  - Wind pressure and load on the hub was considered in the case of this specific study (See Figure 28)
  - Waves: A JONSWAP spectrum was used in the study (See Figure 29)
  - Current: Current has not been considered in this study

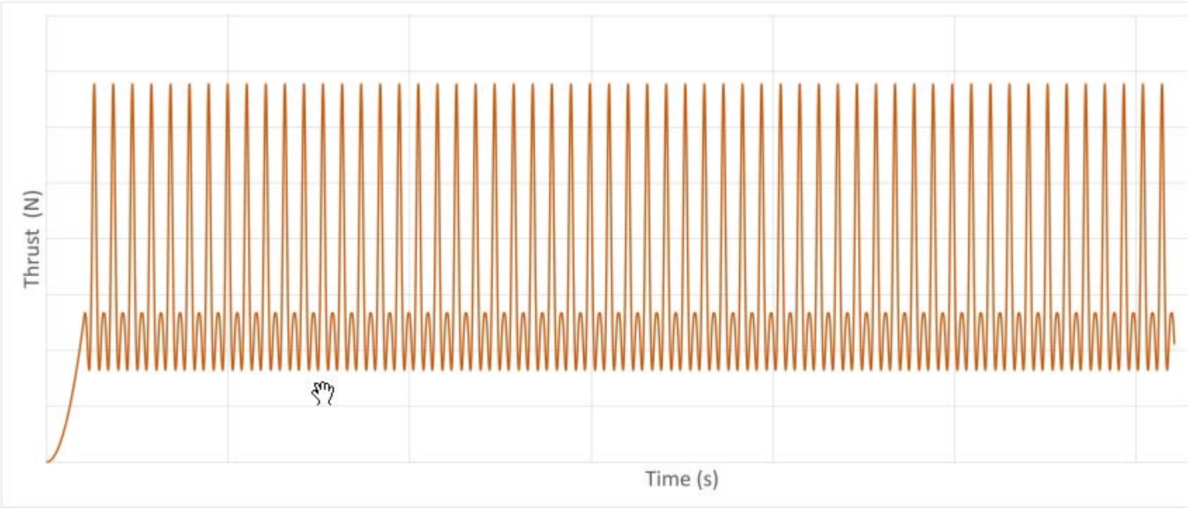


Figure 28 – Wind thrust

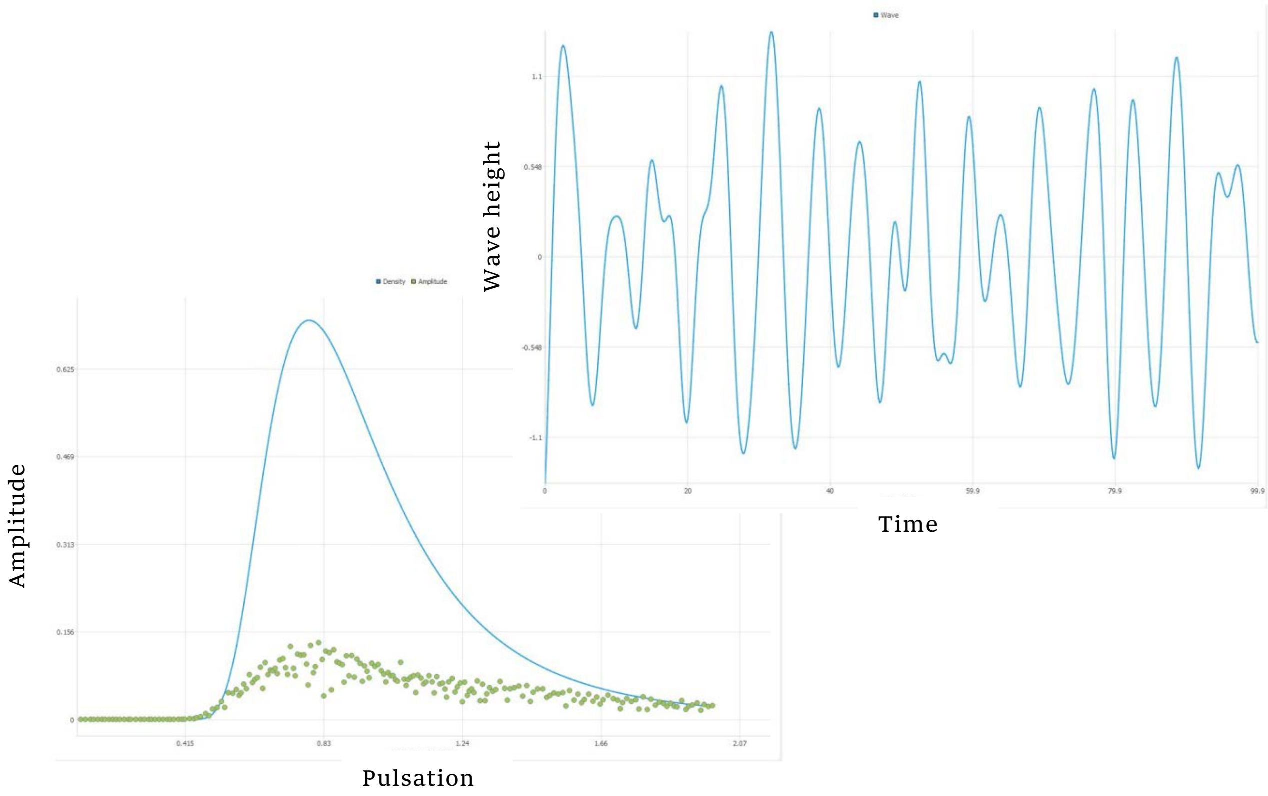


Figure 29 – JONSWAP spectrum (left) and associated time series (Right)

The platform obtained in the OPERA software is presented in Figure 30. Calculation in Opera permits to obtain the displacement over time of the platform and the global loads and moments at several height in the tower (See Figure 31).

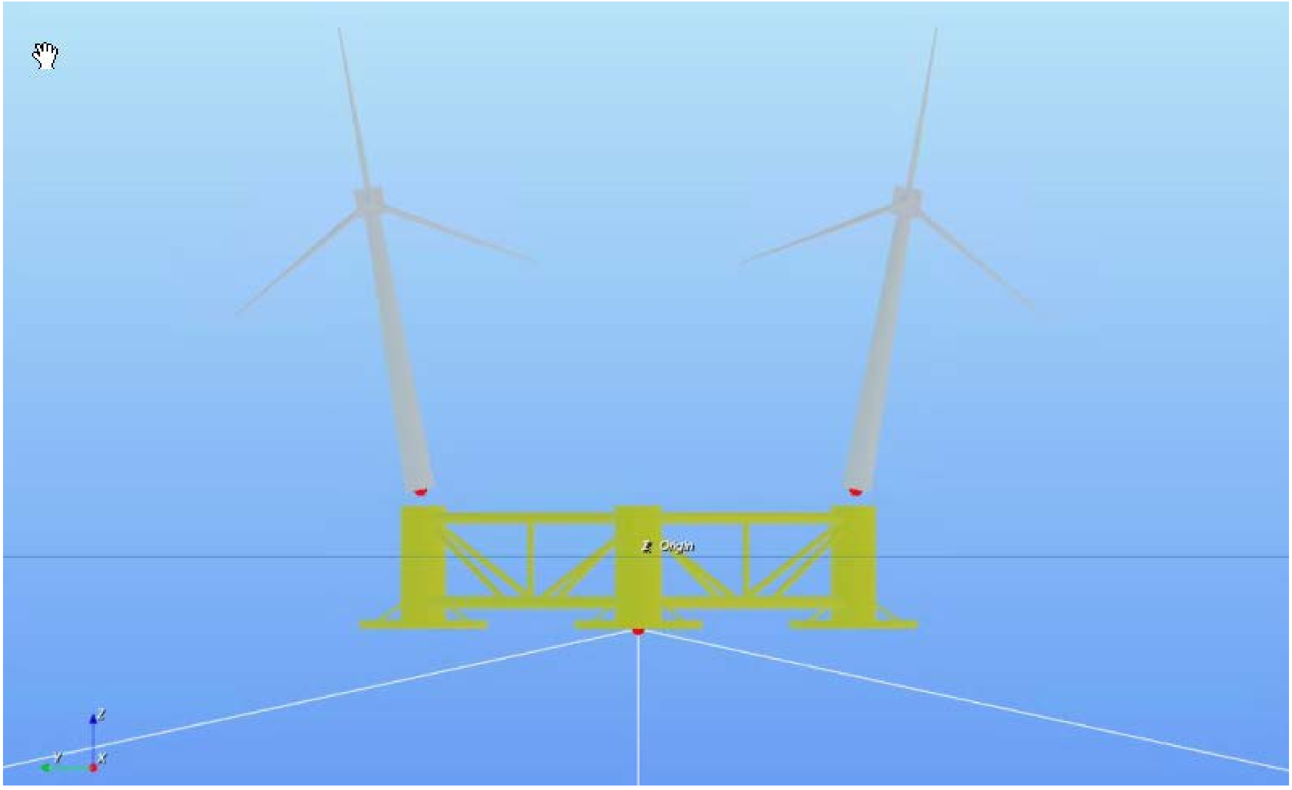


Figure 30 – FOWT platform rendering in OPERA

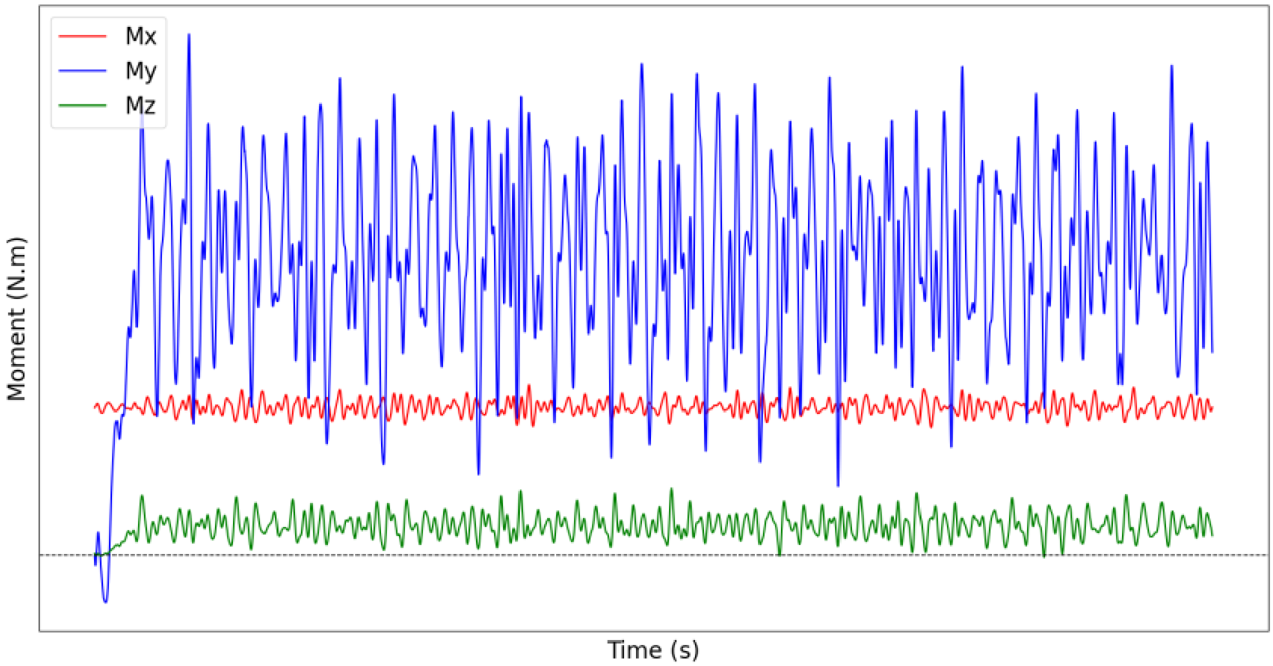


Figure 31 – Bending moments at the tower base

### 12.2.2.4. Finite element simulations FEMAP

In the case of the alternative design methodology, FEMAP was only used to generate the mesh of the floater to be used in Hydrostar (See §12.2.2.2).

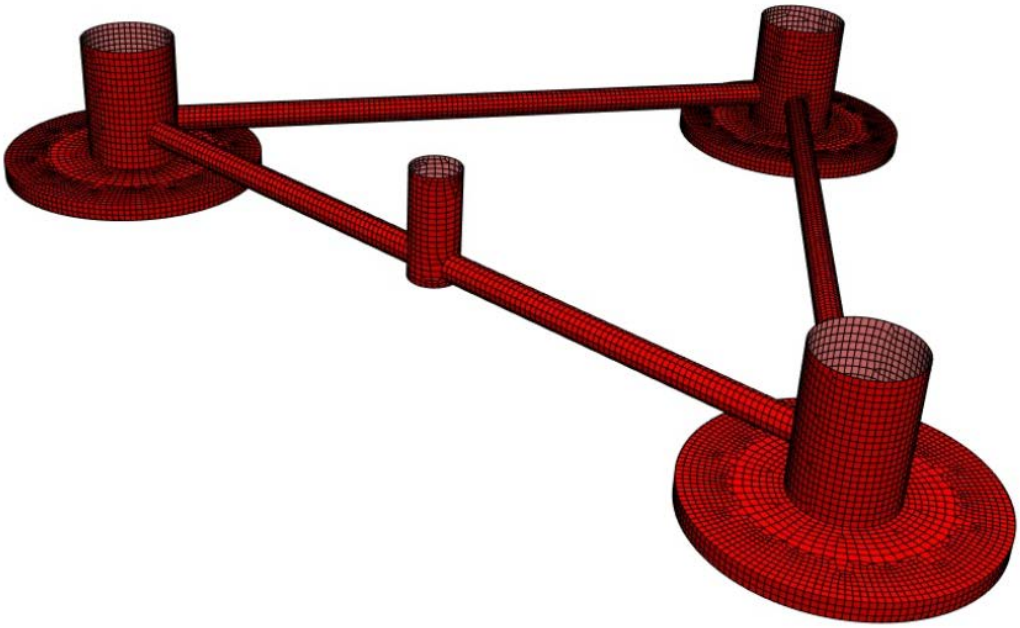

Figure 32 - Mesh of the part of the floater that is under water

For the classical methodology, in addition, a Finite Element model of the tower is built and is presented in the following figure. The composite parts are modelled as multilayered shell elements. Several layups are used depending on the height considered on the tower. The mass of the nacelle and rotor are considered using nodal mass. A rigid link is used to link the nodal masses and the composite tower.

For the boundary conditions, the nodes at the base of the tower are clamped.

For the loads, a wind load at the top of the tower has been applied. In the case of the static calculations, the extreme load obtained from the OPERA calculations is used in conjunction with the gravity load. In the case of the fatigue loading, only unit loads were used in order to obtain stresses in each ply. Those stresses are then combined in the python code. (See §12.2.2.7)

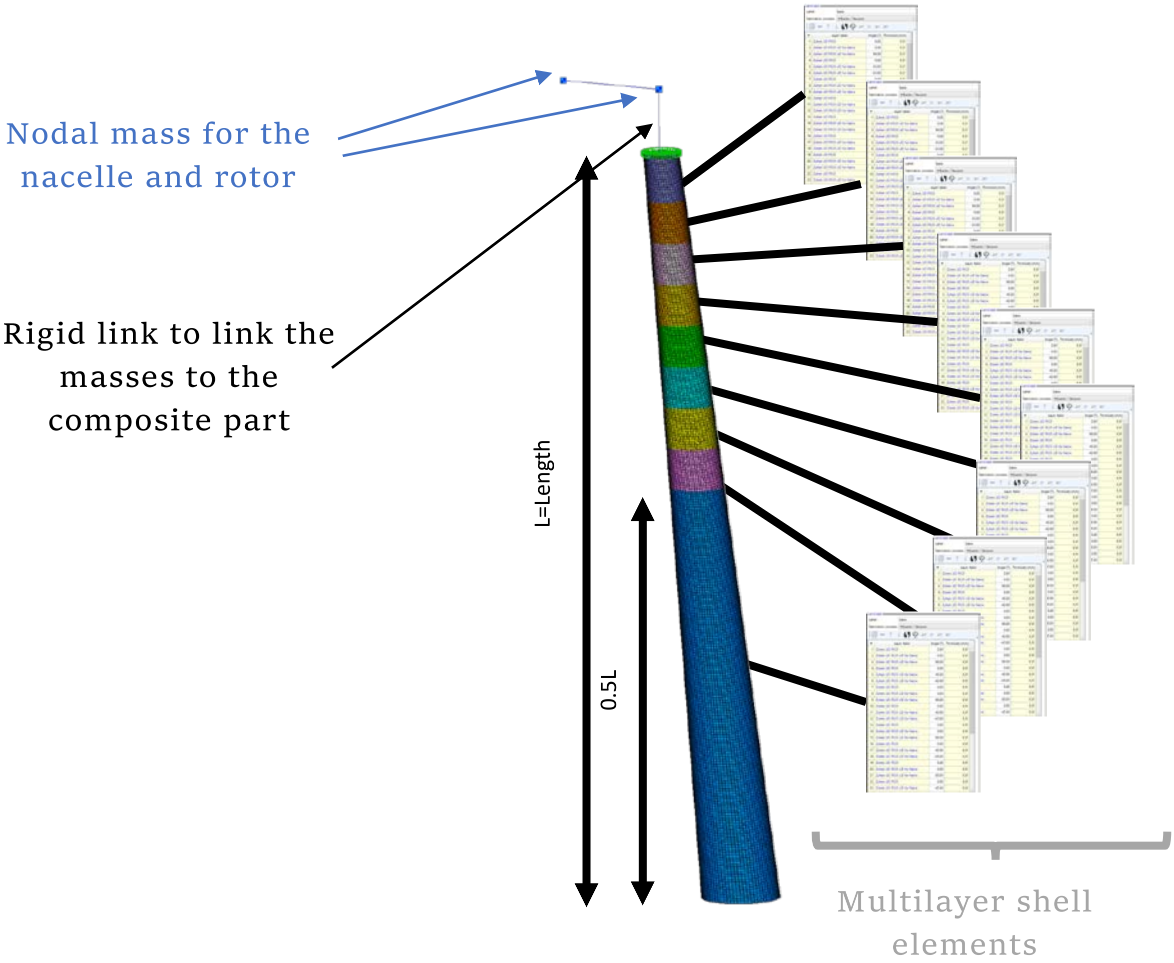


Figure 33 – Finite Element Model of the tower

### 12.2.2.5. Determination of composite characteristics using COMPOSEIT

The material characteristics for the FRP material based on thermoset resin can be determined using ComposeIT (See Figure 34), the characteristics considered for fibre and matrix are given in BV NR546 Rules [11]. Based on the fibre content, the type of ply and the mass of fibre, each ply characteristics can be determined. Based on the ply, the layup of the laminate can be defined. The characteristics of the laminate are computed in the software (ABBD matrix for example). It is then possible to directly perform calculation of a panel in ComposeIT. In the methodology however, it is only uses to define the ply in an easy way and then transfer those data to FEMAP or to Python.

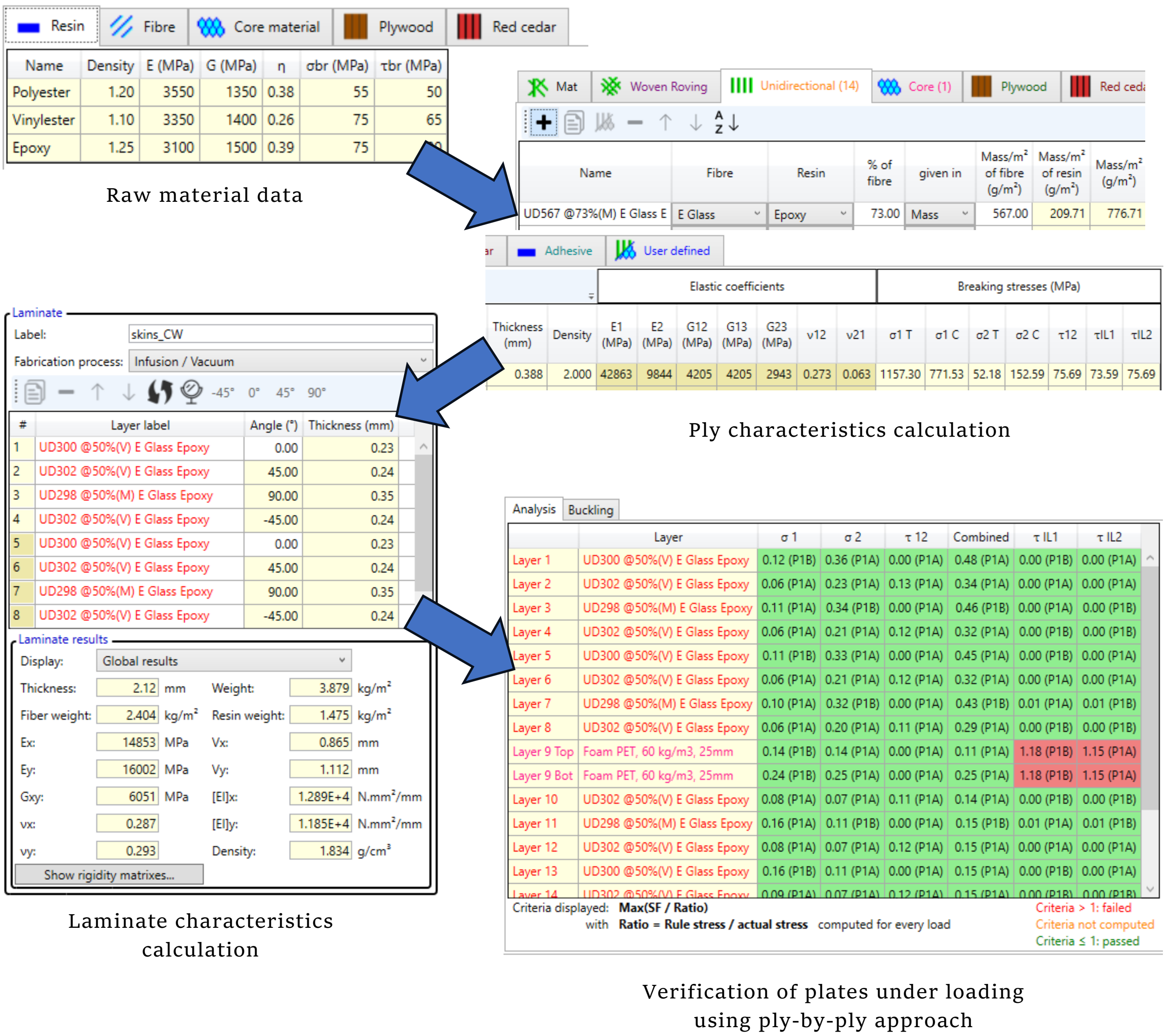


Figure 34 - BV software ComposeIT

#### 12.2.2.6. Analytical determination of stresses in the plies

In order to get the stresses in each plies of the laminate, it is possible to use a finite element model as described in §12.2.2.4 or to use ComposeIT (See §12.2.2.5). For this last case it is necessary to determine the line load (stress multiplied by the thickness) that are applied to the structure. In order to speed up the process to determine the ply stresses in each direction, some analytical expressions have been established in order to get the line loads on the elements. The expressions for the line loads are shown below using the coordinate system from the Figure 35:

- Tension:

$$\zeta_{F_Z} = \frac{2\, F_Z}{\pi(D_o + D_i)}$$

- Torsion:

$$\zeta_{M_Z} = \frac{8\, M_Z\, (D_o + D_i)\, t}{\pi(D_o^4 - D_i^4)}$$

- Bending:

$$\zeta_{M_x} = \frac{32\, M_x\, D_o \sin\theta\;\, t}{\pi(D_o^4 - D_i^4)}$$

$$\zeta_{M_y} = \frac{-32\, M_y\, D_o \cos\theta\;\, t}{\pi(D_o^4 - D_i^4)}$$

- Shear:

$$\zeta_{F_x} = \frac{32\, F_x\, Q_x}{\pi(D_o^4 - D_i^4)}$$

$$Q_x = \frac{D_o^3}{8}\left(\frac{3\, cos\, \theta_{xo}}{4} - \frac{cos\, 3\theta_{xo}}{12} - \sin^2\theta_{xo}\cos\theta_{xo}\right) - \frac{D_i^3}{8}\left(\frac{3\, cos\, \theta_{xi}}{4} - \frac{cos\, 3\theta_{xi}}{12} - \sin^2\theta_{xi}\cos\theta_{xi}\right)$$

$$\zeta_{F_y} = \frac{32\, F_y\, Q_y}{\pi(D_o^4 - D_i^4)}$$

$$Q_y = \frac{D_o^3}{8}\left(\frac{3\, cos\, \theta_{yo}}{4} - \frac{cos\, 3\theta_{yo}}{12} - \sin^2\theta_{yo}\cos\theta_{yo}\right) - \frac{D_i^3}{8}\left(\frac{3\, cos\, \theta_{yi}}{4} - \frac{cos\, 3\theta_{yi}}{12} - \sin^2\theta_{yi}\cos\theta_{yi}\right)$$

Where:

- $D_o$ and $D_i$ are respectively the outside and inside diameter of the tower
- $\theta$ the angle between the considered location in the section and the axis x
- $\theta_{yo} = \arcsin\frac{2y}{D_o}$
- $\theta_{yi} = \arcsin\frac{2y}{D_i}$
- $\theta_{xo} = \arcsin\frac{2x}{D_o}$
- $\theta_{xi} = \arcsin\frac{2x}{D_i}$

Then using the formulation in NR 546 it is possible through the ABBD matrix of the laminate to get the deformation in the laminate and then the stresses in each ply through the rigidity matrix of each ply. Those formulations have been implemented in a Python code.

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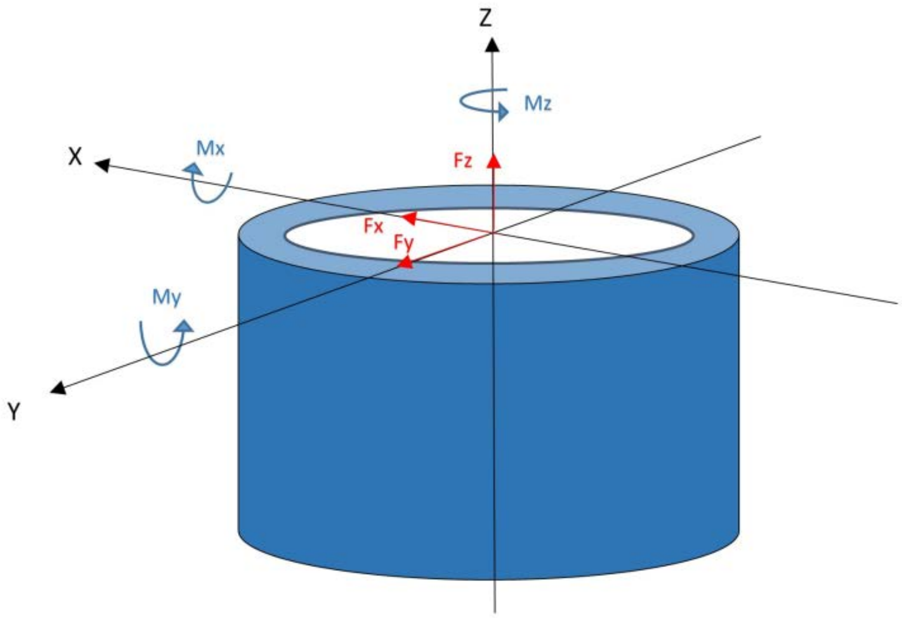


Figure 35 – Coordinate system used for the global tower loads

#### 12.2.2.7. Fatigue tool developed in Python

A python code has been developed with the formulation presented in §7.3. By linking this code to one presented in the previous subsection, it is then possible to obtain the damage in the fibre and matrix for different parts in the tower.

### 12.2.3. First results

Static calculations have been performed using FEMAP. In this case, the maximum thrust load has been applied to the hub. In parallel, a fatigue analysis using the methodology previously presented has been performed. The results in terms of deflection, stresses, eigenvalues, linear buckling analysis and fatigue damage are presented in the following subsections. For the sake of confidentiality, some values have been hidden. These results were obtained for the first design of the tower that was not optimized. The idea is to show the kind of assessment needed in the case of the tower of FOWT platform W2Power.

#### 12.2.3.1. Deflection

The total deflection (amplified) is shown in the Figure 36. The tower height over maximum deflection ratio for the initial design is above 600. The criterion for the deflection ratio is 150. Hence, the deflection of the tower is validated for the design tested.

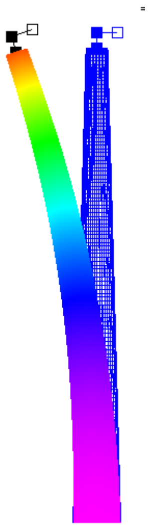

Figure 36 – Deflection of the tower under load (FEMAP Model)

#### 12.2.3.2. Maximum stress

The Hoffman margin obtained is presented in Figure 37. The margin obtained is far above the safety coefficient requires and thus the stresses are validated. In the same way, maximum stresses in each ply are considered and validated.

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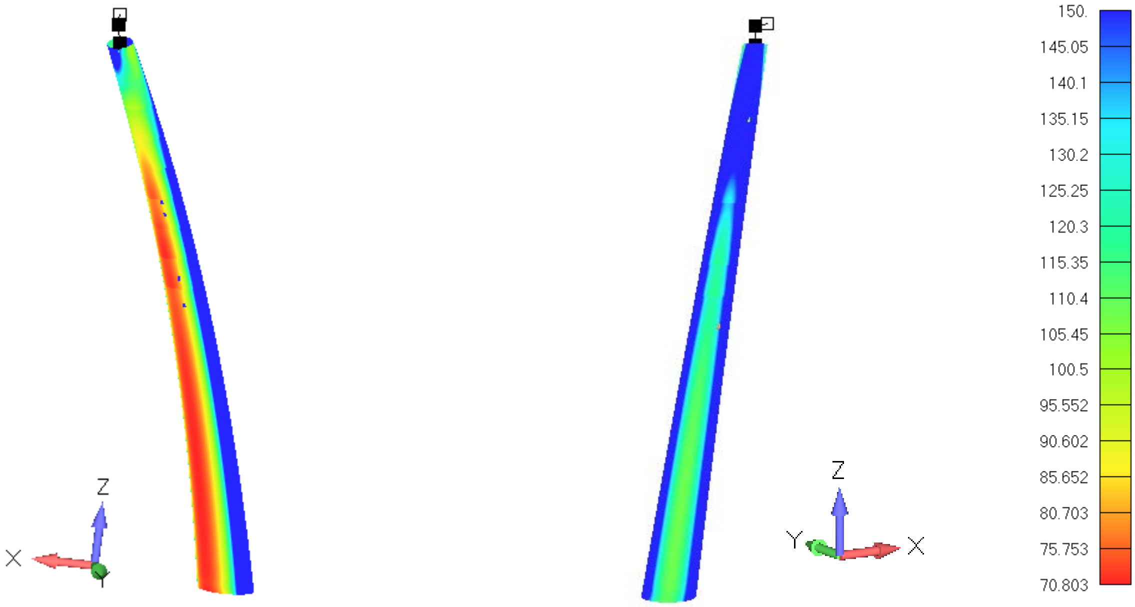
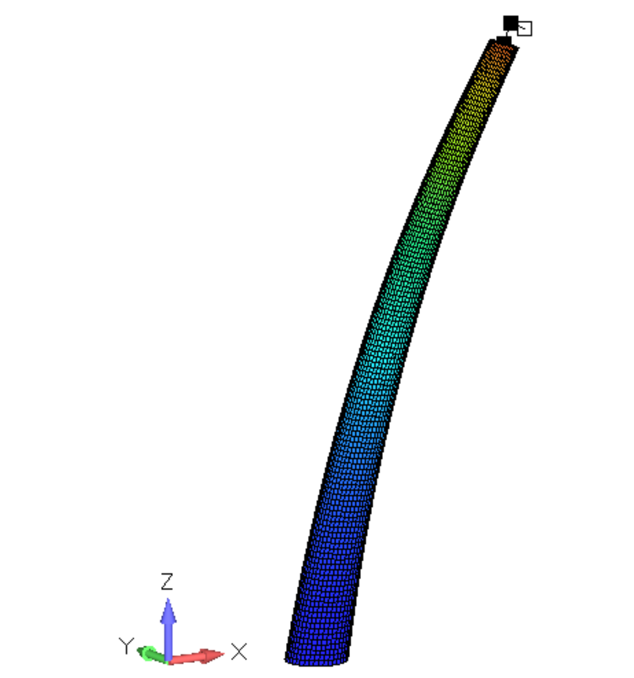
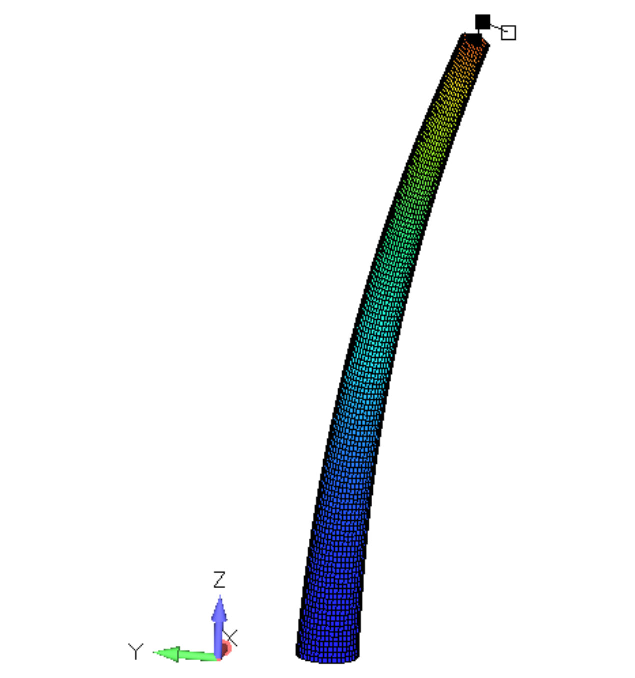



Figure 37 – Hoffman margin of the tower under load (FEMAP Model)

### 12.2.3.3. Modal analysis

The modal analysis was performed in this study and the results are presented in Figure 38 but it was not check if it could lead to problem. It would be needed to compare it to the frequency encountered during services such as rotation frequency of the blades to avoid any resonance phenomenon.

| | |
|---|---|
|  |  |
| Mode 1: 2.9 Hz (bending) | Mode 2: 2.9 Hz (bending) |

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| | |
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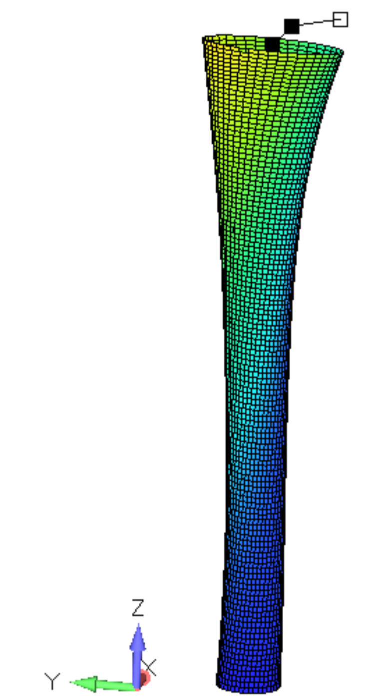
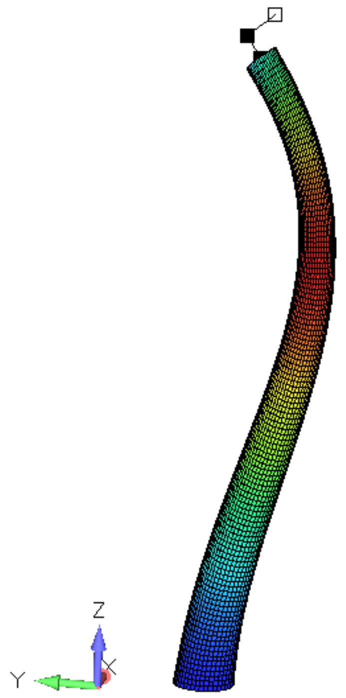
|  |  |
| Mode 2: 13.2 Hz (torsion) | Mode 2: 32.8 Hz (bending) |

Figure 38 – Eigenvalues and associated eigen shape obtained for the tower

### 12.2.3.4. Buckling analysis

A linear buckling analysis has been performed on the composite tower in order to check that no instabilities would occur during the service life of the tower. The first buckling mode occurs for a load factor of 74.6 and the associated mode shape is presented in the Figure 39. The tower is then validated against buckling for this case.

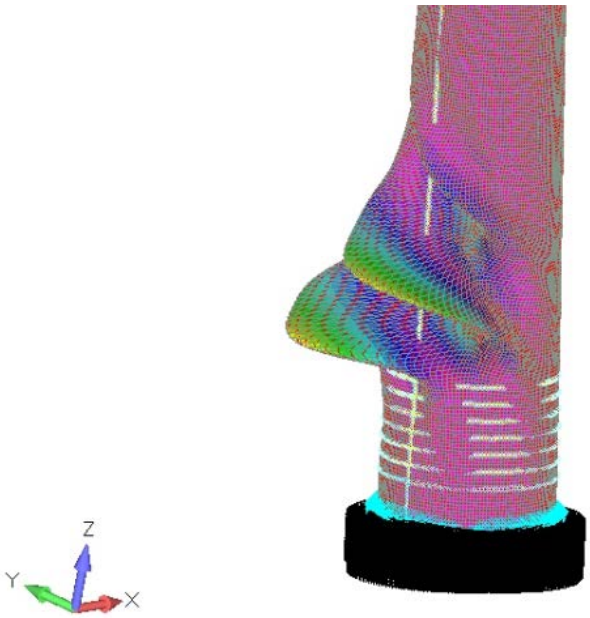



Figure 39 – 1st buckling mode shape obtained for the tower

### 12.2.3.5. Fatigue damage

The fatigue damage was computed using the previously presented methodology in several points of the tower. The critical point considered was at the base of the tower where the tension and compression are the highest due to the bending moment. For those cases, the interpolation in the CFL diagram has been done (In the Figure 40, the zone considered for the interpolation is shown) in order to obtain for each case the SN curve shown in Figure 41.

The fatigue damage obtained for the fibre and the matrix was negligible with the initial design.

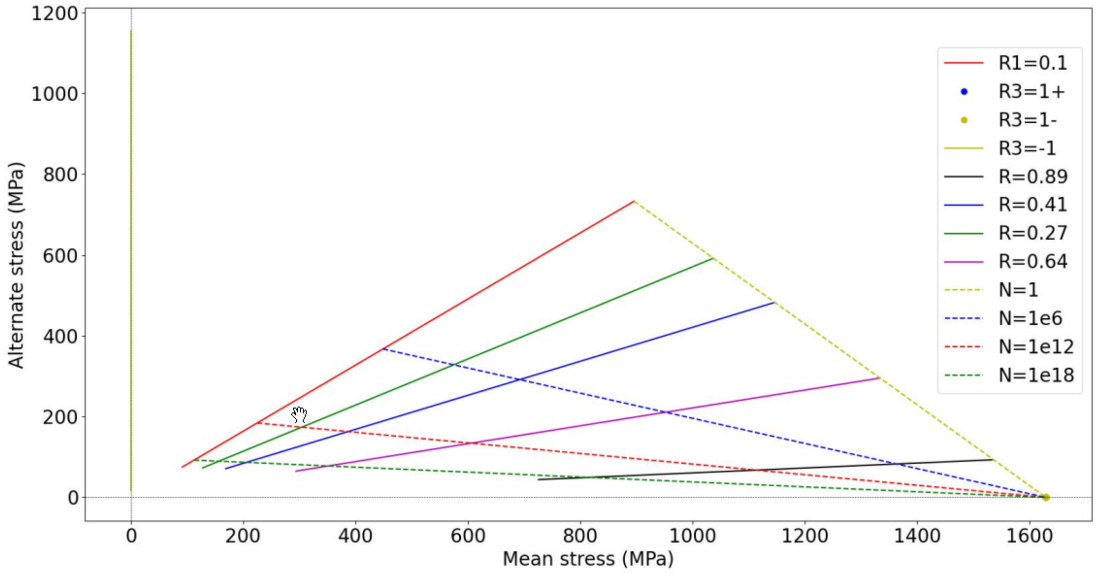



Figure 40 – Part of the CFL diagram for the fibre direction

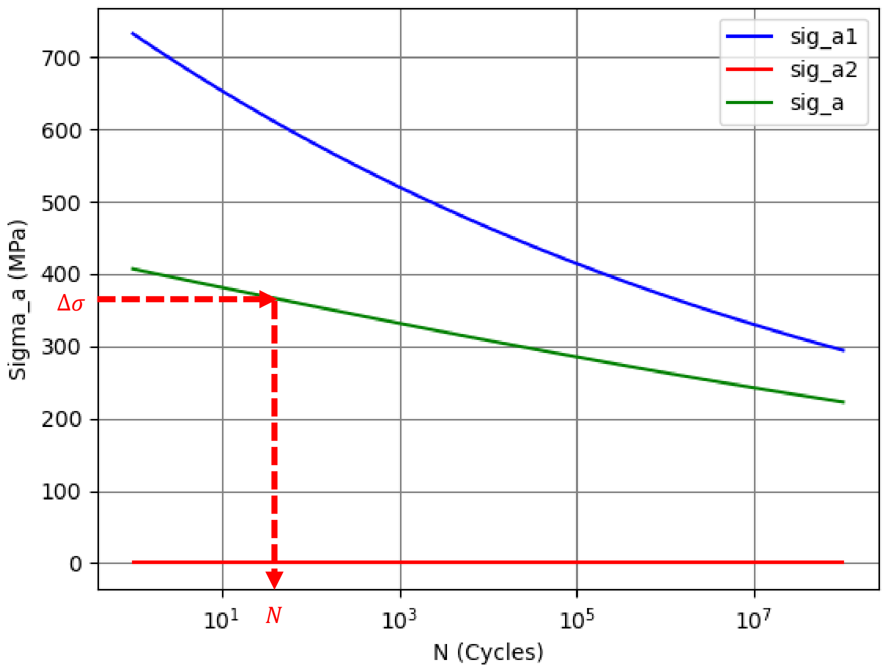



Figure 41 – Interpolated SN curve

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### 12.2.4. Optimisation of the tower

After the first design, the number of plies used was decreased in order to reduce the weight and the cost of the tower. All the previously shown calculations were performed at each loop in order to obtain the final design. The final design permit to have a reduction about 66% of the total mass of the tower. For this scantling the critical criterion was the deflection of the mast. The following table shows the percentage of use for each criterion. It should be noticed that even if the fatigue is 0% the design for which the ultimate stress criterion was not satisfied, the fatigue criterion was not satisfied either. The damage appears to be nonlinear criterion to be checked. It should also be noted that the normal modes frequencies were less than the one obtained for the initial design. A verification of the eigen modes compared to the exciting frequency encountered on the FOWT platform (such as rotation frequency of the blades for example) may pose problems with this design.

| Criterion | Use (including safety factor) |
|---|---|
| Ultimate stress | 28% |
| Fatigue | 0% |
| Deflection | 72% |
| Buckling | 31% |

### 12.2.5. Conclusion on the methodology

A methodology of calculation was developed based on BV software (Hydrostar, OPERA and ComposeIT), Finite element software (FEMAP) and some Python code. It enabled to check several criteria for the tower of the 1:6 scale demonstrator of the W2Power platform: deflection, ultimate strength, fatigue damage, buckling. The normal modes of the structure were also calculated but no criteria were checked for this case. The use of this methodology of assessment enabled to do an optimisation of the thickness of the tower to sustain these criteria. It proves possible to reduce the mass of the structure by 66% compared to the original design.

## 12.3. Recommandations for finite element models in composite materials

This appendix gives recommendations and good practices for the generation of Finite Element models in composite at a macroscale level. The method described here is mainly based on the ply-by-ply approach, which is used in the NR546 [11].

The global safety factor is usually reduced by 10% when performing a FE analysis.

### 12.3.1. Basic hypothesis

#### 12.3.1.1. General

The applicable rules for the model must be specified.

Units must be clearly defined. The typical unit system for FE models is:

- [Force]: N
- [Length]: mm
- [Time]: s
- [Stress]/[Pressure]: MPa
- [Mass]: tons
- [Power]: mW

When using ComposeIT software, these units used are to be consistent with the properties defined.

#### 12.3.1.2. Analysis type

In general, static linear analysis are performed.

Non-linear analysis must be performed in the following cases:

- Non-linear material properties (hyperelasticity, plastic deformation…)
- Geometric non-linearities (large displacement, …).
- Contact…

As the displacement of composite part can be quite large, a non-linear modelling can be preferred to take into account non-linearities in the geometry. Non-linear material properties though are generally not needed as the behaviour of the material is nearly linear elastic until the failure.

Thermal analysis can also be performed based on the scope as the properties of several resins will vary significantly with temperature changes within the operating temperature range.

### 12.3.2. Materials

The materials of each ply used in the model must be specified. The following properties must be defined:

- Young's moduli [MPa] in each direction (will depend if 2D or 3D elements are used)
- Shear moduli [MPa]
- Poisson Coefficients

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- Tensile, compressive and shear strengths [MPa] in each direction, to be defined based on the criteria used for post-processing

Typical materials properties entered in the FE software are shown below (example from FEMAP).

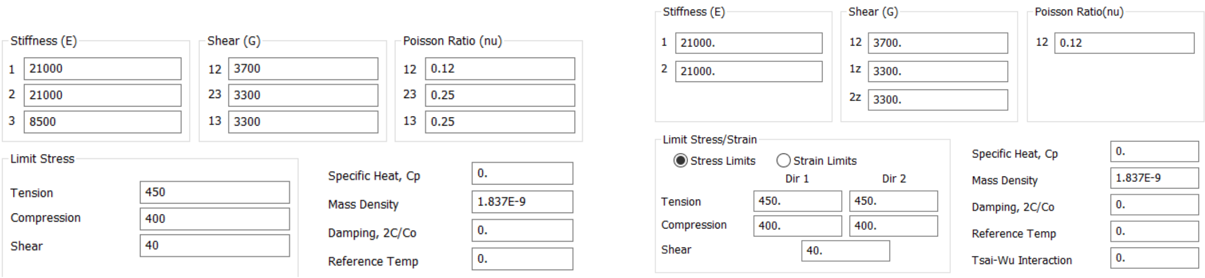


Figure 42: Material properties for 3D orthotropic (left) and 2D orthotropic (right) materials in FEMAP

In addition, following properties are to be know even if they are not used in the model:

- Mass/m$^2$ [g/m$^2$]
- Fibre percentage [%]
- Thickness [mm] (not defined in material properties but in lay-up properties)

In a first approach, theoretical values from ComposeIT software can be used.

Properties assessed by characterization tests (see NR546) on samples representative of the final design are to be considered in the model. More information is given in section 12.3.6.4 for the definition of properties from ComposeIT.

## 12.3.3. Mesh and element types

### 12.3.3.1. Element types

Several type of element may be used when modelling composite structure.

#### Lineic (1D) elements

The elements described in this section can be defined if one of its dimensions is larger than the others. A direction along this dimension as well as a cross section will need to be defined.

Rod elements are line elements with axial stiffness only and constant cross-sectional area along the length of the element.

Beam elements are line elements with axial, torsional and bi-directional shear and bending stiffness and with constant properties along the length of the element. Attention must be paid to the material used in conjunction with this type of element. It can be difficult to accurately represent the axial, shear, bending and torsion of composite beams.

#### Plate/Shell (2D) elements

Plate elements are plane elements with their thickness that is lower than its width and length.

Shell elements are similar except they are curved elements. Plate/shell elements possess in-plane stiffness and out-of-plane bending stiffness and have a constant thickness.

Multilayer shell elements are similar to shell elements that can handle coupling effect between bending and in plane forces. A lay-up will be defined in the element property that contains the different plies and associated thicknesses and orientations. More details are given in section 8. These elements will mainly be used with 2D orthotropic material properties for each ply. Multilayer shell elements are usually the type of elements used in FE model as composite parts are generally thin parts.

#### Volume (3D) elements

Volume elements can also be used, also less convenient than planar elements. Volume elements can be used for thick laminates or if the laminate is loaded in out-of-plane direction and user needs to check how the composite part is behaving in its thickness.

Similarly to laminate plate elements, solid laminate elements can also be defined with the entire lay-up input in the property definition. However, instead of using 2D orthotropic materials, 3D orthotropic materials must be specified.

As out-of-plane properties are usually not characterized, it may be needed to do some assumptions. NR546 gives recommendations to determine the missing out-of-plane properties for UD and roving layers to input in the model.

In case of adhesive or sandwich core parts, they should be modelled with 3D solid elements.

### 12.3.3.2. Linear/Parabolic elements

Linear elements (first-order elements) will only possess corner nodes while parabolic elements (second-order elements) will possess mid-side nodes, as illustrated for triangular elements in Figure 43.

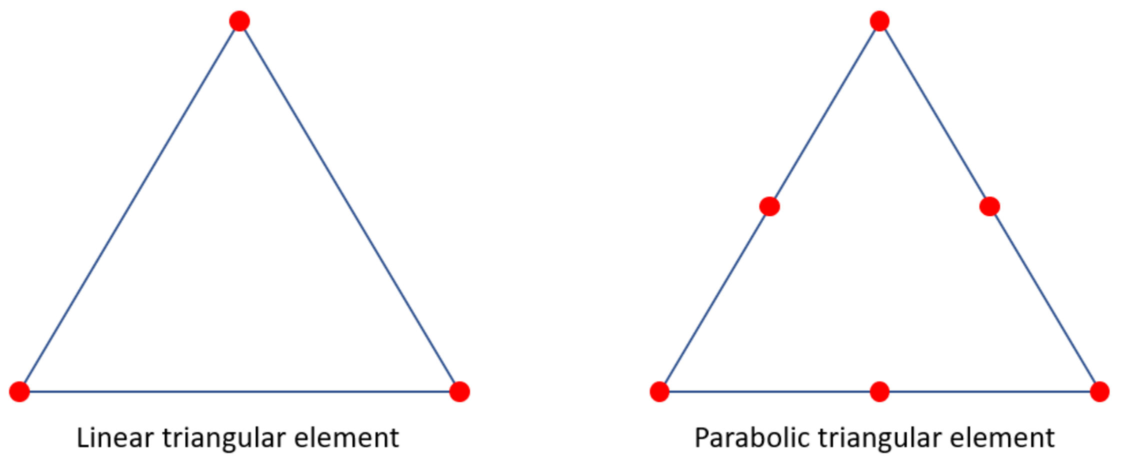


Figure 43: Linear vs parabolic triangular elements

Linear elements use linear shape function while parabolic use quadratic shape function.

Main advantages for linear element will be the computation time but parabolic element, while being more computationally costly, will induce better results for the same number of elements.

### 12.3.3.3. Element shapes

As for the shape of 2D elements, the aspect ratio (ratio of length over width) is not to exceed 3 in general.

The angles of quadrilateral elements should be kept between 60° and 120° while the angles of triangular elements are to be greater than 30° and less than 120°.

The use of triangular shell elements must be kept to a minimum, similarly for tetrahedral elements when doing 3D models. In areas of interest, where the stress is likely to be high, the aspect ratio should be close to 1 and triangular element should be avoided.

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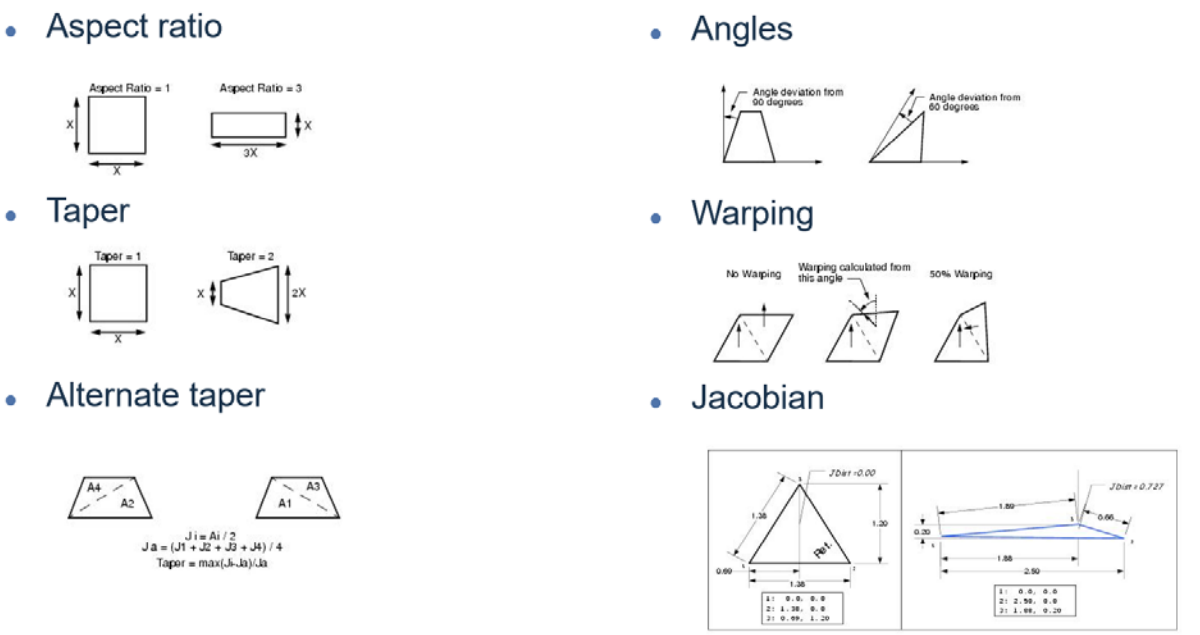
Following requirements must be followed:

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#### 12.3.3.4. Element size

The convergence of stresses in the high stress areas must be assessed and local refinement will usually be needed. Convergence study is to be submitted to the Society.

In stress concentration areas or other types of areas of interest, such as joints, where the element size will be much lower than the rest of the model, it may be useful to create a local model to assess this area and importing the displacements from the global model to have equivalent loading.

In case of stiffening system, the plate elements should follow it as far as practicable, with at least 1 element between every ordinary stiffener and at least 3 elements between primary supporting members.

When ply drop off are modelled, the element size should be below this length to properly model its behaviour.

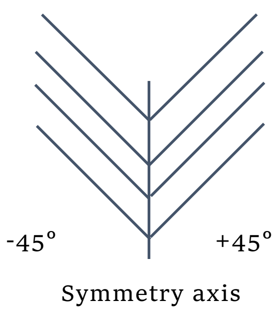
When modelling sandwich core, there should be at least 3 elements in the thickness of the core.

The maximum mesh size depends on the structure and loading.

### 12.3.4. Boundary conditions

Boundary conditions must be specified.

When using symmetries in model, one should be careful about fibre directions. For example, a symmetry on +45° plies will be equivalent to -45° plies on the other side of the symmetry plane that is not representative of the real laminate.



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### 12.3.5. Loading

The type of loading must be specified, along with which rule is applicable, as well as the safety factors applied.

### 12.3.6. Properties & Lay-up

#### 12.3.6.1. Laminate properties

The entire lay-up with all plies must be specified to properly post-process. In case of varying thickness/lay-up in a composite design, several parts with each its property and lay-up must be defined to take into account the variations. The laminate must then be specified for each part (material, orientation, thickness).

#### 12.3.6.2. Coordinate systems

Coordinate systems are to be defined carefully in composite modelling as they have a huge influence on the results.

Global coordinate system axis and origin must be specified. The x-axis is usually directed to the front of the structures, to follow the main UD direction. Several coordinate systems can be defined and care should be taken when orienting the composite based on:

- The element coordinate system: it is based on the elements' definition and is not modified by the user in general. It can be useful to use it to define the material coordinate surface especially when dealing with curved parts modelled with solid elements.
- The material coordinate system: usually used to define the normal (and the associated order from bottom ply to top ply) and main fibre direction (more detailed in next section 12.3.6.3)
- The property coordinate system: can be based on the ply orientation and thus be different for a 90° ply than the material coordinate system, which is for a 0° ply reference.

As the modelling of composite orientation will also depend on the software, all needed coordinate system must be carefully defined and verified. In practice, the element coordinate system is automatically defined when the mesh is created. The user has to define the normal of the element and the main direction in order to set properly the material coordinate system. The property coordinate system is automatically created by the software based on the lay-up definition used.

#### 12.3.6.3. Fibre orientation & laminate order

The orientation of the fibres in the property must follow the design. It may be needed to define multiple coordinate systems for the different parts.

In general, all ply directions are specified based on a reference direction, the 0° direction. Thus, one should be careful when defining this reference direction for each composite part. It can either be based on a global or user defined coordinate system or based on material coordinate system. In case of model with curves, it may be practical to define the normal of the lay-up based on the normal of each element rather than a global or user defined coordinate system.

Along with the fibre orientation, the stacking direction must be specified correctly. The direction will usually be based on the elements' normal, but the vector direction will also influence the lay-up if not

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symmetrical. Usually, the normal direction will indicate the direction from bottom ply to top ply but as it can be software dependent, a check might be needed to verify it.

#### 12.3.6.4. Use of ComposeIT for definition of properties

BV software ComposeIT can be used to define properties as well as post-process with BV safety factors.

In this software, plies can be defined based on raw material used, fibre mass and fibre ratio. The rule properties of the ply will be given for each one.

| Name | Fibre | Resin | % of fibre | given in | Mass/m² of fibre (g/m²) | Woven balance coef (%) | Mass/m² of resin (g/m²) | Mass/m² (g/m²) | Thickness (mm) | Density |
|---|---|---|---|---|---|---|---|---|---|---|
| Roving300 @50%(M) balance 50% HS Carbon Polyester | HS Carbon | Polyester | 50.00 | Mass | 300.00 | 50.00 | 300.00 | 600.00 | 0.418 | 1.437 |

| 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 |
| 51583 | 51583 | 2706 | 2435 | 2435 | 0.028 | 0.028 | 412.66 | 350.76 | 412.66 | 350.76 | 33.55 | 30.20 | 30.20 |

Figure 44: Definition of a ply in ComposeIT and display of its properties

A laminate can be created with the plies previously defined and global properties can be obtained such as the thickness and Young modulus of the whole laminate.

| # | Layer label | Angle (°) | Thickness (mm) |
|---|---|---|---|
| 1 | Roving300 @50%(M) balance 50% H | 0.00 | 0.42 |
| 2 | Roving300 @50%(M) balance 50% H | 0.00 | 0.42 |
| 3 | Mat300 @50%(M) E Glass Polyester | | 0.37 |
| 4 | Mat300 @50%(M) E Glass Polyester | | 0.37 |
| 5 | UD300 @50%(M) E Glass Polyester | 0.00 | 0.37 |
| 6 | UD300 @50%(M) E Glass Polyester | 0.00 | 0.37 |

Laminate results

Display: Global results

| | | | | | |
|---|---|---|---|---|---|
| Thickness: | 2.30 | mm | Weight: | 3.600 | kg/m² |
| Fiber weight: | 1.800 | kg/m² | Resin weight: | 1.800 | kg/m² |
| Ex: | 28187 | MPa | Vx: | 0.923 | mm |
| Ey: | 13293 | MPa | Vy: | 0.661 | mm |
| Gxy: | 3293 | MPa | [EI]x: | 3.494E+4 | N.mm²/mm |
| νx: | 0.098 | | [EI]y: | 1.54E+4 | N.mm²/mm |
| νy: | 0.078 | | Density: | 1.564 | g/cm³ |

Figure 45: Definition of a laminate and display of its properties

For more detail about ComposeIT, see https://marine-offshore.bureauveritas.com/composeit-software-design-assessment-composite-ship-structure.

### 12.3.7. Post Processing

This part presents several recommendations to post-process composite models as well as failure criterion depending on the type of analysis performed.

As the values post-processed are calculated at the mid-plane of each ply, it can be useful to separate into additional small layers at the top and bottom to get the highest tensile or compressive stress.

### 12.3.7.1. Verification of the model

#### Verification of the mesh

Before performing the analysis, a mesh evaluation can be done to check the mesh quality and free edges. Coincident nodes and elements are to be merged.

#### Verification of the loading

After performing the analysis, the force reactions at the constraints can be evaluated to verify the equilibrium with the loadings applied.

If the loading applied induces a large displacement and the analysis was linear static, it may be relevant to perform the simulation again with a non-linear static simulation with progressive loading in multiple steps.

### 12.3.7.2. Stress criterion

The most common criterion to define failure of composite is based on stress assessment (tensile in each direction, compressive in each direction, in-plane shear and interlaminar shear). The different type of stresses of each ply are retrieved and multiple criteria can be used. The failure can be defined as the first ply failure.

Care should be taken during stress post-processing on the coordinate system of the results. Indeed, the results may be expressed using different coordinate systems. For example, in Femap, the interlaminar shear stress is based on the material coordinate system while the stress in the ply (in direction 1,2 and shear) is expressed in the property coordinate system, which depends on the ply orientation.

In general, failure criteria are obtained from tensile and shear mechanical tests and are used for combined stresses. Such criteria give an envelope of the linear elastic area for a laminate under combined stresses. Two criteria families can be defined:

- Energy criterion: Tsai-Hill, Tsai-Wu, Hoffman
- Phenomenological criterion: Hashin, Puck

These criteria can be easily used for the post-processing of composite materials in Finite Element Models.

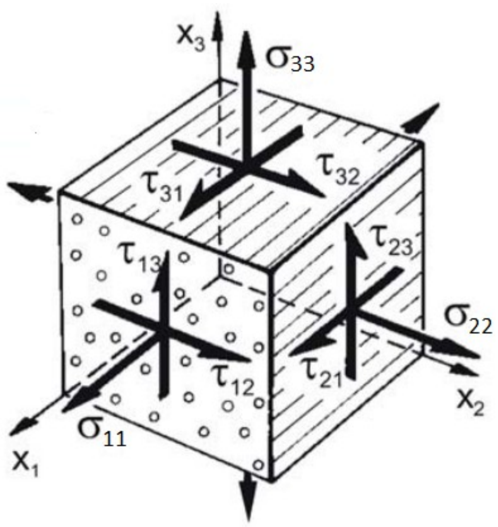


Figure 46: Definition of 3D stresses in a UD laminate

Other criteria based on stress assessment can be evaluated such as:

- Buckling

### Tsai Hill criterion

The Tsai-Hill criterion is a quadratic and interactive stress-based criterion that identifies failure but does not distinguish between modes of failure in tension or compression. Failure occurs whenever the following condition is satisfied:

$$F = \frac{\sigma_{11}^2}{\sigma_{br11}^2} - \frac{\sigma_{11}\sigma_{22}}{\sigma_{br11}^2} + \frac{\sigma_{22}^2}{\sigma_{br22}^2} + \frac{\tau_{12}^2}{\tau_{br12}^2} \geq 1$$

The coefficients $\sigma_{ij}$ and $\tau_{ij}$of the Tsai-Hill criterion are computed as follows:

$\sigma_{ii}$, $\tau_{ij}$: Actual stresses, in N/mm2, in the considered local ply axis induced by the loading case considered,

$\sigma_{brii}, \tau_{br12}$: Ply theoretical breaking stresses, in N/mm2, in the local ply axis.

### Tsai Wu criterion

The Tsai-Wu Criterion is a quadratic, interactive stress-based criterion that identifies failure and taking into account tensile and compression breaking stresses. Failure occurs whenever the following condition is satisfied.

$$F_1\sigma_{11} + F_2\sigma_{22} + F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 + F_{66}\tau_{12}^2 + 2F_{12}\sigma_{11}\sigma_{22} \geq 1$$

The various coefficients $F_{ij}$ of the Tsai-Wu criterion are defined in terms of known/measured strengths of the composite material:

$\sigma_{ii}, \tau_{ij}$ : Actual stresses, in N/mm2, in the considered local ply axis induced by the loading case considered,

$\sigma_{brcii}$ : Ply theoretical breaking stresses in compression, in N/mm2, in the local ply axis,

$\sigma_{brtii}$ : Ply theoretical breaking stresses in tension, in N/mm2, in the local ply axis,

$\tau_{brij}$ : Ply theoretical breaking stresses (absolute value), in N/mm2, in the local ply axis.

With:

$$F_1 = \frac{|\sigma_{brc11}| - |\sigma_{brt11}|}{|\sigma_{brt11}\ \sigma_{brc11}|}$$

$$F_2 = \frac{|\sigma_{brc22}| - |\sigma_{brt22}|}{|\sigma_{brt22}\ \sigma_{brc22}|}$$

$$F_{11} = \frac{1}{|\sigma_{brt11}\sigma_{brc11}|}$$

$$F_{22} = \frac{1}{|\sigma_{brt22}\sigma_{brc22}|}$$

$$F_{66} = \frac{1}{\tau_{br12}^2}$$

The interaction coefficient $F_{12}$ can be defined in one of two different ways. If a biaxial failure stress ($\sigma_{11} = \sigma_{22} = \sigma_{biax}$) is used, $F_{12}$ is computed as follow:

$$F_{12} = \frac{1}{2\sigma_{biax}^2}\left[1 - \left(\frac{1}{|\sigma_{brt11}|} - \frac{1}{|\sigma_{brc11}|} + \frac{1}{|\sigma_{brt22}|} - \frac{1}{|\sigma_{brc22}|}\right)\sigma_{biax} - \left(\frac{1}{|\sigma_{brt11}\sigma_{brc11}|} + \frac{1}{|\sigma_{brt22}\sigma_{brc22}|}\right)\sigma_{biax}^2\right]$$

Otherwise, the interaction coefficient $F_{12}$ is computed as $F_{12} = f^* \sqrt{F_{11} F_{22}}$

where $f^*$ is a user-specified constant, $-0.5 \leq f^* \leq 0$.

### Hoffman criterion

The Hoffman criterion is an extension of Tsai-Hill theory by considering values in tension and compression:

$$F_1\sigma_{11} + F_2\sigma_{22} + F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 + F_{66}\tau_{12}^2 - F_{12}\sigma_{11}\sigma_{22} = 1$$

It is similar to the Tsai Wu criterion except for the formulation of the $F_{12}$:

$$F_{12} = \frac{1}{|\sigma_{brc11}\sigma_{brt11}|}$$

Bureau Veritas composite materials rules (BV NR546) are based on this criterion.

### Hashin criterion

The Hashin criterion identifies four different modes of failure for the composite material: tensile fibre failure, compressive fibre failure, tensile matrix failure, and compressive matrix failure.

If $\sigma_{11} \geq 0$, the tensile fibre failure criterion is:

$$F_{brtf} = \left(\frac{\sigma_{11}}{\sigma_{brt11}}\right)^2 + \alpha\left(\frac{\tau_{12}}{\tau_{br12}}\right)^2 \geq 1$$

If $\sigma_{11} < 0$, the compressive fibre failure criterion is:

$$F_{brcf} = \left(\frac{\sigma_{11}}{\sigma_{brc11}}\right)^2 \geq 1$$

If $\sigma_{22} \geq 0$, the tensile matrix failure criterion is:

$$F_{brtm} = \left(\frac{\sigma_{22}}{\sigma_{brt22}}\right)^2 + \left(\frac{\tau_{12}}{\tau_{br12}}\right)^2 \geq 1$$

If $\sigma_{22} < 0$, the compressive matrix failure criterion is:

$$F_{brcm} = \left(\frac{\sigma_{22}}{2\tau_{br23}}\right)^2 + \left[\left(\frac{\sigma_{brc22}}{2\tau_{br23}}\right)^2 - 1\right]\frac{\sigma_{22}}{|\sigma_{brc22}|} + \left(\frac{\tau_{12}}{\tau_{br12}}\right)^2 \geq 1$$

Note, the Hashin equations include two user-specified parameters: $\alpha$ and $\tau_{br23}$.

- $\alpha$: User-specified coefficient that determines the contribution of the longitudinal shear stress to fibre tensile failure. Allowable range is $0 \leq \alpha \leq 1$, and the default value is $\alpha = 0$.
- $\tau_{br23}$: Transverse shear strength of the composite material in the 23 plane.

### Puck criterion

The Puck criterion identifies fibre failure (FF) and inter-fibre failure (IFF) in a unidirectional composite. FF is based on the assumption that fibre failure under multiaxial stresses occurs at the same threshold level at which failure occurs for uniaxial level. IFF is subdivided into three failure modes, A, B and C, see Figure 47. Mode A occurs when the ply is subjected to tensile transverse stress, whereas modes B and C correspond to compressive transverse stress. The classification is based on the idea that a tensile stress $\sigma_t > 0$ promotes fracture, while a compressive stress $\sigma_c < 0$ prevents shear fracture. For $\sigma_c < 0$ the shear stresses τ have to face an additional fracture resistance, which increases with σ, analogously to an internal friction. The distinction between modes B and C is based on their failure angles, which are 0° for mode B and a different value for mode C. In addition, failure mode C is considered more severe, since it produces oblique cracks and may lead to serious delamination.

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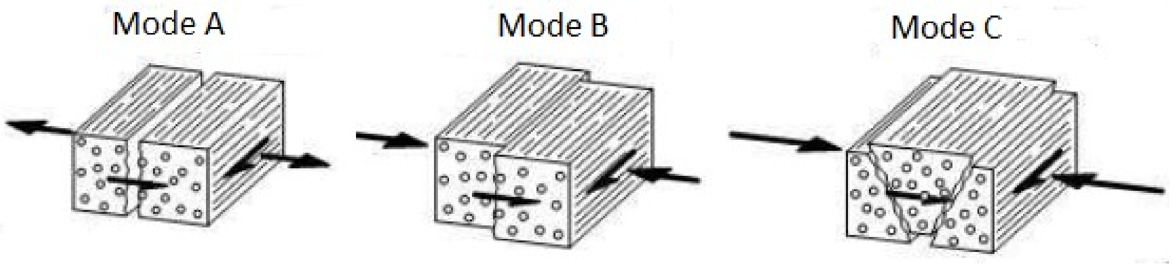


Figure 47: Composites failure modes

Equations for Puck criterion determination are given in Table 13.

Table 13: Equations for Puck criterion (Puck and Schürmann, 1998)

| Type of failure | Failure Mode | Failure Condition ( $f_{E(FF)}$ *or* $f_{E(IFF)}$ ) | Condition for validity |
|---|---|---|---|
| Fiber Failure (FF) | Tensile | $\frac{S}{\varepsilon_{1T}}=1$ | if $S \geq 0$ |
| $S=\varepsilon_1+\frac{v_{f12}}{E_{f1}}m_{\sigma f}\sigma_2$ | Compressive | $-\frac{S}{\varepsilon_{1C}}+(10\gamma_{21})^2=1$ | if $S<0$ |
| Inter Fiber Failure (IFF) | Mode A | $\sqrt{\left(\frac{\tau_{21}}{S_{21}}\right)^2+\left(1-p_{\perp\parallel}^{(*)}\frac{Y_T}{S_{21}}\right)^2\left(\frac{\sigma_2}{Y_T}\right)^2}+p_{\perp\parallel}^{(+)}\frac{\sigma_2}{S_{21}}+f_w=1$ | $\sigma_2 \geq 0$ |
| | Mode B | $\frac{1}{S_{21}}\left(\sqrt{\tau_{21}^2+\left(p_{\perp\parallel}^{(-)}\sigma_2\right)^2}+p_{\perp\parallel}^{(-)}\sigma_2\right)+f_w=1$ | $\sigma_2<0$ and $0 \leq \left\|\frac{\sigma_2}{\tau_{21}}\right\| \leq \frac{R_{\perp\perp}^A}{\|\tau_{21c}\|}$ |
| | Mode C | $\left[\left(\frac{\tau_{21}}{2\left(1+p_{\perp\perp}^{(-)}S_{21}\right)}\right)^2+\left(\frac{\sigma_2}{Y_C}\right)^2\right]\frac{Y_C}{(-\sigma_2)}+f_w=1$ | $\sigma_2<0$ and $0 \leq \left\|\frac{\tau_{21}}{\sigma_2}\right\| \leq \frac{\|\tau_{21c}\|}{R_{\perp\perp}^A}$ |
| Definitions | $p_{\perp\parallel}^{(+)}=-\left(\frac{d\tau_{21}}{d\sigma_2}\right)_{\sigma_2=0}$ of $(\sigma_2,\tau_{21})$ curve, $\sigma_2 \geq 0$ | $p_{\perp\parallel}^{(-)}=-\left(\frac{d\tau_{21}}{d\sigma_2}\right)_{\sigma_2=0}$ of $(\sigma_2,\tau_{21})$ curve, $\sigma_2 \leq 0$ | |
| Parameter relationships | $R_{\perp\perp}^A=\frac{Y_C}{2\left(1+p_{\perp\perp}^{(-)}\right)}=\frac{S_{21}}{2p_{\perp\parallel}^{(-)}}\left(\sqrt{1+2p_{\perp\parallel}^{(-)}\frac{Y_C}{S_{21}}}-1\right)$ | $p_{\perp\perp}^{(-)}=p_{\perp\parallel}^{(-)}\frac{R_{\perp\perp}^A}{S_{21}}$ | $\tau_{21c}=S_{21}\left(\sqrt{1+2p_{\perp\perp}^{(-)}}\right)$ |

### 12.3.7.3. Strain criterion

In the case of large strains with highly stiff materials such as carbon fibres, the stress criterion may not be appropriate anymore, where failure is governed by strain. A criterion may thus be based on the maximal strain of the fibres.

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