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FIBREGY

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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

D5.4 (WP5): Guidance notes for the production of large FPR OWTP

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LIST OF ABBREVIATIONS

AFP	Automated Fibre Placement
CFC	Carbon Fibre Composite
CNC	Computer Numerical Control
COQ	Cost of Quality
CTE	Coefficient of Thermal Expansion
DFMEA	Design Failure Mode and Effect Analysis
DLS	Diestone
EMSA	European Maritime Safety Agency
FA	First Article
FAI	First Article Inspection
FMEA	Failure Mode and Effect Analysis
FRP	Fibre-Reinforced Plastic
IPA	Isopropyl Alcohol
IPS	Individual Process Specification
ISO	International Organization for Standardization
MEK	Methyl-Ethyl-Ketone
MS	Material Specification
NDI	Non-Destructive Inspection
NDT	Non-Destructive Testing
OPC	Optical Particles Counter
OTC	Ozone Transport Commission
OWTP	Offshore Wind and Tidal Power
PBS	Product Breakdown Structure
PET	Polyethylene Terephthalate
PFMEA	Process Failure Mode and Effect Analysis
PN	Part Number
PPAP	Production Part Approval Process
PVC	Polyvinyl Chloride
RPN	Risk Priority Number
SPR	Specific Process Requirements
TDS	Technical Data Sheet
VOC	Volatile Organic Compounds
CAD	Computer-Aided Design
ID	Identification
ASTM	American Society for Testing and Materials
PPE	Personal Protective Equipment
UT	Ultrasonic Testing
RT	Radiographic Testing
TT	Thermographic Testing
VI	Visual Inspection

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1. INTRODUCTION

This document presents the results from the work done in Task 5.3 – *"Development of guidance notes for the production of large FRP OWTPs"*, which is part of Work Package 5 of the FIBREGY project and aims to develop guidance notes for the production of large FRP OWTPs, generalizing the experience acquired throughout the project in the development of the manufacturing and production strategies of the two selected OWTP platforms (W2Power and Tidal Turbine Housing).

These guidance notes cover various aspects of the production such as modular production (chapter 3); production processes (chapter 4) – including its selection, qualification and necessary materials/tools/equipment, as well as other important aspects when particularizing for the processes used throughout the manufacturing of the demonstrators; mechanical and chemical joining (chapter 5); cutting and machining (chapter 6); quality system procedures to ensure the quality of the resulting parts (chapter 7); quality requirements, including control tests, acceptance criteria, and the means to perform non-destructive inspection (chapter 8); and finally the aspirations and future work (chapter 9).

This document was created with valuable inputs from the other partners, particularly the ones involved in the manufacturing of the demonstrators, and also from the comments and feedback provided by the FIBREGY's Advisory Board members during specific workshops that took place to discuss these guidance notes. It is also important to note that this deliverable document complements the work reported in Deliverable 4.7 – *"Project guidelines and recommendations for using FRP in large OWTPs"*. On one facet, the emphasis of D4.7 pertains to the project design guidelines, covering all the design aspects, including the structural design and certification. Conversely, the present document focuses primarily on the production side. In simpler terms, while D4.7 is focused on the R&D and design engineering teams, D5.4 is focused on the process engineers and production team at the shopfloor. It is envisioned that, together, these guidelines and guidance notes will serve as the foundation for future guidelines for the certification and broader implementation of large FRP-based OWTP platforms.

The preliminary version of these guidelines was presented to the industry on the first open-door day in May of 2023 (at Gran Canaria), while the final version will be presented on the second open-door day to take place in La Ciotat in September of 2023. This document is also a crucial contribution to Milestone 15 – *"Development of guidance notes for the production of large FRP OWTPs"*. Overall, these guidance notes for the production of large FRP OWTPs will be a valuable resource for manufacturers looking to develop and optimize the production of large FRP OWTPs, providing a wealth of information on the process selection, fabrication, and quality control considerations that are critical to the success of these projects, as well as the benefits of using modular production and proper joining techniques. In addition, this document will contribute to the development of new standards and guidance notes, particularly from the classification/certification societies, which are currently lacking for FRP-based OWTP platforms (particularly in what concerns their production).

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2. BACKGROUND

Offshore wind and tidal energy are an increasingly important source of renewable energy, with the potential to significantly reduce reliance on fossil fuels. Offshore Wind and Tidal Power (OWTP) platforms, when integrated into offshore wind and/or tidal farms, can provide cost-efficient energy to a large area of the population and power companies and services. Building these large OWTPs in fibre-reinforced polymers (FRP) can very promisingly enable the cost reduction necessary to compete in the energy market (through the reduced maintenance needs, improved fatigue performance, easier transport, etc.); however, because the employment of these materials is not common in offshore construction, there is a lack of certification and classification (assessment) guidelines for the production on these large platforms in FRP, which in turn can inhibit faster industrialization and commissioning for effective implementation of composite materials and the associated technologies.

In order for the production of these large OWTPs to the feasible, new solutions have to be developed for modular production, streamlining the manufacturing process by breaking down the large platform into smaller, more manageable units that can be prefabricated and assembled near shore. The production processes have to be suited to the dimensions of the parts, and quality requirements have to be established to ensure that the requirements (structural and others) are met. Since no standards or guidelines exist for the production of large OWTP platforms in FRP, other guidelines will be considered as reference, namely from other industries, such as aerospace and automotive – where composites have been maturely implemented for several decades [1] – and other guidelines and regulations from the naval and marine industry. In fact, a review of the applicable standards, guidelines, and rules was already made in Deliverable 4.6 – *"Critical review of applicable standards and gaps"*. However, most of these documents are oriented to the structural design and material qualification, having very little information regarding the production processes. Therefore, these guidance notes aim to fill that gap – or at least contribute to its reduction – by providing a critical and comprehensive overview of the necessary steps to ensure process and quality control, further enabling the extensive use of FRP materials in the structure of the next generation of large OWTP platforms. In some cases, to take advantage of the experience and maturity achieved in different composite industries, some information present in this deliverable was adapted from standards (some identified in D4.6), guidance notes and recommendations from those industries.

Particularly from the knowledge acquired throughout the FIBREGY project, two processes will be detailed in this document with the lessons learned, difficulties and other inherent specificities: the Vacuum Infusion process – employed for the production of the W2Power's demonstrators – and the Automated Fibre Placement (AFP) process – employed for the production of the turnable turbine housing demonstrator.

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3. MODULAR PRODUCTION

Over the last decades, in pursuit of more efficient energy platforms, manufacturers are looking to increase the size of their turbines to harvest more energy. For example, if the rotor blades of a wind turbine double in length, the turbine catches four times as much wind (not two times) [1]. However, this comes with serious transportation and installation challenges, not only for the blades but also for the rest of the platform. Because these structures cannot be folded or bent once constructed, modular construction becomes the obvious solution: breaking down the OWTPs into smaller, more manageable units that can be prefabricated and assembled near shore (or even on-site, offshore).

This modular approach has several advantages, including faster construction times, reduced on-site labour requirements, improved quality control and increased safety of the workers. In fact, modularization has seen successful implementation in oil and gas offshore platforms, prefabricating equipment and systems into modules offsite in a controlled manufacturing facility [2][3].

3.1. Product tree

In the context of modular production, a product tree is a simple but effective tool to represent the various modules and components that make up the final product. The product tree typically includes the main modules of the platform, as well as any sub-components or sub-assemblies that are used to build those main modules. Different levels can be outlined depending on the complexity of the product. Similar to a Product Breakdown Structure (PBS), the product tree can be seen as the breakdown of a product into its required components, providing a visual representation of a product's components and the relationship between them.

A product tree can also be used to identify potential areas for optimization or simplification in the production process. By analysing the product tree, manufacturers can identify components or sub-assemblies that are used in multiple locations within the final product, and explore the possibility of standardizing or simplifying those components to reduce production costs and improve efficiency. As already detailed in Deliverable 5.2 – *"Optimum manufacturing and building strategy for the W2Power platform"* and in Deliverable 5.3 – *"Optimum manufacturing and building strategy for the turnable tidal turbine housing",* the selection of the most adequate processes can (and should) also be done for individual modules, blocks, or components (parts). Figure 1 illustrates an example of different partitioning proposals for a heave plate module of the W2Power's columns.

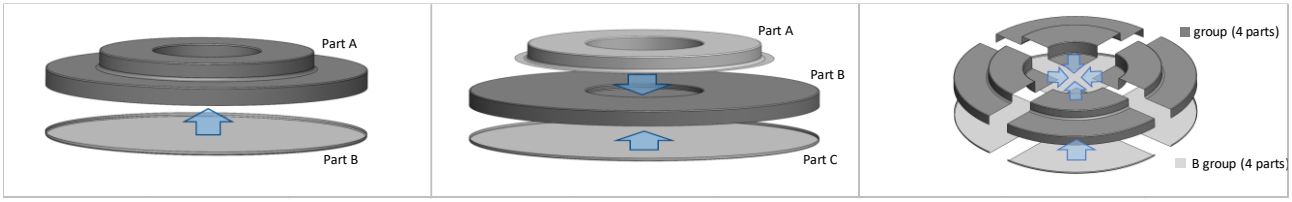

Figure 1 – Different partitioning proposals and assembly for the W2Power's heave plates.

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In the case of the FIBREGY's demonstrators, it was decided to divide the products into the following categories: **Product** > **Subproduct** > **Modules** > **Building Blocks** > **Components**. As an example, the **product** can be the wind turbine platform, divided into different **subproducts** (e.g. towers), which in turn can be constituted by different **modules** (e.g. structural rings) considering the limitations in transport, assembly and dismantling. In most cases, large modules are then partitioned into smaller **building blocks** due to manufacturing process (size) limitations. While the modules are typically assembled using connections easy to disassemble (for maintenance or inspection purposes), the building blocks are usually joined permanently because the size/geometry of the module is adequate for their transport or assembly. Finally, each module or building block is constituted by various **components** such as the shell, stringers, frames, etc.

The following subchapters illustrate an example of a product tree for the W2Power and Tidal Turbine Housing demonstrators. The modules and subsequent categories are only indicated for one of the subproducts, which in this case is the one that will be manufactured.

3.1.1. W2Power

Figure 2 illustrates an example of modularization of the W2Power's towers. This is presented as an example of the modularization process of breaking down the platform into smaller units that can be prefabricated and then assembled before installation. Although it was concluded not to be necessary for the prototype-scaled towers (only divided into two half pipes), built by Exail, the real-scale towers can be divided into three vertical modules, stacked together near shore, and in turn, each module is built from two halves (easier to manufacture by vacuum infusion) which are permanently joined in the factory. Other components are part of the building blocks such as the omega stiffeners, the foam/wood core between the stiffeners, bolts, nuts, washers, adhesives, sealants, paint films or dry coatings.

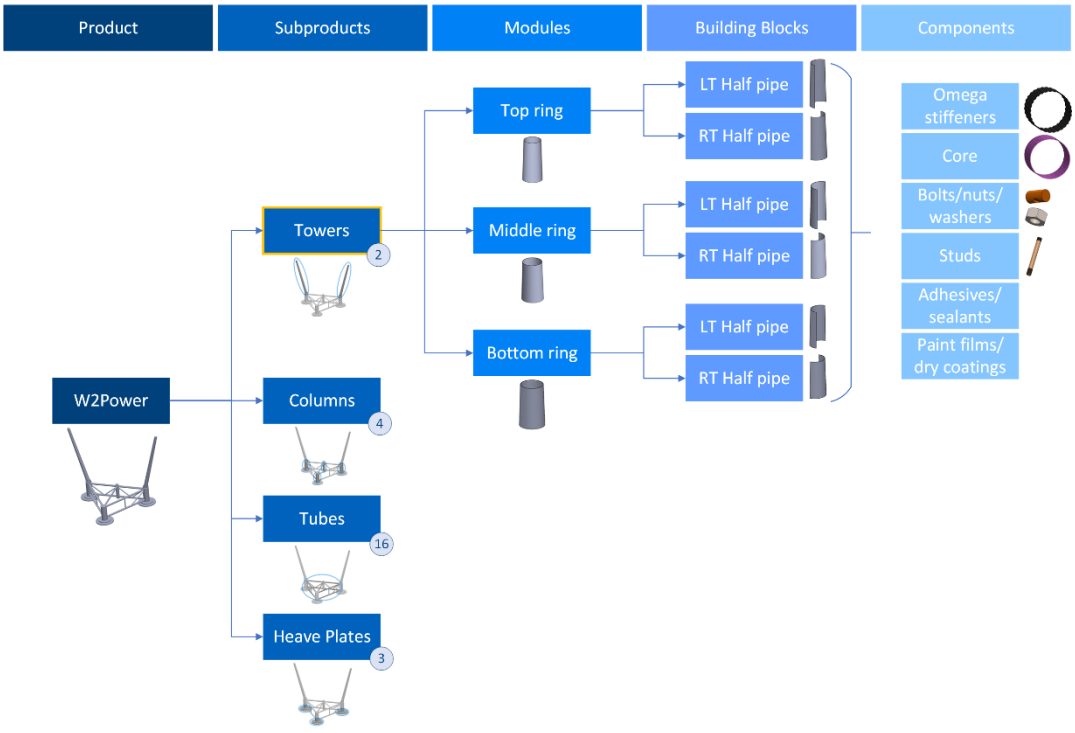

Figure 2 – Example of modularization for the W2Power's towers.

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3.1.2. Tidal turbine housing

Similarly, Figure 3 illustrates an example of modularization of the tidal turret's housing which was built by INEGI at their premisses by Automated Fibre Placement (AFP). In this example, the housing is divided into two modules: forward ("FWD") and after ("AFT") covers. This partitioning was made not only to overcome the transportation, installation and maintenance challenges but also because a complete cut had to be done along its perimeter to allow the composite to demould from the steel mandril, resulting in the two modules. In turn, each module is constituted by three building blocks (fairing, composite cover and flange), all being bonded together with structural adhesive. Besides the adhesive, sealants, bolts, nuts, washers, paint films or dry coatings are also components of these building blocks.

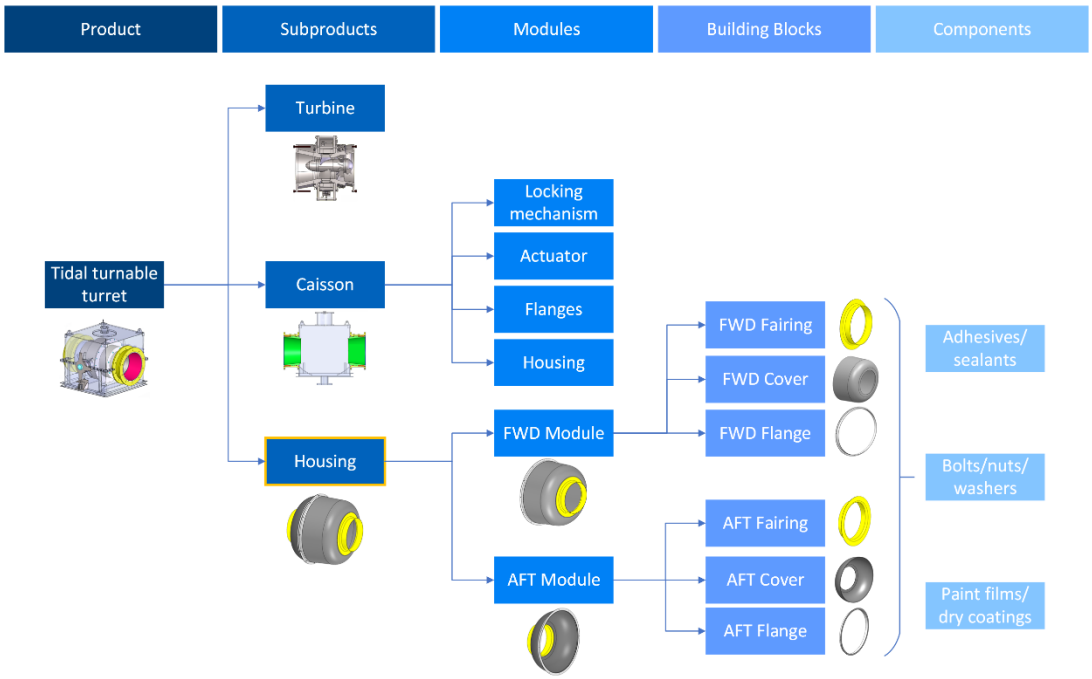

Figure 3 – Example of modularization for the Tidal turret's housing.

It should be noted that the two examples above are solely representative cases of the modularization process. Different strategies of modularization and partitioning can be used in other platforms, necessarily ensuring that the established requirements are met while enabling the transportation and installation of all modules with improved safety and cost-efficiency.

It is also important to mention that other examples of modular production and their specific application in the W2Power platform and the turnable tidal turbine housing are depicted in Deliverables 5.2 and 5.3, respectively.

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4. PRODUCTION PROCESSES

This chapter will establish the requirements and define the necessary procedures and recommendations for the manufacturing of composite structures (monolithic and sandwich) for OWTP platforms made of fibre-reinforced plastics. Namely, structures made of thermoset resins (mainly epoxy) reinforced with carbon fibres and glass fibres and manufactured by means of vacuum infusion and automated fibre placement will be considered. Then again, the materials and processes described were implemented in the FIBREGY project and the conclusions and actual examples described result from the project output.

Notwithstanding the fact that some guidance notes might, in some cases, be applicable to other processes different from the ones mentioned – such as hand lay-up, automated tape laying or filament/towpreg winding –, it should be noted that it is of the manufacturer's responsibility to ensure that they are certified for it, that the different quality requirements are taken into consideration, and to check if more suitable guidelines or standards exist. Furthermore, indications in the Engineering Drawings and Specific Process Requirements (SPR) should prevail over those of these guidance notes.

4.1. General

4.1.1. Manufacturing process documentation

The manufacturing process documentation is made up of many different documents, such as tool drawings, test equipment drawings, inspection procedures, floor layouts, assembly instructions, and fabrication or work instructions. While these documents are called by different names in different companies, they are all part of process documentation [4].

The Specific Process Requirements (SPR) are found in either the design documentation or the manufacturing documentation. When the design engineer feels the need to specify a particular process, he or she typically does that with an SPR either on a separate document or in a note on the face of a part or assembly drawing. That process specification should be treated as design documentation. All other process documentation should be "owned by" manufacturing [4].

Process documents are typically developed alongside the creation of new products. This parallel approach is essential because manufacturing engineers actively contribute to the project team. However, it's worth noting that the release of the product isn't contingent upon the completion of process documents. These documents often rely on the concurrent finalization of related design documents. Additionally, it's advisable not to delay progress due to design changes while waiting for process documents to catch up. In practice, process engineers can typically start revising process documents once the design phase is successfully concluded [4].

Hence, the particular manufacturing conditions for each element should be indicated in the corresponding work/process documentation and applicable SPR. Nevertheless, the following subchapters will cover the specificities, general requirements, recommendations, advantages and disadvantages of different fabrication approaches, particularly those employed during the FIBREGY project using vacuum infusion and automated fibre placement. Other manufacturing processes may be valid for other components on a case-by-case basis.

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Because this will be later addressed in chapters 7 and 8, this chapter will not focus on the importance of quality control measures in the production process, such as the use of non-destructive testing techniques to ensure the integrity of the finished product. Besides, it also does not include the necessary measures to be adopted from the Health and Safety point of view, which may be specific for some industries and location-dependent. While some safety guidelines and recommendations are provided in Deliverable 4.7, we consider that the user of this specification is liable for compliance with the standards established by the Health, Safety and Work Conditions Committee.

4.1.2. Process Failure Mode and Effect Analysis (PFMEA)

Failure Method and Effects Analysis (FMEA) is a structured approach to detect potential failures within the design of a product or process. These failures are the consequences of ways that lead to waste, defects, or detrimental effects for the customer.

There are two broad categories of FMEA:

- Design FMEA (DFMEA);
- Process FMEA (PFMEA).

Process FMEA (PFMEA) will be now addressed as it is the most important in the context of composite production and manufacturing. PFMEA is a systematic approach used to identify the risks involved in process changes. It initially identifies process functions and formalizes their effects on the failure processes. If there are design inputs or special properties, the end-user effect will also be added. The severity rating or risk of the outcome is determined for each outcome of the failure. Then, the causes of the failure system and their mechanisms are identified. The higher the probability of a cause, the more likely it is that the failure mode will enable actions to prevent or minimize the impact of the cause. Detection rankings determine the ability to confirm that the failure mode of specific tests/causes is eliminated. This way, PFMEA monitors improvements through Risk Priority Number (RPN) reductions, and by comparing back and forth to the RPN, the progress and risk mitigation history can be described [5].

PFMEA should be a part of the process selection to identify the risks before acquiring tools or equipment. Reducing the risk identified prior to the First Article (FA) or Production Part Approval Process (PPAP) will ensure the expectation for better process performance. In short, PFMEA should be used when:

- A new technology or new process that is introduced;
- There is a current process with changes, that may include changes due to updated processes or operations, continuous improvement, Kaizen or Cost of Quality (COQ);
- There is a current process of exposure to change in a new environment or location (no physical change made to implement).

Moreover, PFMEA should cover all relevant components and subsystems involved in a certain process, including all equipment and tooling.

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Figure 4 lists the seven main steps of PFMEA:

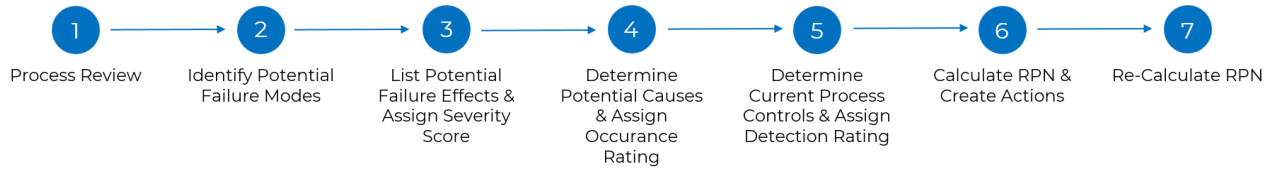

Figure 4 – The seven steps of PFMEA.

Hence, completing a PFMEA will prioritize higher risks with the goal of improving the process, thus giving the process engineers a structured approach to analyse potential failures in the manufacturing process, and what the impact of these failures could be.

4.2. Vacuum Infusion

As previously mentioned, this subsection will delve into the vacuum infusion process, which was employed in the construction of the W2Power demonstrators, including a notable example of the W2Power prototype tower as illustrated in Figure 5. This process has yielded a significant amount of pertinent information that will contribute to the development of these guidance notes.

Figure 5 – W2Power prototype tower

4.2.1. Materials – structural and ancillary materials, material & process specification

This section will provide comprehensive coverage of critical topics related to materials, including both structural and ancillary components, as well as material and process specifications for FRP structures manufactured by vacuum infusion. It encompasses material reception and storage, facilities and equipment, tooling, manufacturing processes, curing, quality control, and demoulding processes.

4.2.1.1. Reception and storage

During the reception and storage of the materials, the manufacturer should ensure that it includes all the necessary documentation, such as [6]:

- Manufacturer's name;
- Product supplier references;

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- The Society product homologation references (number and date of validity of type approval certificates);
- Homologation references from another Classification Society (name and same information as in preceding point);
- Supplier's special requirements, including at least:
    - Minimum and maximum storage temperatures, minimum and maximum storage hygrometry;
    - Product packaging for delivery;
    - Packaging for storage;
    - Maximum shelf life of the product;
    - Type of checks to be performed on incoming products and properties to be tested by shipyard before use;
    - Same type of checks to requalify outdated products (tests to be performed, acceptability criteria, length of extended period of use, special conditions for use).

Besides, the manufacturer's procedures should state arrangements for the reception of incoming materials, in particular [6]:

- Traceability of consignments (references, date of arrival for storage)
- Types of inspection of consignments based on supplier requirements (e.g. check on product packaging);
- Types of tests performed on incoming consignments, to characterise materials;
- Types of specific tests performed (e.g. compatibility between materials);
- Precautions taken when using new materials.

The storage conditions of raw materials should be following the manufacturer's recommendations. Furthermore, it should also be ensured that the manufacturer's procedures include the following information on storage sites and conditions [6][7]:

- Location (or locations):
    - Geographical position in relation to bonding units, stating variations of temperature and hygrometry that products must undergo when transiting from one to another;
    - Ventilation conditions, particularly air-replacement rates;
    - Heating conditions, stipulating means of temperature measurement, recording means, and expected maximum variation (i.e. minimum to maximum temperature);
    - Arrangements for measuring hygrometry, giving at least the same information as for temperature, as well as the intended method of calibration of instruments.
- Recording means available on storage sites:
    - Listing documents related to storage conditions and stored products available on the storage site, and means deployed to ensure that stock managers are informed of arrangements to be made;
    - Listing documents available on measures to be taken by stock managers, if irregularities occur during storage (e.g. excessive storage temperature or hygrometry);

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- Listing documents (and methods of keeping such documents current) to record arrival and departure dates for consignments, with a description of any special event that could affect a consignment during storage.

The manufacturer should also implement procedures to ensure the traceability of materials, from the time of reception until the end of production operations, registering the following information [7]:

- For gel-coats, resins and adhesives:
  - Amount of the various components necessary to prepare the resin systems in relation to the temperature in the laminating unit;
  - Batch reference, date and time of lay-up.
- For reinforcement fabrics:
  - Precautions taken to prevent condensation caused by the temperature difference;
  - Identification of reinforcement fabrics and location in the part to be produced;
  - Batch reference, date and time of lay-up.
- For core materials:
  - Precautions taken to prevent condensation, to avoid gather dust and to reduce the amount of gazing;
  - Identification of core materials and adhesives used for laminating;
  - Batch reference, date and time of lay-up.

4.2.1.2. Structural materials

The raw materials considered as structural materials for vacuum infusion are [8]:

- Thermoset resin's systems;
- Glass, carbon or aramid-based reinforcement fibres and fabrics;
- Core materials.

Other raw materials may be considered, such as the ones mentioned in the NR546 for the manufacturing of hulls in composite, plywood and high-density polyethene materials. This rule note also includes the minimum rule mechanical characteristics of these materials [9].

As a general rule, the main raw materials (resins, reinforcement fabrics and cores) used for structural elements are to be certified by the classification societies (list of EMSA-recognised organisations [10]).

Materials with different resins could be mixed in any type of process, co-curing, co-bonding or secondary bonding for manufacturing a part with a specific "part number", whenever the materials have been qualified as compatible, and this compatibility is stated in the corresponding drawing or applicable SPR.

In non-structural applications, as for example, the co-curing of glass fibre layers as corrosion protection in CFC/Al joints or as prevention against delamination in CFC drilling processes, different materials may be mixed provided that they have been qualified as compatible.

For the selection of composite materials, the standard DNV-ST-C501 [11], for example, covers the design philosophy, design, fabrication and installation of composite components. Deliverable 4.7 also introduces

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the ways to determine the characteristics of the laminate in order to use and to check the design of the structure.

The materials which remain incorporated to the manufactured element should be those indicated in the Engineering Drawings and in accordance with Material Specification (MS). Any change during manufacturing should be cause for rejection and establishment of a Non-Conformity Sheet. Storage terms for each material should be those as indicated in the related material specification – and or Individual Product Specification (IPS). Materials should have a limited life usage within the entire life time – maximum total time at room temperature – and maximum handling life time.

Sandwich construction

In the case of sandwich construction, a more detailed parenthesis will now be made. This is because although there is a wide range of core materials, including foams (PVC, polystyrene, polyurethane, etc.) and honeycombs (aluminium, Nomex, thermoplastic, etc.), a careful selection has to be made to ensure that all factors, besides density, are put into consideration. In particular, if they have a large/open surface cell structure (such as honeycombs), during the vacuum infusion a large mass of resin will be absorbed in their bondlines. Because of this, some core materials are specifically designed for infusion. In some cases, resin grooves can even be added to the core to improve the resin flow and the evacuation of air (Figure 6). Some typical choices of cores for infusion are Soric® infusible core materials, balsa wood, and PVC closed-cell foams [12].

Figure 6 – 3DCORE PET 100 Infusion Foam [13]

Handling of cores, as well as their storage, should be performed in such a way, that no damage, contamination or other circumstances detrimental to the physical and mechanical properties of the core are produced.

For the cutting and machining process, core material should be clean, not showing corrosion, etched or contaminated as a result of contact with grease, oil or other foreign matters. The cores cutting and machining operations should be carried out in areas established for this purpose. They should not be

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performed in the lay-up area or the clean area zone. If necessary, the machining should be carried out with the appropriate jigs and tools, which do not produce tears or contamination of the foam core.

Once the core has been cut and machined to meet the dimensions required in the applicable drawing, and after removing the glass fibre fabrics, adhesive paper, restraining tapes, etc., proceed to clean and store them in tightly sealed bags, identifying them on the outside of the bag.

Special care should be exercised with machined core material equal to or thinner than 1 mm since folds, wrinkles or dents can be easily produced being difficult or impossible to eliminate.

In all cores in which foam adhesive or filler resin has been used and which are to be subsequently bonded, abrade the surface softly with grit 240 to 320 alumina abrasive paper until the gloss disappears.

The forming procedure, if required for curved parts, should be carried in an oven or hot plate press (temperature to be defined according to the material specification), applying forming pressure with the press or transferring the core from the oven to the forming tool, applying forming pressure to avoid the cooling of the hot plate press. During curing, the pressure should be held up to a temperature of ≤60°C.

The cleaning process should be carried out, if required, immediately after the machining and forming processes and should consist of the removal of machining swarf, dust and dirt, etc. by means of vacuum cleaning.

After the cleaning process, the core should be handled with clean gloves and inserted in a plastic bag until it is used.

Ply Cutting

In the case of cutting plies using manual procedure, it should be carried out using appropriate metallic, perfectly clean templates, identified with the following data:

- Identification;
- Position of the ply on the drawing;
- 0° direction (warp direction of fabric or fibre direction in the case of tapes).

The fabrics or tapes, after cutting should not present:

- Contaminations (including the rest of the used film);
- Tearing;
- Cuts or geometry other than those indicated in the drawing.

Depending on the production items to be made and in order to reduce as possible the material exposure at ambient temperature, preparation of kits is advisable.

4.2.1.3. Ancillary materials

Ancillary materials are those used during the fabrication process but not added to the end product, and should be those indicated in the applicable SPR. The purchase, supply and reception should be carried out in accordance with the corresponding Technical Data Sheet or applicable manufacturer normative.

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A list of the typically used ancillary materials is stated below:

- Mould release agent:
  - Liquid or film;
- Peel-ply;
- Release film or fabric:
  - Perforated;
  - Non-perforated;
- Bleeder fabric;
- Breather fabric;
- Film for vacuum bag;
- Sealing paste for vacuum;
- Flow media;
- Solvents:
  - Isopropyl alcohol (IPA);
  - Methyl-ethyl-ketone (MEK);
  - Diestone DLS;
- Miscellaneous:
  - Mould sealer;
  - Polyethylene film for cutting;
  - Cover sheet for protection of manual cutting tables;
  - Rubber pad;
  - Latex rubber pad for compaction;
  - Latex rubber pad for compaction and hot forming;
  - Silicone rubber;
  - Adhesive paper for core fitting;
  - Adhesive tape for core stabilization during machining;
  - High temperature adhesive tape;
  - Double faced self-adhesive tape;
  - Cured silicone edge dam;
  - Polyethylene film for bagging;
  - Anti-humidity barrier;
  - Protector paper;
  - Desiccant;
  - Marking pencil;
  - Marker pen;
  - Identification label;
  - Silicon carbide very fine abrasive felt (Scotch Brite type S);
  - Alumina fine abrasive felt (Scotch Brite type A);
  - Alumina very fine abrasive felt (Scotch Brite type A);
  - Alumina abrasive paper (grit size 80-320);
  - Gloves for handling adhesives film, peel-plies and primed elemental parts prior to bonding:

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- Cotton;
- Nylon;
- Gloves for mould release agent;
- Wipers:
  - Cotton rags;
  - Synthetic rags;
  - Rags soaked in MEK;
  - Rags soaked in JPA;
  - Rags soaked in Diestone DLS;
- Thermocouple wire;
- Spatulas;
- Rigid plastic wedges;
- Cutters and cutting tools.

All ancillary materials which are going to be in direct contact with the structural materials should be stored inside sealed plastic (ideally polyethylene) bags and handled with appropriate gloves. Extreme precautions should especially be taken during the handling and storage of the peel ply, preventing any operation that may prove detrimental to its cleanliness and keeping the material always protected.

4.2.2. Facilities and equipment

Facilities, equipment and personnel should be certified and meet the requirements as established by the manufacturer and the applicable standards.

Eating, drinking, smoking, using waxes or non-cured silicones, usage of motors or equipment that leak oil, grease, lubricant, smoke or any other sort of contaminant, should be prohibited at all production areas.

The lay-up of the structural materials and draping should be carried out in clean, isolated areas, ideally with controlled temperature and humidity. The following section provides some guidance rules for these conditioned zones.

4.2.2.1. Conditioned zones (cleanrooms)

When a conditioned zone (cleanroom) exists for laying up the composite materials, the following practices should be forbidden:

- The use, handling and application of uncured liquid release agents. Exceptionally, for the cleaning of machines inside clean area, whenever are non-removable parts, wipers soaked in MEK or IPA can be used.
- Engines or equipment which release oils, greases, lubricants, fumes or any other type of contaminants.
- Eating, drinking, smoking.
- Using waxes or non-polymerized silicones and any other substance detrimental to the good adhesion of the materials.
- Usage of hand creams.
- Usage of sprays and aerosols except those authorized.

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- Maintenance or cleaning of tools.
- The use of insufficiently cleaned fixtures and tools.
- Sanding and surface preparation before bonding. If it is not avoidable, retouching of parts by light sanding is allowed in restricted zones of the clean area providing that the powder produced is specifically eliminated.
- Any container that may contaminate the clean area.
- Install devices that allow water-free circulation except those as required by the Health and Safety Department.
- Application of resin solutions, for tacking promoter, if it is not avoidable, it can be done guaranteeing that the resin is not transmitted to tools or adhesive materials located around.

The floor should be paved with easily cleaned materials, and the smooth walls should be coated with non-peelable washable paint.

The cleaning of these areas should be performed regularly, according to a predefined inspection calendar. An example is provided below:

Table 1 – Example of cleaning inspection schedule

Cleaning inspection schedule	
Area	Maximum cleaning interval
Equipments, floors, work benches, tools	24 hours, maximum 1 week (ideal: 24 hours)
Walls up to a height of 2,10 m	30 days
Ceilings, hanging devices, etc.	12 months

The workstations should be clean. Cleaning thereof should be required if dirt, dust or contamination is noted after visual examination.

Cleaning of tools and application of mould release agents should not be done within this area.

In order to avoid contamination from the outside in the lay-up area, a minimum 0,5 mm water column overpressure should be maintained, which should be controlled using a differential pressure meter with sufficient accuracy to assure this measurement. A twin door gate-type system, which should be mandatory in the case of direct exit outdoors, is recommended in said areas.

The concentration of airborne particles inside the cleanroom areas has to comply with ISO Class 8 according to EN ISO 14644-1. Sample collection and particle count should be performed by an Optical Particles Counter (OPC) as EN ISO 14644-3. The monitoring plan should be created by the responsible quality department.

4.2.2.2. Thermocouples and vacuum ports

Unless otherwise indicated in the applicable SPR the following requirements must be met (thermocouples only required for heated cure cycles):

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- Number of thermocouples to be used. The parts and control specimens with an area equal to or less than 2 m^2 should be controlled with at least two thermocouples. The parts with an area over 2 m^2 should be controlled with at least one thermocouple per square meter or additional fraction until a maximum of 15 thermocouples is reached.
- The thermocouples distribution should be made homogeneously, in order to know the maximum and minimum temperatures reached in the part. If the thermocouples are not incorporated in the tool, mark their location on the same, and whenever possible, place them between plies in excess areas. When several parts are manufactured on the same tool and under the same vacuum bag, thermocouples must be located per m2 of part area, with a minimum number of thermocouples.
- The location, distribution and number of necessary thermocouples should be defined according to the result of the thermal profile. Manufacturing engineering can authorize to carry out a reduced number of thermal profiles for a family or similar parts, analysing the results and conclusions obtained from the chosen part-tools can be assumed for the rest of the part of the family. If the parts do not require a thermal profile in accordance with manufacturing engineering, the thermocouples should be placed uniformly and between plies in the excess area of the part, inside the vacuum bag.
- In order to prevent any thermocouple displacement during the curing cycle, they should be restrained with high-temperature adhesive tape.
- Check each thermocouple electrically before the curing operation. The accuracy of the thermocouples splice box and the recorder must guarantee ± 3°C between 50°C and 210°C.
- Unless otherwise indicated, two vacuum ports should be used per every m^2 or piece of the part or specimen, placed diagonally and at opposite ends of the bag. One of these should be used as a vacuum source and the other as a control.
- Procedures for the periodic checking of the pressure in the vacuum hoses and connection accessories should be established in order to guarantee their perfect operation.

4.2.2.3. Vacuum pump

The vacuum system used during the infusion process has a big impact on the success of the resulting part, and therefore:

- It's advisable to utilize two types of vacuum pumps: a "high vacuum" pump and a "low vacuum" pump. The high vacuum will be required to pull all the volatiles and moisture out of your material before clamping off the resin feed lines, while the low vacuum will be used after (500mmHg or less). The latter can be an oil-less (or “dry”) rotary vane pump that can handle running at reduced vacuum. Other types of pumps include diaphragm pumps, piston pumps, and oil-lubricated Rotary vane pumps (best for high vacuum).
- In case of necessity, the high vacuum pump can be adjusted using a regulator or bleeder valve.
- When using slightly lower to optimal vacuum conditions, it's essential to adjust the infusion rate, allowing the resin front to effectively displace the remaining air within the dry stack.
- Regular maintenance, including oil changes (if applicable), is an absolute necessity. This upkeep should be conducted every 50 hours of operation or in accordance with the manufacturer's recommendations.

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- To avert production delays arising from potential pump failures, it is strongly recommended to have a contingency plan in place, featuring either a backup vacuum pump or an alternative system.
- Vacuum gauges should be used for monitoring the vacuum levels.

Figure 7 – Examples of pumps (left to right): Gast DOA, Gast 0523, Becker VT-4.16, Edwards E2M-1, Gardner Denver VGD 10, Busch RC0021 [14]

4.2.2.4. Resin trap

Resin traps, or catch pots, are essential to prevent resin from infiltrating the vacuum pump system. The following recommendations can be outlined:

- For larger projects, multiple resin traps are recommended;
- The quantity and volume of resin traps should be calculated in order to avoid overfilling;
- Resin traps come in various designs and configurations to suit diverse applications. Careful consideration should be given to selecting a resin trap that aligns with your specific requirements. In particular, the material of the resin trap should withstand the temperature at which the resin is infused;
- Use discardable buckets inside the resin trap or wax the inside of the tank with mould-release wax to ensure easy removal of the hardened resin;
- Regularly inspect and maintain the resin trap to ensure it functions optimally. Timely maintenance prevents clogs and ensures uninterrupted vacuum performance;
- Determine the required flow rate and capacity of the resin trap based on the volume of resin being processed and the infusion rate. The resin trap should be capable of handling the anticipated resin flow without causing backpressure or overflow;
- Ensure that the materials used in the resin trap are compatible with both the resin and any chemicals or solvents involved in the process. Incompatibility can lead to degradation or contamination issues;
- Choose a resin trap design that facilitates easy inspection, cleaning, and maintenance. Regular maintenance is essential to prevent clogs and maintain consistent vacuum performance;
- Ensure that the resin trap complies with relevant industry standards and safety regulations. Meeting these standards can be essential, especially in industries with stringent quality and safety requirements.

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Figure 8 – Resin traps [15]

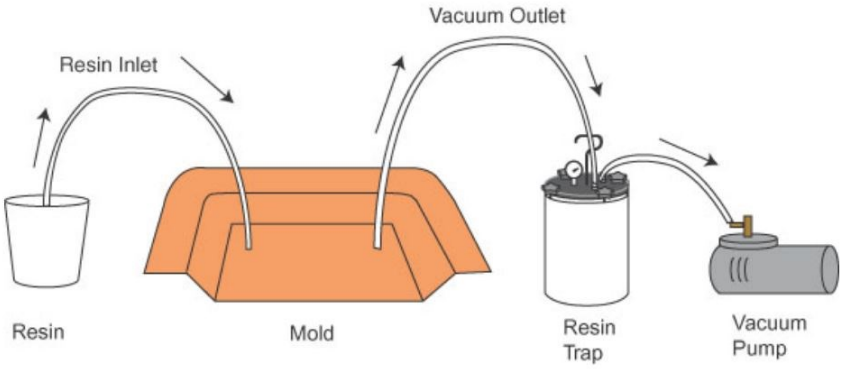

Figure 9 – General sequence of events that comprises vacuum infusion [16]

4.2.2.5. Refrigerators

The refrigerators used for the storage of refrigerated materials (such as adhesives) must be capable of reaching continuous temperatures of -18°C or below the storage temperature indicated in the TDS of the material. Temperature uniformity should be maintained within ± 3 °C.

4.2.2.6. Ply cutting machines

The ply-cutting machines should be certified and must ensure the cutting ply direction inside a tolerance of ± 2° and the ply dimensions within a tolerance of ± 1 mm.

For dimensional and positioning checks of elements, the equipment should have, at least, a precision half of the tolerance required in the drawing of the corresponding element.

All types of lasers used for guidance should be calibrated at least once per year.

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4.2.3. Tooling

Tooling/moulds must be sufficiently rigid to produce parts within the dimensional tolerances, and sufficiently light to comply with the curing cycle heating/cooling rate requirements.

When not indicated in the drawing of the applicable tool, the mould surface in contact with the part should have a surface finish of Ra = 3,2 or better.

The lay-up tools should be identified with the following information:

- Part number (PN);
- The direction of warp fabric or tape fibre direction: 0°.

4.2.3.1. Manufacturing of tools

When manufacturing tools for the vacuum infusion process, adhere to the following guidelines:

- Tools must be constructed in strict compliance with specified requirements and standards.
- The choice of tooling materials should align with project specifications and material compatibility.
- Tool surfaces should be precisely finished to ensure the desired surface quality (Ra = 3,2 or better) and geometry of the final product.
- Tool dimensions, including length, width, and thickness, should conform to design specifications and tolerances.
- The use of appropriate reinforcements, such as ribs or stiffeners, must be considered to maintain tool rigidity and prevent deformation during use.
- Ensure that the tool can withstand the curing temperatures, often exceeding 120°C, without deformation or degradation.
- Account for the thermal expansion of tool materials, such as a coefficient of thermal expansion (CTE) of 40-60 µm/m·K for epoxy composites, to prevent dimensional inaccuracies during temperature fluctuations. For extremely tight tolerances, hard (metal) tools of Invar or Nickel are often used [17]. If the cure if performed at ambient temperature or the tolerances are high, cheaper materials (for example for soft tools) can be considered. An incorrect choice of material can lead to damage to the composite part during the expansion/contraction.
- When using self-heated tools, ensure that the temperature is evenly distributed in the moulding surface and that it can maintain the desired temperature during the entire cure cycle. Heating methods may include electric elements, induction, or specialized heating jackets.
- If multiple tools are used for a single part, ensure they are precisely aligned to maintain part integrity.
- Tool storage should be in a controlled environment, free from excessive temperature fluctuations or moisture exposure, to prevent any potential damage or warping.
- Periodic inspections and maintenance of tools are necessary to address wear, damage, or degradation over time, following as inspection/maintenance plan defined by the quality department.
- For very large tools, materials such as plywood, cut using CNC milling equipment, can be assembled into the final mould if its stability is guaranteed. Air tightness has also to be completely ensured.

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4.2.3.2. Preparation of tools (application of release agents)

- The application and drying of liquid mould release agent should be carried out in a homogeneous, uniform manner and in compliance with the SPR;
- The tool surface preparation prior to placement of the film release agent should be carried out according to the SPR;
- The curing cycle applicable to film release agents is defined in the Engineering Standards;
- The ovens for drying the liquid mould release agents should not be the same ones employed for curing the primers or adhesives, or drying of parts that are to be subsequently bonded or painted;
- Since almost all the liquid release agents contain flammable solvents, it is advisable that the application zone is vented outdoors.

4.2.3.3. Leak testing

Prior to the fabrication process, each recent lay-up tool, either repaired or changed, should be leak proof tested according to the follow procedure:

- Clean and apply mould release agent. A mould sealer material should be applied prior to using mould release material if the tool is recently made or machined.
- Lay up two plies of fibreglass material in the tool.
- Place the thermocouples and vacuum ports.
- Vacuum bag the laminate.
- Cure the composite in accordance with the parameters applicable to the fibreglass material.
- Demould the part.
- Check for leakages by looking for evidence of dark spots on the fibreglass material. No dark spots should be found at the naked eye, independently of their size.
- If any leakage exists, the lay-up tool should be reworked and the leak test performed again.

4.2.4. Manufacturing

4.2.4.1. Preliminary tests

Preliminary tests are highly recommended in order to ensure the feasibility of the vacuum infusion. To do so, the maximum scantling should be put in a mould with a similar section to the real one.

When using carbon fibre materials, because is it difficult to monitor the resin flow and its penetration, a glass fibre layer (which is translucid) can be added on both sides in order to be able to visually see what is happening.

After the curing of the preliminary test part, cut it into several sections to examine it through the thickness and look for voids or dry spots.

4.2.4.2. Lay-up

If refrigerated materials are to be used, after removal from the refrigerator, care should be taken not to open the container before bringing it to room temperature, checking that there is not condensation on the outer surface of the bag. The extraction should be exclusively done inside the lay-up area.

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The kits of materials with a risk of humidity penetrating inside due to breakage of the bags, incorrect closure of the same, etc. should be rejected.

The plies should be placed one on top of the other, respecting the orientations called out in the applicable drawing and minimizing the amount of air occluded below the ply.

Attention should be paid to the nodal core orientation (Ribbon), the ply orientations and the 0° reference direction.

Unless otherwise indicated in the Engineering drawing, the following orientation tolerances should be applied:

- Fabric: ± 5° as regards the warp direction.
- Tape: ± 3° as regards the fibre direction.
- Cores: ± 5° as regards the ribbon direction (for honeycomb cores).

Avoid air occlusions and the formation of wrinkles during the lay-up of the plies. To achieve this, "comb" with spatulas in a parallel direction to the fibres or the warp in the case of fabric.

In order to improve the tack of the fabric during the dry lay-up, specific spray adhesives (such as the one illustrated in Figure 10) may be used to improve adhesion during the moulding. It should be ensured that this adhesive has little or no intrusion in the infusion process to reduce the risk of delamination, and that it meets OTC VOC requirements.

Figure 10 – INFUTAC adhesive spray [18]

Filler Plies and Staggering

Unless otherwise called out in the Engineering drawings or SPR of the parts, the changes in thickness in a laminate should be carried out gradually, by staggering the plies producing a 15° or less transition slope.

When additional filler plies are necessary as indicated in the Engineering drawing, to prevent depressions or gaps in specific core contour areas, the plies should be placed staggered (example in Figure 11). The plies to be used as a filler should be of the same material as that used for manufacturing the part.

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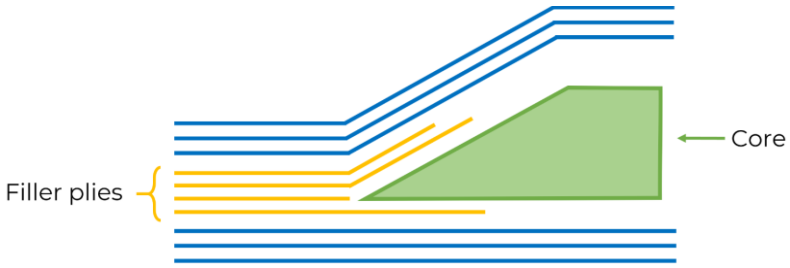

Figure 11 – Illustration of filler plies

Overlaps should be defined in the applicable SPR, and should avoid producing areas with extra thickness. This is achieved by a careful planning distribution of where the overlaps are made.

Peel-plies

The use of peel-ply films is recommended on parts that could possibly be contaminated by machining, prolonged storage, handling etc., which may be detrimental to a subsequent process. Their use should be included in the corresponding SPR. If a bonding process is going to be carried out, it is mandatory that the pre-cured carbon fibre detail parts have the peel ply called out in the SPR.

Peel ply material splicing should be avoided as possible. Splicing should be done flush to the surface of the material if it is unavoidable due to the size of the role. A peel-ply overlap can create a wrinkle condition to the laying material. However, overlaps can be accepted upon approval. Non-porous peel-plies should not be used for vacuum infusion processes.

Waterproofing films and dry coatings

An illustration of how the dry coatings can be integrated into a typical vacuum bag setup for vacuum infusion is represented in Figure 13. The dry coating is intended to be used at the bottom of the mould (between the mould and the laminate) when performing the infusion. The dry coating is located as an extra layer during the fabric layup, as the coating will protect the structure, it is placed directly in contact with the mould, and then dry-reinforcement fibre is laid up on the top followed by a layer of peel ply layer consequently.

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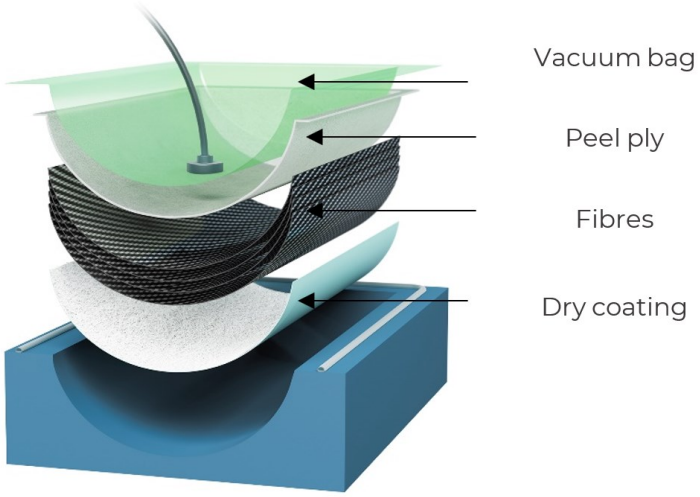

Figure 12 – Use of dry coating in vacuum infusion process principle

Recommendations on the usage of dry coatings as an outcome of the FIBREGY project are provided in Deliverable 6.1 (Public). Some of them can be highlighted here:

- The coating film should be free from any kind of defect, such as pits, cuts, etc.
- During handling, all types of friction, bending or contact with blades and/or cutting items, should be avoided.
- The coating film should be placed from one single pattern whenever permitted by the width of the part.
- When the width of the part exceeds that of the film roll, the pieces should be overlapped approximately 15 - 20 mm, trying, to avoid that the union is produced on the core zone, if possible.
- If allowed by the manufacturer, heat may be applied on the coating film for better adaptation on the surfaces.
- Formation of wrinkles or bridging on the coating film are not permitted.
- In core corners, curved chamfers and irregular surfaces, cuts may be made on the coating film so as to adapt it. There should be no gaps between said cuts, due to which, an additional strip of coating film, 20-30 mm wide, should be placed under the cut.
- Once the coating film has been placed, compaction debulking during 5-10 minutes is recommended.

Flow media

During a vacuum infusion, resin enters the laminate at a fixed point (or points) and must be directed, since resin will always travel in the path of least resistance. This is achieved with the usage of a flow media. Although it is possible to infuse resin into a reinforcement without the addition of flow media, it is rarely successful. The flow media is typically laid as a single layer between layers of reinforcement to provide an easy flow conduit for resin. It is provided in different materials and shapes, providing different infusion times, conformabilities, resin retention, etc. As was seen in section 4.2.1.2, some can even be part of the structure (structural cores) [19].

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4.2.4.3. Debulking

Debulking is the process of compacting a dry fibrous reinforcement prior to resin infusion. This process is meant to decrease the average inter-fibre distance, effectively increasing the fibre volume fraction of the part [20]. In general, the process of debulking consists of:

- Covering ply lay-up with a temporary vacuum bag.
- Apply vacuum to a pressure gage reading in the bag of 530 – 610 mm Hg, at room temperature in sandwich structures (core density ≥ 48 Kg/m^3) and of 635 – 660 mm Hg (core density < 48 KG/m^3), or 76 – 150 mm Hg in laminates. In general, compaction time should not exceed 5 minutes minimum and should not exceed 6 minutes (in the case of a sandwich).
- Disconnect the vacuum and remove the vacuum bag.
- Continue manufacturing/lay-up.

Figure 13 illustrates a temporary vacuum bag scheme for vacuum infusion during debulking.

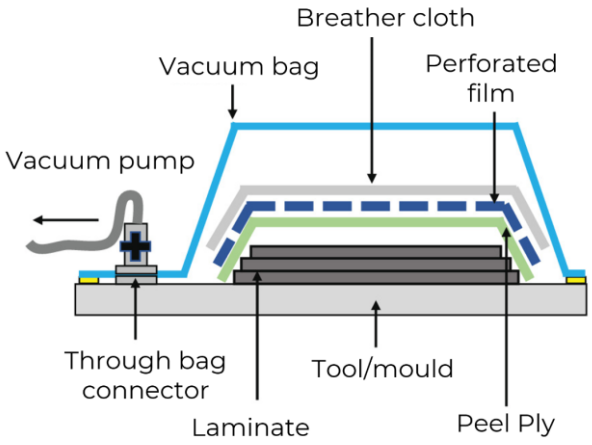

Figure 13 – Vacuum bag scheme [21]

When manufacturing monolithic laminates, debulking should be performed whenever the part is not in lay-up (overnight, for example).

4.2.4.4. Vacuum bagging

The materials used in the construction of the vacuum bag should not be in direct contact with the lay-up, except for peel-plies and release films.

This section indicates general requirements and recommendations for the preparation of the vacuum bag. The specific conditions applicable to each particular part should be indicated in the applicable SPR, and in the corresponding work documentation

After preparation of the vacuum bag, it should remain closed, holding a vacuum up to a pressure (inside the bag) of 0,1-0,8 bars (76-610 mm Hg) for laminates, or up to a pressure (inside in the bag) between 0,7-0,8 bars (530-610 mm Hg) in the case of sandwich structures, up to its vacuum infusion of resin.

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Figure 14 represents a typical vacuum bag scheme for vacuum infusion. The type of bag, construction and materials used should be indicated in the applicable SPR and in the corresponding work documentation.

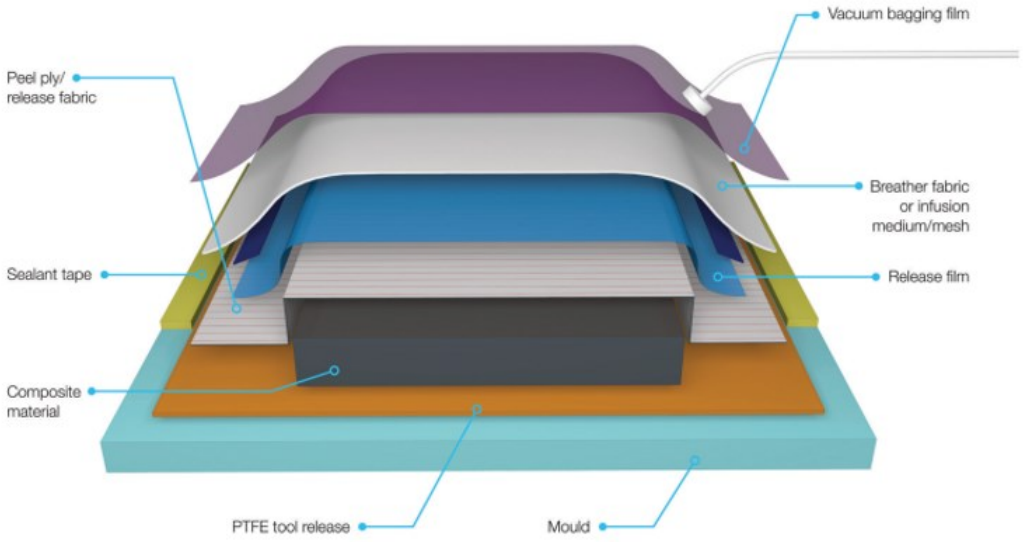

Figure 14 – Illustration of typical vacuum bag setup for infusion [21]

4.2.4.5. Infusion

Before the vacuum bag is closed, careful consideration must be taken in order to set up resin and vacuum lines.

Selection and installation of resin feed lines

The resin will be fed from a standing source (usually a bucket). The line(s) for getting the resin into the laminate will have to be installed before closing the bag, and their position is critical to ensure a good distribution of resin. Typically, spiral tubing (sometimes called spiral wrap) is used, but other materials such as EnkaFusion Filter Jacket [22] can be used as a resin flow channel. Be sure to wrap peel ply around the spiral tubing or place it beneath the Filter Jacket to ensure easy removal from the cured part.

Selection and installation of vacuum lines

In traditional vacuum bagging, a breather/bleeder material is typically used to both absorb excess resin and drive vacuum throughout the laminate. This is typically not used in resin infusion. Instead, the vacuum lines should be extended within the sealed bag.

In order to achieve complete infusion, resin must be pulled to all corners of the laminate. Because the standard set-up infuses into the centre of the laminate, spiral tubing would usually be placed around the flange. Sealant tape should be used to stick the spiral tubing to the mould [19].

A common example of the resin feed and vacuum lines is provided in Figure 15. Spiral tubing is used for both the resin feed and the vacuum line. The resin will enter on one side and fill the length of the tubing very quickly. At that point, the resin will begin to flow across the laminate. While this approach is simpler to set up, the resin will need to travel across a longer distance. Depending on what materials and equipment are

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used, this distance becomes a significant factor. However, on the up-side, the inside surface texture of the finished part will be consistent.

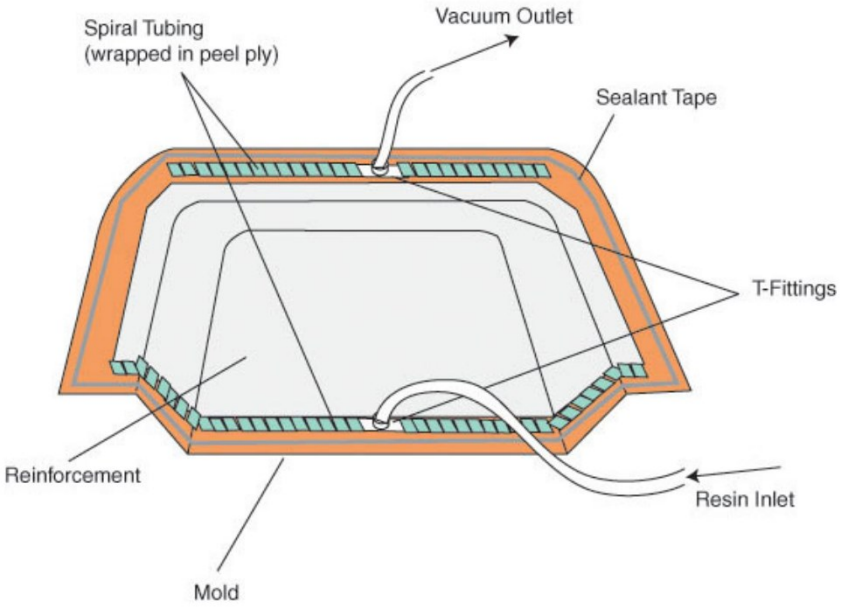

Figure 15 – Example of the resin feed and vacuum lines

Large projects will require multiple resin and vacuum lines. In general, resin lines should not be more than 75-90 centimetres apart under ideal conditions [19]. This number may need to be reduced when using less permeable materials or higher viscosity resins.

Simulation tools of the vacuum infusion process (such as PAM-COMPOSITES [23], example in Figure 16) can help to define this infusion strategy and to plan and predict the resin flow progress

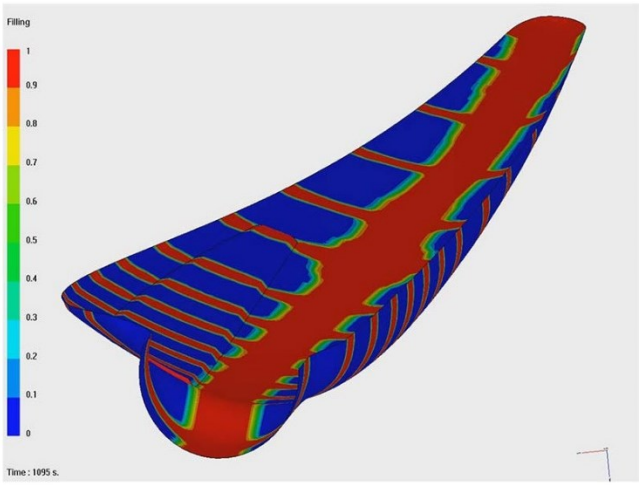

Figure 16 – Wind blade resin infusion with PAM-COMPOSITES [24]

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Clamping

Before the pump is switched on, it is important to clamp off the resin line. Because the vacuum is drawn before the introduction of resin, the resin tube will act as a temporary "leak" that must be sealed off. Clamp off this line by creasing the tube and attaching a flow regulator to hold it in place [19].

Vacuum application

Once all the components are in place, attach the vacuum pump and switch the vacuum on. Search for any leaks within the vacuum bag and vacuum lines by looking for high-pitched noises. An ultrasonic leak detector or a stethoscope may be used.

Resin infusion

Double-check that the resin bucket assembly is firmly in place so the tube will not leave the bucket. Once this is satisfactory, the flow regulator should be removed to unclamp the resin inlet.

Once resin reaches the laminate, the resin feed line will quickly fill up. Once full, the resin will begin to expand outward into the reinforcement. The rate of infusion depends upon many variables, but the resin should be visibly moving. Allow this to continue until the entire laminate is saturated.

Resin clamping off

Once the laminate is completely wet out, crease the tube to stop the resin flow and prevent air bubbles from entering the laminate. This can be achieved by creasing the tube and attaching a flow regulator. Be careful not to perform this without significant force that could potentially spring a new leak. Keep the pump running to maintain constant vacuum pressure until the resin has sufficiently gelled. Otherwise, air could be introduced prematurely.

Monitoring

While infusing, it is recommended to monitor the resin flow rates and resin flow paths over time. This can be done with a simple stop watch and a marker. Start the timer when the resin is first introduced into the laminate. At regular intervals, mark the bag with the resin's current position. This piece of information can be especially helpful upon further infusion attempts, determining if small changes in set-up have any noticeable effect [19].

4.2.4.6. Records

The following information on the different stages of the lay-up process should be registered by the manufacturer during construction:

- Date and time of the operation;
- Temperature and hygrometry during the operation;
- Reference of raw materials used;
- Reference of drawings used;
- Directions of the reinforcement fabrics;
- Preparation of the laminated zone intended for subsequent re-laminating or bonding.

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- Other processes (connections, joints, etc.).

4.2.5. Curing

The specific curing conditions depend on the material and on the type of part to be manufactured. These conditions will be indicated in the SPR of the part and on the corresponding work documentation for each element. The temperature, pressure (if applicable) and vacuum variables should be automatically and continuously recorded. If this is not possible, recordings at maximum intervals of 10 minutes should be taken.

When the resin is of low viscosity and/or high reaction heat, a double-step curing cycle is advisable.

4.2.5.1. Post-curing (if applicable)

Post-curing may be performed when required by the applicable SPR documentation, which should indicate the specific post-curing conditions.

Unless otherwise indicated, the post-cure cycle for previously cured parts subject to a subsequent bonding should be conducted at the same time as the adhesive post-cure. A single post-cure cycle should only be permitted for each assembly installation.

For multiple bonding of part surfaces, the peel ply should only be taken away from the areas that are to be bonded later.

Successive cure cycles should only be conducted for second bonding processes if there is no evidence of stress condition to the part joints existing. For this purpose, the second cure cycle should be performed at a lower temperature.

4.2.6. Process control test panels

Process control test coupons should be made just in case they are required, depending on the maturity, reliability and experience in the manufacturing process used.

The manufacturing of the control test panels should be carried out using the materials that best represent the part to be produced. Ideally, it should travel at all moments with the parts they represent, from lay-up to the final curing, even within the same vacuum bag. If this is not possible, the bags should at least be communicated by means of valves, or ensure that the conditions (resin flow rate, vacuum pressure, temperature, etc.) are applied.

4.2.7. Demoulding

In general, the parts should not be demoulded from the curing tool until a temperature of about 60°C or less has been reached. If applicable, provide the coordinating holes for the contour-cutting operations before the demoulding process.

Avoid causing damage to both the production part and the tool.

During the demoulding operations, the manufacturing control panels should be removed, identifying them with the parts they represent.

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Rigid plastic wedges (Figure 17) can be used to help with the demoulding (placing them between the mould and the laminate), with care not to cause delamination or damage to the tool's surface. Other methods may be used such as cooling the tool or punching (ejector pins).

Figure 17 – Demoulding rigid plastic wedge [25]

4.3. Automated Fibre Placement – Discontinuous Winding

This subsection will delve into the Automated Fibre Placement (AFP) process, which was employed in the construction of the TIDETEC's tidal turbine housing demonstrator, manufactured at INEGI's premisses and illustrated in Figure 18. This process has yielded a significant amount of pertinent information that will contribute to the development of these guidance notes and particularly provide contributes to this sub chapter.

This subsection explores the Automated Fibre Placement (AFP) process, which was utilized in the fabrication of the FRP housing demonstrator for TIDETEC's tidal turbine. This demonstrator was manufactured at INEGI's facilities, as depicted in Figure 18. The AFP process has provided valuable insights and data that will greatly inform the development of these guidance notes, particularly within this subsection.

Bear in mind that the following guidance notes and recommendations were written having in mind the manufacturing of FRP parts with dimensions and configurations that closely resemble the manufactured parts within the scope of the FIBREGY project.

Figure 18 – Tidal turbine housing demonstrator

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4.3.1. Materials

This section will provide comprehensive coverage of critical topics related to materials, including both structural and ancillary components, as well as material and process specifications for FRP structures manufactured by AFP. It encompasses material reception and storage, facilities and equipment, tooling, manufacturing processes, curing, quality control, and demoulding processes.

4.3.1.1. Reception and storage

During the reception and storage of the materials, the manufacturer should ensure that it includes all the necessary documentation, such as [6]:

- Manufacturer's name;
- Product supplier references;
- The Society product homologation references (number and date of validity of type approval certificates);
- Homologation references from another Classification Society (name and same information as in preceding point);
- Supplier's special requirements, including at least:
    - Minimum and maximum storage temperatures, minimum and maximum storage hygrometry;
    - Product packaging for delivery;
    - Packaging for storage;
    - Maximum shelf life of the product;
    - Type of checks to be performed on incoming products and properties to be tested by shipyard before use;
    - The same type of checks to requalify outdated products (tests to be performed, acceptability criteria, length of extended period of use, special conditions for use).

Besides, the manufacturer's procedures should state arrangements for the reception of incoming materials, in particular [6]:

- Traceability of consignments (references, date of arrival for storage)
- Types of inspection of consignments on the basis of supplier requirements (e.g. check on product packaging);
- Types of tests performed on incoming consignments, in order to characterise materials;
- Types of specific tests performed (e.g. compatibility between materials);
- Precautions taken when using new materials.

The storage conditions of raw materials are to be in accordance with the manufacturer's recommendations. Furthermore, it should also be ensured that the manufacturer's procedures include the following information on storage sites and conditions [6][7]:

- Location (or locations):
    - Geographical position in relation to bonding units, stating variations of temperature and hygrometry that products must undergo when transiting from one to another;

  - Ventilation conditions, particularly air-replacement rates;
  - Heating conditions, stipulating means of temperature measurement, recording means, and expected maximum variation (i.e. minimum to maximum temperature);
  - Arrangements for measuring hygrometry, giving at least the same information as for temperature, as well as the intended method of calibration of instruments.
- Recording means available on storage sites:
  - Listing documents related to storage conditions and stored products available on the storage site, and means deployed to ensure that stock managers are informed of arrangements to be made;
  - Listing documents available on measures to be taken by stock managers, if irregularities occur during storage (e.g. excessive storage temperature or hygrometry);
  - Listing documents (and methods of keeping such documents current) to record arrival and departure dates for consignments, with the description of any special event that could affect a consignment during storage.

Refrigerated materials used for manufacturing elements should be within their service lifetimes (i.e. storage lifetime and total lifetime) as pointed out in the material specification requirements.

The refrigerated material should be checked for date and transition time when it is found inside and outside the refrigerator equipment. Also, the handling life time will be checked. Further recommendations on the refrigerator equipment can be found in 4.3.2.1.

If more than one refrigerated material is used for the fabrication of a part, the total lifetime at room temperature will be established considering the material that has less handling lifetime. The time between completion of vacuum bagging and initiation of a cure cycle should be specified in the IPS related to each material. The IPS should also specify the handling life time (time that the material can be exposed to ambient temperature up to lay-up completion).

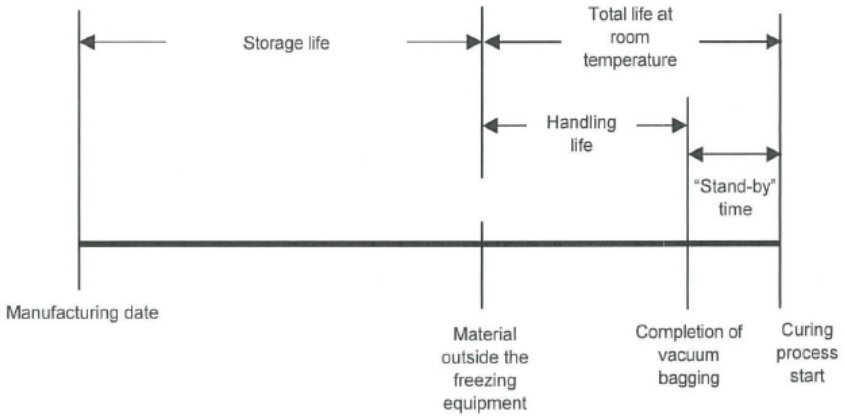

Figure 19 – Recommended definitions of storage, handling life, "stand-by" time and total life.

All these life times (as illustrated in Figure 19) should be taken into consideration, and precautions should be taken to ensure that they are respected from the manufacturing date until the start of the curing process. The transportation conditions of the refrigerated material (e.g. towpreg) should be continuously monitored (temperature history should be provided to the customer), and the temperature controlled using a

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refrigerated truck or if not possible properly conditioned in dry ice. The supplier of the towpreg material should procure a document before shipping, testifying control quality report of the batch.

The manufacturer should also implement procedures to ensure traceability of materials, from the time of reception until the end of production operations, registering the following information [7]:

- For gel-coats, resins and adhesives:
  - Amount of the various components necessary to prepare the resin systems in relation to the temperature in the laminating unit;
  - Batch reference, date and time of lay-up.
- For reinforcement fabrics:
  - Precautions taken to prevent condensation caused by the temperature difference;
  - Identification of reinforcement fabrics and location in the part to be produced;
  - Batch reference, date and time of lay-up.
- For core materials:
  - Precautions taken to prevent condensation, to avoid gather dust and to reduce the amount of gazing;
  - Identification of core materials and adhesives used for laminating;
  - Batch reference, date and time of lay-up.

4.3.1.2. Structural materials

The raw materials considered as structural materials for AFP are [8]:

- Glass, carbon or aramid-based reinforcement fibres and fabrics, pre-impregnated with thermoset resins (although thermoplastic resin systems can also be used) in the shape of towpregs with controlled resin content and a width value of at least a 1/4 inch and ideally 1/2 inch.

While AFP can be adapted for use in sandwich construction in some cases, it's not the most common or conventional choice for creating sandwich structures due to the complexities involved in ensuring proper core-to-skin bonding, core positioning and overall structural integrity. Therefore, the usage of cores will not be considered in this process as AFP parts are almost exclusively monolithic.

Other raw materials may be considered, such as the ones mentioned in the NR546 for the manufacturing of hulls in composite, plywood and high-density polyethene materials. This rule note also includes the minimum required mechanical characteristics of these materials [9].

As a general rule, the main raw materials (resins, reinforcement fabrics and cores) used for structural elements are to be certified by the classification societies (list of EMSA-recognised organisations [10]).

Materials with different resins could be mixed in any type of process, co-curing, co-bonding or secondary bonding for manufacturing a part with a specific "part number", whenever the materials have been qualified as compatible, and this compatibility is stated in the corresponding drawing or applicable SPR.

In non-structural applications, for example, the co-curing of glass fibre prepreg layers as corrosion protection in CFC/Al joints or as prevention against delamination in CFC drilling processes, different materials may be mixed provided that they have been qualified as compatible.

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For the selection of composite materials, the standard DNV-ST-C501 [11], for example, covers the design philosophy, design, fabrication and installation of composite components. Deliverable 4.7 also introduces the ways to determine the characteristics of the laminate in order to use and check the design of the structure.

The materials which remain incorporated into the manufactured element should be those indicated in the Engineering Drawings and in accordance with Material Specification (MS). Any change during manufacturing should be cause for rejection and establishment of a Non-Conformity Sheet. Storage terms for each material should be those as indicated in the related material specification – and or Individual Product Specification (IPS).

The width of 1/2 inch was found to be optimal so that the deposition time covering the whole layup area is reduced while not interfering with the curvature of the mandrel. Also, having a high tow thickness and high filament count (e.g. 48K) helps reducing the layup time. The duration of the layup should not surpass the out life at room temperature of the material and the material will also have a high out life duration.

As an example, the towpreg chosen for the FIBREGY's demonstrator was one from Toray with the designation MR014-2 T800SC-24k-10E /34% and with the characteristics described in Table 2.

Table 2 – Towpreg material properties and characteristics

Toray MR014-2 T800SC-24k-10E /34% Towpreg	
Reinforcement material	Carbon fibre T800SC 48k
Resin type	MR014-2 Towpreg resin
Width of the tow	6.35 mm
Thickness of tow	0.32 mm
Tensile Modulus	4.9 GPa

The material should be stored in a controlled temperature refrigerated chamber, and sealed in plastic bags with a silica bag inside. Before usage of the material, it should be left at room temperature for around 1 hour to prevent condensation around the material when it is in open air.

Unless otherwise specifically indicated, the prepreg materials and structural B-staged adhesives should, in general, be stored in refrigerators at a temperature equal to, or below -18°C, in perfectly sealed polyethene bags, and, whenever possible, in their original packings, avoiding in any case excessive piling up or incorrect placing, which could cause damage to the material. During the defrosting and loading and unloading operations it is permitted to reach maximum peak temperatures of -12°C in the cold-storage rooms, controlled by an environmental thermocouple of these rooms (the prepreg material should be at a maximum temperature of -12°C), for a maximum period of 15 minutes (a total of 60 minutes in 24 hours). Exceeding this period of maximum time and temperature, exposure hours should be charged to the prepreg material.

All materials with limited life, used in manufacturing, should be within their service lifetime.

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4.3.1.3. Ancillary materials

Ancillary materials are those used during the fabrication process but not added to the end product, and should be those indicated in the applicable SPR. The purchase, supply and reception should be carried out in accordance with the corresponding Technical Data Sheet or applicable manufacturer normative.

A list of the typically used ancillary materials is stated below:

- Mould release agent:
  - Liquid or film;
- Peel-ply;
- Release film or fabric:
  - Perforated;
  - Non-perforated;
- Bleeder fabric;
- Breather fabric;
- Film for vacuum bag;
- Sealing paste for vacuum;
- Flow media;
- Solvents:
  - Isopropyl alcohol (IPA);
  - Methyl-ethyl-ketone (MEK);
  - Diestone DLS;
- Miscellaneous:
  - Mould sealer;
  - Resin solution for fixing prepreg layers on tool face;
  - Polyethylene film for cutting;
  - Cover sheet for protection of manual cutting tables;
  - Rubber pad;
  - Latex rubber pad for compaction;
  - Latex rubber pad for compaction and hot forming;
  - Silicone rubber;
  - Adhesive paper for core fitting;
  - Adhesive tape for core stabilization during machining;
  - High temperature adhesive tape;
  - Double faced self-adhesive tape;
  - Cured silicone edge dam;
  - Polyethylene film for bagging;
  - Anti-humidity barrier;
  - Protector paper;
  - Desiccant;
  - Marking pencil;
  - Marker pen;

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- Identification label;
- Silicon carbide very fine abrasive felt (Scotch Brite type S);
- Alumina fine abrasive felt (Scotch Brite type A);
- Alumina very fine abrasive felt (Scotch Brite type A);
- Alumina abrasive paper (grit size 80-320);
- Gloves for handling prepregs, adhesives film, peel-plies and primed elemental parts prior to bonding:
- Cotton;
- Nylon;
- Gloves for mould release agent;
- Wipers:
  - Cotton rags;
  - Synthetic rags;
  - Rags soaked in MEK;
  - Rags soaked in JPA;
  - Rags soaked in Diestone DLS;
- Thermocouple wire;
- Spatulas;
- Rigid plastic wedges;
- Cutters and cutting tools.

All ancillary materials that are going to be in direct contact with the structural materials should be stored inside sealed plastic (ideally polyethene) bags and handled with appropriate gloves. Extreme precautions should especially be taken during the handling and storage of the peel ply, preventing any operation that may prove detrimental to its cleanliness and keeping the material always protected.

4.3.2. Facilities and equipment

Facilities, equipment and personnel should be certified and meet the requirements as established by the manufacturer and the applicable standards.

Eating, drinking, smoking, using waxes or non-cured silicones, usage of motors or equipment that leak oil, grease, lubricant, smoke or any other sort of contaminant, should be prohibited in all production areas.

The lay-up of the structural materials and draping should be carried out in clean, isolated areas, ideally with controlled temperature and humidity. The following section provides some guidance rules for these conditioned zones.

4.3.2.1. Conditioned zones (cleanrooms)

When a conditioned zone (cleanroom) exists for the placement of the AFP robot, the following practices should be forbidden:

- The use, handling and application of uncured liquid release agents. Exceptionally, for the cleaning of machines inside the clean area, whenever there are non-removable parts, wipers soaked in MEK or IPA can be used;

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- Engines or equipment which release oils, greases, lubricants, fumes or any other type of contaminants;
- Eating, drinking, smoking;
- Using waxes or non-polymerized silicones and any other substance detrimental to the good adhesion of the materials;
- Usage of hand creams;
- Usage of sprays and aerosols except those authorized;
- Maintenance or cleaning of tools;
- The use of insufficiently cleaned fixtures and tools;
- Sanding and surface preparation before bonding. If it is not avoidable, retouching of parts by light sanding is allowed in restricted zones of the clean area providing that the powder produced is specifically eliminated;
- Any container that may contaminate the clean area;
- Install devices that allow water free circulation except those as required by the Health and Safety Department;
- Application of resin solutions, for tacking promoter, if it is not avoidable, it can be done guaranteeing that the resin is not transmitted to tools and/or prepregs or adhesive materials located around.

The floor should be paved with easily cleaned materials, and the smooth walls should be coated with non-peelable washable paint.

The cleaning of these areas should be performed regularly, according to a predefined inspection calendar. An example is provided below:

Table 3 – Example of cleaning inspection schedule

Cleaning inspection schedule	
Area	Maximum cleaning interval
Equipment, floors, work benches, tools	24 hours, maximum 1 week (ideal: 24 hours)
Walls up to a height of 2,10 m	30 days
Ceilings, hanging devices, etc.	12 months

The robot equipment and the AFP head should be clean. Cleaning thereof should be required if dirt, dust or contamination is noted after a visual examination.

Cleaning of tools and application of mould release agents should not be done within this area.

In order to avoid contamination from the outside in the lay-up area, a minimum 0,5 mm water column overpressure should be maintained, which should be controlled by means of a differential pressure meter with sufficient accuracy to assure this measurement. A twin door gate-type system, which should be mandatory in the case of direct exit outdoors, is recommended in said areas.

The concentration of airborne particles inside the cleanroom areas has to be in compliance with ISO Class 8 according to EN ISO 14644-1. Sample collection and particle count should be performed by an Optical

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Particles Counter (OPC) as EN ISO 14644-3. The monitoring plan should be created by the responsible quality department.

4.3.2.2. AFP equipment

The equipment for the deposition of the towpreg should be able to perform the winding of the mandrel and have at least six degrees of freedom to enable full translation and rotation of the head. In the case of discontinuous winding the rotation of the mandrel should account for an additional degree of freedom.

The supports needed for the mandrel must possess certifications that ensure they can accommodate mandrels weighing up to 200 kg, with an external diameter of 1000 mm and a distance of 1,5 meters between supports. Additionally, the supports should perform sufficient torque and have sufficient mass inertia tolerance to effectively handle the mandrel.

For instance, the positioner employed in the setup utilized for producing the Tidal housing is the KUKA KP1-HC1000 R1280, as depicted in Figure 20. The characteristics of this positioner can be found in Table 4.

Figure 20 – Kuka positioner used for turning the mandrel

Table 4 – Kuka positioner characteristics

KUKA KP1 – HC1000 R1280	
Max. loading height	1250 mm (2500 mm in diameter)
Rated payload	1000 kg
Permissible mass moment of inertia	719 kg·m^2
Max. load torque	1472 N·m
Usable Distance range between supports	1450 – 3450 mm

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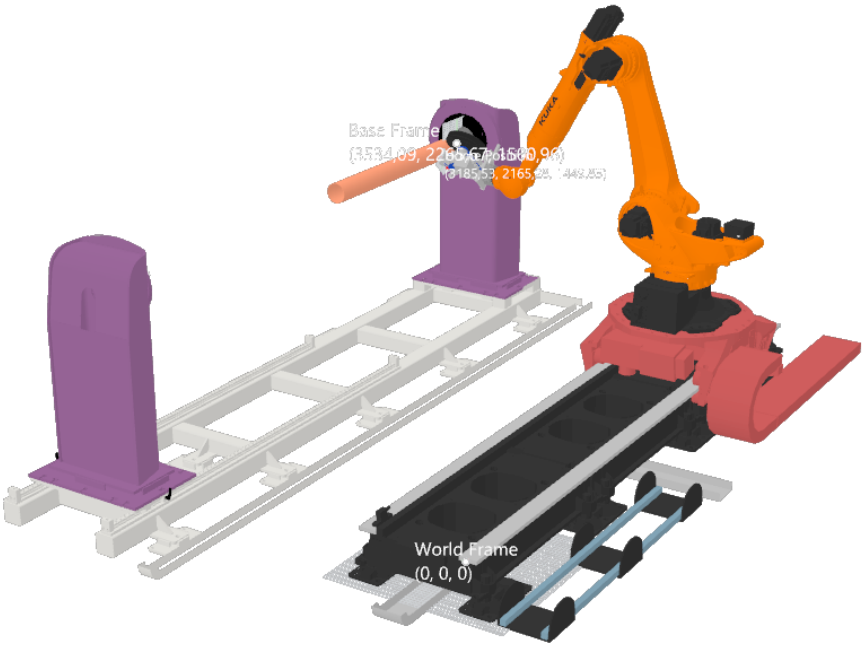

Figure 21 – AFP equipment

The AFP equipment should be certified and should meet requirements established by the manufacturer.

To improve the tacking of the towpreg, these machines can incorporate a controlled heating system (electrical resistance, IR lamps, etc.) to warm (director indirectly) locally the material during a short time ≤2 minutes at a maximum temperature of 65°C. These heating systems should be verified, at least, every 12 months.

4.3.2.3. Autoclaves and curing ovens

The autoclaves and curing ovens should be of the forced circulation type, and capable of:

- Reaching and maintaining the stabilization temperatures of the curing cycles, within a tolerance of ± 5°C;
- Developing heating/cooling rates in the range of 0,5 – 5,0°C/minute;
- Maintaining the required pressures during the curing cycle, within a tolerance of ± 0,35 bars (± 5 psi) (autoclave only);
- Hold on the required vacuum pressure during the cure cycle to an allowance of +/-25 mm Hg;
- Automatically and continuously recording the temperature, pressure and vacuum variables, as applicable. If this is not possible, recording at maximum intervals often minutes is allowed.

It is advisable that the autoclaves operate with nitrogen and be capable of reaching temperatures of up to 250°C, and pressures of up to 10 bars. Up to 600 mmHg vacuum pressure can be reached.

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4.3.2.4. Thermocouples and vacuum ports

Unless otherwise indicated in the applicable SPR the following requirements must be met (thermocouples only required for heated cure cycles):

- Number of thermocouples to be used. The parts and control specimens with an area equal to or less than 2 m^2 should be controlled with at least two thermocouples. The parts with an area over 2 m^2 should be controlled with at least one thermocouple per square meter or additional fraction, until a maximum of 15 thermocouples is reached;
- The thermocouples distribution should be made homogeneously, in order to know the maximum and minimum temperatures reached in the part. If the thermocouples are not incorporated in the tool, mark their location on the same, and whenever possible, place them between plies in excess areas. When several parts are manufactured on the same tool and under the same vacuum bag, thermocouples must be located per each m2 of part area, with a minimum number of thermocouples;
- The location, distribution and number of necessary thermocouples should be defined according to the result of the thermal profile. Manufacturing engineering can authorize to carry out a reduced number of thermal profiles for a family or similar parts, analysing the results and conclusions obtained from the chosen part-tools can be assumed for the rest of the part of the family. If the parts do not require a thermal profile in accordance with manufacturing engineering, the thermocouples should be placed uniformly and between plies in the excess area of the part, inside the vacuum bag;
- In order to prevent any thermocouple displacement during the curing cycle, they should be restrained with high-temperature adhesive tape;
- Check each thermocouple electrically before the curing operation. The accuracy of the thermocouples splice box and the recorder must guarantee ± 3°C between 50°C and 210°C;
- Unless otherwise indicated, two vacuum ports should be used per every m^2 or piece of the part or specimen, placed diagonally and at opposite ends of the bag. One of these should be used as a vacuum source and the other as a control;
- Procedures for the periodic checking of the pressure in the vacuum hoses and connection accessories should be established in order to guarantee their perfect operation.

4.3.2.5. Vacuum pump

The vacuum system used during the curing of the AFP-manufactured has a big impact on the success of the resulting part, and therefore:

- Determine the vacuum level needed for your AFP process. AFP typically requires a high vacuum level. Choose a pump that can achieve and sustain the required vacuum level efficiently;
- Invest in a high-quality vacuum pump from reputable manufacturers. Quality pumps are more reliable, have longer lifespans, and require less maintenance;
- Oil-sealed pumps should be used, as they provide deep vacuum despite requiring oil changes and maintenance;

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- Look for pumps with built-in regulation and control features. These allow you to adjust the vacuum level precisely, crucial for resin infusion control. Vacuum gauges should be used for monitoring the vacuum levels;
- Regular maintenance, including oil changes (if applicable), is an absolute necessity. This upkeep should be conducted every 50 hours of operation or in accordance with the manufacturer's recommendations;
- To avert production delays arising from potential pump failures, it is strongly recommended to have a contingency plan in place, featuring either a backup vacuum pump or an alternative system.

4.3.2.1. Refrigerators

The refrigerators used for the storage of refrigerated materials (such as adhesives) must be capable of reaching continuous temperatures of -18°C or below the storage temperature indicated in the TDS of the material. Temperature uniformity should be maintained within ± 3 °C.

4.3.3. Tooling/Mandrels

Tooling/mandrels must be sufficiently rigid to produce parts within the dimensional tolerances, and sufficiently light to comply with the curing cycle heating/cooling rate requirements.

When not indicated in the drawing of the applicable tool, the mould surface in contact with the part should have a surface finish of Ra = 3,2 or better.

The lay-up tools should be identified as minimum with the following information:

- Part number (PIN);
- Direction of warp fabric or tape fibre direction: 0°.

4.3.3.1. Manufacturing of tools/mandrels

When manufacturing tools for the vacuum infusion process, adhere to the following guidelines:

- Tools must be constructed in strict compliance with specified requirements and standards.
- The choice of tooling materials should align with project specifications and material compatibility.
- Tool surfaces should be precisely finished to ensure the desired surface quality (Ra = 3,2 or better) and geometry of the final product.
- Tool dimensions, including length, width, and thickness, should conform to design specifications and tolerances.
- The use of appropriate reinforcements, such as ribs or stiffeners, must be considered to maintain tool rigidity and prevent deformation during use.
- Ensure that the tool can withstand the curing temperatures, often exceeding 120°C, without deformation or degradation.
- Account for the thermal expansion of tool materials, such as a coefficient of thermal expansion (CTE) of 40-60 µm/m·K for epoxy composites, to prevent dimensional inaccuracies during temperature fluctuations. For extremely tight tolerances, hard (metal) tools of Invar or Nickel are often used [17]. If the cure is performed at ambient temperature or the tolerances are high, cheaper materials (for example for soft tools) can be considered. A mandrel made of a material with high CTE, e.g.

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aluminium, may be desirable as it will help with demoulding. An incorrect choice of material can lead to damage of the composite part during the expansion/contraction.

- When using self-heated tools, ensure that the temperature is evenly distributed in the moulding surface and that it can maintain the desired temperature during the entire cure cycle. Heating methods may include electric elements, induction, or specialized heating jackets.
- If multiple tools are used for a single part, ensure they are precisely aligned to maintain part integrity.
- Tool storage should be in a controlled environment, free from excessive temperature fluctuations or moisture exposure, to prevent any potential damage or warping.
- Periodic inspections and maintenance of tools are necessary to address wear, damage, or degradation over time, following as inspection/maintenance plan defined by the quality department.

Some other recommendations, although being of the design team's responsibility, can be given to the manufacturing team for verification:

- For the end caps of the mandril, it is necessary to have a higher radius of curvature and a high ratio of end cap height to external diameter to prevent tow slippage and steep tool angles. If the end caps are of different sizes, it is possible to have as an additional feature a demoulding angle, which is desirable but should not be steeper than 3°. Alternatively, the mandrel can be designed with modular assembly having a piece that folds on itself to help with the demoulding.
- The final dimensions must be measured and compared against the original CAD model and production drawings. Any variations larger than 1 mm compared to the drawings should be corrected with machining and/or filling products. If filling products are used, the mixing ratios and curing times should be followed in accordance with the respective technical specifications. The final mould should be updated in the CAD model so that the program can plan the tapes in the correct position.
- Other areas that will present difficulties in the demoulding, such as concave and convex areas, negative demoulding angles (Figure 22) or scratches/deep grooves must be addressed and corrected accordingly using machining, sanding and filling (Figure 23).

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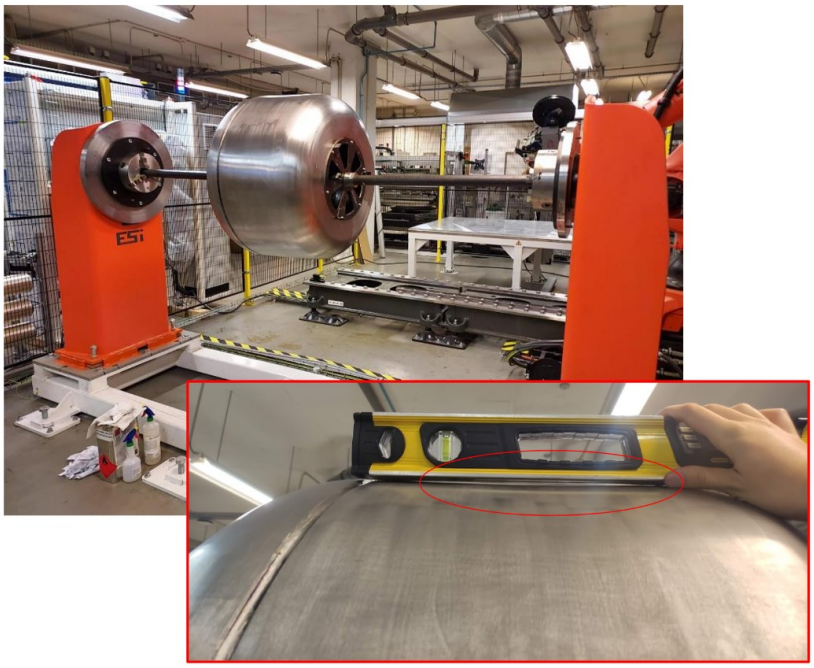

Figure 22 – Example of negative draft angle due to sinking/warping due to welding to the mandrel

Figure 23 – Example of good draft angle after correction

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4.3.3.2. Preparation of tools (application of release agents)

- The application and drying of liquid mould release agent should be carried out in a homogeneous, uniform manner and in compliance with the specifications;
- The tool surface preparation prior to placement of the film release agent should be carried out according to the specifications;
- The curing cycle applicable to film release agents is defined in the Engineering Standards;
- The ovens for drying the liquid mould release agents should not be the same ones employed for curing the primers or adhesives, or drying of parts that are to be subsequently bonded or painted;
- Since almost all the liquid release agents contain flammable solvents, the application zone should be vented outdoors.

4.3.3.3. Leak testing

Prior to the fabrication process, each recent lay-up tool, either repaired or changed, should be leak proof tested according to the following procedure:

- Clean and apply mould release agent. A mould sealer material should be applied prior to using mould release material if the tool is recently made or machined.
- Lay up two plies of fibreglass material in the tool.
- Place the thermocouples and vacuum ports.
- Vacuum bag the laminate.
- Cure the composite in accordance with the parameters applicable to the fibreglass material.
- Demould the part.
- Check for leakages by looking for evidence of dark spots on the fibreglass material. No dark spots should be found at naked eye, independently of their size.
- If any leakage exists, the lay-up tool should be reworked and the leak test performed again.

4.3.4. Manufacturing

4.3.4.1. Preparation for manufacturing - programming

Preliminary tests are highly recommended in order to ensure the feasibility of the automated fiber placement. These preliminary tests, or manufacturing trials, are followed hand-in-hand with successive iterations of the definition of the tape planning programming.

To start the manufacturing trials, it is necessary to build up the first iteration program for the robot to be able to layup the tapes automatically. In the example of INEGI's manufacturing, the AFP head mounted on the robot was made by AddComposites and their tape layup planner is the AddPath plugin for the Rhinoceros 3D Cad program.

In the general sense, after having installed the end tool on the selected robot the manufacturing engineer should follow the suggested documentation for the manufacturer of the head and of the robot, as well as follow its Health and Safety guidelines and its programming language standards and functions.

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The files that describe the geometry should be converted in IGES or STEP format and ensure that any of the dimensions aren't corrupted in the conversion process. Namely, any surfaces or reference points required for the correct definition of the program should be correctly included in said file as can be seen on the example of the following Figure 24.

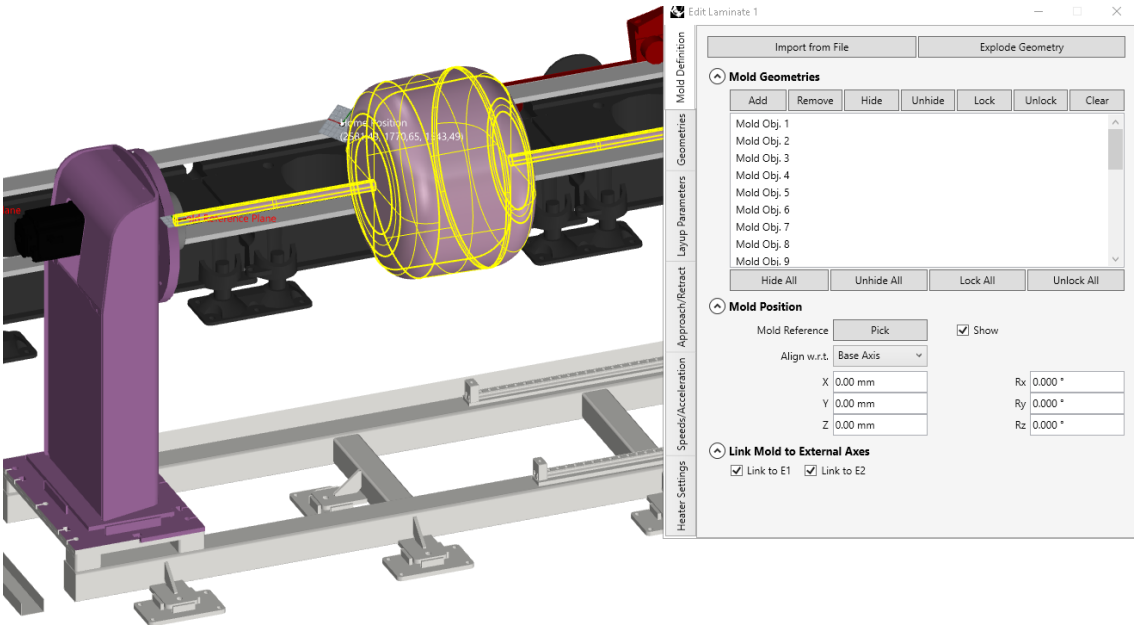

Figure 24 – Mould definition and position in the Rhinoceros 3D using AddPath plugin

Regarding the planning of the tapes the planner mode should be of Discontinuous Winding to ensure proper deposition and required reinforcement of the tapes in the design area. The tapes should be laid in the defined Layup Area, without extending to the Boundary Area. The width of the roller which is wider than the width of the tape should also be considered when defining the Layup Area, so that the robot doesn't damage the deposition roller while in manufacturing. The deposition roller should be inspected regularly at the end of each manufacturing day, ensuring that there isn't any damage that could hinder the manufacturing process. In case of damage, the deposition roller should be replaced. The Direction plane should be set at 0° along the axis direction and 90° in a perpendicular direction to the axis. It is crucial to ensure that the direction of tape stacking is correct, as an inward-facing arrow could result in the robot head colliding with mould. An example of the definition of Layup Area and Boundary area can be seen in Figure 25.

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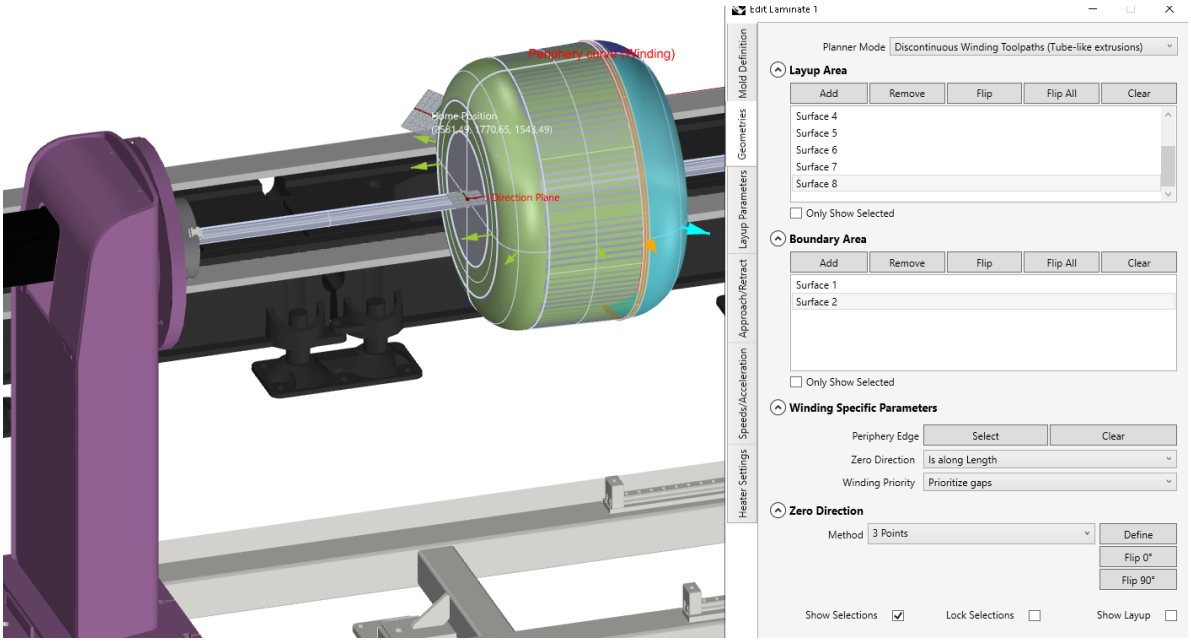

Figure 25 – Planner mode and Layup area definition

In the planning of the tapes, the correct definition of the material parameters should be inputted so that the robot can appropriately calculate deposition paths in accordance to the used material.

The layup angle should be established by trial-and-error iterations, since a higher ply angle results in a larger aperture, whereas a lower ply angle restricts the tapes within the layup area. In other words, this means that the layup area implicates a certain winding angle or conversely, a certain winding angle implicates a layup area.

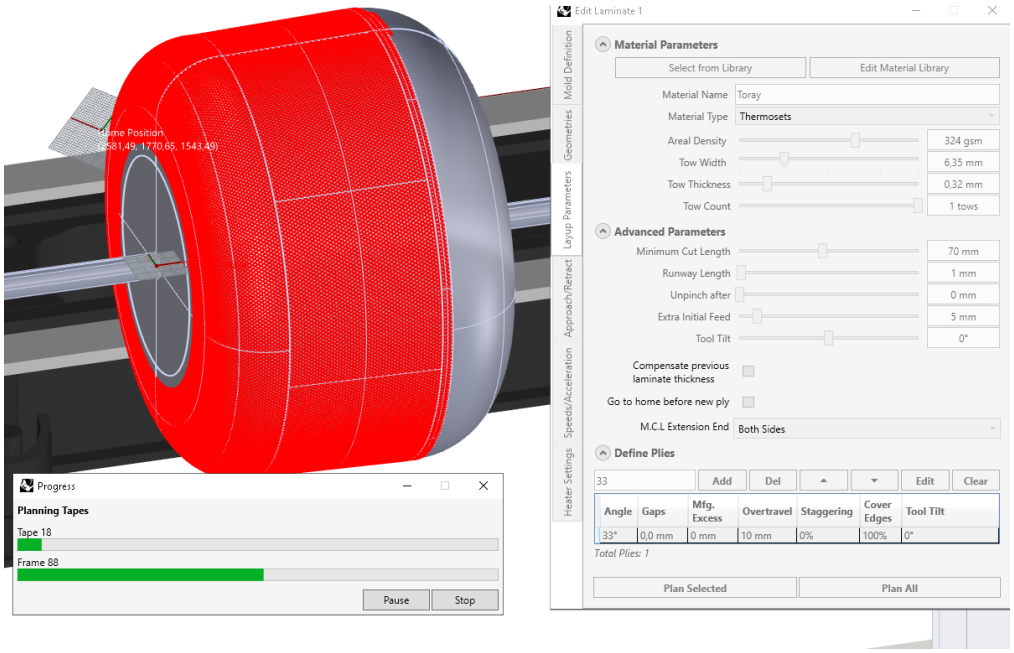

Figure 26 – Layup parameters

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A heating lamp should be programmed during deposition, ensuring that there is roughly 50°C to 60°C (example in Figure 27) on the area of the mandrel closest to the lamp. This temperature will enable optimal adhesion and conformation of the tapes to mandrel, but depends on its natural tackiness and therefore should be adjusted to the specific material used.

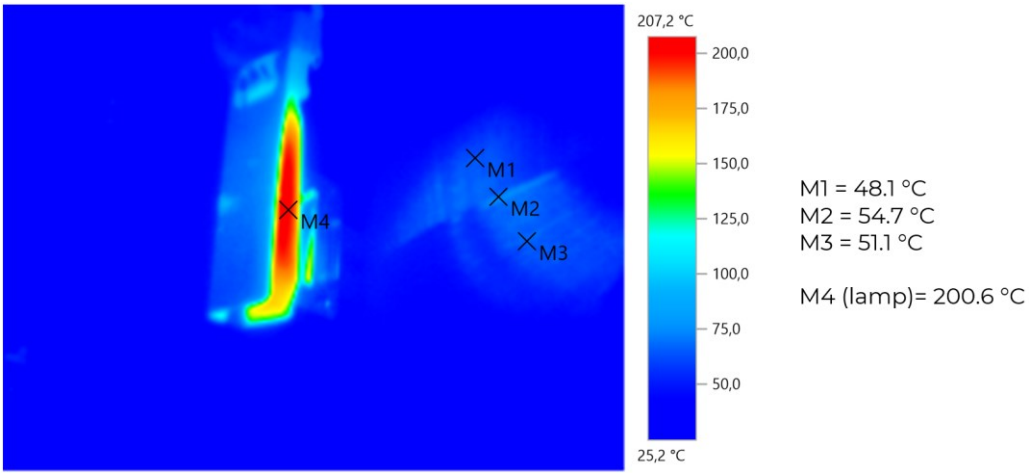

Figure 27 – Thermography near the lamp

An initial test of the deposition of the tapes should be carried out, to ensure proper programming was done. If need be, further alteration of the program should be carried out ensuring correct and safe deposition of the tapes in the mandrel. Some adjustments to the CAD of the mandrel may be implemented to increase the pressure of the deposition roller. The ideal situation is when the tapes are laid out without gaps and without overlapping. Another possible adjustment to be done is to modify the width of the tapes to force the position of the tape.

Figure 28 – Initial manufacturing trials

It is also necessary to verify that the coordinates for the Base axis or centre of the chuck coincide with those from the robot definition and program definition, as otherwise there will be present overpressure on the return and almost no pressure on the roller from the start to the middle of the tape. Such verification should

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be certified with conjunction with the manufacturer of the deposition head. The roller should have a uniform pressure set to 150 to 160 MPa.

The program planned should also be used in conjunction with the respective simulation to check for collisions of the robot in the cell. This will ensure safe usage of the robot. After validating everything, with all the optimal and necessary parameters the final program can be generated using a custom post-processor file.

4.3.4.2. Automated fibre placement

When using AFP for discontinuous winding (as in the FIBREGY's demonstrator), it is crucial to pay special attention to securely fastening the chuck to prevent any sliding of the shafts during rotation. Figure 29 illustrates an example of mandrel assembled into the robot supports.

Figure 29 – Example of assembly of the mandrel on the robot supports

After the successful manufacturing trials, the results and outcomes should be registered and the resulting lessons learned should be carried out during the manufacturing campaign.

The material used during manufacturing should be securely attached to the head and enable correct tensioning. If need be, custom supports or fittings to secure the material to the head can be deployed as long as the feeding of the material is similar to the original support material without performance issues.

As the AFP material is stored frozen, there must be caution to store it in sealed bags with silica bags inside to prevent humidity from damaging the material. Before use and opening the sealed bags, the material should be left at room temperature for about half an hour for the tape reels and one hour for the AFP spools, so that there isn't condensation forming on the material and damaging it.

The first layer should require slower laying tape speed to ensure better adhesion to the mandrel. From the middle of the first layer onwards, the deposition of the tapes will already be happening on top of previous tapes so it can be done at the maximum speed. As each layer is locally taped criss-crossing angles, the actual thickness of one layer is estimated to equal twice the thickness of the tow.

There should be close inspection of the performance of the deposition, as after some tapes, the machine's performance will most likely start to degrade and could even results in warnings of the machines. This decline in performance is the result of accumulation of composite material in the machine as the tapes rub on it. As such, it should be established routine cleaning of the head every such number of layers, and at

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INEGI's example every 50 layers. It should be thoroughly cleaned the feeding roller, the end shut part, the guiding rollers, and the cutting mechanism of the tapes. For this, it should be used IPA or acetone. If using acetone, the machine should be completely dried out before starting using, as acetone can degrade the material in deposition.

In the following set of photos in Figure 30, it is possible to verify, as an example, the progression of the deposition of the tapes onto the mandrel for the FIBREGY housing demonstrator.

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Figure 30 – Production sequence of timelapse photos for the first layer

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For AFP processes in which overlapping is inevitable, a maximum overlap of 1 mm with a 12 mm stagger should be permitted. In special cases, deviations from the mentioned should be permitted with prior agreement between the engineering teams.

Loading of material

When the towpregs and adhesives are removed from the refrigerator, care should be taken not to open the container before bringing it to room temperature, checking that there is not condensation on the outer surface of the bag. The extraction should be exclusively done inside the lay-up area.

The kits of materials with risk of humidity penetrating inside due to breakage of the bags, incorrect closure of the same, etc. should be rejected.

Once the towpreg materials have been brought to room temperature, the material can be loaded onto the robot tool and the program for winding or tape laying can be run. If a protection paper exists, remove one end and place it on the specific bearing, with extreme care so as not to detach strands, alter their alignment nor produce damages.

Peel-plies

The use of peel-ply films is recommended on parts which could possibly be contaminated by machining, prolonged storage, handling etc., which may be detrimental to a subsequent process. Their use should be included in the corresponding SPR. If a bonding process is going to be carried out, it is mandatory that the precured carbon fibre detail parts have the peel ply called out in the SPR.

Peel ply material splicing should be avoided as possible. Splicing should be done flush to the surface of the material if it is unavoidable due to the size of the role. A peel ply overlap can create a wrinkle condition to the laying material. However, overlaps can be accepted upon approval.

Dry coatings

An illustration of how the dry coatings can be integrated into a typical vacuum bag setup for AFP (concave tooling) is represented in Figure 31. The dry coating is intended to be used at the bottom of composite mould (between the mould and the laminate) when performing the fibre placement. The dry coating is located as an extra layer during the fabric layup, as the coating will protect the structure, it is placed directly in contact with the mould, and then dry-reinforcement fibre is laid up on the top followed by a layer of peel ply layer consequently.

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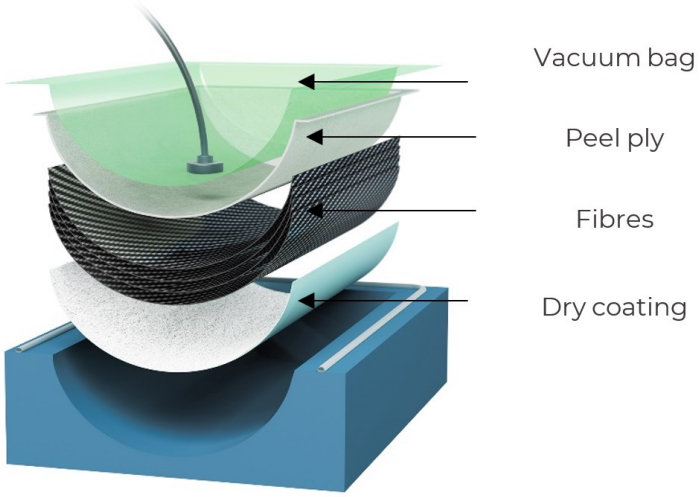

Figure 31 – Use of dry coating in vacuum infusion process principle

Recommendations on the usage of dry coatings as an outcome from the FIBREGY project are provided in Deliverable 6.1 (Public). Some of them can be highlighted here:

- The coating film should be free from any kind of defect, such as pits, cuts, etc.
- During handling, all types of friction, bending or contact with blades and/or cutting items, should be avoided.
- The coating film should be placed from one single pattern whenever permitted by the width of the part.
- When the width of the part exceeds that of the film roll, the pieces should be overlapped approximately 15 - 20 mm, trying, to avoid that the union is produced on the core zone, if possible.
- If allowed by the manufacturer, heat may be applied on the coating film for better adaptation on the surfaces.
- Formation of wrinkles or bridging on the coating film are not permitted.
- In core corners, curved chamfers and irregular surfaces, cuts may be made on the coating film so as to adapt it. There should be no gaps between said cuts, due to which, an additional strip of coating film, 20-30 mm wide, should be placed under the cut.
- Once the coating film has been placed, compaction debulking during 5-10 minutes is recommended.

The same recommendations are applied for the usage of waterproofing films.

4.3.4.3. Vacuum bagging

The materials used in the construction of the vacuum bag should not be in direct contact with the lay-up, with the exception of peel-plies and release films.

This section indicates general requirements and recommendations for the preparation of the vacuum bag. The specific conditions applicable to each particular part should be indicated in the applicable SPR, and in the corresponding work documentation.

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After preparation of the vacuum bag, it should remain closed, holding a vacuum up to a pressure (inside the bag) of 0,1-0,8 bars (76-610 mm Hg) for laminates, or up to a pressure (inside in the bag) between 0,7-0,8 bars (530-610 mm Hg) in the case of sandwich structures, up to its vacuum infusion of resin.

Figure 32 represents a typical vacuum bag scheme for vacuum infusion. The type of bag, construction and materials used should be indicated in the applicable SPR and in the corresponding work documentation.

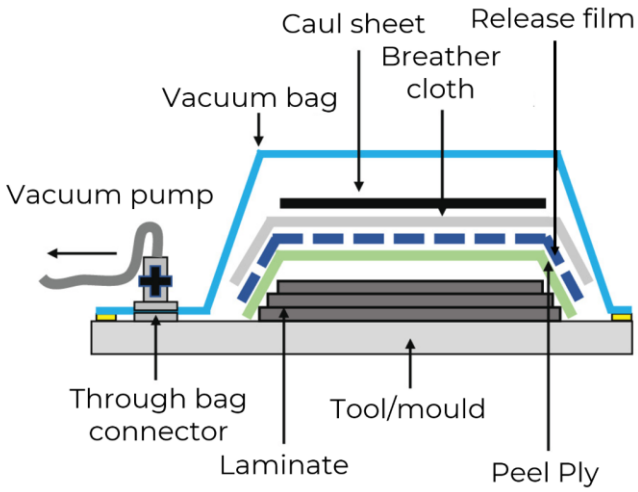

Figure 32 – Illustration of typical bag setup for AFP produced parts

As illustrated in Figure 33, pleats in the vacuum bag should be strategically made to accommodate excess bagging material, avoiding bridges of the vacuum bag and provide room for the proper expansion of the laminate during the curing process. These pleats play a critical role in maintaining consistent vacuum pressure and minimizing the risk of voids or defects in the final composite laminate. The sealant tape should be pressed with a spatula to ensure complete air-tightness.

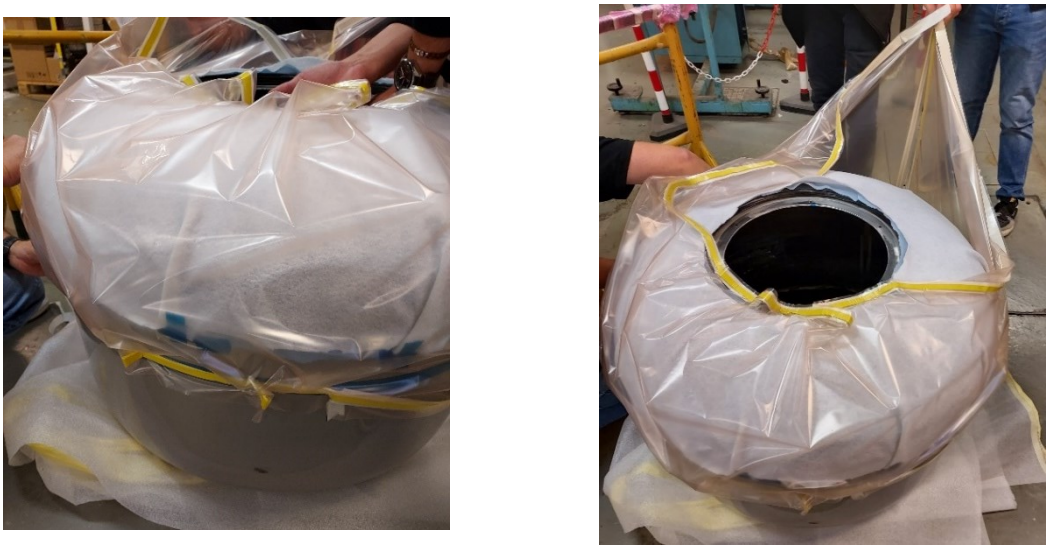

Figure 33 – Application of the vacuum bag

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4.3.4.4. Records

The following information on the different stages of the lay-up process should be registered by the manufacturer during construction:

- Date and time of the operation;
- Temperature and hygrometry during the operation;
- Reference of raw materials used;
- Reference of drawings used;
- Directions of reinforcement fabrics;
- Preparation of the laminated zone intended for subsequent re-laminating or bonding.
- Other processes (connections, joints, etc.).

4.3.5. Curing

The specific curing conditions depend on the material and on the type of part to be manufactured. These conditions will be indicated in the SPR of the part and on the corresponding work documentation for each element. The temperature, pressure (if applicable) and vacuum variables should be automatically and continuously recorded. If this is not possible, recordings at maximum intervals of 10 minutes should be taken.

When the resin of the prepreg is of low viscosity and/or high reaction heat, a double-step curing cycle is advisable.

4.3.5.1. Post-curing (if applicable)

Post-curing may be performed when required by the applicable SPR documentation, which should indicate the specific post-curing conditions.

Unless otherwise indicated, the post-cure cycle for previously cured parts subject to a subsequent bonding, should be conducted at the same time as the adhesive post-cure. A single post-cure cycle should only be permitted for each assembly installation.

For multiple bonding of part surfaces, the peel ply should only be taken away from the areas that are to be bonded later.

Successive cure cycles should only be conducted for second bonding processes if there is no evidence of stress condition to the part joints existing. For this purpose, the second cure cycle should be performed at a lower temperature.

4.3.6. Process control test panels

Process control test coupons should be made just in case they are required, depending on the maturity, reliability and experience in the manufacturing process used.

The manufacturing of the control test panels should be carried out using the materials that best represent the part to be produced. Ideally, it should travel at all moments with the parts they represent, from lay-up to the final curing, even within the same vacuum bag. If this is not possible, the bags should at least be

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communicated by means of valves, or ensure that the conditions (resin flow rate, vacuum pressure, temperature, etc.) are applied.

4.3.7. Demoulding

In general, the parts should not be disassembled from the curing tool until a temperature of about 60°C or less has been reached. If applicable, provide the coordinating holes for the contour-cutting operations before the demoulding process.

Avoid causing damage to both the production part and the tool.

During the demoulding operations, the manufacturing control panels should be removed, identifying them with the parts they represent.

Rigid plastic wedges (Figure 34) can be used to help with the demoulding (placing them between the mould and the laminate), with care not to cause delamination or damage to the tool's surface. Other methods may be used such as collapsible mandrels, cooling of the tool/mandrel or punching (ejector pins).

Figure 34 – Demoulding rigid plastic wedge [25]

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5. JOINING

These guidance notes also address the various methods used to join modules, blocks, or components in the production of large FRP OWTPs. This includes both mechanical and adhesive methods, as well as their relative advantages and disadvantages.

5.1. Bolting

Secure and reliable bolting is paramount to ensuring the structural integrity and longevity of the resulting FRP OWTP structures. This section will provide some recommendations on bolting options and quality control measures.

- Select appropriate bolt types based on the specific composite structure and load requirements. Common options include hexagonal head bolts, socket head cap screws, countersunk bolts, and flange bolts.
- Choose bolts made from materials compatible with composite structures, such as corrosion-resistant stainless steel or high-strength alloys. Avoid materials that may cause galvanic corrosion with composite materials.
- Consider the use of threaded inserts or captive nuts in composite structures to provide secure and durable attachment points for bolts.
- Determine the correct bolt size and length to ensure sufficient engagement with the threaded component while avoiding over-tightening, which could lead to damage to the composite materials.
- Torque specifications should be defined by the engineering team and described in the SPR. Torque wrenches, calibrated to industry standards, should be used to achieve consistent and controlled tightening.

5.2. Bonding

5.2.1. Types of bonding processes

Co-curing

This consists of the curing and/or bonding of the system formed by prepreg materials, adhesives and cores, in one single curing operation.

In the co-curing process, the adhesive used should be compatible and capable of curing under conditions defined for the carbon fibre prepreg.

Co-bonding

Type of curing process in which part of the composite material parts or detail parts which participate in the construction of the element, are in preimpregnated condition and part of them are already polymerized (pre-cured). The prepreg/pre-cured bonded unions should always be carried out using structural adhesive.

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Secondary bonding

The composite elements, which are going to form part of the part, are previously cured (pre-cured) and joined in a final bonding operation using structural adhesive. Co-bonded joints between prepregs/pre-cured should be done always with adhesive.

5.2.2. Surface preparation

All the produced FRP OWTP parts or elements on which a bonding operation is to be carried out should ideally be provided with peel ply on the bonding surface (which should be reflected on the part engineering drawing). Depending on the requirements for the adhesive bonding, it can act merely as a protective layer, or in some cases as the final and only surface treatment before bonding.

Usage of peel plies for structural bonding

When the produced part is protected by a peel-ply, there may be no need to perform an additional abrasion operation after peel-ply removal if the following conditions are fulfilled:

- This peel-ply should be specified in the relevant process specifications of the part (SPR).
- The peel-ply material used should be the same as indicated in the engineering drawing and applicable SPR documents.
- The "open time" between peel-ply removal and application of the adhesive should be within the maximum limit (2h), except if other requirement is defined in SPR.
- The time between the curing of the pre-cured element and the bonding process should not elapse a maximum of 12 months.
- Contamination of the surface to be bonded through fingerprints, oil, water, dust or other substances is not allowed.

If one of the above-described requirements is not respected, then abrasion of the surface after peel-ply removal should be carried out. Furthermore, if during the visual inspection of the element, damage on the peel-ply or areas of the part not covered by it are discovered (Figure 35), a complete reactivation by sanding of the damaged area will also be needed.

The parts should remain preferably in a clean room area or other controlled storage area until the application of the adhesive can be started to avoid damage on the peel-ply surface or contamination.

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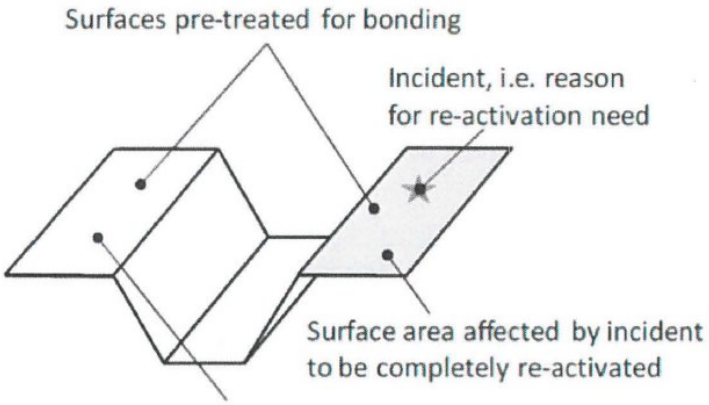

Figure 35 – Example of surfaces that need re-activation

The produced parts that are in direct contact with water (e.g. during NDI or trimming) and will be bonded afterwards should be dried prior to the adhesive application. This drying step can be removed only if the pre-cured part is storage in clean room conditions for at least 32 hours before the bonding process starts. Once the precured element is dried the bonding process should start immediately.

When the peel ply is used as the only surface treatment for bonding, it should be removed just before the application of the adhesive material and from areas that are going to be treated for subsequent bonding only.

The "open time" between peel ply removal and application of the adhesive must not exceed 2 h. Validation of bigger times can be approved by the engineering department. If the part requires multiple bonding steps, the peel ply should be removed only from the area that is going to be bonded in the next phase.

Once the peel-ply is removed, the surface can be cleaned only by aspiration to remove possible fabric debris on the surface.

Surface preparation by sanding

If sanding is required for production parts, the procedure is to be as follows:

- Surfaces should be abraded with grit alumina sandpaper with a grain size sequence from 80 to 240 microns. Alternatively, fine Scotch Brite type A material can be used.
- The abrading should be performed taking care not to damage the fibre. Only the superficial resin ply (light dust colour) should be removed during the sanding procedure. The observation of dark clust colour during the sanding procedure indicates damage on the fibres. Sanding of fibres should be reduced at the minimum technically possible. In the case of unidirectional tapes, the sanding procedure should start in the diagonal direction of the fibres to end in the parallel direction just before changing to the next grain size.
- If for any reason the parts need to be abraded after peel-ply removal, the imprint of peel ply should be completely removed during the sanding procedure as indicated in Figure 36.

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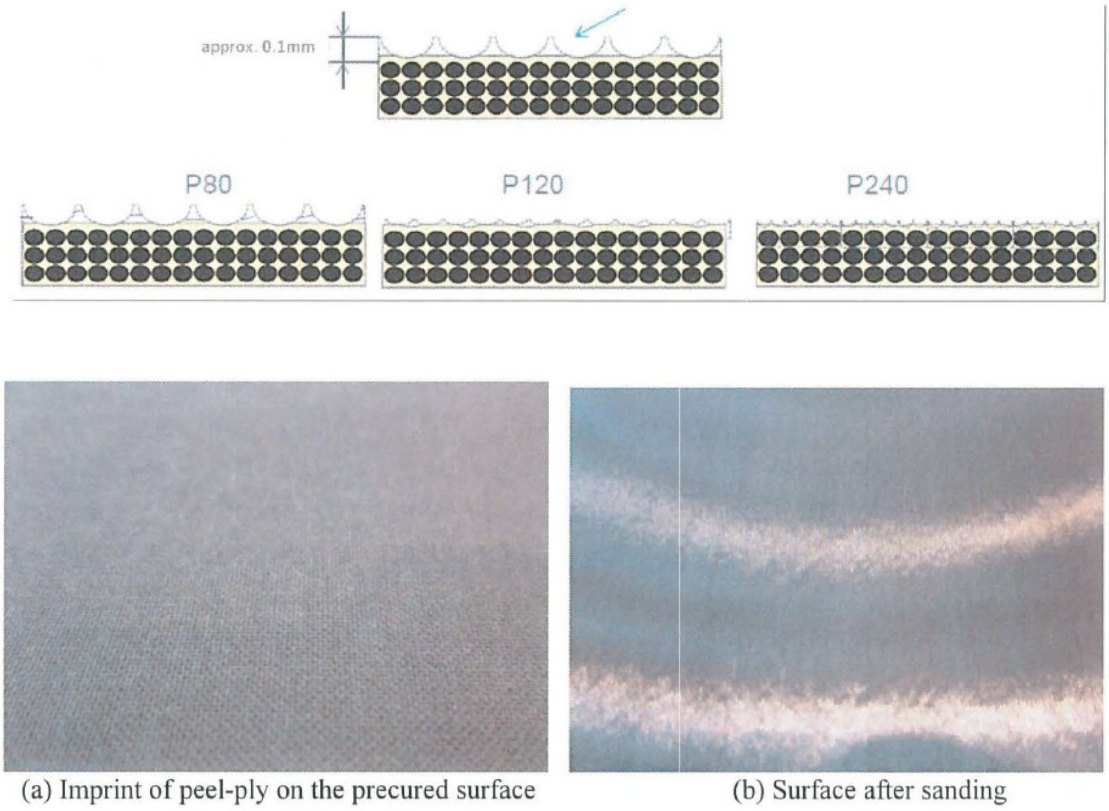

Figure 36 – Removal of peel-ply imprints by sanding

Abraded surfaces should be washed with clean water with the help of very fine Scotch-Brite A. If possible, the element should be placed during the rinsing in the vertical position to prevent water accumulation in the part. If this is not possible, the element should be placed with a certain slope to be able to observe the continuity of the film of water (water break test). If "dry" zones are observed, or if the water is collected in drops or small pools within less than 25 seconds, the elements should be subjected to a second surface treatment operation, cleaning and water break test. Alternatively, abraded surfaces can be cleaned with MEK or IPA using clean cloths until no dirt is observed on the cloth. Other cleaners/degreasers can be evaluated as long as the following requirements are met [6]:

- Cleaner must be able to remove all that is soluble in water (dirt, salts, etc...) and also insoluble in water (dirt, oil, grease, etc...) from the surface;
- Cleaner should evaporate or be removed quickly without any residue;
- Cleaner must not damage the materials to be bonded. That is, as a general concept, not to generate corrosion of metals, for example;
- Cleaning products should be harmless to health and the environment.

Once the part is sanded, cleaned and dried, the adhesive application should be performed immediately in a maximum time of 2 hours, except if another requirement is defined in SPR.

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In the case that the adhesive cannot be performed immediately, the part should be protected from contamination. If bagging was not possible, other methods described by Manufacturing Engineering and validated by Quality that could avoid contamination could be used. Under these conditions, the element can be stored for 72 hours. Past this time sanding procedure should be repeated.

In all cases, the pre-treated parts should be handled with special care to avoid contamination.

Bonding environment

Manufacturer procedures should describe the following environmental conditions for bonding environment [6]:

- Minimum and maximum temperature and hygrometry;
- Means of measuring and recording these values;
- Procedures provided to halt or alter the bonding process when temperature or hygrometry readings exceed limits;
- Positions of various workstations in relation to one another, in particular precautions taken to prevent the presence of dust at some sensitive workstations caused by other operations.

Adhesive application

The procedure for the application of the adhesive should describe [6]:

- Methods, tools and equipment for application of adhesive (manual or automatic application devices...);
- Positioning with traceability;
- Amounts (weight/surface), thickness of adhesive to be applied, and tolerances;
- Means of respecting this thickness;
- Various inspection procedures (e.g. physical examination, measurement of thickness), carried out after bonding operation, and the shipyard reference document for common defects, stating causes and remedies.

Assembly

The manufacturer's procedure for assembly should describe [6]:

- Description of all assembly stages with methods, tools and equipment necessary;
- Means of ensuring contact pressures, immobility of components;
- The minimum and maximum time elapsing between application of adhesive and assembly stage;
- Methods of checking dimensions of components and their positioning;
- Method to control bond line thickness, shape of adhesive bead and tolerance;
- Method for removal of excessive adhesive;
- Method to control that bonding will occur on full surface (removal of bubble, good spreading of adhesives...);
- Procedures provided by the manufacturer when bond line thickness exceeds tolerance limits.

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Curing

The manufacturer's procedure for curing should describe [6]:

- Methods, tools and equipment necessary to maintain assembly parts in position during polymerisation of the adhesive joints;
- Condition specification and control methods to achieve the required curing rate (T°, H%, pressure...)
- Method and equipment for air porosity elimination. · method for heating if relevant with cures cycles specification;
- Inspection methods and criteria for checking the curing of the adhesive.

End control of the assembly

The manufacturer procedure should describe [6]:

- Intended inspection methods and NDT after assembly, acceptability criteria for the assembly, as well as remedies for any defects found, means of handling any non-conformities found;
- Dimensional checks after assembly;
- Storage conditions specification for the assembly

Surface preparation tests

Surface preparation may be tested according to one of the following methods [6]:

- Method 1 – Wettability – NF EN 828 Determination by measurement of contact angle and critical surface tension of solid surface;
- Method 2 – Wetting Tension – ASTM D2578 Standard test method for wetting tension;
- Method 3 – Pull test.

Pull tests are to be performed in the same condition as the bonding. This test consists of applying an upward force and comparing the pulling force with the design force.

5.3. Welding

Since this document focuses on the production of FRP parts using thermoset resins, the welding process, suitable for thermoplastics, was not addressed and was out of the predefined scope. However, other advanced assembly technologies, such as advanced adhesives, automated bonding, robotic induction welding or ultrasound welding, were described and analysed in Deliverables 5.2 and 5.3.

Consult NI613 [6] for guidance notes on adhesive joints and patch repair.

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6. CUTTING AND MACHINING

In the context of large FRP OWTPs, precision cutting and machining are pivotal steps in the manufacturing process. This chapter delves into the various techniques employed for cutting and shaping composite parts, with a particular focus on contour cutting (trimming) and machining. The objective is to offer recommendations, highlight their advantages and disadvantages, and guide the manufacturer through the factors to consider when determining the most suitable method for their specific project.

Contour cutting (trimming)

Contour cutting is a precise method used to shape composite parts according to predetermined patterns or designs. It involves cutting along the outline or contour of the desired shape, ensuring accuracy in the final product. Some of the commonly employed tools for this purpose are:

- Waterjet Cutting Systems:

Waterjet cutting is a versatile and highly accurate method that uses a high-pressure stream of water mixed with abrasive materials to cut through FRP composite materials. It offers exceptional precision, minimal heat generation, and the ability to cut intricate shapes without creating dust or fumes.

Advantages: Precise, minimal heat, versatile.

Disadvantages: Relatively slower than some other methods, abrasive material costs.

- Laser Cutting Machines:

Laser cutting employs a high-intensity laser beam to precisely cut through FRP materials. It is ideal for intricate designs and complex shapes. Laser cutting delivers excellent accuracy, minimal material wastage, and high-speed cutting capabilities.

Advantages: High precision, minimal material wastage, suitable for intricate designs.

Disadvantages: Initial equipment cost, limited thickness capabilities for certain machines.

- CNC Routers:

Computer Numerical Control (CNC) routers are automated cutting machines equipped with rotating bits or blades, which can be programmed to cut specific patterns and shapes. CNC routers offer precision, repeatability, and the ability to handle large composite panels or components.

Advantages: Precision, automation, suitable for large components.

Disadvantages: Initial equipment cost, may not be as fast as some other methods for intricate designs.

- Band Saws and Circular Saws:

Band saws and circular saws equipped with carbide-tipped or diamond-coated blades are used for straight cuts and simple contours in FRP materials. These tools are cost-effective and suitable for bulk cutting tasks. When using these tools, ensure blade quality and safety measures in accordance with local safety guidelines.

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Advantages: Cost-effective, good for straight cuts.

Disadvantages: Limited in cutting complex shapes, may produce more waste material.

- Manual Contour Cutters:

Manual contour cutters are hand-operated tools with sharp blades designed for precision cutting along marked templates or patterns. They are portable, versatile, and suitable for small-scale contour cutting tasks. If manual cutters are used, implement safe handling practices to prevent accidents during manual cutting operations.

Advantages: Portable, versatile for small-scale tasks.

Disadvantages: Labor-intensive, not suitable for high-volume production.

- Electric Jigsaws and Routers:

Electric jigsaws and routers are handheld power tools equipped with fine-toothed blades or bits. They are ideal for cutting curves and intricate contours. These tools offer flexibility and are suitable for on-site adjustments and fine detailing. When using these tools, follow the safety guidelines and wear appropriate personal protective equipment (PPE) when using electric jigsaws and routers.

Advantages: Flexible for curves and intricate contours, portable.

Disadvantages: May require skilled operators for precision work, slower than some automated methods.

Machining

Machining techniques, such as CNC machining, are employed for intricate shaping and refining of composite components. These methods offer high precision and repeatability.

- When using CNC machining, consider the compatibility of cutting and machining techniques with the composite materials used, ensuring that no damage or delamination occurs during the process.
- Choose appropriate cutting tools, including blades, bits, or CNC tools, based on the material, thickness, and complexity of the part being processed.
- Implement effective dust control measures, such as dust extraction systems, to manage airborne particles generated during cutting and machining processes.
- Employ quality control checks to verify dimensional accuracy and surface finish after cutting and machining, ensuring compliance with project specifications.

Before these cutting and machining operations, additional layers of glass fabric may be strategically incorporated into specific areas of the laminate, particularly in the connection regions of FRP OWTP structures. These additional layers serve a dual purpose: first, they provide the flexibility to grind the composite material should geometry issues arise during production, and second, they safeguard the carbon fabric, ensuring it remains intact and unaltered.

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7. QUALITY SYSTEM

This chapter will provide some insights into the quality system and procedures employed to uphold the integrity of large FRP OWTPs. Ensuring high-quality production is crucial, and this involves the implementation of rigorous quality control measures, including non-destructive testing techniques, to guarantee the reliability and durability of the final product.

7.1. Quality system evaluation

The manufacturing evaluation presupposes that the manufacturer quality system is certified to be in conformance with ISO 9001. This system certification is to be carried out by an accredited body that operates according to ISO/IEC 17021. 2.3.2 If the quality system is not certified, an audit is to be performed by the applicable classification society to evaluate the quality system of the Manufacturer.

7.2. Non-Destructive Inspection (NDI) techniques

Non-destructive inspection/testing (NDI/NDT) techniques are an integral part of the quality system for large FRP OWTP platforms. These techniques enable thorough examination and evaluation of the structural integrity without causing any damage to the components. Several NDI/NDT methods can be employed, including but not limited to:

- Ultrasonic Testing (UT): Utilizes high-frequency sound waves to detect internal flaws or voids in FRP structures. It is particularly useful for assessing the thickness of composite layers.
- Radiographic Testing (RT): Involves the use of X-rays or gamma rays to inspect the internal composition of FRP components, revealing any anomalies or defects.
- Thermographic Testing (TT): Utilizes thermal imaging to identify irregularities in temperature distribution, which can indicate hidden defects or areas of concern.
- Visual Inspection (VI): Involves a comprehensive visual examination of the FRP components to detect surface imperfections, cracks, or any visible signs of damage.

These NDI techniques should be selected and applied based on the specific requirements of the OWTP project and the type of defects or anomalies expected. Further advantages and disadvantages of these techniques (and including some others) will be seen in more detail in 8.2.2. Proper training and certification of personnel responsible for NDI are essential to ensure accurate and reliable results.

7.3. Quality records and documentation

Maintaining meticulous records and documentation throughout the manufacturing process is imperative for quality assurance. The following aspects should be considered:

- Ensure that comprehensive records are maintained for all aspects of the manufacturing process, including material specifications, quality control checks, NDT results, and any deviations from established procedures.
- Implement a robust document control system to manage revisions, approvals, and distribution of important documents such as drawings, specifications, and quality procedures.

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- Establish a clear traceability system for FRP components, allowing for the tracking of materials, manufacturing processes, and quality assessments.
- Develop and maintain quality manuals that provide guidance on quality control processes, procedures, and standards. These manuals should be easily accessible to all relevant personnel.
- Ensure that all materials and processes comply with relevant industry standards, certifications, and regulatory requirements. Document compliance and certifications as necessary.
- Conduct regular internal and external audits to verify the effectiveness of the quality system and to identify opportunities for improvement.

7.4. Continuous improvement

Quality assurance is an ongoing process that should continually evolve and improve. Regularly review and analyze quality data, feedback, and audit findings to identify areas where the quality system can be enhanced. Implement corrective and preventive actions to address any issues and promote a culture of continuous improvement within the manufacturing process.

By following the guidance and procedures outlined in this chapter, manufacturers of large FRP OWTPs can maintain a robust quality system that ensures the production of reliable and durable components for offshore wind and tidal energy applications.

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8. QUALITY REQUIREMENTS

This chapter thoroughly explores the essential quality requirements for the production of large FRP OWTPs. It encompasses a comprehensive examination of control tests, acceptance criteria, and the methodologies for conducting non-destructive inspections (NDI).

Furthermore, this chapter underscores the pivotal role of rigorous quality control measures throughout the production process. It highlights the significance of employing non-destructive testing techniques to safeguard the structural integrity and reliability of the final product.

All elements manufactured from composite materials should be classified within their inspection levels, (e.g. Level 1, Level 2, Level 3, ...), in accordance with the type of component and/or structural responsibility at the completed part level. This classification should be set in accordance with the criterion of the responsible person from the Stress/Design department appointed for that specific product and should be stated in the corresponding SPR.

The table below shows an example of 3 possible inspection/control levels and the summary of inspections applicable to each of the levels.

Table 5 – Example of possible inspection/control levels

Inspection/Control Levels	Visual Inspection	Non-destructive Inspection	Acceptance Criteria (see 8.1)
1	X	X	...
2	X	X	
3	X	N/A	N/A

Quality Assurance should ensure compliance with the requirements established in the Engineering drawing and the applicable SPR.

First article inspection (FAI) should be performed if required by the customer, or by a new pa

A First Article Inspection (FAI) should be performed if there is an introduction of a new product, when significant design changes occur, with supplier or manufacturing location changes, in compliance with regulatory or contractual requirements (especially in safety-critical industries), periodically for ongoing quality control, when resolving nonconformances, or at the request of customers. FAIs serve as comprehensive verification processes to ensure that initial production units or modified components meet design specifications, quality standards, and regulatory obligations, ensuring product quality and consistency.

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8.1. General acceptance criteria

General acceptance criterion should be established for each discrepancy identified for the part to be produced, as well as the general repair/rework method, when applicable. This may include a table of typical defects, acceptable values without repair, acceptable values with repair and corresponding correction methods.

Acceptance criteria should be set by the responsible person from the Stress/Design department appointed for the specific FRP part or product to be produced.

The mentioned acceptance criteria should include a list of discrepancies that may be categorized as follows:

- Acceptable values without repair;
- Acceptable values with repair.

When any discrepancy below or equal to "acceptable values without repair" is observed, repair methods should be unnecessary. If the discrepancy is greater than "acceptable values without repair" though below or equal to "acceptable values with repair" it should then be necessary to apply repair/ rework methods. Finally, when any discrepancy in excess of the "acceptable values with repair" is observed, a Non-Conformity Sheet should be established.

Likewise, any type of defect not included in said Tables should be subject to a Non-Conformity Sheet.

Typical defects include:

- Weave anomalies;
- Lack or rupture of reference thread, fuzz, thread splices;
- Defects of a single thread: little stressed, twisted, bridged or broken thread;
- Cuts in plies;
- Folds or wrinkles on plies;
- Fabric deformation;
- Resin flash or resin starved areas;
- Fibre misalignment on unidirectional tapes;

Typical defects for honeycomb cores, splices and fillers include:

- Contour: a) Cell tear out b) Waviness;
- Machining burrs;
- Node separation;
- Splices: unbonded areas;
- Splices: excessive separation in the core splice;
- Surface depressions;
- Cell collapse;
- Contraction of the core fill;
- Crushed core;
- Bubbles/pores in the union adhesive or filler resin;

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- Other defects such as incorrect cell size, double cells, etc.;
- Different core colouring.

Typical defects for finished parts (general acceptance criteria for finished parts):

- Superficial scratches and marks (not covered fibres);
- Superficial depressions;
- Fibre bridging;
- Delaminations, voids, unbonded gaps and other defects detected by NDI;
- Wrinkles on plies;
- Lack of flatness on coupling surfaces;
- Part warping;
- Small surface hales (pin holes);
- Lack of resin on the surface;
- Telegraphing on sandwich structures;
- Lack of material on laminate edges;
- Adhesive defects in structural bondings.

8.2. Control tests

At least, the following controls should be carried out as a control of the structural materials:

- Carbon fibre prepregs and structural adhesives, peel plies, core, etc., should meet the requirements indicated in their corresponding Technical Data Sheet and applicable specification;
- Materials should not exceed their expiry date and exposure times in the workshop;
- Storage and handling of prepregs, resins, cores and adhesives should comply with the requirements in the applicable technical data sheets.

At least, the following controls should be carried out as a control the manufacturing process:

- Operation of autoclaves, ovens, hot forming equipment, etc., as well as their recorders and measuring equipment, checking that they are within their certification validity period;
- Temperature, humidity and cleanliness in the lay-up area;
- Bringing to room temperature of the material stored at low temperature;
- Contamination-free tools and appropriate application of the mould release agent;
- Mixing of structural materials from different suppliers should not be done during the lay-up;
- Removal of protections from the prepregs, adhesives and stabilized cores prior to the lay-up;
- Ply and core orientation:
- If defects exist on the prepreg and/or cores, these should be within the acceptance limits, with or without correction;
- When applicable, the acceptable defects correction systems should be carried out;
- Do not exceed the maximum permitted temperature, if any compaction or adaptation process of the lay-up is carried out;
- Splices of prepregs, cores and adhesives within the permitted tolerances;

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- Placement of waterproofing films and/or peel plies called out in the Engineering drawing or in the SPR of the part;
- Checking of the surface preparation and removal of peel plies in the pre-cured detail parts, which are to be subsequently bonded;
- In the case of bonded assemblies according to section 8.6 check compliance with all instructions included in the same;
- In the curing cycle:
    - Number and correct position of the thermocouples;
    - Leak test of the vacuum bag and pressure ports;
    - Pressure, vacuum, temperature, time and speed of the curing cycle;
- Insertion in the autoclave and identification of the process control test panels.

At least the following controls should be carried out to the finished parts:

- If defects exist, these should be found within the acceptance limits with or without repair;.
- When applicable, the correction methods used for removing the acceptable defects with repair will be carried out in accordance with Table 5.
- The test results of the manufacturing control specimens should comply with the requirements indicated in the SPR or, in default, in Table 7.
- All cured parts should be visually inspected;
- The dimensions and geometry of the finished parts should meet the requirements of the drawing or applicable SPR;
- SPR (Specific Process Requirements) should be prepared for all composite parts, in which, among other requirements, the type of non-destructive inspection to be carried out, the types of specimens, process control tests and acceptance criteria should be indicated;
- The fabrication process for sandwich structures should be performed so that it guarantees the leakage freedom of the parts fabricated;
- During handling and transportation of parts, it should be ensured that no blows or damages, which affect the quality of the finished part, are produced.

Process control specimens should only be made when required by Manufacturing Engineering (see 4.2.6 and 4.3.6).

For the removal/reduction of process control specimens, some key process parameters (KPP's) are mandatory and should be analysed as defined in the table below. Optional key process parameters (KPP's) can be also analysed if considered critical in a specific process.

Mandatory key process parameters may include:

- Temperature + relative humidity of lay-up area;
- Dwell and curing temperature (max);
- Dwell and curing time (max);
- Dwell and curing heat-up rates (min/max);
- Pressure and vacuum during curing;

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- In case of co-bonding or secondary bonding, dwell and curing temperature/time (max) to be evaluated for each cycle;
- Moisture of the adherents (drying parameters) before structural bonding.

While optional KPP's can be:

- Concentration control of particles (contamination) in the lay-up area;
- In case of co-bonding or secondary bonding, dwell and curing temperature/time (min) to be evaluated for each cycle.

Quality Assurance should establish a procedure for the control documentation that guarantees adequate traceability, both as regards the raw materials, (materials, lot, roll, specification, manufacturing date, quality control test results, etc.) as well as all the procedures used in the manufacturing of each element (No. of roll, curing cycle, part no., test or inspection results, etc.), during all the service life of the part.

8.2.1. Mechanical tests

Mechanical and physico-chemical tests are to be performed on test samples that are representative of the part/product to validate (same raw materials, same laminate lay-up and same construction process). These tests are to be defined on a case-by-case, but can include tests of the interlaminar shear strength, flatwise tensile strength, single lap shear tests (adhesive strength), G_{IC}, etc.

The results are to be compared with the theoretical properties of the laminates characteristics defined in the literature. For ship construction, for example, the general requirements for mechanical tests are defined in the NR546, Section 10 [8]. Where deemed necessary by the respective classification society, a prototype model of a set of elements may be requested to be tested.

8.2.2. Non-Destructive Inspection (NDI)

The aim of Non-Destructive Inspection (NDI) is to confirm if the manufacturing process has not generated defects that could reduce the structural integrity. Any available NDI methods have some limitations in terms of the type of detected defects, depth of inspection, and inspected material type. It should be clearly understood that no NDI can provide a quantitative assessment of the part or bonded joint strength. Defects which are not detectable should be prevented by alternative and suitable quality control methods. Special attention is to be drawn at the design stage to ensure the accessibility of inspection equipment. Non-

Destructive controls and results interpretation are to be performed by personnel with relevant qualifications and with sufficient experience. The basic principle of inspection is to proceed to a calibration of the NDI method on the sounded area. Assessment is based on responses comparison between a sounded area and an inspected area which may contain defects.

The non-destructive testing and acceptance criteria are to be defined by the manufacturer. The non-destructive testing processes may be ultra-sonic testing, spectroscopy, thermography or radiography. A non-exhaustive list of NDT/NDI methods is described in Figure 37.

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NDT Methods		Advantages	Disadvantages
Visual inspection	• First NDT method to implement prior any other methods • Highlighted surface defects (cracks / disbond), lack / excess of adhesive	• Simple method	• Not sufficient / only highlighted of gross defects
Taping	• Analysis of the acoustic response of a material to a mechanical shock • Manual or automated methods • Highlighted of large volume defects (few mm)	• Simple method	• Results difficult to interpret for manual method (experienced operator depending) • Low depth controlled • Not suitable for complex shapes
Ultrasonic	• Based on the principle of ultrasonic wave propagation (emission / reception) • Highlighted of small volume defects	• Efficient method • Positioning and sizing of defects • Automated method possible	• Not suitable for all material • Personnel qualification
Acoustic emission	• Acoustic analysis of the tested component response by mechanical straining	• Sensitive to the evolution of defects	• Mechanical straining of the component needed
Mechanical Impedance	• Various methods where the structure is excited with relatively low frequency mechanical vibrations and its response to these excitations is measured	• Commercial available instruments	• Comparative methods with difficulties for calibration
Radiography	• An image is formed following differential absorption of X-ray energy by elements present in the component • Enables the volumetric inspection of components	• Efficient method • Positioning and sizing of small defects • Automated method possible	• Expensive method • Personnel qualification • X-rays safety issues
Thermography	• Heating of the element to check / Analysis of emitted temperature • Any discontinuities affect the rate of heat conduction • Highlighted of medium volume defects	• Efficient method • Suitable for large surface	• Low depth controlled / depend on thickness and material type • Poor accuracy / no sizing of defects

Figure 37 – Comparative table of NDT methods [8].

The manufactured FRP parts may be non-destructively inspected pursuant to the applicable SPR documentation.

The Stress/Design department should state the applicable acceptance criteria for each part. R&D should set the inspection methods applicable to each inspection area set by the Stress/Design department allocated to that specific element. Depending on the Manufacturing Engineering and Quality Assurance criteria, non-destructive inspection might be performed on 100% of manufactured elements or by sampling. This decision should be based on results from the first article inspection (FAI), results from control of manufactured elements and maturity and experience in the manufacturing process used. Quality Assurance should stand responsible for the arrangement of sampling plans, application and follow-up.

8.3. Maintenance

Maintenance of the FRP OWTP structures is crucial for preserving performance but also for addressing any potential issues proactively, contributing to the overall success and sustainability of these renewable energy systems. The following sections will address the vital role of documentation and inspection procedures in maintaining large FRP OWTP platforms.

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8.3.1. Maintenance manual

The maintenance instructions for the FRP OWTP platform should be compiled into a maintenance manual which may include [26]:

- Scheduled maintenance actions including inspection intervals and routine actions;
- Personnel qualifications and skills;
- Required specialized tooling, spare parts and personal protection equipment;
- Access procedures;
- Limiting environmental conditions;
- Description of the OWTP and its major components;
- Start-up, shutdown and re-commissioning procedures;
- Diagnostic procedures and troubleshooting guide;
- Lifting loads and load conditions, when relevant;
- Repair instructions;
- Inspection for marine growth and its removal;
- Maintenance of the scour protection system;
- Maintenance of the corrosion protection system;
- Emergency procedures;
- Safety instructions and planned environmental protection measures;
- Quality recording and record-keeping processes.

Inspection and test plan

The inspection and test plan for the FRP OWTP platform should at least include [26]:

- The components to be inspected;
- The type of inspection (visual inspection, NDI, inspection of the submerged structures, etc.);
- The sampling rate;
- The recurrence of the inspection;
- The qualification of the personnel performing the inspection.

Along the life of the OWTP, the maintenance manuals as well as the inspection and test plan may be updated in order to take into account the accumulated field experience.

8.3.2. Maintenance survey

The FRP OTWP platform should be periodically inspected by a classification society to check that the procedures described in the maintenance manual and in the inspection and test plan are correctly followed. The components covered by inspection may include [26]:

- Rotor blades;
- Drive train, including the gearbox if applicable;
- Generator;
- Electrical installations;

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- Safety and control systems;
- Locking devices and mechanical brakes;
- Main structural components (hub, nacelle frame, etc.);
- Support structure including foundations;
- Corrosion protection system;
- Scour protection system, if applicable.

The interval between inspections is determined on a case-by-case basis depending in particular on the OWTP design, previous experiences with similar technologies and the results of previous inspections. As a guidance, a typical 5-year interval may be considered.

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9. ASPIRATIONS AND FUTURE WORK

This document, "Development of guidance notes for the production of large FRP OWTPs," stands as a collective achievement, driven by the collaboration of partners deeply invested in the manufacturing of large fibre-reinforced plastic (FRP) offshore wind turbine platforms (OWTPs). Important insights and expertise were shared by those actively engaged in the manufacturing of the project's FRP demonstrators, resulting in important conclusions that fed these guidance notes. Additionally, the feedback gathered from FIBREGY's advisory board members, conveyed during specialized workshops, has further enriched this document's content.

Envisioned as a unified resource, the collaboration between D4.7 (“Project guidelines and recommendations for using FRP in large OWTPs”) and D5.4 lays the groundwork for future standards and guidance notes, particularly from classification and certification societies, which are currently lacking in the context of FRP-based OWTP platforms, particularly in terms of their production aspects.

Looking forward, several significant aspirations and areas for future work were identified:

- Industry Adoption and Standardization: We aspire to facilitate the broad adoption of these guidance notes as industry standards, ensuring their integration into the mainstream practices of FRP OWTP manufacturers;
- Certification and Classification Frameworks: Our goal is to craft comprehensive certification and classification frameworks tailored to large FRP OWTP platforms, offering a structured roadmap for their production and certification.
- Continued Research and Innovation: The pursuit of innovation remains at the core of our vision. We are committed to sustained research efforts aimed at refining existing processes, exploring novel materials, and pioneering advanced technologies to enhance the efficacy, durability, and sustainability of large FRP OWTP platforms.
- Environmental Stewardship: Recognizing the vital importance of sustainability, we will intensify efforts to assess and mitigate the environmental impact of large FRP OWTP production and operation, aligning our endeavours with global climate change mitigation strategies.
- Collaborative Partnerships: We seek to foster international collaborations encompassing manufacturers, regulatory authorities, and research institutions. These partnerships will catalyze progress in the renewable energy sector, propelling it toward a more sustainable future.

In conclusion, this document not only marks the culmination of the production of the FIBREGY demonstrators but also signifies the beginning of a new chapter in the production of large FRP OWTP platforms. The commitment to sustainable energy solutions remains unwavering, and we eagerly anticipate a future where offshore wind and tidal power play pivotal roles in mitigating climate change and ushering in a cleaner, more sustainable world.

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