Ref. Ares(2022)4934389 - 06/07/2022

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

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

D2.4 (WP2): Connections in offshore structures

Responsible Partner: INEGI

Contributor(s): INEGI, CIMNE, ULIM, IXBLUE, TUCO, ENEROCEAN, TIDETEC, COMPASSIS, TSI, BV, CORSO

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

DOCUMENT INFORMATION TABLE

CONTRACT NUMBER:	952966
PROJECT ACRONYM:	Fibregy
PROJECT COORDINATOR:	Borja Serván Camas
DOCUMENT RESPONSIBLE:	INEGI
DELIVERABLE TYPE:	Report
DOCUMENT TITLE:	Connections in offshore structures
DOCUMENT ID:	D2.4
DISSEMINATION LEVEL:	PU: Public
FILENAME:	FIBREGY_D2.4
STATUS:	Final Version

Authoring & Review

PREPARED / REVIEWED BY				
Name	Role	Partner	Date	Comments
Bárbara Fernandes	Creator	INEGI	18/06/2021	Connections Benchmark
Jorge Nuno Silva	Contributor	INEGI	18/06/2021	Connections Benchmark
João Manuel Cardoso	Creator	INEGI	09/03/2022	Chapters 3 to 8
Mário Moutinho	Contributor	INEGI	09/03/2022	Chapter 3.2
Fermin Otero	Contributor	CIMNE	27/06/2022	Chapter 5
Pablo Ropero	Reviewer	ENEROCEAN	30/06/2022	Entire document
Olivia Chan Taw	Reviewer	CORSO	06/07/2022	Chapters 1, 6 and 7
Rui Mendes	Reviewer	INEGI	06/07/2022	Entire document

EXECUTIVE SUMMARY

This document presents the results from the work done in Task 2.3 - *Connections in OWTP structures*, which is part of the Work Package (WP) 2 of the FIBREGY project and aims to analyse different connections typologies and configurations to be used in Offshore Wind and Tidal Platform (OWTP) structures. Firstly, a benchmark of connections will be presented, focusing on presenting the most relevant and potential types of connections to join fibre-reinforced polymer (FRP) composite materials to FRP composite materials and FRP to dissimilar materials, including a general comparison between the main connection types (Chapter 2, Subtask 2.3.1); followed by an evaluation and selection of the applicable connections to both platforms (W2Power and Tidal Turbine Housing), resulting in several decision matrices (Chapter 3, Subtask 2.3.2); a review of the reinforcing members of the W2Power columns and towers (Chapter 4); a re-design and optimization, using numerical tools, of the previously selected connections (Chapter 5, Subtask 2.3.3); and finally, the results from the experimental test campaign, carried out at coupon level while performing a comparison between the different connections, as well as a correlation to the numerical simulations, will be presented (Chapter 6, Subtask 2.3.4). Although not planned at the beginning of this task, Chapter 4 was included to address the topic of the reinforcements which, while not being the direct scope of T2.3 of any of its subtasks, was identified as a relevant subject to study and where some of the topics related to the reinforcing members of the structure (such as geometries, interferences, joining types, etc.) were considered.

This document is an important contribution to Milestone 5 – Catalogue of materials and connection, leading to a better knowledge of the most promising joining technologies while considering the properties of the selected composite materials, manufacturing processes and OWTP's geometry and requirements.

TABLE OF CONTENTS

TABLE OF FIGURES

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

TABLE OF TABLES

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

1. Contextualization

Offshore structures are submitted to aggressive environmental conditions, such as the ones presented in Table 1. Typical materials (e.g. steel) are widely used in structural applications in offshore, however, due to corrosion susceptibility and limited fatigue life, the need for other solutions has triggered new investigations and projects around the use of new materials for applications in marine and offshore environments. A potential solution is fibre-reinforced plastics (FRP), as these materials have excellent corrosion resistance and a superior fatigue response. Nevertheless, offshore structures based on FRP have not reached a high Technology Readiness Level (TRL) yet, since there is a lack of design and assessment guidelines.

Table 1 – Marine Environmental Conditions

Marine Environmental Conditions	
Service Temperature	-30 to +70 °C
Exposure to UV Radiation	-
Salinity Degree	3.1 to 3.8 %
Seawater pH	7.5 to 8.5 (alkaline)
Mechanical Loads	Quasi-static (e.g. hydrostatic pressure)
	Cyclic (e.g. waves and currents)
	Dynamic (e.g. wind gusts, wave slamming loads)
Biological Fouling	-
Fatigue Life	High Cycle Fatigue (HCF) – until 10^8 to 10^9 cycles

The structural efficiency of a composite structure usually depends on its joints, so the correct sequence for the design process should be to first determine the location, configuration and dimensions of the joints, considering the characteristics of the elements to join (e.g. materials, thickness, fibre orientation) and then design the basic structure between them.

Joints are a critical part of assemblies and structures since they can act as weak points, leading to failure. Therefore, it is essential to guarantee a careful design for all types and configurations of joining, being paramount to focus on identifying the sources and estimating the magnitudes and directions of present loads, which can be static and/or dynamic.

Joining of two or more components is usually performed due to process limitations, facilitating the production/transportation of large and/or complex structures (as will be seen in Chapter 3 for the two OWTP platforms under development).

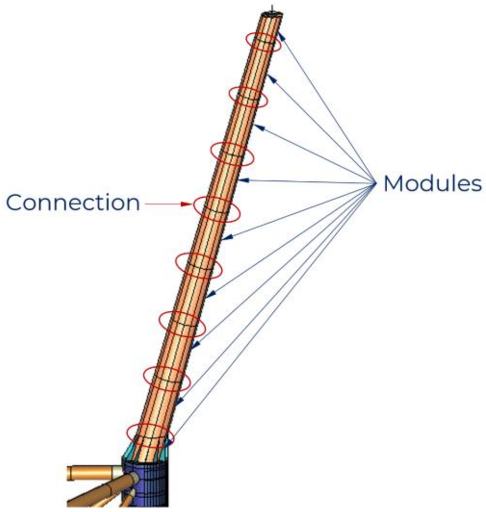


Figure 1 – Connections in W2Power tower

When two or more **joined** interfaces are combined, the resulting assembly is a **connection** (example in Figure 1 for the W2Power towers). In turn, a connection is typically designed to be easily dismantled and therefore allowing for quick and effective maintenance or inspection operations. In summary, the main reasons that justify the importance of joining, thus creating connections, are presented in Table 2.

Table 2 – Reasons for joining structures

Functionality	Manufacturability
To carry or transfer static or dynamic loads; To achieve the size and/or shape complexity not allowed with primary manufacturing processes; To enable specific functionality demanding mixed materials; To allow portability and disassembly; To provide better impact tolerance.	To obtain structural efficiency through the use of built-up details and materials; To optimize material utilization and minimize scrap losses; To overcome limitations on size and shape complexity imposed by primary fabrication processes; To allow on-site erection or assembly of prefabricated details.
Cost	**Aesthetics**
To allow optimal material selection and use; To maximize material utilization and minimize scrap losses; To keep the total weight of materials to a minimum (through structural efficiency); To provide more cost-effective manufacturing alternatives; To facilitate automation of assembly, for some methods; To allow maintenance, service, repair, or upgrade, reducing life-cycle costs; To facilitate responsible disposal.	To enable the use of coatings; To enable the construction of complex structures visually attractive.

2. Connection's benchmark

2.1. Joining technologies

Joining is a process whose aim is to bring together two or more parts, in order to turn them into a single entity. It can occur based on three fundamental forces: **mechanical** forces, **chemical** forces and **physical** forces (see Figure 2), which are involved in the most applied connection types as mechanical fastening, adhesive bonding and welding, respectively. It is worth noting that two or more fundamental forces can be combined (e.g. mechanical and chemical forces), resulting in **hybrid connections**.

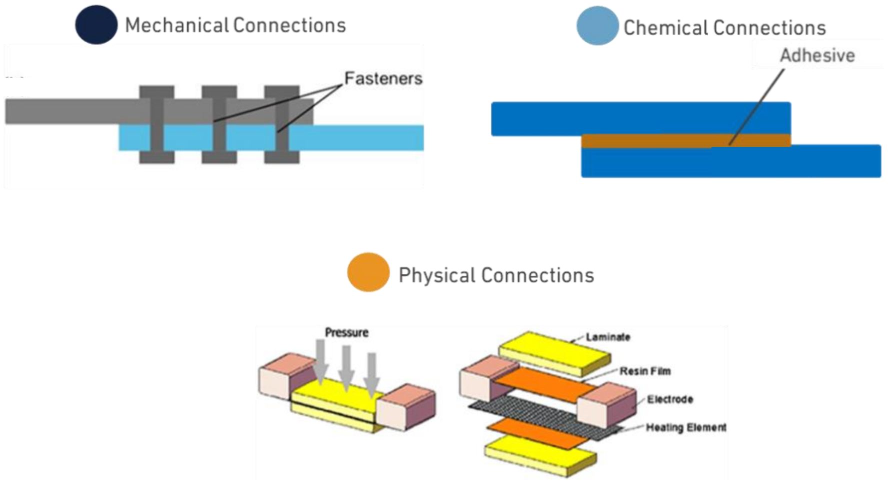
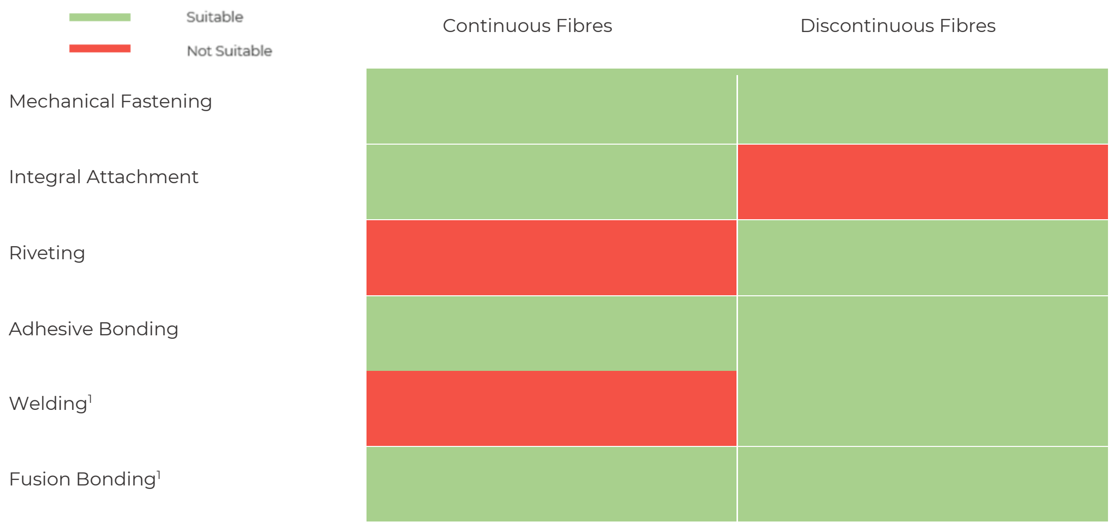


Figure 2 – Taxonomy groups

The most adequate joining method essentially depends on the nature of the matrix and the type and form of reinforcement; the type and magnitude of loads; the geometry; and the environmental conditions. Generally, for polymer-matrix composites, there are **three main options for joining**: mechanical fastening and integral attachment, adhesive bonding and welding (for thermoplastic matrices). Table 3 shows the compatibility between some joining processes and general composite materials based on the type of reinforcement.

Table 3 – Compatibility between joining process and polymer-matrix composite materials based on the type of reinforcement. [1] For thermoplastics only



🟩 Suitable
🟥 Not Suitable

	Continuous Fibres	Discontinuous Fibres
Mechanical Fastening	🟩	🟩
Integral Attachment	🟩	🟥
Riveting	🟥	🟩
Adhesive Bonding	🟩	🟩
Welding[1]	🟥	
Fusion Bonding[1]	🟩	🟩

When selecting and designing a joint, the first step is to determine the magnitude and complexity of loads to be carried or transferred and the stress (load-per-unit-cross-sectional area) that each structural element and joint can endure before failure. The effectiveness of a joint (its capacity to carry or transfer the loads applied, considering its size and weight) is given by:

$$\text{Joint efficiency} = \frac{\text{Joint strength}}{\text{Stress in the structure}} \times 100\% \qquad (1)$$

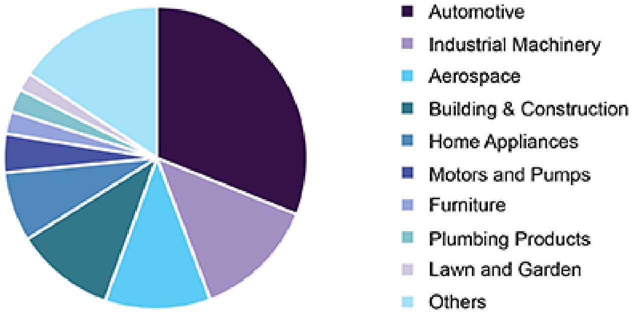
Factors such as dynamic loads (e.g. fatigue, impact), high temperatures and aggressive corrosion environments affect joint efficiency, thus they also should be considered during the design phase. Table 4 displays typical and known values of joint efficiencies for some joining methods applied to composite materials [1].

Table 4 – General Achievable Joint Efficiencies for Various Processes for Composite Materials (in Joining of materials)

Typical Range of Joint Efficiencies for Various Processes in Composites (in %)		
		Composite Materials
Mechanical Attachment		50 - 100
Mechanical Fastening		50 - 100
Adhesive Bonding	Organic adhesive	20 - 60
	Inorganic adhesive	50+
Welding	Fusion processes	~50
	Non-fusion processes	~50
Brazing		~50
Thermal Spraying	Polymers	>50

2.2. Mechanical Connections

Mechanical joining is undoubtedly the oldest and most extensively applied (see Figure 3) joining method by humankind and is based on the joining of components in an assembly using an integral feature or a supplemental device, resulting in two types of mechanical connection: **integral mechanical attachment** and **mechanical fastening**, respectively. In both types, loads are transferred from one component to another simply through purely mechanical forces. Table 5 summarizes the main advantages and limitations of mechanical connections [2], [1].



Source: www.grandviewresearch.com

Figure 3 – Global Industrial Fasteners Market Share, 2018 (%)

Table 5 – General advantages and disadvantages of mechanical connections

Advantages	Disadvantages
Join fundamentally different materials (no need to form chemical or physical bonds)	Accidental disassembly
Disassembly facilitated	Stress concentrators
Relative intentional motion between joined parts while maintaining the geometric arrangement and function	Fastener pull-through or pull-out in laminated composites
No chances in chemical composition and microstructure	Mould costs (integral attachment)
Limits crack propagation	Weight penalty
In the case of mechanical fastening, little or no special surface preparation is required	
In the case of integral attachment, assembly is simpler	
Low cost and fewer operator skills required	
Generally, enables automation	

Due to the lack of low ductility behaviour presented by most FRP composites, mechanical fastening (see Figure 4(a)) is one of the most common joining methods used in these materials, across all industries. Examples of bolted connections in a structural application to join composite materials are displayed in Figures 5 and 6 [3]. The most common types of **mechanical fasteners** are:

- Nails;
- Bolts;
- Rivets;
- Pins;
- Screws;
- Snap-fit fasteners.

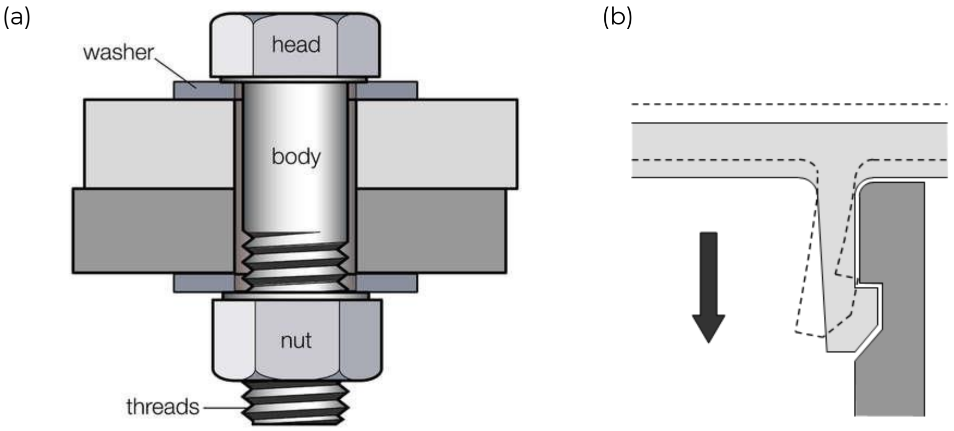


Figure 4 – Examples of mechanical connections. (a) Bolted connection; (b) Snap-fit

When selecting the mechanical fastener, there are a few factors that must be considered:

- Bolt torque and clamping force;
- Fastener's shape and materials;
- FRP composites properties;
- Joint configuration;
- Stacking sequence;
- Strength reduction due to material removal by drilling;
- Temperature and moisture.

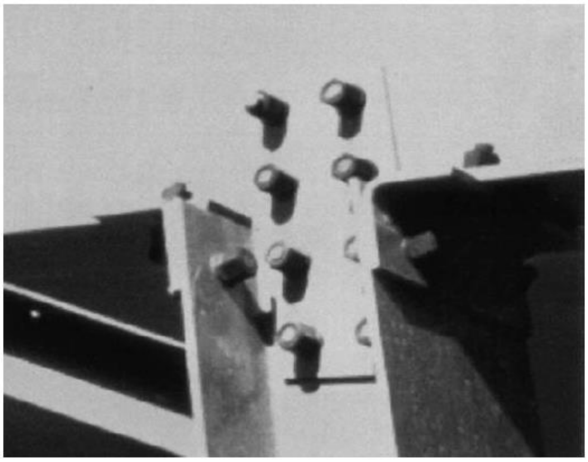


Figure 5 – Bolted beam-to-column joint in a GFRP frame

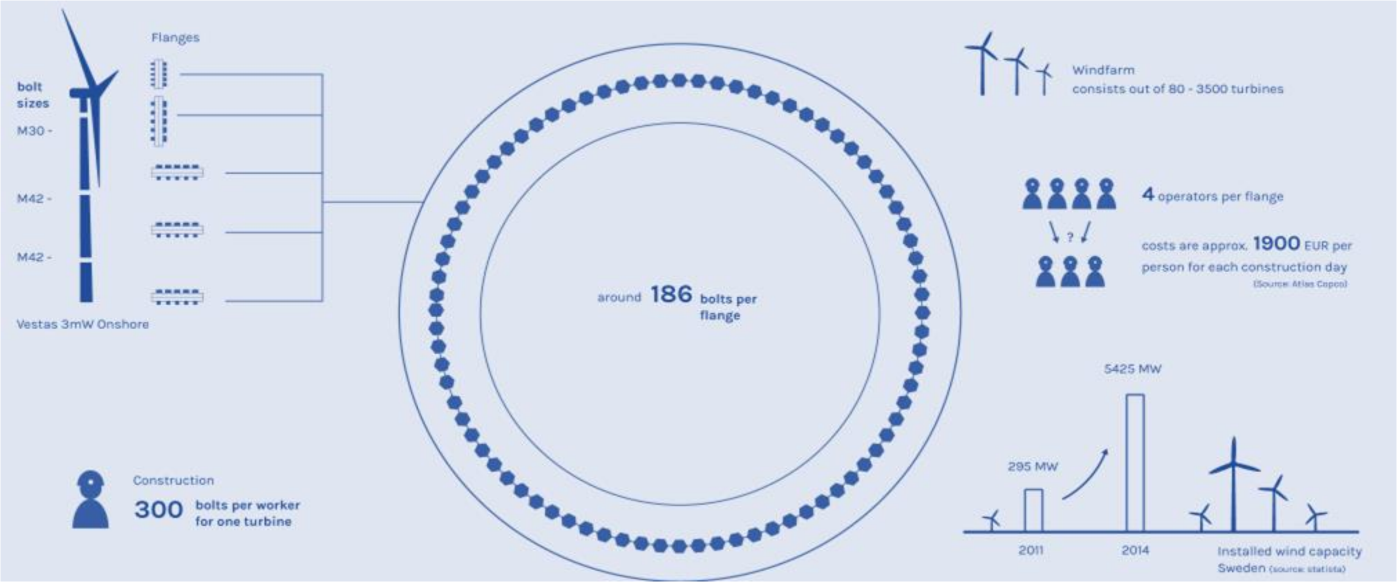


Figure 6 – Application of bolts in the wind turbine industry

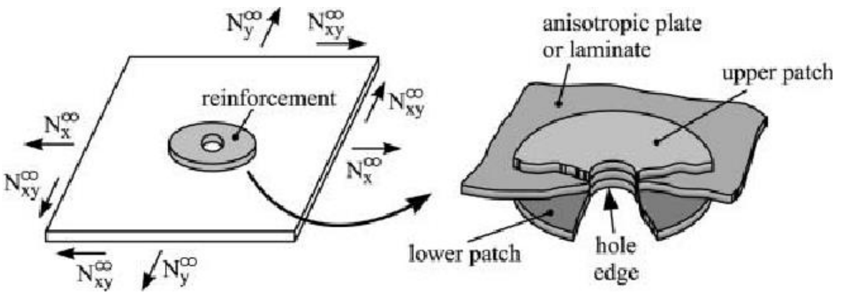
If the fasteners are chosen correctly, galvanic or anodic corrosion, excessive loading through-the-thickness (and consequent delamination), destruction of reinforcements and rapid wear of cutting tools can be mitigated [2], [4].

Regarding **integral mechanical attachments**, these can be categorized into two domains: designed-in and processed-in. Typically, the following integral mechanical attachments can be employed in FRP composites:

- Tongues and grooves;
- Flanges and Shoulders;
- Ears and tabs;
- Bosses and lands;
- Moulded-in insert.

In the case of mechanical fastening, it is very common the need of drilling holes in the material to accommodate the joining element. However, the presence of holes leads to an increase in stress concentration, unless the fastener is an "interference fit" (when the diameter of the hole is slightly smaller than the fastener). Another way of decreasing stress concentration around the hole is by integrating fibres orientated in different directions around the holes or by using doublers, as shown in Figure 7. However, even the most carefully designed joints can only achieve about 50% of the strength of the basic structure. Nevertheless, holes in FRP composites are generally manufactured employing methods such as drilling and countersinking. Alternatives to drilled holes are the use of surface-bonded or embedded fasteners [1], [2], [4], [5].

Figure 7 – Employment of doublers



In order to uniformly characterize each mechanical joining technology, the benchmark was developed based on the parameters presented in Figure 8. Firstly, the mechanical connections were divided into mechanical fastening and integral attachments technologies and, then, were considered a wide set of characteristics such as materials compatibility, mechanical properties, availability, possible joint configurations, etc. In addition, a special subgroup was considered to include novel technologies that could not be fully integrated within the other subcategories. It is worth noting that some technologies are still under development, thus the lack of information. However, it was decided to present them in this document because of their potential to join composite materials.

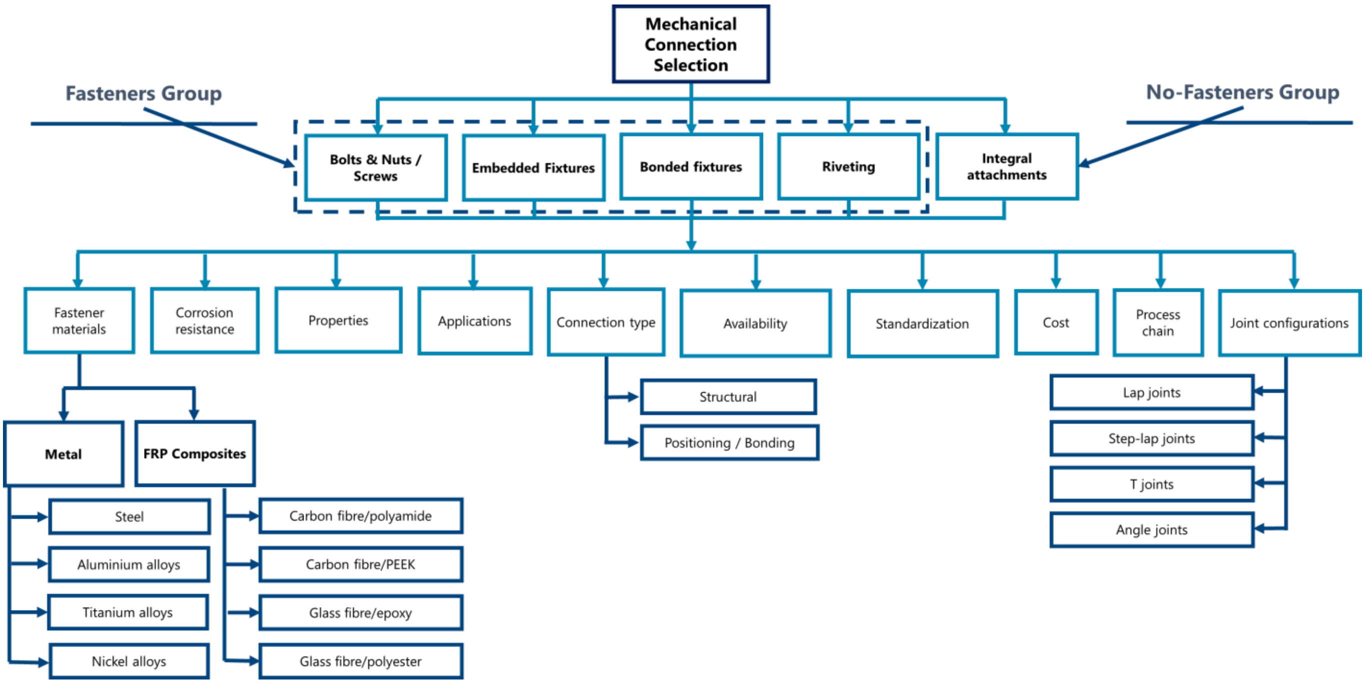


Figure 8 – Classification parameters for mechanical connections

2.2.1. Bolted Connections

When selecting the mechanical fastener, some conditions must be met, such as **corrosion compatibility**. This does not stand as an issue for fibreglass or aramid fibre reinforced composites, but it is a major concern in relation to carbon fibres, since this type of reinforcement can act as a cathodic when in contact with metals like aluminium, cadmium and steel. To overcome this problem, titanium and its alloys (especially Ti-6Al-4V) are the most used, as they present the best compatibility with carbon fibres. However, titanium fasteners are expensive and heavier than aluminium fasteners, resulting in higher costs and weight penalties, which is a major drawback for applications in the aerospace industry, for example [2].

When greater strength is required, superalloys, such as A286 and 718, and multiphase alloys (e.g. MP35N or MP159) can be applied. Nonetheless, in an attempt to eliminate corrosion and weight problems, fasteners made of composite materials have been explored: carbon fibre/polyimide, carbon fibre/PEEK, carbon fibre/carbon composites. After some studies, and despite a set of advantages presented by these bolts, they tend to fail in shear failure mode, in static tests, and have less durability under cyclic loading, resulting in lower fatigue resistance, when compared to titanium fasteners [2].

Another factor to be appraised is the **shape of the bolt head**. Nowadays, there are several available head styles, but, due to the viscoelastic behaviour of FRPs, the head of the fastener should present a greater bearing surface area as possible. In aerospace structures, two main types of fasteners are applied: **protruding head** and **countersunk head**, being the latter the most used as it enhances aerodynamic performance. The drawbacks associated with countersunk head fasteners are their cost and the necessity of slightly larger holes, leading to an increase in stress concentration. Due to interlaminar shearing between the composite plies, **bolt bending** is an existing problem for composite materials. Regarding the properties of the selected fastener, it must have a high modulus and high tensile-strength, in order to prevent the bolt from bending. The geometry and type of bolt affect bolt bending too. In fact, a **threaded core bolt** responds better to bending than a smooth bore, because the former improves stiffness and prevents sliding. Even so, it is important to note that in case of high loads, the threads can compromise the joint response to fatigue. Some researches prove that non-circular cross-sections holes (e.g. elliptical), although being more difficult to manufacture than circular cross-sections, are a better solution to increase joint strength [1], [2], [4].

In Tables 6 to 8 are presented the most relevant type of fasteners for the offshore environment and to join composite materials.

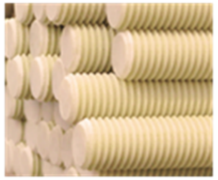
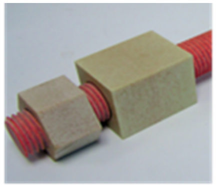
Table 6 – Properties and characteristics of bolts compatible with composites and marine environment

Fasteners			
Materials	**Austenitic stainless steel**	**Aluminium alloys**	**Titanium alloys**
Corrosion Resistance	Galvanic corrosion (CFRP)	Galvanic corrosion (CFRP)	Excellent
Coating	Needed	Needed	-
Metric Thread Size	M1.6– M100	M6 – M36	M6 – M36
Tensile Strength	448 – 1100 MPa	255 – 524 MPa	240 – 1137 MPa
Yield Strength	> 640 MPa	213 – 386 MPa	520 – 1100 MPa
Service Temperature Range	-40 – 225 ºC	-273 – 200 ºC	-273 – 925 ºC
Applications	Wind turbines; Water jets; Sub-sea equipment; Nuclear plants	General Engineering; Aerospace Industry; Pipelines	Submarine Exteriors; Spacecrafts; Aircrafts; Maritime Industry
Connection Type	Structural	Structural	Structural
Commercial Availability	Easily available	Easily available	Easily available
Standards	ASTM F593, ASTM F594, ISO 4014/17, ISO 3506	ASTM F468	ASTM F468
Price per kg	1.62 – 58.29 €	2.01 – 15.43 €	4.27 - 39.28 €
Process Chain	Drilling; Deburr; Bolting; Protecting (optional)		

Table 7 – Properties and characteristics of bolts compatible with composites and marine environment

Fasteners				
Materials	**Nickel alloys**	**Naval Brass**	**Silicon Bronze**	**Aluminium Bronze**
Corrosion Resistance	Excellent	Excellent	Excellent	Excellent
Coating	-	-	-	-
Metric Thread Size	M6 – M36	M6 – M36	M6 – M36	M6 – M36
Tensile Strength	483 – 1379 MPa	250 – 310 MPa	370 – 650 MPa	206 – 760 MPa
Yield Strength	490 – 915 MPa	70 – 110 MPa	135 – 490 MPa	210 – 420 MPa
Service Temperature Range	-273 – 630 ºC	-273 – 130 ºC	-273 – 160 ºC	-273 – 360 ºC
Applications	Turbine Blades; Aerospace Industry	Marine Fittings; Pumps; Heat Exchangers	Chemical Plants; Ducts and Fans for corrosive atmospheres	Pumps; Valves; Marine Fittings
Connection Type	Structural	Structural	Structural	Structural
Commercial Availability	Easily available	Easily available	Easily available	Easily available
Standards	ASTM F468	ASTM F468, ASTM F467	ASTM F468, ASTM F467	ASTM F468, ASTM F467
Price per kg	1.60 – 33.28 €	5.02 – 5.59 €	6.02 – 6.13 €	
Process Chain	Drilling; Deburr; Bolting; Protecting (optional)			

Table 8 – Properties and characteristics of bolts compatible with composites and marine environment

Fasteners		
Materials	Glass fibre reinforced epoxy, polyester or vinyl ester resin	Glass fibre reinforced polyurethane
Corrosion Resistance	Excellent	Excellent
Metric Thread Size	M8 – M30 (it is possible to go up M52)	
Tensile Strength	250 – 500 MPa	229 – 253 MPa
Bending Strength	300 – 650 MPa	-
Compressive Strength	300 – 550 MPa	202 – 254 MPa
Service Temperature Range	-123 – 177 ºC	-51 – 88 ºC
Applications	Offshore Engineering; Generators; Chemical plants	
Connection Type	Structural	Structural
Commercial Availability	Easily available (Durastone®)	
Standards	ISO 965	
Price per kg	1.64 – 27.8 €	0.94 – 6.78 €
Process Chain	Drilling; Deburr; Bolting; Protecting (optional)	

The most common joint configurations for bolted connections are **lap joints**, **T-joints**, **angle joints** and **flange joints**, which are represented in Figure 9 [6].

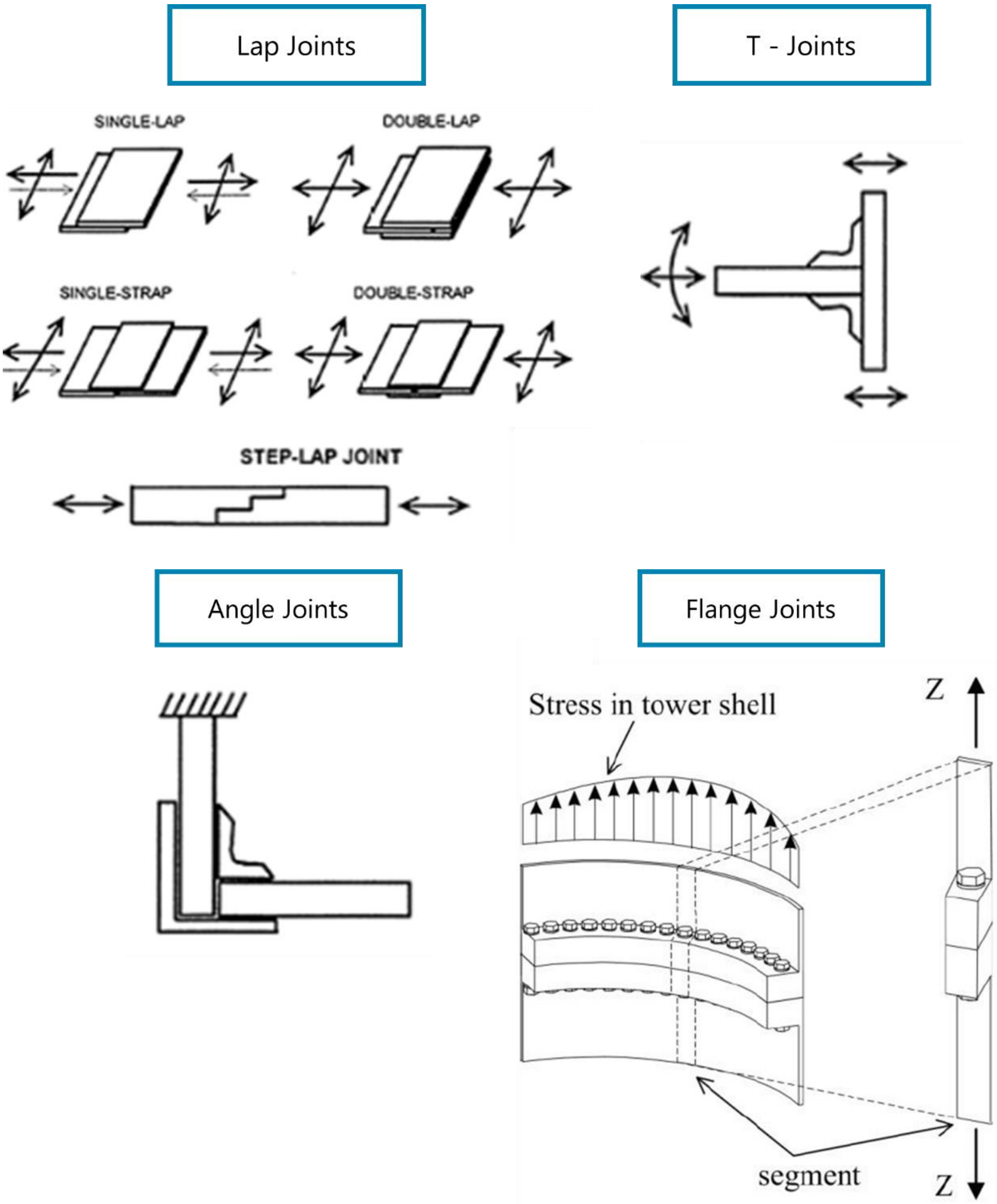


Figure 9 – Most common joint configurations for bolted connections

2.2.2. Embedded Fixtures

As aforementioned, holes act as stress raisers and disrupt the load path of fibres. To overcome this issue, but harvesting the advantages of mechanical fastening, different solutions have been developed, such as embedded fasteners (see Figure 10). The main advantages and disadvantages of the use of embedded fixtures are gathered in Table 9.

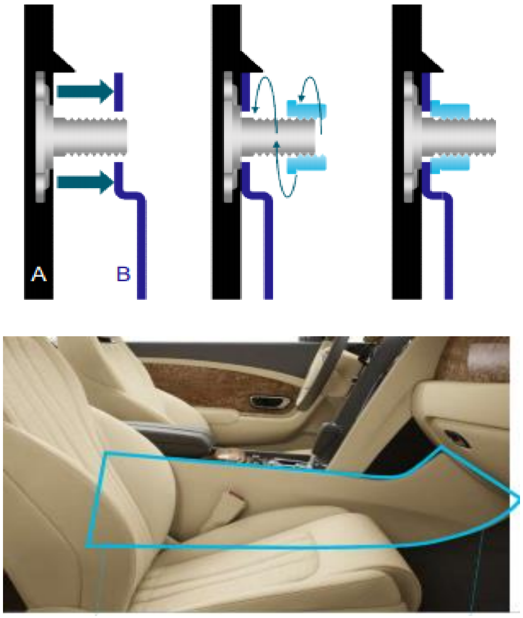


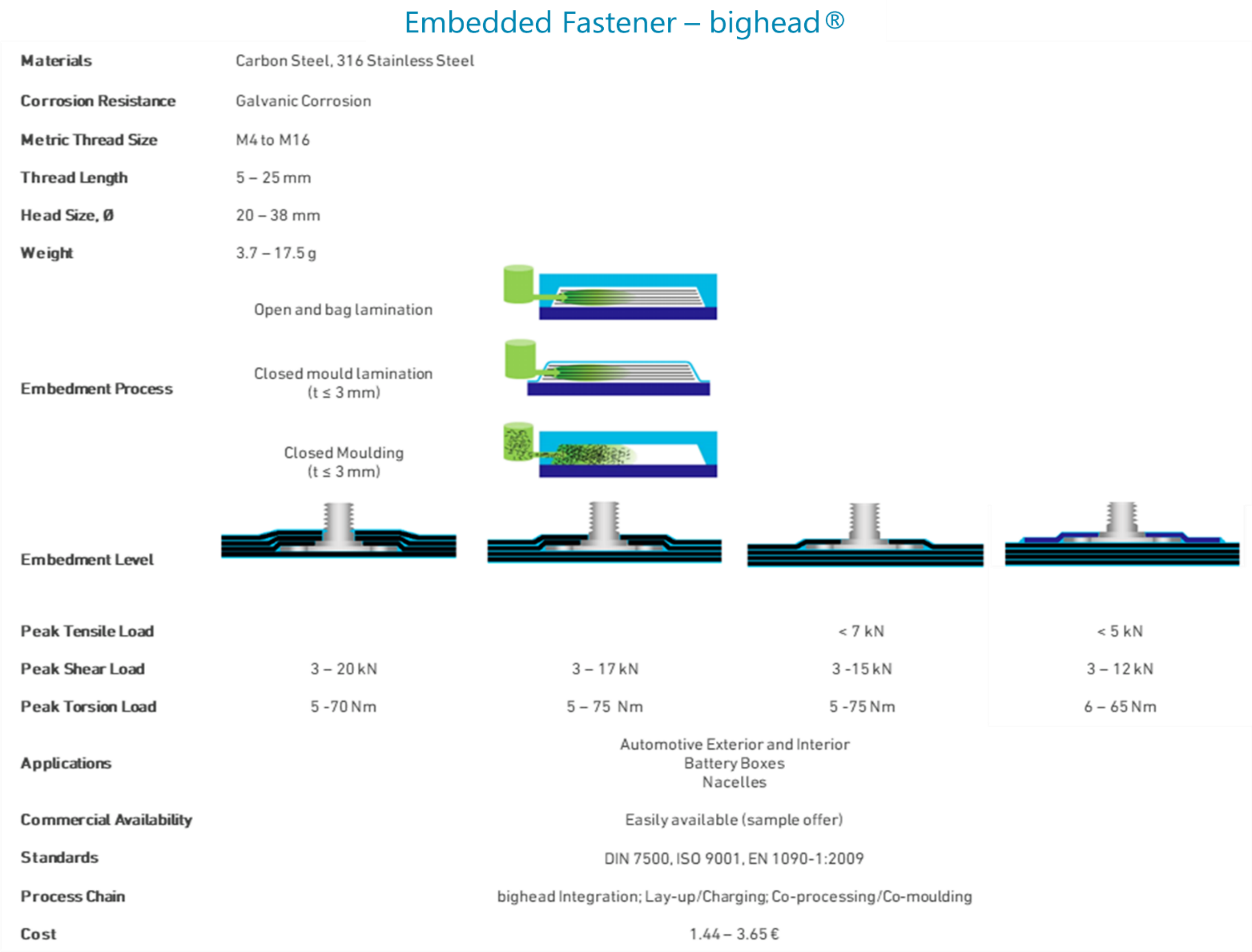
Figure 10 – Mechanism and example of application of an embedded fastener

Table 9 – Advantages and disadvantages of embedded fixtures

Advantages	Disadvantages
Integrated during manufacturing	Weight penalty
No secondary operations	Selection of the right fastener design
Higher resistance to tensile and torsion loads even with thin material sections	Galvanic Corrosion
Design optimisation	
Compatible with thermosets and thermoplastics matrices and glass and carbon fibres	

In Tables 10 and 11 are shown the main characteristics of embedded fasteners manufactured by bighead® and BÖLLHOFF, respectively. The embedment of the fastener within the composite structure can be performed through different processes and different levels of embedment can be achieved, according to the final application and required properties. It is worth noting that embedded fasteners can be generally applied to the same joint configurations as conventional fasteners (see Figure 9).

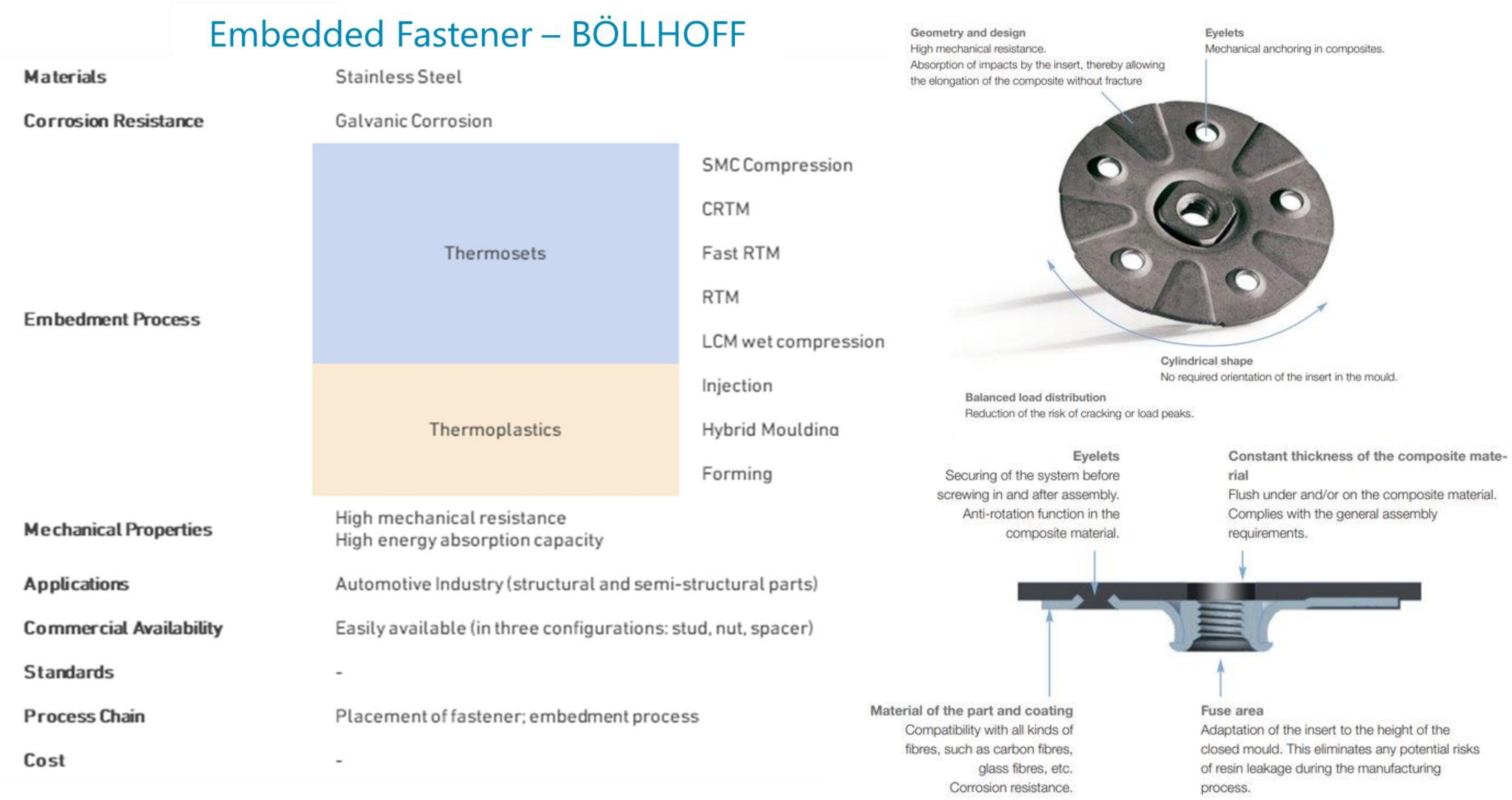
Table 10 – Properties and principal characteristics of embedded fasteners by bighead®



Embedded Fastener – bighead®

Materials	Carbon Steel, 316 Stainless Steel			
Corrosion Resistance	Galvanic Corrosion			
Metric Thread Size	M4 to M16			
Thread Length	5 – 25 mm			
Head Size, Ø	20 – 38 mm			
Weight	3.7 – 17.5 g			
Embedment Process	Open and bag lamination Closed mould lamination (t ≤ 3 mm) Closed Moulding (t ≤ 3 mm)			
Embedment Level				
Peak Tensile Load			< 7 kN	< 5 kN
Peak Shear Load	3 – 20 kN	3 – 17 kN	3 -15 kN	3 – 12 kN
Peak Torsion Load	5 -70 Nm	5 – 75 Nm	5 -75 Nm	6 – 65 Nm
Applications	Automotive Exterior and Interior Battery Boxes Nacelles			
Commercial Availability	Easily available (sample offer)			
Standards	DIN 7500, ISO 9001, EN 1090-1:2009			
Process Chain	bighead Integration; Lay-up/Charging; Co-processing/Co-moulding			
Cost	1.44 – 3.65 €			

Table 11 – Properties and principal characteristics of embedded fasteners by BÖLLHOFF



Embedded Fastener – BÖLLHOFF

Materials	Stainless Steel	
Corrosion Resistance	Galvanic Corrosion	
Embedment Process	Thermosets	SMC Compression
		CRTM
		Fast RTM
		RTM
		LCM wet compression
	Thermoplastics	Injection
		Hybrid Moulding
		Forming
Mechanical Properties	High mechanical resistance High energy absorption capacity	
Applications	Automotive Industry (structural and semi-structural parts)	
Commercial Availability	Easily available (in three configurations: stud, nut, spacer)	
Standards	-	
Process Chain	Placement of fastener; embedment process	
Cost	-	

Geometry and design
High mechanical resistance.
Absorption of impacts by the insert, thereby allowing the elongation of the composite without fracture

Eyelets
Mechanical anchoring in composites.

Cylindrical shape
No required orientation of the insert in the mould.

Balanced load distribution
Reduction of the risk of cracking or load peaks.

Eyelets
Securing of the system before screwing in and after assembly.
Anti-rotation function in the composite material.

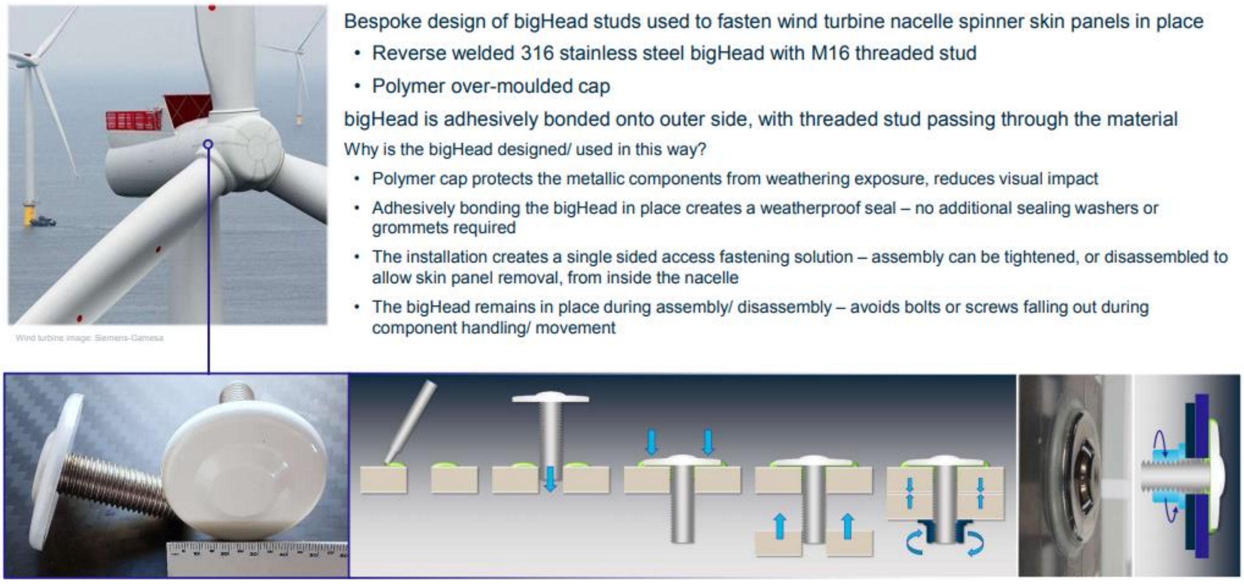
Constant thickness of the composite material
Flush under and/or on the composite material.
Complies with the general assembly requirements.

Material of the part and coating
Compatibility with all kinds of fibres, such as carbon fibres, glass fibres, etc.
Corrosion resistance.

Fuse area
Adaptation of the insert to the height of the closed mould. This eliminates any potential risks of resin leakage during the manufacturing process.

2.2.3. Surface Bonded Fixtures

When there is no chance to embed the fastener within the structure of the composite and one wants to overcome the damage caused by drilling holes in the composite, surface-bonded fasteners can be an alternative. As its name implies, the fastener is bonded on the surface of the material, with the aid of an adequate adhesive, which is selected based on the compatibility with the substrate, the final application requirements and its availability. Surface bonded fasteners can be applied to large structures in extreme environmental conditions, as can be seen by the example given in Figure 11, where a surface bonded fastener was used to connect panels in an offshore wind turbine nacelle spinner skin.



Bespoke design of bigHead studs used to fasten wind turbine nacelle spinner skin panels in place

- Reverse welded 316 stainless steel bigHead with M16 threaded stud
- Polymer over-moulded cap

bigHead is adhesively bonded onto outer side, with threaded stud passing through the material

Why is the bigHead designed/ used in this way?

- Polymer cap protects the metallic components from weathering exposure, reduces visual impact
- Adhesively bonding the bigHead in place creates a weatherproof seal – no additional sealing washers or grommets required
- The installation creates a single sided access fastening solution – assembly can be tightened, or disassembled to allow skin panel removal, from inside the nacelle
- The bigHead remains in place during assembly/ disassembly – avoids bolts or screws falling out during component handling/ movement

Wind turbine image: Siemens-Gamesa

Figure 11 – Example of application and mechanism behind a surface bonded fastener

As surface bonded fasteners involve using an adhesive, a surface preparation phase is required, in order to guarantee the correct application of the adhesive and optimize the joint efficiency. Nevertheless, in general, the process chain is quite simple, as shown in Figure 12.

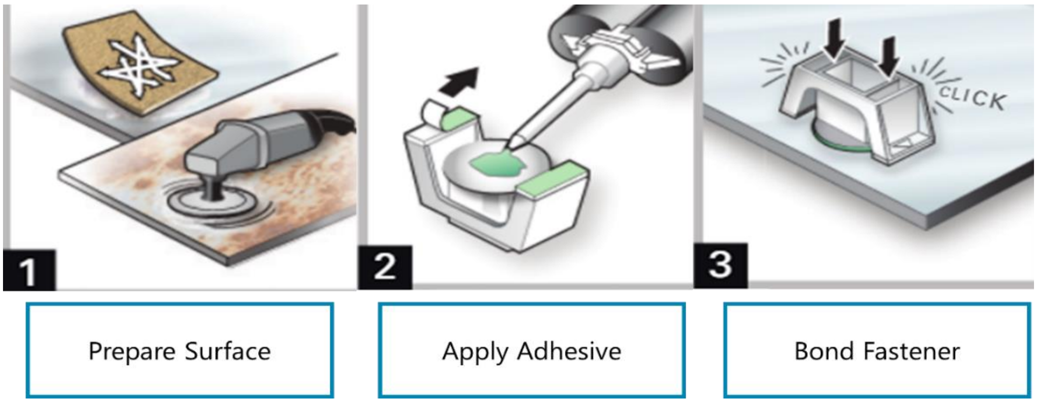
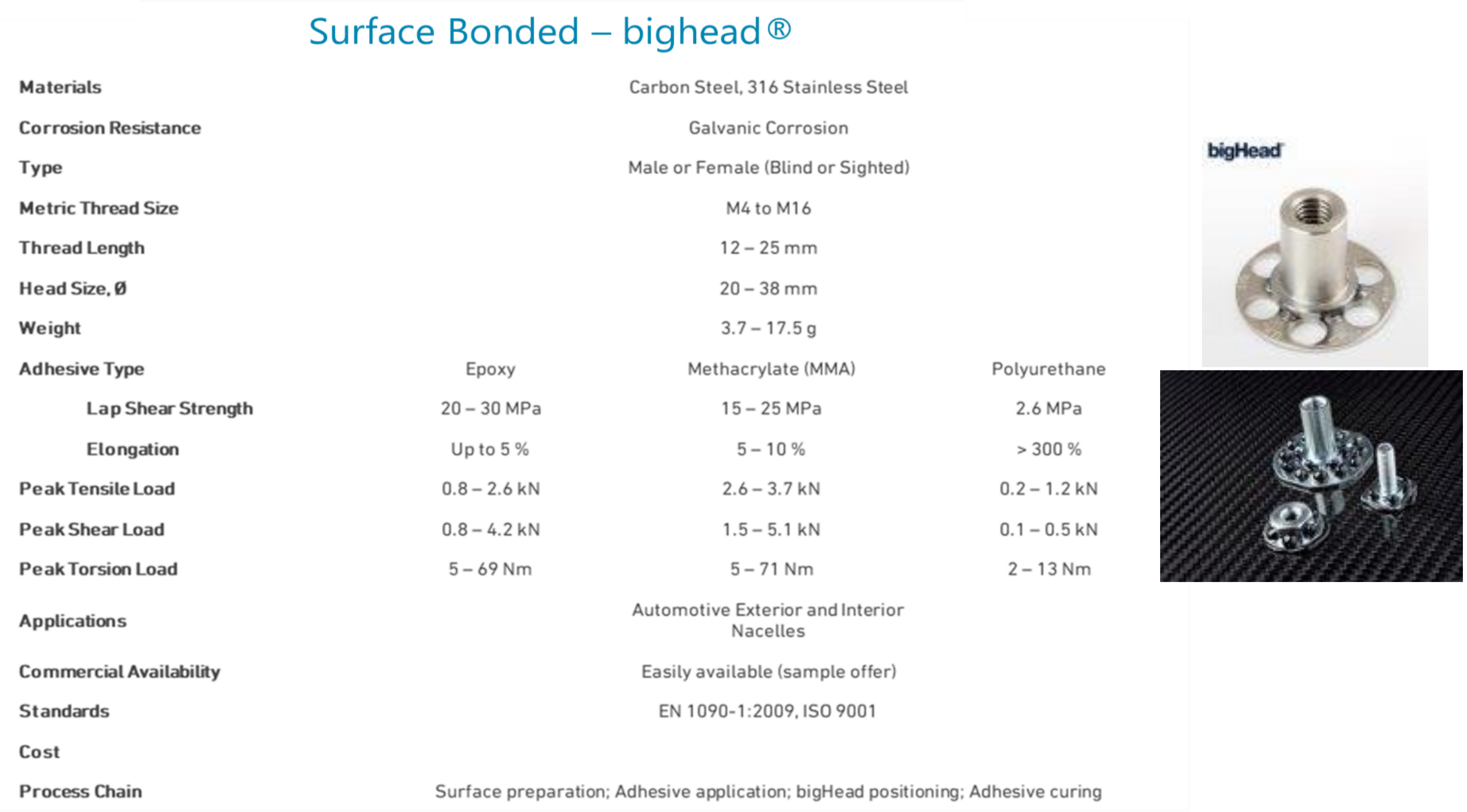


Figure 12 – Application process of surface bonded fasteners

Tables 12 and 13 show the most relevant characteristics of surface-bonded fixtures produced by bigHead® and Click Bond®, respectively.

Table 12 – Principal characteristics of surface bonded fixtures provided by bigHead®



Surface Bonded – bighead®

Materials	Carbon Steel, 316 Stainless Steel		
Corrosion Resistance	Galvanic Corrosion		
Type	Male or Female (Blind or Sighted)		
Metric Thread Size	M4 to M16		
Thread Length	12 – 25 mm		
Head Size, Ø	20 – 38 mm		
Weight	3.7 – 17.5 g		
Adhesive Type	Epoxy	Methacrylate (MMA)	Polyurethane
Lap Shear Strength	20 – 30 MPa	15 – 25 MPa	2.6 MPa
Elongation	Up to 5 %	5 – 10 %	> 300 %
Peak Tensile Load	0.8 – 2.6 kN	2.6 – 3.7 kN	0.2 – 1.2 kN
Peak Shear Load	0.8 – 4.2 kN	1.5 – 5.1 kN	0.1 – 0.5 kN
Peak Torsion Load	5 – 69 Nm	5 – 71 Nm	2 – 13 Nm
Applications	Automotive Exterior and Interior Nacelles		
Commercial Availability	Easily available (sample offer)		
Standards	EN 1090-1:2009, ISO 9001		
Cost			
Process Chain	Surface preparation; Adhesive application; bigHead positioning; Adhesive curing		

Table 13 – Principal characteristics of surface bonded fixtures provided by Click Bond®

Surface Bonded – Click Bond ®	Nutplates	Studs and Standoffs	Bushings	ACRES Sleeves
Materials	A-286 Stainless Steel, Anodized Aluminium	Aluminium*, Stainless Steel*, Titanium**, Composites**	Aluminium*, Stainless Steel*, Titanium**	A-286 Stainless Steel
Corrosion Resistance	-	Galvanic corrosion (CFRP)*, Excellent**	Galvanic corrosion (CFRP)*, Excellent**	Galvanic corrosion (CFRP)
Metric Thread Size	M3 to M10	M3 to M16	M3 – M10	Internal Ø 4 – 12 mm
Adhesive Cure Time	1h – 7 days	1h – 7 days	1h – 7 days	-
Adhesive Shear Strength	N/A – 31 MPa	N/A – 31 MPa	N/A – 31 MPa	-
Adhesive Peel Strength	0.3 – 10.5 kN/m	0.3 – 10.5 kN/m	0.3 – 10.5 kN/m	-
Service Temperature Range	-55 – 135 °C	-55 – 135 °C	-55 – 135 °C	-
Applications	Structural Skins; Access Panels; Stress and Fatigue Critical Areas; Pressurized Vessels;	Modular Equipment; Panels; Cables and Wiring; Decking;	Sandwich Panel Structures; Hinges and Latches; System Attachment; Prevent Moisture Absorption;	Oversize Hole Correction; Hole Protection; Composite Structures; Honeycomb Panels;
Connection Type	Fixtures	Fixtures	Fixtures	Fixtures
Comercial Availability	Good	Good	Good	Good
Standards	NASM25027, FAA TSO, AS9100, ISO 9001, ISO 14001	AS9100, ISO 9001, ISO 14001	AS9100, ISO 9001, ISO 14001	AS9100, ISO 9001, ISO 14001
Best suited for Marine Applications	Sealed and Sleeved	Larger diameter studs	CB3005, CB5005	-
Cost				
Process Chain	Clean substrate surface; Abrade/scuff substrate surface; clean substrate surface; Prepare part and apply bonding agent; Position part in place and apply pressure; Bonding agent cure.			

2.2.4. Riveting

One type of mechanical fastening broadly used in aerospace and automotive industries is riveting, especially when the purpose is to join dissimilar materials. However, conventional riveting is not suitable for FRP composites, especially when continuous reinforcements are used. Thus, new approaches have been studied and developed, which differ from each other mainly in terms of tooling and source of the punching force [4].

2.2.4.1. Self-piercing riveting

Self-piercing riveting, despite resorting to a supplemental device, is a forming process, since it involves the deformation of the parts. It consists in joining together two stacked sheets by punching a rivet into them, as exemplified in Figure 13. This method applies to both thermoset and thermoplastic matrix composites, although being more advisable for the latter. The main advantages and disadvantages of self-piercing riveting are gathered in Table 14 and the process variables are shown in Figure 14 [4], [7], [8].

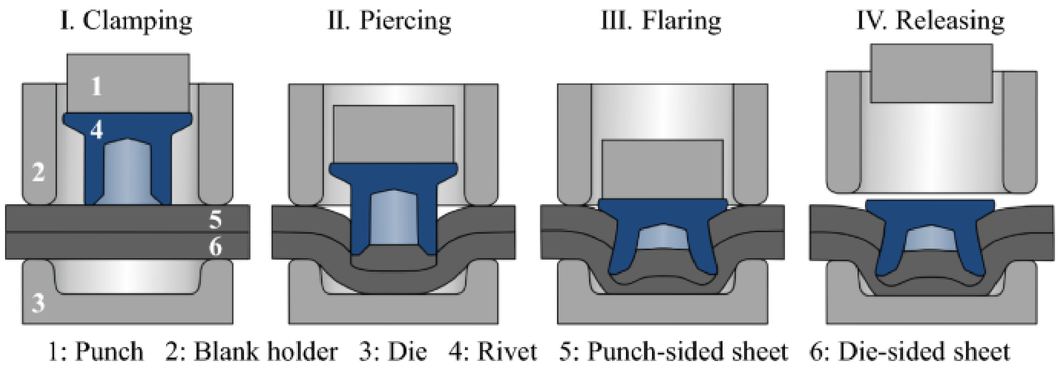


Figure 13 – Mechanism of self-piercing riveting

Table 14 – Main advantages and disadvantages of self-piercing riveting

Advantages	Disadvantages
No need for drilled holes	Can only be applied if both sides of the joint are accessible
Lower production time and costs (single operation)	Disassembly is not possible without destroying the joint
No need for surface pre-treatment	Delamination, fibre damage and matrix cracking can occur and can be intensified under fatigue cyclic stresses
Operator-friendly	The rivet tends to cut the fibres, leading to a stiffness reduction

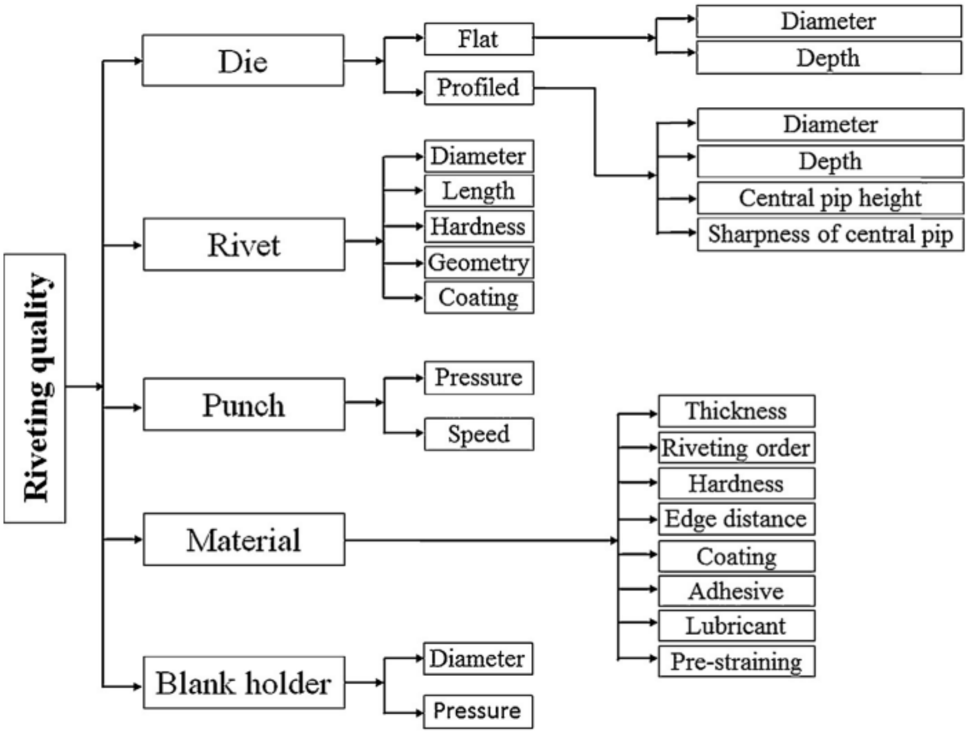


Figure 14 – SPR process variables

2.2.4.2. Friction self-piercing riveting (FSPR)

This technology is quite similar to conventional self-piercing riveting; however, it combines a feeding and rotational motion, as shown in Figure 15. This can improve the joint efficiency and result in a shear strength two times greater than SPR joints. In addition, better fatigue life can be achieved with FSPR compared to clinching or resistance spot welding [9], [10].

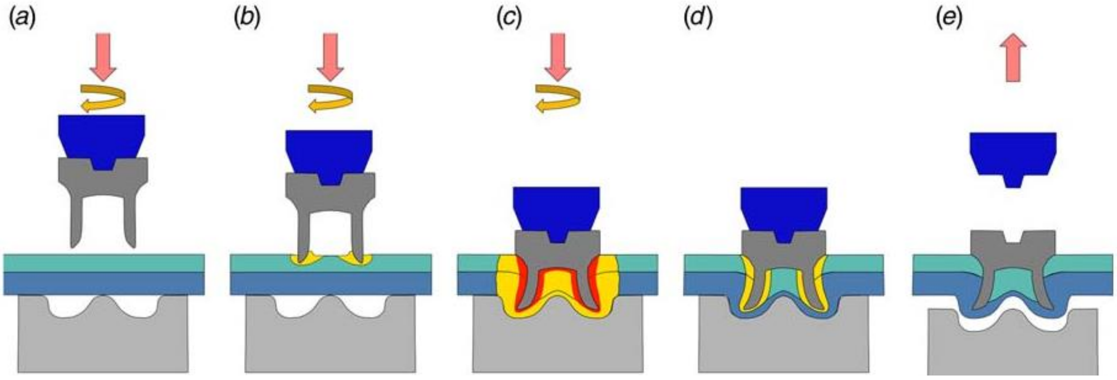


Figure 15 – Friction self-piercing riveting process: (a) starting; (b) penetration; (c) softening and deformation, (d) stop; (e) releasing

2.2.4.3. Double-sided self-piercing riveting

Double-sided self-piercing riveting resorts to tubular rivets with chamfered ends that are placed in-between two sheets – see Figure 16. With the action of a punching tool, the sheets are pushed against each other, deforming the rivet in a way that its ends flare and undercuts are formed, promoting mechanical interlocking. One of the main advantages of this technology is the fact that it is independent of the sheet's thickness, thus joints with large thicknesses can be obtained. It produces invisible joints, as there are no material protrusions [11].

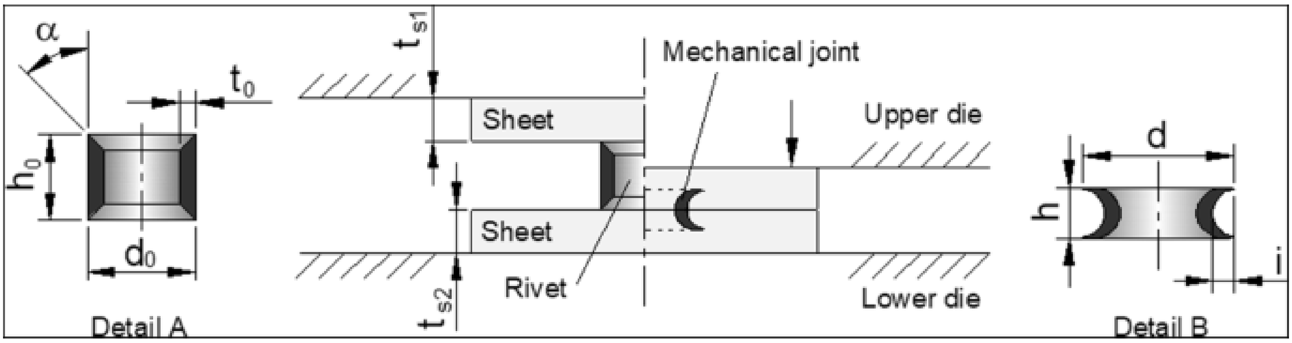


Figure 16 – Double-sided self-piercing riveting

2.2.4.4. Solid self-piercing riveting (SSPR)

The mechanism of solid self-piercing riveting is quite similar to conventional SPR, as can be seen in Figure 17, but resorts to a solid rivet. Regarding this technology, it is worth noting that it can be applied to high-strength materials with limited deformation capability and allows the production of nearly flat joints (almost no protrusions). Typically, the total sheet thickness ranges between 1.5 and 5 mm, but the lower sheet must have a minimum thickness of 1 mm, in order to fill the groove in the rivet shank and establish a strong joint [12].

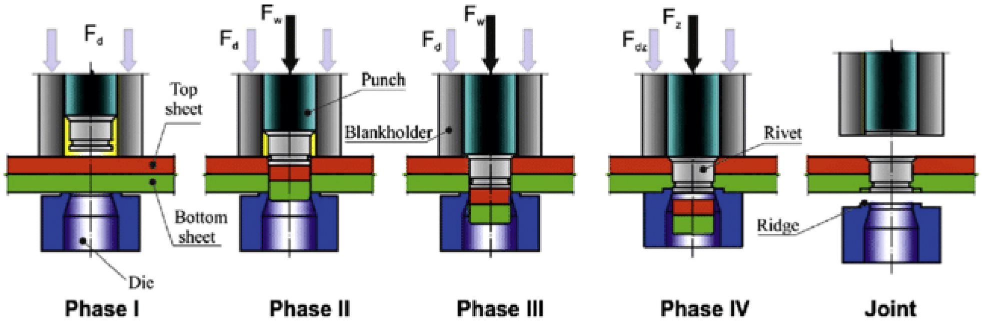


Figure 17 – Phases of solid self-piercing riveting

2.2.4.5. Hydro self-piercing riveting

In hydro self-piercing (see Figure 18), a high-pressure fluid is used instead of a die. The main advantage of hydro self-piercing compared to SPR is the fact that high-pressure fluid prevents strong bending, resulting in increased deformability and widened operating window. The pressure of the fluid and the shape of the rivet influence the quality of the joint, because there is a linear relationship between the mechanical interlocking and the fluid pressure [8].

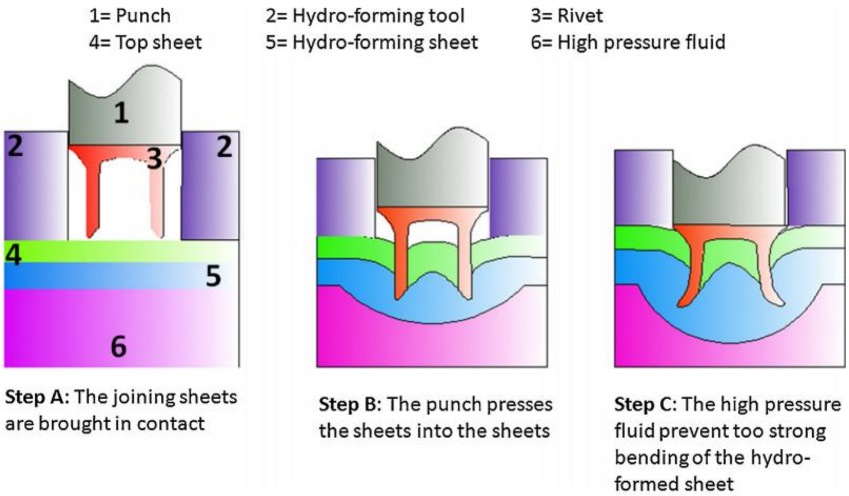


Figure 18 – Hydro self-piercing riveting

2.2.4.6. Ultrasonic self-piercing riveting (USPR)

The principle behind USPR (Figure 19) is the same as conventional SPR; nonetheless, it is an oscillating tool, at a given amplitude and frequency, that punches the rivet into the stacked sheets. The most relevant advantage of this process, compared to SPR, is that the composite structure does not suffer damage, such as cracks and fractures [13].

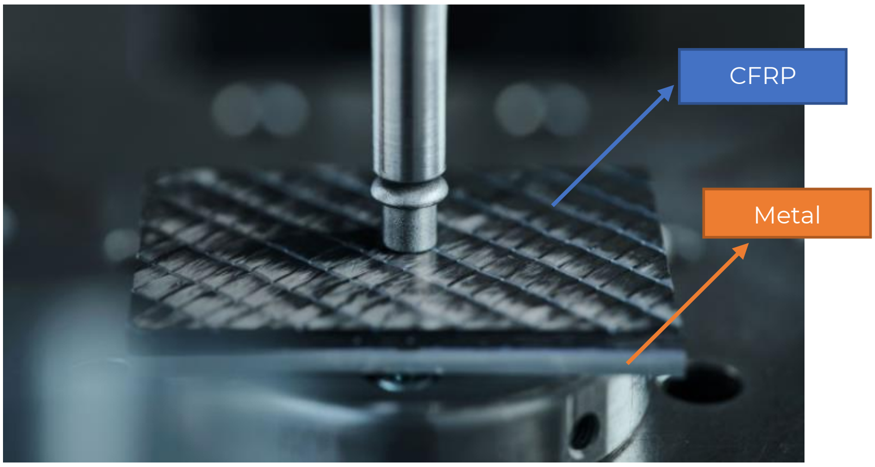


Figure 19 - Ultrasonic self-piercing riveting

2.2.4.7. Friction riveting (FricRiveting)

An investigation was led by [14] to prove the feasibility of using FricRiveting, to connect GFRP elements in composite emergency bridges. As seen in Figure 20, a rotating metallic rivet is punched into two stacked sheets and the generated frictional heat melts and displaces the polymeric matrix around the rivet tip. The local heat softens the rivet, which, under axial pressure, is deformed, creating a mushroom-like shape that promotes mechanical interlocking. In general, this process presents the same advantages and disadvantages as conventional self-piercing riveting. Nonetheless, it is only applicable to thermoplastic matrix composites and thermal degradation can occur. There is a set of parameters that can be controlled in order to optimize the FricRiveting process: rotational speed, forging pressure, friction time and forging time [15], [16].

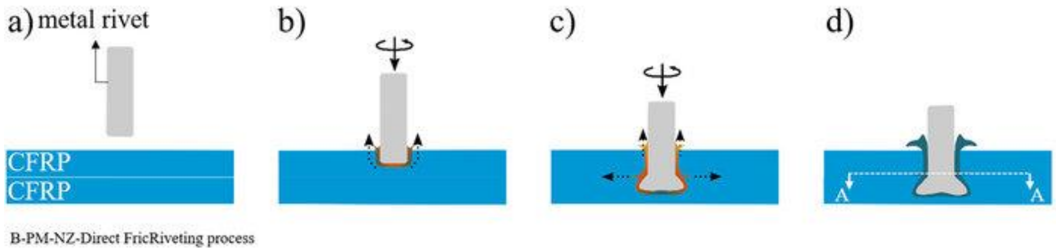


Figure 20 – Application of friction riveting to join two CFRP sheets. (a) Positioning of the parts; (b) Rivet rotation and insertion; (c) Rivet tip plastic deformation; (d) Joint consolidation

2.2.4.8. Friction stir blind riveting

As the name implies, friction stir blind riveting (see Figure 21) is a combination of friction stir riveting and blind riveting. It consists of rotating a blind rivet, which is pushed through the sheets to be joined. The generated frictional heat softens the sheets' materials, which facilitates the penetration of the blind rivet using a lower driving force and torque. A relevant advantage of this process, compared to SPR, is that only one side of the joint needs to be accessible [17], [18].

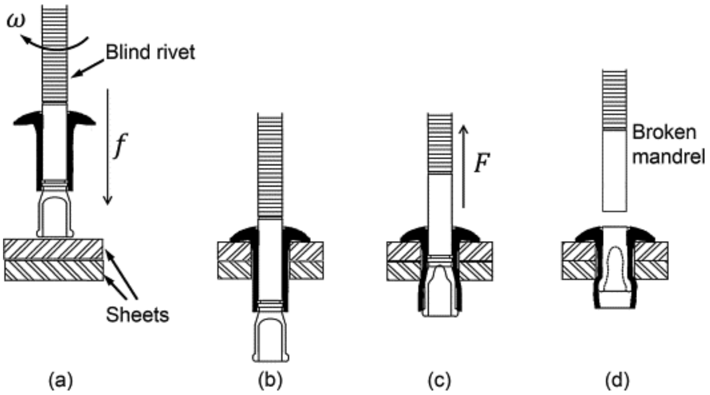


Figure 21 – Friction Stir Blind Riveting

Table 15 summarizes the information regarding the most relevant riveting technologies used to join composites to composites and composites to dissimilar materials. It is worth mentioning that some processes are still under development, which can result in a lack of information, despite their potential. Due to equipment limitations, the most used joint configurations are lap joints, as schematized in Figure 22.

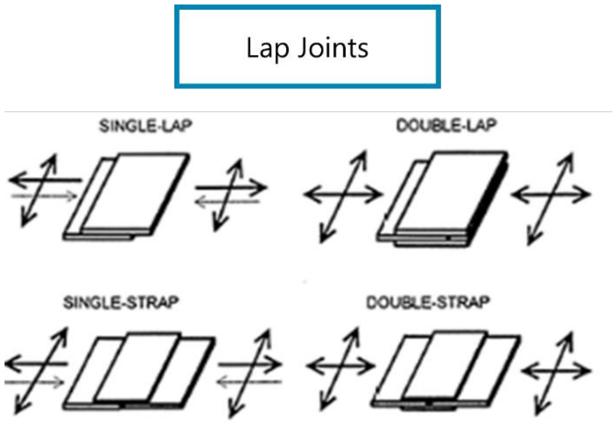
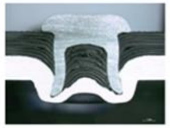
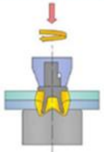
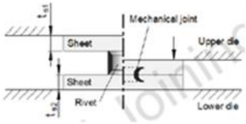
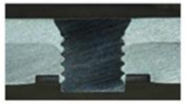
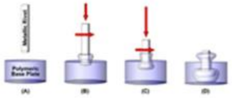
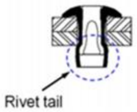


Figure 22 – Lap joints representation

Table 15 – Principal characteristics of riveting technologies

	Self-piercing riveting (SPR)	Friction self-piercing riveting (FSPR)	Double-sided self-piercing riveting	Solid self-piercing riveting (SSPR)	Hydro Self-Piercing Riveting	Ultrasonic Self-Piercing Riveting (USPR)	Friction Riveting (FricRiveting)	Friction Stir Blind riveting
Riveting								
Rivets Materials	Aluminium, Steel alloys, Stainless Steel, Titanium							
Materials to Join	Similar and Dissimilar Materials							
Corrosion Resistance	Galvanic corrosion avoided by using titanium rivets or coating to hinder the contact between aluminium and carbon fibres							
Total Thickness	1.5 – 4 mm	-	-	1.5 – 5 mm	-	-	-	-
Shear Strength		2x greater than SPR joints of same materials	-	-	-	-	Higher than bolted joints	-
Fatigue Strength	Higher than RSW	Higher than RSW and clinching	-	-	-	-	-	-
Service Temperature Range	-	-	-	-	-	-	-	-
Applications	Automotive Industry	-	-	Production of thin-walled car body elements	-	Automotive Industry	Considered to join composite in emergency bridges (specimen level)	-
Standards	DVS-EFB 3440-2:2006-07 DVS-EFB 3490:2006-10	-	-	-	-	-	-	-
Advantages	Single-step operation Does not require pre-drilled holes Operator-friendly Easily automated	-	-	Environmental friendly More than 3 layers can be joined Low energy consumption	-	-	Does not require surface pre-treatment Hermetically seals joints	Consistent joint strength
Disadvantages	Surface cracks Fibre breakage Delamination (minimized by the use of washers)	Surface cracks Fibre breakage	Slender rivets may fail by plastic instability Requires good centring	High deformation (in the material w/ lower strength) when joining materials w/ significant difference between their mechanical properties	-	-	Currently, can only be applied to thermoplastic matrix composites Thermal degradation of the polymer matrix Only spot-like joints	Delamination Joint efficiency affected by stacking-sequence
Cost	7656 – 35233 € (equipment and others)	-	-	-	-	-	-	-
Process Chain	Position substrates; Rivet Substrates.							
Process Time	Decrease in production time	-	-	-	-	Seconds	Seconds	Seconds

2.2.5. Integral Attachments

2.2.5.1. Snap-fit

Integral snap-fits can be applied to polymer-matrix composites; nonetheless, moulding small details can be difficult depending on the type of fibre and the ductility of the matrix. For this reason, snap-fit is more suitable for thermoplastic matrix composites than for thermoset composites [19].

Different set of features can be designed-in or processed-in the composite structure and then assembled. The joints can be permanent or easily disassembled, which results in a very flexible process in terms of functionality, design and aesthetics. This technology is mainly used to join small to medium parts in non-structural applications; however, as can be confirmed in Figure 23, it has been successfully applied in the assembly of bridge decks of glass fibre reinforced polymers [19]. Table 16 gathers the most relevant information on snap-fit technology. The most common joint configurations applied to snap-fit are lap, sleeve and scarf joints as represented in Figure 24.

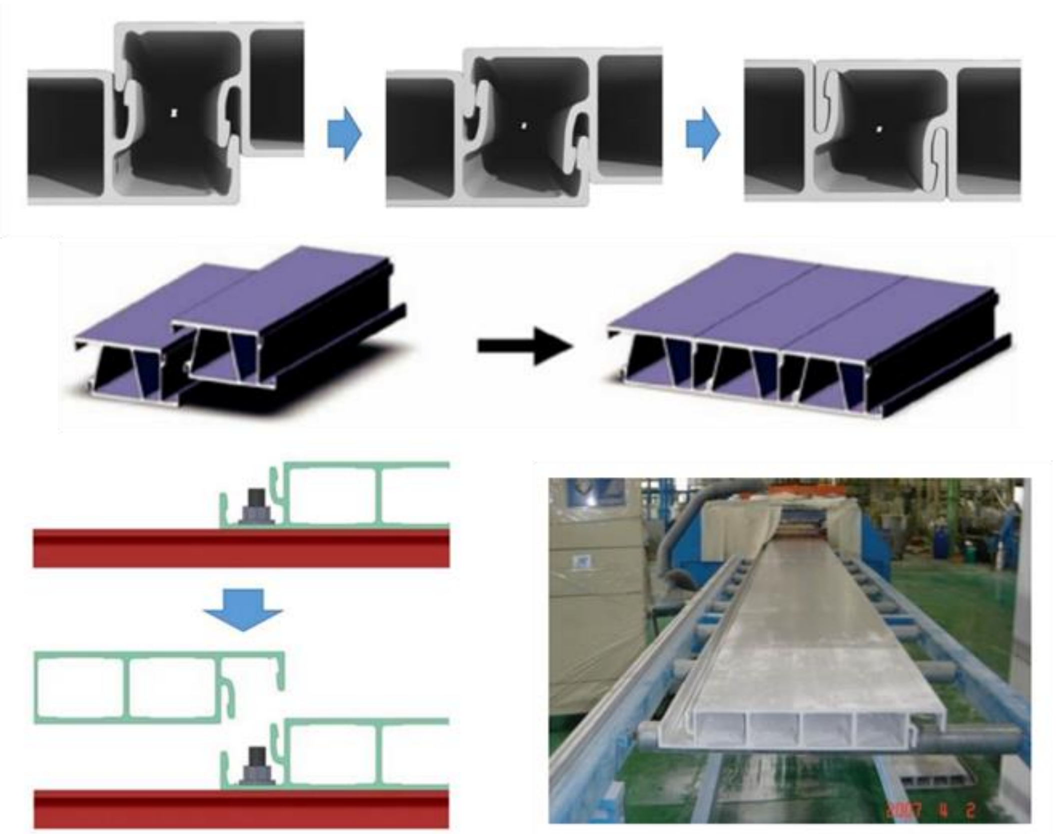
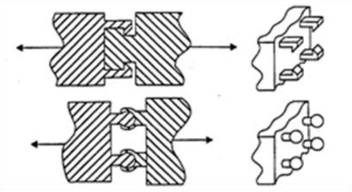


Figure 23 – Applications of GFRP bridge deck with vertical snap-fit connection

Table 16 – Principal characteristics of snap-fit

Snap-fit	  
Materials	Composite materials with a ductile matrix
Corrosion Resistance	Great
Tensile Strength	119 – 635 MPa
Compressive Strength	66 – 386 MPa
Service Temperature Range	-
Applications	Joining small to medium parts Civil industry
Standards	-
Advantages	Easily and quickly installation Can reduce assembly time
Disadvantages	More suitable for thermoplastic matrix composites
Cost (per kg)	5.77 – 8.21 €

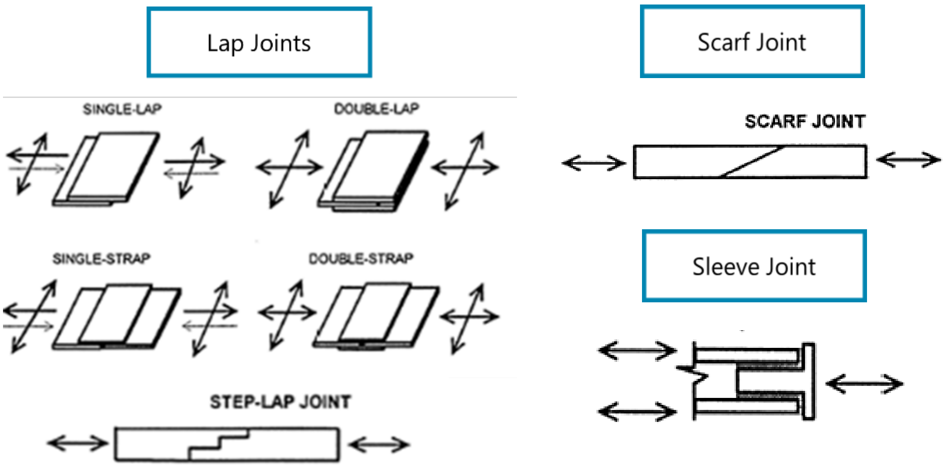


Figure 24 – Most common joint configurations used in snap-fit

2.2.5.2. Staking

Staking is considered a joining by forming process. The staking processes presented in Table 17 differ from each other in terms of heat transfer mechanism. This means the heat is transferred by convection (**hot air staking**), conduction (**hot staking**), intermolecular friction (**ultrasonic staking**) or radiation (**infrared staking**, IR). Figure 25 displays the basic mechanism involved in the staking process. A forming tool, by heat transfer, deforms the rivet pin, which will be responsible for generating mechanical interlocking between the two parts to be joined. Different geometries of the resulting rivet head can be obtained by using different tools. The German Guideline DVS 2216-3 can be consulted in order to provide some information on the best rivet geometries. Nonetheless, this guideline focuses essentially on ultrasonic staking [20].

It is worth mentioning that the joint properties depend on the heat transfer mechanism and on the material properties. By the analysis of the data presented in Figures 26 and 27, it can be concluded that ultrasonic staking is a faster process and that IR staking results in a stronger joint. A general comparison between hot air, ultrasonic and IR staking is presented in Figure 28 and it is based on cycle time, repeatability, tensile strength, equipment and operating costs.

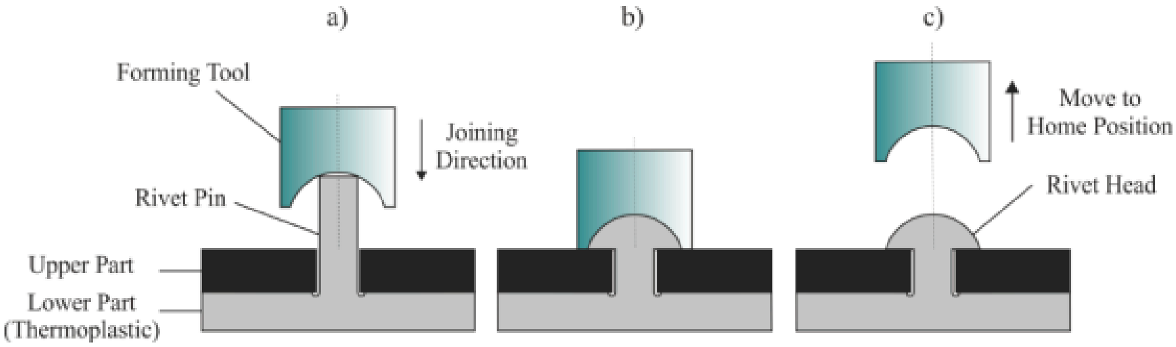


Figure 25 – Principle of the staking process. (a) before staking, (b) rivet formation, (c) tool removal

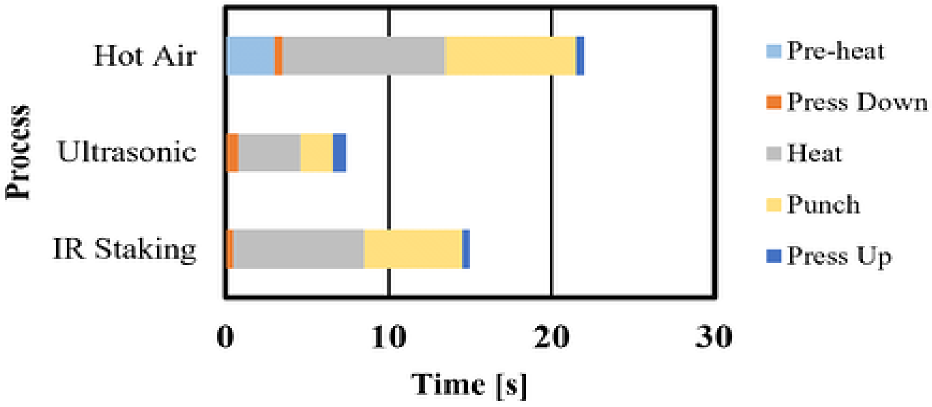


Figure 26 – Process time of hot air, ultrasonic and IR staking processes

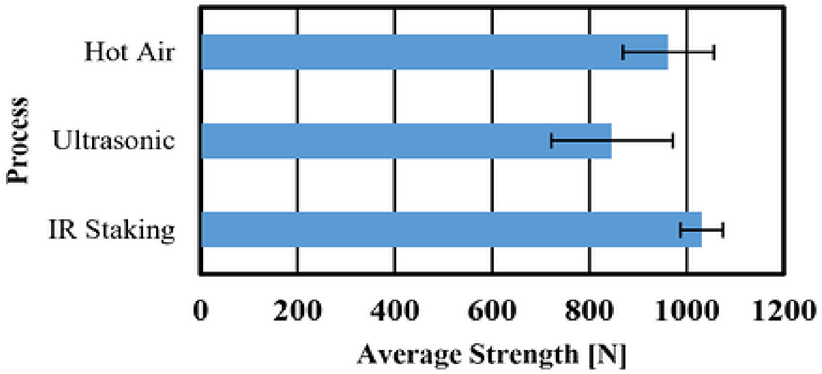


Figure 27 – Average strength of hot air, ultrasonic and IR staking processes

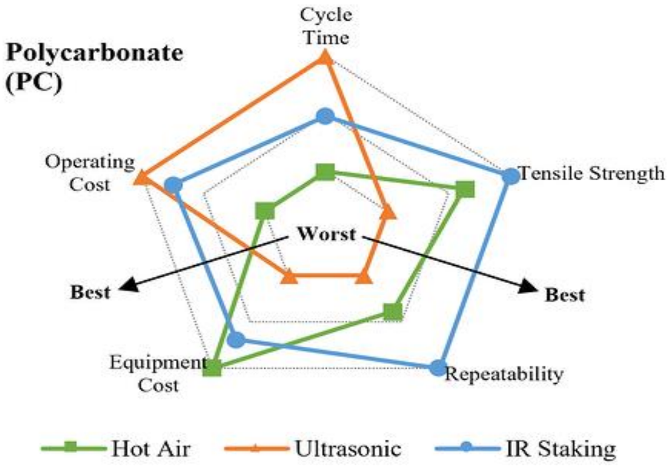
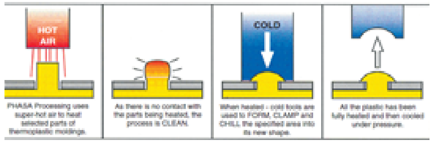
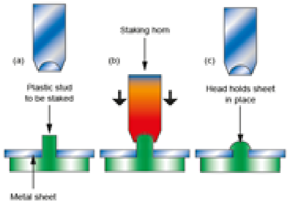
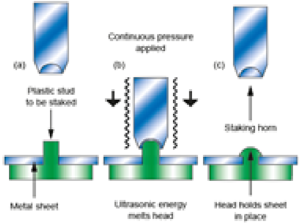


Figure 28 – General comparison between hot air, ultrasonic and IR staking

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

Table 17 – Principal characteristics of staking processes

	Hot Air Staking	**Hot Staking**	**IR Staking**	**Ultrasonic Staking**
Staking			-	
Materials	Metals, Polymers, Composites, Dissimilar Materials			
Corrosion Resistance	Galvanic corrosion (i.e. Al-CFRP systems)			
Specific Parameters	Temperature and Pressure			
Applications	Automotive, Telecom, Appliance Industries			
Standards	ISO 23512:2021, DVS 2216-3			
Advantages	Eliminates the need for screws, rivets or bolts Eliminates the susceptibility to galvanic corrosion No particular environmental hazards Can be disassembled			
Disadvantages	Requires the use of thermoplastics Differences in CTE of dissimilar materials can lead to loosening High investment Joint is not always aesthetically pleasing			
Process Chain	Parts positioning; Thermoplastic heating; Stud formation; Cooling			
Process Time	Fast			
Cost	Economical			

2.2.5.3. Clinching

Clinching is a joining by forming process, very similar to self-piercing riveting; however, it does not require a supplemental device and the joint efficiency depends on geometrical characteristics such as the undercut and the neck thickness. Figure 29 shows the main principle involved in the clinching process. Two sheets are stacked and clamped between the blank holder and the die assembly. Subsequently, the punch is forced onto the sheets, pushing them into the die. The material flows radially and fills the die, resulting in mechanical interlocking, which holds the parts together. Table 18 shows the main advantages and disadvantages of mechanical clinching [15], [21].

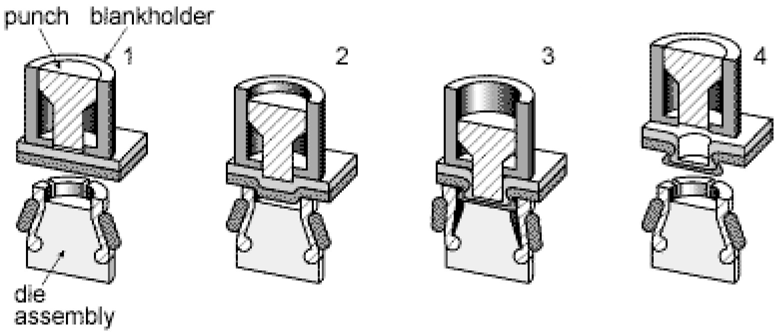


Figure 29 – Clinching process

Table 18 – General advantages and disadvantages of clinching

Advantages	Disadvantages
No need for drilled holes and supplemental devices	Disassembly is not possible without destroying the joint
Lower production time and costs (single operation)	Delamination, fibre damage and matrix cracking can occur and can be intensified under fatigue cyclic stresses
No need for surface pre-treatment	More suitable for thermoplastic matrix composites
Operator-friendly	Limited by the thickness and formability of the materials to be joined

2.2.5.4.Hole Clinching

As clinching involves the deformation of the materials to be joined, composite materials can suffer damages, such as delamination, matrix cracking, and fibre breakage, which leads to a reduction in mechanical performance and failure. In order to overcome this issue, new technologies have emerged, being hole clinching an example (see Figure 30). This joining method consists of pre-punching or drilling pilot holes in the less ductile material, to avoid its deformation, and applying an axial pressure that will deform the more ductile material. As the punch deforms the top workpiece, the material flows into the die through the pre-existent hole, forming mechanical interlocking between the two sheets. The joint efficiency can be optimized by changing the tool geometry, the type of die and/or the force applied [22], [23].

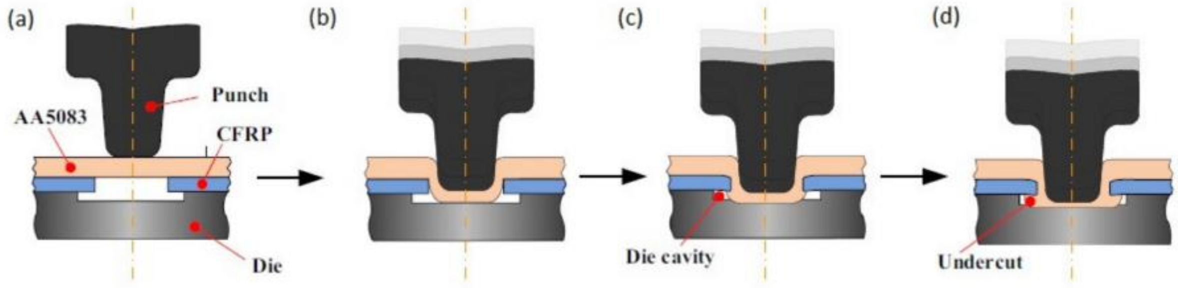


Figure 30 – Hole clinching

2.2.5.5. Shear-clinching

Shear clinching is based on the principle of conventional clinching and shear-cutting (see Figure 31). The lower joining part is indirectly cut by shear and the upper part is extruded into the shear-cut hole, forming mechanical interlocking. As the upper part must undergo a high deformation, it must have a minimum ductility. On the other hand, the lower part must present a minimum strength, in order to withstand the transmitted forces during the process. Therefore, the joint efficiency and final thickness are constrained by the mechanical properties of the materials to be joined and the tool geometry [24].

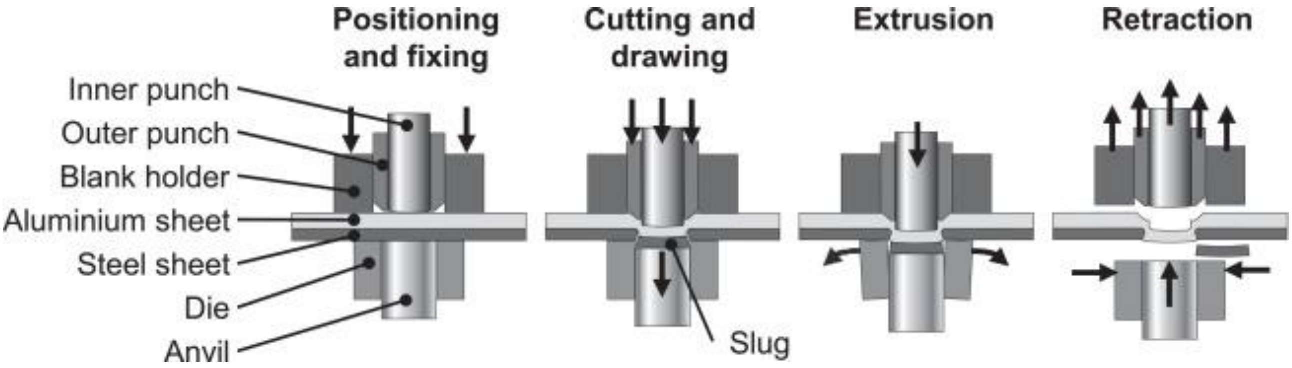


Figure 31 – Shear clinching

2.2.5.6. Injection clinching (ICJ)

Injection clinching joining is a process developed to join a thermoplastic-based part to a metallic or thermoset piece and it is based on the principles of injection moulding, staking and adhesive bonding. Figure 32 displays the mechanism involved in ICJ technology. A thermoplastic stud is inserted in a through-hole in the metallic or thermoset-based element. The stud is subsequently heated and deformed by a punch-piston, in order to create a rivet. After cooling, the two parts remain together by mechanical interlocking and adhesion forces. The holes can present different geometries and features such as chamfers or threads and the generated heat can be from electrical or frictional sources. The main disadvantage of this process is related to the need of drilling holes in the structure. Figure 33 shows a fuselage section, where FRP composite brackets were joined to a lightweight alloy by injection clinching joining [15], [25].

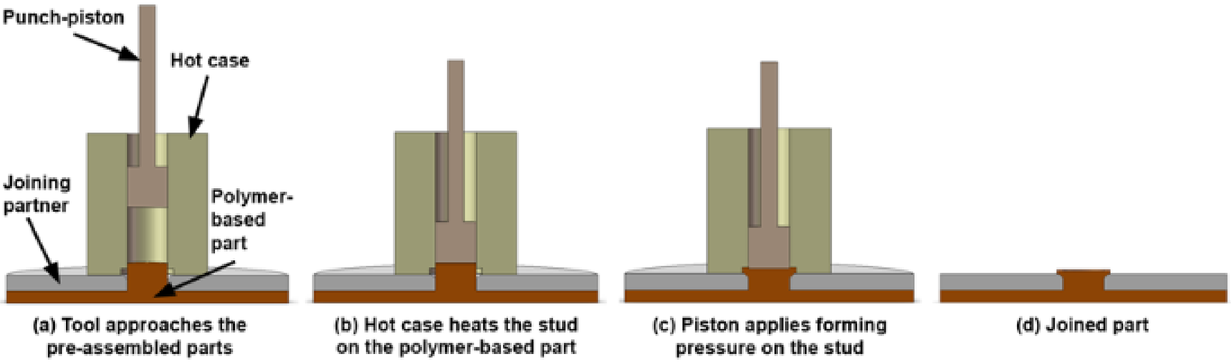


Figure 32 – Injection clinching joining process

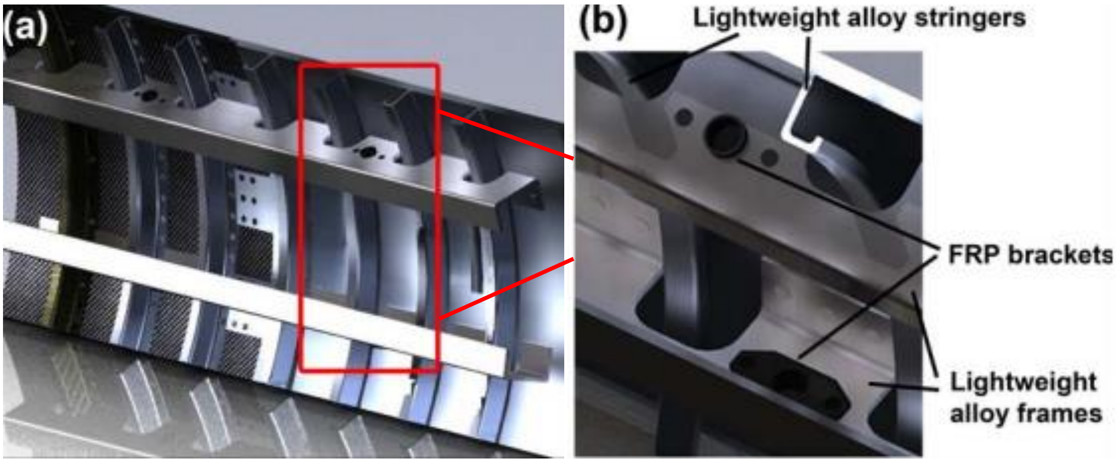


Figure 33 – Application of ICJ to connect FRP brackets to metal frames in an aircraft structure

2.2.5.7. Thermoclinching

Thermoclinching is a process based on principles of staking and conventional clinching. Its mechanism is schematically demonstrated in Figure 34. The parts to be joined – thermoplastic-based part and a metallic part with a pre-drilled hole – are aligned and positioned inside the mould and then heated (above the thermoplastic composite melting temperature), to facilitate the deformation imposed by a tapered pin. The thermoplastic flows into the pre-existent hole and it is constrained by a ring-shaped die. After cooling, the mould is opened and the final joint is achieved. The major drawbacks of this technology are related to the need of drilling a hole in the metal structure and the application of a working temperature above the melting temperature, which can cause thermal degradation [26].

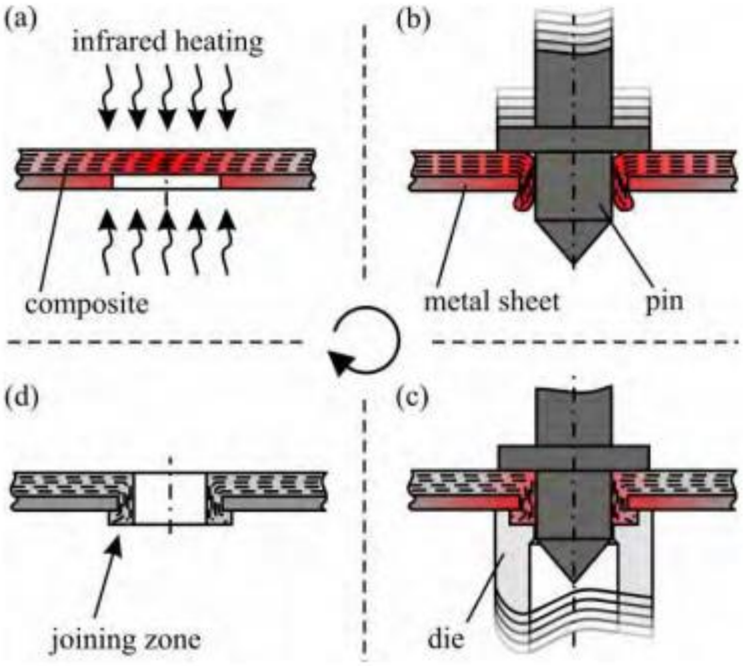


Figure 34 – Representation of thermoclinching process

2.2.5.8. Hydro-clinching

Hydro-clinching is a variant of conventional clinching that harvests the advantages of hydro-forming and mechanical clinching. This process leads to high accuracy, has a decreased number of steps and it is applicable to the joining of dissimilar materials. As can be seen in Figure 35, the die is replaced by a high-pressure fluid and the two sheets are in contact with the forming tool due to the present hydraulic pressure. The hydro-formed sheet is pushed through a hole in the upper sheet and the mechanical interlocking is formed. The joint strength depends on the geometry of the existent hole in the upper sheet, the hydro-formed sheet deformation capability and the pressure of the fluid [27].

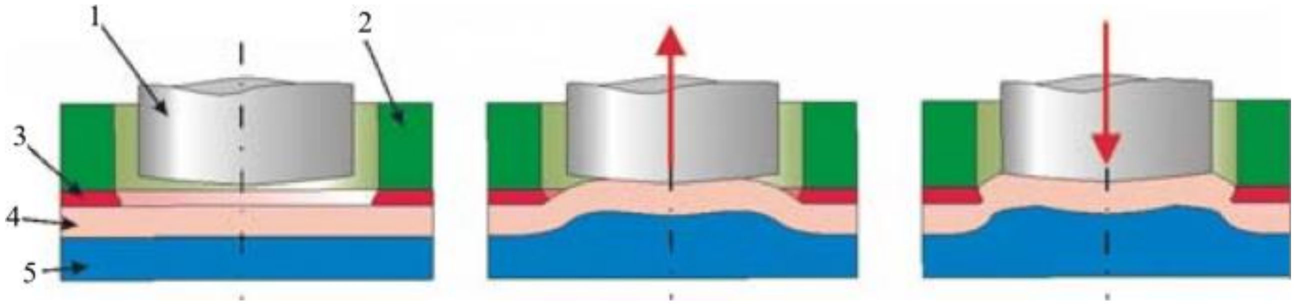


Figure 35 – Hydro-clinching. 1 – punch, 2 – hydro-forming tool, 3 – part to be attached, 4 – hydro-formed sheet, 5 – high-pressure fluid

2.2.5.9. Dieless clinching

Compared to conventional clinching, this technology does not require a bottom die (see Figure 36). The punch applies a high force into the upper sheet, locally deforming it. The deformed material flows in reverse along the punch displacement, causing the deformation of the lower sheet and both parts are joined by mechanical interlocking [27].

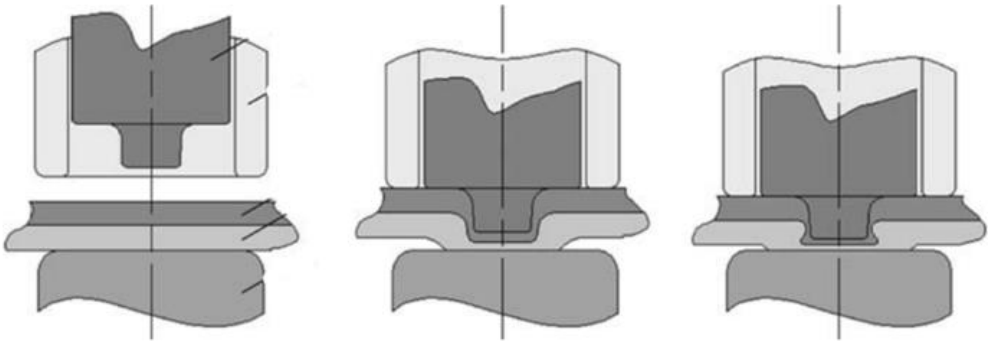


Figure 36 – Dieless clinching

2.2.5.10. Two-step clinching

The main difference between conventional clinching and the two-step process (see Figure 37) resides in a reshaping step after the clinching. This additional stage results in a reduction of the protrusion height and can improve the mechanical strength of the final joint, as it leads to an increase in the neck thickness and undercut [28].

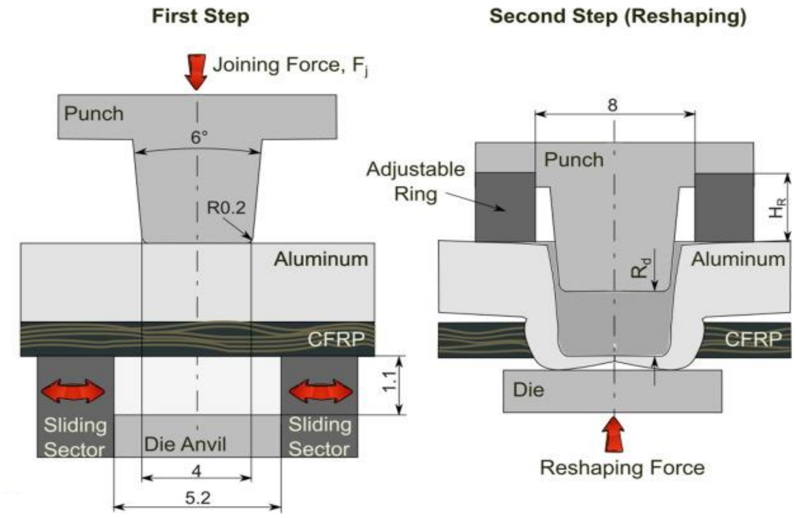


Figure 37 – Two-step clinching

Tables 19 and 20 gather the most relevant characteristics of the referred clinching processes.

Table 19 – Main characteristics of clinching processes

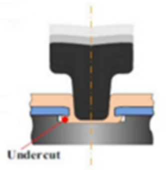
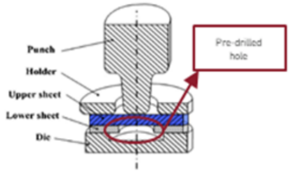
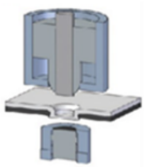
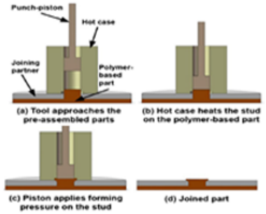
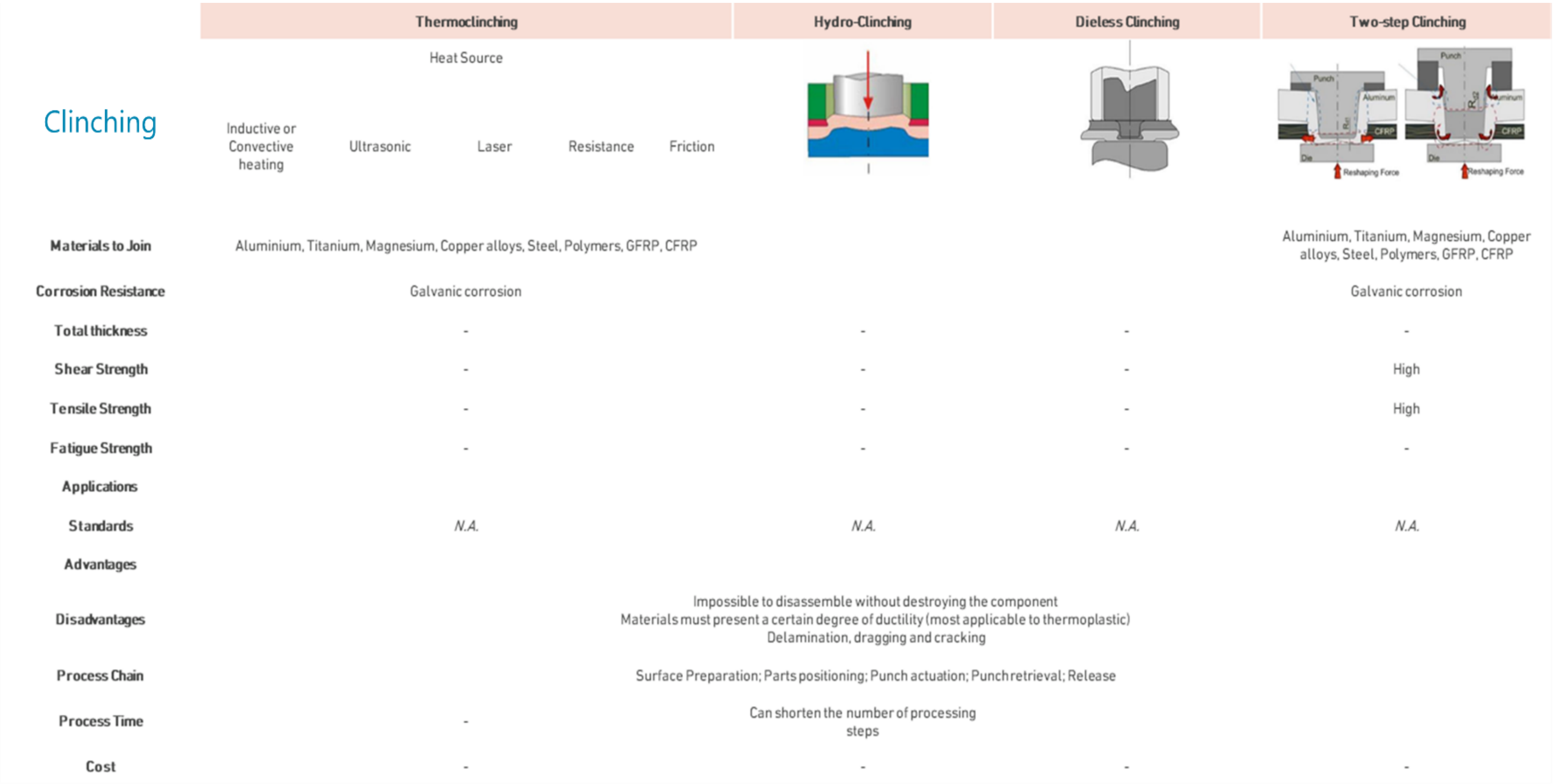
	Conventional Clinching	**Hole-Clinching**	**Shear-Clinching**	**Injection Clinching (ICJ)**
Clinching				
Materials to Join	Aluminium, Titanium, Magnesium, Copper alloys, Steel, Polymers, GFRP, CFRP	Aluminium, Titanium, Magnesium, Copper alloys, Steel, Polymers, GFRP, CFRP	Aluminium, Titanium, Magnesium, Copper alloys, Steel, Polymers, GFRP, CFRP	Aluminium, Titanium, Magnesium, Copper alloys, Steel, Polymers, GFRP, CFRP
Corrosion Resistance	Galvanic corrosion	Galvanic corrosion	Galvanic corrosion	Galvanic corrosion
Total thickness	~ 1.0 – 6.0 mm	-	-	
Shear Strength	Good	High	-	High
Tensile Strength	Good		-	High
Fatigue Strength	Medium	-	-	-
Applications	Successful used in automotive industry	-	-	Lightweight frames (Aerospace Industry)
Standards	DVS-EFB 3420:2012-02, DVS-EFB 3450-1:2007-05	-	-	
Advantages	Lightweight structures Does not require surface pre-treatment Easily automated	-	-	Can substitute riveting in some secondary structural applications
Disadvantages	Impossible to disassemble without destroying the component Materials must present a certain degree of ductility (most applicable to thermoplastic) Delamination, dragging and cracking	Need for perfect coaxial alignment of the hole in the stronger material and the punch tool Impossible to disassemble without destroying the component Requires pre-drilling	Materials must present a certain degree of ductility (most applicable to thermoplastic) Delamination, dragging and cracking	Materials must present a certain degree of ductility (most applicable to thermoplastic) Delamination, dragging and cracking
Process Chain	(Surface Preparation); Parts positioning; Punch actuation; Punch retrieval; Release			
Process Time	Very short	Higher due to predrilling process	One-step continuous process	-
Cost	Reduce production costs (relatively to welding processes) due to: - Low investment cost - Low operating costs - No reworking costs - Short cycle times	-	-	-

Table 20 – Main characteristics of clinching processes (cont.)



Clinching	Thermoclinching	Hydro-Clinching	Dieless Clinching	Two-step Clinching
	Heat Source Inductive or Convective heating Ultrasonic Laser Resistance Friction			
Materials to Join	Aluminium, Titanium, Magnesium, Copper alloys, Steel, Polymers, GFRP, CFRP			Aluminium, Titanium, Magnesium, Copper alloys, Steel, Polymers, GFRP, CFRP
Corrosion Resistance	Galvanic corrosion			Galvanic corrosion
Total thickness	-	-	-	-
Shear Strength	-	-	-	High
Tensile Strength	-	-	-	High
Fatigue Strength	-	-	-	-
Applications				
Standards	*N.A.*	*N.A.*	*N.A.*	*N.A.*
Advantages				
Disadvantages	Impossible to disassemble without destroying the component Materials must present a certain degree of ductility (most applicable to thermoplastic) Delamination, dragging and cracking			
Process Chain	Surface Preparation; Parts positioning; Punch actuation; Punch retrieval; Release			
Process Time	-	Can shorten the number of processing steps		
Cost	-	-	-	-

2.2.5.11. Hemming

Hemming is a joining by forming technique and can be essentially divided into **table-top hemming** and **roller hemming** (see Figure 38). The former involves three steps: flanging, pre-hemming and final hemming. In the first stage, a tool bends the sheet approximately 90°; in the following step, the sheet is pre-folded in 45° and, subsequently, the final fold is obtained by resorting to another tool. Tabletop hemming is easy to control and results in overlapped joints. Due to the high deformation imposed, it can be difficult to apply to composite materials, as it can lead to severe damage of the structure. An alternative to tabletop hemming is roller hemming. It is an incremental process and is easily automated since it is driven by robots. The roller (tool) is responsible for bending the outer part around the edge of the two sheets, in order to form the final joint. In addition, it also involves lower forces than table-top hemming. Table 21 presents the main characteristics of the mentioned hemming technologies. The most used joint configuration in hemming processes is the overlap joint [29], [30].

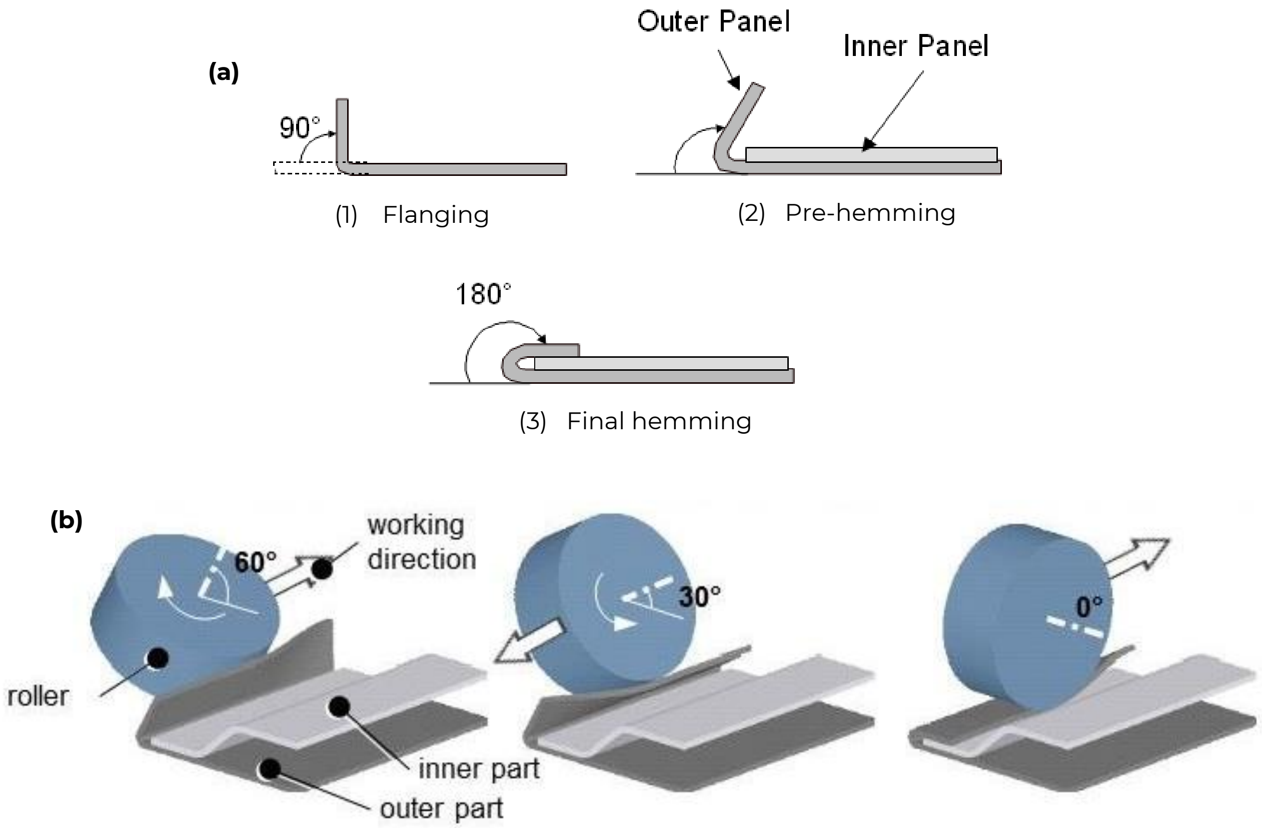


Figure 38 – Hemming. (a) Table top hemming; (b) Roller hemming

Table 21 – Main characteristics of hemming processes

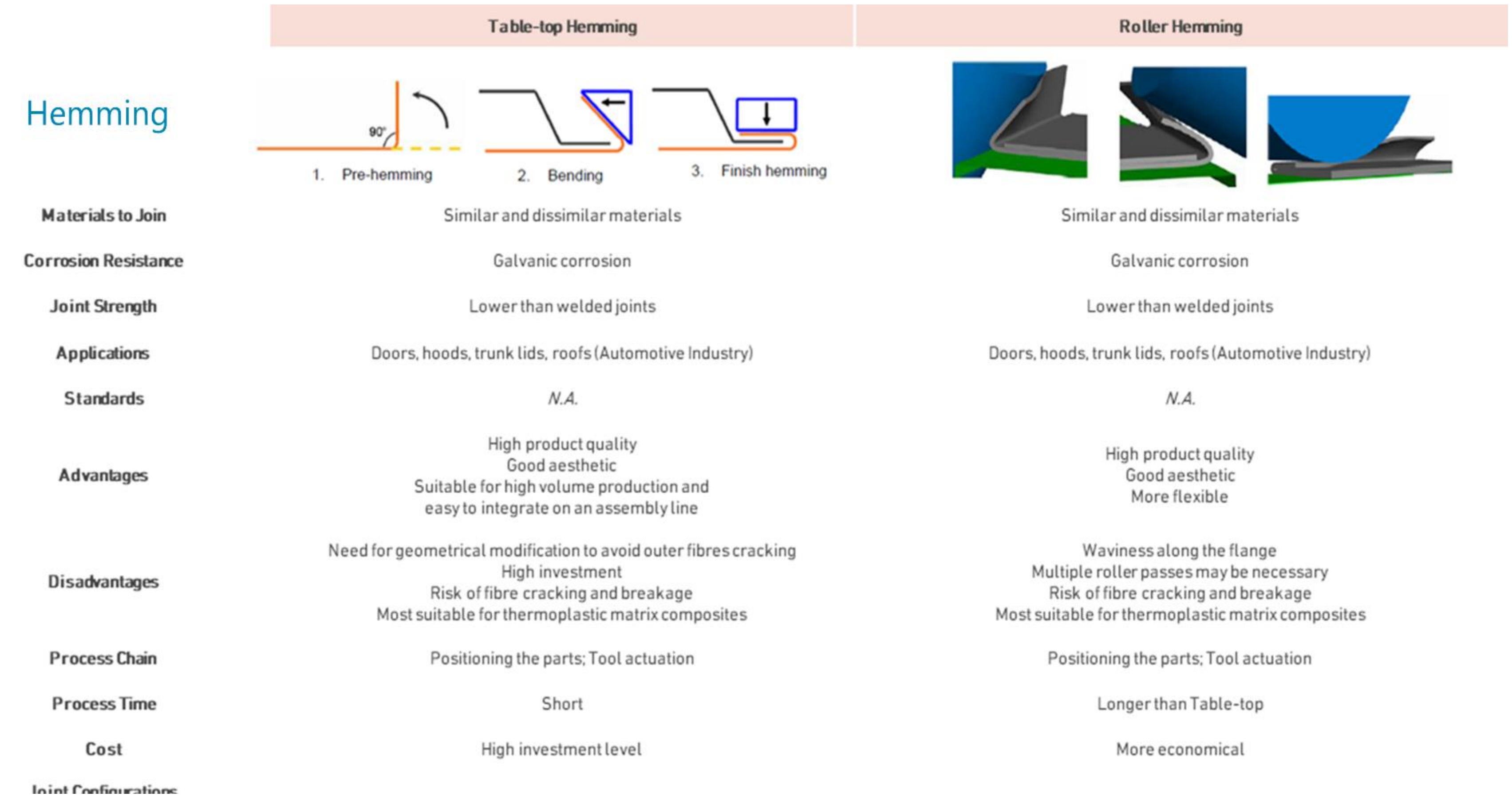


	Table-top Hemming	Roller Hemming
Hemming	90° 1. Pre-hemming 2. Bending 3. Finish hemming	
Materials to Join	Similar and dissimilar materials	Similar and dissimilar materials
Corrosion Resistance	Galvanic corrosion	Galvanic corrosion
Joint Strength	Lower than welded joints	Lower than welded joints
Applications	Doors, hoods, trunk lids, roofs (Automotive Industry)	Doors, hoods, trunk lids, roofs (Automotive Industry)
Standards	*N.A.*	*N.A.*
Advantages	High product quality Good aesthetic Suitable for high volume production and easy to integrate on an assembly line	High product quality Good aesthetic More flexible
Disadvantages	Need for geometrical modification to avoid outer fibres cracking High investment Risk of fibre cracking and breakage Most suitable for thermoplastic matrix composites	Waviness along the flange Multiple roller passes may be necessary Risk of fibre cracking and breakage Most suitable for thermoplastic matrix composites
Process Chain	Positioning the parts; Tool actuation	Positioning the parts; Tool actuation
Process Time	Short	Longer than Table-top
Cost	High investment level	More economical
Joint Configurations		

2.2.6. Special Connections

2.2.6.1. Non-adhesive form locked joints

The oldest and simplest way to join large elements is through bolts, although the use of these elements is associated with drilling holes and, as mentioned earlier, this can lead to material damage in the form of delamination, fibre pull-outs and micro buckling. In addition, larger holes are required in large structures, which removes more fibres and, consequently, disrupts the load paths. Therefore, a new idea has been developed, in order to overcome these issues: **non-adhesive form locked joints**. Firstly, this mechanical connection was designed at the Warsaw University of Technology and was used in a fuselage-wing connection for the commercial and experimental gliders and motogliders PW-5, PW-6 and AOS-71, as shown in Figure 39 [15].

Non-adhesive form locked joints are achieved by cutting holes in dry fabric, which are subsequently infused with resin or in uncured prepreg; metal rings are fitted into the holes and the structure is then cured in an autoclave or a vacuum bag. Next, screws with a hole and nuts are placed into the cut holes of the joint. Bolts are put through the holes of the placed screws to form the assembly. This mechanism allows mitigating delamination and other defects, once it guarantees that the fibres around the joint are in all directions and that the stress are more uniformly distributed [15]. Table 22 gathers the main characteristics of the described joining process. The most used joint configuration with this technology is the flange joint (see Figure 40).

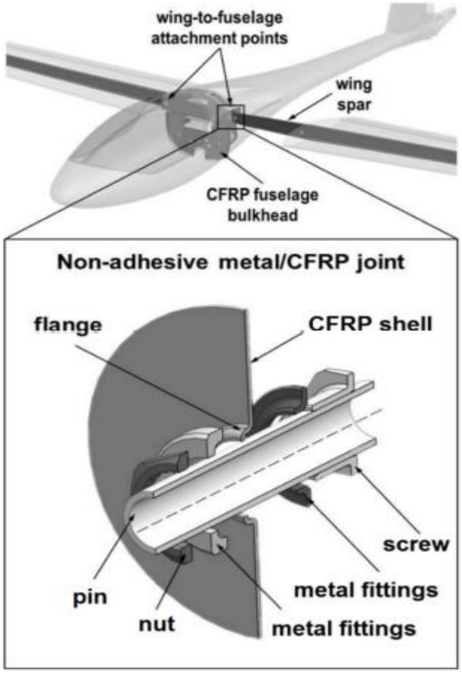
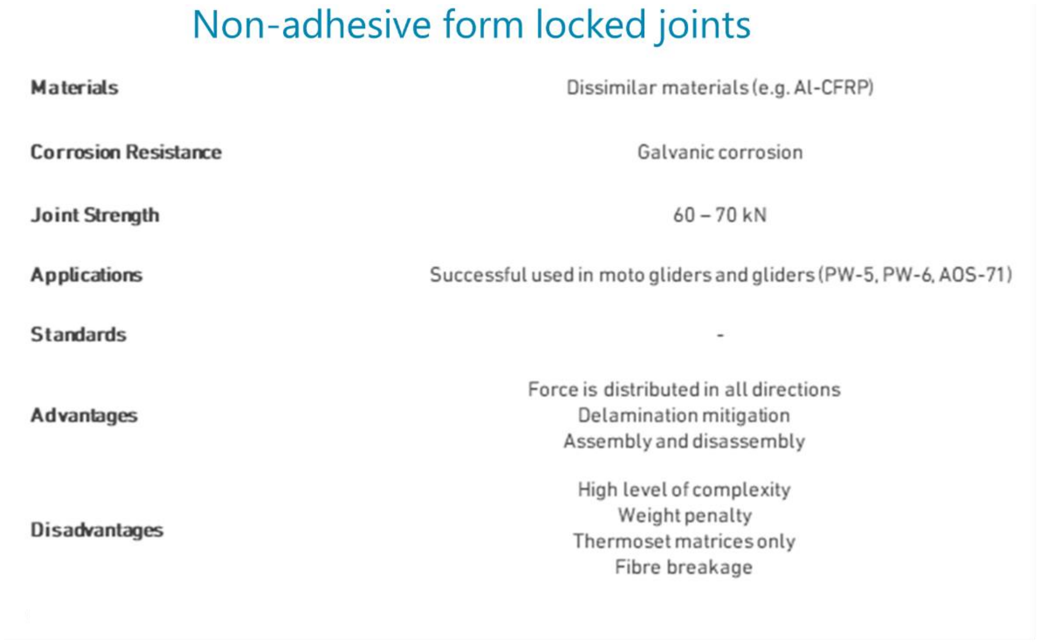


Figure 39 – Non-adhesive form locked joint in AOS-71 motoglider

Table 22 – Characteristics of non-adhesive form locked joints



Non-adhesive form locked joints

Materials	Dissimilar materials (e.g. Al-CFRP)
Corrosion Resistance	Galvanic corrosion
Joint Strength	60 – 70 kN
Applications	Successful used in moto gliders and gliders (PW-5, PW-6, AOS-71)
Standards	-
Advantages	Force is distributed in all directions Delamination mitigation Assembly and disassembly
Disadvantages	High level of complexity Weight penalty Thermoset matrices only Fibre breakage

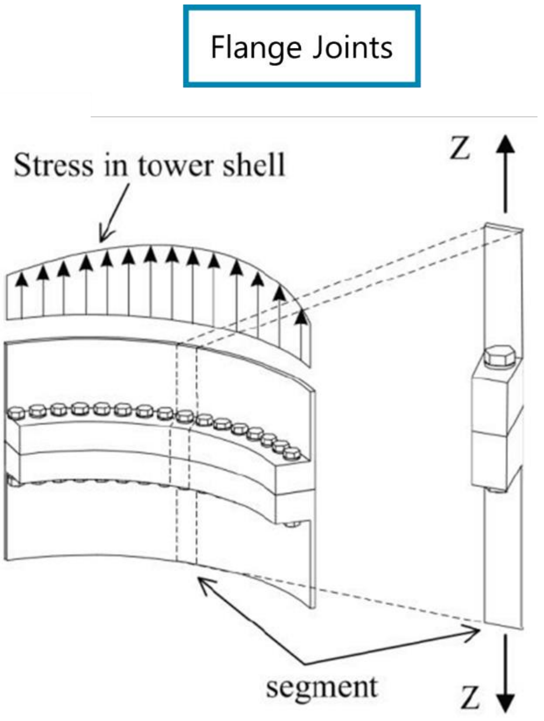


Figure 40 – Most common joint configuration used in non-adhesive form locked technology

2.2.6.2. Material surface modification and metal protusions

A way of joining materials is through the creation of features, such as protrusions or intrusions, in order to promote mechanical interlocking between the two parts to be joined. Nowadays, a wide variety of technologies can be used to achieve this, which can be categorized into **displacive methods** or **additive methods**.

Displacive methods consist of surface modification or restructuring through the action of electron or laser beams, which are responsible for melting the substrate surface and for the material displacement that occurs through the combination of temperature-variant surface tension and vapour pressure. The repetition of the melting process and the material displacement produces features of the desired aspect ratio. The surface topography is changed and the protruding features will promote mechanical interlocking. It is possible to generate different types of features, such as blade-like protrusions or blind hole-type or slot-type intrusions. Figure 41 shows examples of different protrusions geometries [31]–[34], [15].

Comeld™ technology is an example of a displacive method where the FRP composite is connected to the metal part by lay-up of preforms followed by vacuum infusion of a given resin, which constitutes the matrix of the composite but also acts as an adhesive. Nonetheless, some joints require the use of an additional adhesive layer at the bond line.

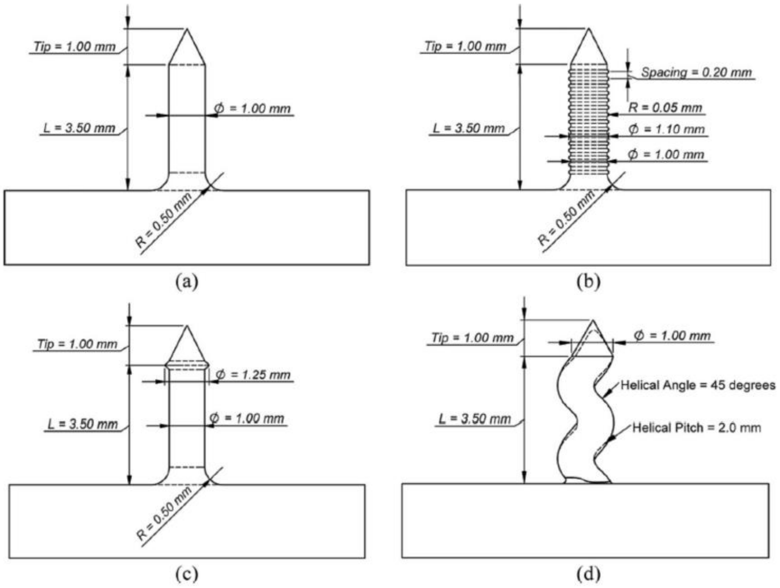


Figure 41 – Examples of geometries of the protrusions

The main disadvantage of this methodology is the high initial investment in the equipment. On the other hand, this joining process does not require drilling holes in the composite structure, which results in less stress concentration in the joint and the occurrence of delamination. However, it is worth noting that the protrusions can disrupt the fibres (see Figure 42).

As the name implies, additive methods involve adding features, such as z-pins, to the material surface. These features will be responsible for creating the mechanical interlocking between the parts to be joined. The mechanical interlocking force depends essentially on the selected production method, the materials to be joined, the geometry, number and positioning of the pins, the joint configuration and the machine setup.

In a general way, these joining processes allow to eliminate the need for drilling holes in the composite structure, leading to an overall better mechanical performance. In Figure 43 are presented the results of mechanical tests performed in a *Hyperjoint*. Compared to a traditional connection, the *Hyperjoint* results in a lap shear 60% higher than bolted joints and approximately twice that of bonded joints. An example of a successful application of this technology is shown in Figure 44 [15], [35], [36].

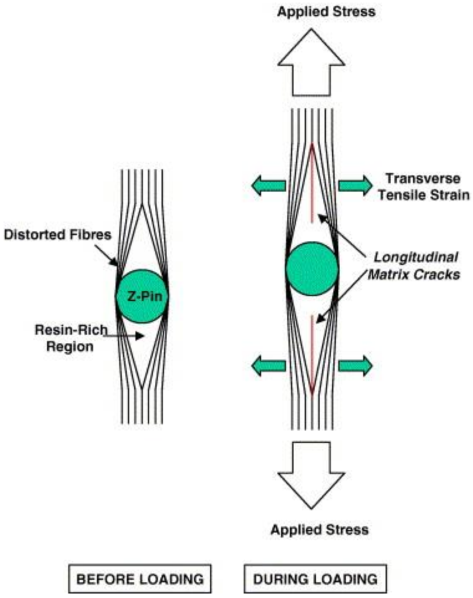


Figure 42 – Fibre distortion due to the presence of z-pin and process of longitudinal cracking in the resin-rich region

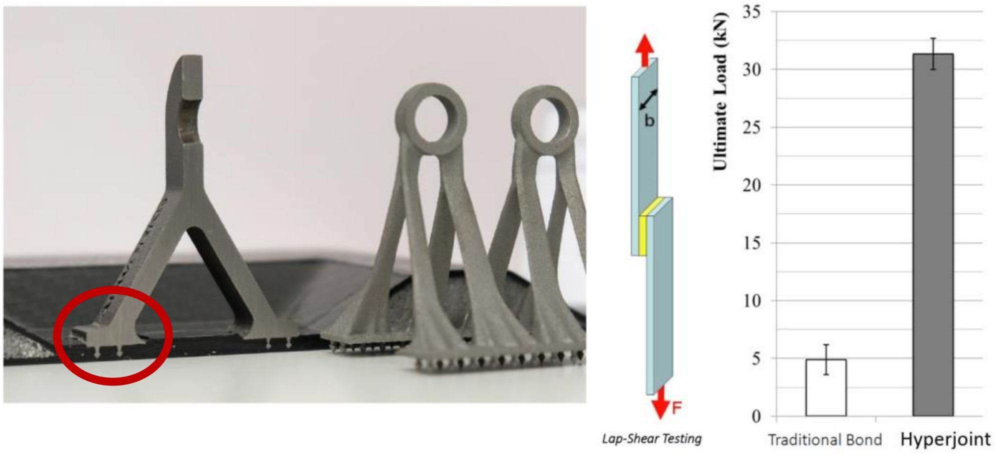


Figure 43 – Comparison between the ultimate load in a traditional connection and in a Hyperjoint

Figure 44 – Application of *Hyperjoints* in seat rails

Tables 23 and 24 gather the main characteristics of the most relevant processes used to obtain this type of joining. Due to equipment limitations, the most common joint configurations obtained with this type of joining process are lap joints and T joints, which are represented in Figure 45.

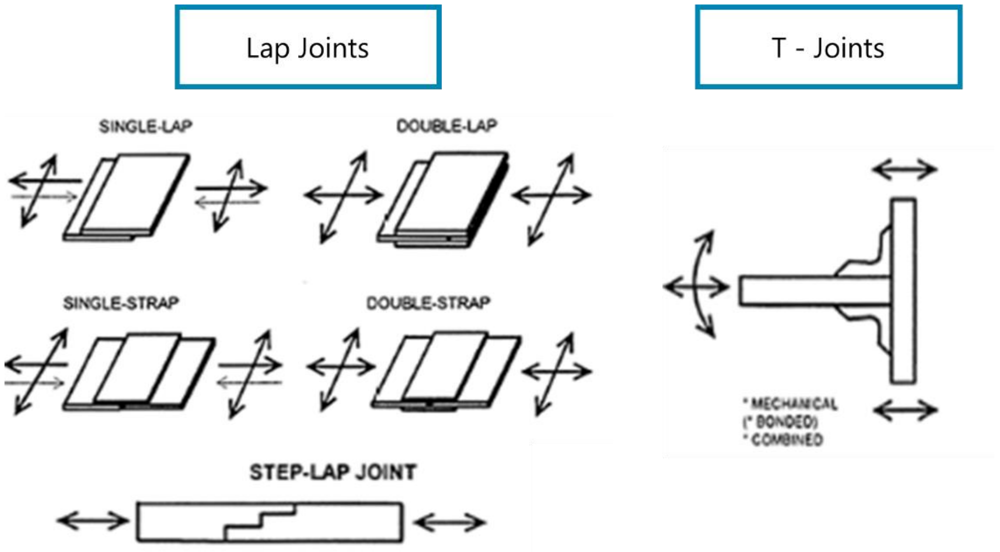


Figure 45 – Most common joint configurations obtained in material surface modification and metal protrusions processes

Table 23 – Main characteristics of Material surface modification and metal protrusions techniques

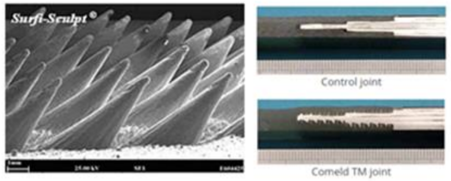
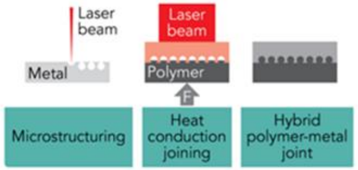
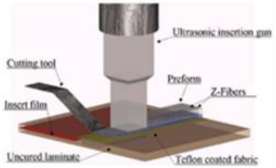
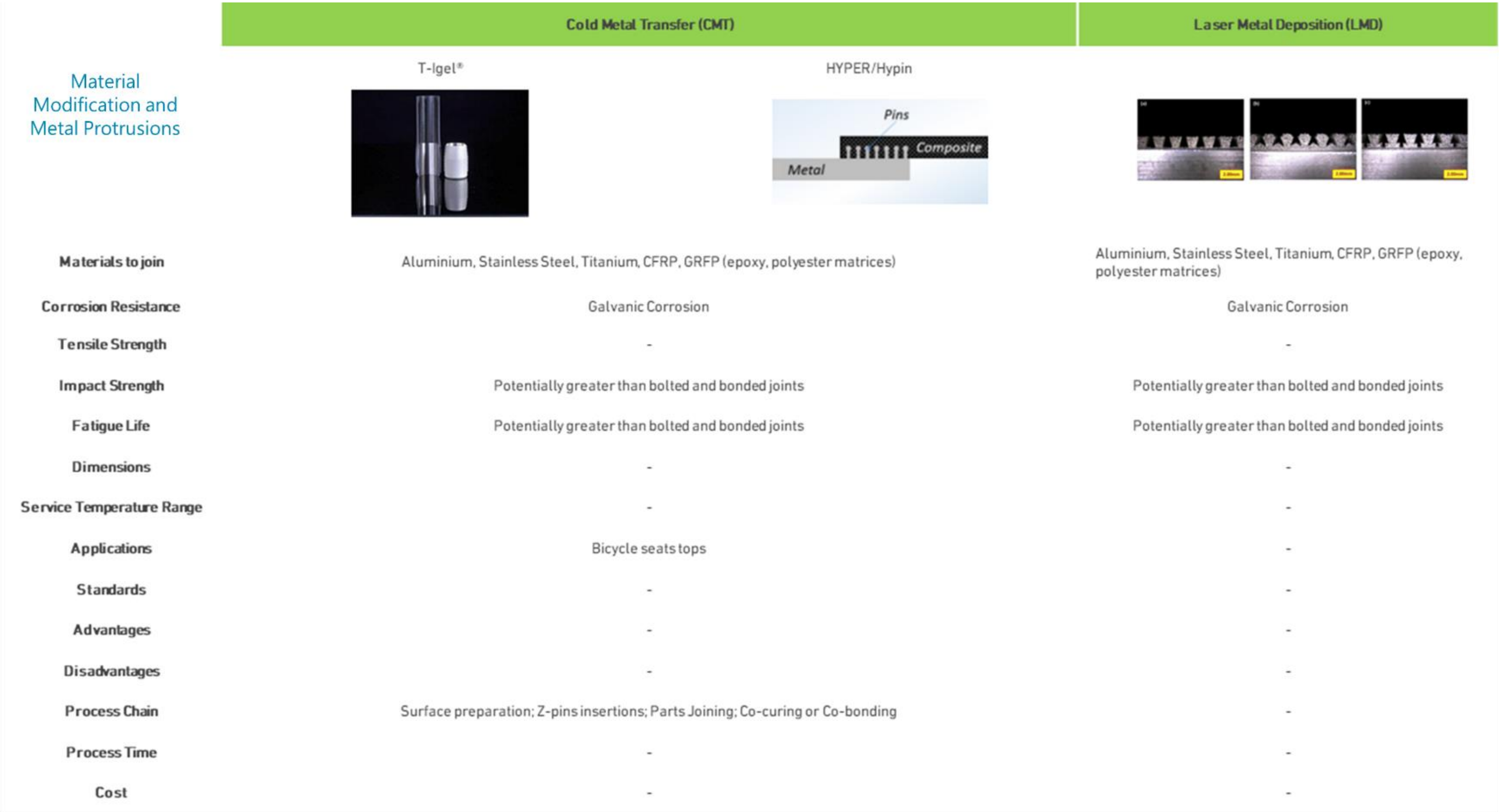
	Electron beam	Laser Beam			Ultrasonic
Material Modification and Metal Protrusions 🟧 Displacive Methods 🟩 Additive Methods	Surfi-Sculpt + Comeld™ 	CW Laser	Pulsed Laser 	Ultrashot Pulsed Lasers	
Materials to join	Aluminium, Stainless Steel, Titanium, CFRP, GRFP (epoxy, polyester matrices)	Aluminium, Stainless Steel, Titanium, CFRP, GRFP (epoxy, polyester matrices)			Aluminium, Stainless Steel, Titanium, CFRP, GRFP (epoxy, polyester matrices)
Corrosion Resistance	Galvanic Corrosion	Galvanic Corrosion			Galvanic Corrosion
Tensile Strength	28 – 37 kN	5.1 – 9.1 kN	-	14.5 kN	-
Impact Strength	Potentially greater than bolted and bonded joints	Potentially greater than bolted and bonded joints			Potentially greater than bolted and bonded joints
Fatigue Life	Potentially greater than bolted and bonded joints	Potentially greater than bolted and bonded joints			Potentially greater than bolted and bonded joints
Dimensions	Smaller features	Larger features			-
Service Temperature Range	-	-	-	-40 – 80 °C	-
Applications	Aerospace and Defence Industries	Automotive Industry (e.g. roof component of BMW 7 Series)			Aerospace industry
Standards	Lack of standardization	DIN EN 1465			
Advantages					High toughness Can be a substitute to mechanical fasteners
Disadvantages	Displacement of fibres around the pin Resin rich regions, voids, fibre misalignment, poor seating of the composite on the metal surface Lack of design guidelines				
Process Chain	Surface Treatment, Metal Surface Microstructuring; Thermal Joining (this step can be suppressed if a in-mould joining process is used)				Surface preparation; Z-pins insertions; Parts Joining; Co-curing or Co-bonding
Process Time	Minutes	0.2 – 0.27 s		187.5 s	
Cost		Depends on the laser medium and equipment			

Table 24 – Main characteristics of Material surface modification and metal protrusions techniques



	Cold Metal Transfer (CMT)		Laser Metal Deposition (LMD)
Material Modification and Metal Protrusions	T-Igel®	HYPER/Hypin	
Materials to join	Aluminium, Stainless Steel, Titanium, CFRP, GRFP (epoxy, polyester matrices)		Aluminium, Stainless Steel, Titanium, CFRP, GRFP (epoxy, polyester matrices)
Corrosion Resistance	Galvanic Corrosion		Galvanic Corrosion
Tensile Strength	-		-
Impact Strength	Potentially greater than bolted and bonded joints		Potentially greater than bolted and bonded joints
Fatigue Life	Potentially greater than bolted and bonded joints		Potentially greater than bolted and bonded joints
Dimensions	-		-
Service Temperature Range	-		-
Applications	Bicycle seats tops		-
Standards	-		-
Advantages	-		-
Disadvantages	-		-
Process Chain	Surface preparation; Z-pins insertions; Parts Joining; Co-curing or Co-bonding		-
Process Time	-		-
Cost	-		-

2.2.6.3. Interlocking Joining

To overcome galvanic corrosion when joining aluminium alloys and carbon fibre reinforced composites, a research group named *Schwarz-Silber* proposed new joining techniques based on the attachment of loops to the aluminium alloys. Three concepts were studied: wire, foil and fibre (see Figure 46). The galvanic corrosion can be prevented by avoiding the direct contact between carbon fibres and aluminium. Thus, this can be achieved by using transitional elements made of titanium, glass or boron fibres [15].

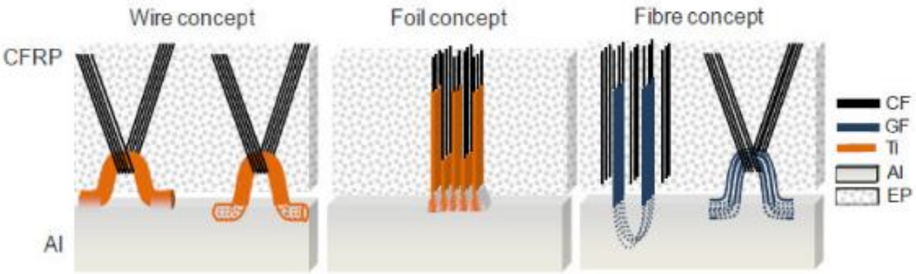


Figure 46 –Concepts developed to join aluminium alloys and CFRP

The **wire concept** consists of welding or casting rows of titanium on the aluminium substrate. The carbon fibres are then threaded through the titanium loops. In the case of the **foil concept**, instead of loops, foils of titanium are welded to the aluminium surface and the carbon fibres are placed between the foils, staying together by friction forces. The **fibre concept** is based on the wire concept; however, titanium loops are replaced by glass or boron fibres. Independently of the concept, the joints are then embedded in resin. Figure 47 shows titanium loops welded to an aluminium structure and Figure 48 displays an example of connection based on the fibre concept [15].

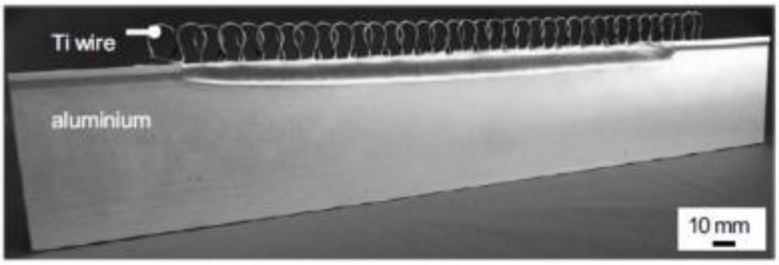


Figure 47 – Titanium loops welded to an aluminium substrate

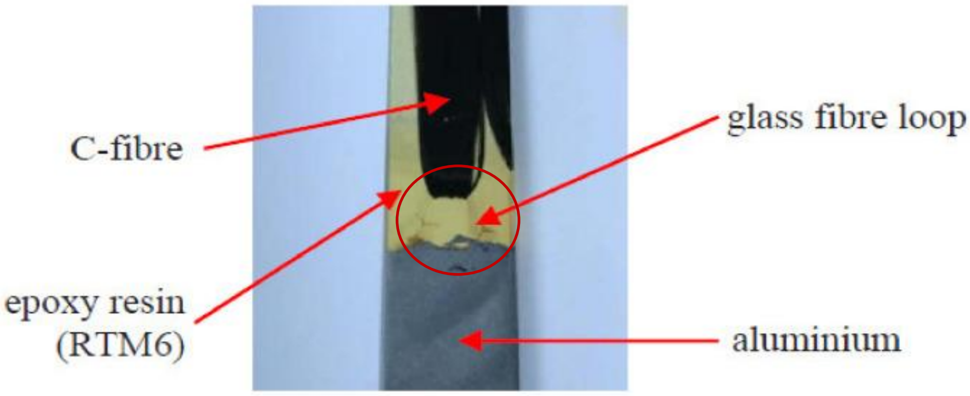


Figure 48 – Connection between CFRP and an aluminium alloy through a loop of glass fibre

There are a lot of technologies that can be used to join the loops on the aluminium substrate. In one study, the titanium loops were joined to the aluminium substrate by laser beam welding and then the structure was impregnated under vacuum by resin. In another investigation, the titanium wire loops and the aluminium were joined by diffusion bonding and hot-pressing processes [15].

Loop joining can also be obtained through **electroforming** and **3D printing** of continuous fibre composites. In order to connect the composite and the metal, the continuous fibres are printed around the metallic part, forming loops, based on the principle represented in Figure 49. Then, an electroforming process, which mechanism is shown in Figure 50, is performed to fill the fibres loop with metal (see Figure 51) [15].

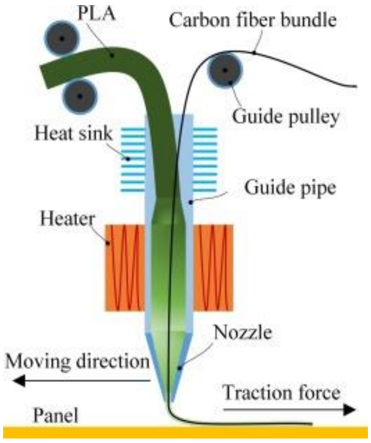


Figure 49 – 3D printing of polylactic acid reinforced with carbon fibres by in-nozzle impregnation

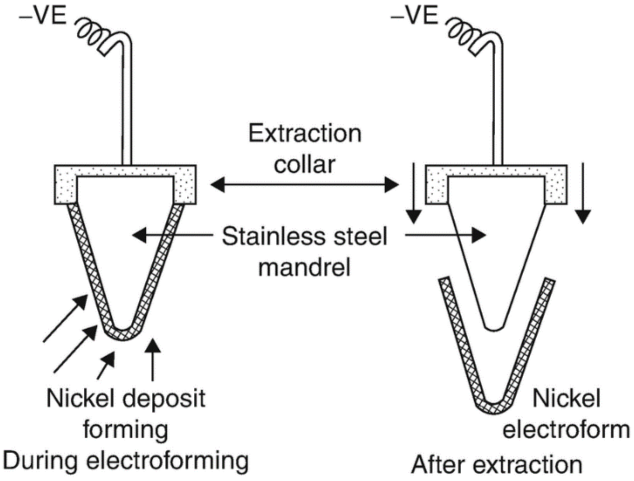


Figure 50 – Principle of electroforming

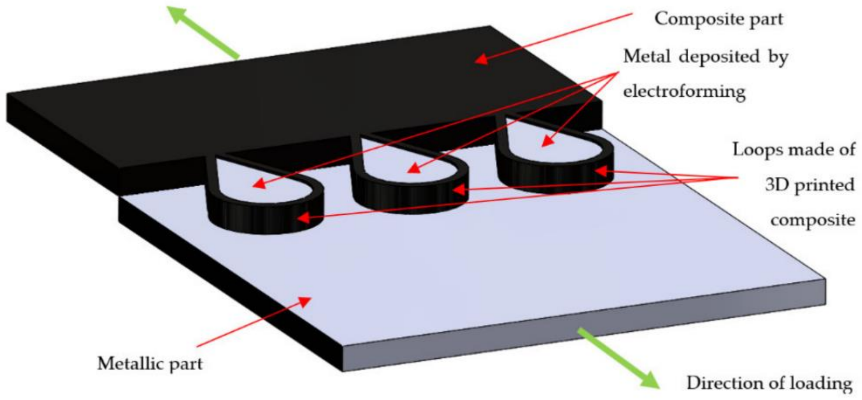
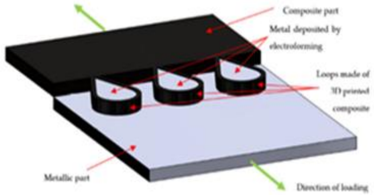
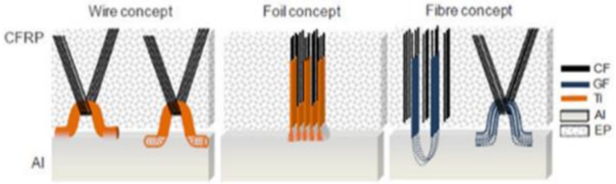


Figure 51 – Composite-metal joining with 3D printing of continuous fibres and electroforming

Table 25 display the principal characteristics of loop joining technologies. However, it is worth noting that such technologies are only in an early stage of development, thus the lack of information.

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

Table 25 – Main characteristics of Interlocking Joining processes

	Electroforming + 3D Printing of fibres	Laser-beam welding	Diffusion Bonding + Hot Pressing
Interlocking Joining 🟩 Additive Methods			
Materials to join	CFRP, Aluminium	Aluminium, CFRP (thermoset matrix only)	
Corrosion Resistance	Galvanic corrosion can be avoided by using an electrically isolated transition of glass fibres embedded in aluminium	Galvanic corrosion avoided by impeding the contact between aluminium substrate and carbon fibres, using titanium, glass fibres or boron fibres as transition elements	
Tensile Strength	-	120 – 186 N/mm (failure strengths)	300 N (480 °C) and 500 N (540 °C)
Impact Strength	-	-	-
Fatigue Life	-	-	-
Dimensions	-	-	-
Service Temperature Range	-	-	-
Applications	Idea level	Specimen level	
Standards	*N.A.*	*N.A.*	
Advantages	Potentially strong connections	Continuity of carbon fibres is not disrupted	
Disadvantages	Thermoplastic matrix composites only Impossible disassembly High complexity	Increase the mass of the joint Impossible disassembly High complexity Glass fibres and boron fibres present lower strength than carbon fibres, thus the structure strength is reduced	
Process Chain	Metal deposition; 3D printing of fibres; Loops covered w/ metal by electroforming	Loops welded to substrate; Thread of carbon fibres through the loops; Impregnation by resin	
Process Time	-	Long	
Cost	-	-	

2.2.6.4. Filament Winding

Filament winding is a manufacturing process primarily used to produce hollow, circular and oval sectioned components. The process mechanism, represented in Figure 52, involves passing fibre tows through a resin bath and, subsequently, wounding them onto a rotating mandrel, in a variety of orientations, while keeping the fibres in tension [37], [38].

Typically, filament winding is used to manufacture chemical storage tanks, pipelines, gas cylinders, fire-fighters breathing tanks, rocket motor casings, etc. Its main advantages and limitations can be consulted in Table 26. Nonetheless, this process can also be applied to join components, as confirmed by the study developed by [39], for joining CFRP automotive space frame structures. In Table 27 can be found the most relevant and available information on filament winding as a joining process. Typically, it is used to originate T joint configurations.

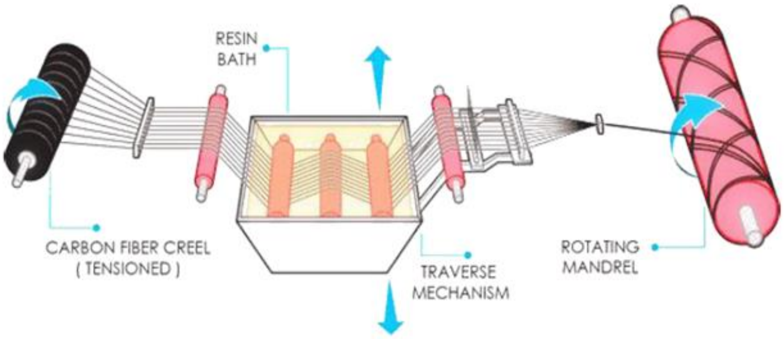


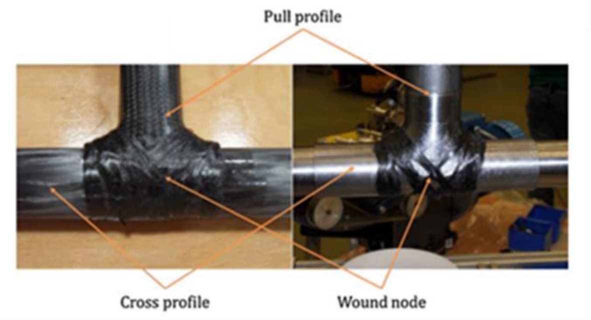
Figure 52 – Principle of filament winding

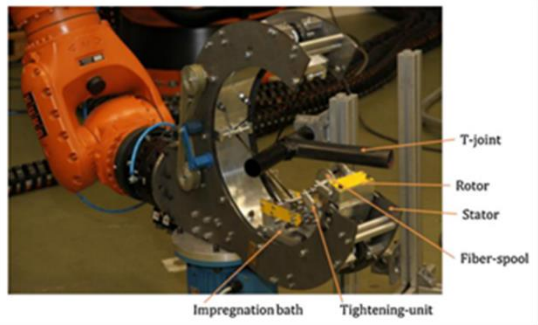
Table 26 – Advantages and disadvantages of filament winding

Advantages	Disadvantages
Fast and economical method	Limited to convex shapes
Resin content can be controlled	Fibre cannot be easily laid exactly along the length of the component
Does not involve secondary processes to convert fibres into fabric before use	Mandrel costs can be quite high
Very good structural properties can be achieved	The external surface can be anaesthetic
	Health and safety properties

Table 27 – Main characteristics of filament winding as a joining process

Filament Winding





Materials to join	Similar and dissimilar materials
Corrosion Resistance	Galvanic corrosion
Joint Strength	High
Applications	Joining lightweight pipelines
Standards	*N.A.*
Advantages	Automatic process High strength and stiffness
Disadvantages	
Process Chain	Parts positioning; Filament Winding
Process Time	

2.3. Chemical Connections

Adhesive bonding enables the joining of materials and structures through the establishment of interatomic or intermolecular bonds, based on chemical reactions (see Figure 53). Its applicability has been including diverse materials, such as engineering thermosetting and thermoplastic polymers, metals and composites. This process can be used for primary structural, load-bearing applications and for non-structural applications such as sealing or vibration damping in a wide range of industries, as seen in Figure 54. Bonded connections can be obtained through co-curing, co-bonding and secondary bonding (see Figure 55) [1], [40], [41].

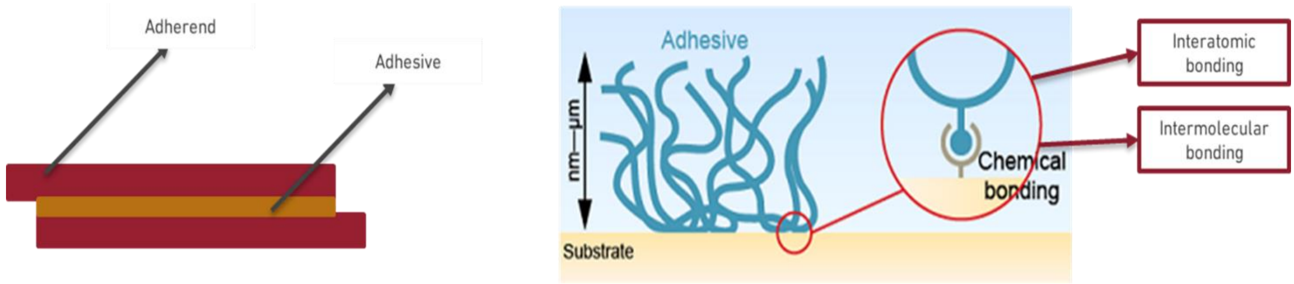
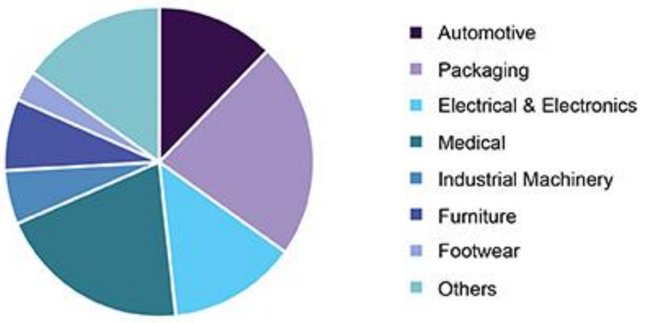


Figure 53 – Adhesively bonded connections. (a) Components of an adhesively bonded joint, (b) Interaction forces between the adhesive and the substrate

The materials being connected are called substrates, before bonding, and adherends after the bonding process occur. The bonding agent is known as adhesive and can transmit stresses from one element of a joint, or one adherend, to another. Compared to other joining processes, such as mechanical joining and welding, stresses are more uniformly distributed around the joint, as proven in Figure 55. The more uniform stress distribution leads to better fatigue strength and better vibration resistance. In addition, if the adhesive is applied properly, it fills the joint completely and creates bonding forces over the entire area, rather than at just the attachment points. In that matter, the larger the area of bonding, the lower the stresses formed.



Source: www.grandviewresearch.com

Figure 54 – Global Industrial Adhesives Revenue Share, 2018 (%)

However, it is worth mentioning that, due to the lack of robust design guidelines and reliable material models and failure criteria, adhesive bonding has not reached its maximum potential, as designers and engineers tend to 'overdesign' composite structures, in order to ensure safety factors in primary load-bearing applications. Thus, most of the time, mechanical fasteners are added, resulting in a heavier and more expensive hybrid connection.

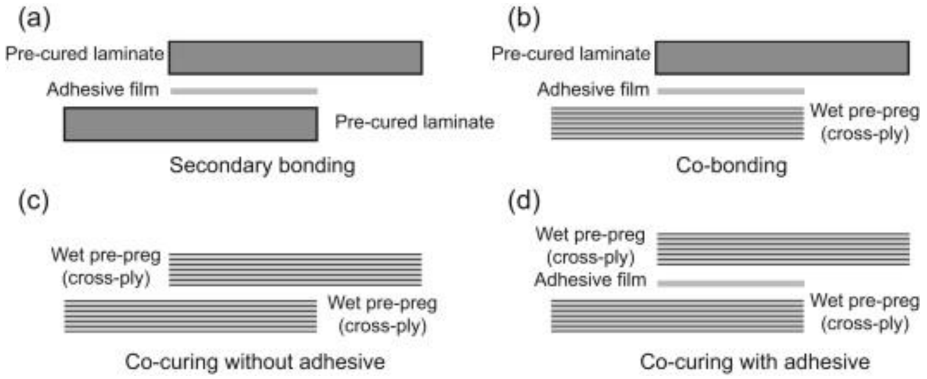


Figure 55 – Most common manufacturing processes used to produce bonded joints between composite adherents

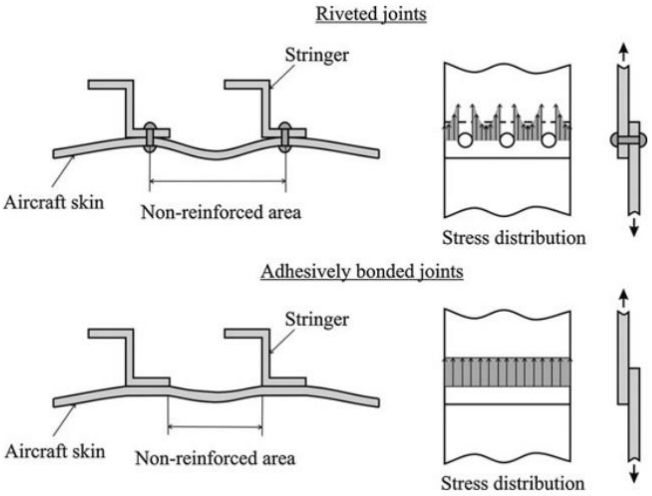


Figure 56 – Comparison between the stress distribution in riveted joints and adhesively bonded joints

Typically, adhesives are applied as thin films or layers over a large area, thus they can also enhance fatigue resistance. Most organic adhesives (which present a viscoelastic behaviour) can withstand static and dynamic strains and shock loads. Therefore, if their selection and design are done correctly, adherends tend to fail before the adhesives. Nonetheless, in order to avoid the accumulation of irreversible damage in the adhesive, a complex joint geometry must be designed to limit the load below the linear elastic capability of the adhesive.

The objective of structural adhesive bonding is to obtain the **maximum strength and quality** possible while **minimizing costs**. However, there are a few key requirements (e.g. wettability) that must be met, in order to guarantee the good performance of the bond between adhesive and adherend(s). Any contaminant, such as grease, cutting coolants and lubricants, moisture or oxides must be carefully removed and avoided to not compromise the final joint strength. Therefore, adherents generally undergo a surface preparation (or pre-treatment) process before the application of the adhesive. Table 28 comprises the main advantages and drawbacks of adhesive bonding.

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

Table 28 – General advantages and disadvantages of adhesively bonded connections

Advantages	Disadvantages
Less stress concentration, more uniform distribution of stresses	Requirement of surface pre-treatment
Weight reduction	Need for fixtures, tools, autoclaves
Virtually any shape	Working time and shelf live
Accommodate large differences in thermal expansion coefficients between different adherends	Direct inspection of bonded area not possible
Better aerodynamics and hydrodynamics	Repair is virtually impossible due to inaccessibility
No microstructure alterations	Limited upper service temperature, especially for organic adhesives
Joining dissimilar and similar materials	Susceptibility to environmental factors
Prevents galvanic corrosion	Manufacturing and surface preparation can be harmful to workers' health
Sealing, insulation and vibration and shock absorption	Difficulty or impossibility of disassembly without damage to components
Significant strength-to-weight ratios	
Can be faster and cheaper than other methods	
Improved damage tolerance and design flexibility	

Adhesively bonded joints are used in a wide range of industries, such as aerospace, marine, automotive, civil, medical, among others. Figure 57 shows an example of adhesives application in the marine industry. ISO 12215-6 2008, "Small Craft-Hull construction and Scantlings – Structural arrangements and details", provides a design criterion for adhesive bonding, alongside nominal and design shear stresses for different types of adhesives, such as epoxies and polyester or vinyl ester. It is worth mentioning that there are a few guidelines for the use of adhesively bonded joints in offshore applications. United Kingdom Offshore Operators Association (UKOOA) has proposed a set of guidelines specifically for the use of GFRP pipework in offshore environments. These guidelines include a quality program that records different key requirements such as [42], [43]:

- Temperature and relative humidity;
- Identification number of the connection;
- Curing temperature and time;
- Signature of pipe fitter and inspector.

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

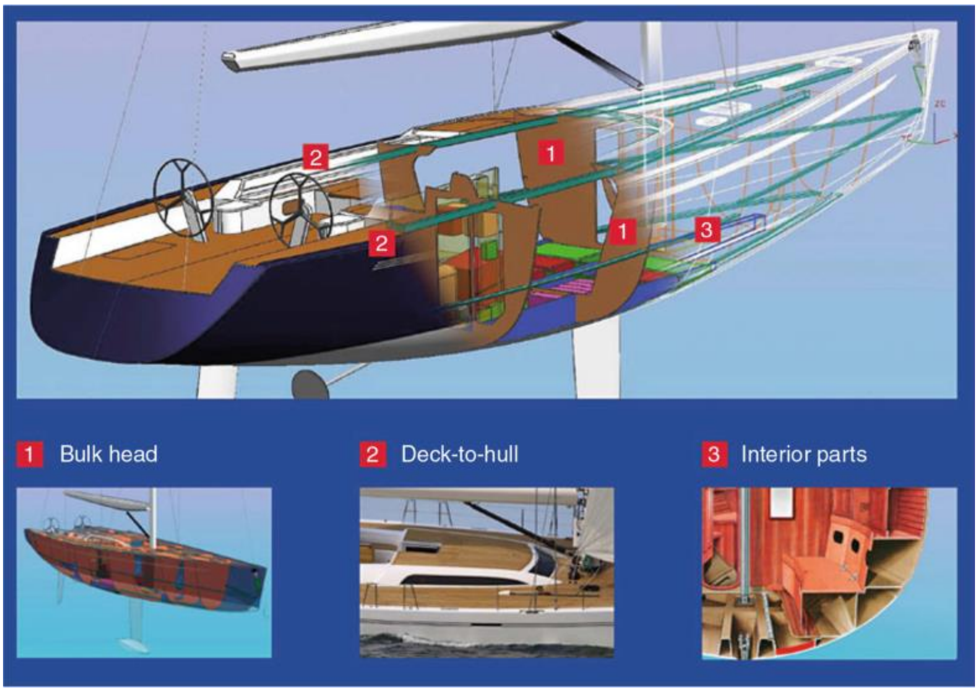


Figure 57 – Types of bonded connections in a small boat

2.3.1. Adhesives

Adhesives can be categorized into two major groups, based on their function: **structural** and **non-structural adhesives** (see Figure 58). The formers are typically thermosetting adhesives and the latter are generally obtained in the form of a single component and are thermoplastic-based. Figure 59 shows the most suitable adhesives for joining composite materials and different substrates [44].

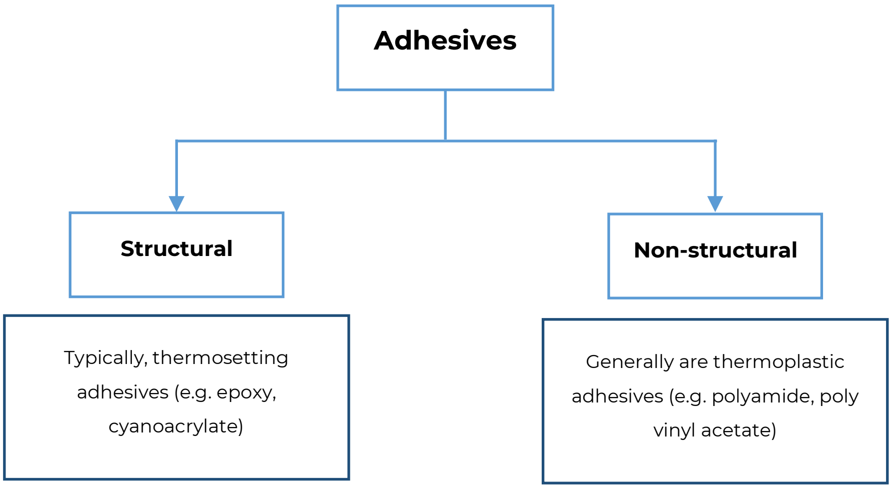
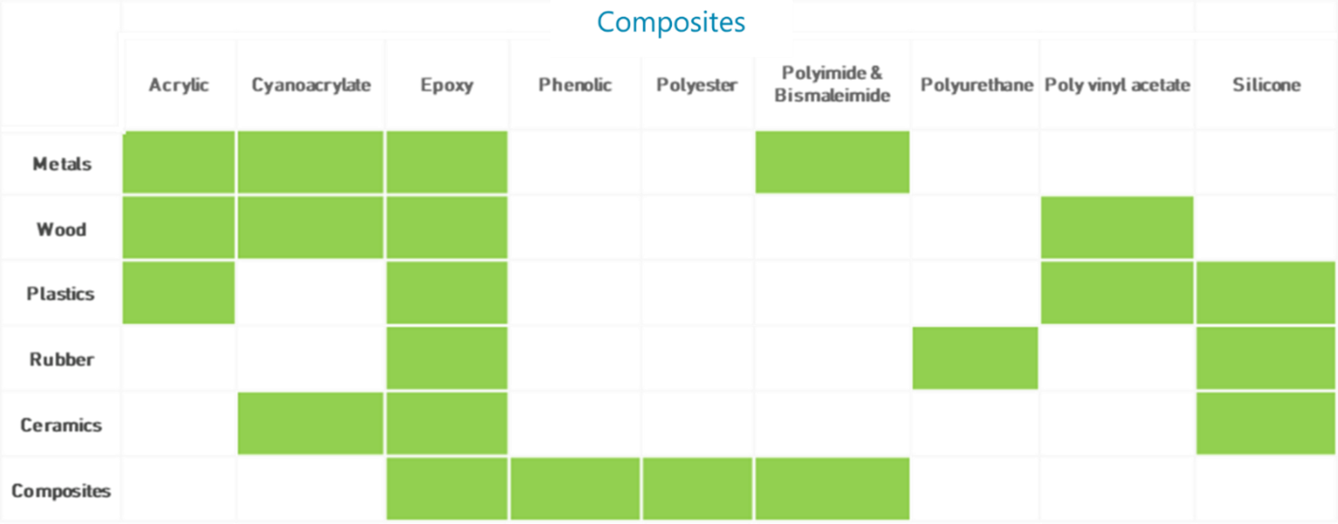


Figure 58 – Classification of adhesives based on their main function

The compatibility between the adhesive and the substrates is a very important parameter to be considered during the selection process. In addition, the adhesive properties, joint configuration, environmental conditions, availability, cost and process chain are also determinant parameters for the adhesive selection. For that reason, those factors were taken into consideration for the benchmark of the most adequate adhesives to join composite materials in an offshore environment (see Figure 60).



	Composites								
	Acrylic	Cyanoacrylate	Epoxy	Phenolic	Polyester	Polyimide & Bismaleimide	Polyurethane	Poly vinyl acetate	Silicone
Metals	🟩	🟩	🟩			🟩			
Wood	🟩	🟩	🟩					🟩	
Plastics	🟩		🟩					🟩	🟩
Rubber			🟩				🟩		🟩
Ceramics		🟩	🟩						🟩
Composites			🟩	🟩	🟩	🟩			

Figure 59 – Compatibility of adhesives with different systems of substrates

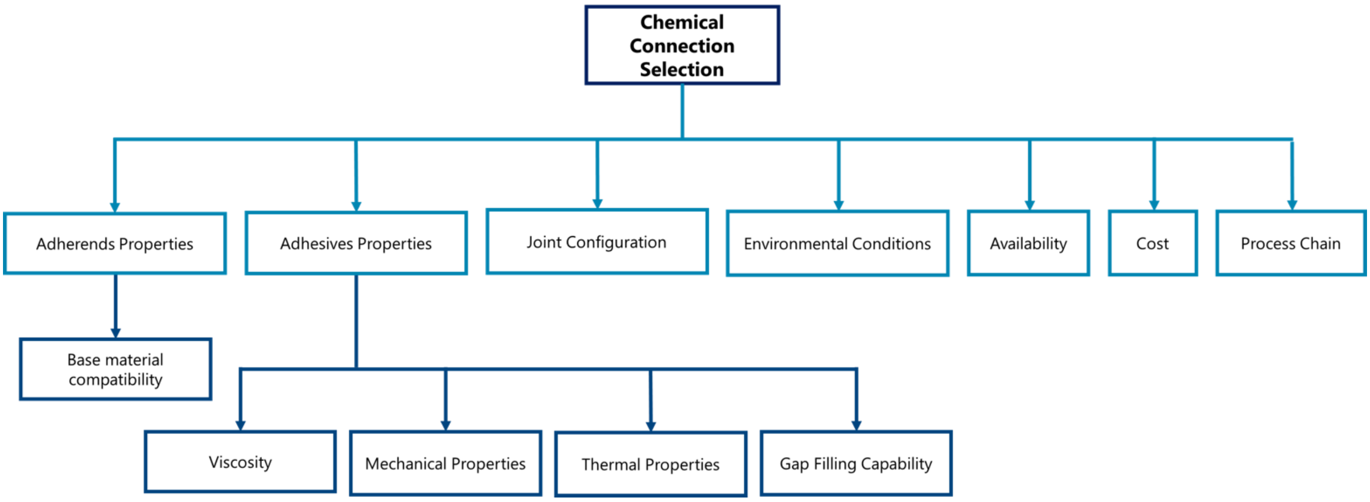


Figure 60 – Classification parameters for chemical connections

Figure 61 shows a comparison between four types of adhesives based on the most relevant properties for a given automotive application. Each property was rated from 0 to 5, 0 corresponding to the worst classification and 5 to the best.

The joint configurations determine the efficiency of the joint, since it constrains the load application and allows to avoid peel failure. Figure 62 represents the most used adhesively bonded joint configurations and Figure 63 shows some recommendations on the load application.

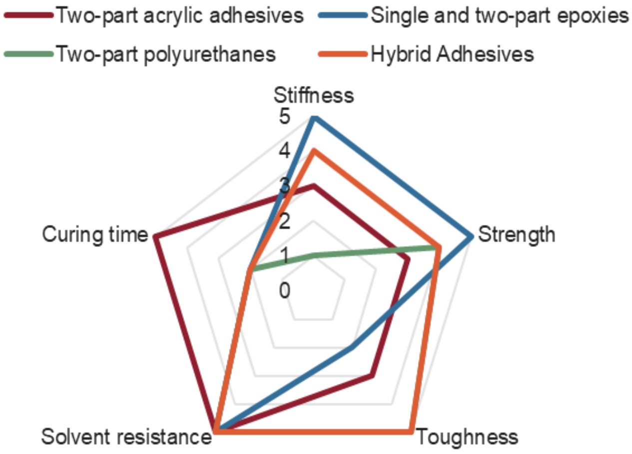


Figure 61 – Comparison between four types of adhesives based on relevant properties for an automotive application

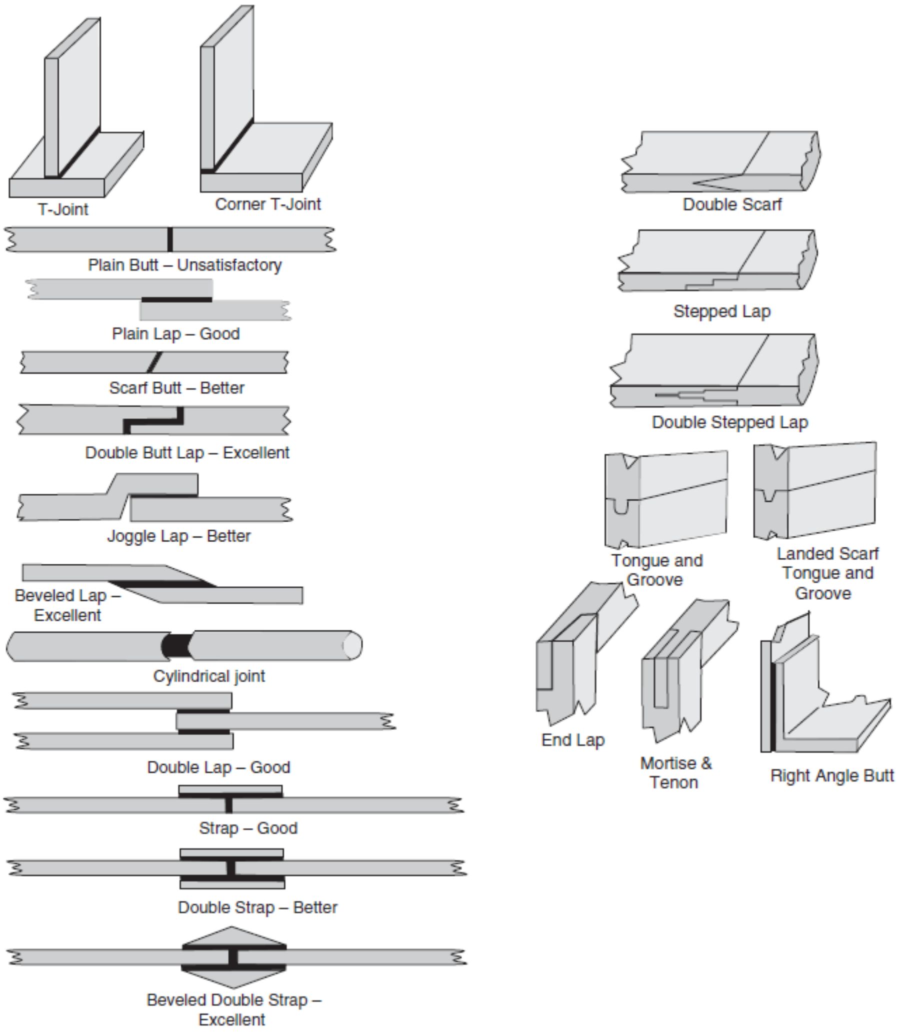


Figure 62 – Most used adhesively bonded joint configurations

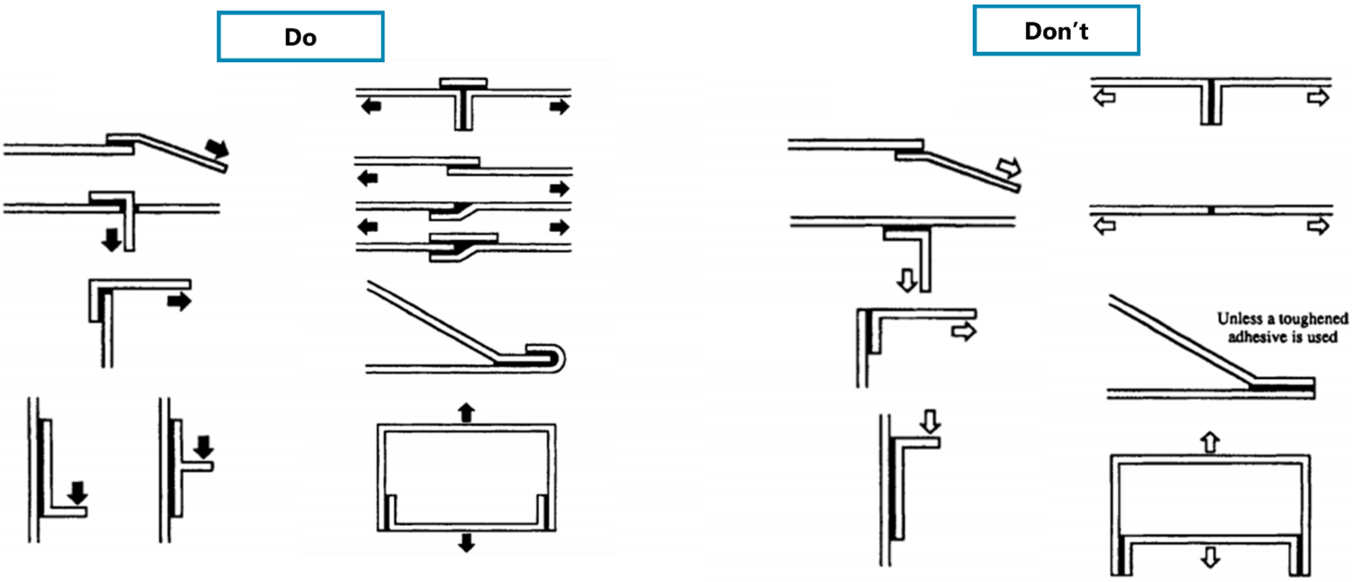


Figure 63 – Recommendations on load application based on the joint configuration

2.3.1.1. Epoxy

Epoxies are one of the most relevant adhesives used in diverse industries such as aerospace, automotive, railway, etc., since they have a low shrinkage coefficient and great strength, despite their brittleness. One of the major drawbacks of epoxy is its exothermic cure reaction, which limits the thickness to apply. This application of epoxy requires the use of EPIs because it can cause dermatosis, when in contact with the skin of the operator, and breathing problems. In order to compensate for its brittleness, hybrid epoxies have been developed, being an example epoxy-polyurethane, which has an excellent toughness and a great resistance to impact at low temperature (-30°C).

Figure 64 displays an example of the application of an epoxy adhesive to assemble filament wound glass-epoxy composite tubes, using flange joints, in an offshore application [42].

Figure 64 – Adhesively bonded pipework for offshore application

2.3.1.2. Acrylic

Acrylic adhesives generally present a short cure time, leading to fast assembly operations. In addition, they can be used in some applications to replace spot welding. They are applied in diverse industries such as marine, aerospace, automotive and medical, as they can withstand immersion in motor oil, aircraft hydraulic fluid, 10% sodium chloride solution; present an excellent resistance to environmental conditions, including salt spray; and can be applied in joints where the substrates have different coefficients of expansion. The acrylic family includes anaerobic, cyanoacrylates and modified acrylic adhesives (e.g. methyl acrylate) [40].

Anaerobic adhesives are primarily used as sealants and have an excellent gap-filling capability. Typically, they can be applied to increase the holding force of a mechanical joint, acting as threadlockers [40].

Cyanoacrylates, also known as *Superglue*, generally form strong bonds without the need for heat or catalysts. However, they have a low resistance to moisture [40].

2.3.1.3. Polyurethane

Polyurethane is a flexible, highly deformable and tough adhesive. It is found in one or two parts form and is generally used in automotive industry and cryogenic applications. The main disadvantage of one-part polyurethane is that it requires moisture to cure, which can lead to a slow cure process.

BMW Group, in order to connect CFRP components of their electric BMW i3 car (see Figure 65), resorted to Dow Automotive Systems' urethane composite bonding adhesive, BETAFORCE. This adhesive presents multiple advantages such as good adhesion to a vast type of materials, high elongation and enables the movement of body parts in relation to each other – key requirement within the automotive industry. However, for bonding the chassis and the plastic body panels, BMW i3 used 16 kilograms of adhesive, which counterbalanced the weight reduction desired when selecting composite materials [45], [46].

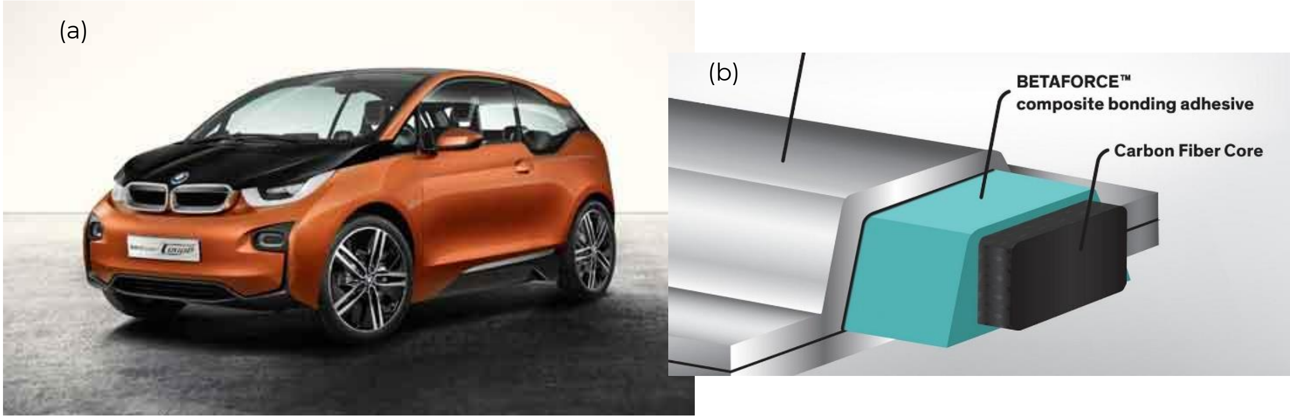


Figure 65 – Application of a polyurethane adhesive. (a) BMW *i3* (b) Connection using BETAFORCE™ adhesive

2.3.1.4. Phenolic

Phenolic adhesives are one of the first adhesives used and have good resistance to environmental conditions (e.g. hot water) and high temperature. They present good tensile and shear strengths and are fire-resistant. However, their cure demands a high temperature and pressure; in addition, volatiles products are released during cure, which can result in porous bond lines and low peel strength. Generally, they have low cost, but, due to their limitations, they are mainly used in hybrid formulations [45],[46]. The most used hybrid formulation are: **epoxy-phenolics**, which have a good peel and shear strength and can be applied in a temperature range from -250 ° to 260 °C; **nitrile-phenolics**, which have excellent resistance to water, oil, salt and biodegradation; and **polyvinyl formal-phenolics**, which offer a good fatigue performance and a good resistance to diverse environmental conditions [47], [48].

2.3.1.5. Polyester

Polyester adhesives can be divided into two categories: unsaturated thermosetting resins and saturated thermoplastics. The formers are resistant to water, weak acids and other solvents, being applied in diverse applications within the automotive and construction industries, for example, and widely used to join glass fibre composites. Saturated thermoplastic polyester can be used as a high-performance **hot melt adhesive** [49].

2.3.1.6. Vinyl Ester

Vinyl ester are thermosetting adhesives, which derivate from epoxy. Typically, vinyl esters present better thermal and chemical resistance compared to unsaturated polyester adhesives, which results in excellent durability. This type of adhesive tends to cure rapidly at room temperature and features a high impact strength and tensile elongation. Due to their attractive properties, they are widely used in marine applications [50], [51].

2.3.1.7. Polyaromatic

Examples of polyaromatics adhesives are polyimide, bismaleimide and polybenzimidazole. These adhesives are expensive and extremely suitable for high-temperature applications, such as spacecrafts and F1 race cars. However, they present a low peel strength, low ductility, and are difficult to process [52]–[54].

2.3.1.8. Polyamide

Polyamides are typically used as high-performance **hot melt adhesives**. They do not require mixing, as their formulations are sold in a ready-to-use state. They are environmentally friendly, present a reduced flammability, do not have a strong odour, and are resistant to solvents and oils. For the mentioned reasons, polyamide adhesives are applied in the automotive and electrical industries, for example. However, these adhesives easily absorb moisture from the atmosphere, which can result in a weak bond; they have a shorter shelf life than other hot melt adhesives and require careful storage [55], [56].

2.3.1.9. Silicone

Silicone adhesives are synthetic polymeric materials which, due to their formulations, can present a wide range of viscosities. Typically, they have good flexibility, good resistance to temperature variations and to UV and IR radiation. In addition, they are resistant to water and have a good gap-filling capability, which makes them applicable in different industries such as construction, marine and automotive. However, these adhesives are generally used as sealants (Figure 66) [44].

Figure 66 – Example of application of a silicone sealant in a marine structure

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

2.3.1.10. Polyvinyl acetate

Polyvinyl acetate (PVA) is easy to apply and adaptable to automation. These adhesives have low toxicity, being, for that reason, applicable in food packaging applications. In terms of mechanical properties, PVA presents high cohesive strength and toughness. They also have a high resistance to oxidation and the effects of ozone and UV radiation. However, PVA is not very resistant to creep, thus its use is typically limited to non-structural applications. In addition, this type of adhesive can be applied in the marine industry, nevertheless, it is not recommendable for submersed components and structures [44], [57].

Tables 29 and 30 were built for the most relevant adhesive families, based on the scheme of Figure 59.

Table 29 – Principal characteristics of different adhesive families

Designation		Epoxy		Acrylic			Polyurethane		Phenolics
				Methyl Methacrylate (MMA) based	Anaerobic	Cyanoacrylate	Thermoplastic	Thermoset	
Constitution		One part	Two parts	Two parts	One part	One part	One part	Two parts	
Form		Film, paste, liquid	Paste	Paste, liquid		Liquid	Liquid, paste		Liquid, film
T_g		50 – 200 °C		60 – 120 °C			20 – 50 °C		
Cure Method		Chemical Reaction	Chemical Reaction	Chemical Reaction		Chemical Reaction	Chemical Reaction and Solvent release		Chemical Reaction (H_2O release)
Cure Conditions		Heat	Heat	Heat	Absence of O_2	Heat or UV light	Moisture	Heat	Heat and Pressure
Cure Temperature		~150 ° C	RT (can be accelerated @ high T)	RT	RT (can be accelerated @ high T)	RT (can be accelerated @ high T and activated by atmospheric moisture)	RT		~140 °C
Cure Time		Minutes to days		10 s – 24 h	5 min – 24 h	Seconds to minutes	Hours to days	Seconds to hours	
Application Method		Manual	Manual or Automated				Cartridge		
Shear Strength		High	Very high	Very high	High	High	-	High	High
Peel Strength		Low	Medium	High	Very low (can be toughened)	Low	-	High	Medium
Impact Strength			High	High	Very low (can be toughened)	Low	-	High	Low
Gap-filling		Excellent		Limited	Limited	Limited	Excellent		
Connection Type		Structural		Structural	Sealing	Structural	Structural or Sealing		
Resistance	UV	Excellent	Good	Excellent			Very good		
	Salt water	Excellent		Excellent	Excellent		Very good		Excellent
	Moisture	Excellent	Good	Very good	Excellent	Poor	Very good		Good
	Chemicals	Excellent	Good	Very good	Excellent	Poor	Very good		Good
Shrinkage		Low (4 – 5%)		Low/Medium (5 -10%)	Low/ Medium (6 – 9%)		Low (3 – 5%)		
Service Temperature Range		-40 - 180 °C	-40 – 100 °C	-70 – 120 °C	-54 – 232 °C	up to 180 °C	-200 – 120 °C		-40 – 260 °C
Applications		Aerospace Industry Automotive Industry Railways		Marine Industry Aerospace Industry Automotive Industry Composites	Thread-locking of mechanical fasteners	Medical devices Better for non-porous materials	Marine Automotive industry Cryogenic applications Very used to bond GRP		Flame retardant applications Mixed w/ other adhesive materials (e.g. epoxy-phenolic)
Advantages		High cohesive strength Wide variety of forms and properties High levels of adhesion to a wide variety of substrates		Ability to be reprocessed for recycling Higher flexibility than epoxies Tolerant of imperfect mixing ratios Can be applied without any prior surface preparation	Low odour levels High durability Generally, slow cure rate Possible dismantling (weak adhesives)	Availability of multiple viscosities High tensile strength	High cohesive strength Wide variety of forms and properties Can withstand cryogenic conditions		Resistance to biodegradation Good fatigue properties
Disadvantages		Storage Cures @ high T Exothermic Reaction Dermatosis Breathing Problems	Slow curing Voids Exothermic Reaction Dermatosis Breathing Problems	Strong odour Limited open time	Unsuitable for porous surfaces At least one of the substrate must be metallic	Joint brittleness Rapid bonding to skin Low creep resistance Short shelf life	Susceptible to hydrolytic degradation	Very slow cure	VOCs release during cure Brittle
Standards		Consult 'Engineering and Structural Adhesives' (22 -26)							
Process Chain		Cleaning and Degreasing; Surface Abrasion; Application of surface activator; Application of a primer; Application of the adhesive							
Cost		Low		Relatively high (compared to epoxies)	Relatively high (compared to epoxies)	High	Medium to high		Low
Obs.		Some adhesives can be found in an hybrid formulation (e.g. epoxy-phenolic, epoxy-urethane, etc.)							

Table 30 – Principal characteristics of different adhesive families (cont.)

Designation		Polyester		Vinyl ester (VE)	Polyimide	Bismaleimide (BMI)	Polyamide	Silicone		Poly vinyl acetate
		Saturated (Thermoplastic)	Unsaturated (Thermoset)							
Constitution			Mainly two parts		One part			One part	Two parts	
Form		Film, Solution			Film, Solvent Solution, Paste	Film, paste	Film, Solvent Solution			Film, Solvent Solution
T_g				55 – 145 °C	315 - 370 °C	232 – 310 °C	~140 °C	~ 130 °C		
Cure Method		Chemical Reaction	Chemical Reaction and Solvent Release	Chemical Reaction (radical initiation)	Chemical Reaction	Chemical Reaction		Chemical Reaction		
Cure Conditions		Heat	Heat and Pressure	Heat	Heat and Pressure	Heat and Pressure	Heat and Pressure	Moisture	Heat	Heat and Pressure/Evaporation of water or solvent
Cure Temperature		RT	@ High T	RT	177 – 357 °C	191 – 350 °C		RT (can be accelerated @ high T)	RT (can be accelerated @ high T)	
Cure Time		Minutes to days	Minutes	Hours	1.5 – 2 h	4 – 13 h		Hours to days		Days
Application Method			Cartridge							
Shear Strength						High		Low		
Peel Strength			High	High		Low		High		
Impact Strength				High						
Gap-filling										
Connection Type			Structural	Structural	Structural	Structural	Structural	Structural or Sealing		Sealing
Resistance	UV		Fair	Fair				Excellent		
	Salt water			Excellent						
	Moisture			Excellent	Good	Good		Good		Fair
	Chemicals			Excellent	Good	Good	Good	Good		Good
Shrinkage				Low	Low					
Service Temperature Range					-40 – 300 °C	-55 – 230 °C	-60 – 130 °C	-160 – 350 °C		
Applications		Hot-melt	Repairments of fibreglass boats, automobile bodies, concrete floors	Marine industry Offshore applications		Printed circuit boards (PCB)	Hot-melt Automotive industry Electronic products Furniture	Electronic and medical products		Insulating (steam plants and ships) Used in hot-melts formulation
Advantages		Colour stability Can be used as high performance holt-melt	More flexible than epoxy	Higher strength and elongation than polyesters Great adhesion between metals and FRPs			Environmentally friendly Acts as an oxygen barrier Reduced flammability Low odour High creep resistance	Good adhesion to a wide range of substrates Good flexibility Different curing formulations		Most versatile in terms of formulations and uses Odourless
Disadvantages		Cannot withstand high stress applications Susceptibility to 'chalking', thus it must be protected from UV radiation		Release of VOCs Susceptibility to 'chalking', thus it must be protected from UV radiation	Difficult processability High curing temperatures Innate brittleness	Difficult processability High curing temperatures Innate brittleness	Requires careful storage	Need of primer to wet the surface Low level of cohesive strength Potential swelling by nonpolar solvents		
Standards		Consult 'Engineering and Structural Adhesives' (22 -26)								
Process Chain		Cleaning and Degreasing; Surface Abrasion; Application of surface activator; Application of a primer; Application of the adhesive								
Cost			Low	Higher than polyester	Very high	High	High	High to Very high		Low
Obs.		Some adhesives can be found in an hybrid formulation (e.g. epoxy-phenolic, epoxy-urethane, etc.)								

2.3.2. Overlamination

Overlamination is a joining technique especially used to connect composite products in **naval applications**, such as bulkheads and other reinforcing elements (see Figure 67). This method consists of placing a sequence of strips of FRP impregnated with resin around a corner profile, resulting in a T-joint, as demonstrated in Figure 68 [42], [58].

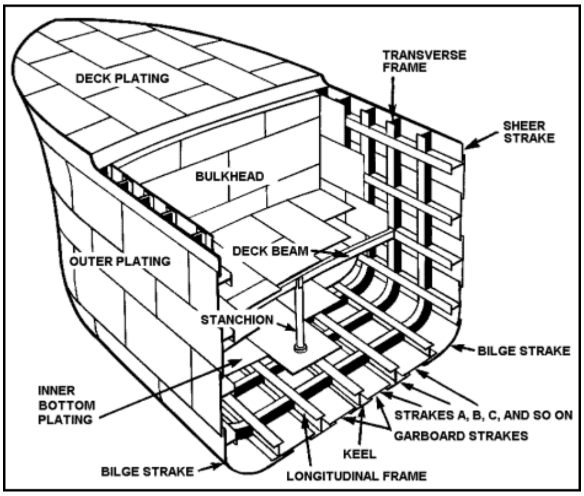


Figure 67 – Architecture of a boat

Figure 69 shows examples of connection types based on overlamination. In addition, the direction of overlapping defines the type of overlamination, being examples the double zeta and omega – see Figure 70. In the former, the layers are placed from the right and from the left with additional unidirectional layers in between. In the latter, the overlapping layers follow the shape of the structure. However, in both cases, a filler (typically a structural adhesive) is used to fill the corner gap [58], [59].

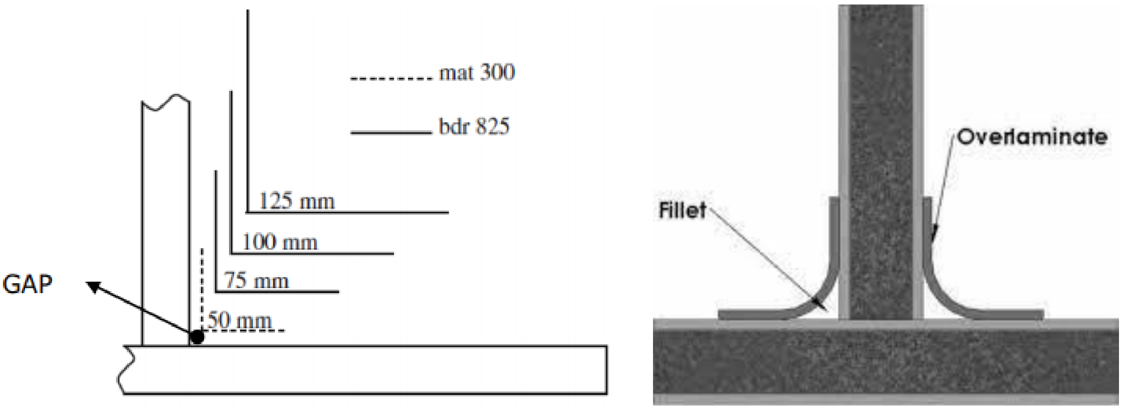


Figure 68 – Overlamination sequence

In Figures 71 and 72 is shown the joint of structural elements in boats through overlamination. Table 31 comprises the most useful information regarding the overlamination technique.

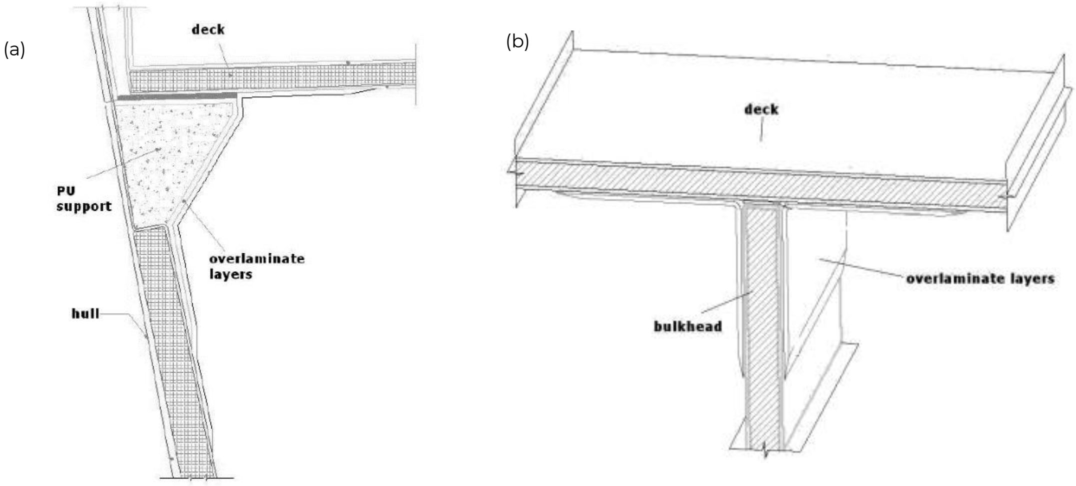


Figure 69 – Examples of overlaminated joints. (a) Deck-side shell connection (b) T-joint connecting deck and bulkhead

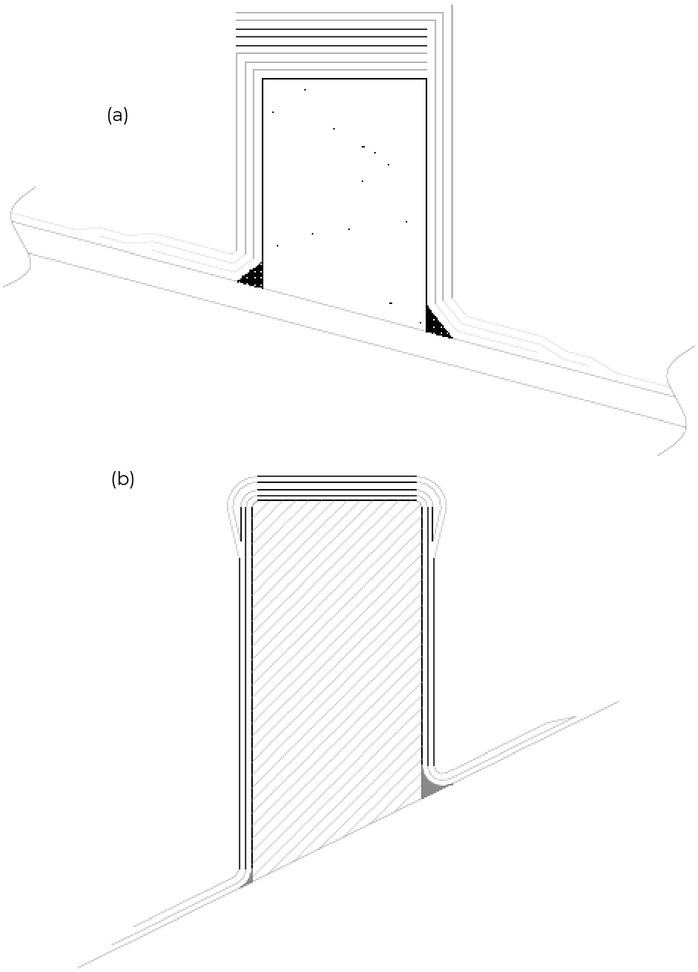


Figure 70 – Types of overlamination. (a) double zeta (b) omega

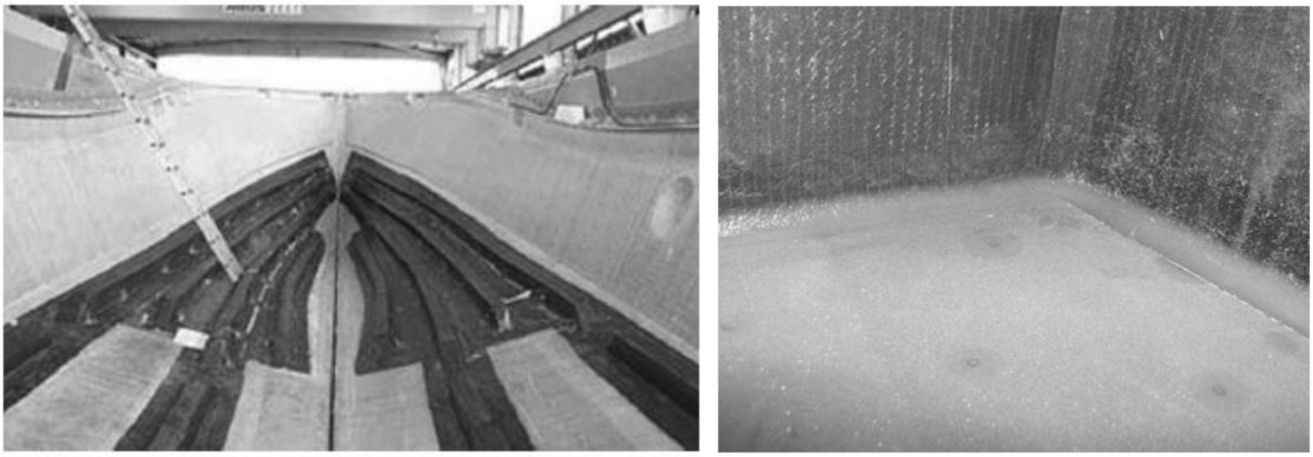


Figure 71 – Tamar joints. (a) Hull shells and centreline joints (b) Transverse frame structural fillet

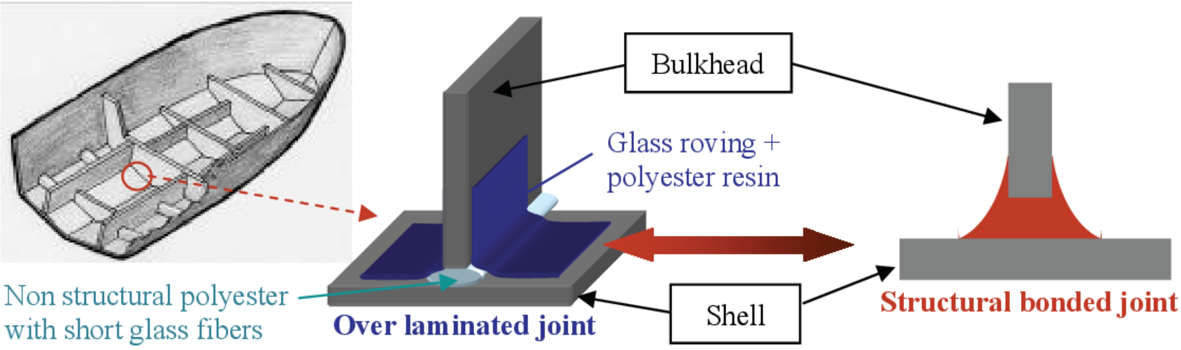


Figure 72 – Structural junction between the shell and the bulkheads by overlamination and structural bonding

Table 31 – Principal characteristics of overlamination

Overlamination

Materials to join	FRP composites and dissimilar materials
Corrosion Resistance	Galvanic corrosion can occur between aluminium or steel and carbon fibres closest to the interface
Joint Strength	Higher than bonded-bolted joints
Fatigue Performance	-
Applications	Marine industry
Connection Type	Structural
Standards	*N.A.*
Advantages	Structural continuity
Disadvantages	Critical point (gap) must be filled w/ a structural adhesive Air bubbles may be entrapped in each laminate and between layers
Cost	Manufacturing costs can be reduced by 50%
Process Chain	Overlapping layers; Cure

2.3.3. Dismantlable Adhesives

As can be consulted in Table 28, one of the major drawbacks of adhesively bonded joints is the impossibility of disassembly without damaging the structure. However, there are a few solutions to overcome this issue, such as hot melts, adhesives with blowing agents, with chemically or electrochemically active materials.

Hot melts are thermoplastic adhesives that, by heat action, soften and allow disassembly (see Figure 73). Examples of hot melts are polyamides and some saturated polyesters. They can be obtained in the form of powder, granules, blocks, rods or films and, despite not being used in structural applications, high shear strength, fair peel strength and good chemical resistance can be achieved with some formulations [51].

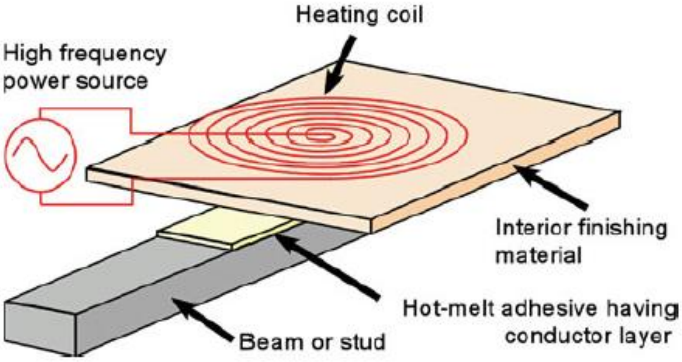


Figure 73 – Principle of hot melt adhesives

As previously mentioned, some agents, such as microcapsules, can be mixed with the adhesive and, by heat activation, expand, enabling dismantlability – see Figure 74. The expansion of the microcapsules generates internal stresses in the resin of the adhesive, which are responsible for causing the interfacial separation between the adhesive and the adherends. Figure 75 shows an example of the application of this type of dismantlable adhesive [51].

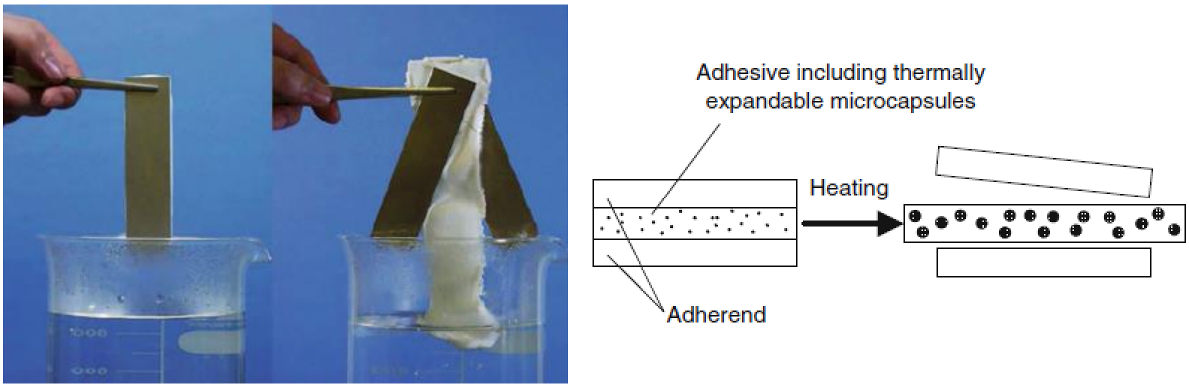


Figure 74 – Dismantlable adhesive with thermally expandable microcapsules

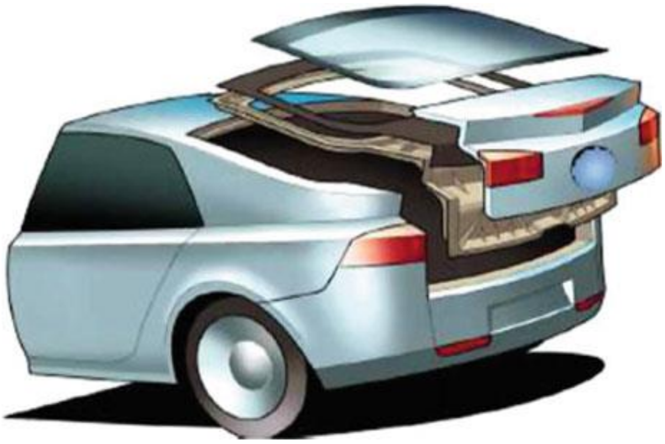


Figure 75 – Application of dismantlable adhesives containing thermally expandable microcapsules in the automotive industry (ECODISM project)

Another method to obtain dismantlable adhesive is by mixing chemically active materials with the adhesive resin. Expandable graphite and aluminium hydroxide are examples of such chemically active materials (see Figure 75) [51].

Some formulations, such as the commercially available Electrelease® adhesive, can be separated from the adherend by the occurrence of an electrochemical reaction in the interface between the adhesive and the adherend.

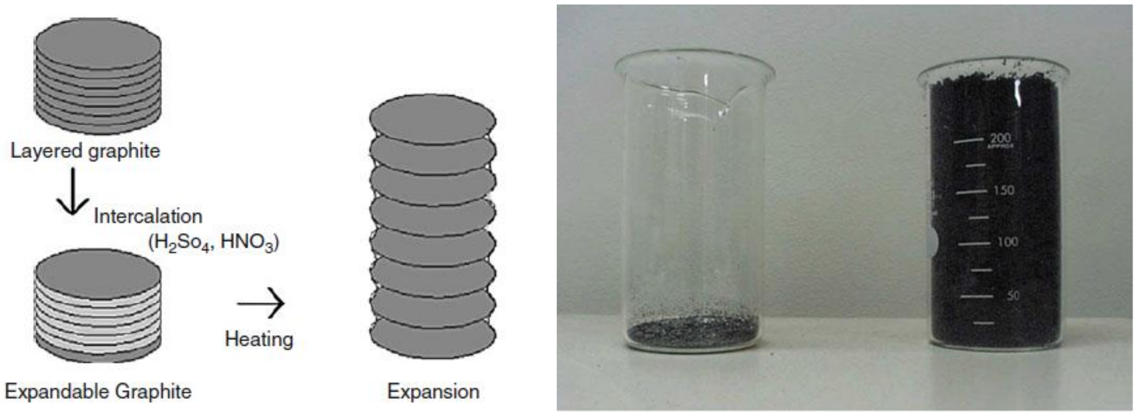


Figure 76 – Expandable graphite particles

2.3.4. Optimization and reduction of stress concentration

Adhesively bonded joints tend to concentrate less stress than bolted joints or welded joints, because the stresses are more uniformly distributed along the joint line. However, there are some methods to reduce even further the stress concentration and optimize joint's efficiency. It can be used with mixed adhesives, which means that two adhesives, with different mechanical properties, are applied in the joint, as represented in Figure 77.

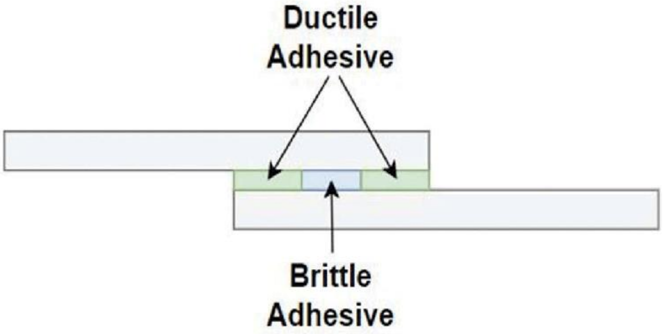


Figure 77 – Mixed adhesives joint

In addition, the same adhesive can be used, but through differentiated cure, use of dielectric nanoparticles, thermally expandable particles or magnetic coated particles, different properties along the joint line can be obtained, resulting in a functionally graded adhesive, (see Figure 78). The major drawback of functionally graded adhesives is the change of the properties with time, especially if a differentiated cure is used.

Functionalization can also be applied to the substrates (see Figure 79) and can be achieved by different methods, such as:

- Layer toughening by adding a metal or a polymer;
- Z-pinning;
- Stitching;
- Graded perforations;
- Additive manufacturing (AM).

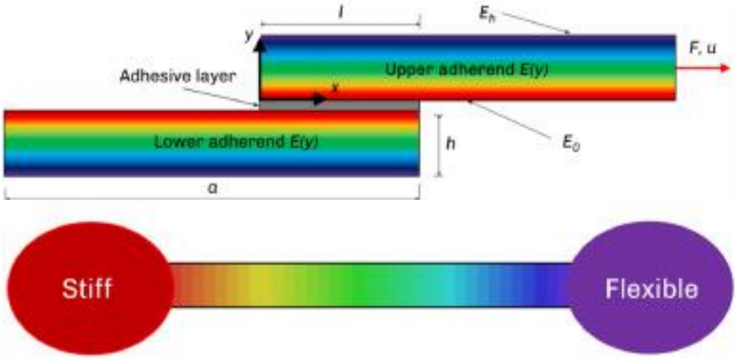


Figure 78 – Functionally graded adhesive

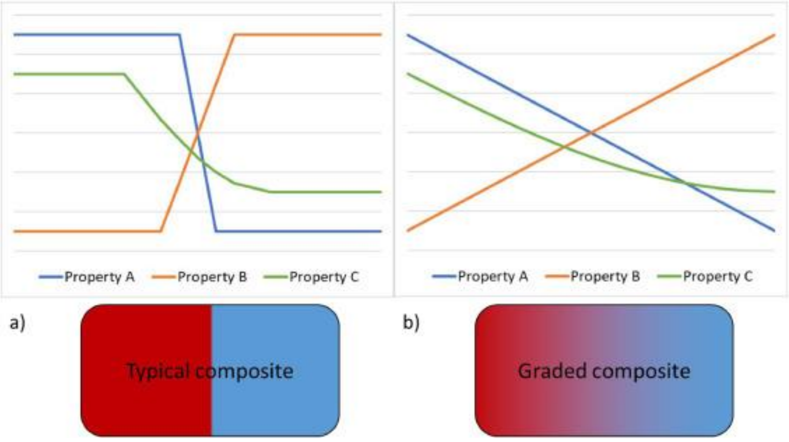
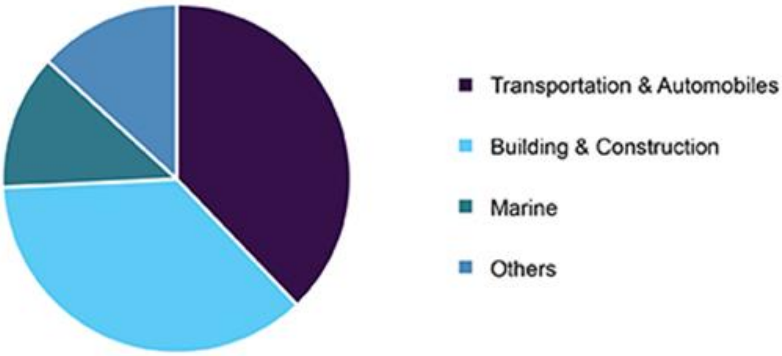


Figure 79 – Functionally graded substrate

2.4. Welding

Welding is a physical joining process widely applied to join metals in diverse industries, as can be seen in Figure 80. Regarding welding of composite materials, it is typically applied to polymer-matrix composites where the matrix phase is a thermoplastic. The reason for this is the possibility of refusion and reshaping presented only by thermoplastics. However, its application is not fully exploited, because the presence of reinforcements can limit the application of welding processes to join composite materials. In addition, as FRP composites have a viscoelastic behaviour and, in general, a low conductivity, severe thermal degradation can occur.



Source: www.grandviewresearch.com

Figure 80 – Global welding products market share, 2019 (%)

Welding can be categorized into two major groups based on how the bonding occurs: **fusion welding** or **solid-state welding**. In addition, welding processes can be subcategorized in **frictional**, **electromagnetic** and **thermal** techniques according to the heating source, as schematized in Figure 87. The main advantages and limitations associated with welding processes are gathered in Table 32.

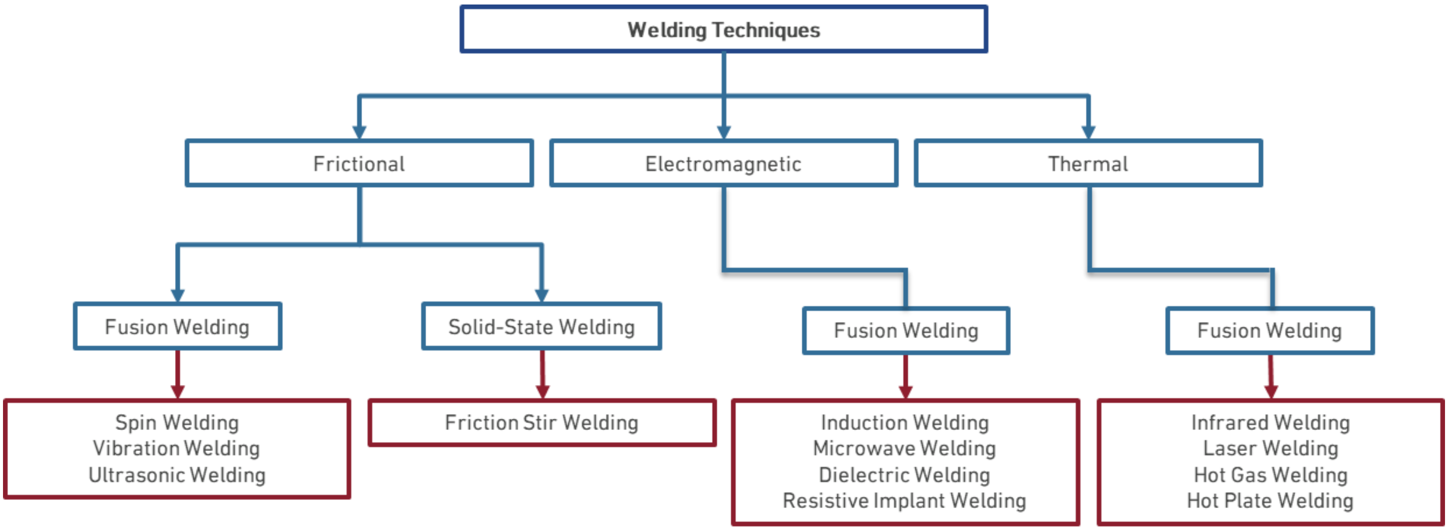


Figure 81 – Classification of the welding processes based on the heating source

Table 32 – General advantages and disadvantages of welding processes

Advantages	Disadvantages
Joints are permanent, preventing accidental disassembly and loosening	Cannot be disassembled without destroying the joint
Wide variety of processes	Process temperature can cause degradation of the materials to be joined
Reasonable overall costs	The initial investment can be high, especially for automated processes
Can result in leak-proof joints	High susceptibility to defects
	Only applicable to thermoplastic composites

In order to develop this benchmark and to characterize the most relevant techniques to join FRP composite materials, some parameters such as the materials compatibility, properties, compatible joint configurations, cost, application, standardization and process chain were considered, as shown in Figure 82. Nevertheless, it is worth mentioning that the great majority of the considered welding techniques, despite their great potential, are not yet fully developed or present a high Technological Readiness Level (TRL).

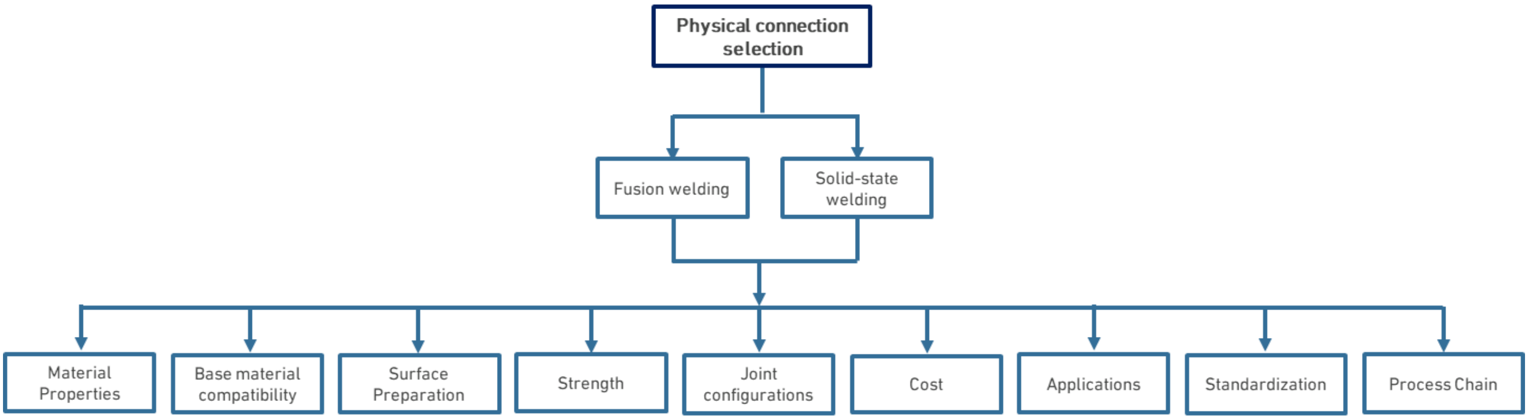


Figure 82 – Classification parameters for physical connections

Additionally, in a general perspective, the most common welded joint configurations are demonstrated in Figure 83. As can be inferred, the joint configurations are very similar to the ones used in adhesively bonded connections.

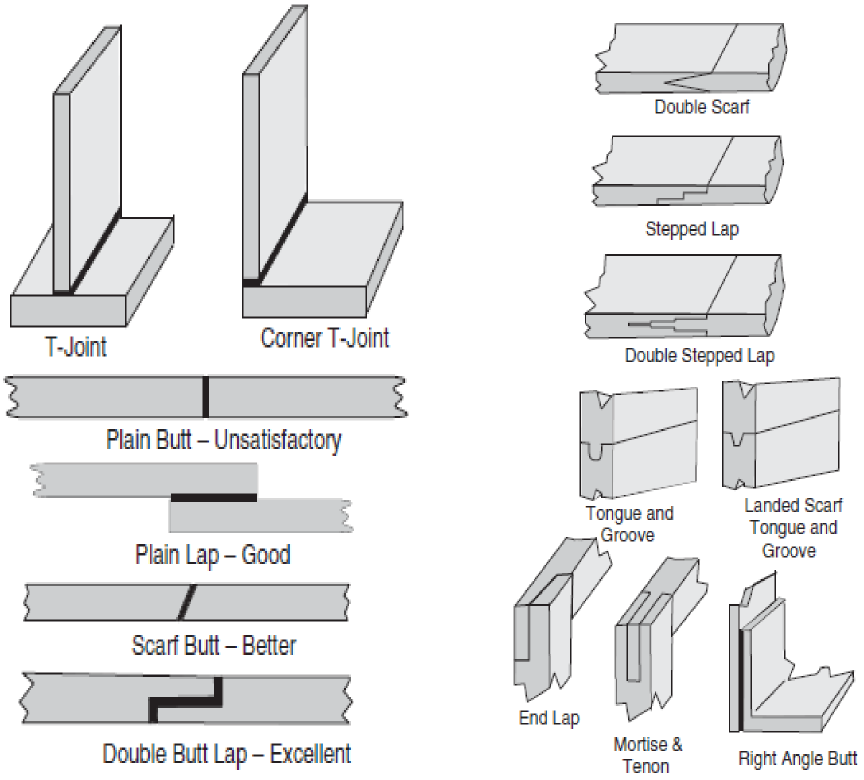


Figure 83 – Most common welded joint configurations

2.4.1. Frictional Welding

2.4.1.1. Spin Welding

Spin welding is one of the most used friction welding methods for joining thermoplastic materials and thermoplastic composites. As seen in Figure 84, during the process one part is fixed whilst the other is rotationally moved against it. This rotational movement generates frictional heating, which is responsible for melting the thermoplastic matrix at the joint line. The system is then cooled, in order to consolidate the weld (see Figure 85). One of the major drawbacks of this method is that it is limited to circular joint areas [60], [61].

In this process, the most relevant **parameters** are welding velocity, welding pressure, forging pressure and welding time. Among the advantages of spin welding are its high quality resulting weld, its simplicity, speed, and reproducibility [61].

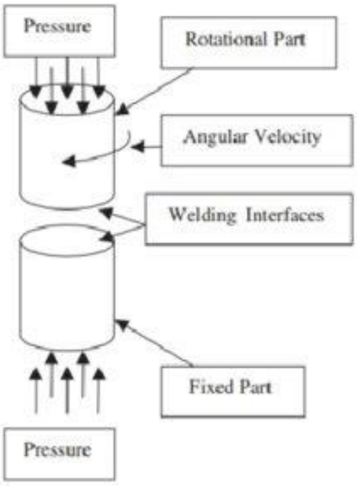


Figure 84 – Principle of spin welding

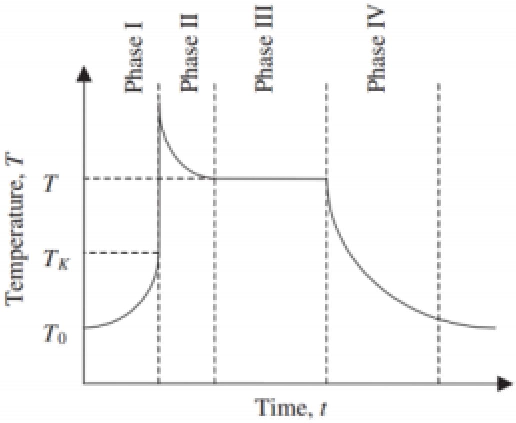


Figure 85 – Phases of spin welding

2.4.1.2. Vibration Welding

It is also known as linear friction welding. The heat generation comes from the mechanical movement between the components to be joined, thus the two parts must be in contact. One part stays fixed, whilst the other moves in a rapid linear motion in the plane of the joint. This motion is responsible for generating heat, which melts the parts locally. Figure 86 shows the setup of the vibration welding machine. The vibration is cessed, the parts are aligned and submitted to cooling under pressure to consolidate the weld [60].

When applied to composite materials, vibration welding requires the application of a higher force, which can promote fibre damage. However, vibration welding is a good alternative to ultrasonic welding when the objective is to obtain linear joints with a length above 200 mm. It is also a faster process than hot plate welding (up to four times faster for large weld areas). In addition, this welding technique is currently well established at the industrial level and widely used in the automotive industry [60].

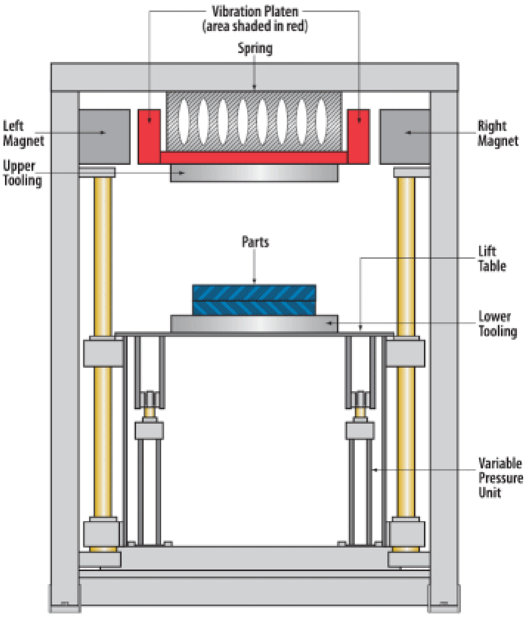


Figure 86 – Setup of vibration welding

2.4.1.3. Ultrasonic Welding

Ultrasonic welding is a fast process that can be easily automated, and thus can be ideal for mass production. It consists of applying a high frequency (typically within the range from 15 to 70 kHz) to soften or melt the thermoplastic, allowing the joining of the two parts (see Figure 87). The parts to be joined are held into position under pressure while ultrasonic vibrations are applied. It is worth noting that the heating effect depends on the crystallinity of the material being welded and, consequently, its mechanical properties. Ultrasonic welding is limited to a weld length of 250 mm, approximately [60]–[62].

This technique is extensively used in the automotive, medical and electronic industries, among others. When joining composite materials, attention must be taken regarding the volume fraction of fillers, as highly filled materials can result in weak joints. Figure 88 shows an example of the application of ultrasonic spot welding in the aerospace industry [60].

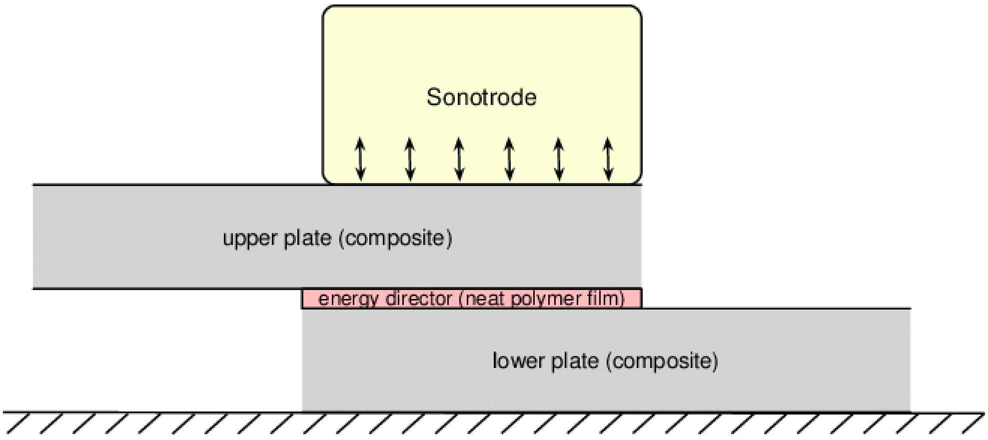


Figure 87 – Ultrasonic welding

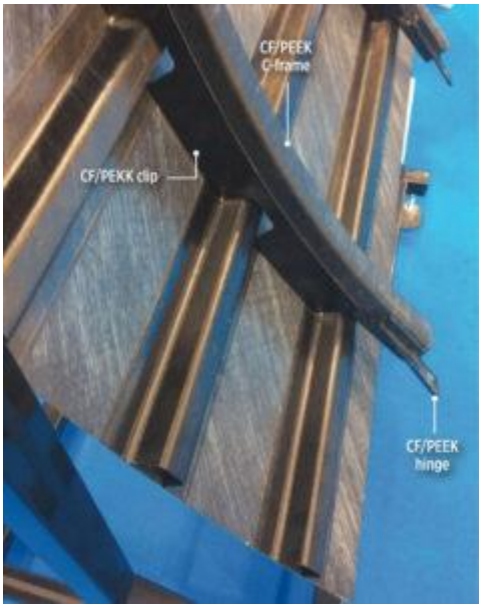


Figure 88 – Ultrasonic spot welding used to join CFRP frames in an aircraft structure

2.4.1.4. Friction Spot Joining (FSpJ)

Friction Spot Joining (FSpJ) is a joining technique based on the Friction Spot Welding (FSpW) for metals, but it is adequate to join dissimilar materials such as polymer-based and metal structures. In FSpJ, a non-consumable tool is responsible for generating frictional heat. This tool is composed of three parts: clamping ring, sleeve and pin, as can be observed in Figure 89. The clamping tool holds together the parts to be joined; the pin and the sleeve can rotate independently and the friction generated between these parts and the workpiece produces the heat that will make the joining possible [63], [64].

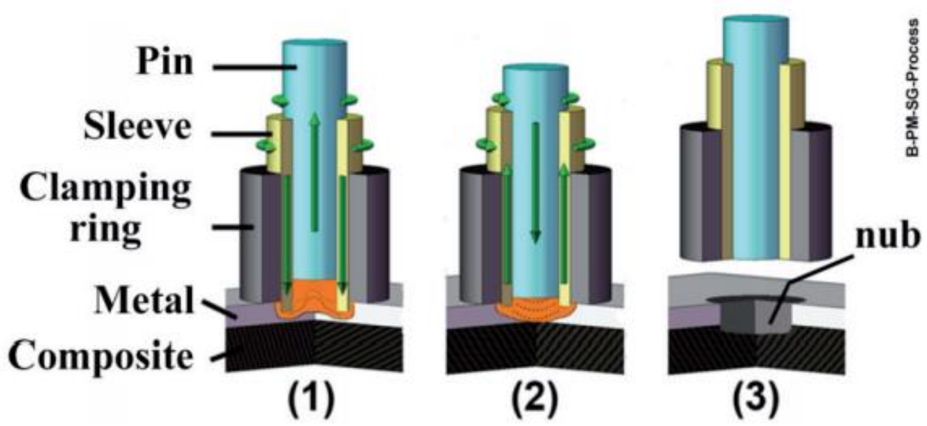


Figure 89 – Principle of friction spot joining

In this process, two variables can be considered: **pin plunge** and **sleeve plunge**. These two factors are important because the rotating sleeve plunges into the metal (top sheet of the overlapping configuration) to a pre-defined depth (up to 40 % of metal thickness, in order to avoid excessive degradation of the polymer matrix and fibres) and the pin retracts. The friction resulting from the movement between the sleeve and the metallic sheet, generates heat, which softens and plasticizes the metal ($T_{process} < T_{melt}$). The plasticized material flows in the space left by the pin retraction. Subsequently, the pin is pushed against the plasticized metal, in order to refill the key-hole and the tool is retracted. Subsequently, the joint consolidates under pressure [63], [64].

The tool deforms the metal through the plunging motion, which results in an undercut in the form of a *nub*, as indicated in Figure 89. This nub will increase the **mechanical interlocking** between the metallic and composite sheets. It is worth noting that the generated frictional heat will be transferred from the metal to the composite interface via conduction, which will form a thin layer of molten polymer that will flow throughout the overlap region. Under pressure, this molten polymer layer is consolidated and enhances the joining forces between the metal and the composite through the establishment of **adhesion forces**. In conclusion, the primary bonding mechanisms associated with FSpJ are mechanical interlocking and adhesion forces. Figure 90 shows the result of a joint between a composite and metal, obtained through FSpJ. A specific example of application of this technology is demonstrated in Figure 91, where FSpJ was used to join metal structures to composite structures in an aircraft [63], [64].

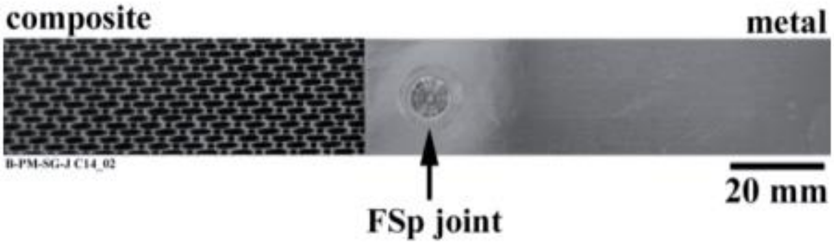


Figure 90 – Example of a joint between a composite and a metal obtained through FSpJ

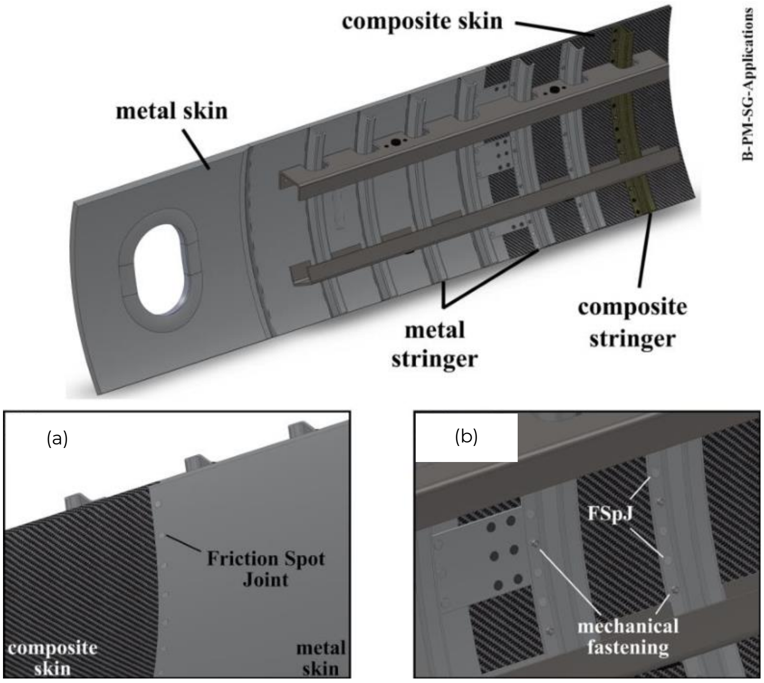
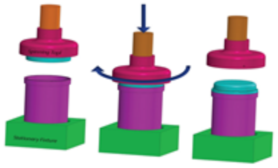
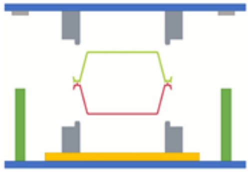
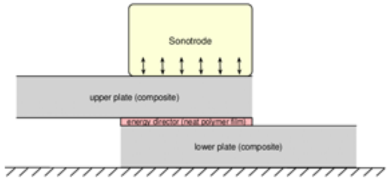
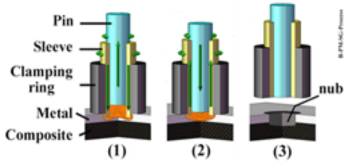


Figure 91 – Aircraft structure (a) joining of a composite skin to a metal skin. (b) joining of a metal stringer to a composite skin

Table 33 summarizes the most relevant characteristics of the mentioned welding techniques.

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

Table 33 – Main characteristics of friction welding techniques

Frictional Welding Methods	**Spin Welding**	**Vibration Welding**	**Ultrasonic Welding**	**Friction Spot Joining (FSpJ)**
🟥 Fusion Welding 🟦 Solid State Welding				
Materials to Join	Thermoplastic matrix composites reinforced w/ short or continuous fibres (check matrix compatibility)	Almost any thermoplastic matrix composite	Thermoplastic matrix composites and dissimilar materials	Dissimilar materials (e.g. Al-CFRP)
Corrosion Resistance	-	-	Galvanic Corrosion	Galvanic Corrosion
Maximum Dimension	(Theoretically, no limit) Ø < 1 m can be joined Typically, ≤ 300 mm parts are joined	~ 610 x 1520 mm	Parts greater than 250 x 300 mm cannot be welded in a single operation	-
Joint Strength	High	High	High	Medium (shear) Low (torsion and peeling)
Specific Parameters	Rotational Speed, Friction pressure, Forge pressure	Frequency, Amplitude, Pressure	Frequency, Power input, Pressure, Amplitude	
Applications	Containers, fuel filters, aerosol cylinders, truck lights, assembly of structural components	Electrical and automotive applications	Automotive, medical, textile, packaging, electronic	Transport Industries
Standards	-	-	-	-
Advantages	Simple Highly energy efficiency Hermetic joints Environment-friendly	Low polymer degradation Energy efficiency Insensitivity to surface preparation Hermetic joints	Robust hermetic joints Energy efficiency Mass production	Avoid excessive degradation of matrix and damage to the load-bearing fibres
Disadvantages	Limited to circular fitments	Not recommended to thin-walled applications Limited to flat surfaces	Specifically designed joint details are required Can damage electrical components	Sharp interfaces (metal and composite do not mix) Disassembly not possible Thin sheets (t<1mm) cannot be currently joined
Process Chain	Loading the parts; Press actuation; Welding; Welded part removal	Loading parts; Vibration application; Melting; Pressure; Release	Parts positioning; Ultrasonic vibration application; Melting; Pressure; Cooling; Welded part removal	-
Process Time	Short	Short	Fastest known technique (up to 60 parts/min)	Short
Cost	Initial investment lower than ultrasonic welding	Initial high capital cost of the equipment and tooling (ranging from 40 000 to 250 000 $)	Initial high capital cost of the equipment and tooling	-
Joint Configurations	Butt, Tongue-and-groove, Angled (w/ or without flash traps)	Butt, Tongue-and-groove	Lap, Butt, Step, Shear	Lap

2.4.1.5. Friction-Stir Welding (FSW)

Friction stir welding is a welding technique initially developed by The Welding Institute (TWI) to join aluminium alloys. However, it is also suitable to join thermoplastics, and, subsequently, composite materials with a thermoplastic matrix. It is a solid-state welding technique; thus, it does not occur fusion of the materials to be joined ($T_{process} < T_{melt}$), and its principle is represented in Figure 92. *"Friction stir welding involves driving a rotating or reciprocating tool along the joint-line between two fixed components"* [60]. Typically, FSW is divided into three stages: (1) plunge and dwell, (2) traverse and (3) retracting, which are represented in Figure 93. The contact between the tool and the material generates frictional heat, which is responsible for softening the material and the movement of the tool along the joint-line plastically deforms the soften material, creating a weld zone. In order to avoid defects, different variables should be correctly selected and controlled during the process, such as load and torque, tilt angle, welding and spindle speed, tool design, workpiece properties and size.

The main advantages of FSW are the low heat input, which leads to less material degradation; the possibility of joining dissimilar materials; and the less introduction of residual stresses.

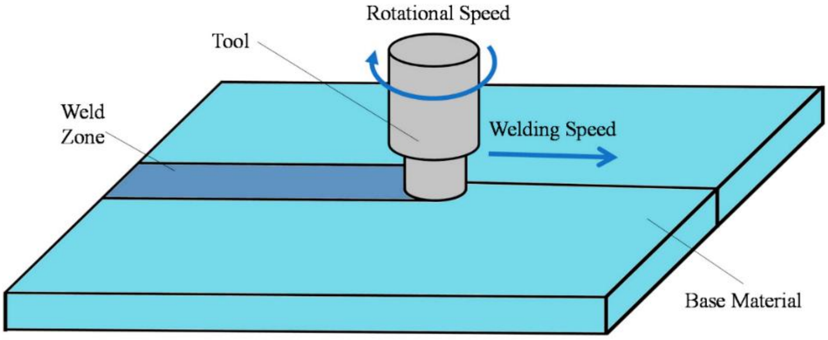


Figure 92 – Principle of Friction Stir Welding (FSW)

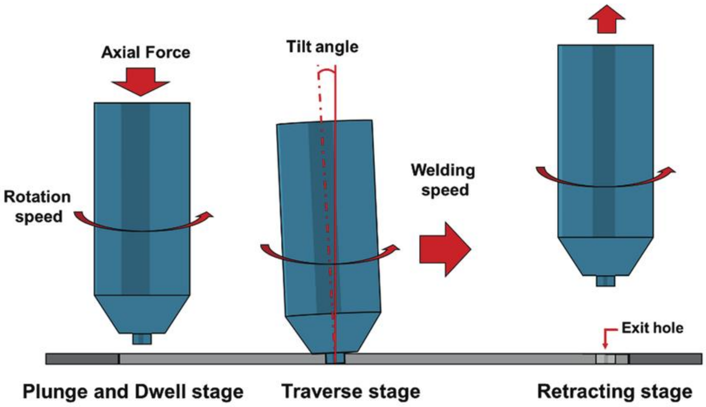


Figure 93 – Stages of FSW

2.4.1.6. Friction Stir Spot Welding (FSSW)

As can be observed in Figure 94, FSSW relies on the same principle of conventional friction stir welding. However, the tool does not complete the traverse stage; instead, it forms a localised spot weld. FSSW has a lot of potential, especially in terms of replacing mechanical fasteners, such as rivets, which can contribute to weight addition in aerospace and automotive applications, for example. It can also facilitate the joining of dissimilar materials, which can be hindered through fusion welding processes. Despite its advantages, FSSW implementation has been constrained once it leaves an exit hole (potential stress raiser) on the joint area. In order to overcome this issue, a variant process has been developed: **refill friction stir spot welding** (RFSSW) – see Figure 95. The major difference is in the fact that the soften material expelled by the pin is now confined by the shoulder and then, when the pin starts to retract, the shoulder pushes downwards the material, filling the gap formed previously [65], [66].

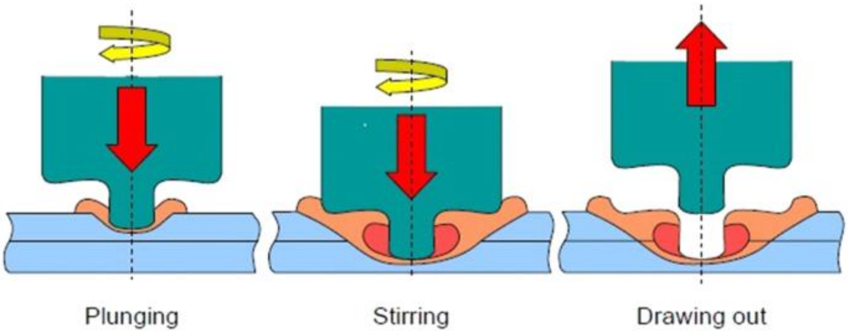


Figure 94 – Principle of Friction Stir Spot Welding

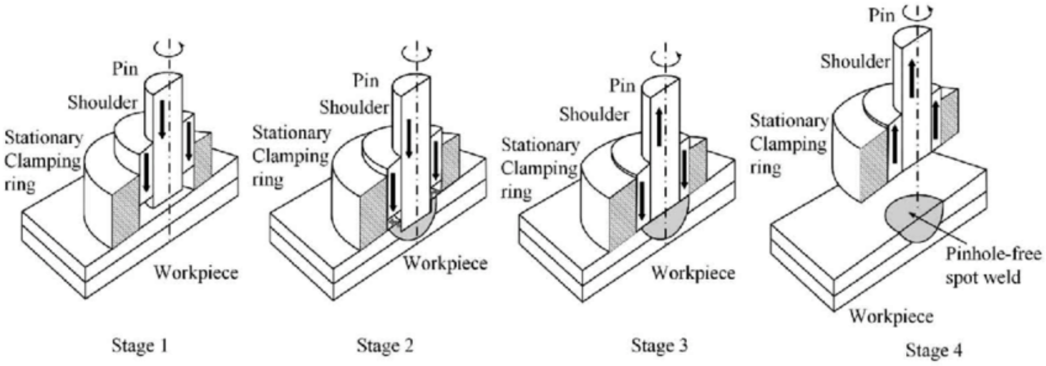


Figure 95 – Refill Friction Stir Spot Welding (RFSSW)

2.4.1.7. Stationary Shoulder Friction Stir Welding (SSFSW)

In conventional FSW, both shoulder and pin rotate, which can result in thermal degradation of some materials and bad surface quality. Thus, TWI developed a process where the pin rotates inside a stationary shoulder, so the frictional heat is only generated by the rotating pin and its contact with the materials to be joined (see Figure 96). In addition, SSFSW leads to a more uniform temperature distribution and, consequently, to a more homogenous weld. This process is more advisable to join polymeric materials (including FRP composites) than conventional FSW [65], [66].

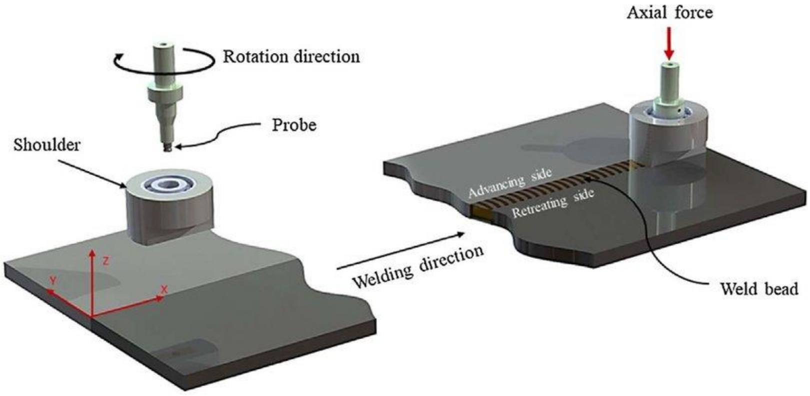


Figure 96 – Stationary Shoulder Friction Stir Welding (SSFSW)

2.4.1.8. Friction Stir Additive Manufacturing (FSAM)

Friction stir additive manufacturing is based on the same principle of conventional FSW. However, the main difference between FSAM (Figure 97) and FSW resides in the fact that the former relies on the joining of layer by layer which is associated with the reheating and re-sintering of the materials. This technology allows to join dissimilar materials and obtain larger structures than conventional FSW [67]–[69].

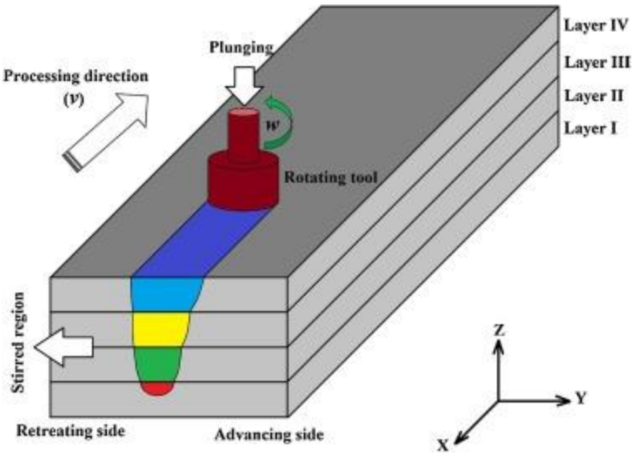


Figure 97 – Friction Stir Additive Manufacturing (FSAM)

As can be seen in Figure 98, FSAM has a lot of potential across a wide range of industries and academic fields. An example of a potential FSAM application is exhibited in Figure 99, where it was used to build vertical stringers in an aircraft structure.

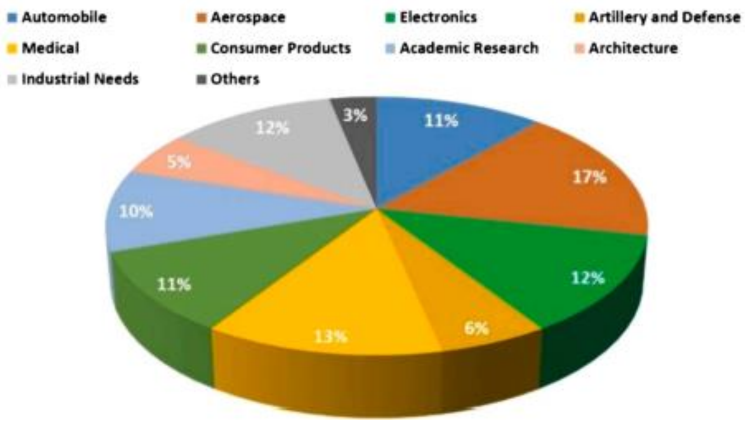


Figure 98 – Estimated contribution of FSAM in diverse fields

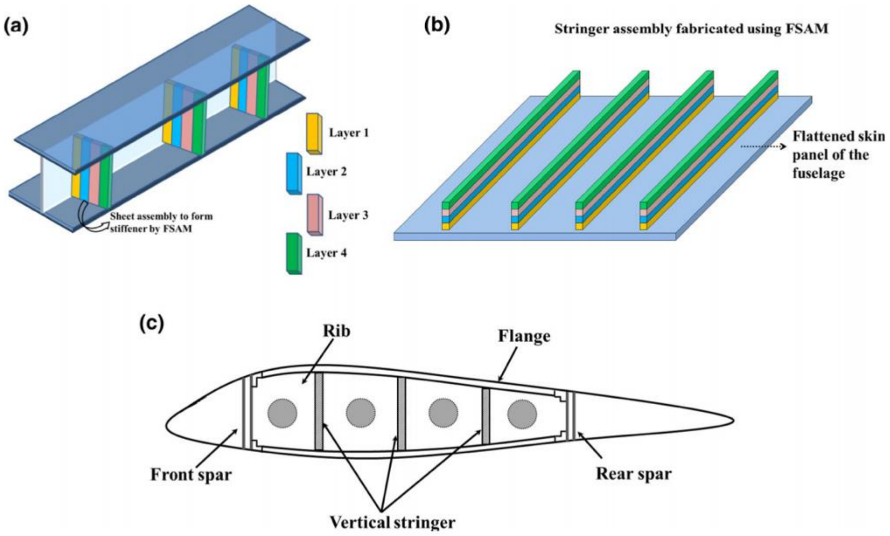


Figure 99 – Example of FSAM application

2.4.1.9. Friction Self-Riveting Welding (FSRW)

Friction self-piercing welding is a technique mainly applicable to join composites and metals. As can be seen in Figure 100, holes are drilled in the metal part. Then, the welding tool softens the polymeric material, forcing it to flow up the drilled holes. It is worth mentioning that a microporous oxide structure should be induced in the metal surface (see Figure 101), in order to enhance the mechanical interlocking and promote the formation of adhesive bonding between the parts to be joined. One of the main advantages of this process is the ease of automation. Furthermore, holes are filled with the polymer-based material, forming smooth joints [70].

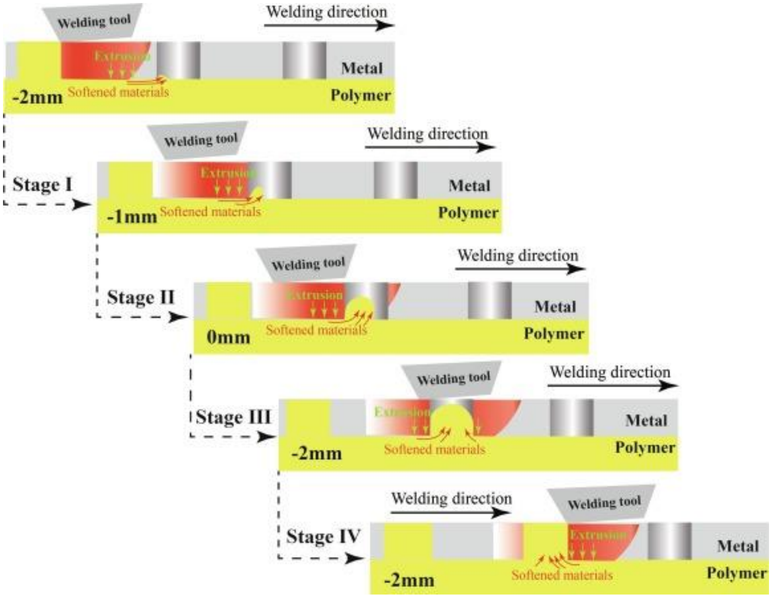


Figure 100 – Principle of friction self-riveting welding

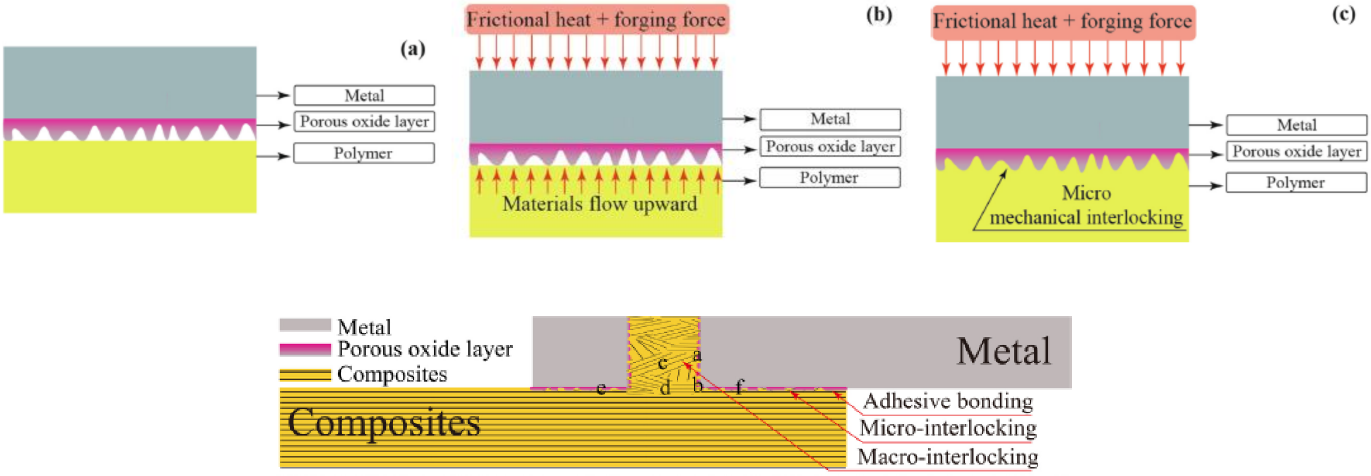
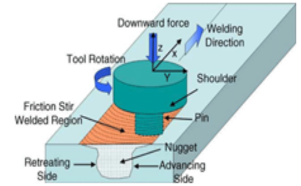
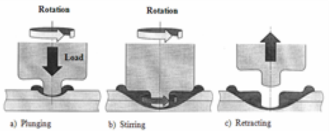
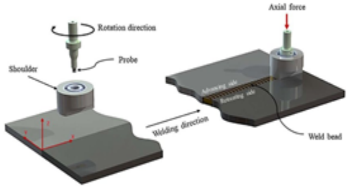
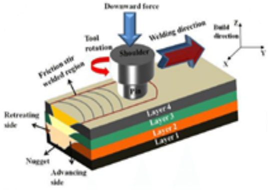
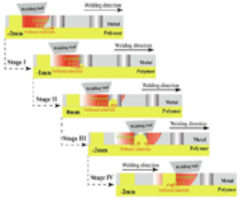


Figure 101 – Material filling model. (a) before welding, (b) the materials suffer from frictional heat and forging force, and (c) after consolidation

In Table 34 can be consulted the information regarding FSW and its variants.

Table 34 – Main characteristics of Friction Stir Welding and its variants

	Friction Stir Welding (FSW)				
	Conventional Friction Stir Welding (FSW)	Friction Stir Spot Welding (FSSW)	Stationary Shoulder Friction Stir Welding (SSFSW)	Friction Stir Additive Manufacturing (FSAM)	Friction Self-Riveting Welding
Frictional Welding Methods 🟧 Fusion Welding 🟦 Solid State Welding					
Materials to Join	Similar and dissimilar materials	Similar and dissimilar materials	Similar and dissimilar materials	Similar and dissimilar materials	Dissimilar materials, such as thermoplastic matrix composites and metals
Corrosion Resistance	Galvanic corrosion	Galvanic corrosion	Galvanic corrosion	Galvanic corrosion	Galvanic corrosion
Maximum Dimension	Limited to the equipment and material used	Limited to the equipment and material used	Limited to the equipment and material used	Large components	-
Joint Strength	High		High	-	-
Specific Parameters	Tool design and material, machine variables, other variables	Tool design and material, machine variables, other variables	Tool design and material, machine variables, other variables	Tool design and material, machine variables, other variables	Tool design and material, machine variables, other variables
Applications	Automotive Industry Aerospace Industry Shipbuilding	Automotive Industry	Aerospace Industry	Skin panels (Airbus and Boeing)	Specimen level
Standards	ISO 25239, ISO 18785	-	-	-	-
Advantages	Temperature < T_{melt}	Low energy consumption Cost efficiency Environment-friendly Competitive process (may substitute conventional spot welding)	More uniform heat input (enables to weld more effectively low conductivity materials) Smooth weld seam	Less material waste Faster production rates High degree of reproducibility	Ease of automation
Disadvantages	Voids in the welded joint Low speed of welding Nonuniform crown or weld bead Bad quality surface (adopt process variant)	Limited to specific geometries and applications Demands a good and effective clamping system Keyhole post process	May need external heating sources	-	Need for drilling the metal
Process Chain	(Surface preparation); Parts positioning/clamping; FSW process; Release	(Surface preparation); Parts positioning/clamping; FSW process; Release	(Surface preparation); Parts positioning/clamping; FSW process; Release	(Surface preparation); Parts positioning/clamping (2) ; FSW process (3); Release * steps (2) and (3) are repeated until the pretended number of layers is achieved	(Surface preparation); Parts positioning/clamping; FSW process; Release
Process Time	~3 min	-	-	-	-
Cost	~ 9270 € (equipment)	-	-	-	-
Joint Configurations	Lap, Butt, T, Fillet	Lap	Butt, T	Lap	-

2.4.2. Electromagnetic Welding

2.4.2.1. Induction Welding

The heat generation comes from the application of an induction field obtained through eddy currents induction or due to hysteretic losses. This process has recently achieved a high TRL, namely 9. It should be noticed that carbon-fibre reinforced thermoplastics can be welded without any additional material because carbon fibres are electrically conductive. On the other hand, glass fibre reinforced thermoplastics demand the use of an additional electrically conductive material, which must be placed between the parts to be joined. A representation of the induction welding process is displayed in Figure 102 [60], [71], [72].

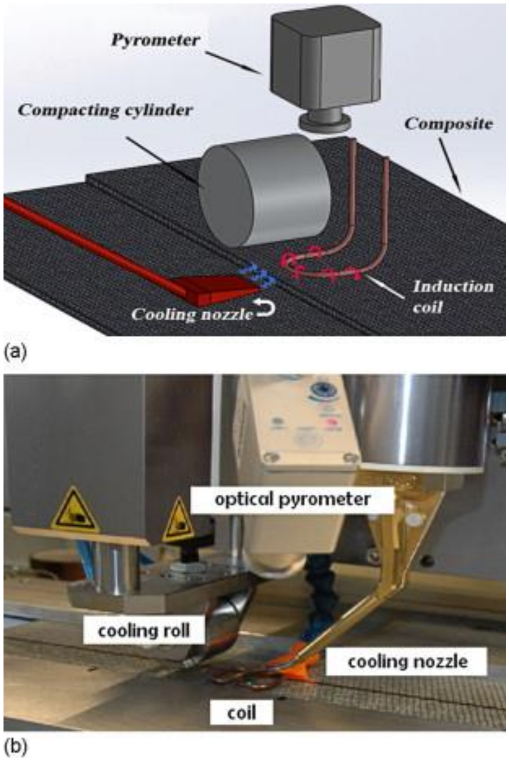


Figure 102 – Induction welding (a) representation of the induction welding equipment; (b) picture of the welding head

Figure 103 displays a potential application of induction welding in the aerospace industry to join unidirectional CFRP stringers to CFRP skin panels, while allowing adjusting for variations in the thickness of the structure.

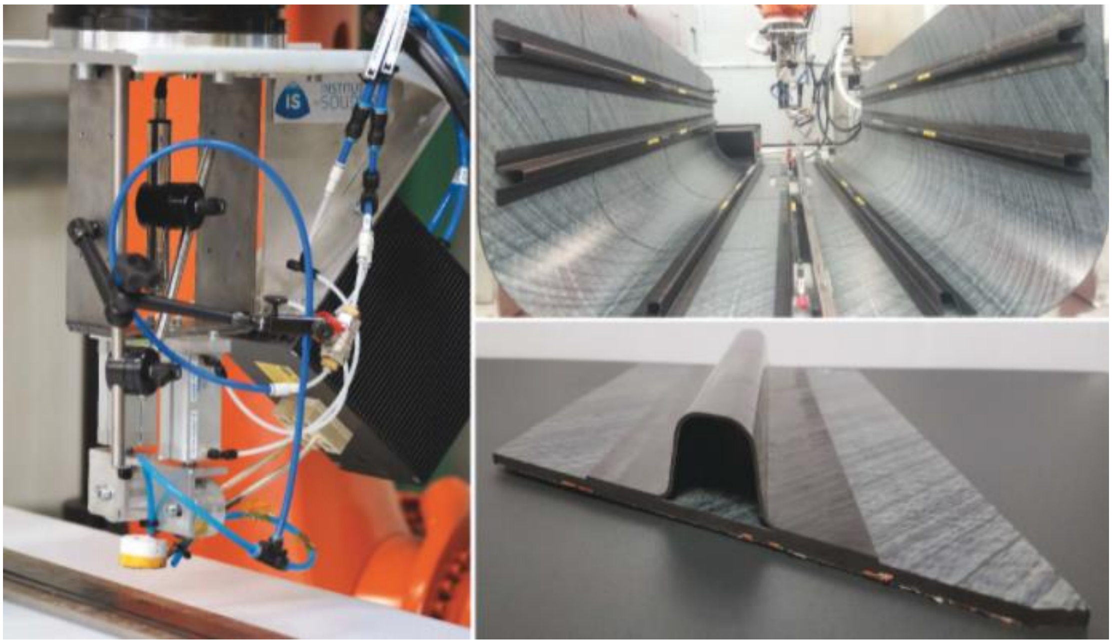


Figure 103 – Joining of unidirectional CF/PEKK stringers to CF/PEKK skin

2.4.2.2. Microwave Welding

Typically, in microwave welding it is applied a frequency within the range of $3x10^8$ Hz to $3x10^{10}$ Hz. However, it requires the use of an implant to absorb the microwave energy and transmit it to the materials to be joined, as most thermoplastics do not heat up when irradiated with microwave radiation. Microwave welding allows to weld complex geometries and it is currently considered as the most cost-effective and fastest (welds are typically created in less than a minute) welding technique for mass production. Figure 104 demonstrates the general mechanism involved in this joining technology [60], [61], [73].

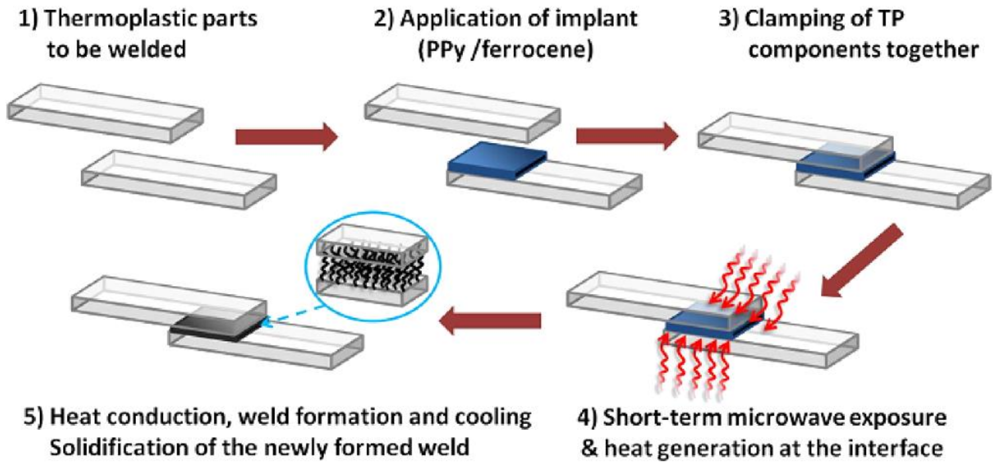


Figure 104 – Microwave welding

2.4.2.3.Dielectric Welding

Also known as high frequency (HF) or radio frequency (RF) welding, this process consists of applying a high electric voltage (in the order of MHz) across the two parts to be joined together. Typically, this method is used to join thin sheets of polar thermoplastic materials. An alternating electric field is generated and it causes oscillation of the polar groups, which results in a temperature rise and melts the materials. Pressure must be applied in order to form the weld. Non-polar materials can also be joined by dielectric welding if a buffer material with a high dielectric loss factor, which will heat up and melt the surrounding material, is placed between the electrodes and the materials to be welded. Thin laminates are easier to join. The principle of dielectric welding is represented in Figure 105 [60], [61].

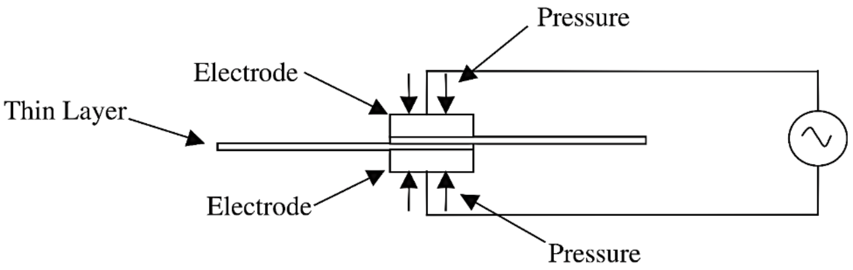


Figure 105 – Principle of dielectric welding

2.4.2.4. Resistive Implant Welding

Resistance welding requires an electrically resistive implant placed between the parts to be joined, which is responsible for generating the necessary heat to melt the surfaces. The temperature rises when the supplied energy exceeds the thermal losses of the material and the surroundings. The joined materials are cooled under pressure, in order to guarantee a direct contact between the parts and allow the occurrence of molecular diffusion, consolidating the weld. Figure 106 shows the principle involved in this technique. Some of the problems related to this process is that heat distribution can be uneven, not resulting in a good quality weld. Additionally, fibre movement can occur, which interferes with the integrity and strength of the joint [61].

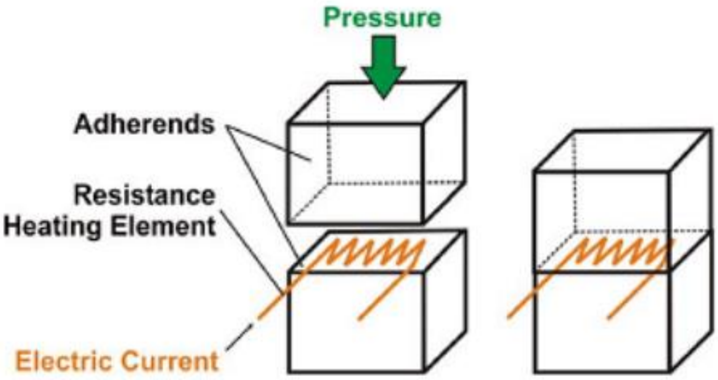


Figure 106 – Principle of resistance welding

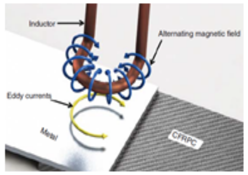
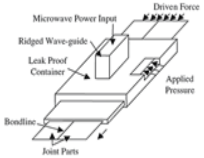
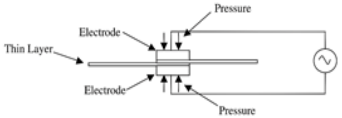
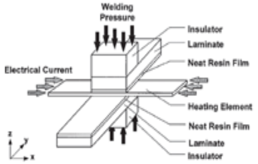
In order to reduce the heating time and mitigate issues associated with delamination and overheating, a new technique, based on resistance welding, was developed: **impulse resistance welding** (IRW). This process involves the application of discontinuous high-energy impulses [61].

At Premium AEROTEC Paris Air Show (2019), a demonstrator for a plane in the Airbus 320 series was displayed (see Figure 107). The carbon fibre-reinforced thermoplastic (CFRP) components were joined by state-of-the-art resistance welding and presented the same mechanical properties as traditional versions of the pressure bulkhead, which are typically made of riveted aluminium components. However, the welded CFRP components lead to a 10-15% weight savings and a 50% reduction in production time [74].

Figure 107 – 1:1 demonstrator of a thermoplastic carbon fibre-reinforced plastic (CFRP) welded pressure bulkhead for a single-aisle jetliner

Table 35 summarizes the most pertinent characteristics of the mentioned electromagnetic technique.

Table 35 – Main characteristics of electromagnetic welding techniques

	Induction Welding	Microwave Welding	Dielectric Welding (or High Frequency or Radio Frequency)	Resistive Implant Welding
Electromagnetic Welding Methods 🟧 Fusion Welding 🟦 Solid State Welding				
Materials to Join	Similar and dissimilar materials	Materials containing polar groups in the molecular structure Materials without polar groups can be welded but requires a microwave absorber implant	Materials containing polar groups in the molecular structure (e.g. PU, PVC) Materials without polar groups can be welded but requires a conductive-composite implant @ the joint interface (e.g. PTFE)	Thermoplastic matrix composites and dissimilar materials (including thermosets and metals by using a thermoplastic interlayer)
Corrosion Resistance	Galvanic Corrosion	-	-	Galvanic corrosion
Maximum Dimension	Bond lines up to 6 m	-	Limited	No limit (thickness)
Joint Strength	High	-		High
Specific Parameters	Amplitude, Frequency	Frequency	Frequency	Power input, Pressure, Resistance of the heating element
Applications	Ideal for attaching metallised tops to plastic bottles Elevators and rudder on the Dassault Falcon *5X*	Automotive under-body components and aerospace components	Beach balls, life jackets, credit card holders, blood bags	Aerospace and Defence (US Air Force) Marine industry Pipes Secondary and tertiary load-bearing components
Standards	-	-	-	-
Advantages	Clean products and complex geometries Possible disassembly No prior surface treatment necessary Multiple joints can be welded simultaneously Reject rates are low Low thermal stresses	Complex and three-dimensional joint geometries Very low power consumption Ease of disassembly	Easily automated Reproducibility Minimal flash formation Capable of welding multiple layers simultaneously	Hermetic joints w/ long-term durability Possible disassembly and repairment Simple to control Large structures
Disadvantages	Voids formation (avoided w/ proper surface preparation and high weld pressure) Delamination Non-uniform heat distribution along the bond line Fibres need to be oriented in different angles to generate eddy currents (0/90° ideal) Surface preparation required	Material degradation Shielding effect of the fibres (can be improved by adding an electromagnetic absorbent material at the interface) Lack of information on the feasibility	Limited joint complexity Component size limitations	Possibility of uneven heating Implant can act as a void affecting local mechanical stress distribution
Process Chain	Placement pf the implant; Pressure application; Induction heating; Cooling; Welded part removal	Implant application; Clamping; Heating; Heat conduction and melting; Colling; Release	Parts placement between the platens; Press platens; Apply RF energy; Press opens; Welded joint release	Parts positioning/clamping; Heating; Pressure; Cooling; Release
Process Time	Short	Short	Short (up to 20 parts/min)	Short (60 – 90 s/ 1.5 m join)
Cost	Economical in terms of energy requirements, however implants can increase the cost	Reduction in capital cost of equipment, especially for complex geometries	Economical	-
Joint Configurations	Lap, Tongue-and-groove, Step, Shear		Lap	Lap

2.4.3. Thermal Welding

2.4.3.1. Infrared Radiation Welding

Infrared radiation welding is a contactless welding process; thus, contamination can be avoided. Its principle is represented in Figure 108 and it consists of heating the surfaces of the parts to be welded through infrared radiation, while pressure is applied. The heating source can be a tungsten filament line or an electrically heated metal plate. It is similar to hot plate welding, however, with this technique, welding times can be improved and low modulus materials can be welded [60], [61].

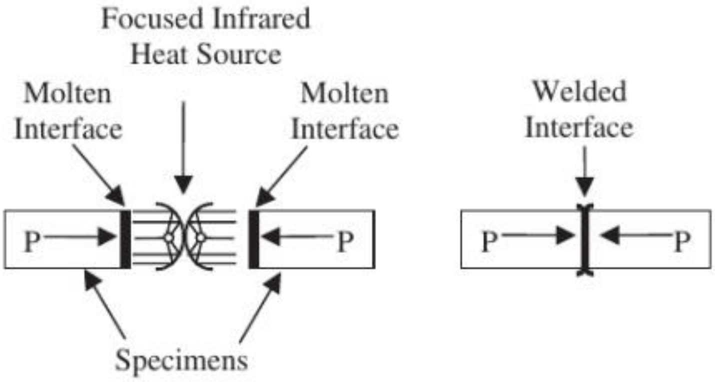


Figure 108 – Principle of infrared radiation welding

2.4.3.2. Laser Welding

In laser welding, the parts to be joined are in direct contact with each other, when the laser beam (generally in the infrared area of the electromagnetic spectrum) is applied, in order to heat the absorbing material. This material is responsible for conducting the heat to the other material. Laser welding requires that one of the materials is transparent enough to be crossed by the laser radiation and the other must be absorbent enough to be heated up by the radiation – see Figure 109.

This technique has the advantage of not generating vibrations and resulting in minimal weld flash. Also, it is suitable for high volume production, despite the welding time depending on the polymer matrix absorption power. The laser beam is controllable, which reduces the risk of distortion or damaged components and allows obtaining accurate and strong joints. It is worth mentioning that fibres in reinforced polymers may disrupt the transmission of the laser and, consequently, make the process inviable [60], [61], [75], [76].

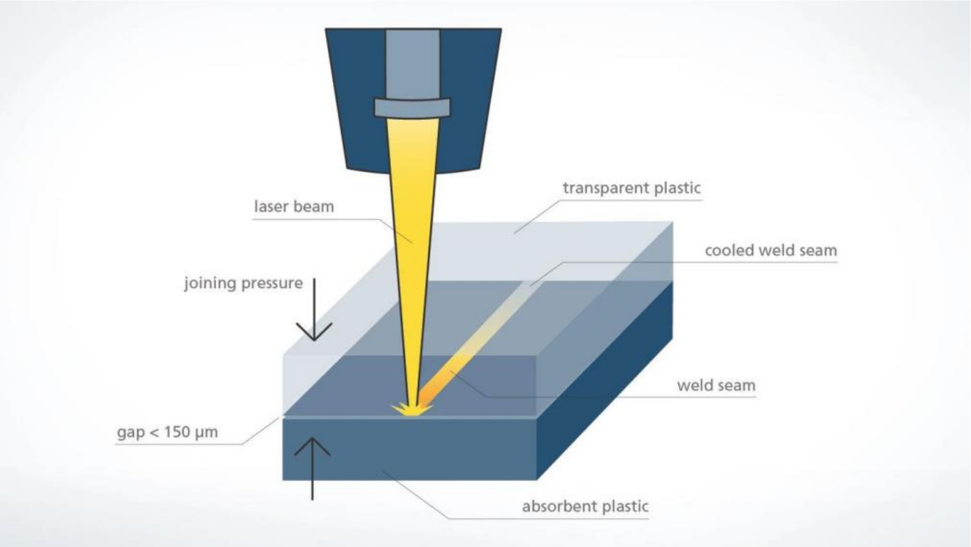


Figure 109 – Principle of laser welding

2.4.3.3. Hot Gas Welding

Hot gas welding is analogous to oxygas welding of metals and it is performed manually. As observed in Figure 110, a stream of gas (typically hot air) is responsible for melting or softening the polymer and a filler rod. The weld is achieved by melting the thermoplastic parts and the filler rod together. The filler rod is made of the same material as the parts to be joined. One of the main advantages of hot gas welding is that the equipment is portable. It is also suitable to join large and complex parts. Nevertheless, the process is slow and the weld quality is highly dependent on the operator skill [60], [61].

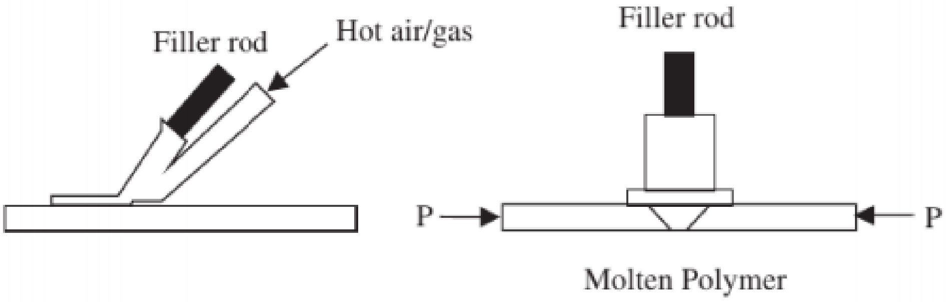


Figure 110 – Principle of hot gas welding

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

2.4.3.4. Hot Plate Welding

Hot plate (or hot tool) welding is a simple and economical process that leads to strong welds. Figure 111 displays the principle of hot plate welding. The parts to be joined are pressed to a hot plate, which is responsible for melting their surfaces. The hot tool is removed and the molten surfaces are then pressed together, in order to accomplish the welding process. Due to its mechanism, contamination can occur. In addition, the processing time for thick plates can be significantly increased (from seconds for small components to hours for large components). It is worth noting that for composite welding, higher pressure is required. Hot plate welding is used in the automotive industry and to join thermoplastic water and gas pipes. An example of a simple application of hot plate welding is shown in Figure 112 [60], [61].

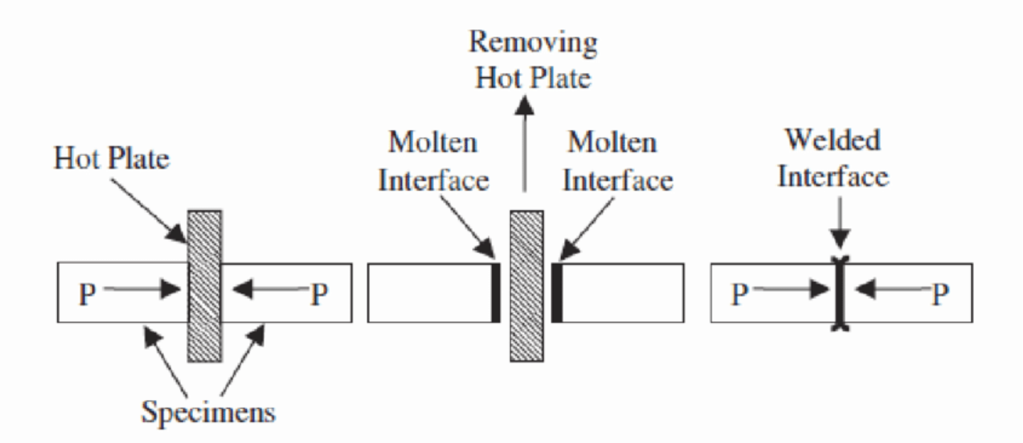


Figure 111 – Principle of hot plate welding

Figure 112 – Car light welded using a heated tool

2.4.3.5. Flash-free Welding

Flash-free welding is a technique that does not produce any weld flash, since its principle is based on the constraint of the melt during the process. The absence of beads or flash mitigates the accumulation of contaminations or microorganisms and reduces the stress concentration in the joint area, resulting in higher integrity. The major drawbacks of this technology are the long welding cycles, as it relies on the heat conduction from the surface through the full thickness of the workpiece, and the maximum wall thickness restriction (~3mm). It is essentially used to join polymeric pipes, solid extrusions and sheets. Its principle is schematized in Figure 113 [77].

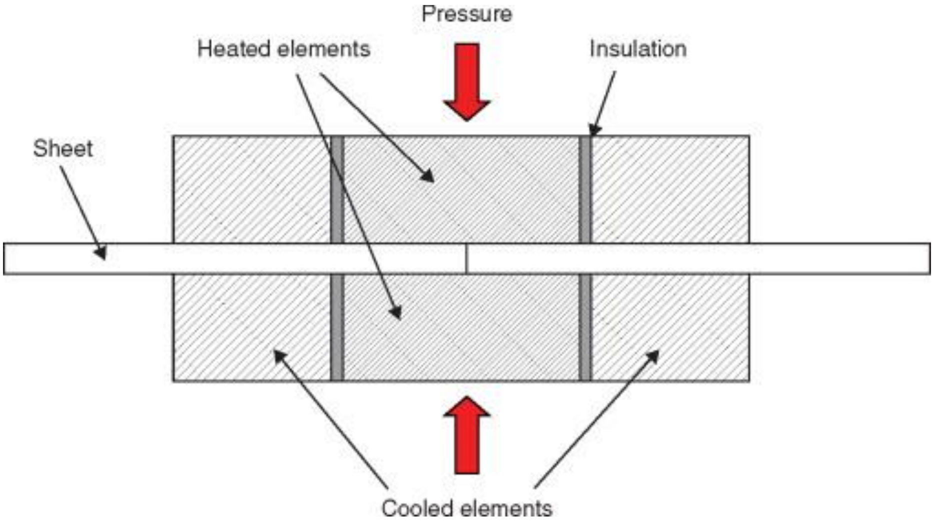
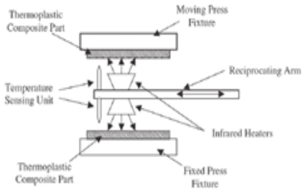
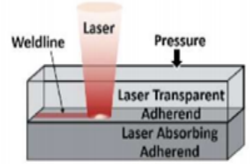
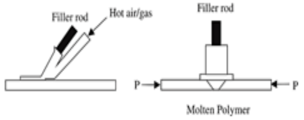
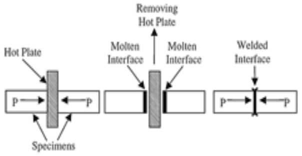
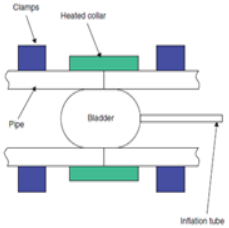


Figure 113 – Flash-free welding

The main properties of the aforementioned welding techniques are depicted in Table 36.

Table 36 – Main characteristics of thermal welding techniques

	Infrared Radiation Welding	Laser Welding	Hot Gas Welding	Hot Plate (or Hot Tool) Welding	Flash-Free Welding
Thermal Welding Methods 🟥 Fusion Welding 🟦 Solid State Welding					
Materials to Join	Thermoplastic matrix composites (not suited for clear materials unless an absorbing material is used @ the interface)	Thermoplastic matrix composites and dissimilar materials	Thermoplastic matrix composites reinforced w/ short fibres or particles	Similar and dissimilar, but compatible, materials	-
Corrosion Resistance	-	Galvanic Corrosion	-	-	-
Maximum Dimension		Thickness limitations (especially for highly crystalline materials)	Practically, can be used to weld any shape and size	-	3 mm (thickness) and Ø between 20 and 63 mm
Joint Strength	High	Acceptable		High	
Specific Parameters	Power input, Pressure, Frequency	Beam temperature, Pressure	Gas flow, Temperature, Rod angle		Temperature
Applications	Aeronautical applications	Thin to thick components in the aeronautical sector (in development)	Chemical Storage Vessels Pipework	Fluid reservoirs Window frames Automotive Industry	Where cleanliness and high purity are priority (e.g. semiconductor, pharmaceutical)
Standards	-	-	EN 13067 or AWS B2.4 (related to operator certification)	-	-
Advantages	Attenuate contamination risks (non-contact technique) Able to weld low modulus materials Automation Flexibility (possibility to join large flat and curved areas)	Low residual stresses Complex shapes can be obtained Hermetic joints Automation	Portable and light equipment Repairments of large components in-situ Slow welding speed	Simple Defective welded parts can be easily recycled	Joints without beads or flash Less stress concentration
Disadvantages	Colorants and pigments change polymer absorption properties Thermal residual stresses	High intensity laser beams decompose the polymers Health and safety issues Top material must transmit laser radiation and bottom material must absorb it (an absorber element can be placed @ the interface)	Manual (analogous to oxygas welding of metals) Weld quality depends on the operator skill	Surface contamination Limited to flat surfaces	Relies on the conduction of heat from the surface through the full thickness
Process Chain	Loading parts; Press actuation; IR radiation application; Changeover; Hold phase; Unloading	Surface preparation; Clamping parts; Laser beam application; Cooling; Release	Surface preparation; Weld-rod preparation; Parts positioning/clamping; Welding; Cooling		Parts positioning/clamping; Heating; Pressure application; Cooling; Release

2.5. Hybrid Connections

Hybrid connections are a combination of two or more fundamental processes (mechanical, chemical and physical connections), so they generally result in a **synergy** of the two (or more) parent processes. Figure 114 shows different examples of hybrid connections. This is translated into better mechanical properties, such as fatigue performance. As observed in Figure 115, combining a drilled rivet joint and an adhesive can lead to an improvement in the fatigue life of the joint. In addition, as confirmed by the observation of Figure 116, using a hybrid joint can significantly enhance the static strength of the joint, compared to a simply bolted or bonded joint.

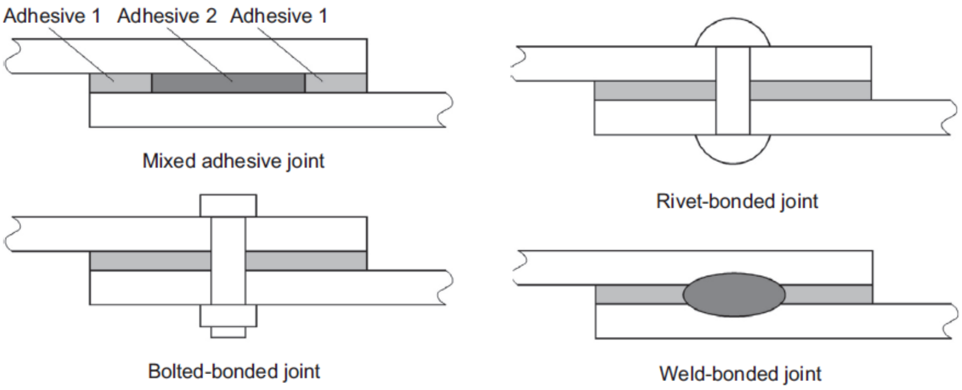


Figure 114 – Hybrid joints

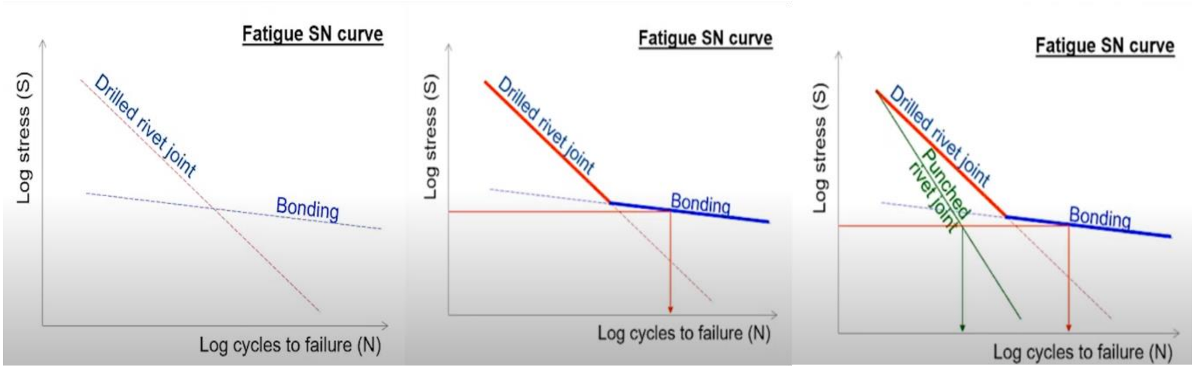


Figure 115 – Fatigue performance improvement

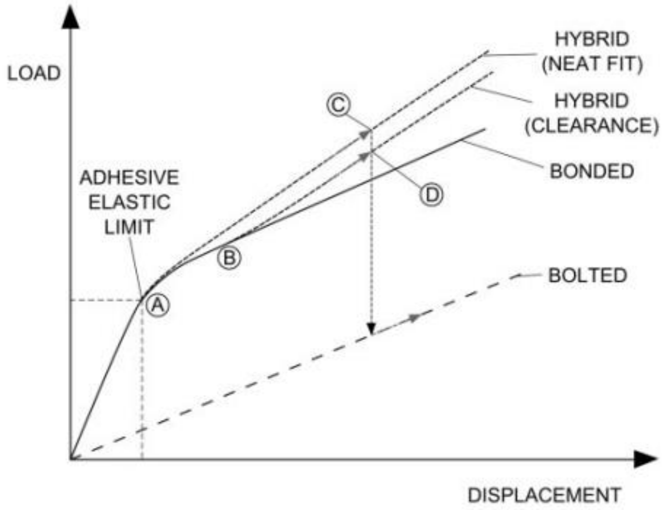


Figure 116 – Load-displacement behaviour of a hybrid bolted-bonded joint

The advantages and properties of hybrid connections depend essentially on the combined processes, thus the considered hybrid joining technologies were characterized on a similar basis to the other processes. Figure 117 shows the parameters taken into consideration, which include the materials to be joined, the joint properties, main applications, availability, cost, standardization, process chain and joint configurations.

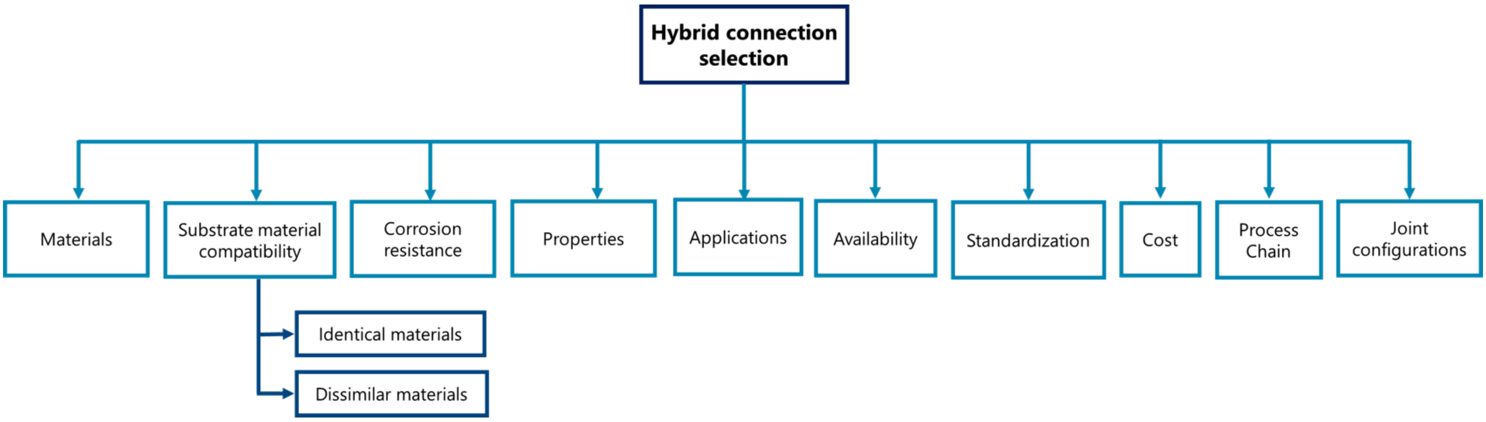


Figure 117 – Classification parameters for hybrid connections

2.5.1. Conventional Fasteners and Adhesives

Due to the lack of design guidelines, adhesives use is yet constrained across diverse industries, as designers and engineers cannot always guarantee a high level of safety, especially in structural applications. Thus, adhesives are often combined with fasteners, resulting in hybrid bonded-bolted joints (HBB) – see Figure 118. Typically, this results in better mechanical properties, such as a greater fatigue performance. In addition, the use of an adhesive enhances the joint corrosion resistance, since it also acts as a sealant. Table 37 gathers the most relevant information on bolted-bonded connections [51], [78], [79].

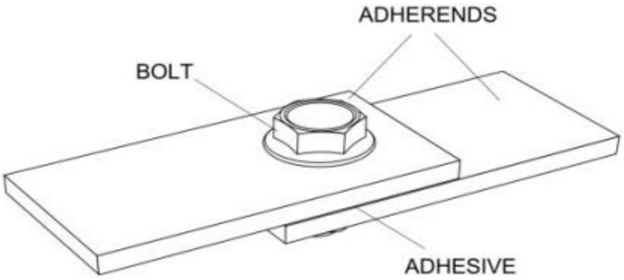
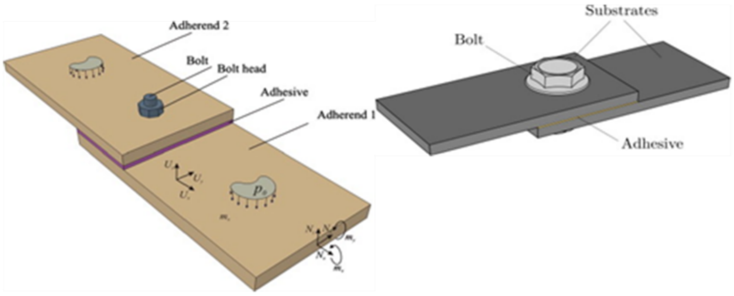


Figure 118 – Hybrid bolted-bonded (HBB) connection

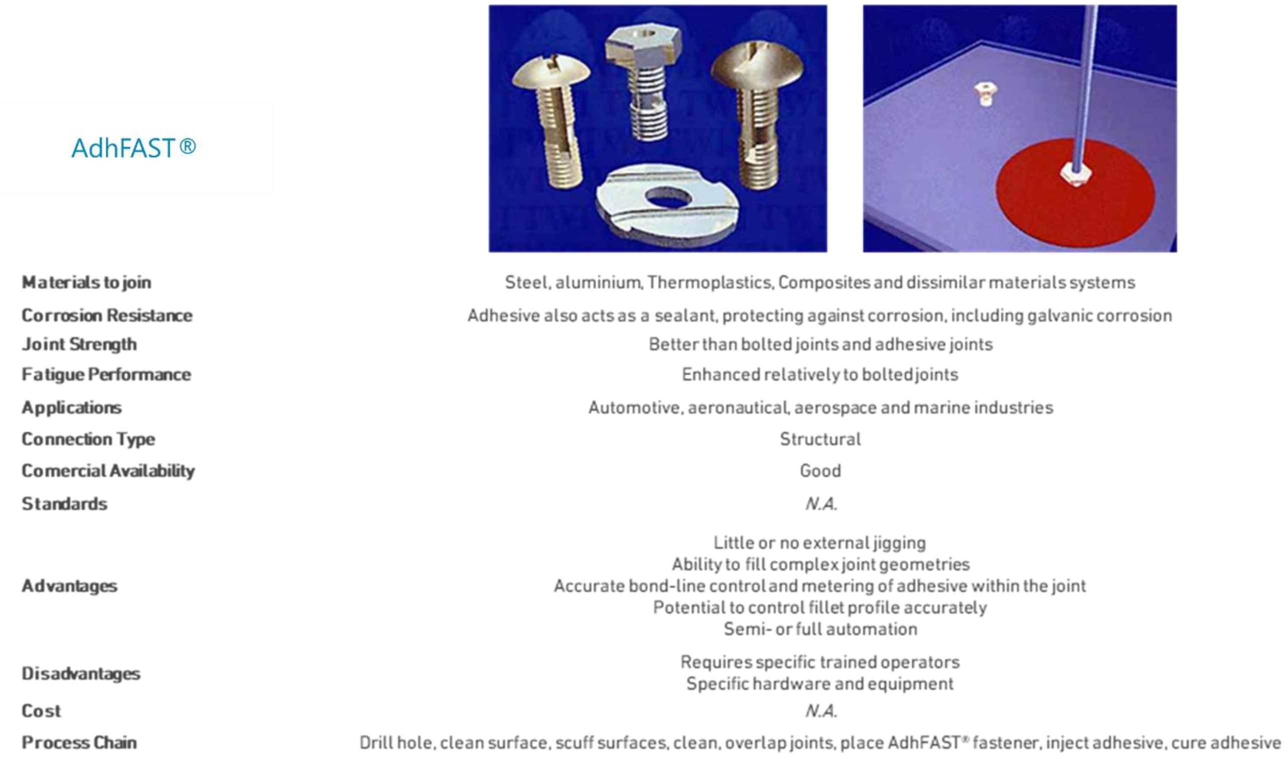
Table 37 – Main characteristics of hybrid bolted-bonded connections

Conventional Fasteners & Adhesive	
Materials to join	Similar and dissimilar materials
Corrosion Resistance	Adhesive also acts as a sealant, protecting against corrosion, including galvanic corrosion
Joint Strength	Better than bolted joints and adhesive joints
Fatigue Performance	Enhanced relatively to bolted joints
Applications	Automotive, aeronautical, aerospace and marine industries
Connection Type	Structural
Comercial Availability	Good
Standards	*N.A.*
Advantages	Better load distribution Vibration absorption
Disadvantages	Adhesive is the primary load bearer and the bolt acting as secondary resistor
Cost	*N.A.*
Process Chain	Drill hole, clean surface, scuff surfaces, clean, apply adhesive, overlap joints, place fastener, cure adhesive

2.5.2. AdhFast®

AdhFast® is a hybrid technology, developed by TWI, that combines fasteners and adhesives; nonetheless, it differs from HBB joints from an application mechanism point of view, once it involves injecting the adhesive through the middle of the fastener. It harvests the most relevant advantages of mechanical fastening and adhesive bonding, without requiring extensive operator skill, as its exposure to the adhesive is minimised. The bond line thickness is easily controlled because the volume of adhesive injected can be automatically controlled and monitored [80], [81]. In Table 38 are reunited the most relevant characteristics of such joining technology. According to the literature, AdhFast® is generally used to form lap joints (see Figure 9).

Table 38 – Principal characteristics of AdhFast® technology

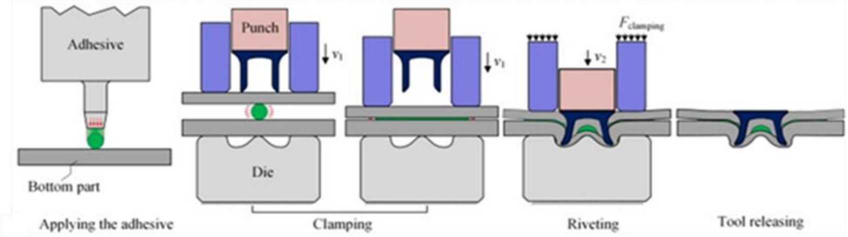


AdhFAST®	
Materials to join	Steel, aluminium, Thermoplastics, Composites and dissimilar materials systems
Corrosion Resistance	Adhesive also acts as a sealant, protecting against corrosion, including galvanic corrosion
Joint Strength	Better than bolted joints and adhesive joints
Fatigue Performance	Enhanced relatively to bolted joints
Applications	Automotive, aeronautical, aerospace and marine industries
Connection Type	Structural
Comercial Availability	Good
Standards	*N.A.*
Advantages	Little or no external jigging Ability to fill complex joint geometries Accurate bond-line control and metering of adhesive within the joint Potential to control fillet profile accurately Semi- or full automation
Disadvantages	Requires specific trained operators Specific hardware and equipment
Cost	*N.A.*
Process Chain	Drill hole, clean surface, scuff surfaces, clean, overlap joints, place AdhFAST® fastener, inject adhesive, cure adhesive

2.5.3. RivBonding

This technology combines self-piercing riveting with adhesive bonding, leading to continuous joints with, generally, greater strength and higher stiffness. The adhesive is first applied to the joint and, subsequently, the rivet is pierced into the two adhesively bonded sheets. However, the cure of the adhesive normally occurs after the setting of the rivet. Table 39 displays the principal characteristics of the RivBonding technology. Regarding the joint configurations, the most common are lap joints [82].

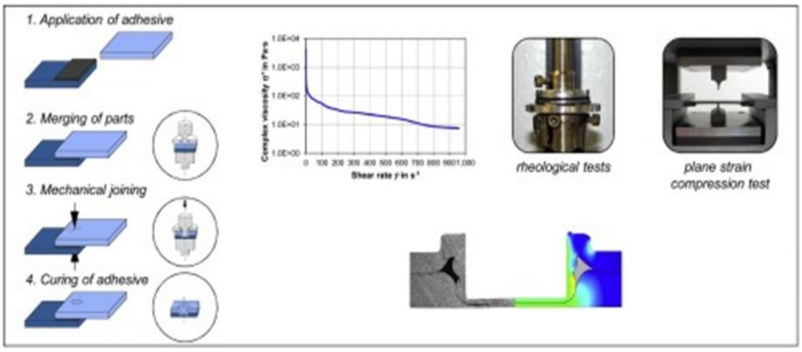
Table 39 – Principal characteristics of RivBonding

RivBonding	
Materials to join	Steel, Aluminium, Thermoplastics matrix composites
Corrosion Resistance	Adhesive also acts as a sealant, protecting against corrosion, including galvanic corrosion
Joint Strength	Higher than individual processes (generally)
Fatigue Performance	Higher than individual processes (generally)
Applications	Automotive industry, Aerospace (panel bonding)
Connection Type	Structural
Comercial Availability	Good on dedicated facilities
Standards	*N.A.*
Advantages	Continuous joint instead of point joint Increased joint stiffness Leak-tight joint Can be applied to painted substrates
Disadvantages	Longer processing times compared with self-piercing riveting alone Contamination of the riveting tooling Inhomogeneous adhesive distribution results from localized pressure caused by the riveting operation
Cost	*N.A.*
Process Chain	Clean surface, scuff surfaces, clean, apply adhesive, apply rivet, cure adhesive

2.5.4. ClinchBonding

As the name implies, ClinchBonding combines mechanical clinching and adhesive bonding. The adhesive is placed between the two sheets to be joined and, subsequently, the mechanical clinching process is performed. The joint is kept in place by mechanical interlocking and adhesion forces [83]. Table 40 shows the most relevant information related to ClinchBonding. Nonetheless, it is worth noting that the practical application of such technology is yet very limited. Due to equipment limitations, ClinchBonding is most applied to form lap joints (see Figure 9).

Table 40 – Main characteristics of ClinchBonding

ClinchBonding	
Materials to join	Steel, Aluminium, Thermoplastics matrix composites
Corrosion Resistance	Adhesive also acts as a sealant, protecting against corrosion, including galvanic corrosion
Joint Strength	-
Fatigue Performance	-
Applications	Practical implementation still very limited. Automotive, aeronautical and aerospace industries
Connection Type	Structural
Comercial Availability	Poor
Standards	*N.A.*
Advantages	Improved load dispersion and joint strength Improved fatigue strength No thermal damage induced to the adhesive Dumping of noise and vibration Corrosion protection
Disadvantages	Clinching reduces significantly the adhesive bonding area Does not allow disassembly without damaging the structure Limited to materials with ductility (only thermoplastic) Material damage
Cost	*N.A.*
Process Chain	Clean surface, scuff surfaces, clean, apply adhesive, clinch joint, cure adhesive

2.5.5. Rivet-Welding

Rivet-weld hybrid joining results in a synergy between self-piercing riveting and resistance spot welding (RSW), as represented in Figure 119. This process was mainly developed to overcome issues related to the joining of dissimilar materials, however, there is a lack of information on its full applicability to join composite materials. Rivet-welding demands the use of a weldable rivet which is pierced through the top sheet. When the rivet pierces the bottom sheet, a current is applied, causing a local heat increase that melts the rivet and the bottom sheet. After cooling, the joint is formed by combining mechanical and physical interaction forces between the two sheets and rivet. In Table 41 are summarized the most relevant characteristics of Rivet-Welding [84].

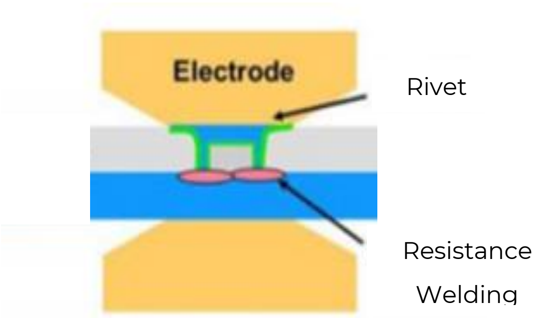


Figure 119 – Rivet-Welding principle

Table 41 – Main characteristics of Rivet-Welding technology

Rivet - Welding

Materials to join	Similar and dissimilar materials
Corrosion Resistance	Galvanic Corrosion
Joint Strength	-
Fatigue Performance	-
Applications	Automotive, aeronautical and aerospace industries
Connection Type	Structural
Comercial Availability	Poor/medium
Standards	*N.A.*
Advantages	Allow for joining dissimilar materials Requires less energy in comparison to normal spot welding as the energy is concentrated in the fastener
Disadvantages	Fastener welded to the bottom sheet Requires pre-drilling Requires access to both sides of the plate
Cost	*N.A.*
Process Chain	Place materials, apply rivet, spot weld

2.5.6. WeldBonding

The basic principle of WeldBonding is based on the combination of a welding process and adhesive bonding (see Figure 120), resulting in a strong joint formed by chemical and physical forces. Hybrid welded-bonded joints can be achieved through two different approaches:

- First, the adhesive is applied in the joint line and, subsequently, welds are produced along the bond line;
- Second, the two parts to be joined are welded and, then, the adhesive is back-infiltrated into the voids between the welds.

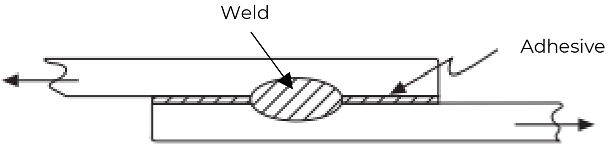
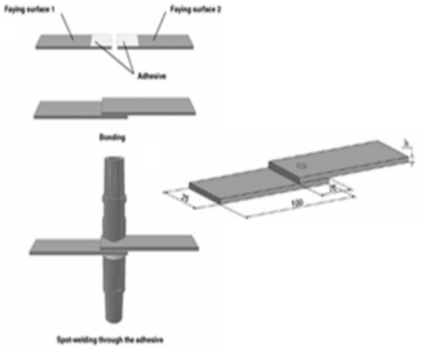
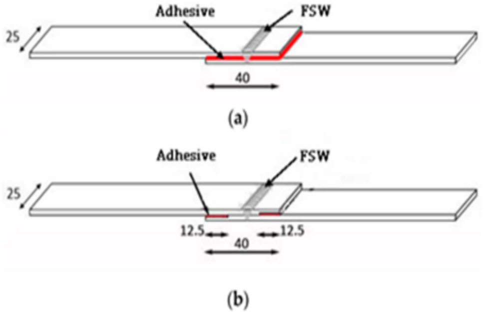


Figure 120 – Hybrid welded-bonded joint

In Table 42 can be consulted the most relevant characteristics of WeldBonding processes, which typically rely on resistance spot welding or friction stir welding (FSW). In addition, the most applied joint configurations are essentially coincident with the ones presented for adhesive bonding (see Figure 62) [85], [86].

Table 42 – General characteristics of WeldBonding processes

	Adhesive + Spot Welding	Adhesive + Friction Stir Welding
WeldBonding		
Materials to join	Steel, Aluminium, Thermoplastics matrix composites (only similar systems)	Steel, Aluminium, Thermoplastics matrix composites and dissimilar materials
Corrosion Resistance	Adhesive also acts as a sealant, protecting against corrosion, including galvanic corrosion	Adhesive also acts as a sealant, protecting against corrosion, including galvanic corrosion. However, in the welded line, it my be required a protective element, depending on the substrates
Joint Strength	Higher than individual processes	Higher than individual processes
Fatigue Performance	Higher than individual processes	Higher than individual processes
Applications	Automotive industry	
Connection Type	Structural	Structural
Comercial Availability	Poor	Poor
Standards	*N.A.*	*N.A.*
Advantages	Vibration/sound isolation Corrosion protection	Improved joint characteristics over the standard friction stir process
Disadvantages	Thermal damage to the adhesive due to heat generated during welding Material compatibility required	Thermal damage to the adhesive due to heat generated during welding Adhesive mixture within the weld pool
Cost	*N.A.*	*N.A.*
Process Chain	Clean surface, scuff surfaces, clean, apply adhesive, cure adhesive, spot weld joint	Clean surface, scuff surfaces, clean, apply adhesive, cure adhesive, FSW process

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

2.6. Final remarks

This document gathers the most relevant joining technologies to connect FRP composite materials. It was divided into four major groups - mechanical, chemical, physical and hybrid connections - based on the interaction forces involved.

In the mechanical connections group, it was considered joining technologies that require the use of a supplemental device, such as bolted connections (including embedded and surface-bonded fasteners) and self-piercing riveted joints; and integral mechanical attachments processes, namely snap-fit, staking, clinching and hemming. A special subgroup was developed to include novel technologies such as non-adhesive form locked joints, material surface modification processes, interlocking joining and filament winding as a joining technique.

Regarding chemical connections, the mentioned adhesives were selected based on their compatibility with the composite substrate and the marine environment. Therefore, the down-selection includes epoxy, acrylic, polyurethane, phenolic, polyester, vinyl ester, polyimide, bismaleimide, polyamide, silicone and poly vinyl acetate. Overlamination, which is a specific adhesive bonding technique, was also characterized grounded on the pre-defined parameters of this benchmark. Within this topic, it was presented a brief introduction to dismantlable adhesives and methods to optimize the adhesively bonded joint efficiency.

Welding techniques were divided into three major groups based on the heat source: frictional, electromagnetic and thermal. In the former group were listed the main characteristics of spin welding, vibration welding, ultrasonic welding, friction spot joining, friction stir welding and its variants. Subsequently, the electromagnetic welding techniques – induction welding, microwave welding, dielectric welding and resistive implant welding – were described within the defined parameters. At last, the thermal welding processes, which include infrared radiation welding, laser welding, hot gas welding, hot plate welding and flash-free welding, were characterized.

The benchmark was concluded with hybrid connections, which comprise combining conventional fasteners and adhesive bonding, RivBonding, AdhFast® technology, ClinchBonding, ClinchRiveting and Rivet-Welding.

Despite the lack of information related to some technologies, each presented solution can be potentially used to join FRP composite materials or FRP composites to metals in extreme environmental conditions. A qualitative comparison between the three main connection types is presented in Table 43. In addition, Tables 44 and 45 establish a comparison between different joining technologies based on their process chain and general properties of the diverse processes, respectively.

Table 43 – Qualitative comparison between bolted, adhesively bonded and welded joints in CFRP frames in aircraft structures

Criteria	Bolted joints	Adhesive joints	Welded joints
Experience	++	+	–
Degree of automation	++	–[a]	+
Cycle time	++	–[a]	+
Quality assurance effort	+	–	0
Dismantling possibility	+	–[a]	0
Structural repair possibility	++	–	0
Optical appearance	–	+	+
Impact on drag	–	+	+
Impact on weight	–	+	+
Impact on non-recurring cost	–	–[a]	0
Impact on recurring cost	–	0	+

[a] Adhesive joining refers to materials and processes with adhesive film and autoclave cure; other adhesives and processes can demonstrate improved properties

Table 44 – General process chain of the main joining processes

Technology	Process Chain				
Mechanical Fastening	Drilling and Countersinking	Fastener positioning and tightening	Protection	Final inspection	
Integral Attachment	Design or process-in desired feature	Parts positioning and assembly	Final inspection		
Adhesive Bonding	Surface preparation	Adhesive application	Joint assembly	Adhesive cure	Final inspection
Welding	Surface preparation	Parts positioning	Welding	Cooling	Final Inspection

Table 45 – Comparison between different joining processes

	Bonding	Fastening/Riveting	Joining by forming of sheet, tube and sectional parts	Welding
Mechanism	Physical absorption and chemical bonding (limited by conditions of temperature and moisture)	Mechanically affix two or more parts w/ bolts, screws and rivets)	Force-closed (interfacial pressure), form-closed and material-closed	Melting w/ addition of filler materials
Shape of the connections	Lap and strapped joints	Lap and edge joints (other shapes w/ accessories)	Arbitrary	Butt, lap, corner and edge joints
Joining Temperature	RT or higher curing temperature	RT	RT (can be assisted by heat)	Melting point
Heat-affected zones	No	No	No	Yes (microstructure changes and distortion from thermal cycles)
Stress-affected zones	Uniform stress distribution	Stress concentration around the holes	Low residual stresses	Residual stresses
Materials	Similar and Dissimilar	Similar and Dissimilar	Similar and Dissimilar	Similar materials
Coated Materials	Not recommended (compatibility and surface smoothness)	Possible	Possible	Very difficult or impossible
Energy Consumption	Medium	Low	Medium	High
Productivity	Low (use of clamps and jigs + curing time)	High	High	Medium (use of clamps and jigs)
Cost	Medium (surface preparation)	Low	Medium/Low	High (labour, inspection and equipment)
Environmental friendliness	Medium (solvent-based adhesives and cleaners, non-detachable joints)	High (easy disassembly)	High	Low (toxic fumes, smoke, dust particles, non-detachable joints)

3. Evaluation and selection of applicable connections

Taking into account the work presented in the last chapter, the first proposals of connections for the W2Power and Tidal Turbine Housing will now be presented and evaluated using selection matrices which will consider several parameters. Each proposal will be individually analysed not only in terms of advantages and disadvantages but also regarding its manufacturability and integration. This process of evaluating and selecting the applicable connections will be performed separately for the W2Power and Tidal Turbine platforms.

3.1. W2Power platform

From the analysis of the complete **W2Power** platform, it was possible to identify its associated **connections groups**:

1. Tower to Column;
2. Tower to Nacelle;
3. Tower to Tower;
4. Tube to Column;
5. Tube to Tube.

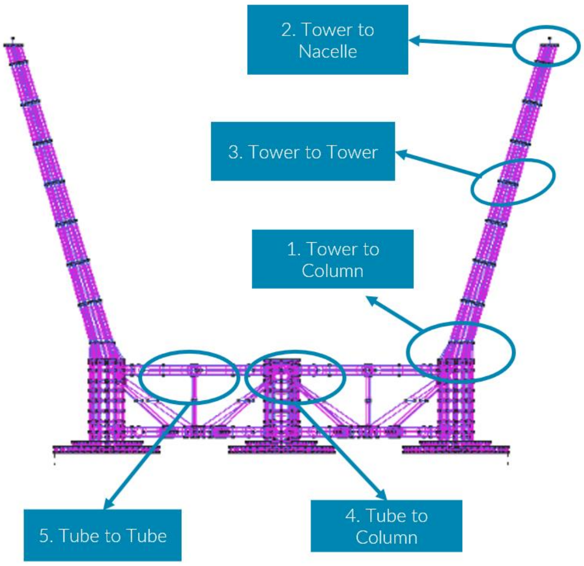


Figure 121 – W2Power platform connection's groups

The connections considered above are applied to connect the different modules and they will be designed taking into consideration the possibility of easy assembly of the modules (on-shore) and dismantling (for maintenance/inspection/end-of-life disposal operations).

At this phase no redesign of the platform was done, therefore the geometry of the current W2Power platform (in steel) will be considered for both the real scale and prototype (scale 1:6).

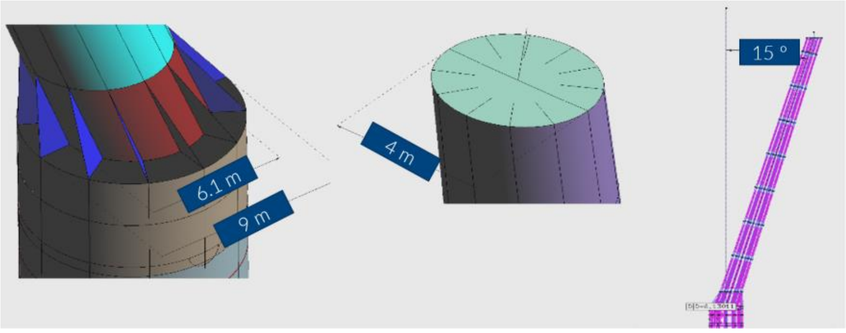


Figure 122 – Main dimensions of the real scale W2Power tower (from *RamSeries* model).

The main dimensions for these two scales are identified in Figure 122 and Table 46.

Table 46 – Main dimensions of the real W2Power tower (real scale and prototype).

	Height of the tower	**Height of the column**	**Ø of the column**	**Ø of the tower at the bottom**	**Ø of the tower at the top**	**Angle between the axis of the tower and the vertical line**	**Width of the platform**
Real Scale	66 m	23 m	9.0 m	6.1 m	4.0 m	15°	117 m
1:6 Scale	11 m	3.8 m	1.5 m	1.02 m	0.67 m	15°	19.5 m

For each of the connection groups previously identified, several options were considered, and for each option, a 3D model was developed for better visualization (while using preliminary design for manufacturing), followed by a concept of assembly, an analysis of its advantages and disadvantages as well as a definition of a possible process chain for its assembly.

Followed are the presented proposals for each of these groups of connections. Because of their similarity, the Tower to Column and Tower to Nacelle concepts will be addressed as the same ("Top and Bottom Tower Connections"):

3.1.1. Top and Bottom Tower Connections

As already mentioned, and illustrated in Figure 123, these connections apply to both the top of the tower (tower to nacelle) and the bottom of the tower (tower to column). Then, the main concepts developed are presented.

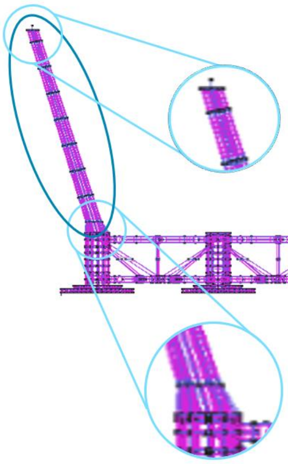


Figure 123 – Top and bottom tower connections

3.1.1.1. Flange Connection – Option A

This concept is illustrated in Figure 125 and uses a steel or FRP flange, bolted to the column/nacelle and to which the tower will then be bonded on its exterior surface. The assembly is illustrated in Figure 126 to Figure 128.

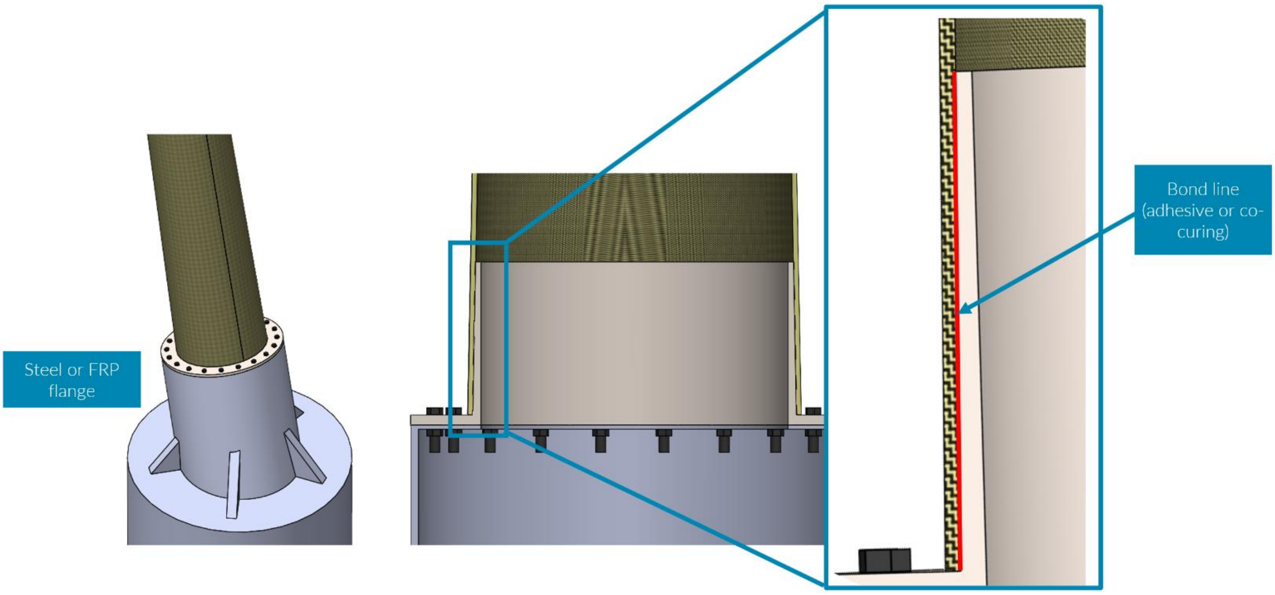


Figure 124 – Flange connection (option A)

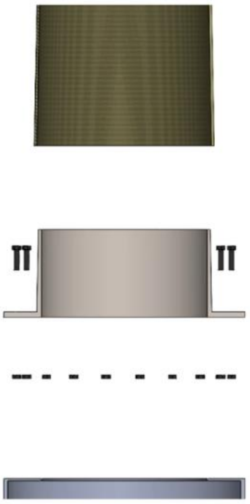


Figure 125 – Simplified assembly view (step 1)

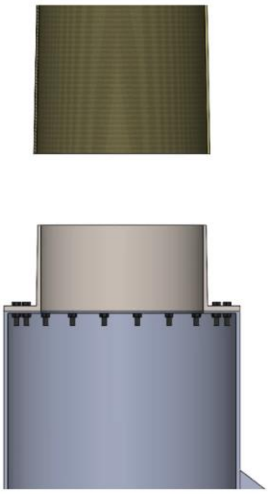


Figure 126 – Simplified assembly view (step 2)

Figure 127 – Simplified assembly view (step 3)

Although not illustrated in the figures above, a smaller thickness (taper) at the upper end of the flange can be made to minimize the stress concentrations in this area (Figure 128).

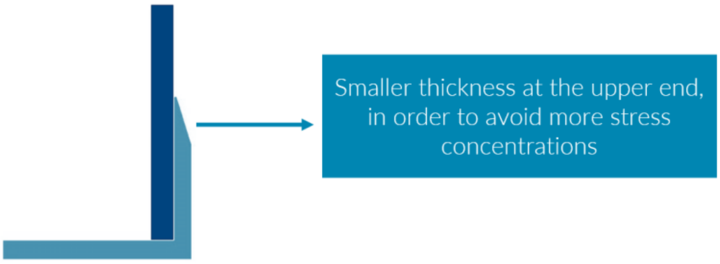


Figure 128 – Detail of thickness variation for fewer stress concentrations

And the main advantages and disadvantages are identified in Table 47.

Table 47 – Advantages and disadvantages

Advantages	Disadvantages
The flange can have different geometries (straight, tapered, stepped, etc.)	Hindered accessibility to the bolts. On 1:6 scale blind bolts (Figure 129) can be applied
Enables disassembly (flange to flange)	Connection between the tower and flange is permanent
Tower is not subjected to high-stress concentration	Dimension control of the inside surface of the tower for adhesive bonding
	Different coefficients of thermal expansion (CTE)
	Thixotropy of adhesive to be controlled (gravity does not help the application)

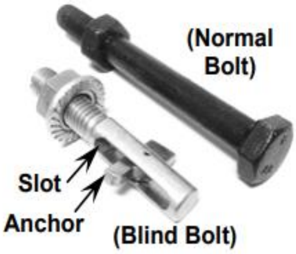


Figure 129 – Normal bolts and blind bolts

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 130.

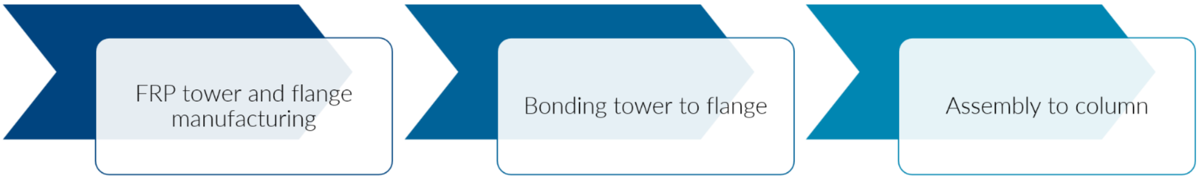


Figure 130 – Process chain

3.1.1.2. Flange Connection – Option B

This concept is illustrated in Figure 132 and uses a steel or FRP flange, bolted to the column/nacelle and to which the tower will then be bonded on its interior surface. The assembly is illustrated in Figure 133 to Figure 135.

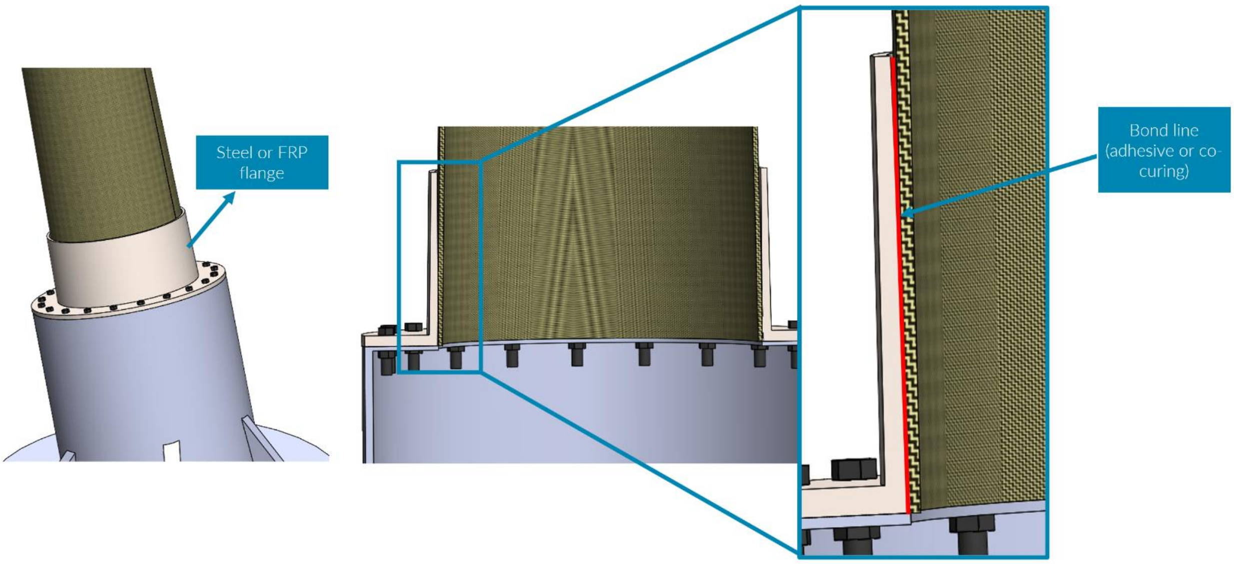


Figure 131 – Flange connection (option B)

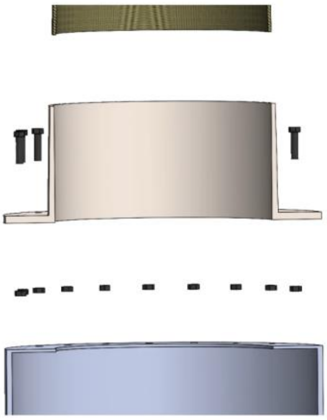


Figure 132 – Simplified assembly view (step 1)

Figure 133 – Simplified assembly view (step 2)

Figure 134 – Simplified assembly view (step 3)

And the main advantages and disadvantages are identified in Table 48.

Table 48 – Advantages and disadvantages

Advantages	Disadvantages
The flange can have different geometries (straight, tapered, stepped, etc.)	Hindered accessibility to the bolts. On 1:6 scale blind bolts can be applied (Figure 129)
Allows an easy on-site assembly	Connection between tower and flange is permanent
Enables disassembly (flange to flange)	Higher exposure of the adhesive to environmental conditions
Tower is not subjected to high stress concentration	Different coefficients of thermal expansion (CTE)
	Thixotropy of adhesive to be controlled (gravity does not help the application)

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 135.

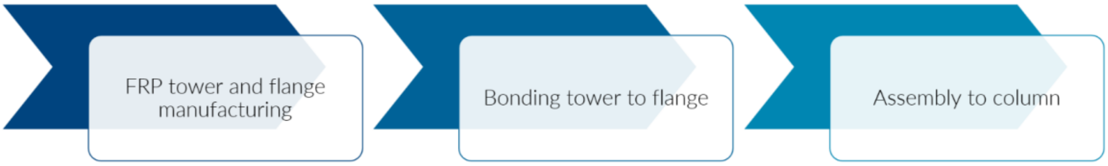
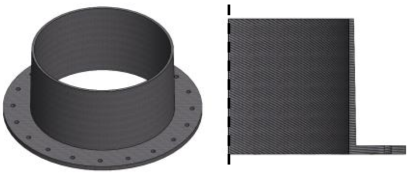
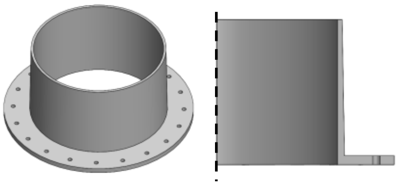


Figure 135 – Process chain

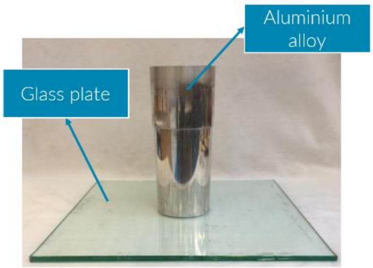
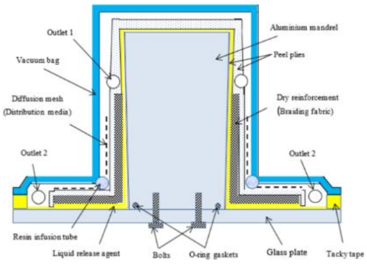
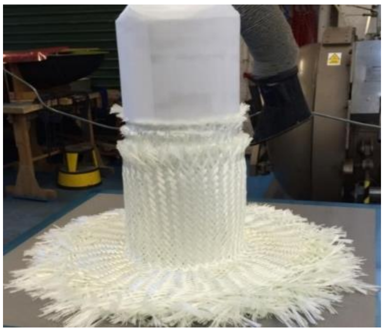
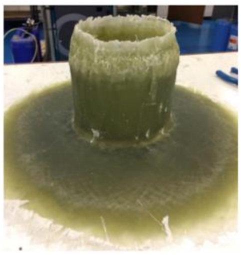
Regarding the materials of the flange, it can be done in either steel or FRP [87], which advantages and disadvantages, as well as possible manufacturing processes, are mentioned in Table 49.

Table 49 – Materials for flange connections

	Flange Material	
	FRP	**Steel**
		
Advantages	Less susceptibility to corrosion Same material as the FRP tower (similar CTE, easier bonding)	More common manufacturing
Disadvantages	Load dispersion around the holes Risk of voids at the 90° angles Drilling may lead to damage	More susceptibility to corrosion Dissimilar material from the FRP tower (different CTE)
Manufacturing Process	Infusion, RTM, Hand Lay-up	Casting, Welding

And an example of its possible fabrication [87] is illustrated in Table 50:

Table 50 – Example of manufacturing of a FRP flange

Example of manufacturing of a FRP Flange		
Mould	Setup	Result
	  	 Before the cutting  After the cutting

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

3.1.1.3. Flange Connection – Option C

This concept is illustrated in Figure 137 and uses a steel or FRP flange (an integral part of the module), bolted to the column/nacelle and to which the tower will then be bonded on its exterior surface. The assembly is illustrated in Figure 138 to Figure 140.

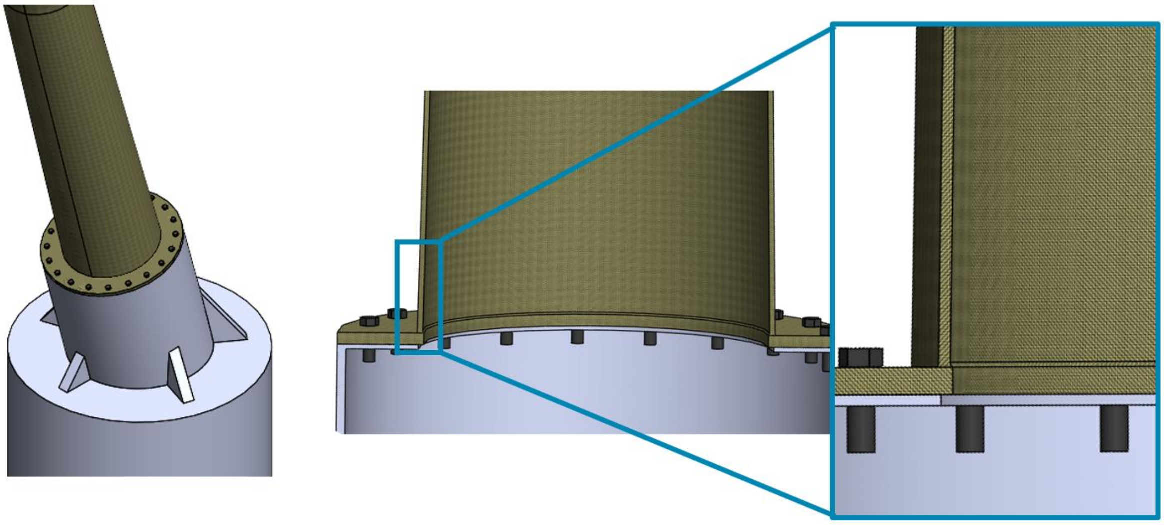


Figure 136 – Flange connection (option C)

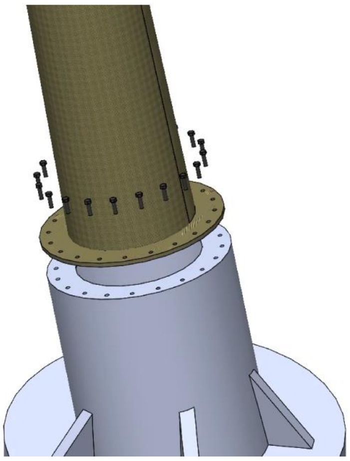


Figure 137 – Simplified assembly view (step 1)

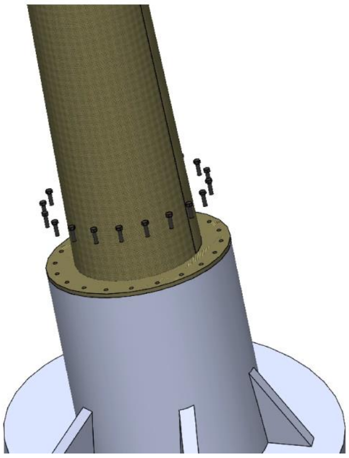


Figure 138 – Simplified assembly view (step 2)

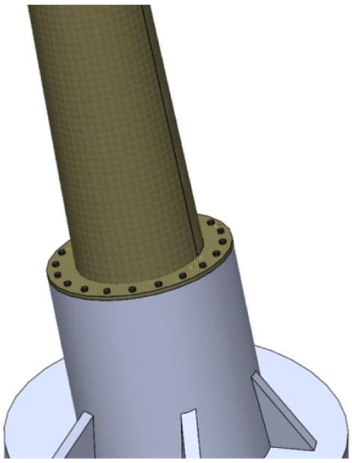


Figure 139 – Simplified assembly view (step 3)

And the main advantages and disadvantages are identified in

Table 51.

Table 51 – Advantages and disadvantages

Advantages	Disadvantages
Allows an easy assembly	Hindered accessibility to the bolts. On 1:6 scale blind bolts can be applied (Figure 129)
Enables disassembly (flange to flange)	The connection between tower and flange is permanent
Half flange and half tower are a single part	Introduction of high stresses in the composite around the holes

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 140.

Figure 140 – Process chain

3.1.1.4. Flange Connection FibreFlex based – Option A

The idea for this concept came from the fibre-reinforced cable protection solution called FibreFlex™ [88] [89] (Figure 141). This high-performance protection system for subsea power cables in the offshore wind sector has a glass fibre lattice, which reinforces an elastomeric polyurethane matrix and mechanically locks into each segment's end stainless steel connectors [89].

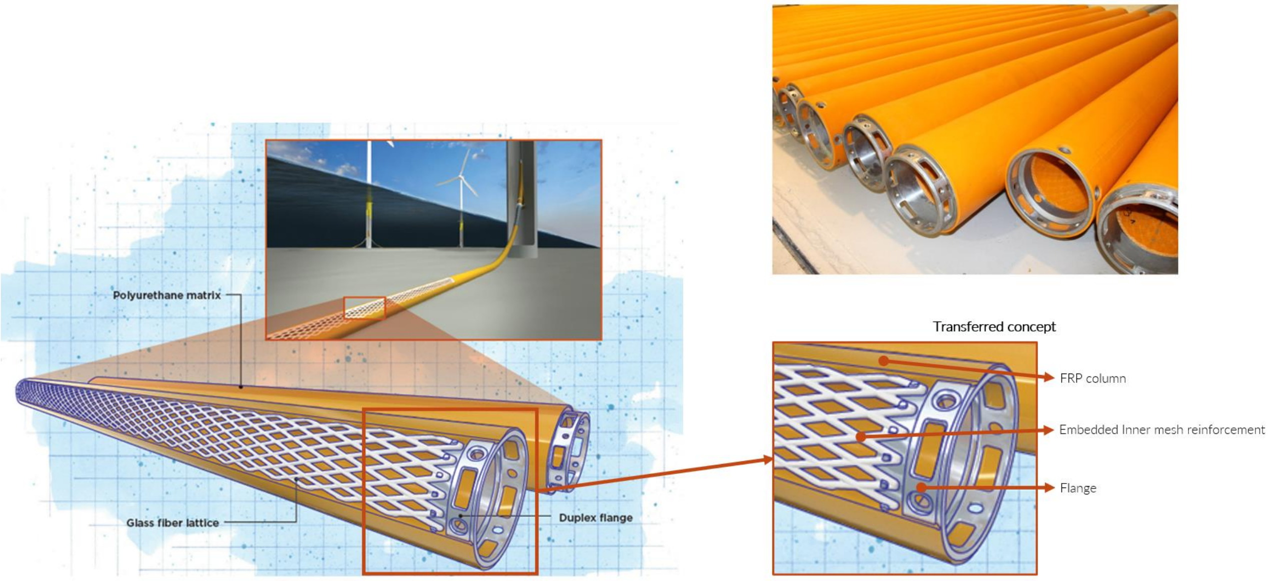


Figure 141 – FibreFlex™ cable protection system [88][89]

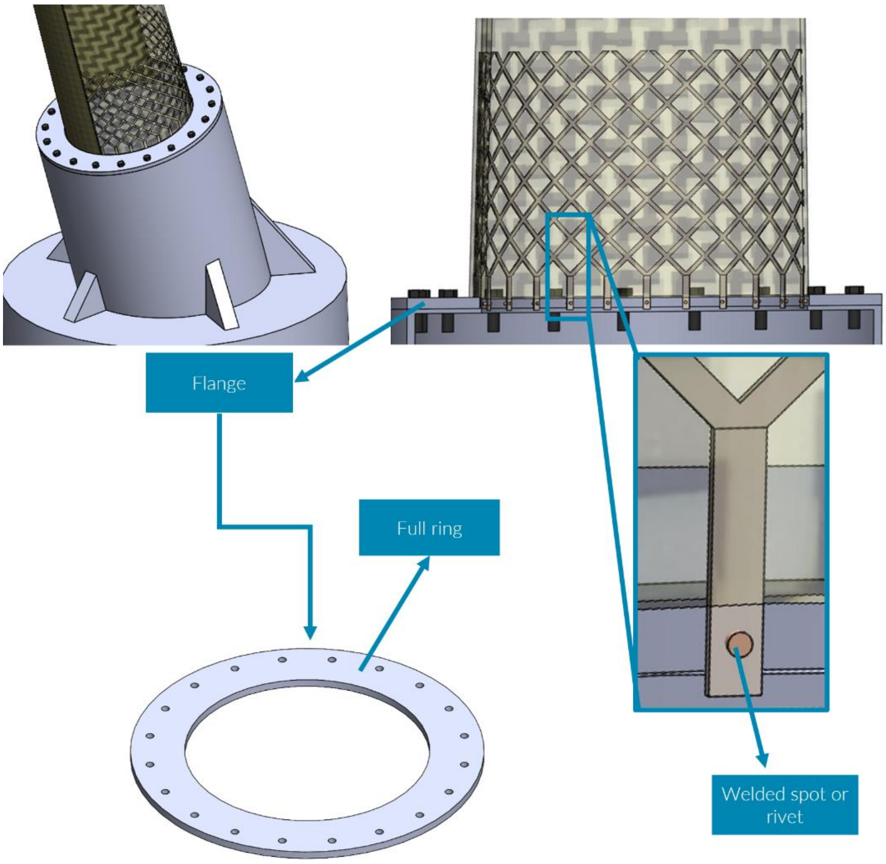


Figure 142 – Flange connection FibreFlex based (option C)

This concept is illustrated in Figure 142 and uses a FRP or steel ring to which the flange with reinforcing FRP lattice (welded or riveted) is bolted. The main advantages and disadvantages are identified in Table 52.

Table 52 – Advantages and disadvantages

Advantages	Disadvantages
Allows an easy assembly	Hindered accessibility to the bolts. On 1:6 scale blind bolts can be applied (Figure 129)
Enables disassembly (flange to flange)	The connection between the tower and flange is permanent
Tower is not subjected to high-stress concentration	Weight penalty (compared to previous flange solutions)
Potential to have better fatigue and creep performance	Need for extra joining technologies (welding or riveting)
Reinforcement of the connection area of the FRP tower	Different coefficients of thermal expansion (CTE)

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 143.

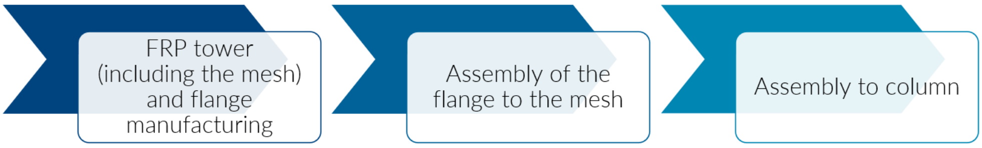


Figure 143 – Process chain

3.1.1.5. Flange Connection FibreFlex based – Option B

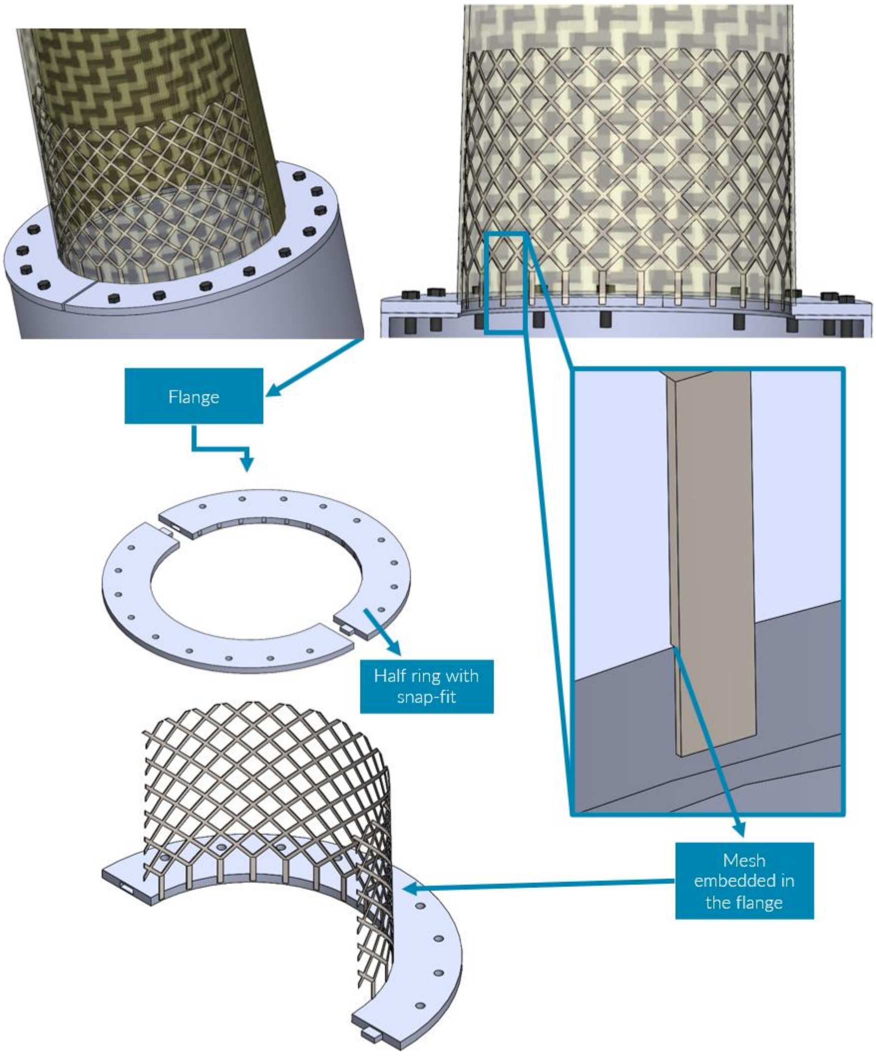


Figure 144 – Flange Connection FibreFlex based (option B)

This concept is illustrated in Figure 144 and uses two FRP or steel half-rings to which the flange with reinforcing FRP lattice (embedded in the flange) is bolted. The main advantages and disadvantages are identified in Table 53.

Table 53 – Advantages and disadvantages

Advantages	Disadvantages
Allows an easy assembly	Hindered accessibility to the bolts. On 1:6 scale blind bolts can be applied (Figure 129)
Enables disassembly (flange to flange)	Connection between the tower and flange is permanent
Tower is not subjected to high stress concentration	Weight penalty (compared to previous flange solutions)
Potential to have a better fatigue and creep performance	Need for fixtures or snap-fits to guarantee the correct position of the flange
Reinforcement of the connection area of the FRP tower	Different coefficients of thermal expansion (CTE)
Half flange and half tower are a single part	

A possible process chain for the manufacture and assembly using this concept is the one illustrated in Figure 145.

Figure 145 – Process chain

3.1.1.6. Sleeve Connection – Option A

This concept is illustrated in Figure 147 and consists of an internal steel sleeve and bolting the tower to the column/nacelle. The assembly is illustrated in Figure 148 to Figure 150.

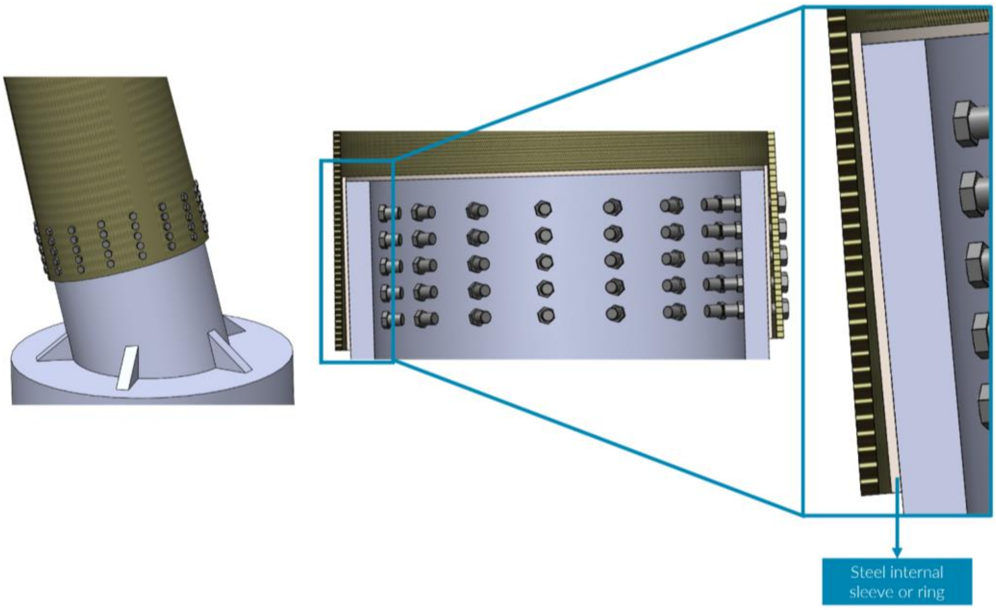


Figure 146 – Sleeve connection (option A)

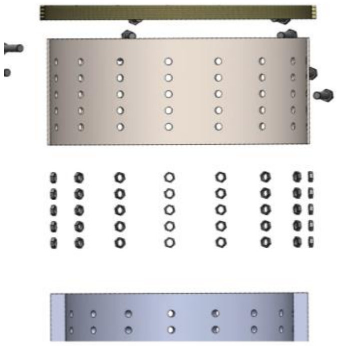


Figure 147 – Simplified assembly view (step 1)

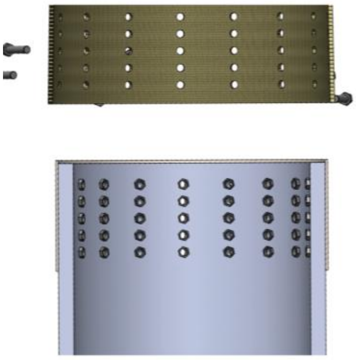


Figure 148 – Simplified assembly view (step 2)

Figure 149 – Simplified assembly view (step 3)

And the main advantages and disadvantages are identified in Table 54.

Table 54 – Advantages and disadvantages

Advantages	Disadvantages
Possible assembly on-site	Stress concentrations on the FRP tower (bolt holes)
Possible disassembly	Hindered accessibility to the bolts. On 1:6 scale blind bolts can be applied (Figure 129)
No adhesives	Dimension control of the inside surface of the tower
Easier to manufacture the ring versus the flange	Drilling and mounting alignment might be quite complicated
	Gap between metallic sleeve and the composite tower must be carefully controlled

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 150.

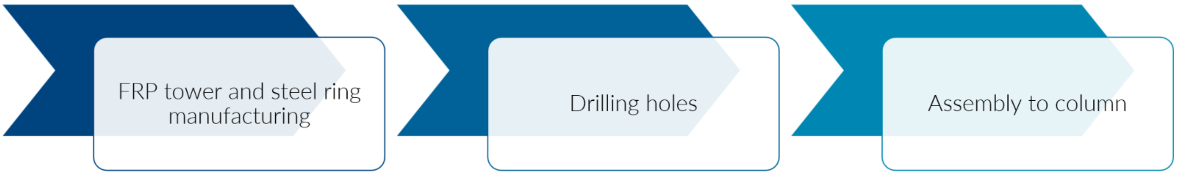


Figure 150 – Process chain

3.1.1.7. Sleeve Connection – Option B

This concept is illustrated in Figure 152 and consists of an internal and external steel sleeves and bolting the tower to the column/nacelle. The assembly is illustrated in Figure 153 to Figure 155.

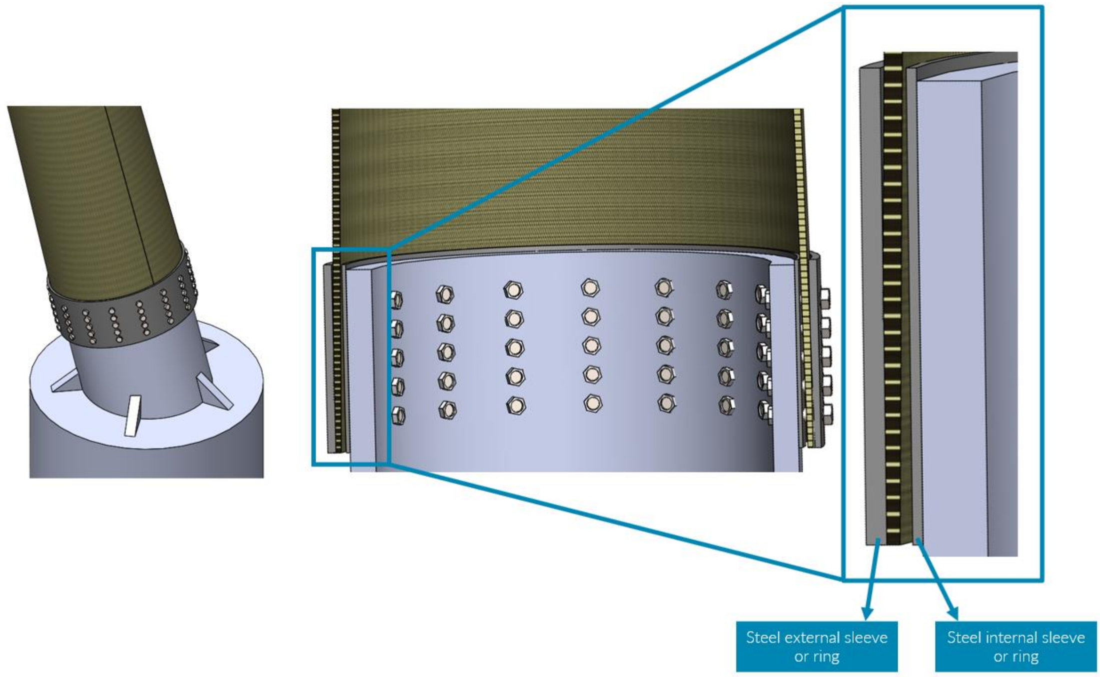


Figure 151 – Sleeve connection (option B)

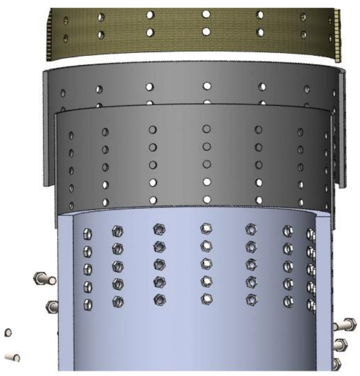


Figure 152 – Simplified assembly view (step 1)

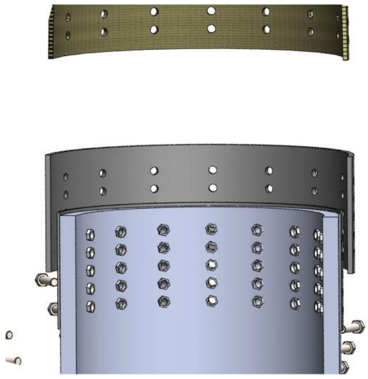


Figure 153 – Simplified assembly view (step 2)

Figure 154 – Simplified assembly view (step 3)

And the main advantages and disadvantages are identified in Table 55.

Table 55 – Advantages and disadvantages

Advantages	Disadvantages
Possible assembly on-site	Stress concentrations on the FRP tower (bolt holes)
Possible disassembly	Hindered accessibility to the bolts. On 1:6 scale blind bolts can be applied (Figure 129)
No adhesives	Dimension control of the inside surface of the tower
Easier to manufacture the ring versus the flange	Drilling and mounting alignment might be quite complicated
External sleeve helps distributing the stress concentration around the bolt holes	Gap between metallic sleeve and the composite tower must be carefully controlled

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 155.

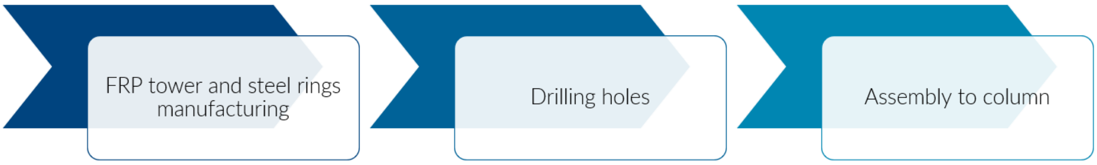


Figure 155 – Process chain

3.1.1.8. T-bolt or "IKEA" Connection

This concept, based on the T-bolts or "IKEA" connection commonly used to connect the wind blades to the hub, is illustrated in Figure 158. The assembly is illustrated in Figure 159 to Figure 161.

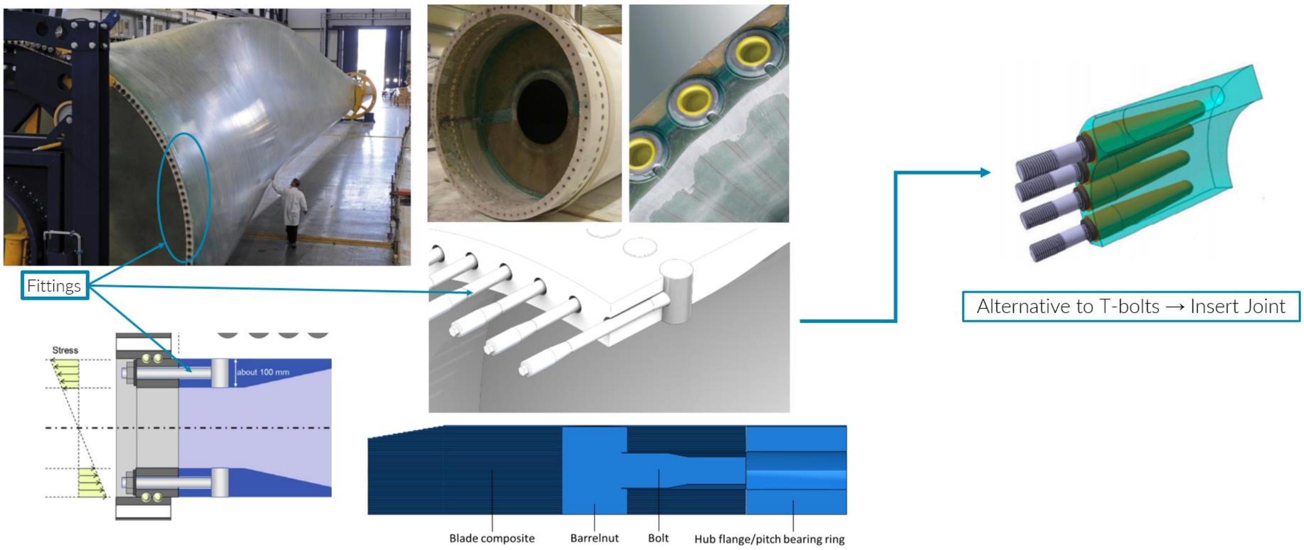


Figure 156 – T-bolts used to connect the blade to the hub

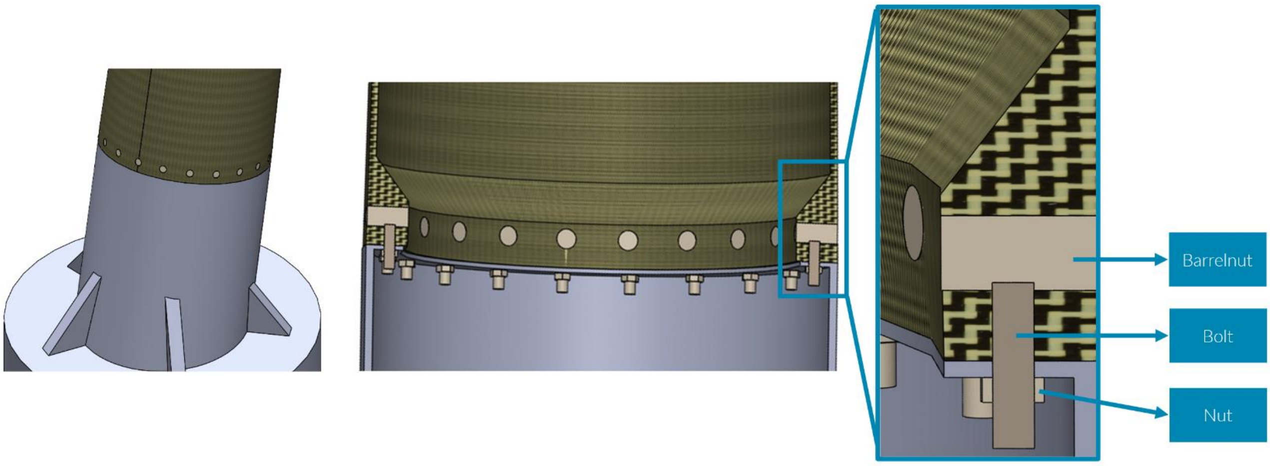


Figure 157 – T-bolt or "IKEA" connection

Figure 158 – Simplified assembly view (step 1)

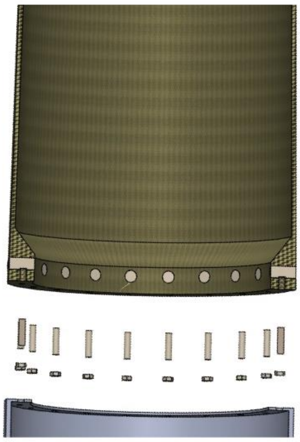


Figure 159 – Simplified assembly view (step 2)

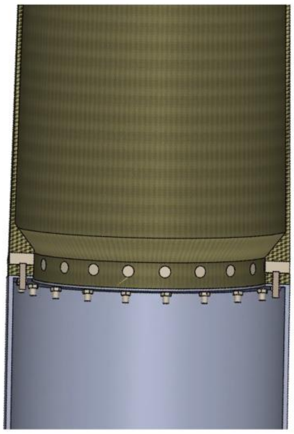


Figure 160 – Simplified assembly view (step 3)

And the main advantages and disadvantages are identified in Table 56.

Table 56 – Advantages and disadvantages

Advantages	Disadvantages
Possible assembly on-site	Increase of material usage in the connection area
Possible disassembly	Introduction of high stresses in the composite around the T-bolt
No adhesives	Hindered accessibility to the bolts. On 1:6 scale blind bolts can be applied (Figure 129)
The fittings can have different geometries (e.g. inserts)	Design parameters (bolt tension, barrelnut diameter, bearing strength, etc.) may be difficult to define
Weight savings in comparison with previous solutions	

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 161.

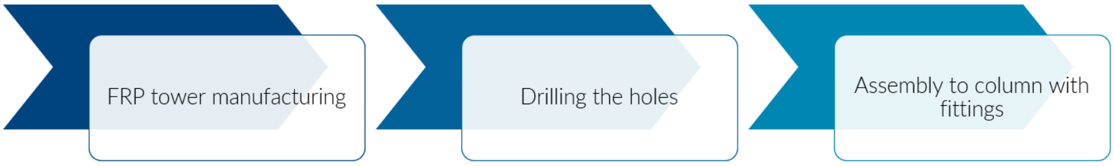


Figure 161 – Process chain

3.1.2. Tower to Tower Connection

As illustrated in Figure 162, this connection applies to the joining of the different modules of the tower.

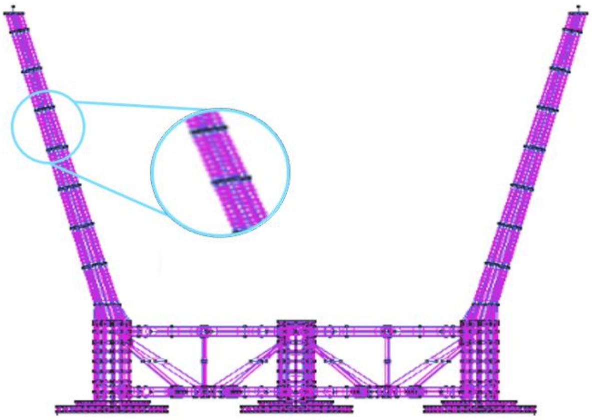


Figure 162 – Tower to tower connection

3.1.2.1. External Flange Connection

The first concept consists of an external flange connection (one in which module of the tower) and bolted together. As illustrated in Figure 163, and similarly to what was presented for the bottom and upper connections, the tower can be either placed outside of the flange (bonded), inside of the flange (bonded), or using the reinforcing lattice (welded or riveted as in the FibreFlex^{TM} concept).

Although it is a simple and effective way to connect the different parts of the FRP tower, it may not be recommendable as it can generate a disruption in the tower geometry and consequently affect aerodynamics.

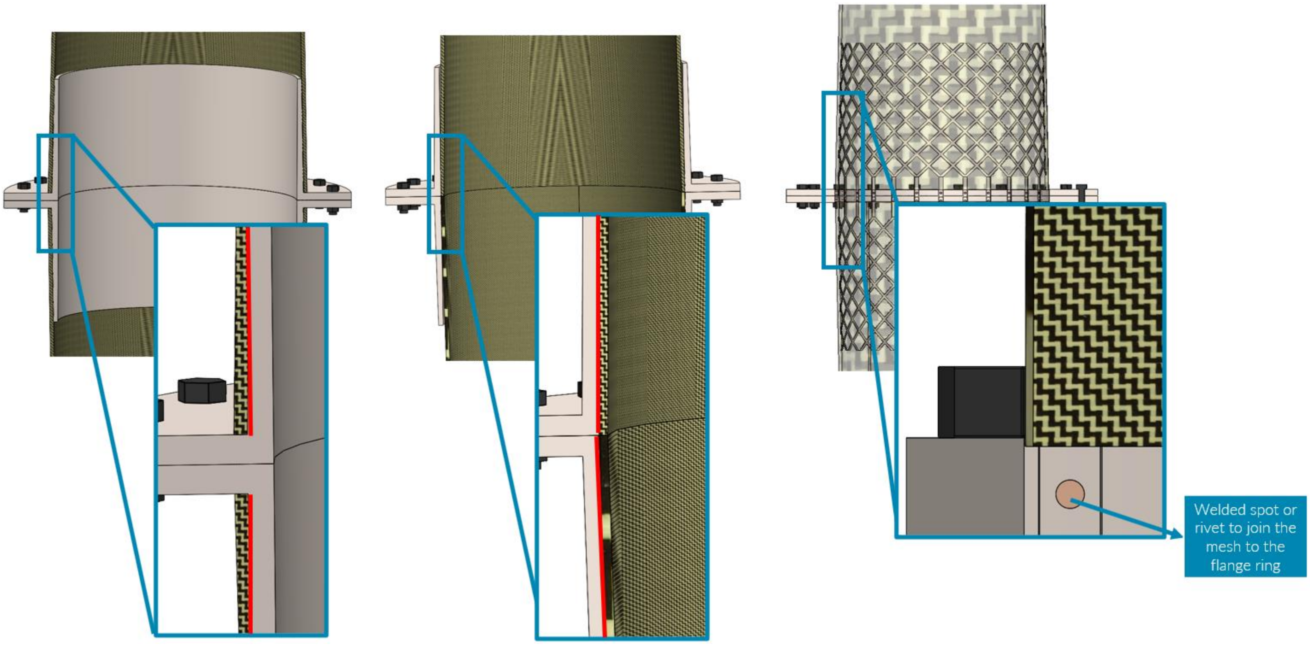


Figure 163 – External flange connection

3.1.2.2. Internal Flange Connection

On the other hand, an interior flange (Figure 164) can reduce the negative impact on aerodynamics. However, it is worth noting that the second option (in the middle of Figure 164, with part of the flange exposed) is much more susceptible to the effect of environmental conditions than the other solutions.

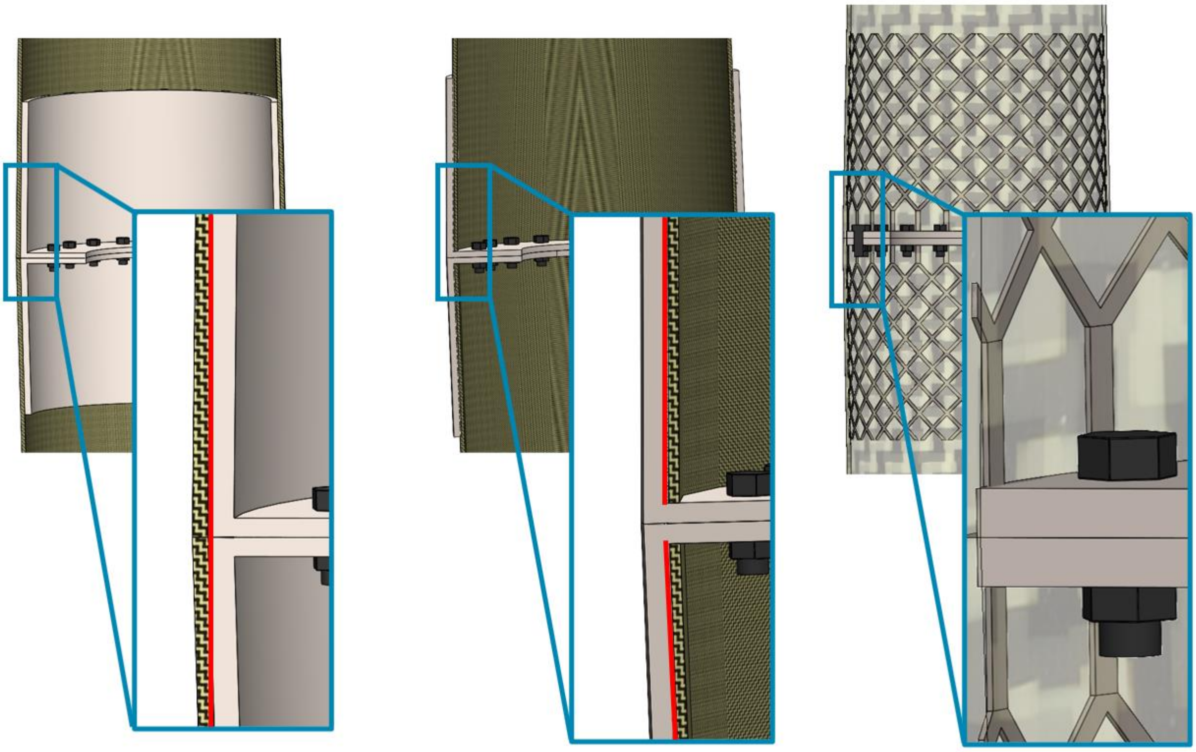


Figure 164 – Internal flange connection

3.1.2.3. Sleeve connection

A sleeve connection (Figure 165) can also be a good solution, however, it can lead to lower aerodynamic performance and cause visual impact.

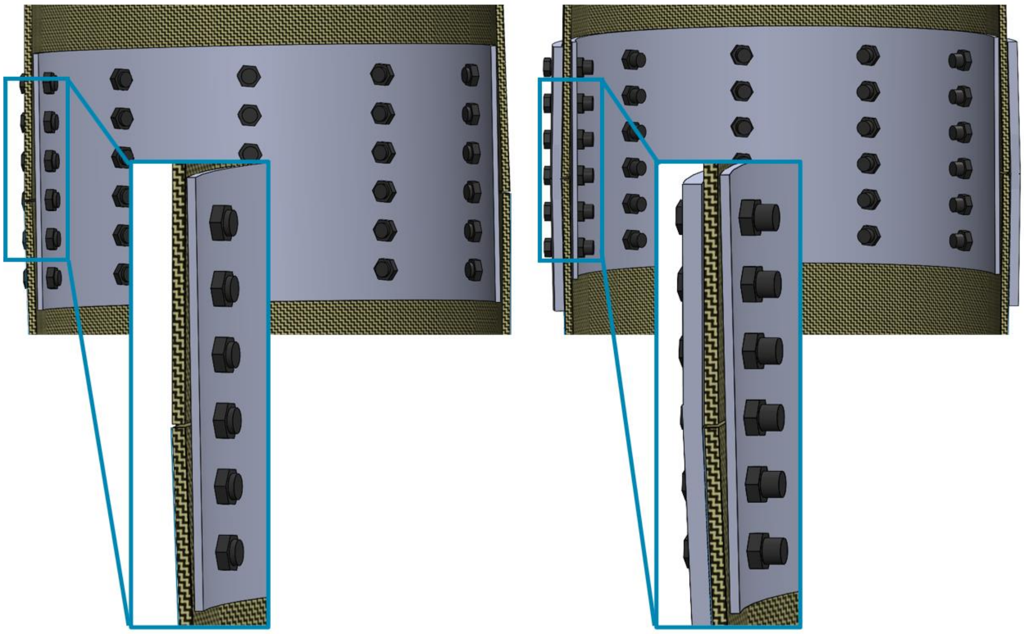


Figure 165 – Sleeve connection

3.1.2.4. Adhesively Bonded Connection

This concept is illustrated in Figure 167 and Figure 168 and consists in overlapping the tower modules (different diameters) and bonding them. The main advantages and disadvantages are identified in Table 57.

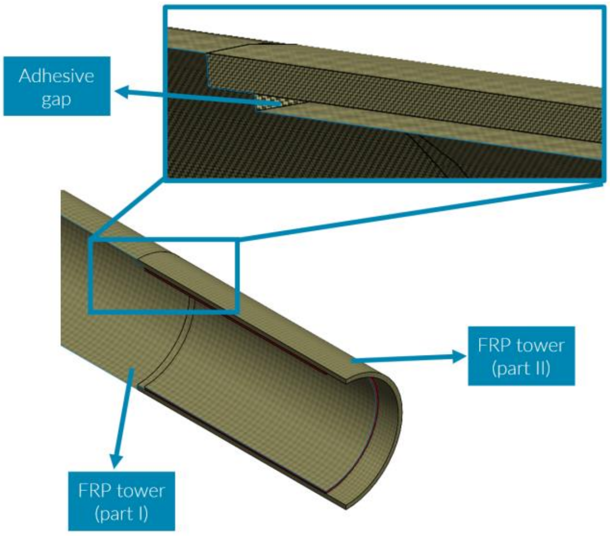


Figure 166 – Adhesively bonded connection

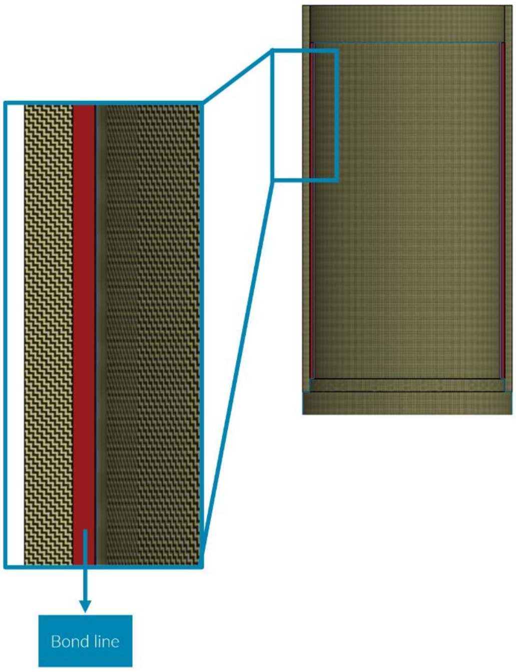


Figure 167 – Adhesively bonded connection (bondline)

Table 57 – Advantages and disadvantages

Advantages	Disadvantages
Tower is not subjected to high-stress concentration	Requires surface pre-treatment, fixtures, tools and a controlled environment
Weight savings in comparison with previous solutions	Impossible disassembly without damaging the structure
Better aerodynamics and hydrodynamics compared to previous solutions	Dimension control of the inside surface of the tower for adhesive bonding
	Exposure of the adhesive to environmental conditions

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 168.

Figure 168 – Process chain

And the most suitable adhesive families for this application are the ones mentioned in Figure 169.

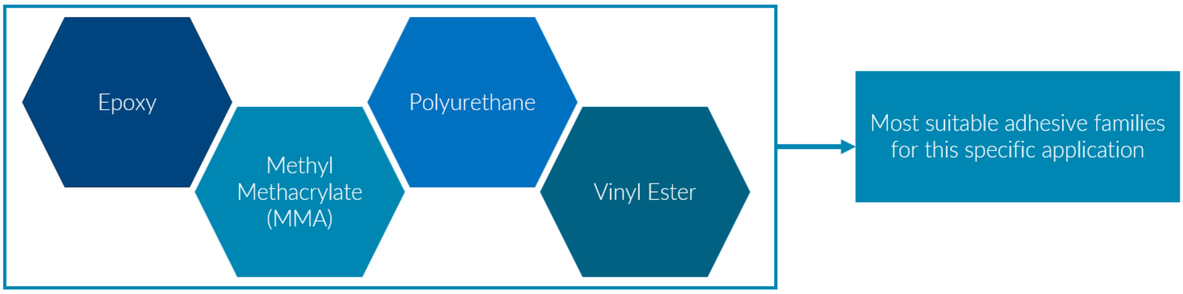


Figure 169 – Most suitable adhesive families

3.1.2.5. Hybrid Adhesively Bonded Connection

This concept, illustrated in Figure 171, is similar to the previous but besides bonding the tower modules, it also uses bolts that go through the adherends and the adhesive, acting as redundancy and giving extra strength, especially under peeling stresses. The main advantages and disadvantages are identified in Table 58.

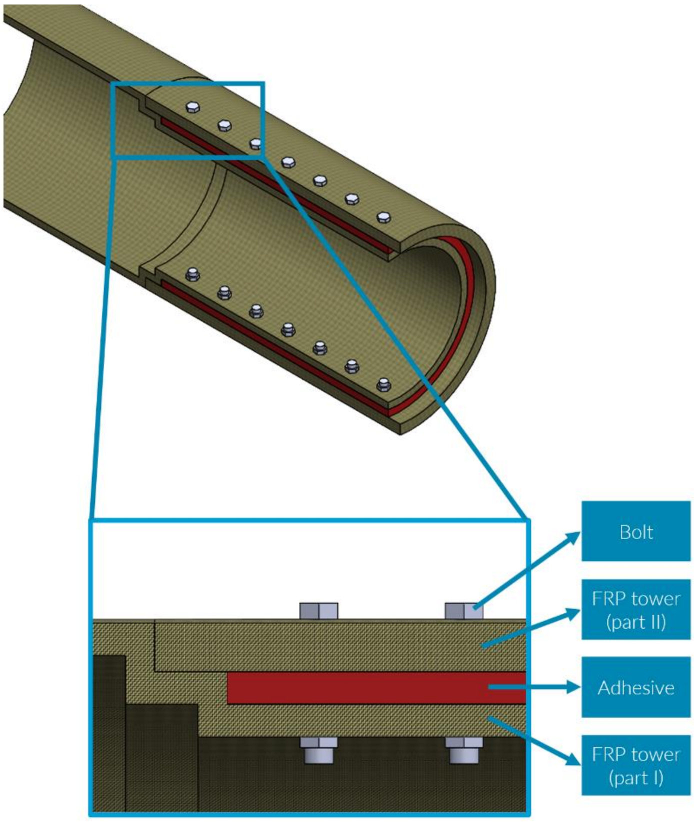


Figure 170 – Hybrid adhesively bonded connection

Table 58 – Advantages and disadvantages

Advantages	Disadvantages
Tower is not subjected to high-stress concentration	Requires surface pre-treatment, fixtures and tools
Allows an easy on-site assembly	Impossible disassembly without damaging the structure
Better mechanical properties, more stability and safety in comparison to the previous solution	Dimension control of the inside surface of the tower for adhesive bonding
	Exposure of the adhesive to environmental conditions
	Might be needed the use of a sleeve or insert in order to minimize the damage caused by the drilled holes in the composite
	Insertion of bolts must be carefully done in order to avoid the formation of air bubbles in the adhesive layer

A possible process chain for the manufacture and assembly using this concept is the one illustrated in Figure 171.

Figure 171 – Process chain

And the most suitable adhesive families for this application are again the ones mentioned in Figure 172.

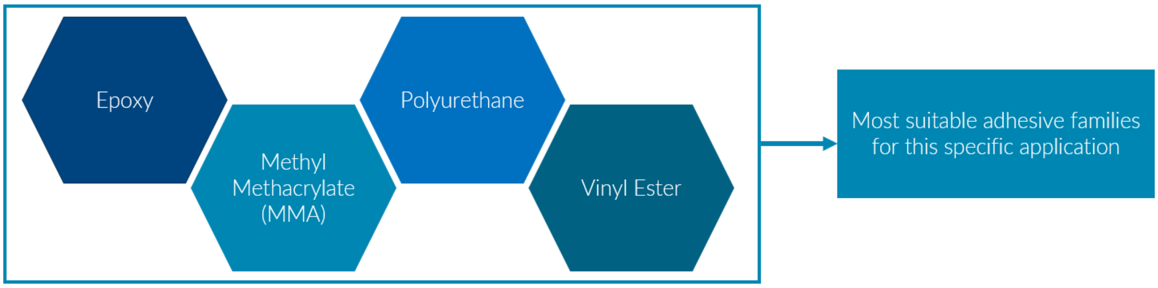


Figure 172 – Most suitable adhesive families

3.1.2.6. Slotted Connection – Option A

This concept is illustrated in Figure 174 and uses a slotted connection that is then bolted using bolts and nuts from the inside. The main advantages and disadvantages are identified in Table 59.

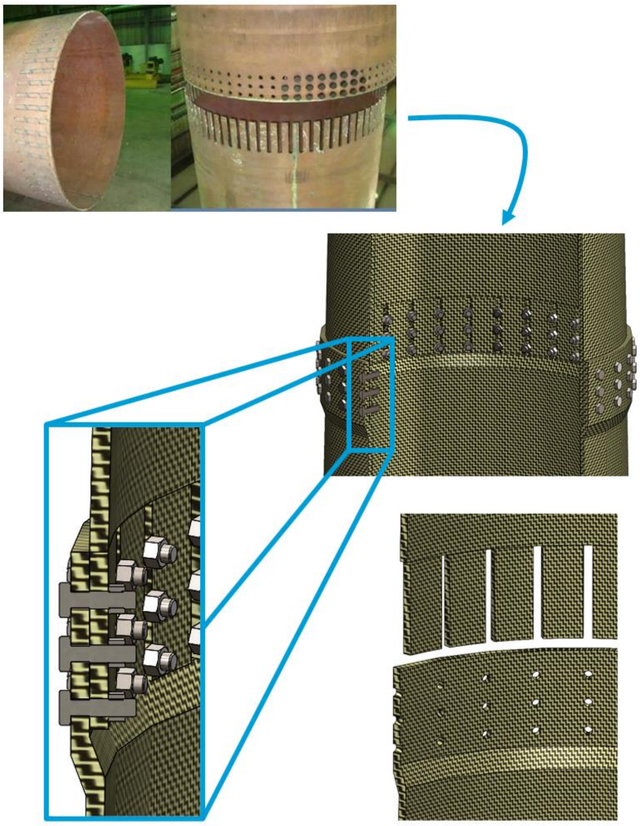


Figure 173 – Slotted connection (option A)

Table 59 – Advantages and disadvantages

Advantages	Disadvantages
No extra parts required	Poor load distribution in the area of the bolt
Allows an easy* on-site assembly	Bolt clamping will damage the composites part when bolted directly
Good aesthetics	Localized stress concentration
	Locking only by friction in the nut contact surface
	Bolts place in single shear
	Slotting the composite breaks fibre continuity and promotes crack formation and propagation

*Requires access from the inside to secure the nuts

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 174.

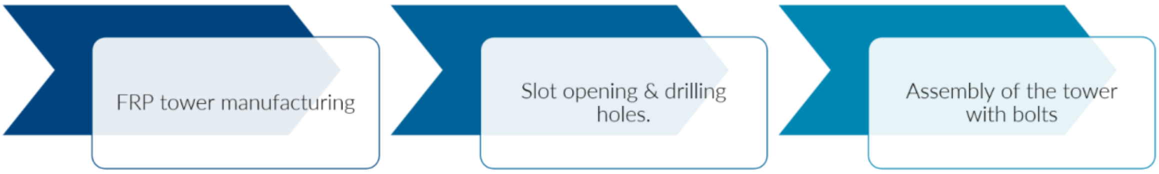


Figure 174 – Process chain

3.1.2.7. Slotted Connection – Option B

This concept, illustrated in Figure 176, is similar to the previous one and uses a slotted connection with clamping plates using bolts and nuts. The main advantages and disadvantages are identified in Table 60.

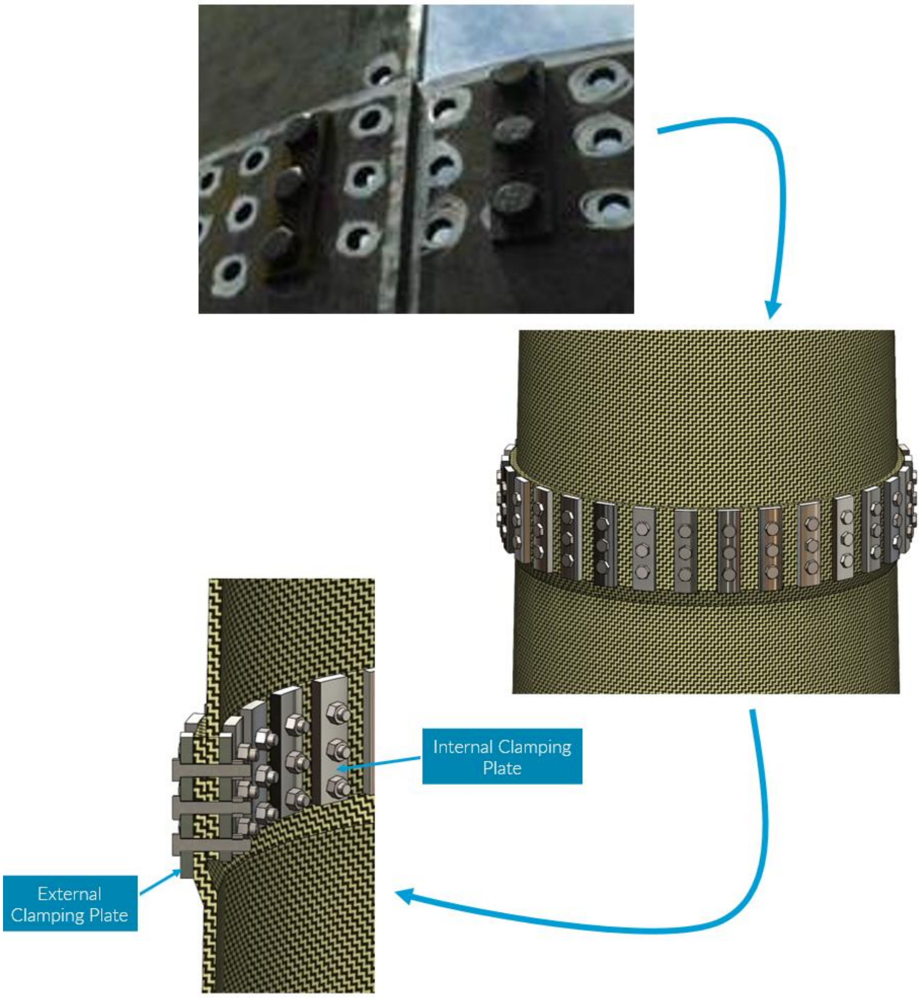


Figure 175 – Slotted connection (option B)

Table 60 – Advantages and disadvantages

Advantages	Disadvantages
No extra parts required	Poor load distribution in the bolts area
Allows an easy* on-site assembly	Bolt clamping will damage the composites part
	Localized stress concentration
	Bolts place in single shear
	Load transfer only by friction between composites
	Slotting the composite breaks fibre continuity and promotes crack formation and propagation

*Nuts welded to the internal clamping plate allow for easier installation than previous solution, but still requiring internal access for positioning.

A possible process chain for the manufacture and assembly using this concept is the one illustrated in Figure 176.

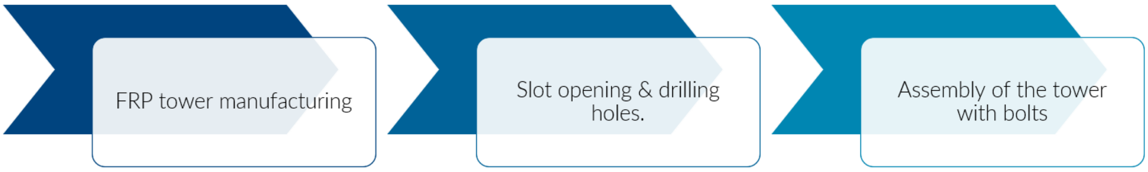


Figure 176 – Process chain

3.1.2.8. Slotted Connection w/ Sleeve – Option C

This concept is illustrated in Figure 178 and differs from the previous by also using a metallic sleeve (inner and outer) bonded to the tower. The main advantages and disadvantages are identified in Table 61.

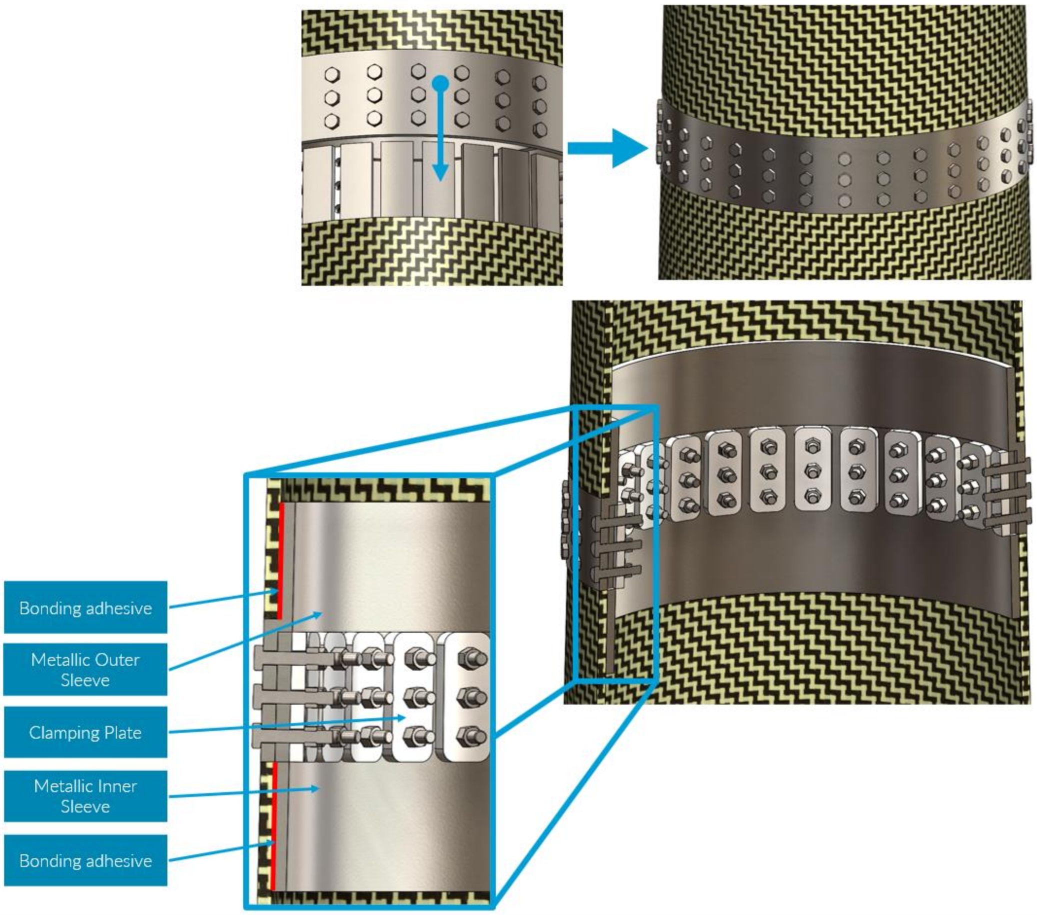


Figure 177 – Slotted connection with sleeve (option C)

Table 61 – Advantages and disadvantages

Advantages	Disadvantages
Allows an easy on-site assembly	Poor load distribution in the bolts area.
Good load distribution	Increased weight due to the metal sleeves
No damage caused by the bolts in the composite structure	Bolts place in single shear.
Improved aesthetics	Load transfer only by friction between the metallic sleeves
Simplified manufacture of the composite tower	Different coefficients of thermal expansion (CTE)

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 178.

Figure 178 – Process chain

3.1.3. Tube to Column Connection

As illustrated in Figure 179, this connection applies to the joining of the tubes to the columns.

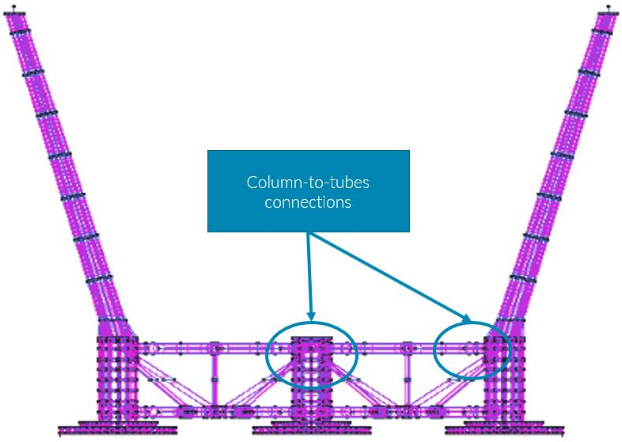


Figure 179 – Tube to column connection

3.1.3.1. Adapter Flange – Option A

This concept is illustrated in Figure 181 and uses an adapter flange bonded to the inside of the column; and the tube is bonded to the inside of the flange. The main advantages and disadvantages are identified in Table 62.

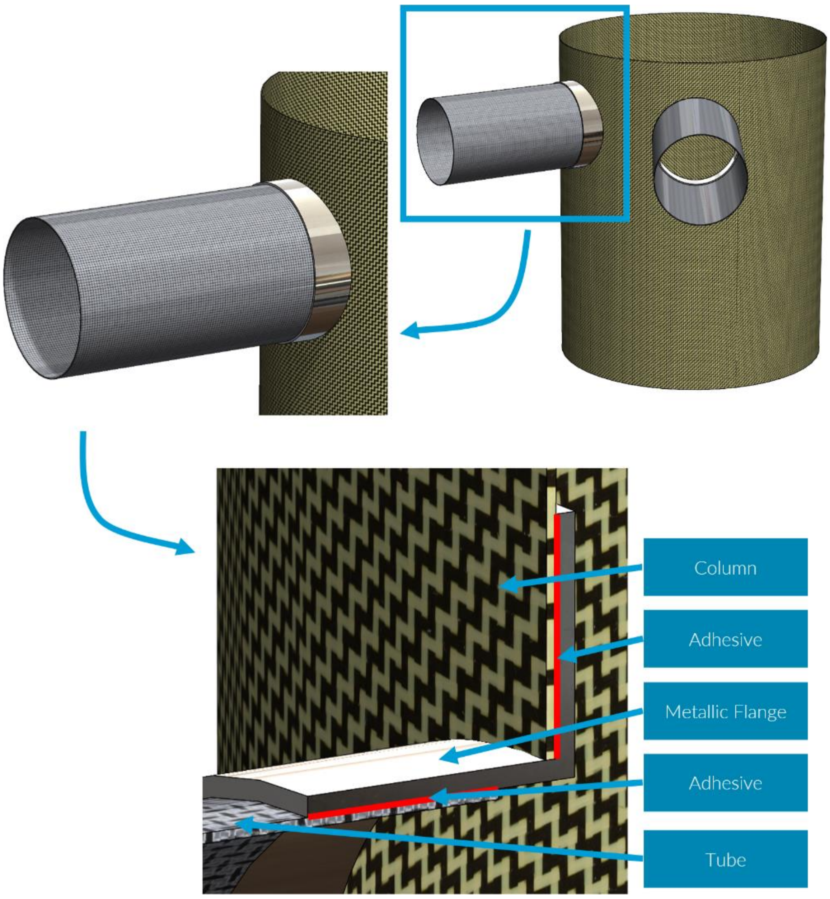


Figure 180 – Adapter flange (option A)

Table 62 – Advantages and disadvantages

Advantages	Disadvantages
No added weight (without bolts)	Impossible disassembly without damaging the structure
No stress concentration spots	Exposure of the adhesive to environmental conditions (mainly on the tube connection)
	Requires surface preparation on the connection areas
	For the vertical bonding flange: tensile load on the horizontal tube is not a problem, however compression will generate peel on bonding

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 181.

Figure 181 – Process chain

3.1.3.2. Adapter Flange – Option B

This concept is illustrated in Figure 183 and uses an adapter flange bonded to the inside of the column; and the tube is bonded to the outside of the flange. The main advantages and disadvantages are identified in Table 63.

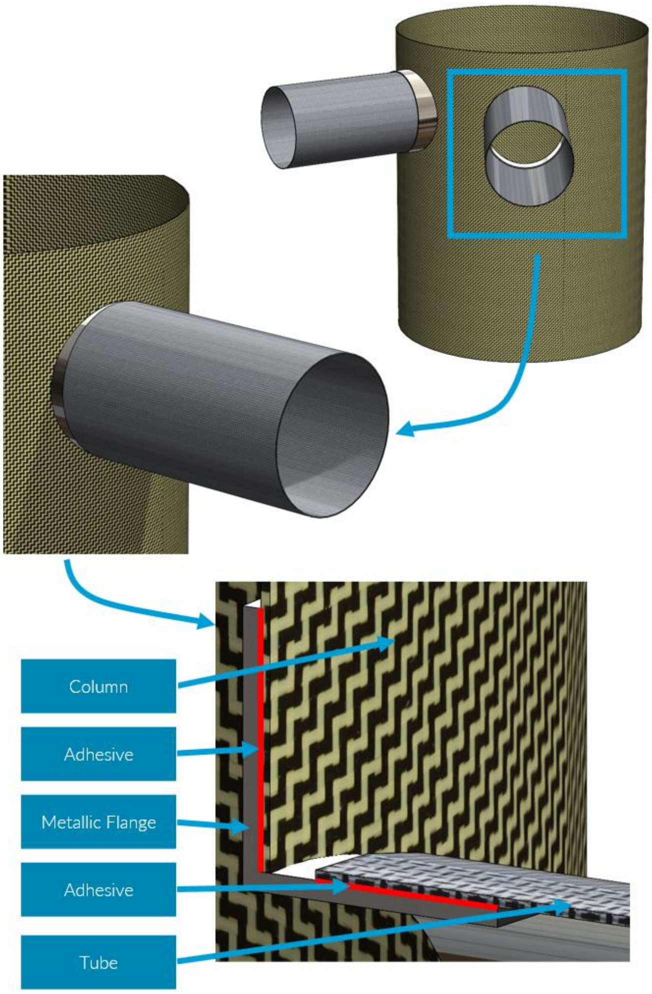


Figure 182 – Adapter flange (option B)

Table 63 – Advantages and disadvantages

Advantages	Disadvantages
No added weight (without bolts)	Impossible disassembly without damaging the structure
No stress concentration spots	Exposure of the adhesive to environmental conditions (mainly on the tube connection)
	Requires surface preparation on the connection areas
	For the vertical bonding flange: tensile load on the horizontal tube is not a problem, however compression will generate peel on bonding

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 183.

Figure 183 – Process chain

3.1.3.3. Overlamination – Option A

This concept is illustrated in Figure 185 and consists in overlaminating fibres between the tube and the column. Structural adhesive can be placed as a filler between the radius created by fibres bridging. The main advantages and disadvantages are identified in Table 64.

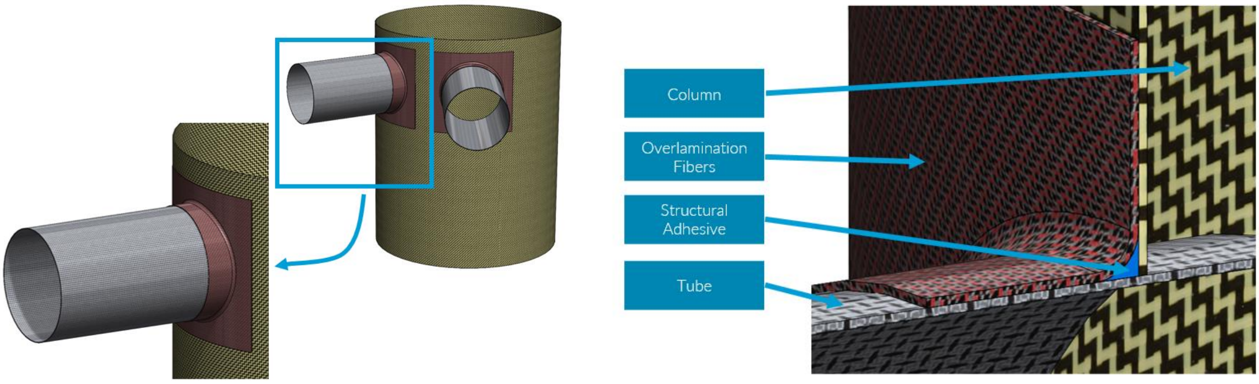


Figure 184 – Overlamination (option A)

Table 64 – Advantages and disadvantages

Advantages	Disadvantages
Structural continuity	Need for structural adhesive to fill the gap
Simple and less expensive moulds and tools	Possibility of air bubbles entrapment between layers
FRP products are not limited by size or shape	Final quality depends on the operator experience, environmental conditions and type of materials used
Proved success in the maritime and offshore industries	Specialized manual labour required
Applicability on-site	Without an inner laminate, peel effect might occur
Good load dispersion	

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 185.

Figure 185 – Process chain

3.1.3.4. Overlamination – Option B

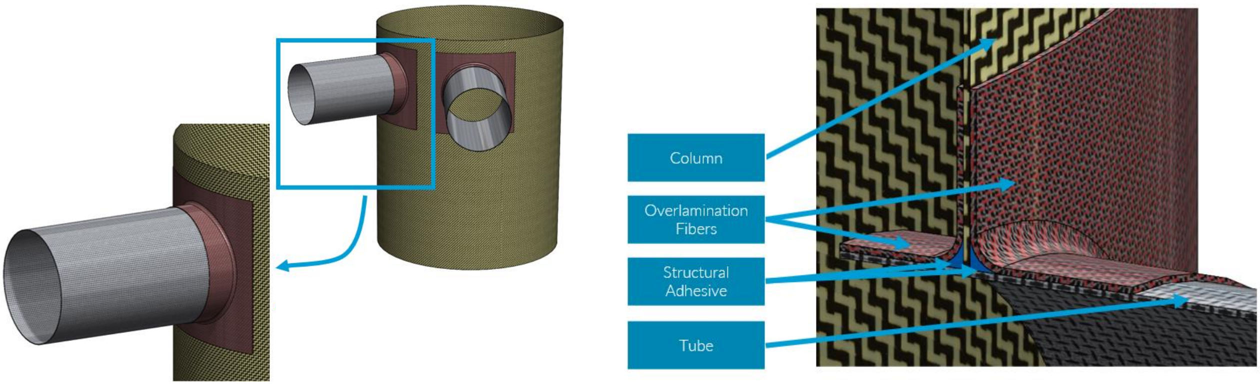


Figure 186 – Overlamination (option B)

This concept is illustrated in Figure 186 and differs from the previous by also overlaminating fibres on the inside of the column between the extension of the tube and the column, giving extra support and strength, especially under flexion of the tube. The main advantages and disadvantages are identified in

Table 65.

Table 65 – Advantages and disadvantages

Advantages	Disadvantages
Structural continuity	Need for structural adhesive to fill the gap
Simple and less expensive moulds and tools	Possibility of air bubbles entrapment between layers
FRP products are not limited by size or shape	Final quality depends on the operator experience, environmental conditions and type of materials used
Proved success in the maritime and offshore industries	Specialized manual labour required
Applicability on-site	Increased material usage
Improved load dispersion	

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 187.

Figure 187 – Process chain

3.1.4. Tube to Tube Connection

As illustrated in Figure 188, this connection applies to the between the tubes of the base structure.

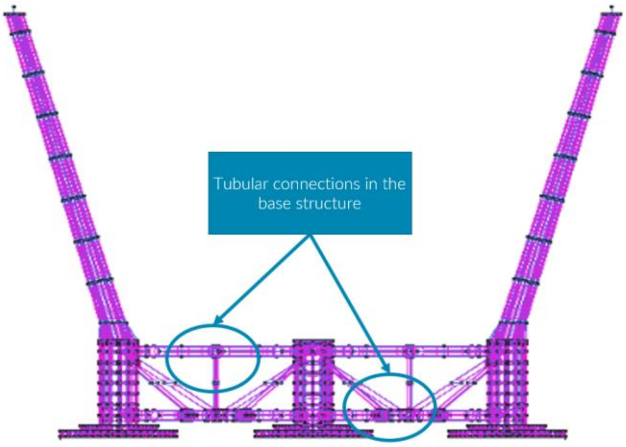


Figure 188 – Tube to tube connection

3.1.4.1. Hand Lay Up/Overlamination

This concept is illustrated in Figure 190 and consists of hand laying (overlaminating) a patch of fibre (prepreg or dried for posterior impregnation) around the tube. As before, the "empty" fillet radius can be filled with structural adhesive. A representation of the laid-up layers (scarfed for better stress distribution) is illustrated in Figure 191.

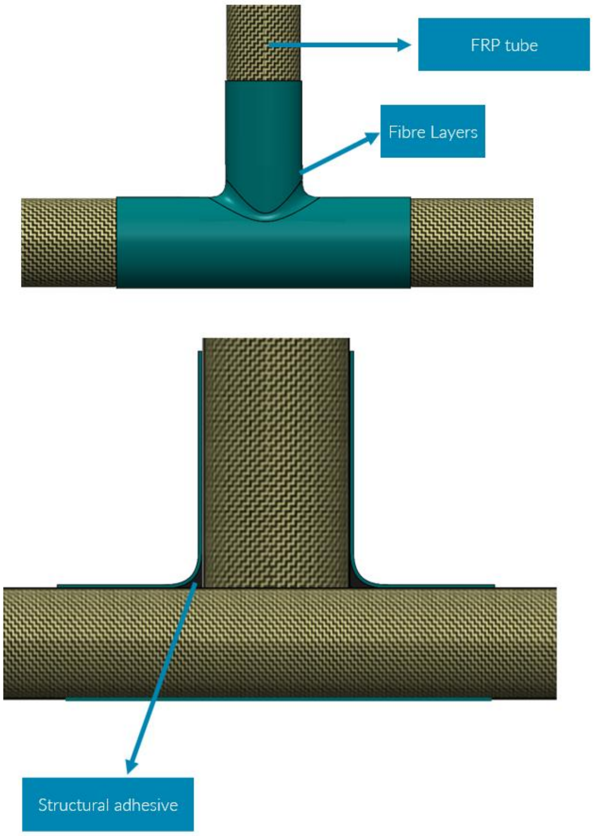


Figure 189 – Hand lay-up/overlamination

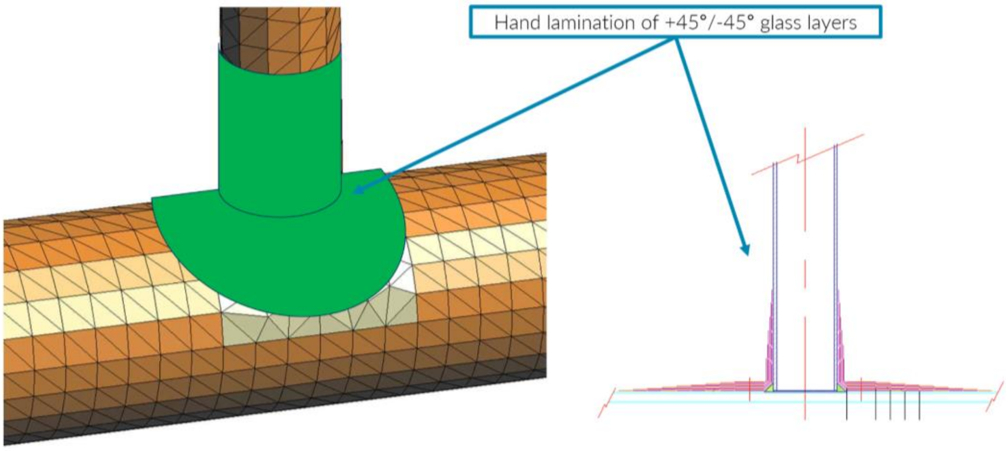


Figure 190 – Possible distribution of layers with scarfed layup

The main advantages and disadvantages are identified in Table 66.

Table 66 – Advantages and disadvantages

Advantages	Disadvantages
Structural continuity	Need for structural adhesive to fill the gap
Simple and less expensive moulds and tools	Possibility of air bubbles entrapment between layers
FRP products are not limited by size or shape	Final quality depends on the operator experience, environmental conditions and type of materials used
Proved success in the maritime and offshore industries	Depending on the applied loads, out of plane shear must be anticipated on the largest tube, if no reinforcement is provided in the smallest one
Applicability on-site	

A possible process chain for the manufacture and assembly using this concept is the one illustrated in Figure 191.

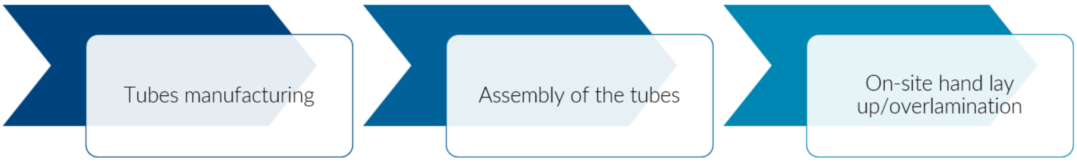


Figure 191 – Process chain

3.1.4.2. Filament Winding

This concept is illustrated in Figure 193 (as an example) and uses the process of filament winding to wound the fibres around the tubes. The main advantages and disadvantages are identified in Table 67.

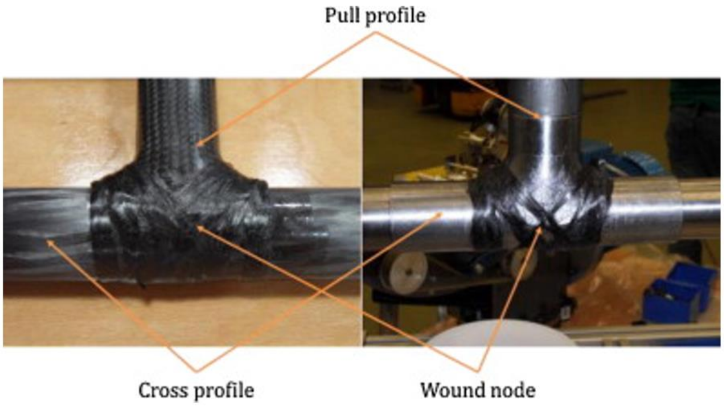


Figure 192 – Filament winding

Table 67 – Advantages and disadvantages

Advantages	Disadvantages
Automated process	Requires specific equipment
Resin content can be controlled	Poor external finishing
Very good mechanical properties can be achieved	Requires the use of low viscosity resin
	Alignment of the fibres can be difficult
	Limited by the dimensions of the equipment

A possible process chain for the manufacture and assembly using this concept is the one illustrated in Figure 193.

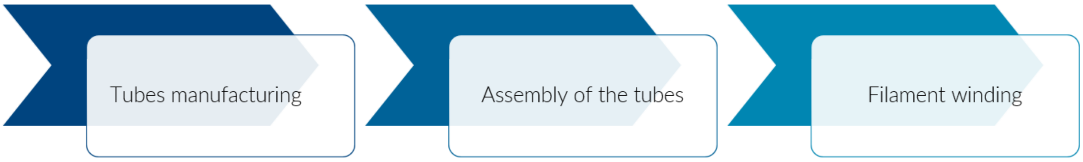


Figure 193 – Process chain

3.1.4.3. Sleeve Connection

This concept is illustrated in Figure 195 and uses a FRP or steel sleeve divided in two halves and bolted together. Additionally, adhesive can be put between the sleeve and the tubes. In case the sleeve is made in FRP, 90° angles (as illustrated) cannot be achieved and there will be a small radius. There are several examples of application of this type of connection in the literature [90], [91].

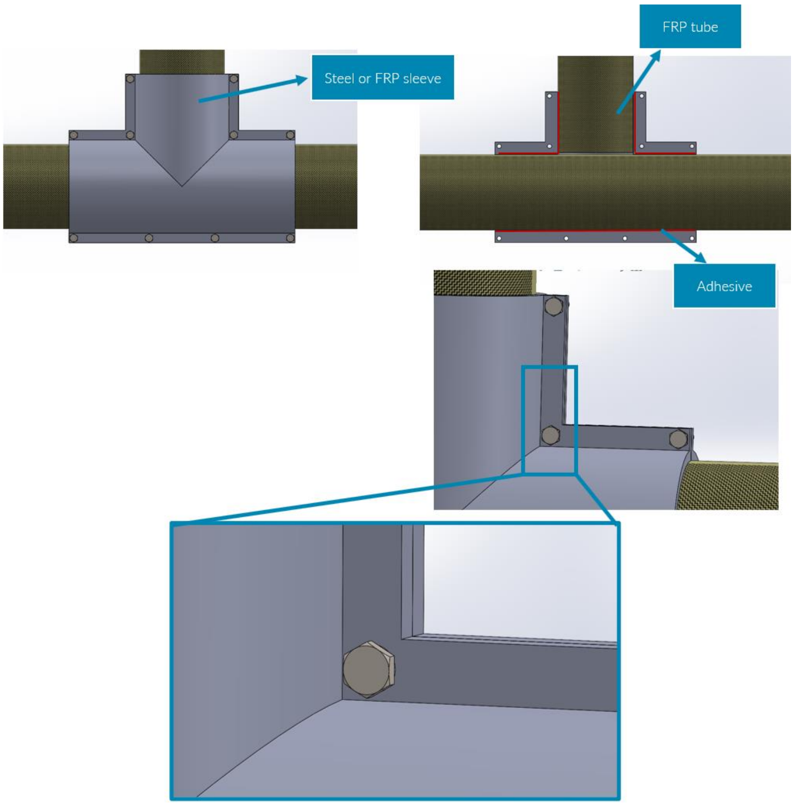


Figure 194 – Sleeve connection

The main advantages and disadvantages are identified in Table 68.

Table 68 – Advantages and disadvantages

Advantages	Disadvantages
Easy assembly	Requires surface pre-treatment, fixtures, tools and a controlled environment
The adhesive layer is more protected from the harsh environment	Impossible disassembly without damaging the structure, unless a reversible adhesive is used

A possible process chain for the manufacture and assembly using this concept is the one illustrated in Figure 195.

Figure 195 – Process chain

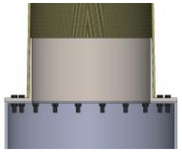
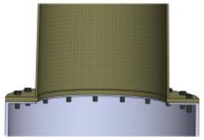
3.1.5. Selection matrix

All of the previously presented concepts were evaluated using a selection matrix in order to select the most suitable one for each application. The following parameters were considered and weighted: Manufacturing complexity (13%); Enables the use of coatings (8%); Ease of assembly on-site (automation of assembly and accessibility) (10%); Portability (2%); Ease of disassembly/replacement (10%); Structural efficiency (9%); Stress concentration (10%); Fatigue life (12%); Resistance to environmental conditions (5%); Visual Impact (2%); Aerodynamics (2%); Potential to apply the solution on larger scales (10%); Cost and availability (5%); Weight penalty (2%).

The final matrices can be seen in the next pages and were made for both the real scale and prototype (scale 1:6) demonstrators for the top and bottom connections of the tower. Since only the tower will be built on a prototype-scale, only the real scale was evaluated for the other group of connections (tower to tower, tube to column and tube to tube).

3.1.5.1. Top and Bottom Tower Connections (Real Scale)

Fibregy
Task 2.3. Connections in OWTP Platforms (Subtask 2.3.2.)

			Solutions for connections to be potentially applied in the tower of the W2Power Demonstrator						
			Flange Joint - Option A	**Flange Joint - Option B**	**Flange Joint - Option C**	**Flange Joint - Fibreflex**	**Sleeve Joint - Option A**	**Sleeve Joint -Option B**	**T-bolt or "IKEA" Connection**
			#1	#2	#3	#4	#5	#6	#7
	Parameters	**Weightning**							
🟩	Manufacturing complexity	**13%**	**3**	**3**	**3**	**2**	**4**	**4**	**4**
🟨	Enables the use of coatings	**8%**	**3**	**3**	**3**	**5**	**4**	**4**	**5**
	Ease of assembly on-site (automation of assembly and accessibility)	**10%**	**3**	**3**	**4**	**2**	**2**	**2**	**3**
	Portability	**2%**	**3**	**3**	**3**	**2**	**3**	**3**	**3**
	Ease of disassembly / replacement	**10%**	**4**	**4**	**4**	**2**	**4**	**4**	**4**
🟥	Structural efficiency	**9%**	**3**	**3**	**4**	**3**	**4**	**4**	**4**
	Stress concentration	**10%**	**4**	**4**	**4**	**3**	**3**	**3**	**4**
	Fatigue life	**12%**	**4**	**4**	**4**	**3**	**4**	**4**	**4**
	Resistance to environmental conditions	**5%**	**3**	**4**	**4**	**4**	**3**	**3**	**3**
	Visual Impact	**2%**	**3**	**4**	**4**	**4**	**4**	**4**	**5**
	Aerodynamics	**2%**	**2**	**2**	**2**	**3**	**3**	**3**	**5**
⬜	Potential to apply the solution on larger scales	**10%**	**4**	**4**	**3**	**2**	**4**	**4**	**5**
	Cost and availability	**5%**	**4**	**4**	**3**	**2**	**4**	**3**	**5**
	Weight penalty	**2%**	**3**	**3**	**4**	**3**	**4**	**4**	**4**
	Final score		**3.45**	**3.52**	**3.58**	**2.73**	**3.61**	**3.56**	**4.10**
		100%							Real scale

Relevance levels

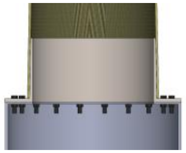
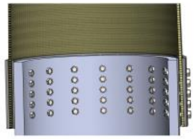
Manufacturing	13%
Assembly	30%
In-Situ Application	40%
Others	17%

100%	1	2	3	4	5
	Extremely bad	Bad	Fair	Good	Excellent

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

3.1.5.2. Top and Bottom Tower Connections (Prototype Scale)

Fibregy
Task 2.3. Connections in OWTP Platforms (Subtask 2.3.2.)

			Solutions for connections to be potentially applied in the tower of the W2Power Demonstrator						
			Flange Joint - Option A	Flange Joint - Option B	Flange Joint - Option C	Flange Joint - Fibreflex	Sleeve Joint - Option A	Sleeve Joint -Option B	T-bolt or "IKEA" Connection
			#1	#2	#3	#4	#5	#6	#7
	Parameters	**Weightning**							
🟩	Manufacturing complexity	13%	3	3	3	2	4	4	2
🟨	Enables the use of coatings	8%	3	3	3	5	4	4	5
	Ease of assembly on-site (automation of assembly and accessibility)	10%	3	3	4	2	3	3	3
	Portability	2%	3	3	3	2	3	3	2
	Ease of disassembly / replacement	10%	4	4	4	2	4	4	3
🟥	Structural efficiency	9%	3	3	4	3	4	4	4
	Stress concentration	10%	4	4	4	3	3	3	4
	Fatigue life	12%	4	4	4	3	4	4	4
	Resistance to environmental conditions	5%	3	4	4	4	3	3	3
	Visual Impact	2%	3	4	4	4	4	4	5
	Aerodynamics	2%	2	2	2	3	3	3	5
▨	Potential to apply the solution on larger scales	10%	4	4	3	2	4	4	5
	Cost and availability	5%	4	4	3	2	4	3	3
	Weight penalty	2%	3	3	4	3	4	4	4
	Final score		**3.45**	**3.52**	**3.58**	**2.73**	**3.71**	**3.66**	**3.62**
		100%					Prototype		

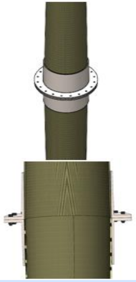
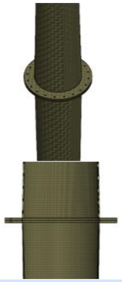
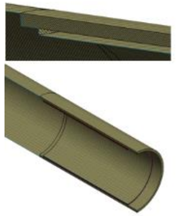
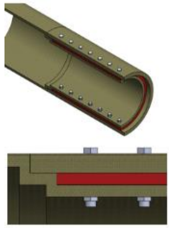
Relevance levels

🟩 Manufacturing	13%
🟨 Assembly	30%
🟥 In-Situ Application	40%
▨ Others	17%

100%	1	2	3	4	5
	Extremely bad	Bad	Fair	Good	Excellent

3.1.5.3. Tower to Tower Connection (Real Scale)

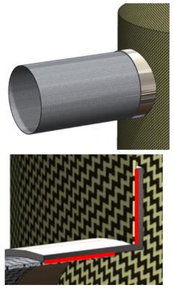
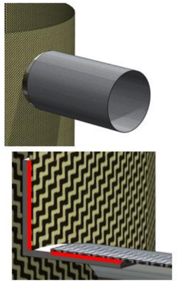
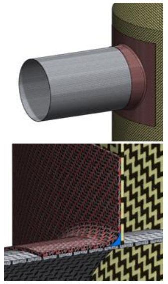
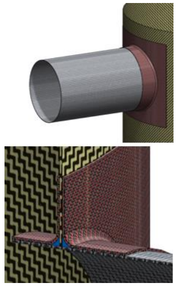
Fibregy
Task 2.3. Connections in OWTP Platforms (Subtask 2.3.2.)

			Solutions for connections to be potentially applied in the tower of the W2Power Demonstrator								
			Flange Joint - Option A	Flange Joint - Option B	Flange Joint - Option C	Flange Joint - Fibreflex	Bonded Joint - Option A	Bonded Joint - Option B	Slotted Joint - Option A	Slotted Joint - Option B	Slotted Joint - Option C
			#1	#2	#3	#4	#5	#6	#7	#8	#9
	Parameters	Weightning									
🟩	Manufacturing complexity	13%	3	3	2	2	4	4	2	2	2
🟨	Enables the use of coatings	8%	3	3	3	3	5	5	3	3	3
	Ease of assembly on-site (automation of assembly and accessibility)	10%	4	4	4	3	2	2	4	4	4
	Portability	2%	4	4	4	3	3	3	3	3	3
	Ease of disassembly / replacement	10%	5	5	5	4	2	2	3	3	3
🟥	Structural efficiency	9%	2	2	3	2	4	5	3	3	3
	Stress concentration	10%	3	3	4	3	5	5	3	3	3
	Fatigue life	12%	3	3	3	3	4	5	3	3	3
	Resistance to environmental conditions	5%	4	4	4	3	4	4	3	3	3
	Visual Impact	2%	3	2	3	3	5	4	2	1	2
	Aerodynamics	2%	3	3	3	3	5	5	3	3	3
⬛	Potential to apply the solution on larger scales	10%	4	4	4	3	5	5	4	4	4
	Cost and availability	5%	4	4	3	2	4	4	4	3	4
	Weight penalty	2%	3	3	4	3	4	4	3	3	2
	Final score		3.43	3.41	3.46	2.83	3.90	4.09	3.10	3.03	3.08
		100%						Real Scale (Prototype does not need this connection)			

Relevance levels

🟩 Manufacturing	13%	100%	1	2	3	4	5
🟨 Assembly	30%		Extremely bad	Bad	Fair	Good	Excellent
🟥 In-Situ Application	40%						
⬛ Others	17%						

3.1.5.4. Tube to Column Connection (Real Scale)

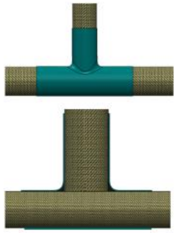
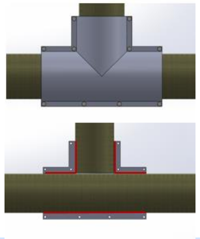
	Fibregy **Task 2.3. Connections in OWTP Platforms (Subtask 2.3.2.)**		**Solutions for connections to be potentially applied in the tower of the W2Power Demonstrator**			
			Adapter Flange - Option A	**Adapter Flange - Option B**	**Overlamination - Option A**	**Overlamination - Option B**
			#1	#2	#3	#4
	Parameters	**Weightning**				
🟩	Manufacturing complexity	**13%**	**4**	**4**	**3**	**3**
🟨	Enables the use of coatings	**8%**	**4**	**4**	**4**	**4**
	Ease of assembly on-site (automation of assembly and accessibility)	**10%**	**3**	**3**	**3**	**3**
	Portability	**2%**	**3**	**3**	**3**	**3**
	Ease of disassembly / replacement	**10%**	**2**	**2**	**2**	**2**
🟥	Structural efficiency	**9%**	**2**	**2**	**3**	**4**
	Stress concentration	**10%**	**2**	**2**	**3**	**4**
	Fatigue life	**12%**	**2**	**2**	**4**	**4**
	Resistance to environmental conditions	**5%**	**3**	**3**	**3**	**3**
	Visual Impact	**2%**	**2**	**2**	**4**	**4**
	Aerodynamics	**2%**	**4**	**4**	**4**	**4**
⬜	Potential to apply the solution on larger scales	**10%**	**4**	**4**	**4**	**4**
	Cost and availability	**5%**	**4**	**4**	**3**	**3**
	Weight penalty	**2%**	**4**	**4**	**4**	**4**
	Final score		**2.97**	**2.97**	**3.26**	**3.45**
		100%				Prototype and Real Scale

Relevance levels

🟩 Manufacturing	13%
🟨 Assembly	30%
🟥 In-Situ Application	40%
⬜ Others	17%

100%	1	2	3	4	5
	Extremely bad	Bad	Fair	Good	Excellent

3.1.5.5. Tube to Tube Connection (Real Scale)

	Fibregy **Task 2.3. Connections in OWTP Platforms (Subtask 2.3.2.)**		**Solutions for connections to be potentially applied in the tower of the W2Power Demonstrator**	
			Hand Lay up	**Sleeve Joint**
			#1	**#2**
	Parameters	**Weightning**		
🟩	Manufacturing complexity	**13%**	**4**	**2**
🟨	Enables the use of coatings	**8%**	**4**	**3**
	Ease of assembly on-site (automation of assembly and accessibility)	**10%**	**3**	**5**
	Portability	**2%**	**2**	**4**
	Ease of disassembly / replacement	**10%**	**3**	**4**
🟥	Structural efficiency	**9%**	**4**	**2**
	Stress concentration	**10%**	**4**	**2**
	Fatigue life	**12%**	**4**	**2**
	Resistance to environmental conditions	**5%**	**5**	**3**
	Visual Impact	**2%**	**5**	**2**
	Aerodynamics	**2%**	**4**	**3**
⬛	Potential to apply the solution on larger scales	**10%**	**4**	**3**
	Cost and availability	**5%**	**3**	**4**
	Weight penalty	**2%**	**4**	**3**
	Final score		**3.78**	**2.91**
		100%	Prototype and Real Scale	

Relevance levels

🟩 Manufacturing	13%
🟨 Assembly	30%
🟥 In-Situ Application	40%
⬛ Others	17%

100%	1	2	3	4	5
	Extremely bad	Bad	Fair	Good	Excellent

3.2. Tidal Turbine Housing

From the analysis of the complete **Tidal Turbine Housing** it was possible to identify the main associated connection (Figure 196):

1. Main Body to AFT Cover;

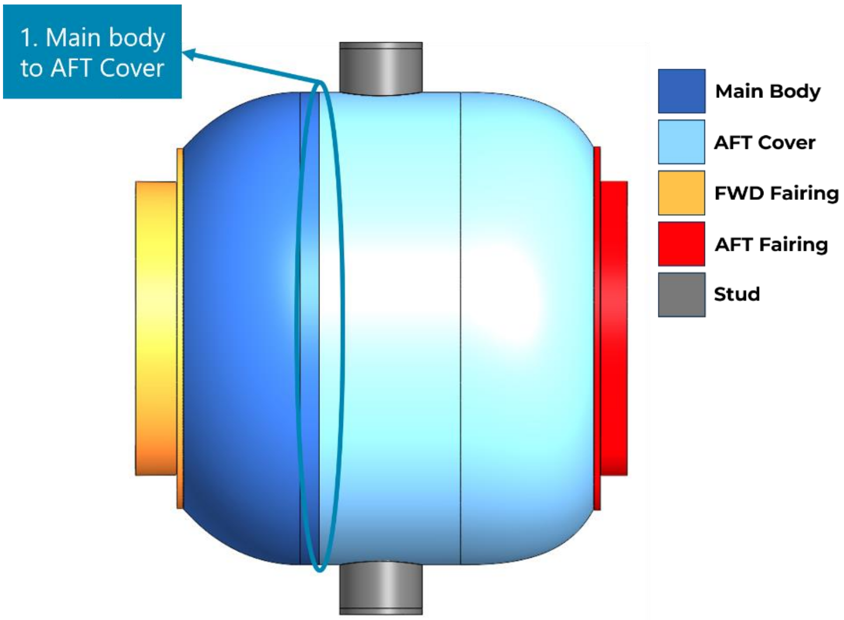


Figure 196 – Tidal Turbine Housing connection group

The Main Body and AFT Cover will be made by Towpreg Winding from a single-cylinder piece that will be cut into these two parts represented by two different shades of blue.

The main dimensions for real scale and demonstrator of both the turbine and turbine housing are identified in Table 69.

Table 69 – Main dimensions for the turbine and turbine housing

	Ø of the housing	Length of the housing
Demonstrator	790 mm	750.98 mm

In the following sections, follows some possible solutions for this connection of the Main Body to the AFT Cover, as well as a proposed assembly and manufacturing sequence for each and its respective advantages and disadvantages.

3.2.1. External Flange with outside placement

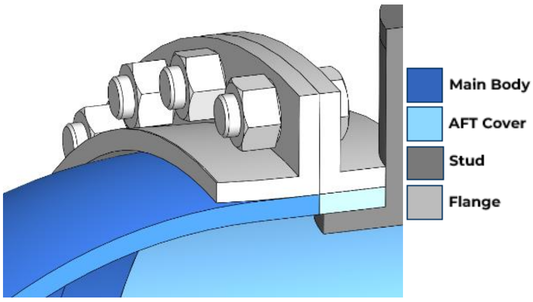


Figure 197 – External flange connection

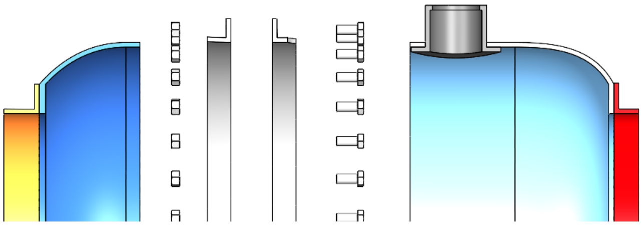


Figure 198 – Simplified Assembly view (step 1)

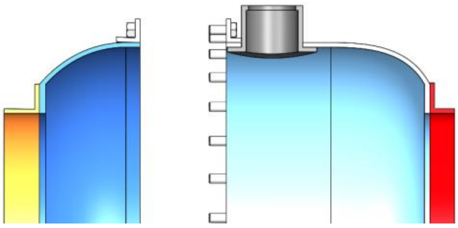


Figure 199 – Simplified Assembly view (step 2)

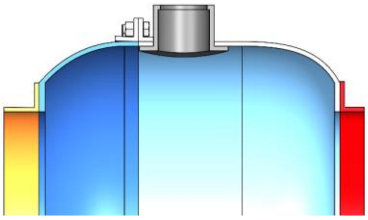


Figure 200 – Simplified Assembly view (step 3)

And the main advantages and disadvantages are identified in

Table 70.

Table 70 – Advantages and disadvantages

Advantages	Disadvantages
The flange can have different geometries (straight, tapered, stepped, etc.)	Requires gasket to prevent leakage
Enables disassembly (flange to flange)	Permanent bond between the Main Body/AFT cover and its respective flange
Allows an easy on-site assembly	Dimension control of the outside surface of the housing for adhesive bonding
Easier serviceability on the turbine	Different coefficients of thermal expansion (CTE)
	Thixotropy of adhesive to be controlled (gravity does not help the application)
	Corrosion (depending on the material selection for the flange and bolts/nuts)

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 201.

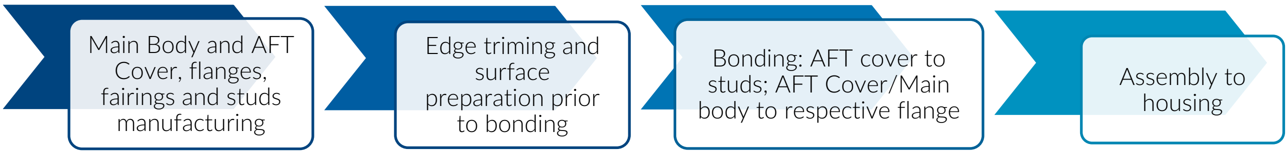


Figure 201 – Process chain

3.2.2. External Flange with inside placement

The previous external flange can also be adapted, so that the flange is bonded in the inside surface of the housing instead. The result is as shown in Figure 202. The respective proposed sequence of assembly is as shown in Figure 203 to Figure 205.

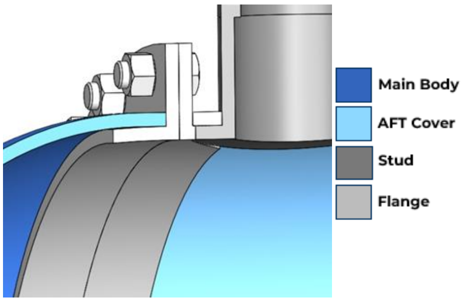


Figure 202 – External flange with flange bonded on the inside of the housing

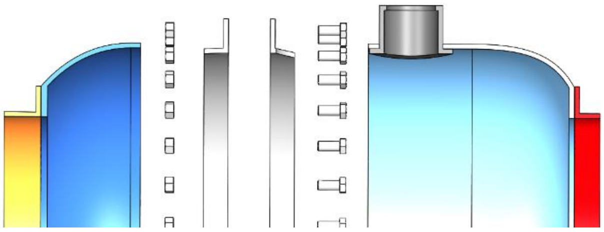


Figure 203 – Simplified Assembly view (step 1)

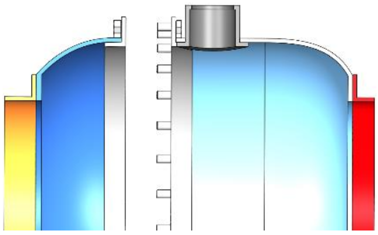


Figure 204 – Simplified Assembly view (step 2)

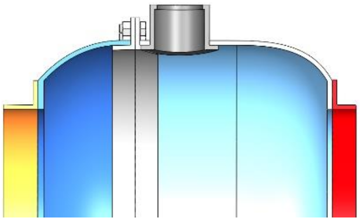


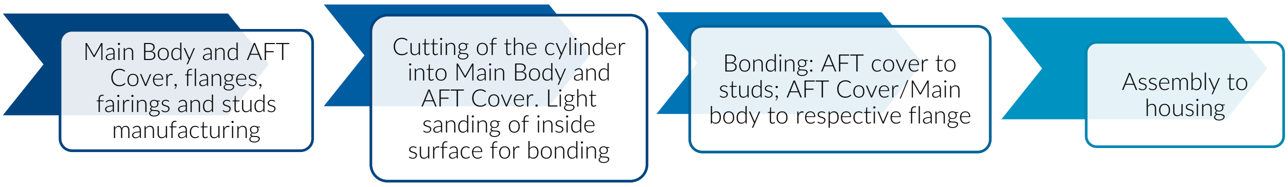
Figure 205 – Simplified Assembly view (step 3)

And the main advantages and disadvantages are identified in Table 71.

Table 71 – Advantages and disadvantages

Advantages	Disadvantages
The flange can have different geometries (straight, tapered, stepped, etc.)	Requires gasket to prevent leakage
Enables disassembly (flange to flange)	Permanent Connection between the Main Body/AFT cover and its respective flange
Allows an easy on-site assembly	Dimension control of the outside surface of the cylinder for adhesive bonding
Cleaner look from the outside	Different coefficients of thermal expansion (CTE)
Easier serviceability on the turbine	Thixotropy of adhesive to be controlled (gravity does not help the application)
	Corrosion (depending on the material selection for the flange and bolts/nuts)

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 206.



Main Body and AFT Cover, flanges, fairings and studs manufacturing

Cutting of the cylinder into Main Body and AFT Cover. Light sanding of inside surface for bonding

Bonding: AFT cover to studs; AFT Cover/Main body to respective flange

Assembly to housing

Figure 206 – Process chain

3.2.3. Internal Flange

The flange connection can also be considered to be internal as shown in Figure 207. The respective proposed sequence of assembly is as shown in Figure 208 to Figure 210.

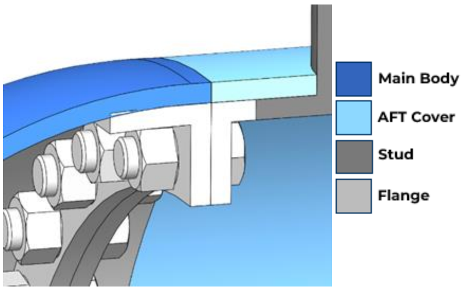


Figure 207 - Internal Flange Connection

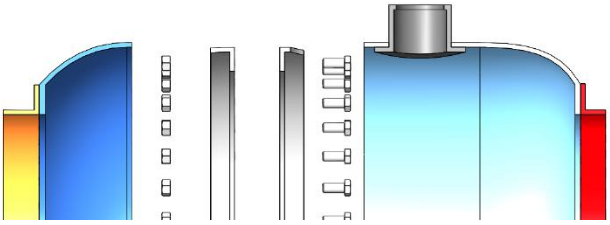


Figure 208 – Simplified Assembly view (step 1)

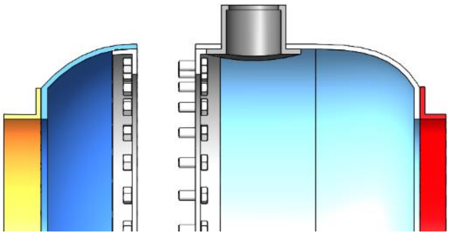


Figure 209 – Simplified Assembly view (step 2)

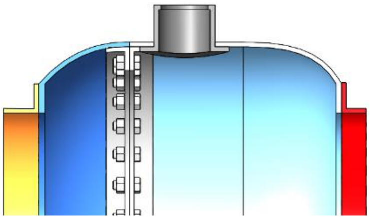


Figure 210 – Simplified Assembly view (step 3)

And the main advantages and disadvantages are identified in

Table 72.

Table 72 – Advantages and disadvantages

Advantages	Disadvantages
The flange can have different geometries (straight, tapered, stepped, etc.)	Requires gasket to prevent leakage
Enables disassembly (flange to flange)	Permanent Connection between the Main Body/AFT cover and its respective flange
	Dimension control of the outside surface of the housing for adhesive bonding
	Different coefficients of thermal expansion (CTE)
	Flange can collide with curvature of the inside of the housing
	Very difficult to assemble with turbine inside
	Corrosion (depending on the material selection for the flange and bolts/nuts).

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 211.

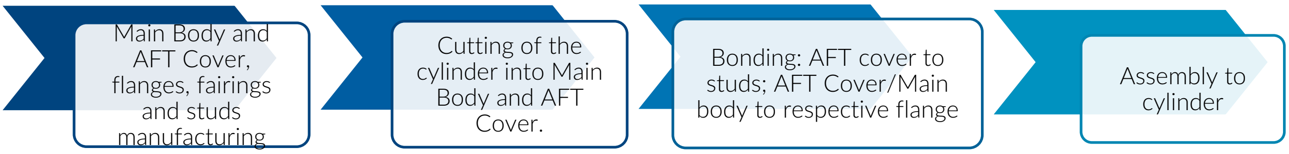


Figure 211 – Process chain

3.2.4. Slotted Connection with Sleeve

The connection between the two cut parts of the housing can also be done by means of a sleeve as shown in Figure 212. The respective proposed sequence of assembly is as shown in Figure 213 to Figure 216.

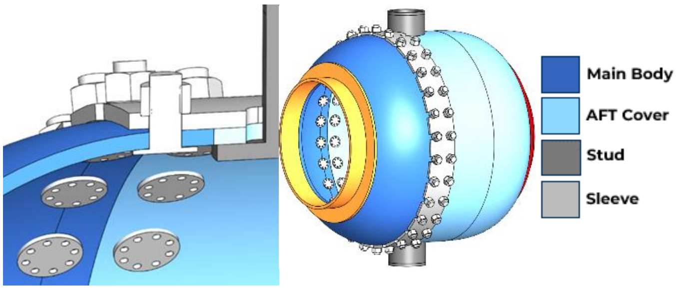


Figure 212 – Slotted connection with sleeve

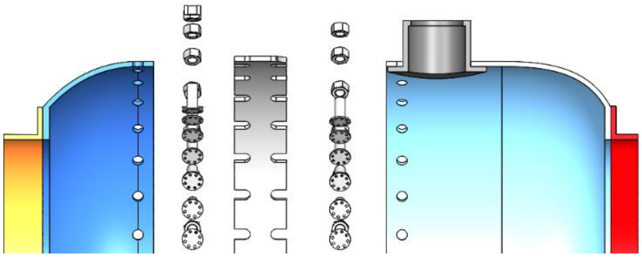


Figure 213 – Simplified Assembly view (step 1)

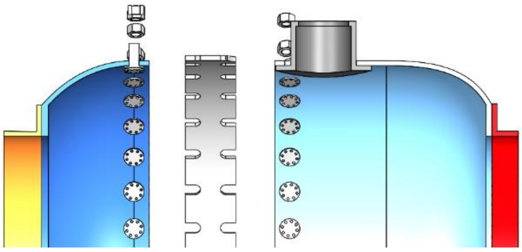


Figure 214 – Simplified Assembly view (step 2)

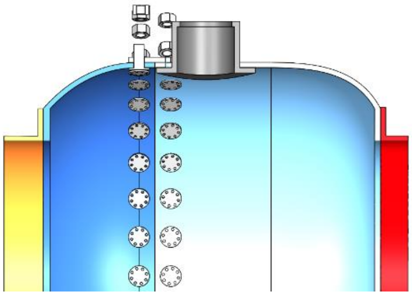


Figure 215 – Simplified Assembly view (step 3)

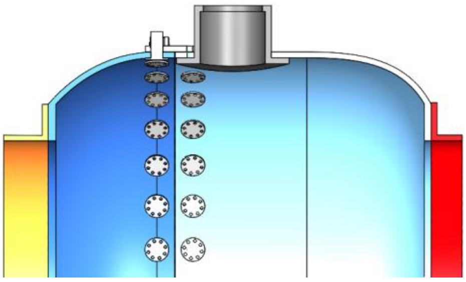


Figure 216 – Simplified Assembly view (step 4)

And the main advantages and disadvantages are identified in Table 73.

Table 73 – Advantages and disadvantages

Advantages	Disadvantages
Allows an easier on-site assembly than nut and bolt connections	Assembly requires more steps and axial reinforcement may be hindered
Enables disassembly	Permanent Connection between the housing and threaded inserts (Figure 217)
No need to access the inside for disassembly.	Requires double the number of threaded inserts relative to required number of bolts in other solutions
	Different coefficients of thermal expansion (CTE)
	Sleeve manufacture with this geometry can lead to less accurate part
	Corrosion (depending on the material selection for the flange and bolts/nuts)
	Shear loads placed on the inserts and in the sleeve.

Figure 217 – Threaded Inserts

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 218.

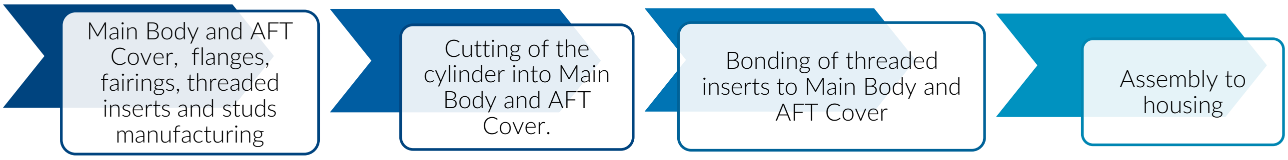


Figure 218 – Process chain

3.2.5. Slotted Connection with sleeve Part 2

One solution for the problem of axial loading regarding the previous subsection 3.2.4 would be to have in the sleeve an L-shaped slot, as shown in Figure 219 and Figure 220. During assembly, the sleeve is rotated radially, so that threaded inserts become positioned in the L-shaped groove. This way, the axial loadings will be locked.

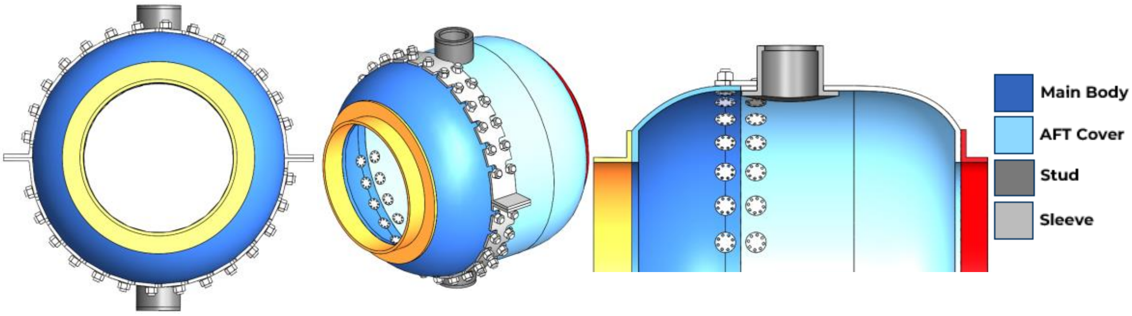


Figure 219 – L-shaped slots in the sleeve connection for axial loads compensation

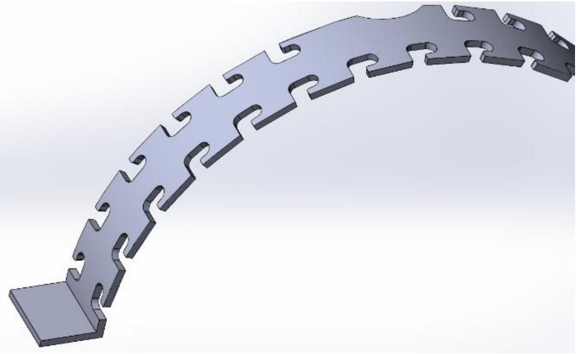


Figure 220 – Sleeve with axial compensation

3.2.6. Slotted Connection with sleeve Part 3

After the manufacturing of the sleeve with L-shaped slots, defects may be found in the part. In order to obtain sleeves without defects, an alternative solution is presented in Figure 221. This sleeve can be accurately manufactured and be easily assembled afterwards. However, it does not constrain as well axial loads on the assembly (only the friction between sleeve and housing prevents axial loading). This will be the considered geometry of the sleeve for the sleeve solution.

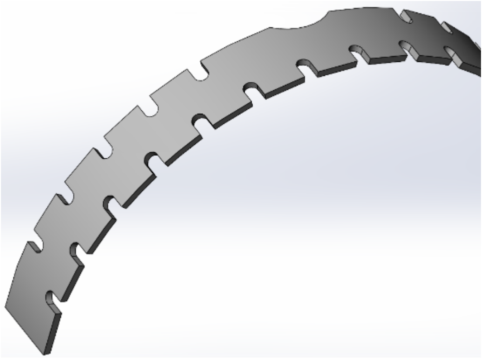


Figure 221 – Sleeve for better manufacturability and resulting part

The resulting connection between the two cut parts of the housing considering this sleeve design is shown in Figure 222. The assembly process is very similar to the one illustrated for the solution of subsection 3.2.4 in Figure 213 through Figure 216.

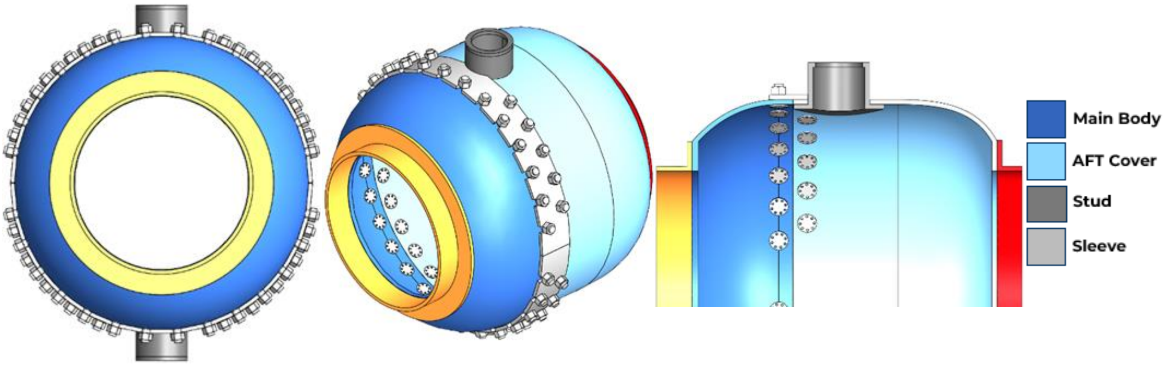


Figure 222 – Sleeve design for better manufacturability

And the main advantages and disadvantages are identified in

Table 75.

Table 74 – Advantages and disadvantages

Advantages	Disadvantages
Allows an easier on-site assembly than nut and bolt connections	Assembly requires more steps and axial reinforcement may be hindered
Enables disassembly	Permanent Connection between the housing and threaded inserts (Figure 223)
No need to access the inside for disassembly.	Requires double the number of threaded inserts relative to required number of bolts in other solutions
	Different coefficients of thermal expansion (CTE)
	Corrosion (depending on the material selection for the flange and bolts/nuts)
	Shear loads placed on the inserts and in the sleeve.

Figure 223 – Threaded Inserts

A possible process chain for the manufacturing and assembly using this concept is the one illustrated in Figure 224.

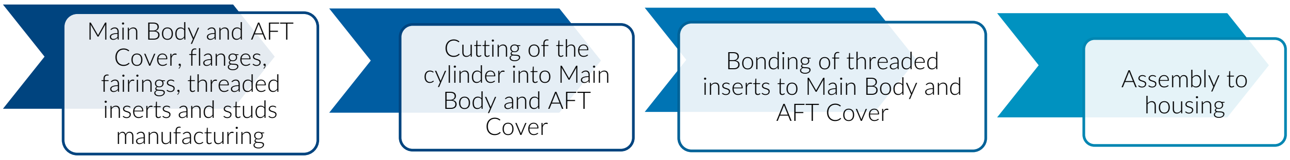


Figure 224 – Process chain

3.2.7. Slopped Connection with slots

A version of this considering slots and threaded inserts is as follows in Figure 225. The respective proposed sequence of assembly is shown in Figure 226 to Figure 229.

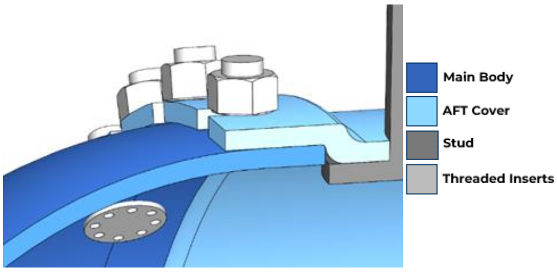


Figure 225 – Slopped connection with slots

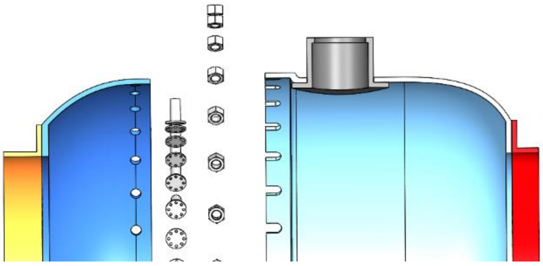


Figure 226 – Simplified Assembly view (step 1)

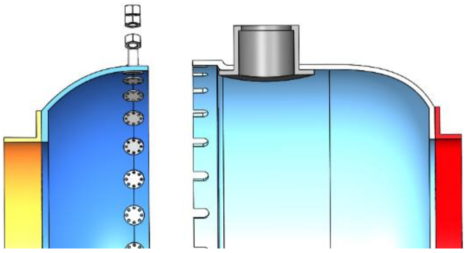


Figure 227 – Simplified Assembly view (step 2)

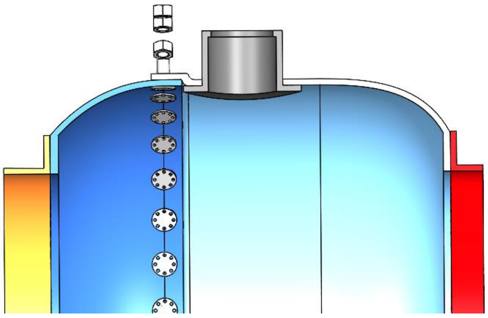


Figure 228 – Simplified Assembly view (step 3)

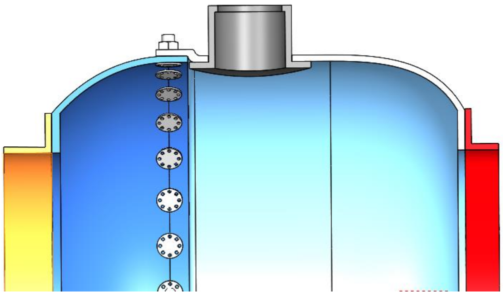


Figure 229 – Simplified Assembly view (step 4)

And the main advantages and disadvantages are identified in

Table 75.

Table 75 – Advantages and disadvantages

Advantages	Disadvantages
Allows an easier on-site assembly than nut and bolt connections	More difficult manufacturing by FW because of the slope in diameter in the AFT cover
Enables disassembly	Axial reinforcement may be hindered
	Permanent connection between the housing and threaded inserts (Figure 230)
	Different coefficients of thermal expansion (CTE)
	Corrosion (depending on the material selection for the flange and bolts/nuts)
	Shear loads placed on the inserts and in the sleeve.

Figure 230 – Threaded Inserts

A possible process chain for the manufacture and assembly using this concept is the one illustrated in Figure 231.

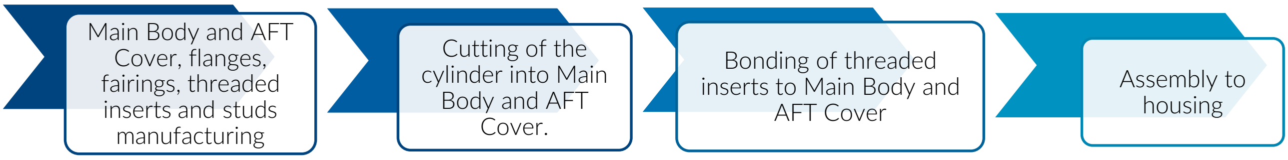


Figure 231 – Process chain

3.2.8. Slopped Connection without slots

Instead of the threaded inserts used in the previous solution, a possible alternative would be to use a bolt/nut connection, as depicted in Figure 232. The nut could be glued and/or punched with a threaded insert nut (see Figure 233 b)) or pronged nut (see Figure 233 a)) to the internal surface of the housing with the aid of a jig to better facilitate assembly. The respective proposed sequence of assembly is shown in Figure 234 to Figure 237.

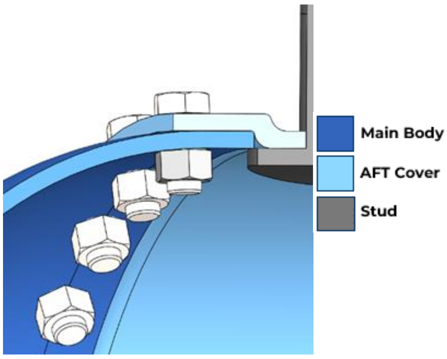


Figure 232 – Slopped Connection without slots

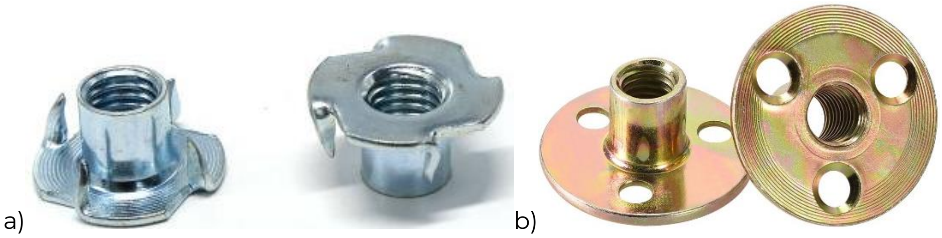


Figure 233 – a) Pronged insert tee nut. b) Threaded Insert Nut

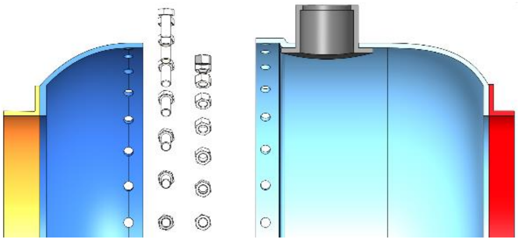


Figure 234 – Simplified Assembly view (step 1)

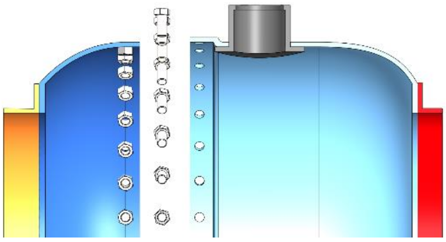


Figure 235 – Simplified Assembly view (step 2)

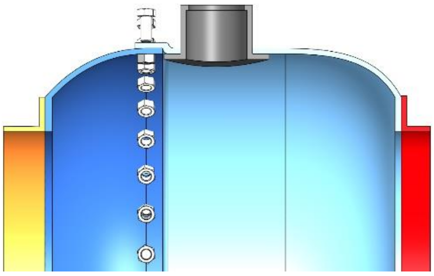


Figure 236 – Simplified Assembly view (step 3)

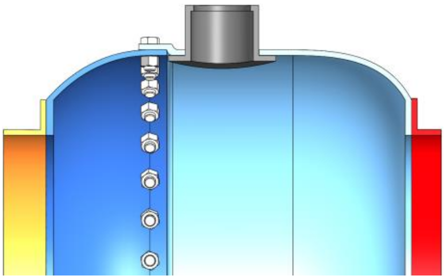


Figure 237 – Simplified Assembly view (step 4)

And the main advantages and disadvantages are identified in

Table 76.

Table 76 – Advantages and disadvantages

Advantages	Disadvantages
Enables disassembly	More difficult manufacturing by FW because of the slope in diameter in the AFT cover
Axial loads	Different coefficients of thermal expansion (CTE)
	Reduced hole mechanical properties due to damage on the fibre composite material from drilling.

A possible process chain for the manufacture and assembly using this concept is the one illustrated in Figure 238.

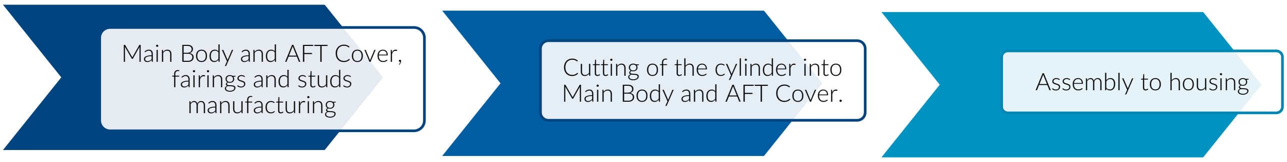


Figure 238 – Process chain

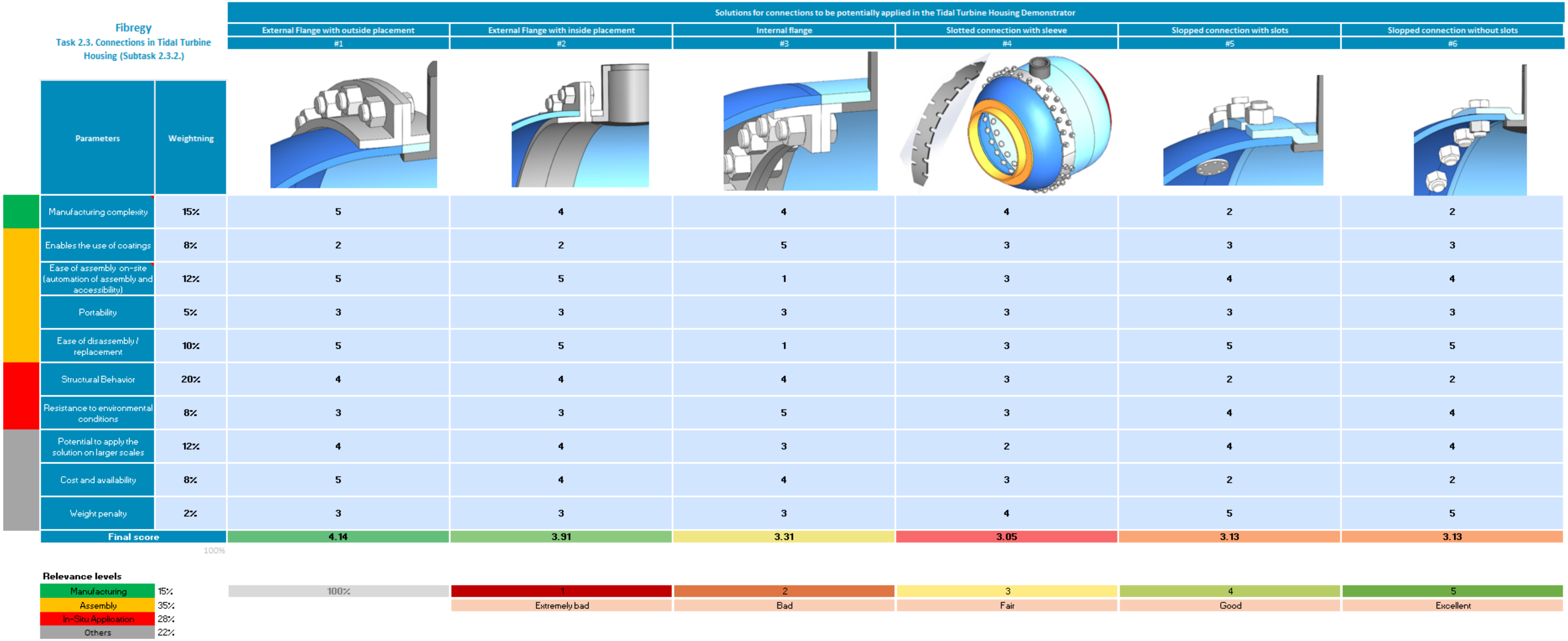
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

3.2.9. Selection Matrix

All of the previously presented concepts were evaluated using a selection matrix in order to select the most suitable one for each application. The following parameters were considered and weighted: Manufacturing complexity (13%); Enables the use of coatings (8%); Ease of assembly on-site (automation of assembly and accessibility) (10%); Portability (2%); Ease of disassembly/replacement (10%); Structural efficiency (9%); Stress concentration (10%); Fatigue life (12%); Axial Loading (5%); Visual Impact (2%); Aerodynamics (2%); Potential to apply the solution on larger scales (10%); Cost and availability (5%); Weight penalty (2%).

The final matrix can be seen on the next page for the connection between the two parts of the main cylinder, the AFT Cover and the Main Body.

Table 77 – Selection Matrix for the Tidal Turbine Housing connection



Fibregy
Task 2.3. Connections in Tidal Turbine Housing (Subtask 2.3.2.)

			Solutions for connections to be potentially applied in the Tidal Turbine Housing Demonstrator					
			External Flange with outside placement	External Flange with inside placement	Internal flange	Slotted connection with sleeve	Slopped connection with slots	Slopped connection without slots
			#1	#2	#3	#4	#5	#6
	Parameters	Weightning						
🟩	Manufacturing complexity	15%	5	4	4	4	2	2
🟨	Enables the use of coatings	8%	2	2	5	3	3	3
	Ease of assembly on-site (automation of assembly and accessibility)	12%	5	5	1	3	4	4
	Portability	5%	3	3	3	3	3	3
	Ease of disassembly / replacement	10%	5	5	1	3	5	5
🟥	Structural Behavior	20%	4	4	4	3	2	2
	Resistance to environmental conditions	8%	3	3	5	3	4	4
⬜	Potential to apply the solution on larger scales	12%	4	4	3	2	4	4
	Cost and availability	8%	5	4	4	3	2	2
	Weight penalty	2%	3	3	3	4	5	5
	Final score	100%	**4.14**	**3.91**	**3.31**	**3.05**	**3.13**	**3.13**

Relevance levels

🟩 Manufacturing	15%
🟨 Assembly	35%
🟥 In-Situ Application	28%
⬜ Others	22%

100%	1	2	3	4	5
	Extremely bad	Bad	Fair	Good	Excellent

4. Reinforcements

4.1. Introduction

This chapter addresses the main conclusions from various meetings' discussions regarding the reinforcements of the W2Power platform, particularly necessary to its towers and columns (Figure 239). Although not directly related to the scope of the T2.3 (connections), this was discussed with the same task partners as it can interfere with the previously selected connections. For that same reason, it was agreed that the outcomes from this study should be reported in this deliverable.

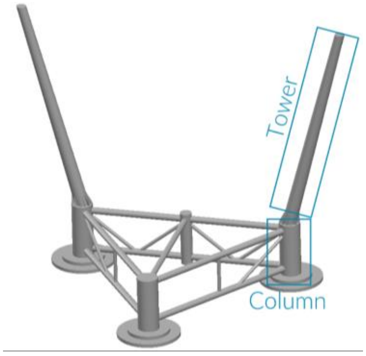


Figure 239 – Subproducts where reinforcements will be necessary

These reinforcements (also called stiffeners) are the longitudinal and transverse internal members that characterize a semimonocoque structure such as the one represented in Figure 240. Although the monocoque typology might seem easier to manufacture (which can be true for metal construction), when dealing with composite structures it would be extremely challenging to manufacture large components with very thick (> 40 mm) outer shells – since the shell has to support and the stresses and loads – without being very cost-intensive and structural ineffective. The semimonocoque construction, on the other hand, allows for the usage of much smaller shell/skin thicknesses by supporting it with a combination of internal reinforcements such as frames (transverse/circumferential) and stringers (longitudinal).

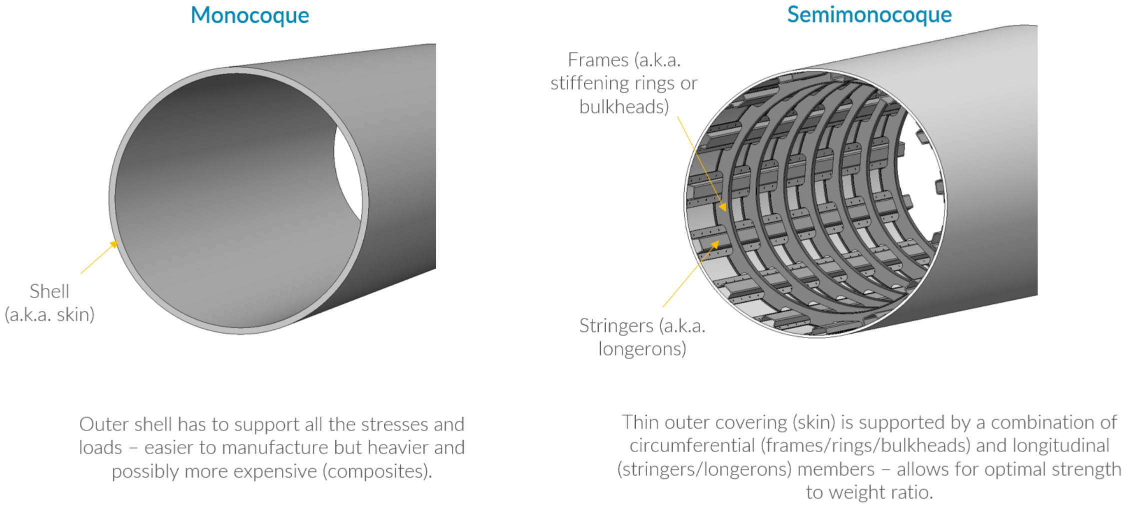


Figure 240 – Comparison between monocoque and semimonocoque construction typologies

For these reasons, semimonocoque construction is the standard in aerospace structures (fuselage, wing, empennage) since several decades ago, inclusively using CFRP components (Figure 241). On wind turbine towers, because there are usually built-in concrete or steel, the combination of transverse and longitudinal members (cables are usually used instead of stringers) is not so common, however, frames are used to prevent buckling failure (Figure 242).

Figure 241 – Stiffened panel in Boeing 787 fuselage [90]

Figure 242 – Buckling failure of a wind tower [91]

A summary of reinforcements (stiffeners) bending is given in Figure 243, the upper part showing context in the stiffened panel, between frames and uniform loading. The lower part of the figure shows the typical bending patterns and bending stresses in the stiffener/plate combination.

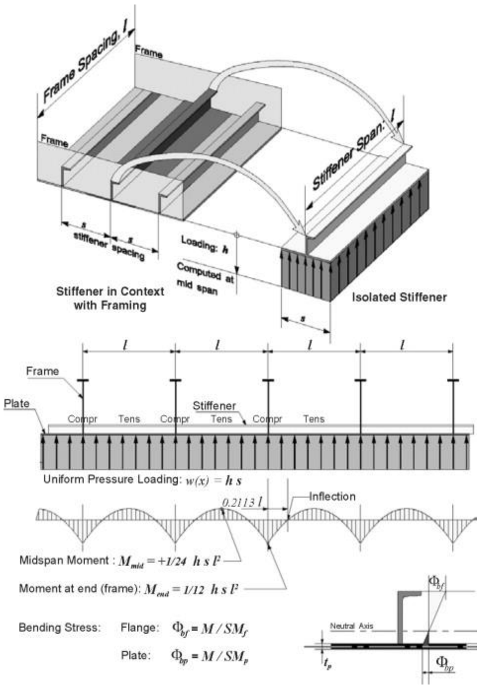
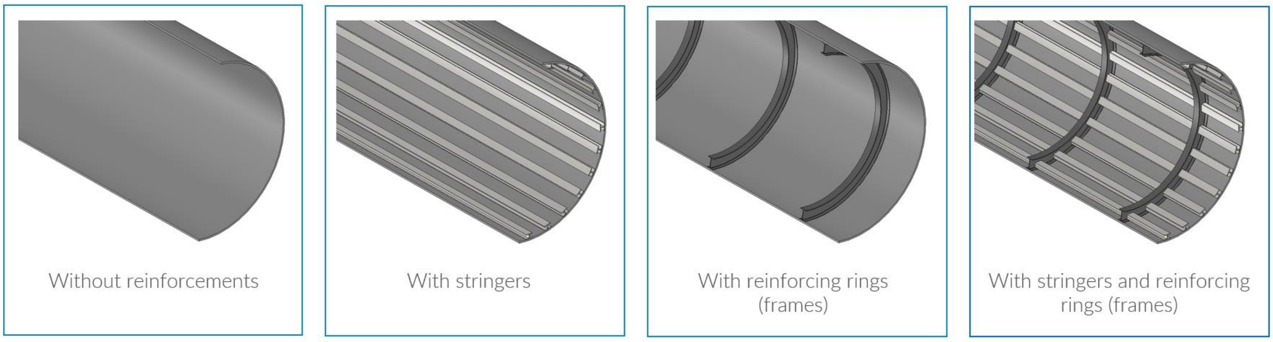


Figure 243 – Summary of stiffener bending [92]

Depending on the expected loading scenario for the structure being designed, either stringers (longitudinal members), frames/reinforcing rings (transverse members), or a combination of both, can be used (Figure 244).



Without reinforcements

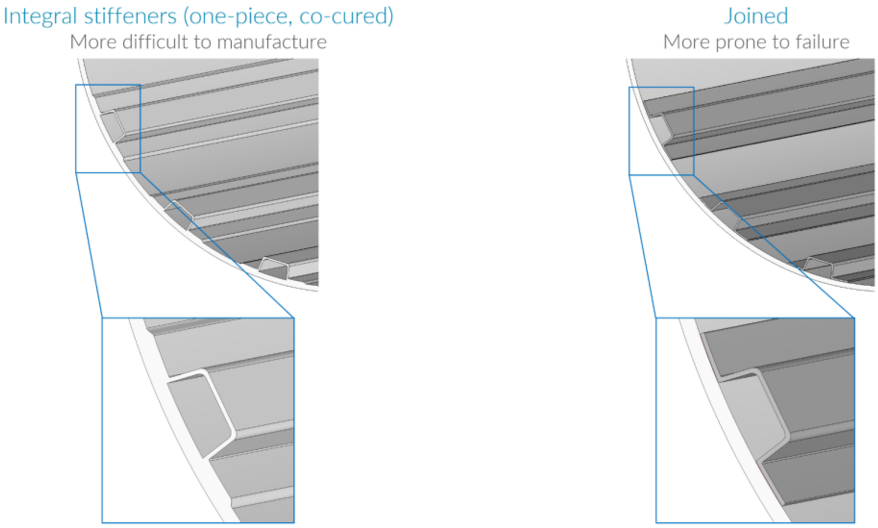
With stringers

With reinforcing rings (frames)

With stringers and reinforcing rings (frames)

Figure 244 – Possibilities of stiffeners' integration

In turn, these stiffeners can be either co-cured together with the composite part or joined afterwards (Figure 245).

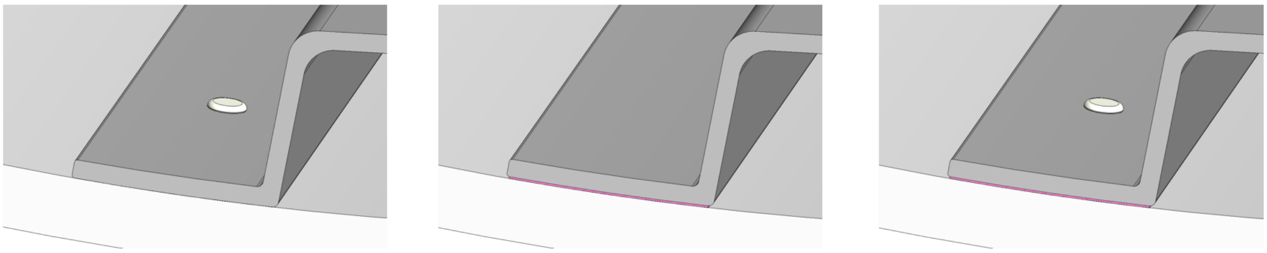


Integral stiffeners (one-piece, co-cured)
More difficult to manufacture

Joined
More prone to failure

Figure 245 – Manufacturing of stiffeners

In case of joining being the most viable solution, they can be either riveted or bolted, bonded, or both (hybrid joint), as illustrated in Figure 246. The choice of the best joining solution for a given application needs to be based on several factors, such as the desired production volume, financial resources, availability of equipment and required joint performance.



Riveted/bolted

- More common in metals;
- Higher stress concentrations;
- Easy to replace and inspect;
- Holes may cause delamination in composites.

Bonded w/ structural adhesive

- More common in composites;
- Better stress distribution;
- Prone to peeling stresses;
- Require surface pretreatment;
- Difficult to replace and inspect.

Bonded+riveted

- Holes induce stress concentrations and may cause delamination;
- Bolts/rivets can act as a redundancy and prevent catastrophic failure by peeling.

Figure 246 – Stiffeners' joining options and main characteristics

On the other hand, the stiffeners can also have different geometries/sections, being the most typical illustrated in Figure 247. Other common structural sections used in aircraft stiffeners are illustrated in Figure 248. At this time, it was decided by the design team that the tower would use "Omega" stiffeners while the column would use "H" stiffeners.

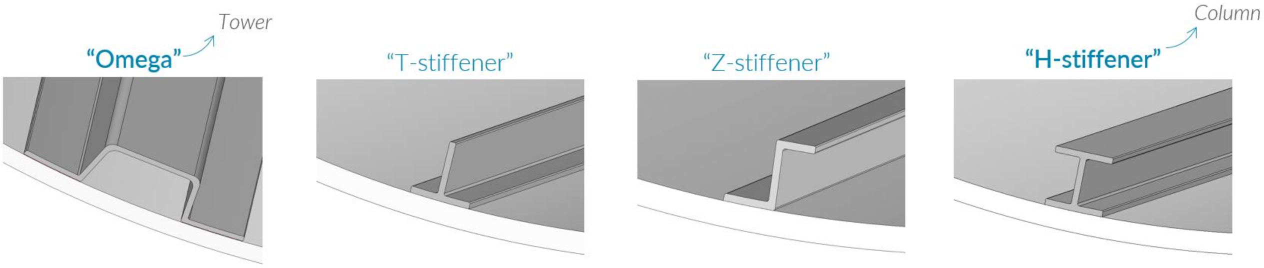


Figure 247 – Different stiffener's section geometries

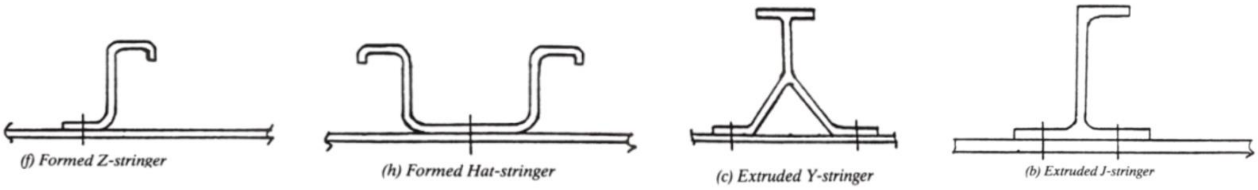


Figure 248 – Typical aircraft structural flange/plate sections [42]

For the particular case of using both stringers and frames, three different options of integration were proposed to avoid interferences between the transverse and longitudinal components.

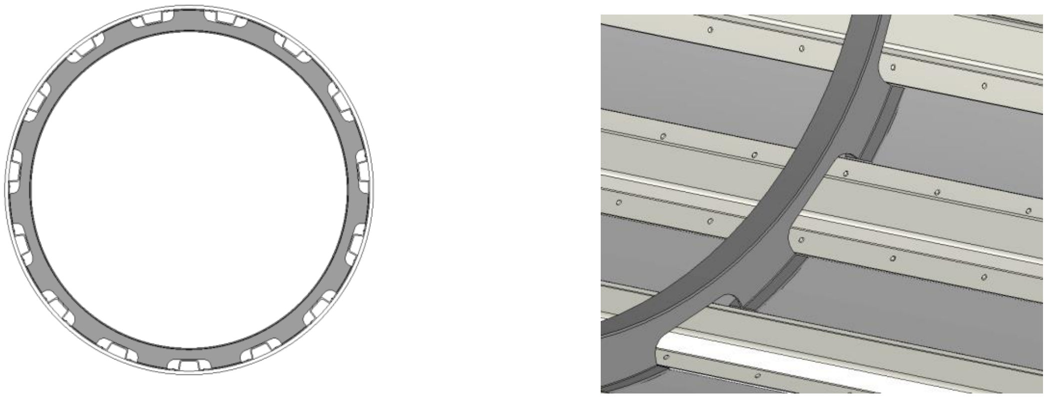


Figure 249 – Option 1) Continuous stringers (rings with openings)

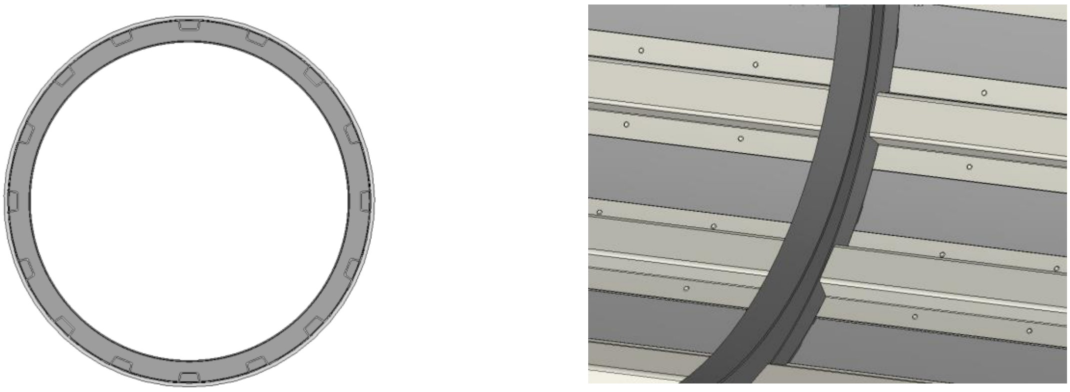


Figure 250 – Option 2) Discontinuous stringers (closed rings)

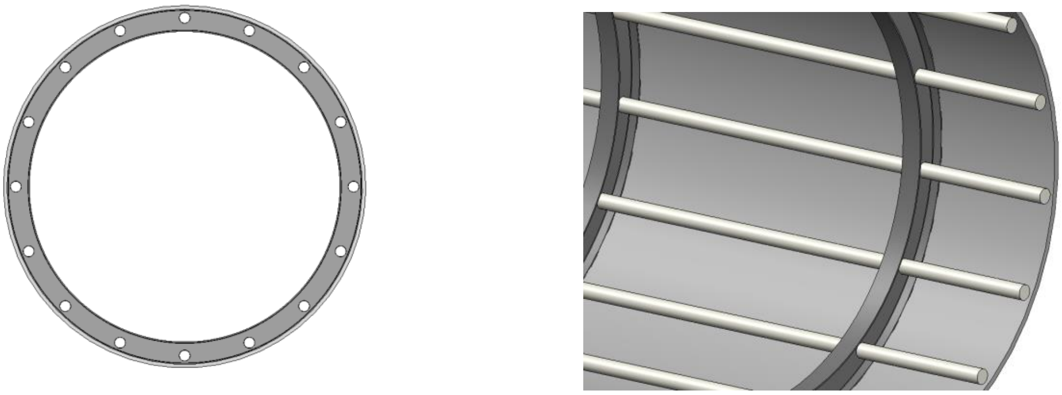


Figure 251 – Option 3) Floating stringers (through rings)

4.1. W2Power

After discussing with the design team, and as expected, it was decided that the towers of the W2Power platform would require a dense distribution of (large) internal reinforcements to achieve the inertia of the sections required for structural considerations.

The manufacture and installation of these reinforcements, using conventional techniques, could require a relevant part of manual labour if joined afterwards. To avoid this, a procedure for the manufacture of the towers by infusion with co-cured stiffeners was proposed and is illustrated below (Figure 252). It was discussed that only stringers (option 1) will likely be used.

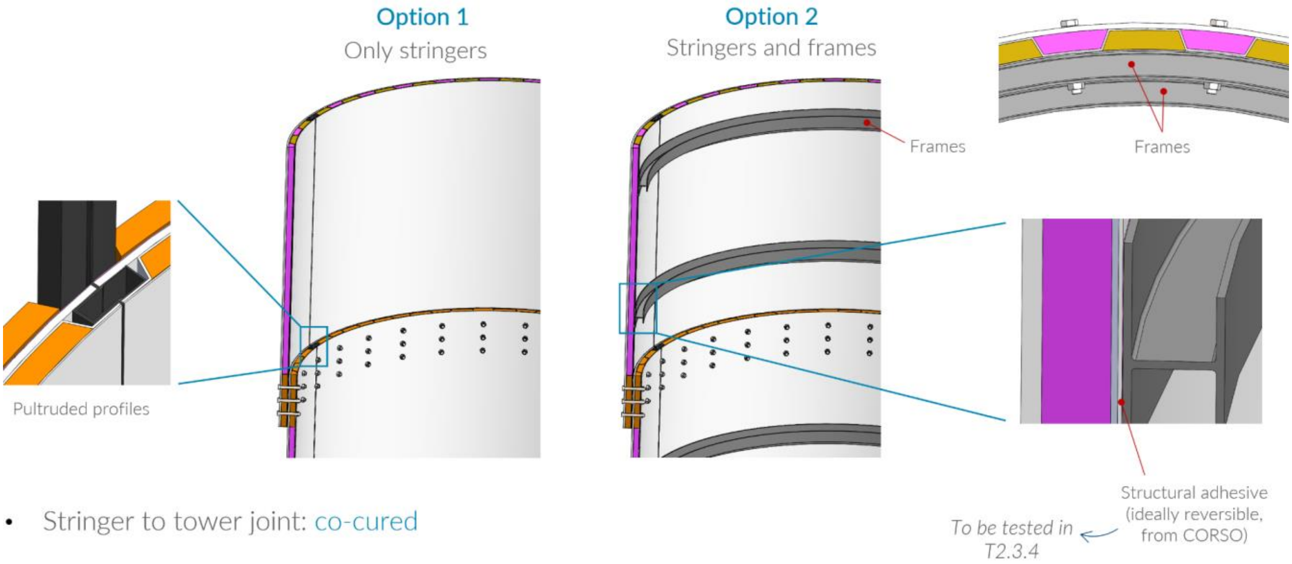


Figure 252 – Integration of stiffeners in the W2Power towers

4.1.1. Tower-to-tower connection

Regarding the tower-to-tower vertical connection, this has suffered some small modifications since the 1st concept presented in Chapter 3, and is not illustrated in Figure 253 with the proper integration in the stiffened modules.

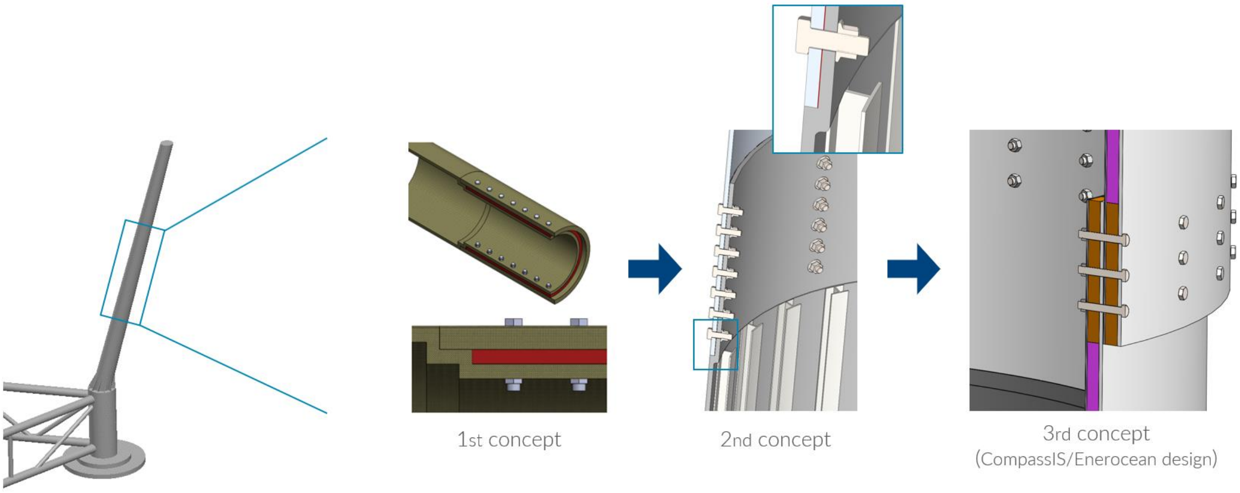


Figure 253 – Tower to tower vertical connection

The omega-shaped stiffeners will be laid up on top of the machined foam with the desired "omega" shape, but will be removed over the connection area and replaced by wood (in orange in Figure 254), high density foam or other material light and workable that supports the bolt compression torque. The adhesive used will ideally be the reversible one from Corso Magenta, so that it is possible to easily dismantle the different modules, but first we will carry a comparison test between this and a marine-grade adhesive in the experimental campaign in task 2.3.4.

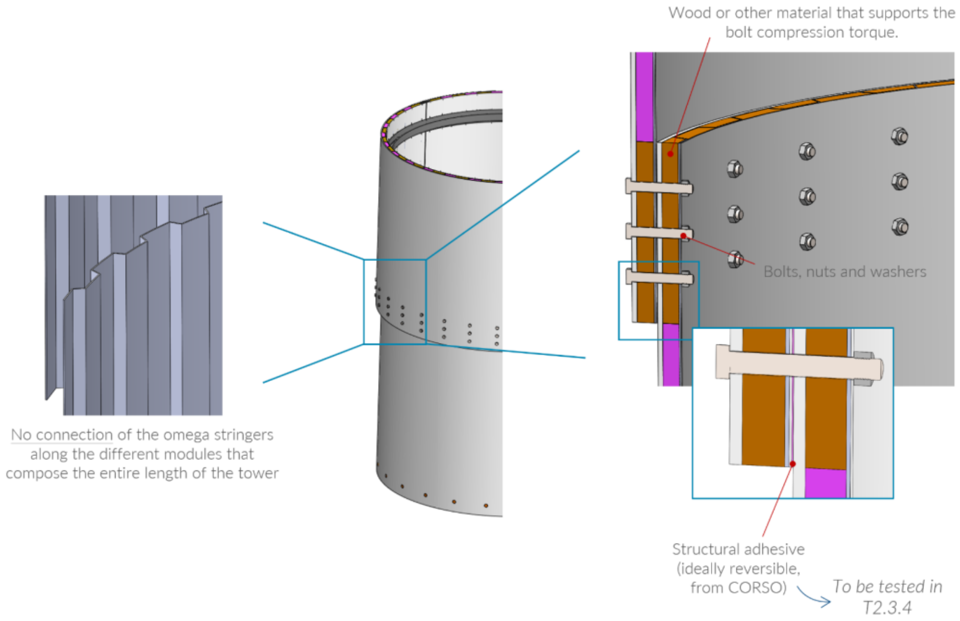


Figure 254 – Details about the tower to tower connection

4.1.2. Tower to column/nacelle connection

Regarding the tower to column connection (which is the same as the tower to nacelle), two proposals were made with different interface options which are small modifications from the IKEA (or T-bolt) joint.

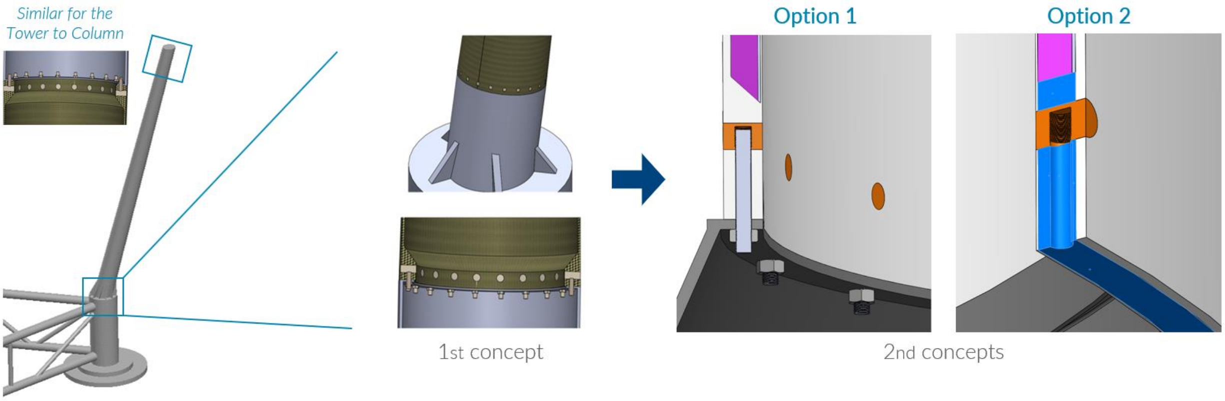


Figure 255 – Tower to column/nacelle connection

The first option consists of drilling holes through the monolithic FRP (foam would be entirely replaced by FRP in this area), which can be quite difficult to execute due to the drilling being performed between the fibre layers (where the poor interlaminar strength can lead to delamination) and the second option is replacing the foam by a solid metal ring (bonded to the FRP skins) after which the holes can be safely drilled.

Both options are illustrated in Figure 256 and will be more thoroughly studied and analysed in the next chapter.

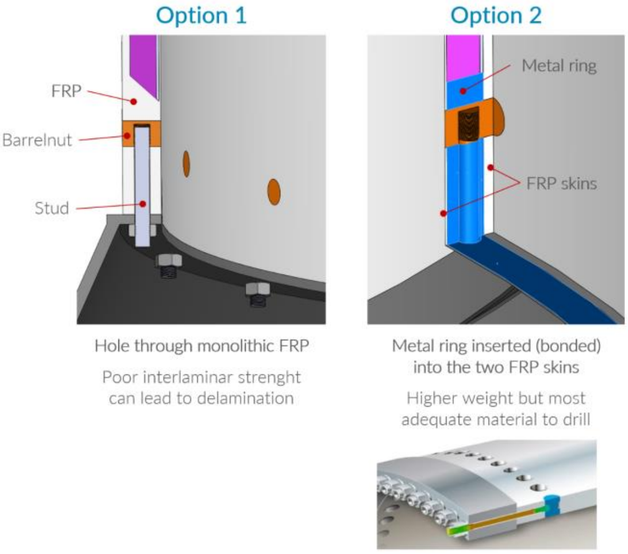
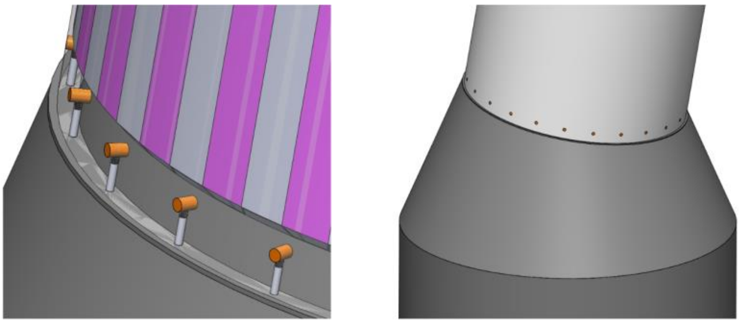


Figure 256 – Options of interface for the tower to column/nacelle connection

On the other hand, it can also be visualised in Figure 257 a more detailed view of option 1, together with a recent modification proposed for the geometry of the column, which now incorporates a smoother transition to the tower without requiring a stepped (flanged) change.



Visualization of the connection with transparent FRP

Column to tower transition will be smother without requiring a flange (the shape of this transition will be optimized in T2.3.3)

Figure 257 – Details of the IKEA connection (a) and smoother transition from the tower to the column (b).

4.1.3. Tube to column connection

The final connection that was studied concerning the reinforcements, was the tube-to-column connection, which was previously decided to be overlamination both inside and outside of the column (Figure 258).

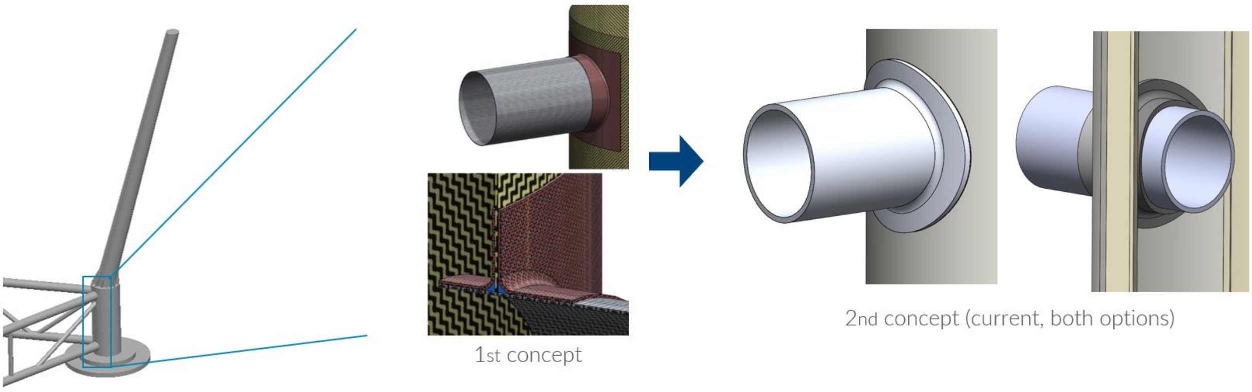
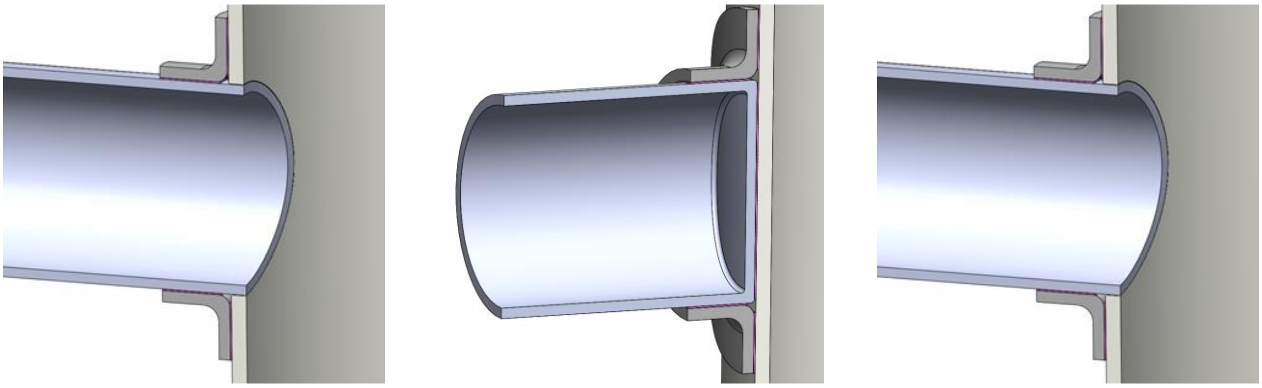


Figure 258 – Tube-to-column connection

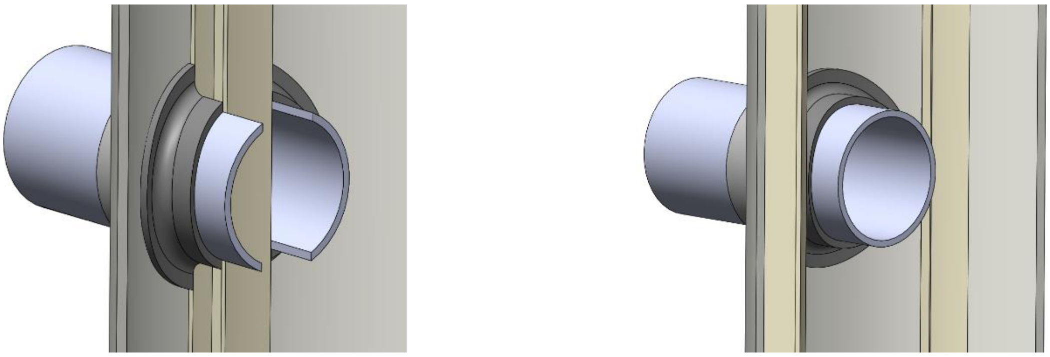
However, it became obvious that if the tube penetrates the column, there would be an interference between the horizontal tubes and the reinforcements of the column. For this reason, other options were also considered, particularly (
Figure 259):



Option 1 – Tube is bonded to the flange

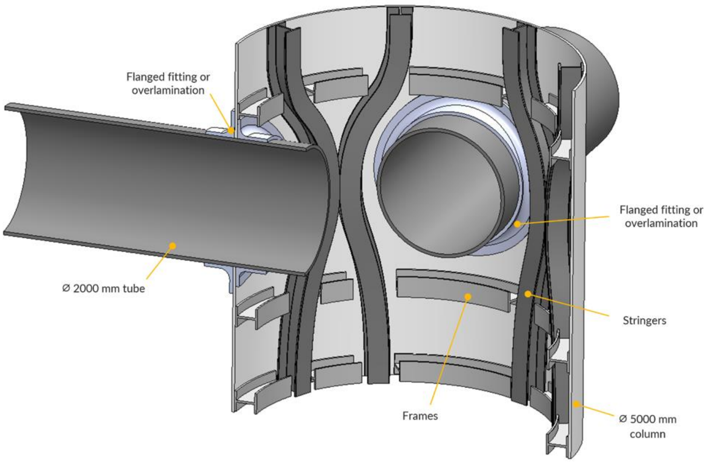
Option 2 – Tube is bonded to the flange and to the column

Option 3 – Tube is bonded to the flange and supported in the skin



Option 4 – Includes and interior flange (or overlamination) which is cut to allow for reinforcement intersection

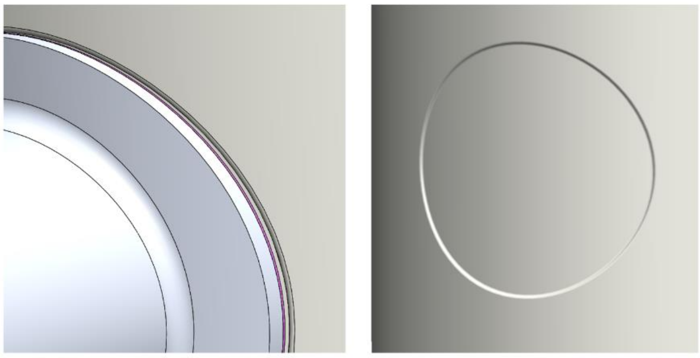
Option 5 – Includes an interior flange (or overlamination) of less diameter than the reinforcements' separation



Option 6 – New suggestion with penetrating tube (iXblue) and curved stringers that go around the tubes

Figure 259 – New options for the tube-to-column connection

It was also suggested that the column would incorporate an indentation/recession with the tube's flange shape (Figure 260) in order to compensate for the lack of strength against peeling stresses along the bondline, however, it was also noticed that this would cause an interference of the interior pultruded stringers (Figure 261).



Tube bonded to column with indentation/recession

Column with indentation/recession

Figure 260 – Indentation/recession in the column

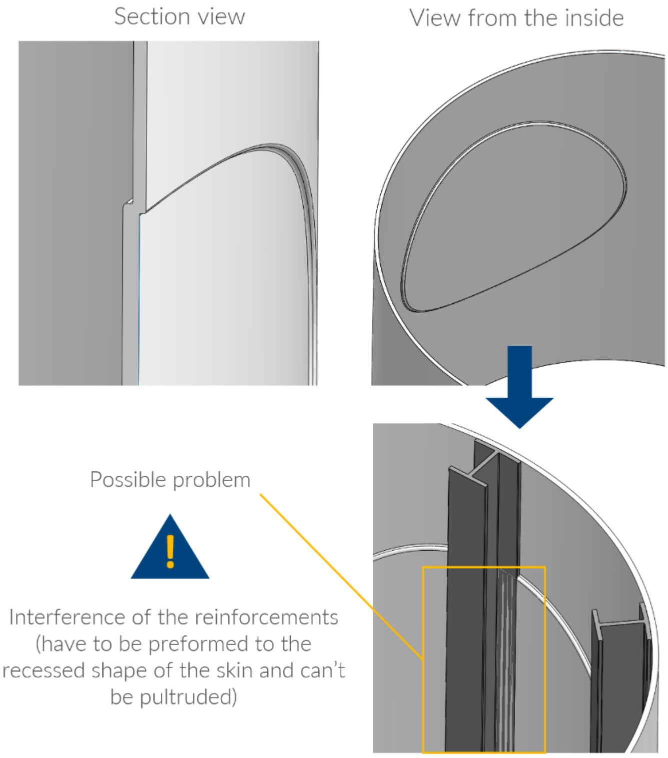


Figure 261 – Interference between the stringers and the indentation

It was also identified the possible problem of integrating together the stringers and the frames, and two possible solutions are illustrated in Figure 262.

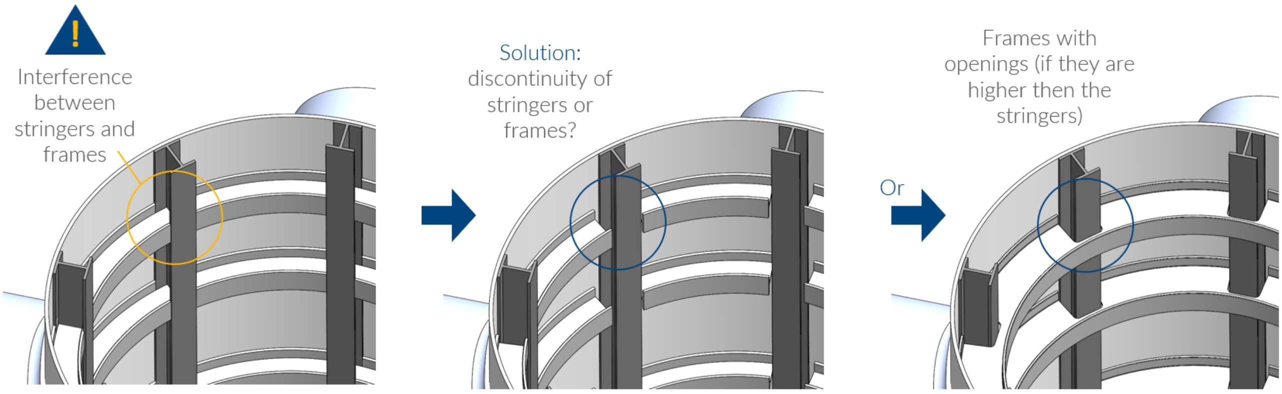


Figure 262 – Integration of stringers and frames in the column

Similarly to what was said for the tower to tower connection, the adhesive used for bonding the stiffeners to the column's skin will ideally be the reversible one (Figure 263), however it lacks validation that will be performed in T2.3.4.

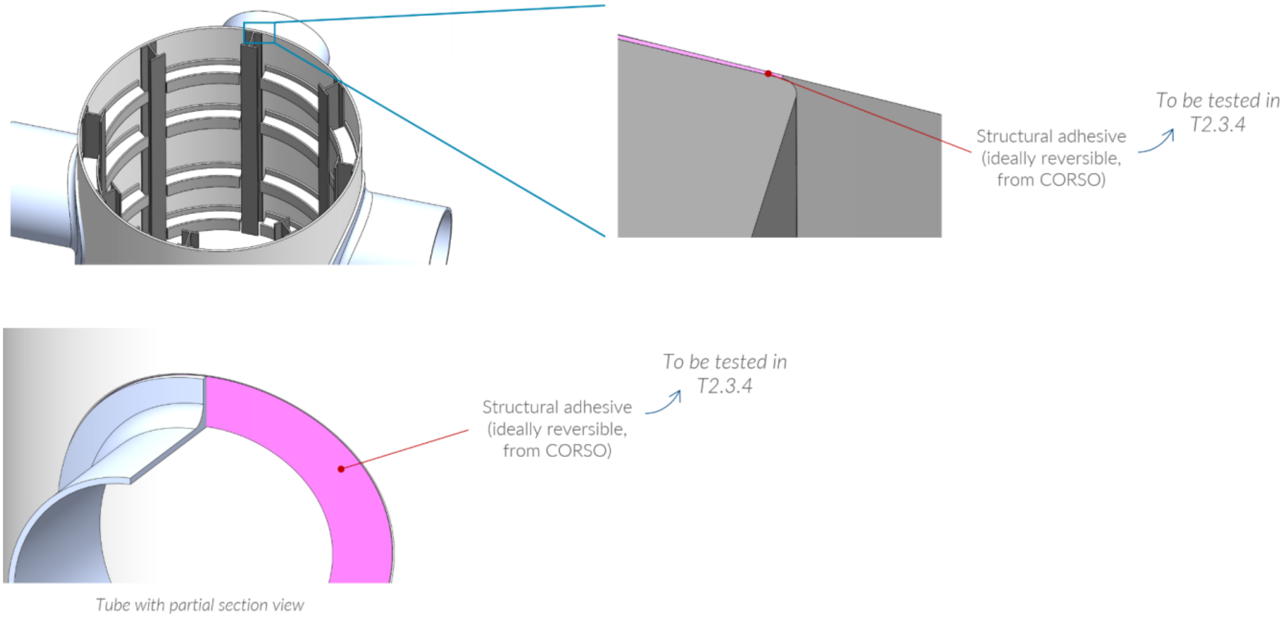
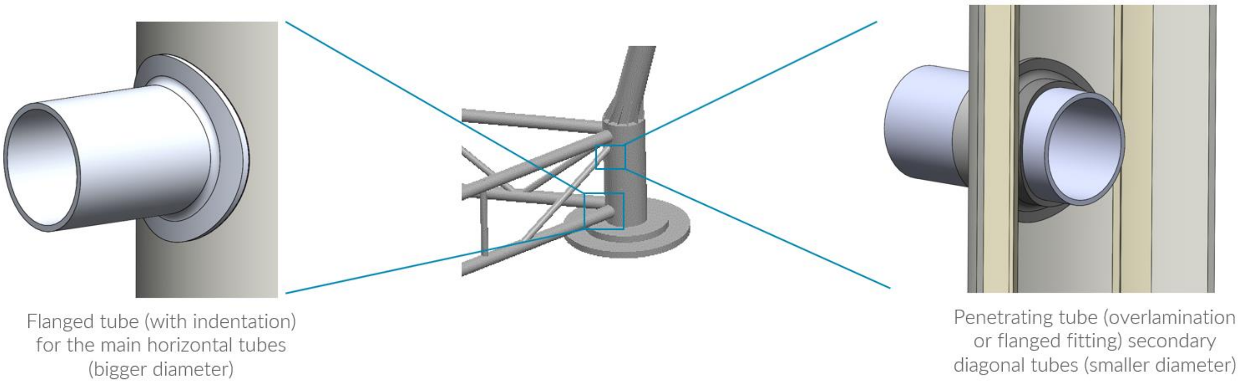


Figure 263 – Components joined by bonding

Finally, and although a final conclusion will only be made during the next chapter, one of the main conclusions was that the connection type can depend on the diameter of the tube. In other words, and depending on other design inputs, it might be possible to have the secondary (smaller) diagonal tubes penetrating the column, while the larger horizontal tubes can be joined only on the outer surface (Figure 264).



- Tube (horizontal) to column connection: bonded flanged tube
- Tube (diagonal) to column connection : penetrating tube with overlamination/flanged fitting
- Redesign (optimization) to be performed in T2.3.3.

Figure 264 – Different possibilities of connection depending of the tubes' size

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

5. Re-design and optimization of connections

Once the connections have been selected, it will be necessary to re-design, optimize and adapt them to fulfil the specific requirements of the demonstrators. Additionally, some concepts of connections could be generated.

5.1. Tube to Column

Although the decided connection between the column and the tube was overlamination (option B, illustrated in Figure 265), it became evident, after discussing with all the task partners (and also others, such as DNV) that this solution, despite being the best among all the proposals, might not be considered a fail-safe design due to the peeling stresses induced in the overlaminated patch. Furthermore, the solution has to be compatible and allow continuity of the reinforcing members to be placed inside the column.

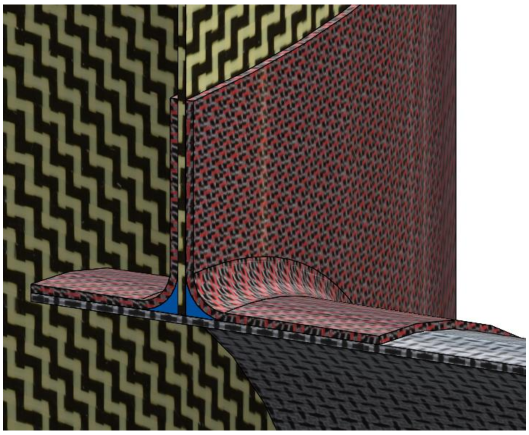


Figure 265 – Tube to column connection (Overlamination, option B)

In order to overcome this, it was proposed by the design (WP4) team to develop a new structural solution for this connection that would include transitioning the tubular shape of the tubes to a squared section which would run through the column and could be easily supported by decks, as illustrated below in Figure 266. This new option will now be studied in more detail using numerical simulations, and comparing its performance to the other options to achieve a final conclusion.

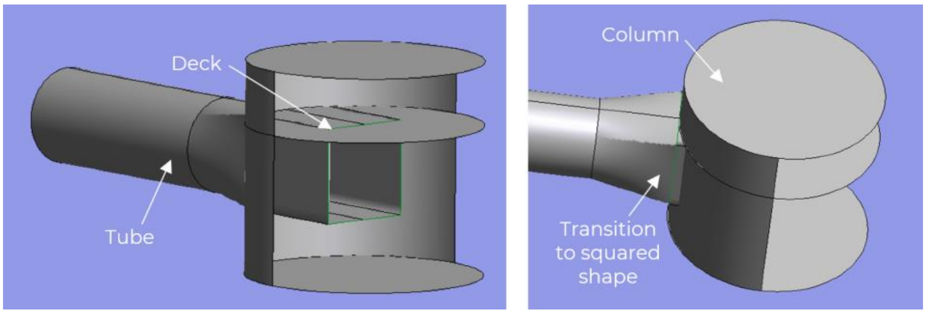


Figure 266 – New proposal for the connection between the tube and column

5.1.1. Methodology

First simulations tried to optimize round-shaped tube connections, all of them fitting a reinforcement flange, but with different ending configurations. This reinforcement flange was considered bonded. Some configurations had tubes that went through the column and others don't, then the first differences were found. Then the shape of the tube was modified when joining to the column to get a better response. Some frames have been implemented to obtain much better performance as well.

To optimize the joint shape, just a load case has been generated and all samples have been tested under the same conditions in order to know which configuration features a better behaviour, referring to stress distribution and displacement.

The optimization process was carried out using isotropic material (steel), and once the optimal shape was reached, laminate material was introduced to check the joint behaviour. When new material was applied, thickness proportion between tube and column was kept according to steel tower but adapted to newly applied materials, as explained in point 5.3.1.

Table 78 – Steel and laminate dimensions applied to column and tube

	External diameter (m)	**Thickness (mm)**
Steel column	9	16
Steel tube	9	28
Steel flange	9,6	28
Steel frames (decks)	8,94	16
Composite column	2,8	46
Composite tube	2,8	81
Composite flange (overlamination)	9,6	81
Composite frames (decks)	8,84	46

5.1.1. Round-shaped tube joints

As explained before, the first idea was to design round-shaped tube to column joints, but there were some options to evaluate. First, round-shaped joints where tubes cut the wall of the column were tested (illustrated in Figure 267), and within these kinds of joints, a model with neither frames nor decks, and model with decks, and a model with decks and tube fixed between them were tested.

It was quickly seen that intersecting the wall of the column caused inadmissible stresses around the flange and along the column section, whereas the rest of the material was under controlled conditions (Figure 268 left). Two decks were added to reduce the stress effect (Figure 268 right), and some stress reduction was achieved, but too far from desirable values.

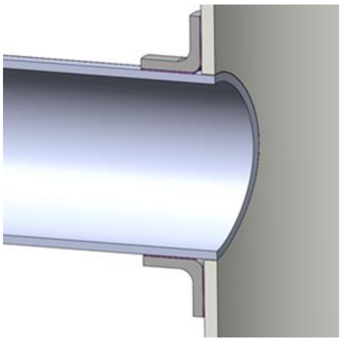


Figure 267 – Overall view of tube intersecting column joint

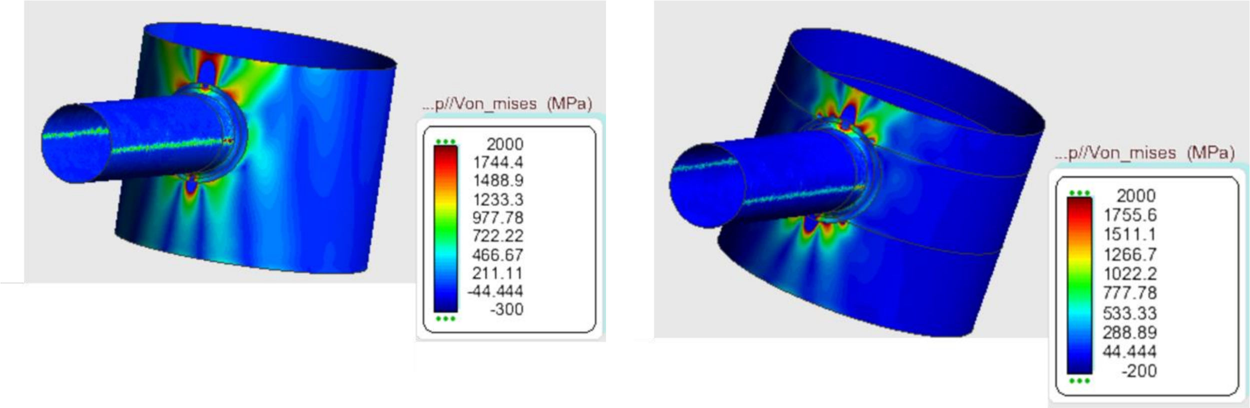


Figure 268 – Round-shaped joints, intersected column, no decks (left), two decks without contact with the tube (right)

To take advantage of the decks, the tube was forced to get into the column up to half the diameter of the column, as said before and agreed with all task partners. Both decks are attached to the tube inside the column (Figure 269).

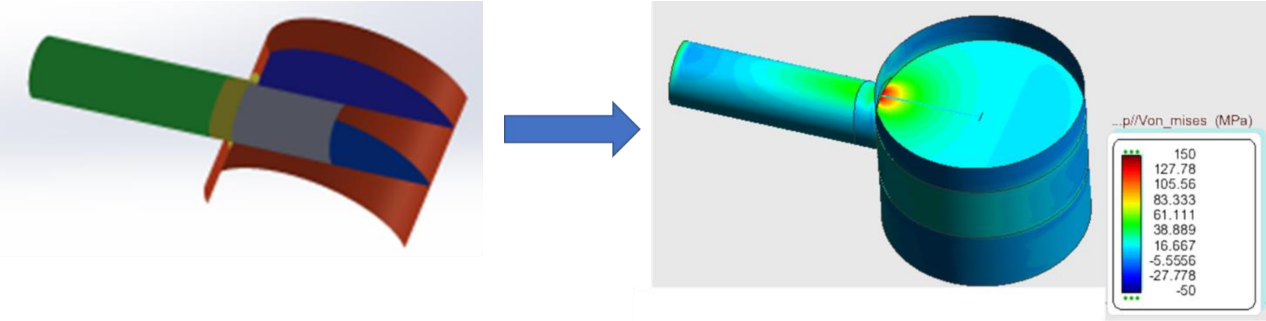


Figure 269 – Round-shaped joint with tube attached to two decks

Stresses dropped off significantly and the behaviour of all elements of the joint was satisfactory except for a point with high-stress concentration on the decks next to the column. It was supposed to be due to the tiny surface area in contact between the tube and the decks, so, it made sense to develop squared transitions into the column to increase the surface area in contact between decks and tube.

The second alternative was tested as well (tube without intersecting column). Obviously, the tube didn't get into the column section and in this simulation, no decks were modelled either (Figure 270).

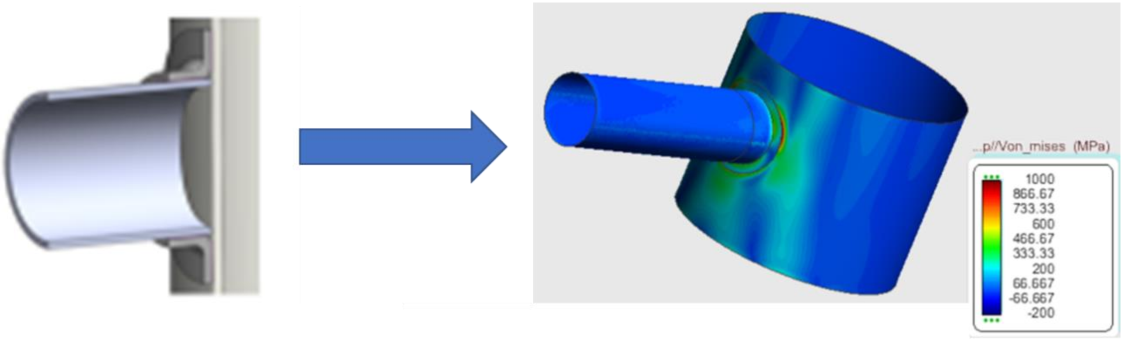


Figure 270 – Model with neither column intersection nor decks

Although stresses are lower than obtained ones with the same model without decks but with an intersecting column, they are still inadmissibly high, not only around all column section, but especially around the connection flange. These results show how important was to test square-shaped joints.

Evidently, the material of the column when intersects the tube will be removed. Although it was said that doing that worsened joint's behavior, benefits of lengthening the tube between the two decks are worth it.

5.1.2. Rectangular-shaped tube joints

With the aim of improving the contact surface between decks and the inner tube, a rectangular-shaped tube was designed (Figure 271).

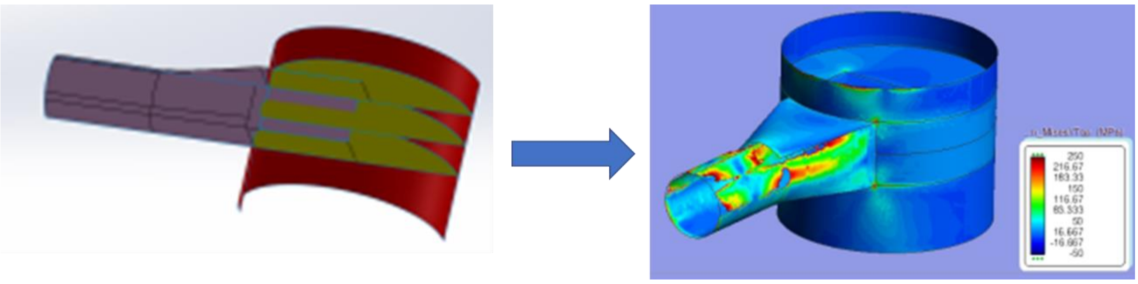


Figure 271 – Rectangular-shaped tube with three decks

New problems were found, since even though the joint between tube and column showed a very smooth transition (except for some stress concentration at the corners), lateral plates were prone to buckling and high stresses were located there and along the round tube as well (but within admissible limits). In order to minimize buckling potential problems, a third deck was modelled and squared-shaped joints were developed to get a better stress distribution.

5.1.3. Square-shaped tube joints

To avoid all problems featured by rectangular-shaped joint, but to keep all benefits it had, simply the rectangular geometry was changed to a squared geometry, keeping external dimensions of the round tube, and doing that, the possibility of intersections with other tubes connecting to the column was minimized (illustrated in Figure 272). Behaviour against buckling was improved as well.

Stresses and deformations were highly reduced compared to prior models. Connection between tube and column is completely smooth with low-stress values compared to other elements of the structure. However, a round chamfer has been implemented and optimized to obtain even a smoother transition between tube and column.

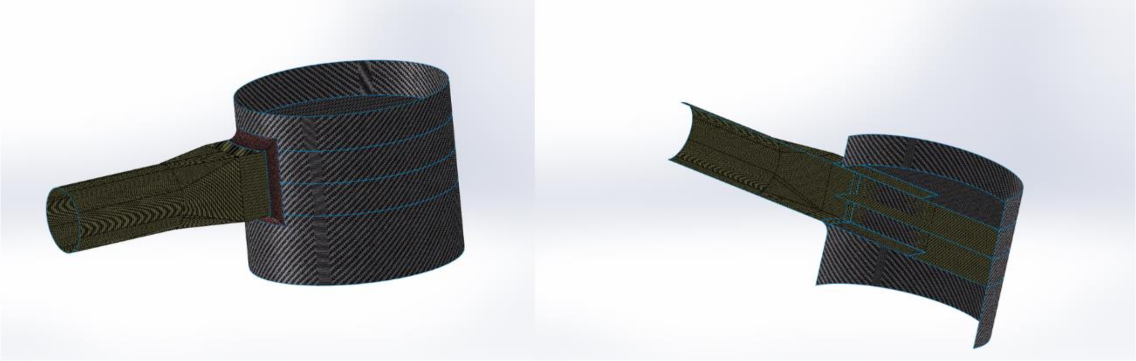


Figure 272 – Optimized tube to column joint

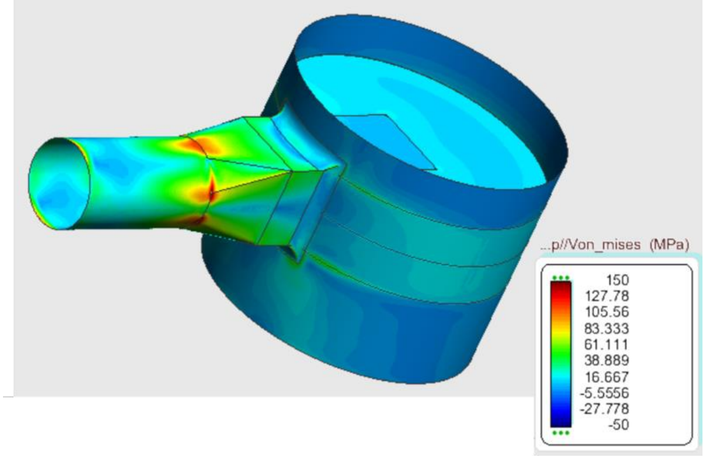


Figure 273 - Final joint geometry and VM stresses

It can be seen how maximum stresses are located just at the transition area between the tube and the squared section, but within a completely safe range. Stress distribution along the whole structure is smooth and admissible, then, the proposal made by WP4 team is optimal.

Once the geometry has been validated, new laminate material was introduced according to chapter 5.3.1. Some simulations were carried out to check displacements under the same load conditions between steel material and laminate material.

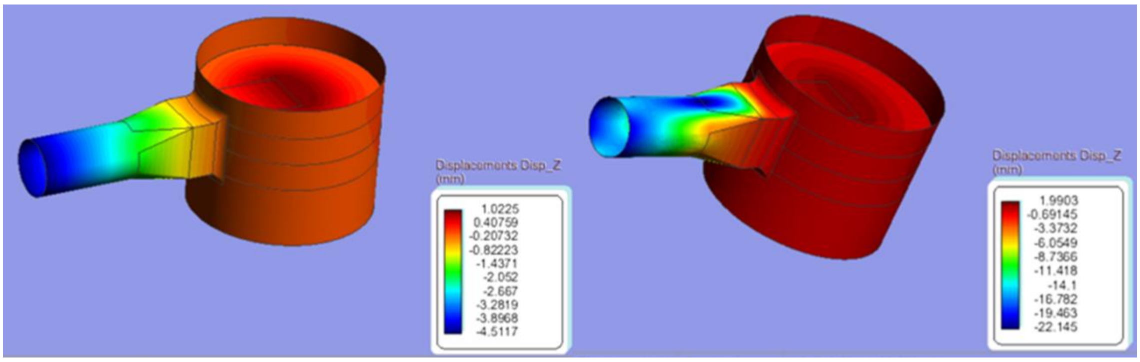


Figure 274 - Z displacements (mm). Laminate (left). Steel (right)

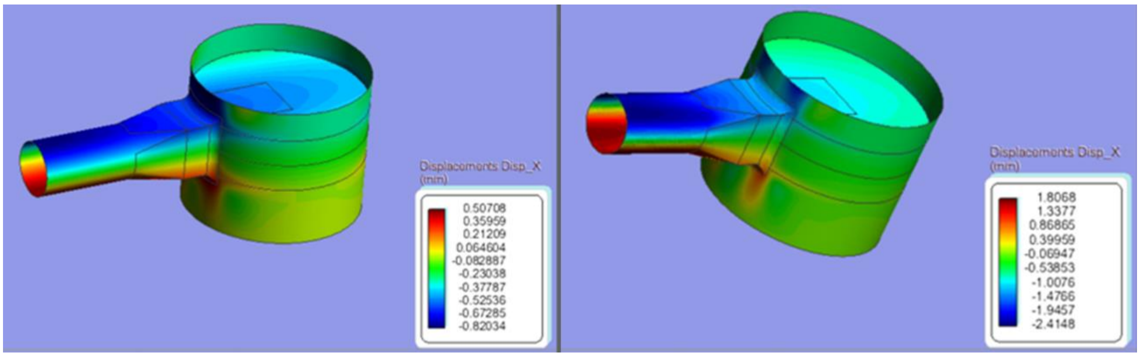


Figure 275 - X displacements (mm). Laminate (left). Steel (right)

Figure 274 and Figure 275 illustrate how displacements are smaller when the laminate configuration is used, but not too small to think that the laminate is oversized.

A round chamfer was designed to achieve a smoother stress transition between the tube and column. Considerable dimensions of the structure required a high radius chamfer, so a gap exists between the chamfer surface and tube and column surfaces (Figure 276). This gap can be filled with some foam, as usual, and no relevant differences are expected.

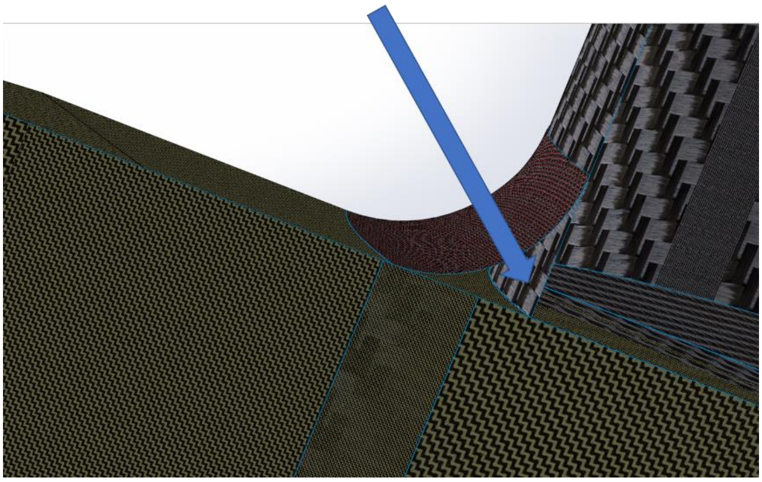


Figure 276 – Round chamfer gap

5.2. Tower to Column

These joints between the tower and column are bolted joints, so it's very important to know how the number of bolts can affect the performance of the joint and how the number of drilling holes necessary to hold the bolts can weaken the structure. It'll be the main goal of this chapter to determine whether some laminate in the base will be enough to hold the tower safely or it'll be needed to be reinforced using some steel pieces.

5.2.1. Main "IKEA" joint characteristics

"T-bolt" or IKEA connection has been selected and optimized regarding the number and position of T-bolts. Simulations have been focused on how a certain number of holes to keep barrel nuts can affect the integrity and limits of the material surrounding them. Also, simulations have been carried out whether with barrel nuts directly embedded into compose material or adding a steel ring (in blue colour Figure 278 right).

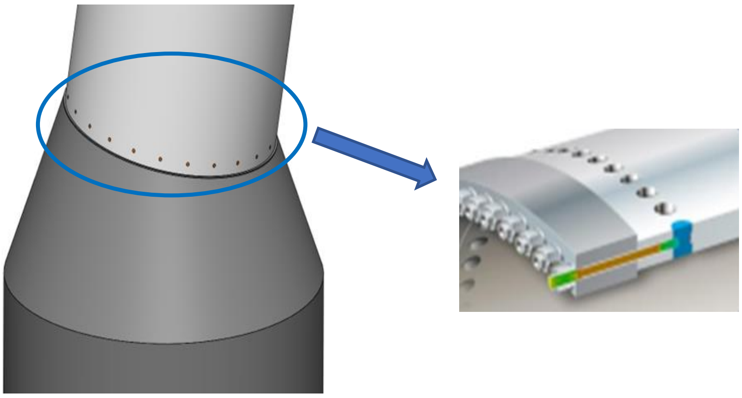


Figure 277 – Overall "IKEA joint" concept

Tower wall has been simulated undergoing thicknesses and shapes shown in Figure 279 and it has been connected to the bolted join in order to obtain a proper simulation. It's important to say that foam that fills the gaps between omega shape and inner and outer skin has been removed because it doesn't improve results and it has an important computational cost.

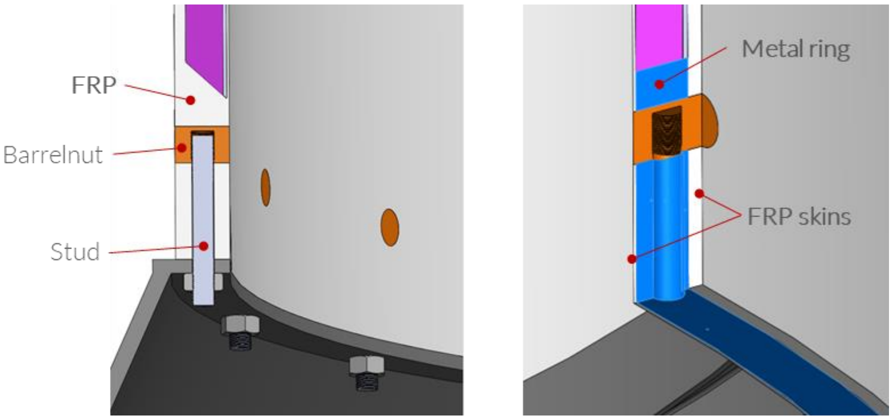


Figure 278 – "Ikea" joint options, without and with steel-ring

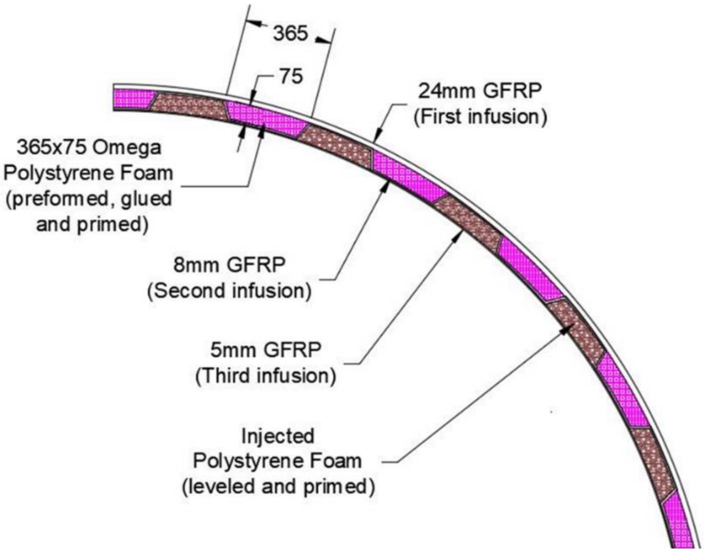


Figure 279 – Tower wall design

5.2.2. Main base ring material selection

Figure 280 illustrates a section of the tower wall (symmetry is applied). This figure shows the steel ring (grey coloured).

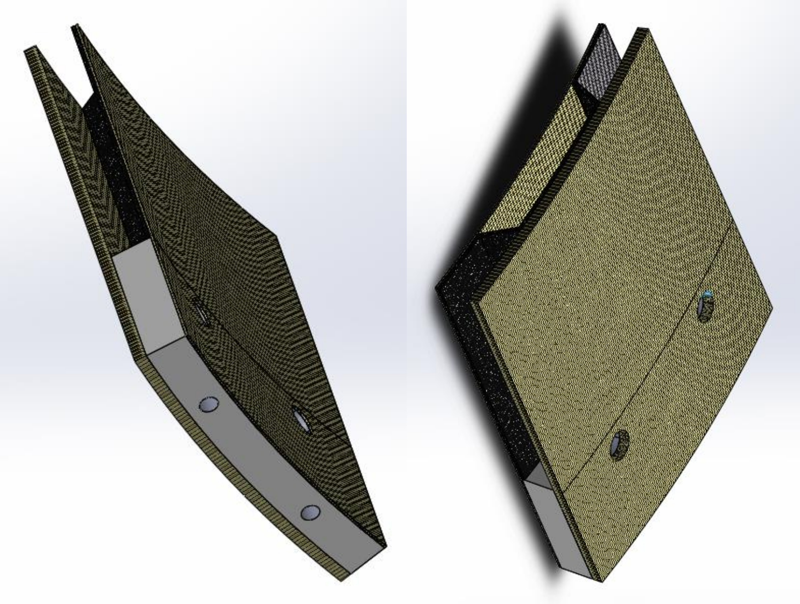


Figure 280 – Tower-column joint with steel-ring model

To select if fitting a steel ring was a good idea or it must be better to build this ring using a laminate lay-out, just the solid corresponding to the ring was tested, first configured as isotropic steel material, and then configured as e-glass plus epoxy composite according to to point 5.3.2.

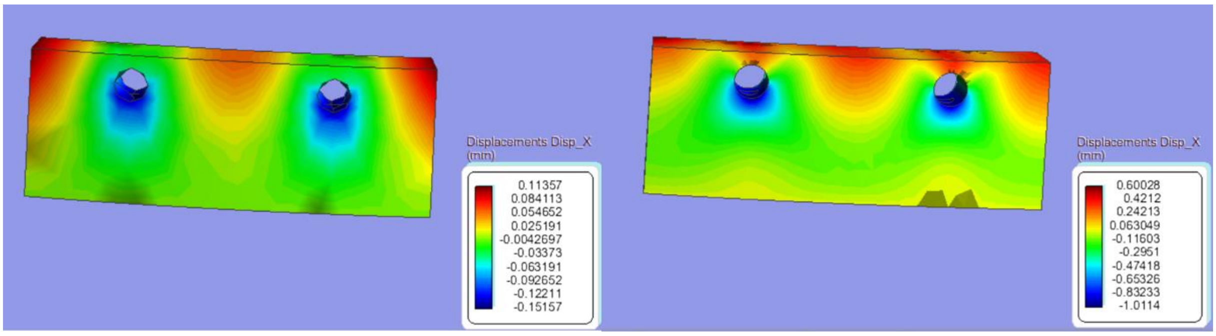


Figure 281 - Vertical ring displacements (mm). Steel (left). Laminate (right)

Figure 281 shows how vertical displacements are significantly higher when the ring is made using laminate. It seems reasonable because due to design constraints, both rings have the same thickness and because of the fact that the laminate that has been used has mostly fibres at +45 and -45 to try to weaken as less as possible the laminate due to the effects of the drilling.

As result, next simulations were carried out fitting a steel ring along the base to assure better performance of the joint.

5.2.3. Number of bolts

To determine how many bolts would be reasonable to install, and since it was determined that installing a steel ring was safer, steel rings with different configurations were simulated. When analyzing these cases, stresses were taken into account instead of displacements.

Even though it has been said that only base rings were tested, a complete section was tested too, to check the main behaviour of the wall, not only the ring. Figure 282 illustrates how stresses at barrel nut holes are extremely high (compared to the rest of the material) if it's expected the whole base to stay in touch with the column and under compression (as it'd be desirable), whereas the rest of the materials show a behaviour under normal parameters.

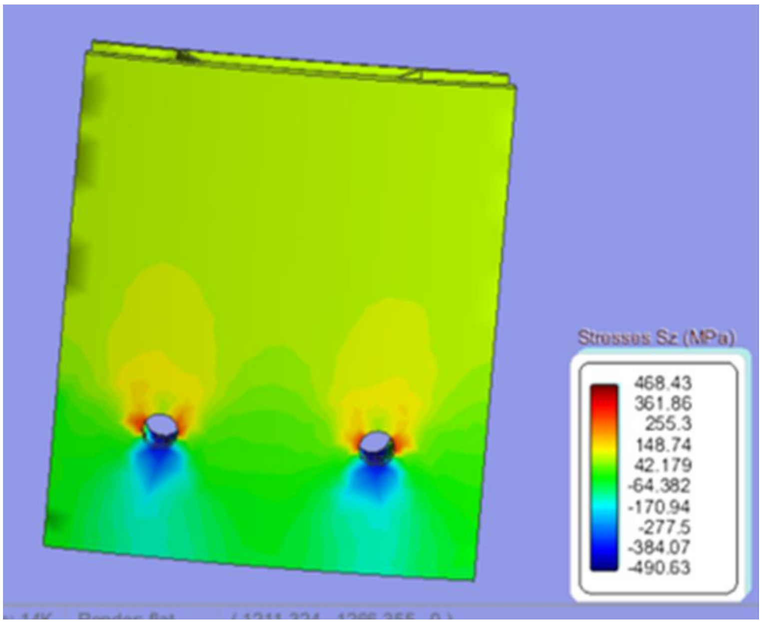


Figure 282 – First simulation, tower-column joint

Then a comparison of different models with different holes configurations were run to try to obtain better spread stresses along the whole ring, but specifically around the barrel nuts holes.

From Figure 283, Figure 284, and Figure 285 can be determined that increasing the number of holes improves the stress spreading along the material, however, a huge number of them concentrates high-stress values between them and it can be a cause of material failure (Figure 285). A little number of them causes high-stress values not only around the holes, but also a good part of the material, so a good compromise solution is one that spreads properly stresses along the material, but holes are not close enough to get the material to a failure, for instance, as illustrated in Figure 284, with 4 holes in this section, that means that al tower connection will feature 100 T-bolts.

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

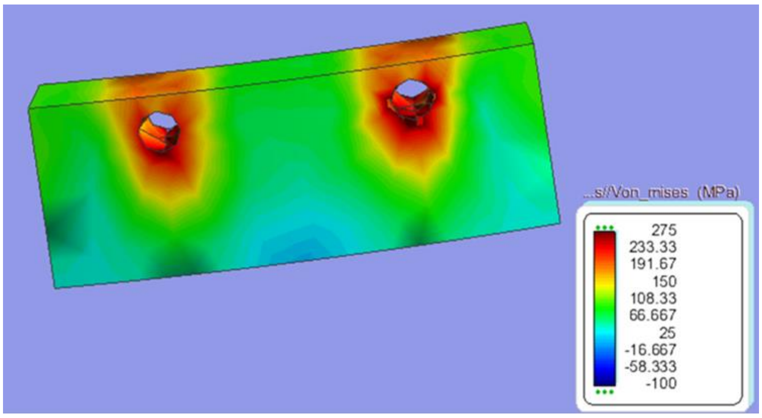


Figure 283 - 2-hole configuration steel ring. VM stresses

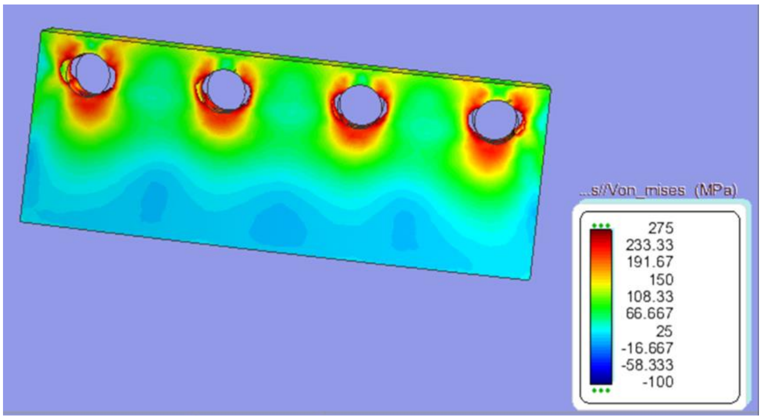


Figure 284 - 4-hole configuration steel ring. VM stresses

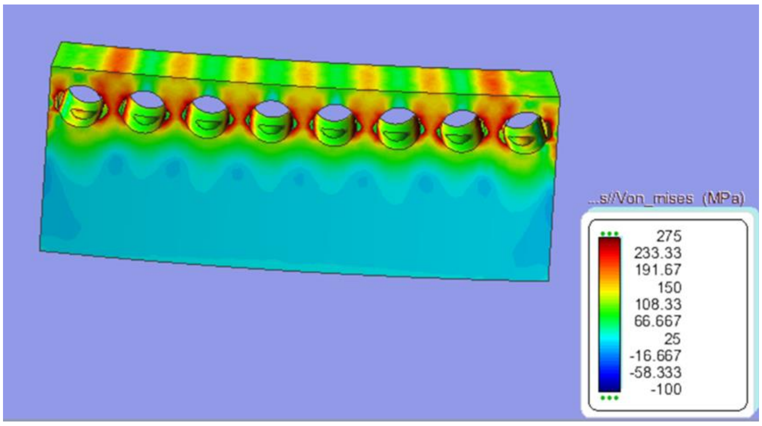


Figure 285 - 8-hole configuration steel ring. VM stresses

It has to be taken into account that a huge number of holes would weaken first infusion and third infusion laminates, so the proposed solution seems reasonable, although it has been seen in prior chapters that some steel commercial towers feature even more number of bolts than proposed here, but they don't have to deal with laminate failures and fibres intersections.

5.3. Composite materials proposal

Some layers and laminates are proposed to obtain an optimal behaviour of the structure. As expected, E-Glass fibre and epoxy resin have been used as the basis of the layers and laminates.

Saertex 1182 g/m^2, unidirectional, E-Glass fabric (material no 30007627) is the base for all simple layers for all laminates, except for the third-infusion or internal wall of the tower, which is based on Saertex 640 g/m^2, unidirectional, E-Glass fabric (material n° 30007510).

As said before, laminates have been designed undergoing a thumb rule of 3:1 proportion between laminate thickness and steel thickness. This procedure has been largely tested for years and it has been validated in prior chapters. Some calculations have been carried out as well, and it has been determined that even though axial stiffness is around 50% lower with selected laminates than with steel, flexural stiffness is more than 200% higher when using these laminates. Maximum stresses are often related to flexural strength; therefore, the design of these laminates can be considered optimal.

EUROCOMP design code has been taken into account when designing these laminates, since at least 12,5% of unidirectional layers are oriented to 90°, 12,5% are oriented to 45°, and 12,5% are oriented to -45%. The rest is oriented to 0°. Designed laminates are symmetric and balanced as well.

5.3.1. Tube to column materials

Main layer characteristics:

Table 79 – Tube to column simple layer main characteristics

Name	Fibre	Resin	Fibre %	in	Fibre mass/m^2 (g/m^2)	Resin mass/m^2 (g/m^2)	Mass/m^2 (g/m^2)	Thickness (mm)	Density
UD1182 @65%(M) E Glass Epoxy	E Glass	Epoxy	65,00	Mass	1.182,00	636,46	1.818,46	0,969	1,876

Table 80 – Tube to column simple layer elastic properties

Name	E1 (MPa)	E2 (MPa)	G12 (MPa)	G13 (MPa)	G23 (MPa)	ν12	ν21
UD1182 @65%(M) E Glass Epoxy	36.321	7.398	3.382	3.382	2.367	0,286	0,058

Table 81 – Tube to column simple layer breaking stresses (MPa)

Name	σ1 T	σ1 C	σ2 T	σ2 C	τ12	τIL1	τIL2
UD1182 @65%(M) E Glass Epoxy	980,68	653,78	39,21	114,67	60,87	59,18	60,87

Tube proposed lay-out:

Table 82 – Tube laminate lay-out

# Groups	Angle
7 x	0
	45
	0
	-45
	0
	90
7 x	90
	0
	-45
	0
	45
	0
total layers	84
thickness (mm)	81,228

Table 83 – Tube Laminate Global Results

Thickness (mm):	81,40	**Weight (kg/m²):**	152,751
Fiber weight (kg/m²):	99,288	Resin weight (kg/m²):	53,463
Ex (MPa):	23.649	Vx (mm):	40,702
Ey (MPa):	14.342	Vy (mm):	40,702
Gxy (MPa):	5.601	[EI]x (N.mm²/mm):	1,085E+9
νx:	0,289	[EI]y (N.mm²/mm):	6,101E+8
νy:	0,175	Density (g/cm³):	1,876

<u>Column proposed lay-out:</u>

Table 84 – Column proposed lay-out

# Groups	**Angle**
4 x	0
	45
	0
	-45
	0
	90
4 x	90
	0
	-45
	0
	45
	0
total layers	48
thickness (mm)	46,416

Table 85 – Column lay-out global results

Thickness (mm):	**46,52**	**Weight (kg/m²):**	**87,286**
Fiber weight (kg/m²):	56,736	**Resin weight (kg/m²):**	30,550
Ex (MPa):	23.649	**Vx (mm):**	23,258
Ey (MPa):	14.342	**Vy (mm):**	23,258
Gxy (MPa):	5.601	**[EI]x (N.mm²/mm):**	2,056E+8
νx:	0,289	**[EI]y (N.mm²/mm):**	1,092E+8
νy:	0,175	**Density (g/cm³):**	1,876

5.3.2. Tower to column materials

Main layer characteristics (first infusion, omega and base layer)

Table 86 – First infusion, omega and base simple layer main characteristics

Name	Fibre	Resin	Fibre %	in	Fibre mass/m² (g/m²)	Resin mass/m² (g/m²)	Mass/m² (g/m²)	Thickness (mm)	Density
UD1182 @65%(M) E Glass Epoxy	E Glass	Epoxy	65,00	Mass	1.182,00	636,46	1.818,46	0,969	1,876

Table 87 – First infusion, omega and base simple layer elastic properties

Name	E1 (MPa)	E2 (MPa)	G12 (MPa)	G13 (MPa)	G23 (MPa)	ν12	ν21
UD1182 @65%(M) E Glass Epoxy	36.321	7.398	3.382	3.382	2.367	0,286	0,058

Table 88 – First infusion, omega and base breaking stresses (MPa)

Name	σ1 T	σ1 C	σ2 T	σ2 C	τ12	τIL1	τIL2
UD1182 @65%(M) E Glass Epoxy	980,68	653,78	39,21	114,67	60,87	59,18	60,87

Main characteristics third infusion layers

Table 89 – Third infusion simple layer main characteristics

Name	Fibre	Resin	Fibre %	in	Fibre mass/m² (g/m²)	Resin mass/m² (g/m²)	Mass/m² (g/m²)	Thickness (mm)	Density
UD640 @65%(M) E Glass Epoxy	E Glass	Epoxy	65,00	Mass	640,00	344,62	984,62	0,525	1,876

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

Table 90 – Third infusion simple layer elastic coefficients

Name	E1 (MPa)	E2 (MPa)	G12 (MPa)	G13 (MPa)	G23 (MPa)	ν12	ν21
UD640 @65%(M) E Glass Epoxy	36.321	7.398	3.382	3.382	2.367	0,286	0,058

Table 91 – Third infusion breaking stresses (MPa)

Name	σ1 T	σ1 C	σ2 T	σ2 C	τ12	τIL1	τIL2
UD640 @65%(M) E Glass Epoxy	980,68	653,78	39,21	114,67	60,87	59,18	60,87

First infusion lay-out:

Table 92 – First infusion lay-out

# Groups	Angle
2 x	0
	45
	0
	-45
	0
	90
1x	0
2 x	90
	0
	-45
	0
	45
	0
total layers	25
thickness (mm)	24,175

Table 93 – First infusion laminate global results

Thickness (mm):	**24,23**	**Weight (kg/m²):**	**45,462**
Fiber weight (kg/m²):	29,550	**Resin weight (kg/m²):**	15,912

Ex (MPa):	24.156	**Vx (mm):**	12,114
Ey (MPa):	14.083	**Vy (mm):**	12,114
Gxy (MPa):	5.512	**[EI]x (N.mm^2/mm):**	2,992E+7
νx:	0,289	**[EI]y (N.mm^2/mm):**	1,409E+7
νy:	0,169	**Density (g/cm^3):**	1,876

Omega lay-out:

Table 94 – Omega lay-out-

# Groups	**Angle**
1 x	0
	45
	-45
	90
1x	0
1 x	90
	-45
	45
	0
total layers	9
thickness (mm)	8,703

Table 95 – Omega global results

Thickness (mm):	**8,72**	**Weight (kg/m^2):**	**16,366**
Fiber weight (kg/m^2):	10,638	**Resin weight (kg/m^2):**	5,728
Ex (MPa):	19.424	**Vx (mm):**	4,361
Ey (MPa):	16.388	**Vy (mm):**	4,361
Gxy (MPa):	6.341	**[EI]x (N.mm^2/mm):**	1,351E+6
νx:	0,290	**[EI]y (N.mm^2/mm):**	6,056E+5
νy:	0,244	**Density (g/cm^3):**	1,876

Third infusion lay-out:

Table 96 – Third infusion lay-out

# Groups	Angle
1 x	0
	45
	-45
	0
	90
1 x	90
	0
	-45
	45
	0
total layers	10
thickness (mm)	5,25

Table 97 – Third infusion global results

Thickness (mm):	**5,25**	**Weight (kg/m²):**	**9,846**
Fiber weight (kg/m²):	6,400	**Resin weight (kg/m²):**	3,446
Ex (MPa):	21.094	**Vx (mm):**	2,624
Ey (MPa):	15.571	**Vy (mm):**	2,624
Gxy (MPa):	6.019	**[EI]x (N.mm²/mm):**	2,985E+5
νx:	0,290	**[EI]y (N.mm²/mm):**	1,248E+5
νy:	0,214	**Density (g/cm³):**	1,876

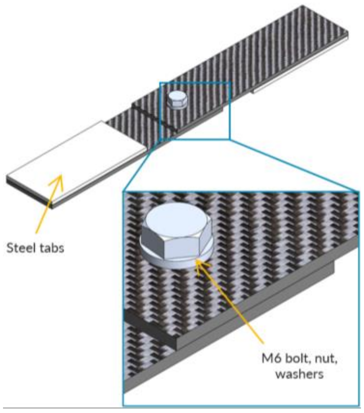
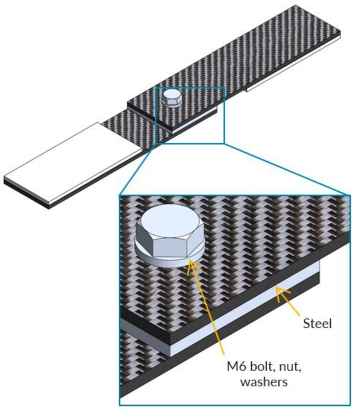
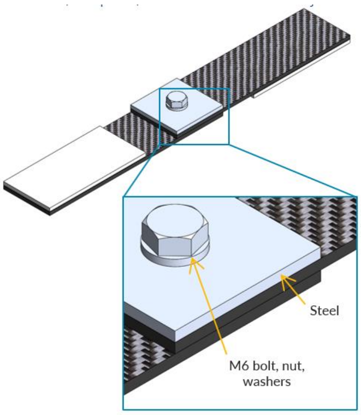
6. Test campaign

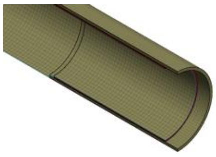
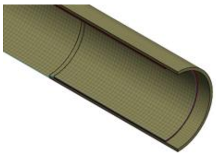
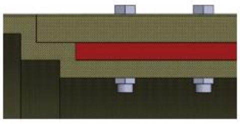
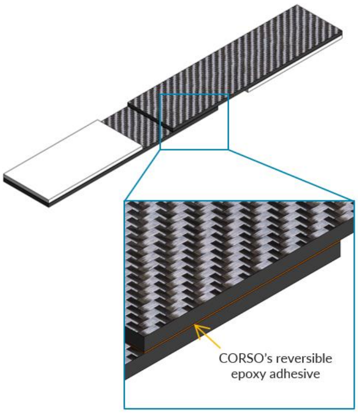
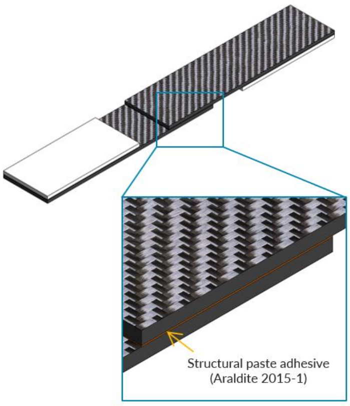
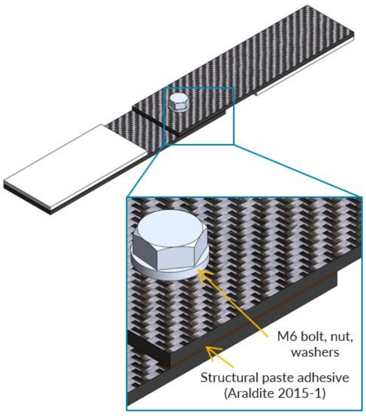
According to planned, the evaluation of the different connections will be completed (in task 2.3) after conducting an experimental campaign that will allow for further comprehension of the behaviour of the main connection types. Since this test campaign will be performed at coupon level and cannot be scalable to the final connections' geometry, the primary aim will be to perform a comparison between the different joining methods (bonded, bolted, hybrid), understand their behaviour under quasi-static tensile loads and make a correlation between the simulations performed in the previous subtask and these experimental results. These conclusions can then be used as an important input to feed the validation/prediction models and to support decisions during the design phase of the actual platforms.

6.1. Test plan

Table 98 illustrates the six geometries of specimens that were established to replicate – at coupon level – some of the main connections proposed in Chapter 3.

Table 98 – Specimens to be used in the test campaign

Connection to replicate	Bolted sleeve connection (no ring)	Bolted sleeve connection (internal ring)	Bolted sleeve connection (external ring)
			
Suggested small-scale specimen	Shear bolted joint **(configuration n.° 1)**	(Adapted) double shear bolted joint **(configuration n.° 2)**	(Adapted) double shear bolted joint **(configuration n.° 3)**
			

Connection to replicate	Overlap bonded connection	Overlap bonded connection	Hybrid overlap connection
			
Suggested small-scale specimen	Bonded single lap shear joint **(configuration n.° 4)**	Bonded single lap shear joint **(configuration n.° 5)**	Hybrid (bonded) shear bolted joint **(configuration n.° 6)**
			

These small-scale specimens will be tested under tensile loads, and it was agreed, after ULIM's suggestion, to use the geometry of the specimens defined in the ASTM D5961 [93], as illustrated in Figure 286. Figure 287 highlights some of the other specimens' dimensions.

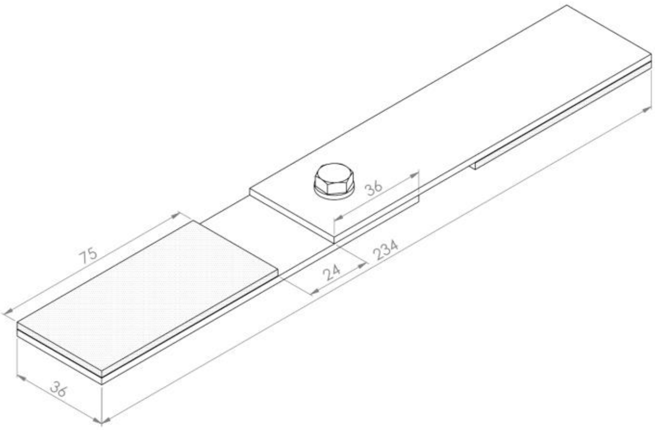


Figure 286 – ASTM D5961 specimens' geometry and main dimensions

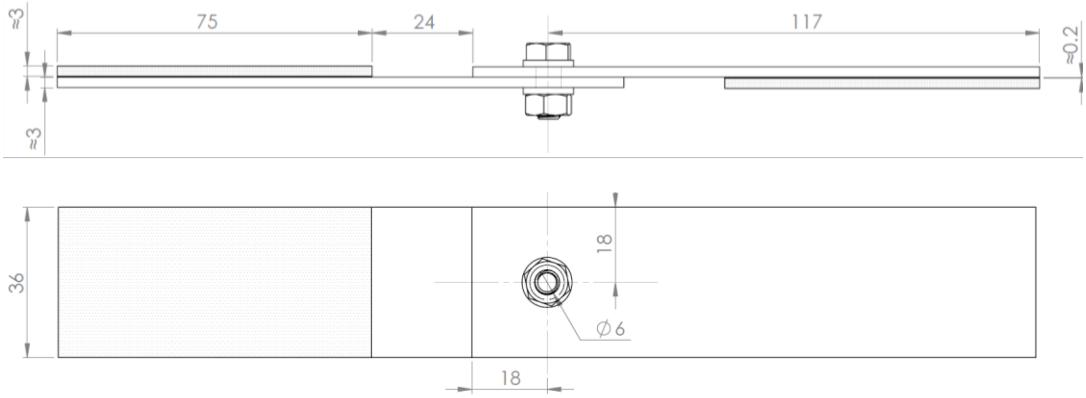


Figure 287 – Additional specimens' dimensions

Although not specific for the evaluation of shear strengths of differently connected adherends, this standard was chosen over others (such as ASTM D1002-10 [94] or ASTM D5868-01 [95], both very commonly used to assess lap shear strengths of single lap joints) because of its larger width which allows for greater spacing between the bolt and the adherends' limits. Therefore, a total of 36 rectangular coupons with 36x135 mm were manufactured, thus creating 18 connection specimens that will be tensile tested (3 for each configuration).

The results expected from this experimental campaign are the ones illustrated in Table 99.

Table 99 – Expected results from the experimental campaign

	Specimens					
	1	2	3	4	5	6
Comparison between CORSO's reversible adhesive and an OTS aerospace-grade structural adhesive				■	■	
Comparison between bolted, bonded and hybrid joints	■				■	■
Comparison between sleeve joints with no ring, internal ring and external ring	■	■	■			
Find the worse and better connection in terms of shear strength	■	■	■	■	■	■
Other considerations about the connection's behaviour under tensile loads	■	■	■	■	■	■

Regarding their fatigue performance, it was agreed that this would be moved forward to task 2.4, since it is already focused on the fatigue performance of the connections, so it would be redundant to perform it in subtask 2.3.4 as well.

6.2. Specimens' preparation

In order to manufacture the small-scale connection specimens, a total of 36 CFRP coupons with 36x150 mm had to be produced. These were cut out from three larger plates of 200x635, which in turn were manufactured by vacuum infusion.

The materials used were the same that will be used to manufacture the W2Power prototype towers. Hence, the laminate is constituted by the CFRP multidirectional fabrics (ZOLTEK PX35 50K +/-45° and 0/90°, both with 600gr/m^2 [96]) and the resin SR InfuGreen 810 (hardener SD 4771 [97]). Both materials are illustrated in Figure 288 and Figure 289, respectively. Because the fabrics were provided by iXblue which at that time only had available the +/-45° fabric, the 0/90° layers were cut from the same material (ID PX35MD060A-127) by cutting it at a 45° angle – resulting in layers with 0° fibres in one side and 90° fibres on the opposite stitched side.

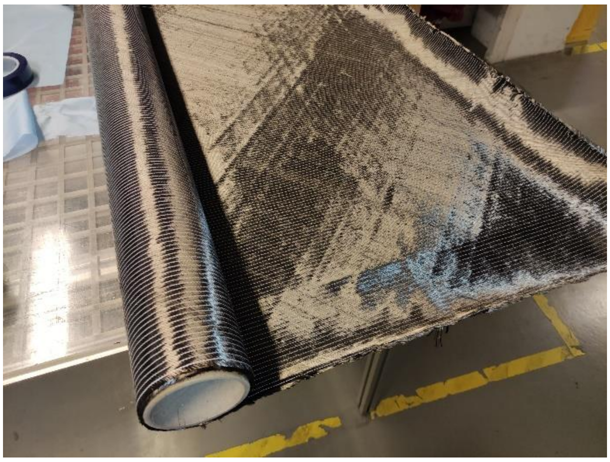


Figure 288 – Zoltek PX35 50K +/-45° carbon fabric

Figure 289 – SR InfuGreen a810 and SD 4771

It was decided to use a quasi-isotropic, symmetric and balanced stacking sequence of the carbon fibres, as this would allow for constant strength and stiffness of the material regardless of the direction in which it is loaded, a typical layout and very close to the one that will be used on the demonstrators. The complete sequence is the one indicated in Figure 290 and was decided after the conclusions from the previous chapter.

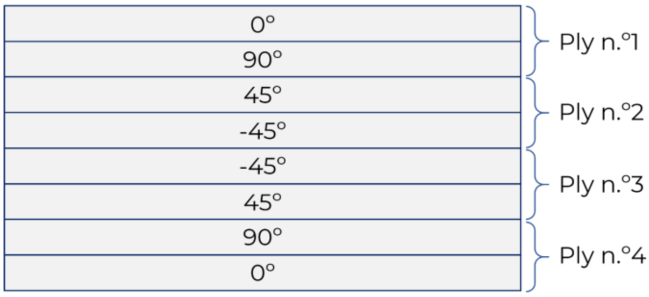


Figure 290 – Stacking sequence

Concerning the setup, a prismatic steel toll was used, which is displayed in Figure 291, along with its respective dimensions. Figure 292 depicts the complete setup, including the resin container, the resin inlet and outlet hoses, the resin trap and the vacuum pump.

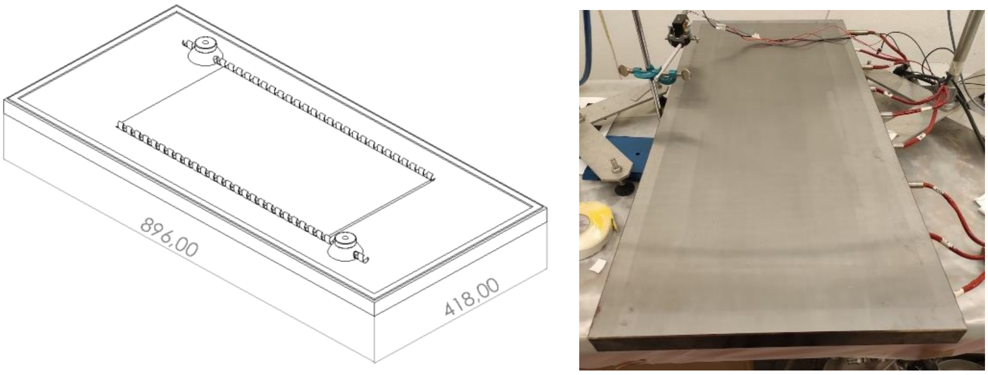


Figure 291 – Illustration of the tool

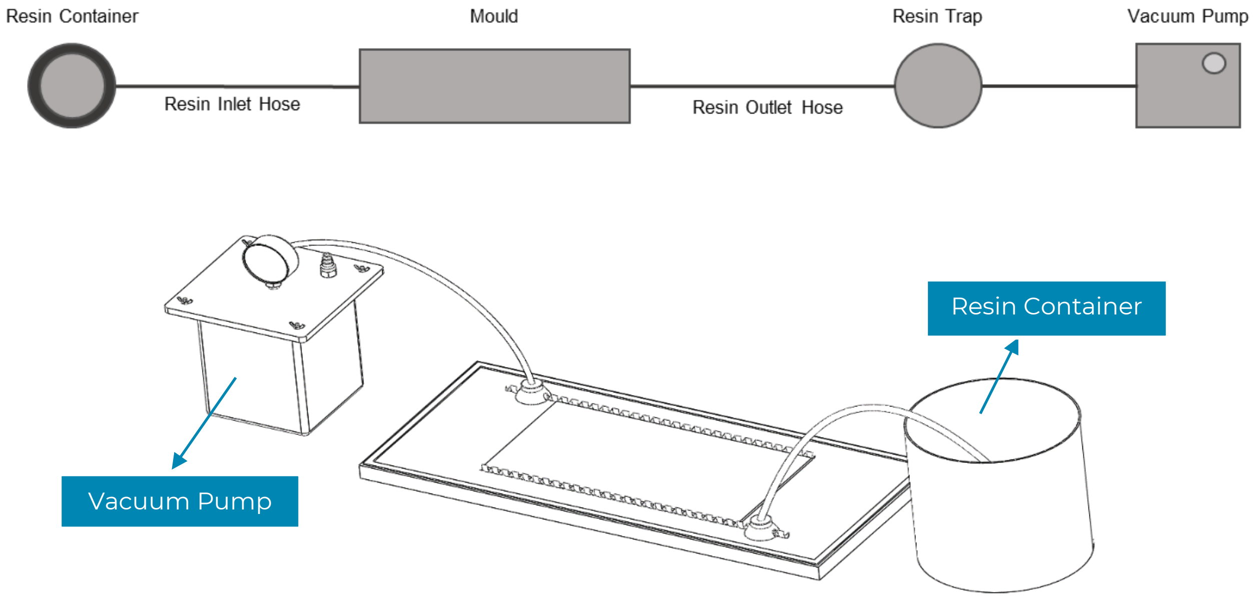


Figure 292 – Representation of the used vacuum infusion setup

After gathering the necessary components to perform the vacuum infusion process, the steps presented in Table 100 were followed. First, the mould has been degreased with acetone, then it was cleaned with a mould cleaner and a cotton cloth. Subsequently, it was applied a mould sealer (Loctite® Frekote® B-15), 3 coats of release agent (Loctite® Frekote® 770-NC) with an interval of 10 minutes between coats and a final wax coating.

Table 100 – Procedure steps of the vacuum infusion process

Procedure	
1	Preparation of the mould
2	Placement of the bottom peel ply
3	Cutting and stacking of the carbon fibre layers
4	Placement of the spiral wraps and T-fittings
5	Placement of the peel ply and flow distribution mesh
	Placement of the flow distribution mesh covering about 70% of the parts' surface
6	Preparation and sealing of the vacuum bag
7	Connection of the resin inlet and resin outlet hoses
8	Clamping off the resin line and switch on the vacuum pump
9	Apply vacuum and test for leaks/losses of vacuum pressure
10	Open the resin line
11	Resin flow until it impregnates the full length and width of the carbon fibre layers
12	Clamping off the resin line
13	Cure of the CFRP composite
14	Demoulding of the cured laminate sheet

The following step was placing a layer of peel-ply before the carbon fibre layers, which were then cut and stacked according to the desired sequence (Figure 290). The spiral wrap (Figure 293) and T-fittings (Figure

293) were placed next to the stacked fibres, as they are responsible for allowing and facilitating the resin flow. A peel ply was also placed after the last layers of fabric, and a distribution mesh above this upper peel ply. Afterwards, sealant tape was bonded to the vacuum bag, which was then placed above the blue adhesive tape (Figure 293) that was on the tool's surface. Carefully, the tape was pressed against the tool to assure complete air tightness. The system was connected to a vacuum pump, which was switched on to compact the components and fix present leaks. The illustration of the final vacuum bag setup can be found in Figure 294.

Figure 293 – (a) Spiral Wrap; (b) T-fitting; (c) Airtech Flashbreaker 1 Tape

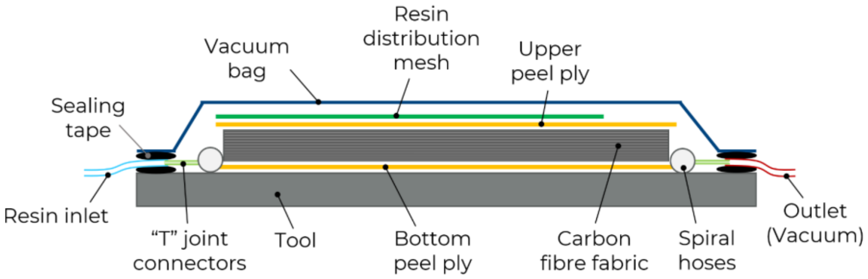


Figure 294 – Vacuum bag setup (components not at scale)

The next step concerned the preparation of the resin. As the laminate is composed of four layers (600gr/m^2), it was recommended to use approximately 700 g of resin, with a mix ratio (epoxy to hardener) of 100/29, calculated using the formulas in Table 101. Once the mixture was prepared, the resin inlet hose was immersed in the resin container and the vacuum pump (Figure 295) was switched on (vacuum pressure of -0,5 bar), leading to the beginning of the impregnation of the fibres by the resin. The infusion process was performed at ambient temperature (as well as the tool) and is illustrated in Figure 296.

Table 101 – Formulas

	Formulas
Number of layers	[Fibre Fraction Volume x Fibre Density x Desired Thickness] / Areal Weight
Resin Weight	[Resin Ratio / (Resin Ratio + Hardener Ratio)] x Desired Weight
Hardener Weight	[Hardener Ratio / (Resin Ratio + Hardener Ratio)] x Desired Weight

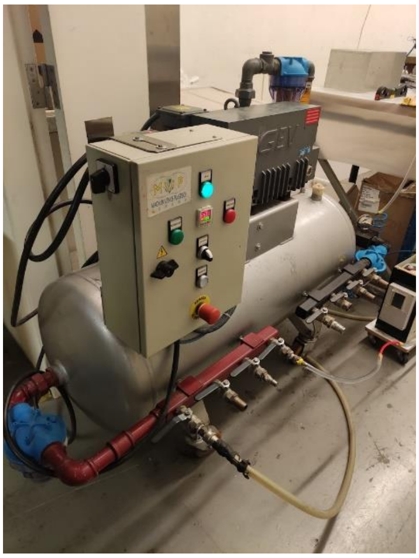


Figure 295 – Magnus Venus Plastech vacuum pump

About 10 minutes after the resin has impregnated the full length and width of the fabric, the resin inlet was ceased and the sample was left to cure. According to the datasheet of SR InfuGreen 810 and SD 4771, at room temperature, the composite cures in 24 hours, nonetheless, the plates were only demolded after 48 hours. After demolding, the excesses and the 36x150 mm coupons were cut off using an abrasive diamond disc (Figure 297).

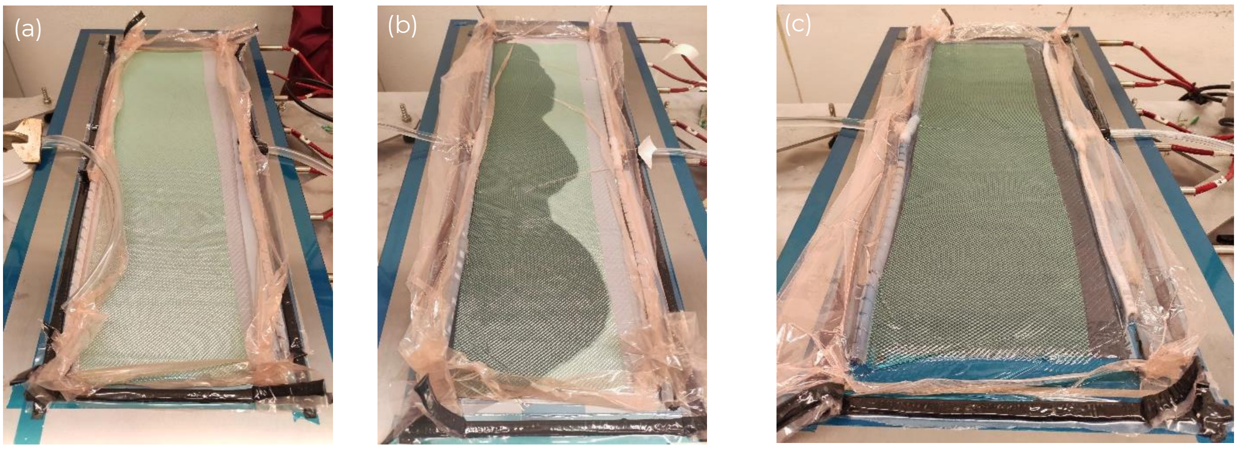


Figure 296 – Infusion process: (a) Before infusion; (b) During infusion; (c) After infusion

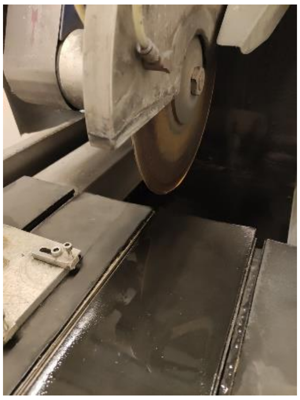


Figure 297 – Abrasive diamond disc

The final coupons have an average thickness of 3,22 mm (standard deviation 0,14). On the side in contact with the tool (controlled surface) the peel ply was maintained and will only be removed just prior to bonding (in case of bonded or hybrid connections) to protect the bonding surface from water ingression or any contaminants during cutting and subsequent procedures, and will also be the method used for surface treatment. Although other surface preparations methods, such as abrasion, have shown to lead to higher bonding strengths [98], this was decided to be the simplest method to provide a clean and roughened surface with high repeatability and satisfactory results, which is why it continues to be the most frequently specified surface preparations for bonding fiber-polymer composites [99].

6.2.1. Bolted specimens (configurations n°1, n°2 and n°3)

Specimens from the configurations n°1, n°2 and n°3 were prepared by drilling a ⌀6 mm hole in the place defined by the ASTM D5961 (Figure 287). To ensure this, a special drilling jig was designed and manufactured by FFF (Fused Filament Fabrication) using a Markforged Onyx One desktop 3D-printer [100] and Onyx™ filament (nylon filled with micro carbon fibre [101]). This jig (illustrated in Figure 298) slides in the coupon to drill with a very close fit and provides a single path for the drill bit, resulting in well-positioned holes even when using a manual pneumatic drilling machine.

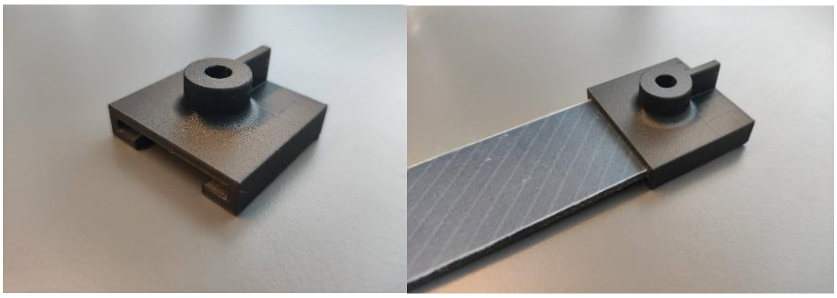


Figure 298 – Drilling 3D-printed jig

Holes were then drilled using this jig, a conventional 6 mm carbide drill bit, a wood back plate and paper tape on both sides of the coupon (Figure 299), resulting in well-defined holes without visible delamination or chipping (Figure 300).

Figure 299 – Drilling process

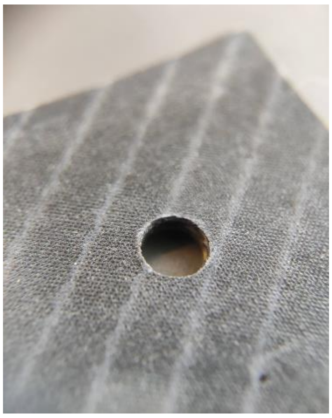


Figure 300 – Example of resulting hole

The coupons were then bolted using hex cap M6x20mm zinc plated carbon steel (quenched and tempered) class 8.8 bolts (ISO 4017, DIN933), hex nuts and A4 stainless steel washers on both sides. The bolts were torqued to 0.5 Nm using a calibrated torque wrench (Figure 301), which according to [102] is the minimum repeatable torque that could be applied and corresponds to a "finger-tight" torque value (finger-tight represents the worst-case scenario of a bolt loosened during fatigue loading from an initial fully torqued condition).

Figure 301 – "Snap-on" calibrated torque wrench

6.2.2. Bonded specimens (configurations n°4 and n°5)

A bonding setup tool was made using 3 mm steel plates in order to guarantee that the bondine thickness is constant and around 0,2 mm, as suggested in the literature [103]. This will be achieved by using shim tapes, assuring that the gap between the bottom and upper adherends is the desired adhesive thickness value (Figure 302). The alignment of the adherends will be assured visually and by using blue adhesive tape (Airtech Flashbreaker® 1) as illustrated in Figure 303.

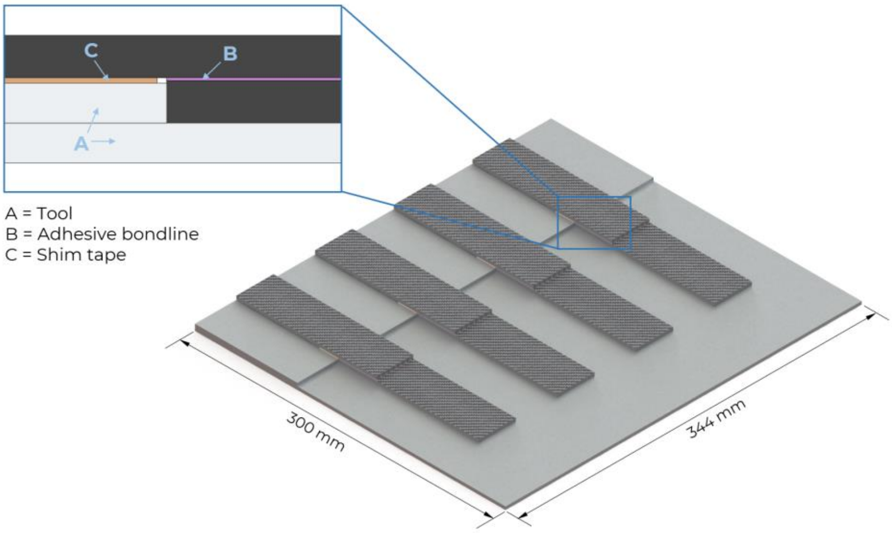


Figure 302 – Bonding setup tool

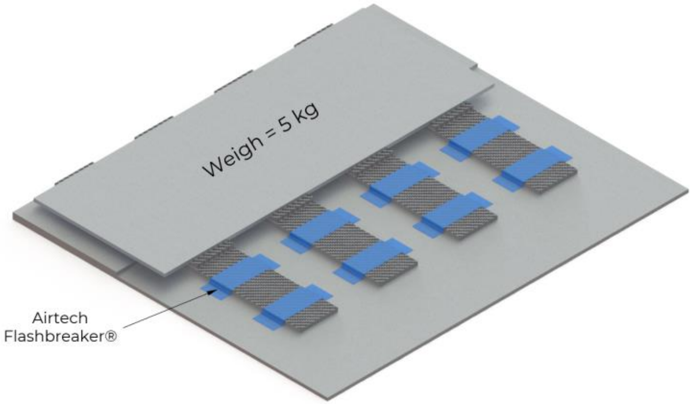


Figure 303 – Bonding setup during curing

As previously indicated in Table 98, the single lap bonded joints of the specimens with the configuration n°4 were made using the reversible adhesive from Corso Magenta, while the specimens with the configuration n°5 used a marine-grade adhesive Araldite® 2015-1 [104].

The reversible adhesive from Corso Magenta is a 3-component epoxy adhesive, which apart from Figure 304, no further details of its composition can be shared at this moment because of intellectual property.

Figure 304 – Corso Magenta reversible adhesive components

The Araldite® 2015-1 is a two-component paste structural adhesive, thixotropic and non-sagging up to 10 mm thickness. It can be cured at room temperature and is ideal for bonding GRP, SMC and dissimilar substrates. It has also a very good resistance to weathering, which is why it is commonly used in marine construction (such as in hull-to-deck bonding in shipbuilding) [105]. Its lap shear strength at 25°C (A501) is > 15 MPa – other typical cured properties are indicated in the technical datasheet [104], [106].

Immediately after removing the peel-ply, the Araldite® 2015-1 adhesive was applied directly into the surface using an adhesive dispensing gun and mixed through the provided nozzle (Figure 305). After application, the adhesive was laid out using a wooden spatula to cover the entire bonding surface with a uniform thickness, after which the two adherends were pressed together in the bonding jig. The time between the opening of the cartridge and the last application was around 30 minutes, which is less than the adhesive pot life at room temperature [104].

Figure 305 – Adhesive dispensing gun and nozzle [107]

Regarding the Corso Magenta reversible adhesive, and in order to help with the mixing of the components, the paste epoxy (component A) was heated in a laboratory oven Venticell *404 standard* [108], at 50°C and for 10 minutes, reducing its very high viscosity. Nevertheless, after the first observations it was possible to conclude that the epoxy returned to its original viscosity (similar to caramel) just after one minute at room temperature (time between the removal from the oven and the transport to the scale), which resulted in being impossible to mix it with the hardener (component B).

Figure 306 – Epoxy (Component A) becoming solidified after a few minutes at T_{amb}.

To overcome this, the mixing process was done using a laboratory hot plate (set to 50°C) which has helped in this process. After obtaining a close-to-homogeneus paste (A+B), the component C was added and mixed for 10 minutes. The adhesive was then placed into the adherends (Figure 307) following a similar process to the one carried for the Araldite® 2015-1. Because of the reasons mentioned above, the process was far from, especially because the difficulties in mixing might not guarantee acceptable and repeatable adhesive preparations.

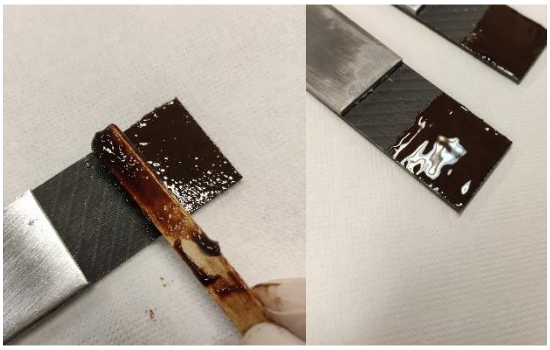


Figure 307 – Reversible adhesive application

The same bonding setup was used for configurations n°4 and n°5, but as recommended by the adhesives' manufacturers, the specimens with the reversible adhesive were cured at 40°C for 24 hours, while the ones bonded with the Araldite® 2015-1 were cured at 40°C for 16 hours. The temperature was controlled by placing all the setup in a laboratory oven Venticell *404 standard* [108]. All specimens were allowed to cool down before testing.

6.2.3. Hybrid specimens (configuration n°6)

The hybrid specimens (configuration n°6), being both bolted and bonded, were prepared without using the bonding setup and, instead, applying the adhesive just before bolting. Although this might result in challenging control of the bondline, it was found that this method is the most viable for on-site assembly, as it is unfeasible to have a real scale bonding jig setup while assembling the different platform modules. A similar process chain to that mentioned in Table 37 was followed – removing the peel ply, applying the adhesive, overlapping the coupons, placing the fastener and then curing the adhesive.

The same bolting torque of 0.5 Nm was applied, being observed a squeeze out of the adhesive to the final thickness of the adhesive of around 0,1 mm.

6.2.4. Tabbing and painting for DIC

Tabbing of the specimens was made by bonding steel tabs (36x75 mm) – cut from a 3 mm plate using a sheet metal shearing guillotine machine, abraded with 120 grit sandpaper and cleaned with acetone – to the CFRP adherends using the paste adhesive Araldite® 2015-1 which was cured at 40°C for 16 hours while applying pressure with plastic spring clamps.

The specimens were also prepared for Digital Image Correlation (DIC) by spraying the side surface (through the thickness) with a high-contrast pattern with black dots over a white coat, as illustrated in Figure 308. The resulting speckle pattern will allow for the DIC software to register the changes in the position of these dots during the deformation period, calculating the deformed shape and allowing the derivation of the deflections and strains of the investigated object, if revealed necessary.

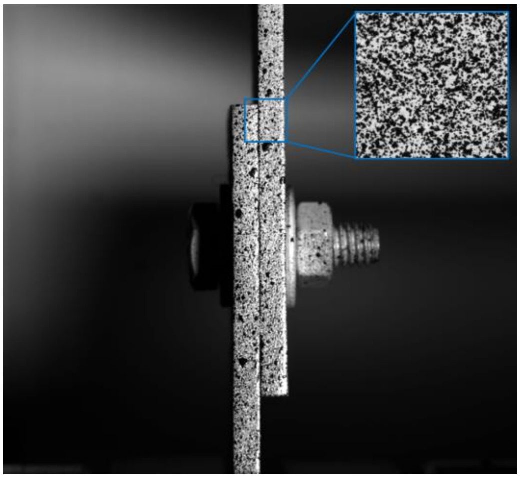


Figure 308 – Speckle pattern for DIC

6.3. Experimental campagin

The experimental campaign was conducted by INEGI, using a universal testing machine Instron 5900R, with a load cell of 200kN and hydraulic grips (clamping pressure of 100 MPa), as illustrated in Figure 309.

Figure 309 – Instron 5900R and setup

Quasi-static tensile tests were performed with a crosshead speed of 2mm/min and following the guidelines from ASTM D5961 [93].

6.4. Results

The resulting load-displacement curves will now be presented individually for the six different connection configurations. A detailed analysis of the failure modes will also be made, and subsequently making a comparison between all configurations in terms of maximum load, displacements and stiffness at maximum load, among other relevant observations/characteristics.

6.4.1. Configuration n°1

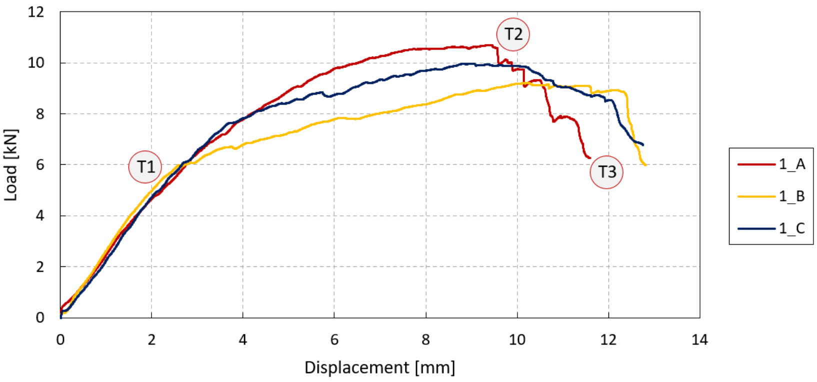


Figure 310 – Load-displacement curves obtained from configuration n°1 specimens

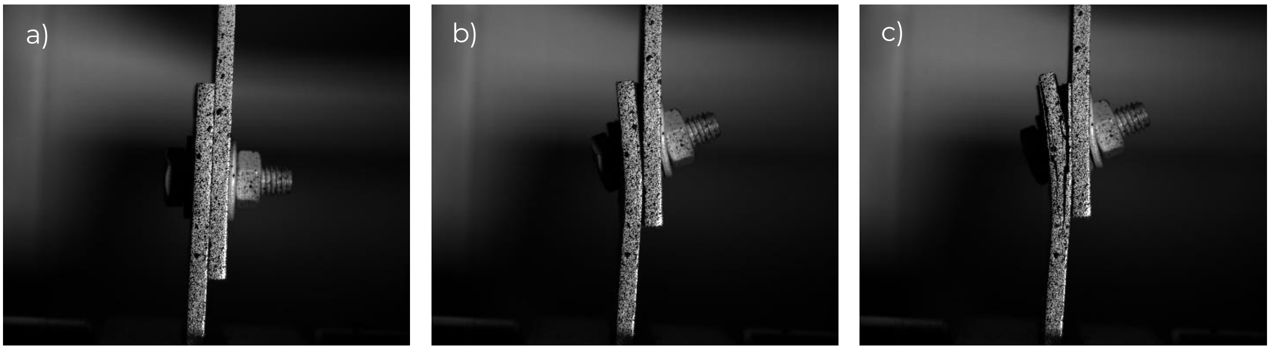


Figure 311 – DIC captures at different timestamps of specimen 1_A: a) T1; b) T2; c) T3

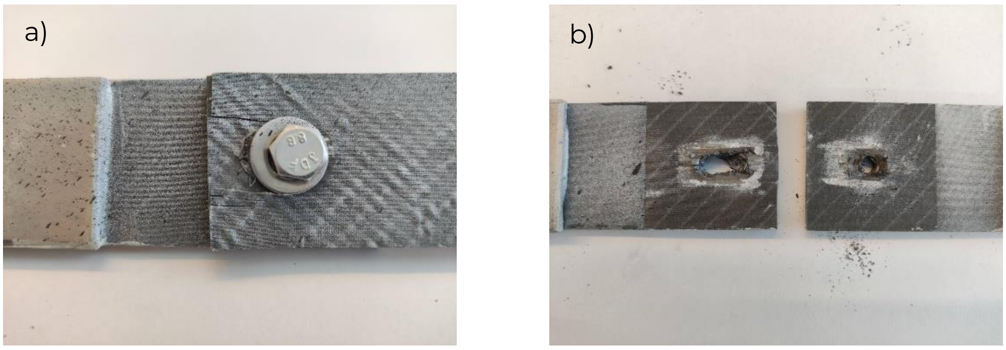


Figure 312 – Specimens' failure surfaces: a) Exterior; b) Interior

Following the observations presented in Figure 310 to Figure 312, it is possible to conclude that the main driving failure mechanism was bearing (Figure 313 a)), which has, in two out of three specimens, led to intralaminar failure within the outer 0° plies (due to fibre/matrix interface failure), as well as interlaminar failure (delamination) between the 0° and 90° plies (Figure 313 b)). As observed in Figure 311 c), fracture then progresses throughout all layers of the laminate. The main types of fibre failure in drilled FRP substrate are illustrated in Figure 314.

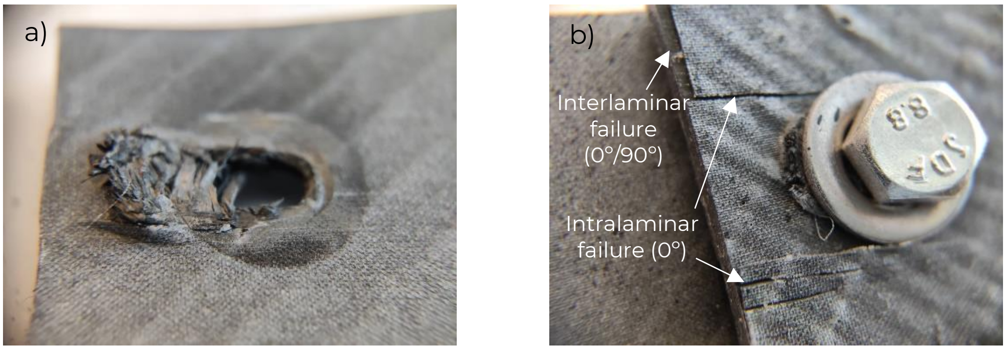


Figure 313 – Specimens' failure surfaces: a) Bearing; b) Laminar failure

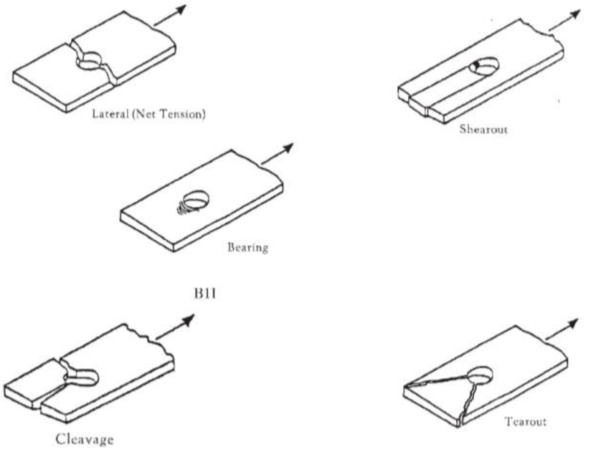


Figure 314 – Types of fibre failure in drilled FRP substrate

6.4.2. Configuration n°2

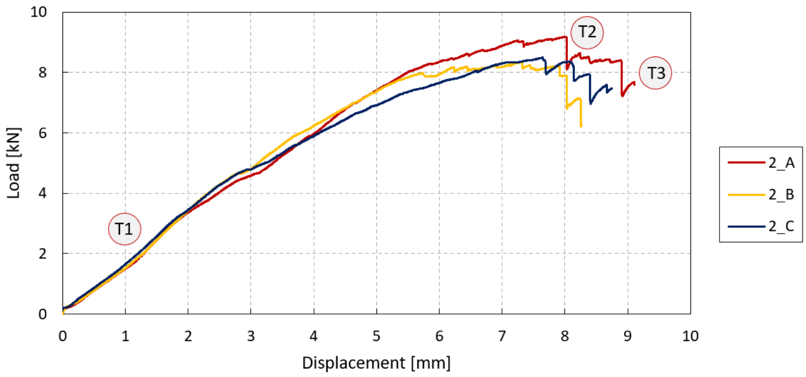


Figure 315 – Load-displacement curves obtained from configuration n°2 specimens

Figure 316 – DIC captures at different timestamps of specimen 2_A: a) T1; b) T2; c) T3

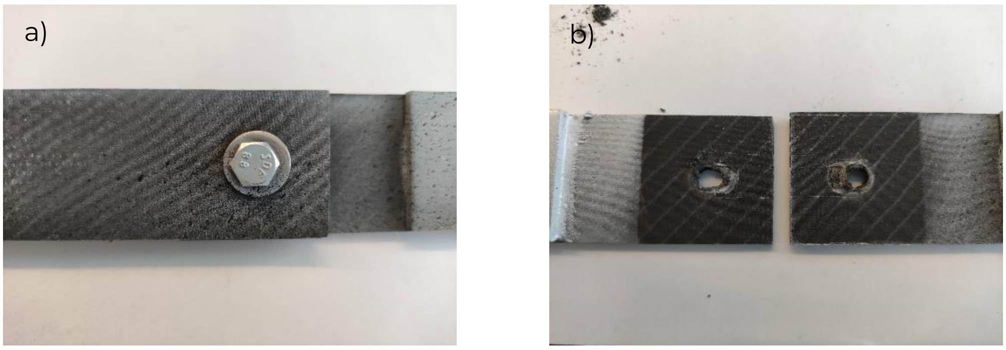


Figure 317 – Specimens' failure surfaces: a) Exterior; b) Interior

Following the observations presented in Figure 315 to Figure 317, it is possible to conclude that the main driving failure mechanism was again bearing of the carbon fibre laminate, but this time not typically resulting in interlaminar failure (except in one specimen, illustrated in Figure 318). A small degree of intralaminar failure of the outer 0° plies (between tows) was observed in all three specimens but just on the contacting surfaces of the specimens. None of the steel sleeves was damaged during the test duration. Significant misalignment (horizontally) between the three components was observed (Figure 316) due to cleavage (mode I) and sliding (mode II).

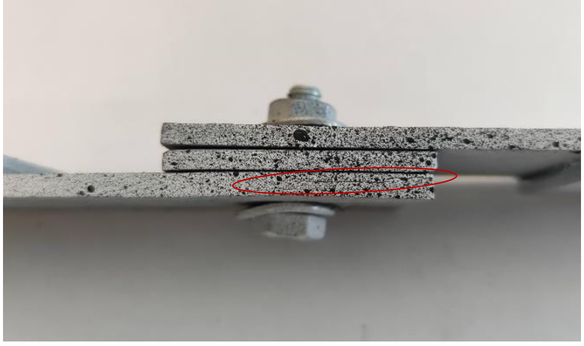


Figure 318 – Interlaminar failure

6.4.3. Configuration n°3

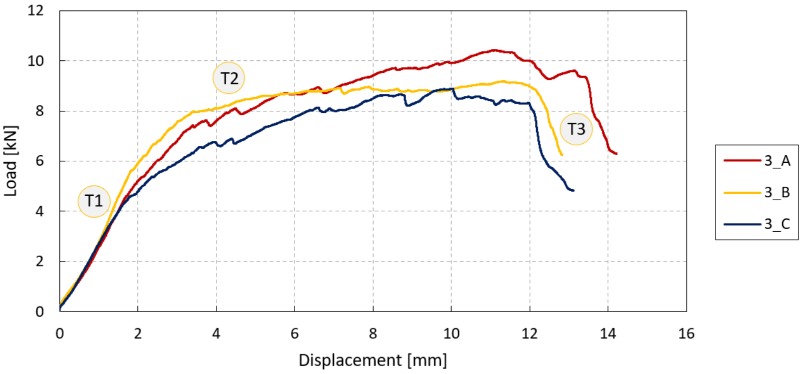


Figure 319 – Load-displacement curves obtained from configuration n°3 specimens

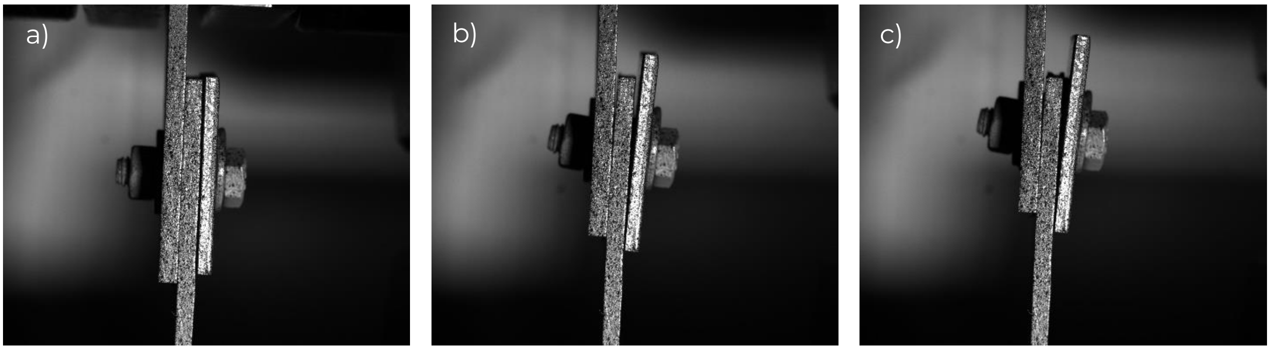


Figure 320 – DIC captures at different timestamps of specimen 3_B: a) T1; b) T2; c) T3

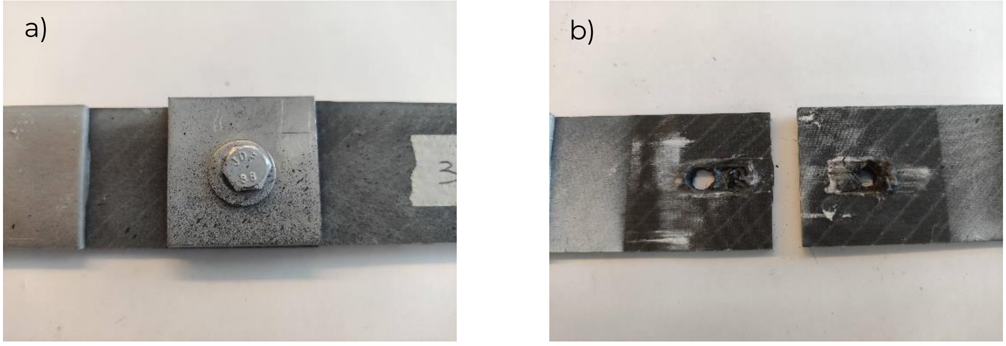


Figure 321 – Specimens' failure surfaces: a) Exterior; b) Interior

Following the observations presented in Figure 319 to Figure 321, it is possible to conclude that the main driving failure mechanism was one again bearing (Figure 322). None of the specimens has undergone laminar failure outside the bearing zone, and none of the steel sleeves was damaged during the test duration. Significant misalignment (horizontally) between the three components was observed (Figure 316) due to cleavage (mode I) and sliding (mode II).

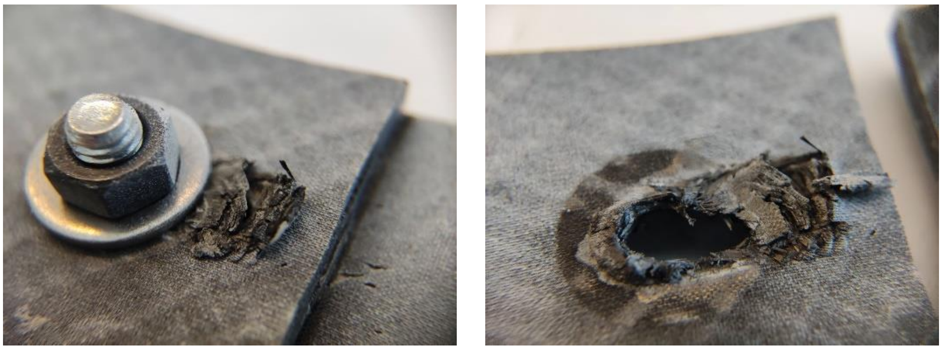


Figure 322 – Specimens' failure surfaces – bearing failure

6.4.4. Configuration n°4

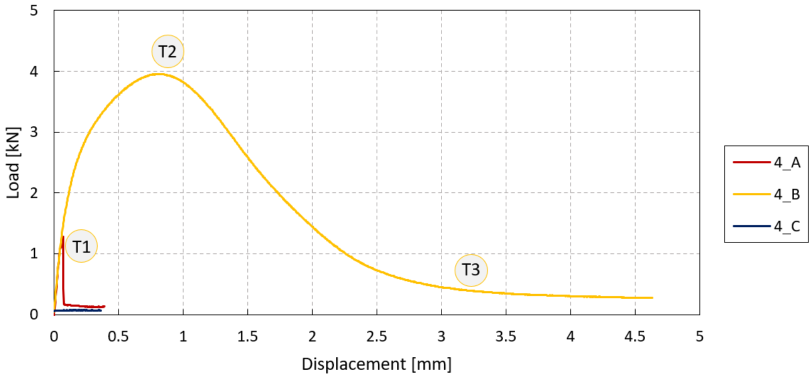


Figure 323 – Load-displacement curves obtained from configuration n°4 specimens

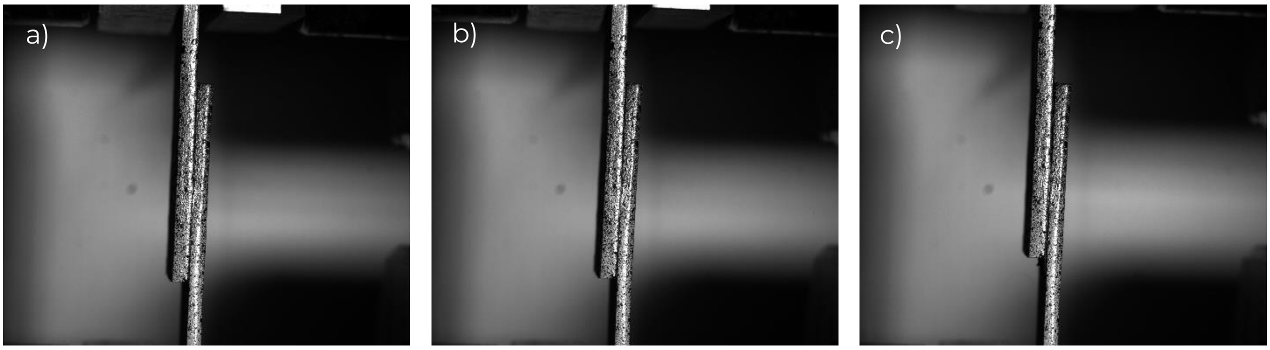


Figure 324 – DIC captures at different timestamps of specimen 4_B: a) T1; b) T2; c) T3

Regarding this configuration, which is consisted of single lap joints bonded with the reversible adhesive from Corso Magenta, only one specimen can be considered valid. Despite being presented in Figure 323, specimen 4_A has failed very prematurely (only reaching a load of 1.28 kN) which can be explained by poor preparation of the adhesive as explained in 6.2.2. The results from sample 4_B indicate a moderate ductile behaviour but poor strength of the adhesive. After inspecting the fractured surfaces, a surface indicating cohesive failure was found, with adhesive on both specimens – meaning that the peel ply surface treatment was effective, and the adhesive strength was the limiting factor that led to failure within the adhesive. Other types of failure are indicated in Figure 325.

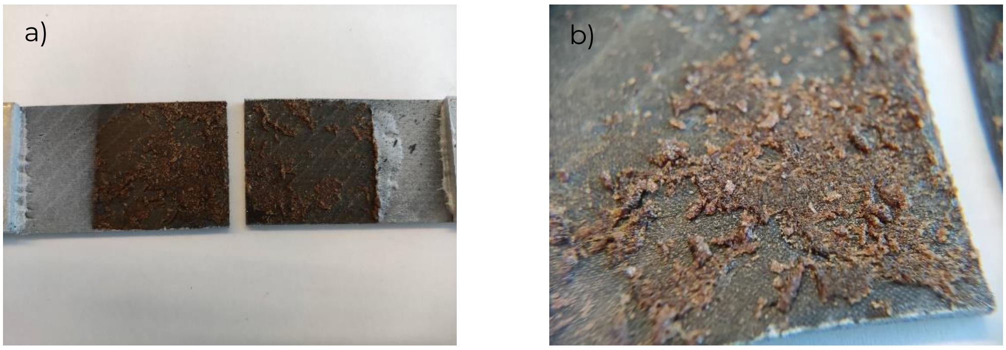


Figure 325 – Specimens' failure surfaces: a) Exterior; b) Interior

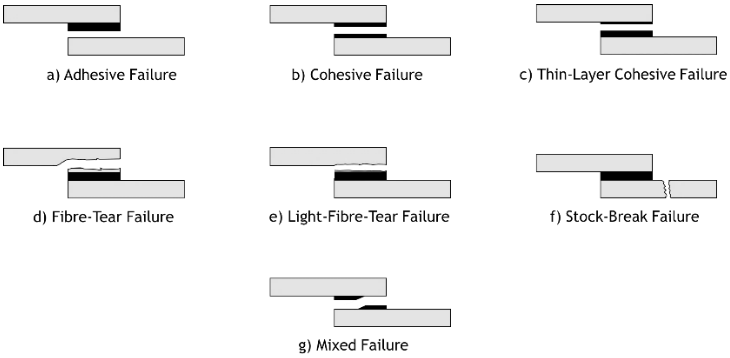


Figure 326 – Classes of failure modes on FRP joints

Specimen 4_C has failed before initiating the best while clamping it using the hydraulic grips, presumably due to its low strength which could not cope with the minimum misalignments and pre-load. Both specimens exhibited cohesive failure along the adhesive bondline (Figure 330). No laminar failure was found for any of the specimens.

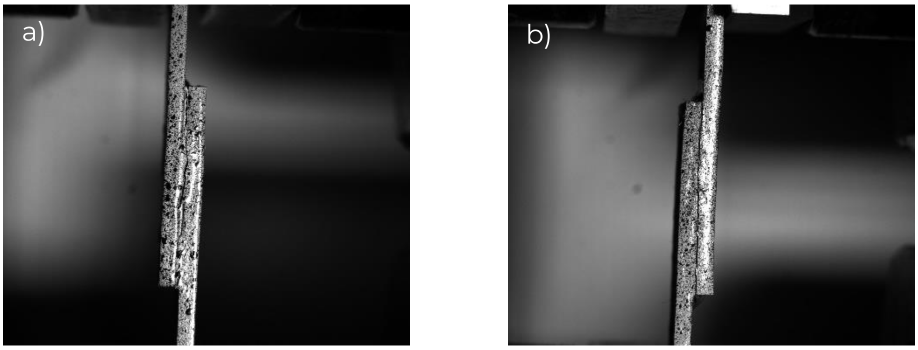


Figure 327 – DIC captures after failure: a) Specimen 4_A; b) Specimen 4_C

6.4.5. Configuration n°5

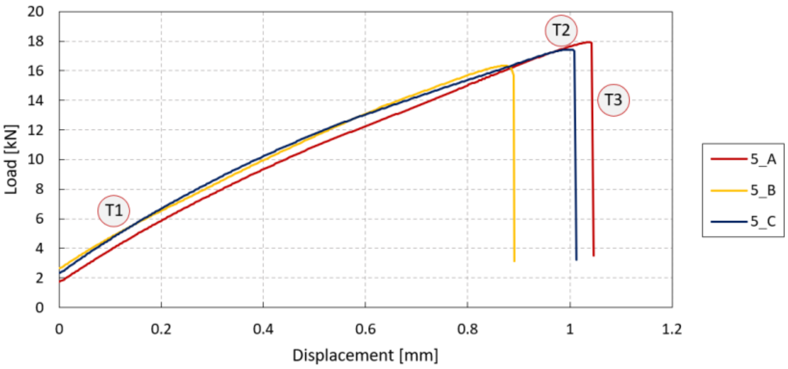


Figure 328 – Load-displacement curves obtained from configuration n°5 specimens

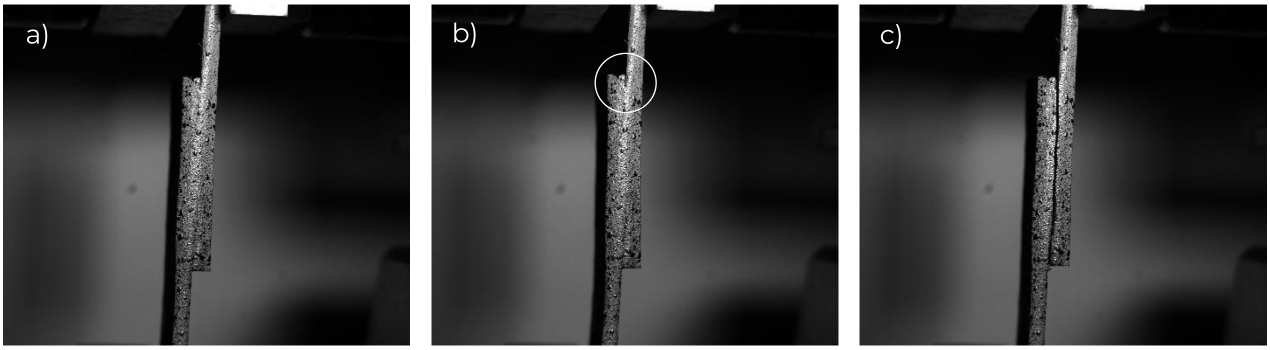


Figure 329 – DIC captures at different timestamps of specimen 5_A: a) T1; b) T2; c) T3

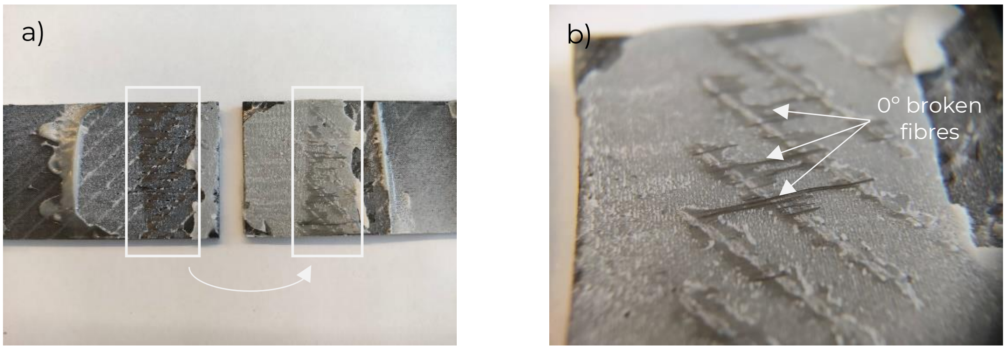


Figure 330 – Specimens' failure surfaces: a) Both specimens; b) Detail on light-fibre-tear failure

As it is possible to deduct from Figure 328, these single lab joints bonded with Araldite® 2015-1 had a brittle fracture, as it is not clearly seen any elastic region during the experimental tests. Despite not showing any post-yield behaviour, in Figure 329 it is possible to see that the crack initiates at the adhesive spew at the composite free end (where the shear stresses are maximum, as illustrated in X) and then propagates along the the bondline.

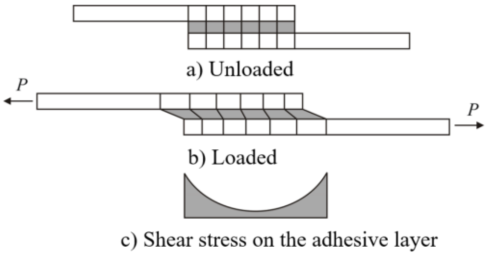


Figure 331 – Stresses acting on the adhesive layer [109]

Similarly to what was found for the previous configuration, single lab joints bonded with Araldite® 2015-1 also exhibited cohesive failure with all specimens, but also with light-fibre-tear failure of some of the 0° fibres on the layer in contact with the adhesive. In a closer inspection, it is possible to observe that some of these fibres' tensional strength was surpassed, breaking them and transferring them to the adhesive on the opposite side (being visible in detail in Figure 330). No further laminar failure was found since there was a total separation of the adherends after the connection had reached its maximum load.

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

6.4.6. Configuration n°6

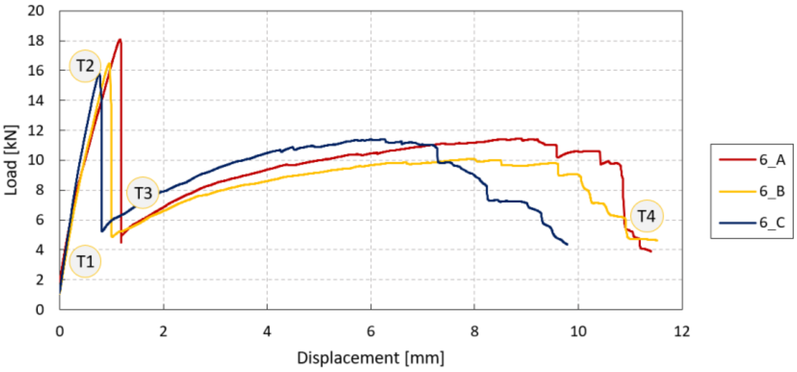


Figure 332 – Load-displacement curves obtained from configuration n°6 specimens

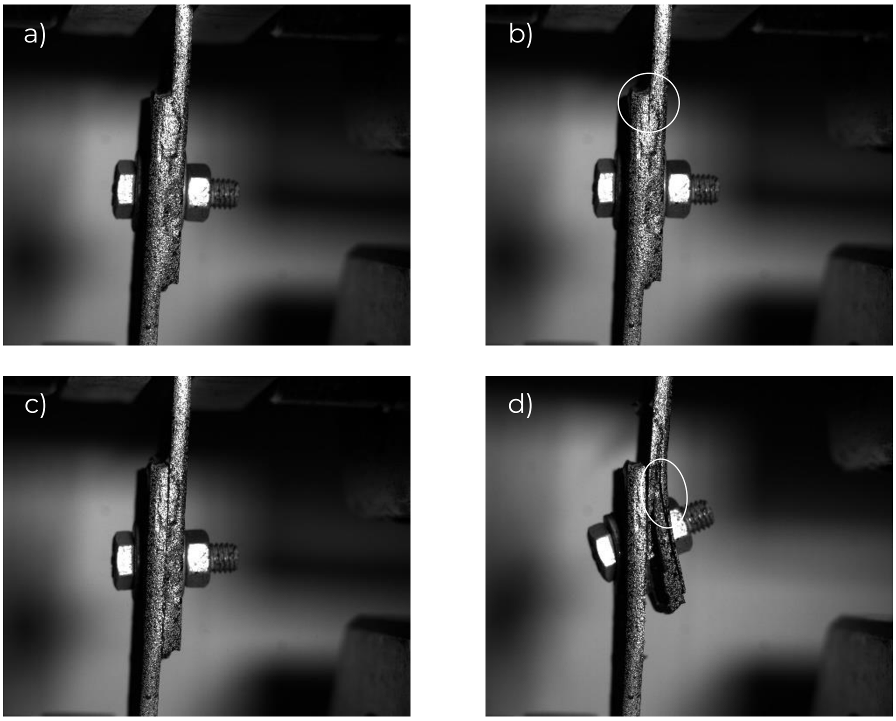


Figure 333 – DIC captures at different timestamps of specimen 6_B: a) T1; b) T2; c) T3; d) T4

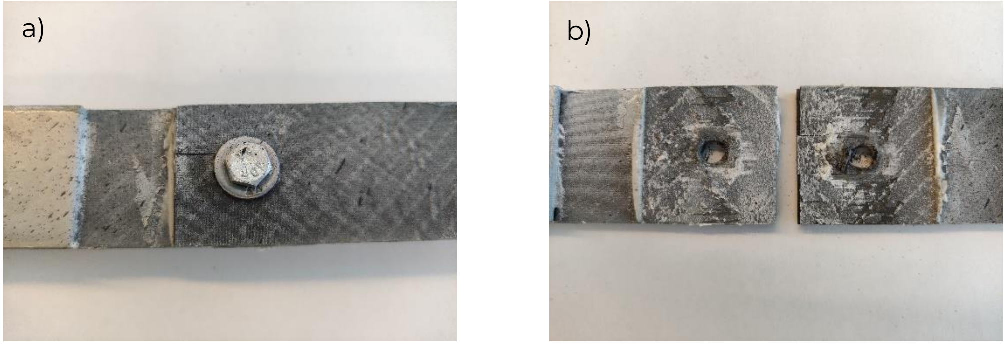


Figure 334 – Specimens' failure surfaces: a) Exterior; b) Interior

This last connections' configuration, being both bonded and bolted, had similar behaviour to both configurations n°1 and n° 5. When analysing Figure 332 and Figure 333 it is possible to conclude that the failure initiation and progress up to the moment of maximum carried load was very comparable to the previous configuration of bonded joints using the same Araldite® 2015-1. A crack has initiated at the spew edge (T2) and the response was brittle while achieving around the same values of maximum load. From that point, and even though the bondline has been completely separated (again by cohesive failure), the connection could already carry more load while undergoing the same laminar failure phenomena as reported for the bolted configurations. Being only connected by the bolt, the connection has carried up to 70% of its maximum load, which is around the same that was achieved in configuration n°1 (bolted connection). When analysing the failure surfaces (Figure 334), both cohesive failure of the adhesive and laminar failure of the adherends was found. In a closer look (Figure 335), bearing in clearly visible, as well as the previously reported intralaminar failure (0° plies on the adhesive's side), fibre breaking and interlaminar failure starting from the inside plies and progressing towards the centre of the laminate.

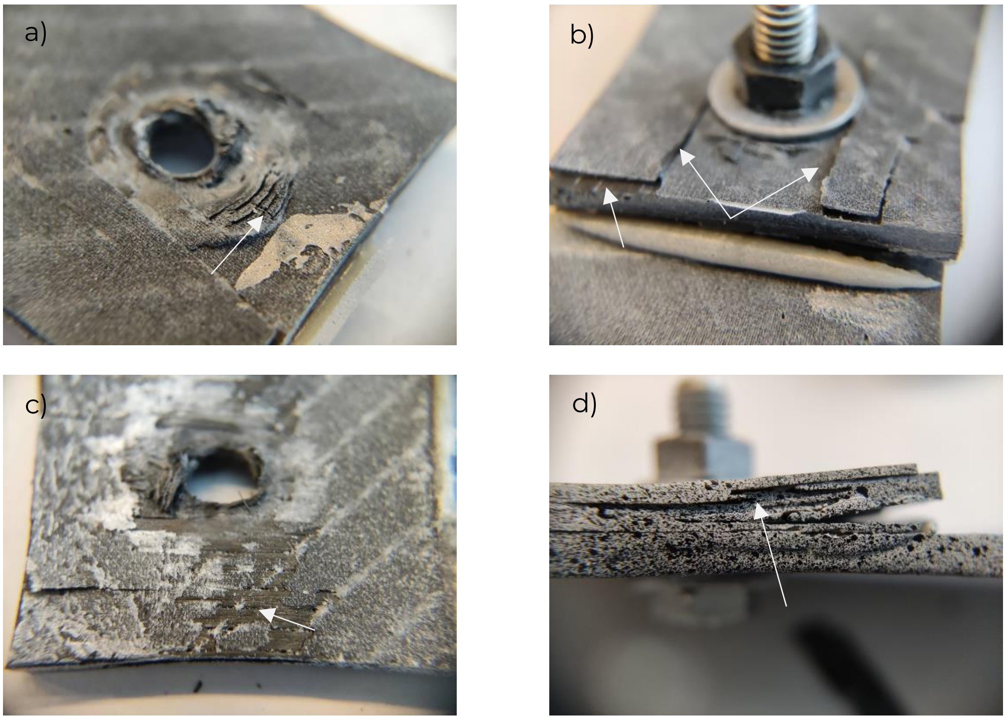


Figure 335 – Specimens' failure surfaces: a) Bearing; b) Intra and interlaminar failure; c) Intralaminar failure and fibre breakage; d) Laminar failure

6.4.7. Conclusions

Tensile tests on differently connected specimens have provided the results indicated in Table 15, in terms of maximum load (P_{max}), displacement at maximum load ($\delta_{P_{max}}$), and stiffness at maximum load ($K_{P_{max}} = P_{max}/\delta_{P_{max}}$):

Table 102 – Tensile tests results: maximum load P_{max}, displacement at maximum load $\delta_{P_{max}}$, and stiffness at maximum load $K_{P_{max}}$ (average $\pm$ relative standard deviation)

	P_{max} [kN]	$\delta_{P_{max}}$ [mm]	$K_{P_{max}}$ [kN/mm]
Configuration 1	9.96 ± 7%	9.57 ± 6%	1.04 ± 12%
Configuration 2	8.68 ± 5%	7.66 ± 5%	1.13 ± 2%
Configuration 3	9.50 ± 9%	10.79 ± 6%	0.88 ± 7%
Configuration 4*	3.95	0.84	4.73
Configuration 5	17.24 ± 5%	0.97 ± 9%	17.84 ± 4%
Configuration 6	16.78± 7%	0.96 ± 21%	17.78 ± 15%

*Values of relative standard deviation are not presented because only one specimen led to valid results

The results for the maximum load and stiffness are also shown in Figure 336 a) and Figure 336 b) (respectively) in the format of a bar chart:

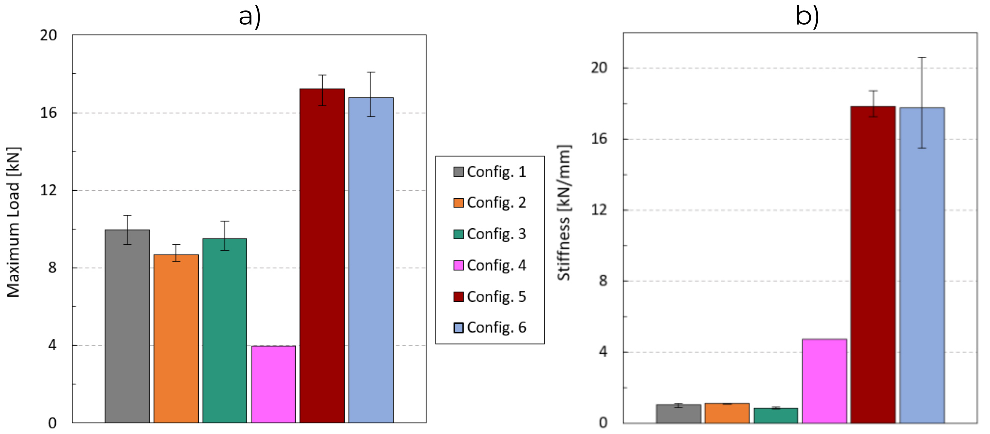


Figure 336 – Average values of maximum load (a)) and stiffness at maximum load (b)) for each configuration (error bars indicate maximum and minimum values)

In Figure 337 it is plotted the load-displacement curves of the best-performing specimen (in terms of maximum load) of all configurations:

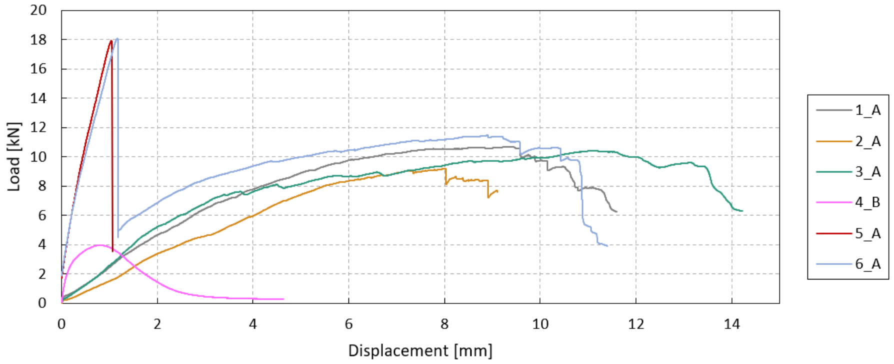


Figure 337 – Comparison between the load-displacement curves of all configurations

By analysis of the obtained values for the maximum load, displacement at maximum load and stiffness, it is possible to establish the following conclusions:

The specimens which performed the best in terms of maximum load capacity were the ones bonded with the Araldite® 2015-1 adhesive, being followed by the hybrid specimens (practically the same, only about 3% less) which were bonded with the Araldite® 2015-1 adhesive and bolted with an M6 bolt. The specimens bonded with the Corso Magenta reversible adhesive behaved clearly worse than the other configurations, with an approximately 55% decrease in terms of maximum load when compared to the second worse configuration (n°2). Therefore, it is possible to conclude that all the specimens bonded with the Araldite® 2015-1 adhesive reached satisfactory values of maximum load, independently of having an additional bolt or not.

The displacement (at maximum load) values followed a different trend, being much higher (and therefore the stiffness lower) for the solely bolted specimens (configurations n°1, n°2 and n°3). This is directly related to the observation of the failure mode and failure sequence, which was definitely more rapid and brittle for the bonded specimens, while the bolted ones suffered progressive bearing and transferred their load-carrying capability to the adherends' fibres, which underwent continuous intra and interlaminar failure since the yield point.

All bonded specimens exhibited cohesive failure (a thin layer of adhesive in both adherends' surfaces), evidencing that the peel ply treatment was adequate in providing a clean and chemically active surface.

Following these results, the reversible adhesive for Corso Magenta could not be validated for structural applications and therefore lacks further validation. It is suggested that the mixing process is revised to ensure a repeatable and controlled mixing that can be performed without requiring special laboratory tools.

No advantages were seen when using a middle or exterior metal sleeve plate, as they did not result in higher values of maximum load nor significantly higher values of displacement at maximum loads. Adding weight and the lower degree of laminar failure being explained by the lower loads and a distribution of the bolt clamping load through an increased area, both the configurations n°2 and n°3 are not advantageous when compared to the simpler configuration n°1.

Both the configurations n°5 and n°6 have provided satisfactory results. While no advantages in terms of strength (maximum carried load) could be found when including an additional bolt to the bonded joint, this may provide a more fail-safe design as it combines the advantages of both individual joining techniques, in particular the easier application (without the need for a bonding jig, as the bolt keeps parts in place while the adhesive is curing), providing immediate handling strength while the adhesive is not fully cured and a two-stage cracking process before the final failure with improved overall durability of the connection/joint. On the other side, the ease of dismantling may be compromised if a permanent adhesive is used. This is aligned with the conclusions from the literature [110].

7. Conclusion

This document provides an extensive report on the work developed during task 2.3, and presented, according to the sequential approach that was directly related to its four subtasks, all the outcomes from each of these studies.

Regarding the benchmark of connections, a broad review of the different joining technologies was made and reported in Chapter 2, which then served as a basis for the selection of the most appropriate joining types in FRP composite materials. The conclusions allowed for a clear comprehension of each technology's capabilities and limitations. Some of the covered technologies are currently limited to low TRL demonstrators and have revealed unfeasible to the application to this project at a functional scale, but some others were identified as opportunities to be exploited in the future.

As described in Chapter 3, all the potential connections that could be applied to the W2Power and Tidal Turbine Housing platforms were then brought to the discussion, studying the advantages and disadvantages of each and finally identifying the most promising ones for each application with the aid of selection matrices, where several parameters were considered and weighted.

Chapter 4 addressed the main conclusions from different topics regarding the reinforcements of the W2Power platform, particularly necessary to its towers and columns, and although not directly related to the scope of the T2.3 but having a transverse impact throughout over several work packages, was particularly relevant to identify new connections possibilities or connecting components that could be optimized or redesigned.

In Chapter 5, several options of connection configurations and geometries were studied using finite element analysis, in particular for the tube to column connection – where round-shaped joints were compared to rectangular and square-shaped joints – and the tower to column connection, where different IKEA-joint configurations where analysis, including the number of holes/bolts. A final proposal for the composite materials and its lay-out was made.

Lastly, in Chapter 6, the carried experimental campaign has successfully led to important conclusions regarding the different joining methods (bonded, bolted, hybrid), concluding that among the different configurations tested, both the bonded (configuration n°5) and hybrid (configuration n°6) led to satisfactory results, which were mostly dependent on the adhesive's strength and behaviour. The hybrid configuration provides a more fail-safe design as it combined the advantages of both bolting and bonding in a two-stage cracking process. The manufacturing processes for the connections were properly described, and identified possible troublesome topics such as the reversible adhesive preparation. Failure surfaces were described, depicting the failure modes and mechanisms, stepping up the comprehension of these connections and hereafter improving the numerical models to be employed.

The conclusions drawn from obtained results, regarding the type of connections to employ in different platforms and applications, will be used throughout the development of the Fibregy project, particularly supporting the decision-making process and CAE models during structural design and manufacturing.

8. References

[1] "Joining of Materials and Structures - 1st Edition.".

[2] D. B. Miracle and S. L. Donaldson, "ASM Handbook, Volume 21 - Composites."

[3] P. Camanho and S. R. Hallett, *Composite Joints and Connections: Principles, Modelling and Testing*. Elsevier, 2011.

[4] A. Galińska, "Mechanical Joining of Fibre Reinforced Polymer Composites to Metals—A Review. Part I: Bolted Joining," *Polymers (Basel).*, vol. 12, no. 10, Sep. 2020, doi: 10.3390/polym12102252.

[5] H. Engels, D. Zakharov, and W. Becker, "The plane problem of an elliptically reinforced circular hole in an anisotropic plate or laminate," *Arch. Appl. Mech.*, vol. 71, no. 9, pp. 601–612, Sep. 2001, doi: 10.1007/s004190100167.

[6] J. L. Clarke and European Structural Polymeric Composites Group, Eds., *Structural design of polymer composites: EUROCOMP design code and handbook*. London: E & FN Spon, 1996.

[7] "Improvement of a rivet geometry for the self-piercing riveting of high-strength steel and multi-material joints | SpringerLink." .

[8] R. Haque, "Quality of self-piercing riveting (SPR) joints from cross-sectional perspective: A review," *Arch. Civ. Mech. Eng.*, vol. 18, no. 1, pp. 83–93, Jan. 2018, doi: 10.1016/j.acme.2017.06.003.

[9] Y. Ma, H. Shan, S. Niu, Y. Li, Z. Lin, and N. Ma, "A Comparative Study of Friction Self-Piercing Riveting and Self-Piercing Riveting of Aluminum Alloy AA5182-O," *Engineering*, Jul. 2020, doi: 10.1016/j.eng.2020.06.015.

[10] Y. Ma, Y. Li, and Z. Lin, "Joint Formation and Mechanical Performance of Friction Self-Piercing Riveted Aluminum Alloy AA7075-T6 Joints," *J. Manuf. Sci. Eng.*, vol. 141, p. 1, Feb. 2019, doi: 10.1115/1.4042568.

[11] L. M. Alves, R. M. Afonso, and P. A. F. Martins, "Double-sided self-pierce riveting," *Int. J. Adv. Manuf. Technol.*, vol. 108, no. 5, pp. 1541–1549, May 2020, doi: 10.1007/s00170-020-05503-7.

[12] "Rebite de punção sólido." .

[13] "New joining technique for automotive lightweighting," *Bosch Global*. .

[14] L. Blaga, J. F. dos Santos, R. Bancila, and S. T. Amancio-Filho, "Friction Riveting (FricRiveting) as a new joining technique in GFRP lightweight bridge construction," *Constr. Build. Mater.*, vol. 80, pp. 167–179, Apr. 2015, doi: 10.1016/j.conbuildmat.2015.01.001.

[15] A. Galińska and C. Galiński, "Mechanical Joining of Fibre Reinforced Polymer Composites to Metals-A Review. Part II: Riveting, Clinching, Non-Adhesive Form-Locked Joints, Pin and Loop Joining," *Polymers (Basel).*, vol. 12, no. 8, Jul. 2020, doi: 10.3390/polym12081681.

[16] N. Zocoller Borba, J. Körbelin, B. Fiedler, J. dos Santos, and S. Amancio-Filho, "Low-velocity impact response of friction riveted joints for aircraft application," *Mater. Des.*, vol. 186, p. 108369, Nov. 2019, doi: 10.1016/j.matdes.2019.108369.

[17] S. Lathabai *et al.*, "Friction Stir Blind Riveting: A Novel Joining Process for Automotive Light Alloys," *SAE Int. J. Mater. Manuf.*, vol. 4, no. 1, pp. 589–601, Apr. 2011, doi: 10.4271/2011-01-0477.

[18] J. Min, J. Li, Y. Li, B. E. Carlson, J. Lin, and W.-M. Wang, "Friction stir blind riveting for aluminum alloy sheets," *J. Mater. Process. Technol.*, vol. 215, pp. 20–29, Jan. 2015, doi: 10.1016/j.jmatprotec.2014.08.005.

[19] S. Park, K.-J. Hong, and S.-W. Lee, "Structural Behavior and Application of Snap-fit Connected GFRP Composite Bridge Decks," Jan. 2013.

[20] S. Härtel, E. Brueckner, B. Awiszus, and M. Gehde, "Development of a Numerical Model of the Hot Air Staking Process Based on Experimental Data," *Appl. Sci.*, vol. 10, no. 20, p. 7115, Jan. 2020, doi: 10.3390/app10207115.

[21] "What is clinching and how does it work?" .

[22] C.-J. Lee, S.-H. Lee, J.-M. Lee, B.-H. Kim, B.-M. Kim, and D.-C. Ko, "Design of Hole-Clinching Process for Joining CFRP and Aluminum Alloy Sheet," *Int. J. Precis. Eng. Manuf.*, vol. 15, pp. 1151–1157, Jun. 2014, doi: 10.1007/s12541-014-0450-6.

[23] C.-J. Lee, B.-M. Kim, B.-S. Kang, W.-J. Song, and D.-C. Ko, "Improvement of joinability in a hole clinching process with aluminum alloy and carbon fiber reinforced plastic using a spring die," *Compos. Struct.*, vol. 173, pp. 58–69, Aug. 2017, doi: 10.1016/j.compstruct.2017.04.010.

[24] S. Wiesenmayer and M. Merklein, "Potential of shear-clinching technology for joining of three sheets," *J. Adv. Join. Process.*, vol. 3, p. 100043, Jun. 2021, doi: 10.1016/j.jajp.2021.100043.

[25] "Injection Clinching Joining A. Abibe," *studylib.net*. .

[26] C. Vogel, A. Freund, M. Gude, R. Kupfer, and W. Hufenbach, "Thermoclinching - a novel joining process for lightweight structures in multi-material design," Mar. 2014.

[27] H. Peng, C. Chen, H. Zhang, and X. Ran, "Recent development of improved clinching process," *Int. J. Adv. Manuf. Technol.*, vol. 110, no. 11, pp. 3169–3199, Oct. 2020, doi: 10.1007/s00170-020-05978-4.

[28] F. Lambiase and D.-C. Ko, "Two-steps clinching of aluminum and Carbon Fiber Reinforced Polymer sheets," *Compos. Struct.*, vol. 164, pp. 180–188, Mar. 2017, doi: 10.1016/j.compstruct.2016.12.072.

[29] S. Swillo *et al.*, "Detection and Characterization of Surface Cracking in Sheet Metal Hemming Using Optical Method," *Trans. North Am. Manuf. Res. Inst. SME*, vol. 33, pp. 49–55, May 2005.

[30] "(PDF) Springback Simulation of the Process Chain Press Line Forming and Roller Hemming Processes." .

[31] E. E. Feistauer, J. F. dos Santos, and S. T. Amancio-Filho, "A review on direct assembly of through-the-thickness reinforced metal–polymer composite hybrid structures," *Polym. Eng. Sci.*, vol. 59, no. 4, pp. 661–674, 2019, doi: https://doi.org/10.1002/pen.25022.

[32] "COMELD - An innovation in composite to metal joining." .

[33] "What is Surfi-Sculpt?" .
[34] P. Chang, A. P. Mouritz, and B. N. Cox, "Properties and failure mechanisms of z-pinned laminates in monotonic and cyclic tension," *Compos. Part A Appl. Sci. Manuf.*, vol. 37, no. 10, pp. 1501–1513, Oct. 2006, doi: 10.1016/j.compositesa.2005.11.013.
[35] "Hyperjoint: additive metal + composites = stronger, tougher joints." .
[36] J. Excell, *Additive assembly: the 3D printed fastener*. 2014.
[37] M. Quanjin, M. R. M. Rejab, J. Kaige, M. S. Idris, and M. N. Harith, "Filament winding technique, experiment and simulation analysis on tubular structure," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 342, p. 012029, Apr. 2018, doi: 10.1088/1757-899X/342/1/012029.
[38] "Filament winding, reinvented." .
[39] J. Fleischer and J. Schaedel, "Joining automotive space frame structures by filament winding," *CIRP J. Manuf. Sci. Technol.*, vol. 6, pp. 98–101, Dec. 2013, doi: 10.1016/j.cirpj.2013.02.003.
[40] *Adhesives Technology Handbook*. Elsevier, 2015.
[41] "Industrial Structural Adhesives - Basics & Best Practices," *LORD Corp*, Apr. 2018. .
[42] P. Davies, "Marine Industry," in *Handbook of Adhesion Technology*, L. F. M. da Silva, A. Öchsner, and R. D. Adams, Eds. Cham: Springer International Publishing, 2018, pp. 1391–1417.
[43] J. B. Jørgensen, "Adhesive Joints in Wind Turbine Blades," 2017, doi: 10.11581/DTU:00000027.
[44] R. J. Hussey and J. Wilson, *Structural Adhesives: Directory and Databook*. Springer US, 1996.
[45] "Structural adhesives, Part I: Industrial." .
[46] "Composite bonding adhesive joins carbon fiber core to metal," *plasticstoday.com*, May 2016. .
[47] "Adhesives in Marine Engineering | ScienceDirect." .
[48] S. Ebnesajjad and A. H. Landrock, "Chapter 11 - Durability of Adhesive Bonds," in *Adhesives Technology Handbook (Third Edition)*, S. Ebnesajjad and A. H. Landrock, Eds. Boston: William Andrew Publishing, 2015, pp. 297–338.
[49] "Polyester Adhesives." .
[50] "Tech Data-2011- Marine.pdf." .
[51] L. F. M. da Silva, A. Öchsner, and R. D. Adams, Eds., *Handbook of Adhesion Technology*, 2nd ed. Springer International Publishing, 2018.
[52] "BMI Adhesives | High Temp Bismaleimide Adhesive : Renegade Materials." .
[53] "Polyimide Adhesive for Aerospace Applications: Renegade Materials." .
[54] Q. Guo, *Thermosets: Structure, properties, and applications: Second edition*. 2017.
[55] "Your Complete Guide to Polyamide Hot Melt," *Hotmelt.com*. .
[56] "Sharnet® PA128 Polyamide Hot Melt Web Adhesive | Bostik.com." .
[57] "Is PVA good for boatbuilding, Poly Vinyl Acetate Glue comes in Waterproof, Water resistant and Regular strength." .
[58] G. Di Bella, G. Galtieri, E. Pollicino, and C. Borsellino, "Joining of GFRP in Marine Applications," 2012.
[59] A. Roy, Y. Nadot, and P. CASARI, "Adhesive bonding for structural marine applications," *RINA - Int. Conf. - Innov. High Perform. Sail. Yachts, Pap.*, pp. 133–138, Jan. 2008.
[60] "Welding technologies for polymers and composites." .
[61] V. Kalas and L.-J. Roos, "Welding of thermoplastic composites," Jun. 2016.
[62] A. Levy, I. Villegas, and S. Le Corre, "Ultrasonic Welding of Thermoplastic Composites. Modeling the Heating Phenomena," Jan. 2013, pp. 5713–5724.
[63] S. M. Goushegir, "Friction Spot Joining of Metal-Composite Hybrid Structures," p. 180.
[64] S. M. Goushegir, J. F. dos Santos, and S. T. Amancio-Filho, "Friction Spot Joining of aluminum AA2024/carbon-fiber reinforced poly(phenylene sulfide) composite single lap joints: Microstructure and mechanical performance," *Mater. Des.*, vol. 54, pp. 196–206, Feb. 2014, doi: 10.1016/j.matdes.2013.08.034.
[65] N. Bhardwaj, G. Narayanan, U. Dixit, and M. s. J. Hashmi, "Recent developments in friction stir welding and resulting industrial practices," *Adv. Mater. Process. Technol.*, vol. 5, pp. 1–36, Jun. 2019, doi: 10.1080/2374068X.2019.1631065.
[66] "Refill Friction Stir Spot Welding." .
[67] A. Srivastava, A. Dixit, and N. Kumar, "Friction stir additive manufacturing – An innovative tool to enhance mechanical and microstructural properties," *Mater. Sci. Eng. B*, Oct. 2020, doi: 10.1016/j.mseb.2020.114832.
[68] S. Palanivel, P. Nelaturu, B. Glass, and R. S. Mishra, "Friction stir additive manufacturing for high structural performance through microstructural control in an Mg based WE43 alloy," *Mater. Des.*, vol. 65, pp. 934–952, Jan. 2015, doi: 10.1016/j.matdes.2014.09.082.
[69] S. Palanivel, H. Sidhar, and R. Mishra, "Friction Stir Additive Manufacturing: Route to High Structural Performance," *JOM*, vol. 67, Mar. 2015, doi: 10.1007/s11837-014-1271-x.
[70] X. Meng *et al.*, "Friction self-riveting welding between polymer matrix composites and metals," *Compos. Part A Appl. Sci. Manuf.*, vol. 127, p. 105624, Dec. 2019, doi: 10.1016/j.compositesa.2019.105624.
[71] S. Pappadà, A. Salomi, J. Montanaro, A. Passaro, A. Caruso, and A. Maffezzoli, "Fabrication of a thermoplastic matrix composite stiffened panel by induction welding," *Aerosp. Sci. Technol.*, vol. 43, pp. 314–320, Jun. 2015, doi: 10.1016/j.ast.2015.03.013.
[72] R. Rudolf, P. Mitschang, and M. Neitzel, "Induction heating of continuous carbon-fibre-reinforced thermoplastics," *Compos. Part A Appl. Sci. Manuf.*, vol. 31, no. 11, pp. 1191–1202, Nov. 2000, doi: 10.1016/S1359-835X(00)00094-4.
[73] S. Poyraz, L. Zhang, A. Schroder, and X. Zhang, "Ultrafast Microwave Welding/Reinforcing Approach at the Interface of

Thermoplastic Materials," *ACS Appl. Mater. Interfaces*, vol. 7, Sep. 2015, doi: 10.1021/acsami.5b06484.

[74] "Premium AEROTEC displays thermoplastic CFRP pressure bulkhead." .

[75] *Laser welding plastics webinar*. 2017.

[76] "Laser plastic welding | TRUMPF." .

[77] M. J. Troughton, Ed., "Chapter 13 - Flash-Free Welding," in *Handbook of Plastics Joining (Second Edition)*, Boston: William Andrew Publishing, 2009, pp. 127–130.

[78] K. Bodjona and L. Lessard, "Hybrid bonded-fastened joints and their application in composite structures: A general review," *J. Reinf. Plast. Compos.*, vol. 35, Jan. 2016, doi: 10.1177/0731684415627296.

[79] G. Kelly, "Load transfer in hybrid (bonded/bolted) composite single-lap joints," *Compos. Struct.*, vol. 69, no. 1, pp. 35–43, Jun. 2005, doi: 10.1016/j.compstruct.2004.04.016.

[80] "How can AdhFAST improve quality assurance?" .

[81] "AdhFAST™ - fastener to revolutionise adhesive use," *Assem. Autom.*, vol. 20, no. 2, Jan. 2000, doi: 10.1108/aa.2000.03320baf.001.

[82] "What is riv-bonding?" .

[83] T. Gerstmann and B. Awiszus, "Hybrid joining: Numerical process development of flat-clinch-bonding," *J. Mater. Process. Technol.*, vol. 277, p. 116421, Mar. 2020, doi: 10.1016/j.jmatprotec.2019.116421.

[84] K. Martinsen, S. J. Hu, and B. Carlson, "Joining of dissimilar materials," *CIRP Ann. - Manuf. Technol.*, vol. 64, Aug. 2015, doi: 10.1016/j.cirp.2015.05.006.

[85] R. W. Messler, "Weld-bonding: the best or worst of two processes?," *Ind. Robot An Int. J.*, Apr. 2002, doi: 10.1108/01439910210419150.

[86] G. P. Marques, R. D. S. G. Campilho, F. J. G. da Silva, and R. D. F. Moreira, "Adhesive selection for hybrid spot-welded/bonded single-lap joints: Experimentation and numerical analysis," *Compos. Part B Eng.*, vol. 84, pp. 248–257, Jan. 2016, doi: 10.1016/j.compositesb.2015.09.002.

[87] A. Aljuboury and A. Marie, "The Design and Manufacture of a Glass Fibre Reinforced Polymer (GFRP) Bolted Flange Joint for Oil and Gas," 2019, [Online]. Available: https://pearl.plymouth.ac.uk/bitstream/handle/10026.1/13659/2019Aljuboury10503464PhD.pdf?sequence=1&isAllowed=y.

[88] Balmoral Comtec Ltd, "Balmoral FibreFlex™ cable protection system." [Online]. Available: https://www.balmoraloffshore.com/fibreflex.

[89] G. Gardiner, "Composites protect subsea cables for offshore wind power." CompositesWorld, 2021, [Online]. Available: https://www.compositesworld.com/articles/composites-protect-subsea-cables-for-offshore-wind-power.

[90] O. Braydi, R. Younes, P. Lafon, and A. Samrout, *Reliability based optimization of a hat stiffened panel*. 2017.

[91] National Wind Watch, "Wind turbine topples in South Kent; 'Extreme load of some kind' may have caused damage, says expert," 2018.

[92] J. Halkyard, "Chapter 7 - Floating Offshore Platform Design," S. K. B. T.-H. of O. E. CHAKRABARTI, Ed. London: Elsevier, 2005, pp. 419–661.

[93] A. International, "ASTM D5961: Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates," 2017. doi: 10.1520/D5961_D5961M-13.

[94] ASTM International, "ASTM D1002-10: Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)," 2019. doi: 10.1520/D1002-10R19.

[95] ASTM International, "ASTM D5868-01: Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding," 2014. doi: 10.1520/D5868-01R14.

[96] Zoltek Corporation, "Technical Datasheet ZOLTEK ™ PX35 Multi-Directional Fabrics Technical Datasheet ZOLTEK ™ PX35 Multi-Directional Fabrics," vol. 300, pp. 1–2, [Online]. Available: http://zoltek.com/wp-content/uploads/2016/01/PX35-MD-Fabrics.pdf.

[97] Sicomin, "SR InfuGreen 810 Technical Datasheet." pp. 1–9, 2017.

[98] J. V Cardoso, P. V Gamboa, and A. P. Silva, "Effect of surface pre-treatment on the behaviour of adhesively-bonded CFRP T-joints," *Eng. Fail. Anal.*, vol. 104, pp. 1188–1202, 2019, doi: https://doi.org/10.1016/j.engfailanal.2019.05.043.

[99] L. J. Hart-Smith, "Adhesively Bonded Joints in Aircraft Structures BT - Handbook of Adhesion Technology," L. F. M. da Silva, A. Öchsner, and R. D. Adams, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 1101–1147.

[100] Markforged, "Onyx One 3D-printer." [Online]. Available: https://markforged.com/3d-printers/onyx-one.

[101] Markforged, "Onyx material." [Online]. Available: https://markforged.com/materials/plastics/onyx.

[102] J. X. Dhôte, A. J. Comer, W. F. Stanley, and T. M. Young, "Study of the effect of liquid shim on single-lap joint using 3D Digital Image Correlation," *Compos. Struct.*, vol. 96, pp. 216–225, 2013, doi: https://doi.org/10.1016/j.compstruct.2012.08.058.

[103] D. Gleich, M. Van tooren, and A. Beukers, "Analysis and evaluation of bondline thickness effects on failure load in adhesively bonded structures," *J. Adhes. Sci. Technol. - J ADHES SCI TECHNOL*, vol. 15, pp. 1091–1101, Jan. 2001, doi: 10.1163/156856101317035503.

[104] Huntsman, "Araldite 2015 Adhesive Datasheet," vol. 100, pp. 1–6, 2015, [Online]. Available: https://us.aralditeadhesives.com/index.php?option=com_docman&view=download&alias=166-araldite-2015-us-e&Itemid=146&lang=us.

[105] Samaro, "Araldite® 2015-1, Araldite® 2051 and Araldite® 2023, three new references adapted to the needs of the marine industry."

[106] Huntsman, “Araldite® 2015-1 Technical Datasheet.” p. 6, 2017, doi: 10.1201/b10862-5.
[107] Polyestershoppen B.V., “Colle epoxy - Araldite 2015-1.” [Online]. Available: https://polyestershoppen.fr/lijmen-en-kitten/araldite-2015-epoxylijm-196.html.
[108] Venticell, “Venticell - Laboratory Ovens with Forced Air Convention,” no. Rj 45.
[109] L. F. M. da S. J. Monteiro, R. M. Salgado, T. da Rocha, G. Pereira, E. A. S. Marques, R. J. C. Carbas, “Effect of Adhesive Type and Overlap Length on the Mechanical Resistance of a Simple Overlap Adhesive Joint J.,” *U.Porto J. Eng.*, vol. 12, no. 1, 2021, doi: 10.24840/2183-6493.
[110] A. Öchsner, L. F. M. da Silva, and Holm Altenbach, *Hybrid Adhesive Joints*. 2019.