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QUALIFY
LIGHTWEIGHT

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EXECUTIVE SUMMARY

The QUALIFY project aims to remove the technological and regulatory barriers that currently prevents the widespread application of adhesive bonding of primary hybrid structures (metal-composite) for marine and offshore applications.

The objectives of this deliverable are:

- To give an overview of the advantages and current challenges of adhesive bonding;
- To present current application of adhesive bonding in offshore with examples of cost analysis and potential future applications;
- To present hybrid joints in ship building and adhesive bonding technique together with some case studies;
- To promote the use of adhesive bonded hybrid joints in marine environment.

This market study has been carried out by SIRRIS and DAMEN for offshore and marine applications, respectively. A survey was developed to map the current status of adhesive bonding, the needs of the market and potential future applications, the results of which are presented in this report.

SUMMARY

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1. INTRODUCTION

1.1. Opportunities for lightweight/hybrid materials

The use of composite materials in maritime and offshore structures is becoming increasingly common, offering advantages of weight reduction (leading to lower transport costs for structures and increased range/payload capacity for ships), as well as a reduction in corrosion. Hybrid metal and composite structures require a joint between the two materials. Historically this has been a mechanical joint (bolts or rivets), however, bonded joints offer benefits in reduced weight, reduced costs through life maintenance and removal of the stress concentrations which result from holes and mechanical fasteners.

A number of European research projects have previously investigated bonded composite to steel joints (e.g. BONDSHIP [1]), however, these have typically been focused on optimizing joint design, where the QUALIFY project is focussed on the qualification procedure of the joints.

The purpose of this deliverable is to document the maritime and offshore market for adhesive bonded joints and the potential for knowledge transfer towards other sectors, e.g. construction. This is done to maximize the impact of the Interreg 2 Seas project 'QUALIFY' which aims to remove the technological and regulatory barriers that currently prevent the widespread application of bonded hybrid structures (metal/composite) in the industry.

Case study 1- Hybrid assembly

Theuws Polyester developed an adhesive solution to modify the cabin entry step, including fender on a limited series of specialized vehicles. With this solution they were able to reduce the cost and lead time for their customer since there was no need to develop and produce new equipment.

Once the existing structure Sheet Moulding Compound (SMC) polyester is machined to the correct shape, the new polyester Resin Transfer Moulding (RTM) part is bonded onto the existing structure and steel braces are bonded onto the RTM part. The adhesive (SG300) allows the assembly of all three different materials (SMC, RTM and painted steel) in one production step and is able to compensate the tolerances of each part. The end result is expected to remain functional for many years in various environmental conditions [1]

Figure 1: Theuws Polyester

1.2. Joining technologies for hybrid materials

Multi-material designs or metal-composite designs have several advantages such as weight reduction or corrosion resistant design. However, such combination of materials requires joining technologies between these dissimilar materials. Figure 2 shows the main four categories of available joining technologies for metal-composite structures. The techniques presented show only a few examples of each category, one could equally well list other joining methods in the classification diagram. Furthermore, these technologies may offer alternative process variants, which are also not specified, to keep the diagram simple and representative. Adhesive bonding, mechanical fastening, welding-based technologies and also hybrid-technologies together with some examples are presented.

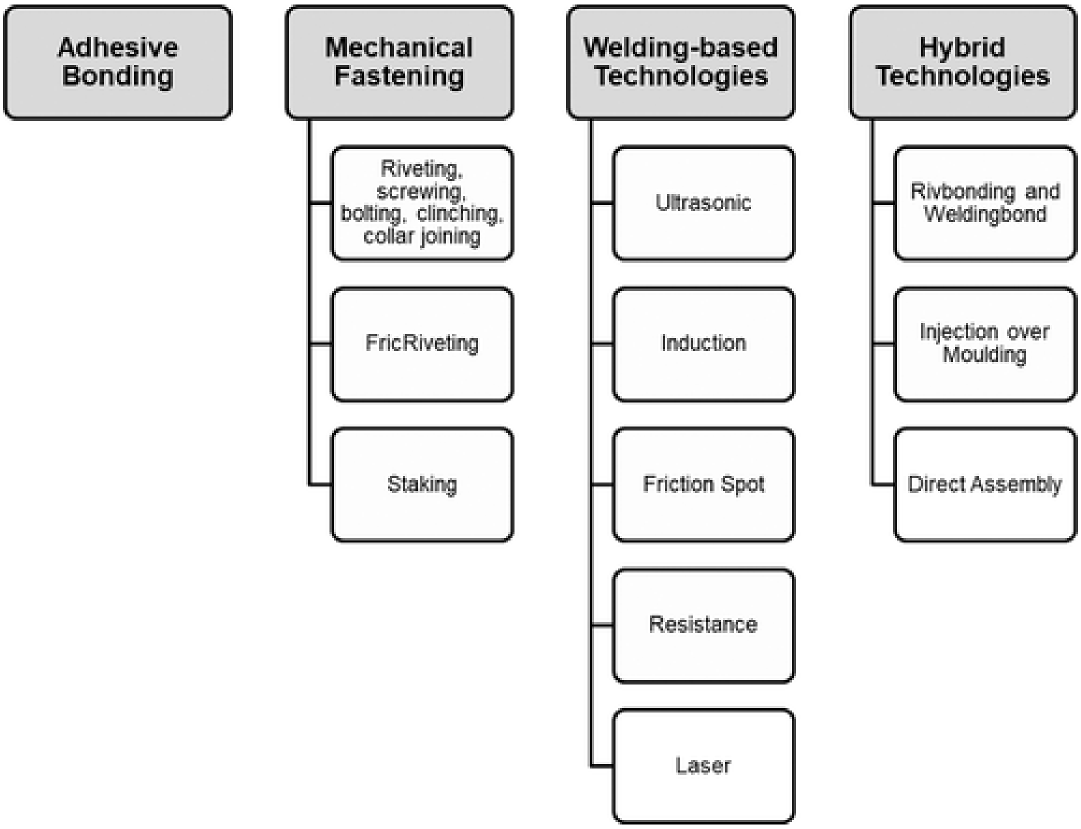


Figure 2: Available joining technologies for metal-composite hybrid structures [1]

Hybrid technologies which consists of a combination of two joining technologies, are developed to create high-performance metal-composite joint. The examples are rivbonding (rivet+adhesive), weldbonding (spot weld + adhesive) [2].

1.3. Pros and cons with adhesives

Adhesive bonding has emerged as a structurally efficient and cost-effective fabrication process in aerospace. It is used in primary aerospace structural components without mechanical fasteners. This successful experience has inspired other sectors such as automotive, domestic, rail transport and marine. The major advantage of adhesive bonding compared to other bonding techniques are as follows [3], [4].

Technical benefits:

- Adhesive joints are “uninterrupted” joints;
- Absence of residual stress and distortion associated with welding;
- Adhesive joints ensure even stress distribution in the joint, which results in high fatigue strength;
- Possibility of connecting dissimilar materials;
- Reduction of corrosion due to the absence of welds or metal fasteners and the additional benefit of the adhesive acting as a sealant;
- Possibility for electrically or thermally conductive or insulating connections;

- Adhesive joints are damping vibration.

Design benefits:

- The connections are often invisible;
- Connecting very thin materials and small parts is possible;
- The design possibilities are increased to create complex joints.

Economic benefits

- Savings in construction time;
- When the adhesive has the correct gap-filling properties, the dimensional tolerances can be less strict;
- Lower maintenance costs mainly due to less corrosion and less fatigue.

Technical drawbacks:

- Long term durability under severe service condition is uncertain due to a shortage of design data at present;
- Afterwards, the adhesion obtained is difficult to check non-destructively;
- In general, the connections are difficult to disassemble;
- A drying or curing time must be observed;
- The strength of the adhesive bond, as a construction element, is difficult to be calculated in advance.

Economic disadvantages:

- Additional time and costs for equipment for surface preparation;
- Costs related to safety, working conditions and the environment.

For more information regarding adhesive joints, risk assessment and bonding system assessment we refer to [5].

1.4. Case studies from other industries

The focus of this report is on the application of adhesive bonding in marine and offshore. However, in this chapter some interesting case studies of the application of adhesives for load carrying joints in other sectors will be presented. An overview of the adhesive joints in the air sector, as well as rail, civil engineering and automotive sectors is reported in [6]. Adhesive bonding is also applied in fasteners for several applications such as aerospace, industrial applications but also marine and offshore [7], [8], [9].

Case study 2- infrastructure application

An example is the bridge in Utrecht. The bridge is made of steel truss girder and a deck of FRP (made by Infracore). The light weight of the bridge was a design criteria which also enabled the prefabrication of the bridge. This was the first bridge with a combination of steel and composite and long performance was rather unknown. To assure this hybrid joining methodology, combination of adhesive bonding and pin-hole connection was applied [10].

Figure 3: installation of the composite deck between the steel griders [10]

Case study 3- Composite tank containers

Tankwell has developed the world's lightest tank container for intermodal transportation of liquids. One of the essential features of the design is the construction of the hybrid composite tank - carbon steel frame connection. Application of an adhesive that joints the tank to the frame, allows external forces on the frame during handling of the container to be distributed over a larger surface to the tank structure. Compared to a welded (conventional steel tank containers) or bolted construction, peak stresses are therefore much lower. Among others this results in superior fatigue properties and a longer life time of the tank containers.

Tankwell lightweight tank containers are ADR and CSC approved. Type testing involves several static and dynamic mechanical, impact and pressure tests relevant for the application of tank containers. The composite tank containers have a 40% lower weight and 50% better thermal insulation compared to conventional steel tank containers. The extra payload allows for a 5% reduction of shipments and results to a more than 5% improvement of the CO_2-footprint of liquid logistics [11]

Figure 4: Tankwell composite tank container [11]

Case study 4- Composite bus structure

For the design of buses, lightweight and safe structure and energy efficiency are required. The bus body is typically made of steel beams which are welded. However, such joints are prone to fatigue which can cause crack in the structure. In order to solve this issue the application of CFRP is proposed and to replace the welded joints using adhesive bonding. The results of the new design study showed that:

- The strength of the new design joint can be higher than the welding joints;
- Higher elasticity can be obtained resulting in strains up to 30% higher which can minimize mechanical fatigue;
- Lower weight of the joint is obtained and as a result lower weight of the bust structure. This reduced also fuel consumption.

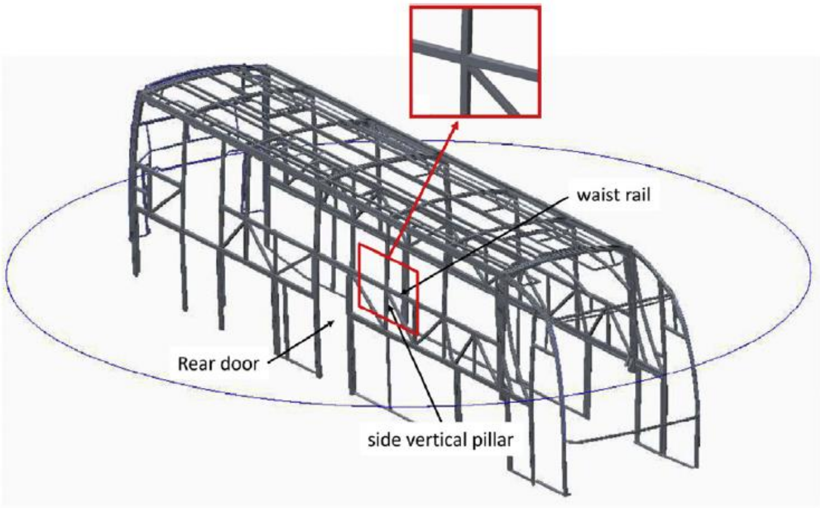


Figure 5: Selected nodes of the bus structure [12]

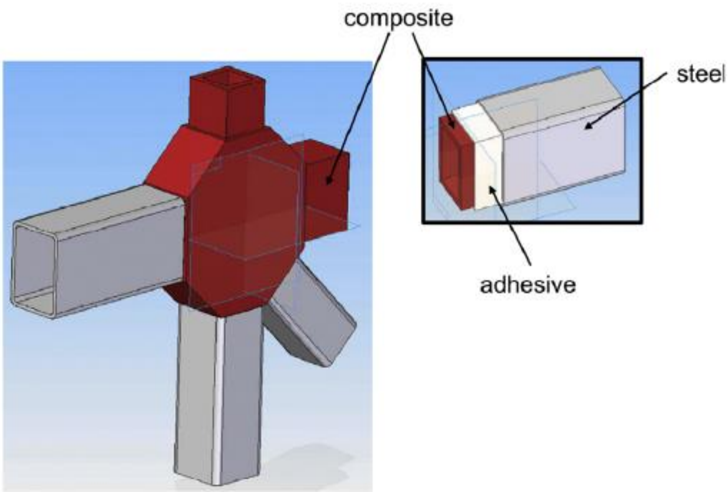


Figure 6: Proposed new design of CFRP node adhesive bonded to steel beams of the bus structures [12]

2. SURVEY RESULTS

In the framework of Interreg QUALIFY project a survey was developed to map the current position and the market potential for the application of adhesive bonding. The survey was addressed to all the sectors to have an overview of the market and to enable learning from the experience of different sectors. An overview of the participants' country, organizational type and categories is given here.

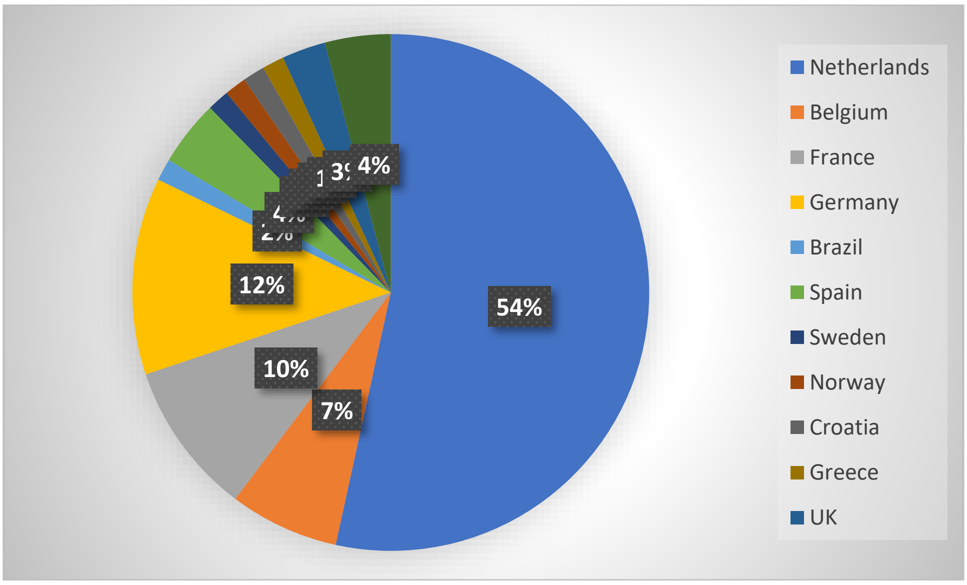


Figure 7: Survey participants by **countries**

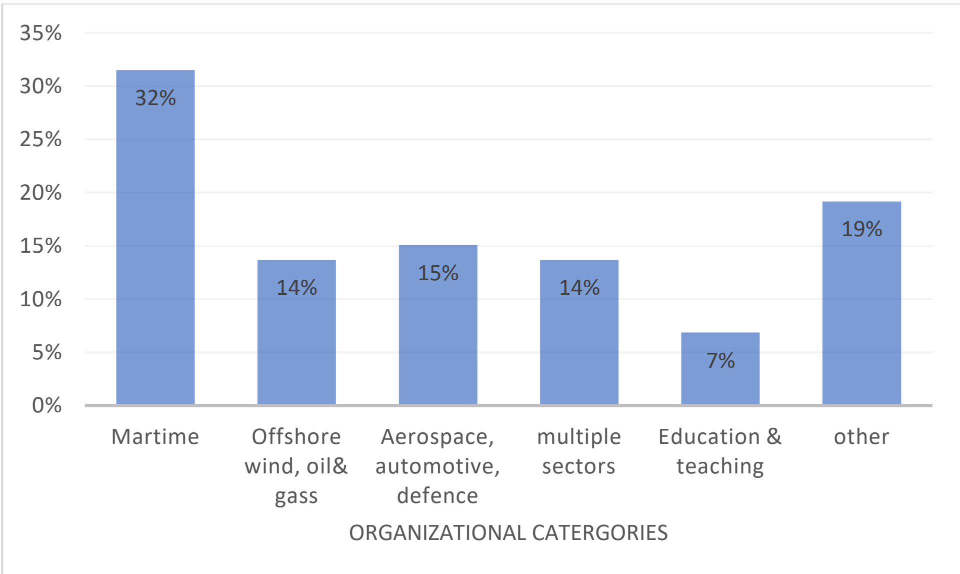


Figure 8: Survey by participants organizational categories

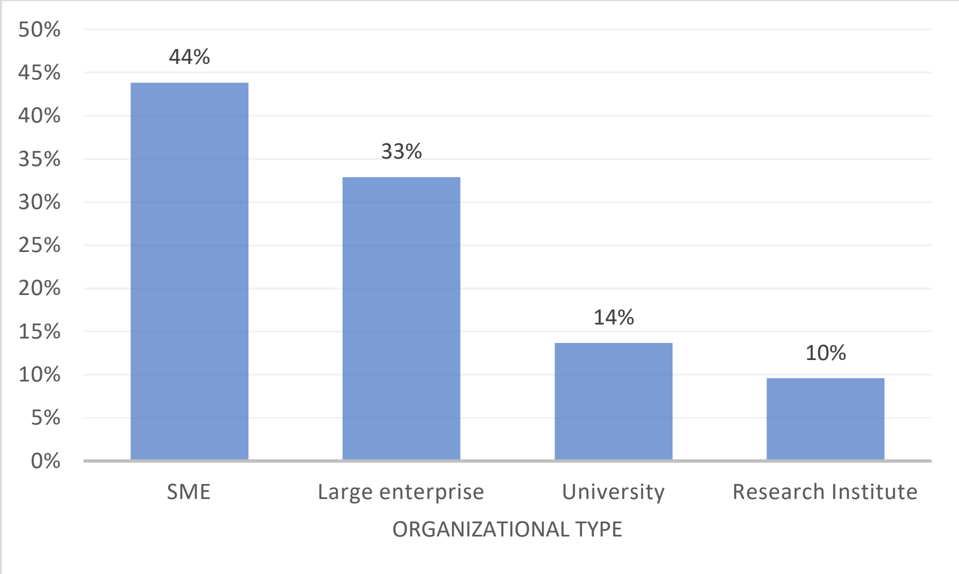


Figure 9: Survey by participant organizational types

The participants' answers will be presented separately for SME's and large enterprises and universities and research institutes, respectively. For SME's and large enterprises, a further clustering was made as maritime sector, which includes marine (ships), offshore (wind turbines) and oil& gas.

2.1. SME's and large enterprises

The participants were asked to rank the criteria for joint selection method, assuming all joints meet the structural requirements. The given responses highlight the importance of lead time of assembly, which was ranked 53% as the first criteria from maritime sector (49% for all the SME's and large enterprises). Cost of material and reliability were the next highest ranked as the first criteria.

Table 1: Ranking the criteria for selecting a joining method assuming all joints meet the structural requirements, response of maritime sector

	1st criteria	2nd criteria	3rd criteria
a. Lead time (of assembly)	53%		
b. Cost of material	15%	19%	
c. Cost of labour		26%	24%
d. Flexibility in production (changes during production)		19%	29%
e. Repairability			24%
f. Reliability	12%	19%	24%
g. Weight		11%	

The participants were asked whether or not they apply already adhesive bonding. 47% of maritime sector (40% for all industrial sectors) apply adhesive bonding for high risk structural members with or without mechanical fastening. Including the application for low-risk structural members the scores are 74% (66% for all industrial sectors).

Table 2: Application of adhesive bonding for high risk (major stresses) or low risk (minor stresses) structural members

	Response of all SME's and large enterprises	Response of maritime sector
Yes, for high risk structural members	23%	29%
Yes, for high risk structural members but combined with mechanical fastening	17%	18%
Yes, for low risk structural members	26%	27%
No, but we are considering it for high risk structural members	10%	11%
No, but we are considering it for low risk structural members	5%	4%
No	19%	13%

Next, the advantages of having adhesive joints were asked. A list of advantages was provided and the participants could select multiple responses. The first column from left shows the provided list of advantages, the second column presents the responses from all the SME's and large enterprises, and the third column presents the responses of maritime sector.

The ability to join dissimilar materials has scored the most. In addition to the list of advantages shown in the table, easy to apply in complex geometry, not intrusive no hot works or welding, good shock resistance, better strength (per unit length) and possibility to intervene in ATmosphere EXplosible (ATEX) environments with no production disruption were the advantages added by the participants.

Table 3: Advantages of application of adhesive bonding

	Response of all SME's and large enterprises	Response of maritime sector
Ability to join dissimilar materials (for example composite-to-metal);	21%	19%
Provides design flexibility;	16%	16%
Faster/cheaper production or installation times (CAPEX);	14%	16%
Sealing properties (adhesive fills gaps and voids);	13%	12%
Uniform distribution of mechanical stress over the joint;	12%	11%
Good vibration damping properties;	9%	9%
Good fatigue resistance;	8%	9%
Ease of inspection and maintenance (OPEX);	6%	8%

Current roadblocks for the application of adhesive bonding was the next question. The response of maritime sector is presented in the following table.

Table 4: Current roadblocks for the application of adhesive bonding, response of maritime sector

Unclear regulations/certification requirements;	29%
Required testing campaign;	17%
Risk of failure due to aging/thermal expansion;	15%
Insufficient “know-how” of production, design and quality assurance;	11%
Not allowed by client;	9%
other	8%
Cleaning and surface preparation of the adherents ;	7%
Not commercially interesting (compared to welding or bolting);	3%

The responses highlight the importance of regulation/ certification, 29% by the maritime sector (25% by all industrial sectors). Required testing campaign and risk of failure due to aging/ thermal expansion are the next most common answers.

2.1.1. Objectives of QUALIFY

To further narrow down the road blocks and categorize them aligned with the objectives of the QUALIFY project, more specific questions were asked:

- What could be the issues regarding the durability of adhesive bonding?
- What could be the issues regarding regulatory requirements?
- What could be the issues regarding inspection and maintenance?

2.1.1.1 Durability of adhesive bonding

Table 5: Issues regarding durability of adhesive bonding, response of maritime sector

Lack of data;	37%
Joint design and failure modes;	28%
Adhesive performance;	27%
other	8%

Lack of data was scored 37% by maritime industry (39% by all enterprises). Aging in marine environment, insufficient static and fatigue strength, creep and NDT, knowledge of steel degradation beneath the adhesive, surface preparation knowledge e.g. roughness, cleanness, salt concentration are examples of lack of data.

2.1.1.2 Regulatory requirements

Table 6: Issues regarding regulatory requirements, response of maritime sector

Structural requirements;	49%
Fire safety;	49%
Other	2%

We can see that the importance of the structural requirement. It was scored 49% by maritime sector (55% by all the SME's and large enterprises). Fire safety was also scored 49%, as well. But if we look at the responses of those who already apply adhesive bonding (either for high or low-risk structural members) 58% scored fire safety as an issue, which highlights its importance.

2.1.1.3 Inspection and maintenance

Table 7: Issues regarding inspection and maintenance, response of maritime sector

Lack of a reliable inspection protocol;	34%
Lack of repair and maintenance methodologies;	21%
Non-reversible adhesive bonding process;	21%
Labour training;	17%
Other	6%

34% of the maritime sector indicated lack of a reliable inspection protocol as the prime concern (33% of all SME's and large enterprises). Lack of repair and maintenance methodologies was scored second.

2.2. Universities and research institutes

Except from SME's and large enterprises, universities and research institutes also participated in the survey. The responses of this group show the potential of the future market. Their replies to current road blocks for the application of adhesive bonding are listed as follows:

Table 8: Current roadblock for the application of adhesive bonding, universities and research institutes responses

Risk of failure due to aging/thermal expansion;	30%
Unclear regulations/certification requirements;	27%
Insufficient "know-how" of production, design and quality assurance;	23%
Required testing campaign;	7%
Other	7%
Cleaning and surface preparation of the adherents ;	3%
Not commercially interesting (compared to welding or bolting);	3%
Not allowed by client;	0%

Table 9: Issues regarding the objectives of QUALIFY, universities and research institutes responses

Durability of adhesive bonding	Lack of data;	33%
	Joint design and failure modes;	27%
	Adhesive performance;	27%
	Other	13%
Regulatory requirements	Structural requirements;	52%
	Fire safety;	28%
	Other	20%
Inspection & maintenance	Lack of a reliable inspection protocol;	44%
	Lack of repair and maintenance methodologies;	26%
	Labour training;	11%
	Other;	15%
	Non-reversible adhesive bonding process;	4%

The other issues reported by the participants are listed as follows:

- Certification and lack of analysis methods to predict damage propagation in the bond line;
- Sensitivity to moisture and temperature, lack of reliable life time prediction methods, typically brittle failure and no post-failure load capacity;
- NDI detection of joint strength decrease;
- Uncertainty how well accelerated durability test methods correlate to reality; material variety i.e. test results for aged specimen may not apply to materials available in the market today;
- Missing long term experience regarding the adhesion of sets of (pretreated) substrates and adhesives.
- To fulfil the means of compliance;
- Environmental issues (toxicity);
- Requirements related to continuous airworthiness.

3. OFFSHORE WIND INDUSTRY

Offshore wind industry is a growing market. In 2021 wind turbines with diameter of 220 m and energy output of 12 MW were realised. In this section an overview of the wind turbine structure is given and then current joining technologies and the application of adhesive bonding are presented [13].

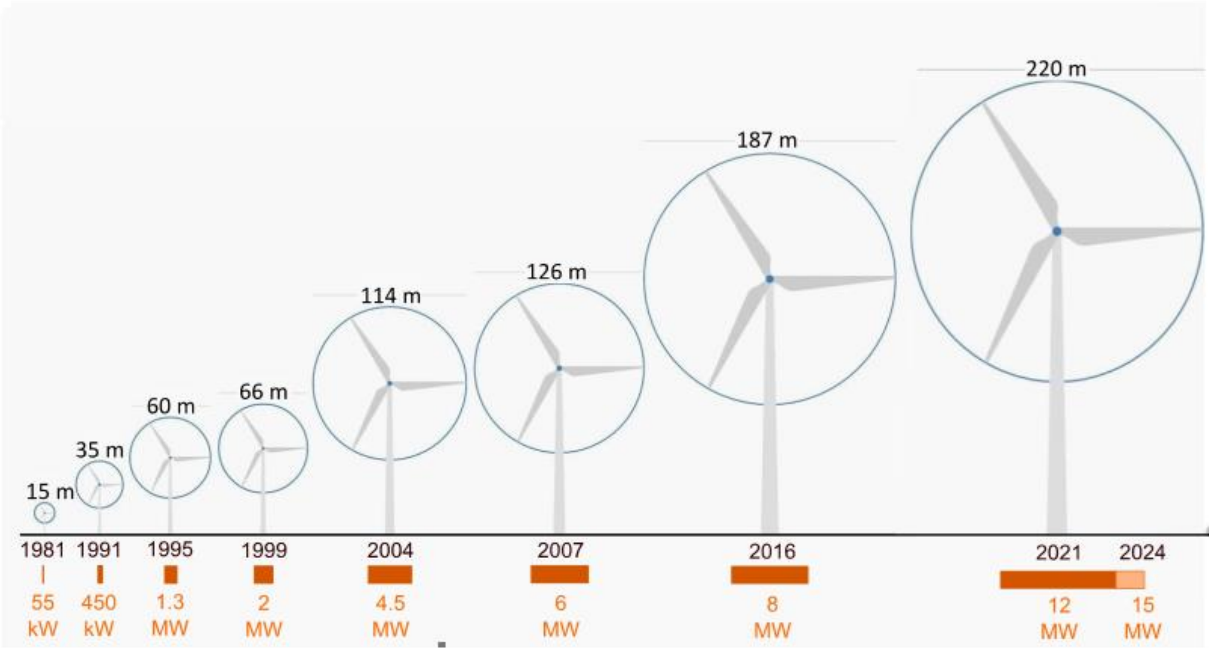


Figure 10: Progression of wind turbine sizes and their rated energy output

3.1. Introduction in offshore wind turbines

3.1.1. Overview of main structural components

The main components of the wind-turbine system are its foundation support structure, transition piece, tower, rotor blades, and nacelle, as shown in Figure 11. The foundation is for proper operational position of the wind turbine. The transition piece enables correction of possible misalignment of the monopile during the installation. The nacelle contains essential electro-mechanical components such as gearbox and generator to convert wind energy to electrical energy [14].

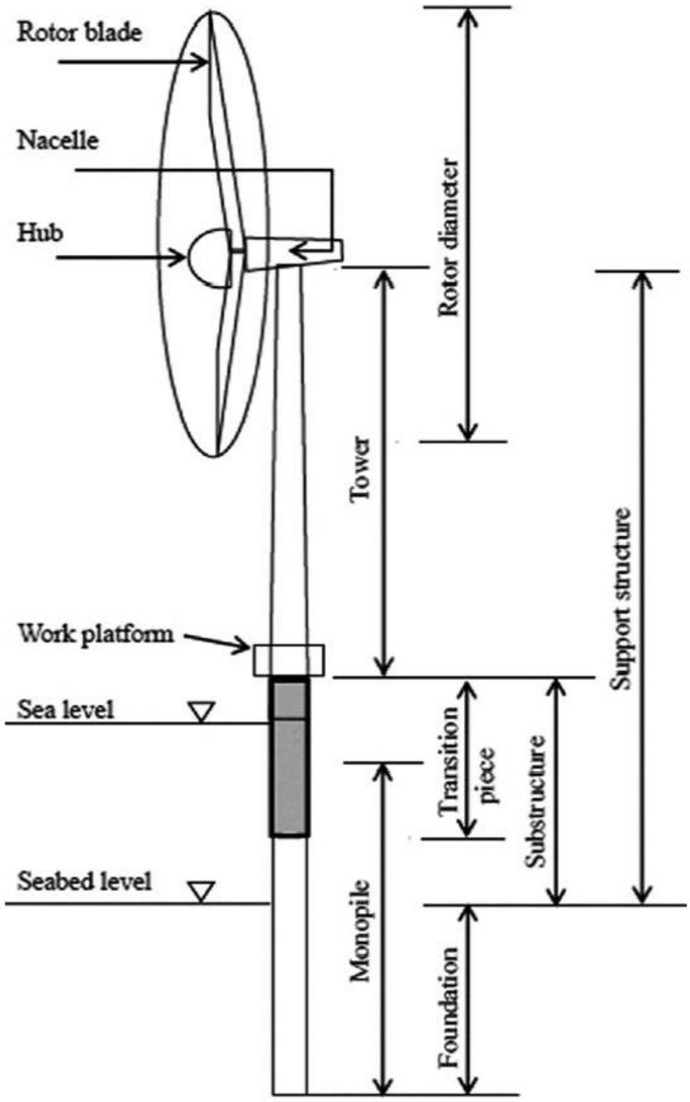
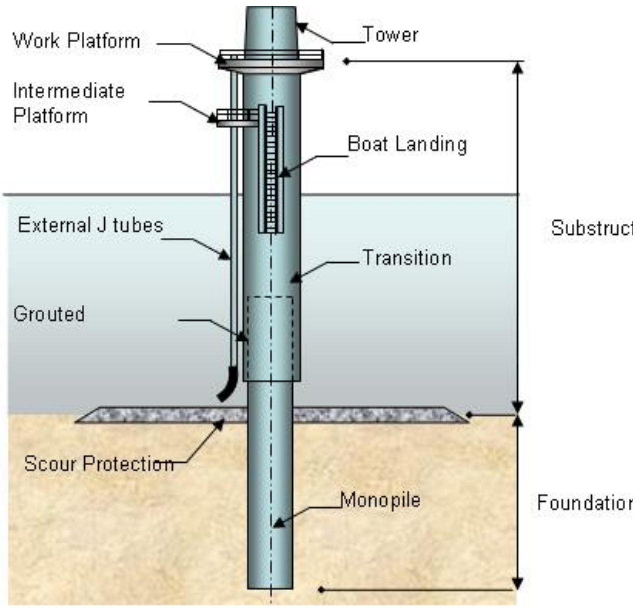
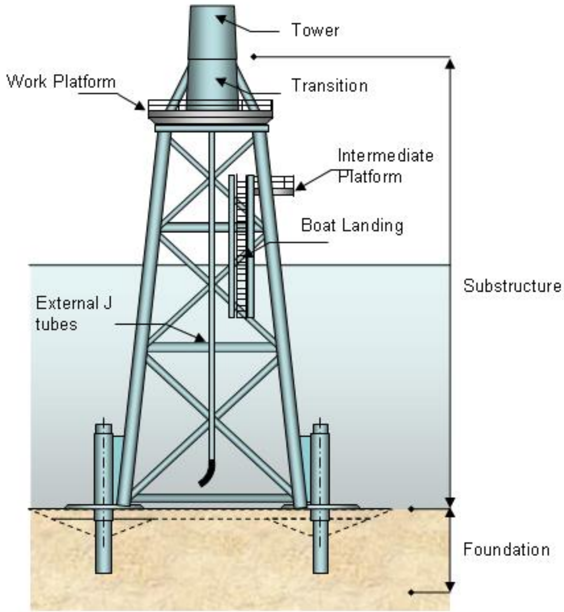


Figure 11: Main components of offshore wind turbine system [14]

Wind turbine steel structures can be categorized as primary and secondary. Primary steel is important to support the turbine, but the purpose of secondary components is to fulfil the interface requirements for operation and maintenance. External platform, boat landing, work platform and access systems, electrical and cable installation interface are known as secondary steel structures. Figure 12 illustrates examples of offshore wind turbine foundation structure, where boat landing and work platform can be seen.





a) monopile structure **b) tripod structure**

Figure 12: examples of offshore wind tubine foundations structures [15]

3.1.2. Value chain and market forecast and cost break down

Value chain assessment for offshore wind consists of many parts which all influence the cash flow and ultimately the project value. DNV GL has made a probabilistic analysis, in which time schedule, the physical flow, economics and weather can be studied.

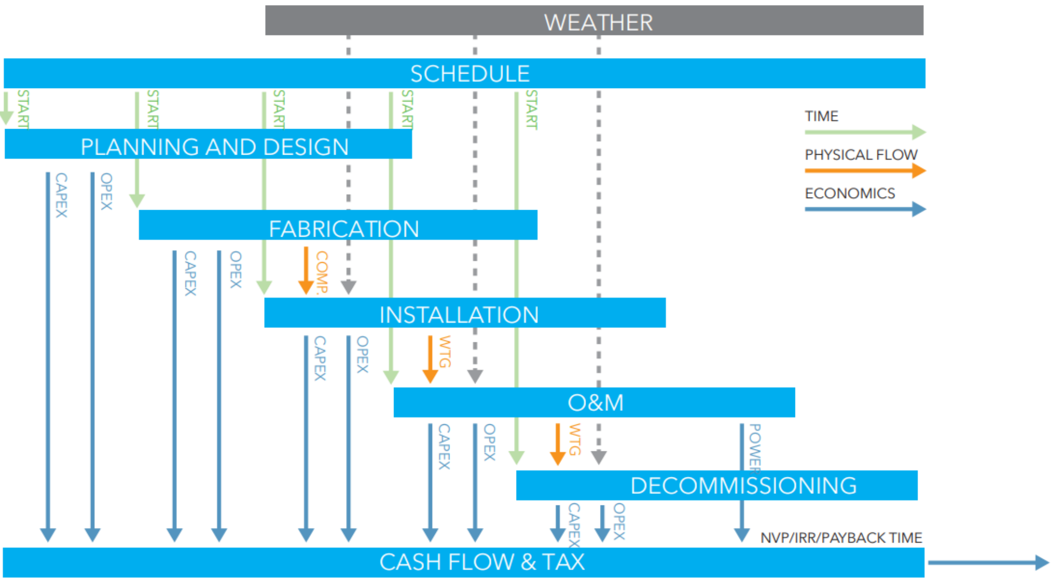


Figure 13: Value chain assessment service tool of DNV GL for offshore wind [16]

The capital cost of offshore projects differs markedly from those onshore, with perhaps 50% of the capital cost being due to the non-turbine elements, compared to less than 25% in onshore projects. A typical break down of cost for an offshore wind farm is shown in Figure 14:

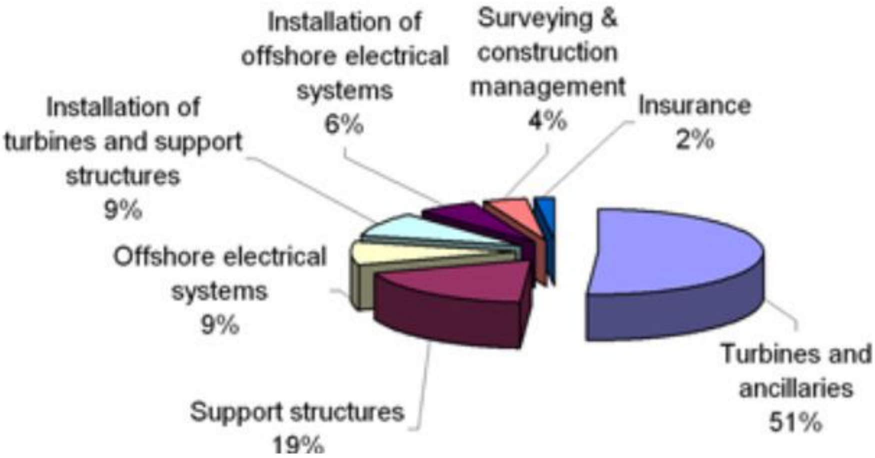


Figure 14 : Capital cost breakdown for a typical offshore wind farm [17]

3.2. Challenges with adhesive joint in offshore

The use of adhesive bonding could be an option for the structural joint between composite blade sections or the connection to the hub. Different composite components of a blade which cannot be manufactured as a single part (due to cost or technical constraints) can be bonded using adhesives. As blade sizes increase in wind turbines, the need for joining of components will likely only increase.
Also for walkway gratings and steel supports this could be an option. In the latter case, use of adhesive bonding circumvent current problems and maintenance costs associated to corrosion of the bolts used to fix the gratings to their steel supports. Furthermore, future developments will likely see the introduction of load-bearing composite components in the structure, for example replacing the steel support for the gratings by a composite support.

Adhesive joints can be structurally efficient, light and inexpensive. They have low stress concentrations and good damage tolerance. However, the use of (large) adhesive bonds also present a number of challenges for assembly on site:

1. Lack of inherent self-alignment of adhesive joints;
2. It may take some time after processing to achieve the full joint strength;
3. Surface preparation, temperature and humidity affect the quality of adhesive joints;
4. Good control over the bond thickness is important to avoid stress concentrations;
5. Air entrapment can drastically reduce the strength of adhesive joints.

Because of the large number of factors influencing the quality of an adhesive joint, proper control of the joining process and post-installation inspection also put some major challenges.
The durability of adhesive joints in a harsh environment is currently not well understood. UV, water, humidity, salinity, etc. can all have a negative impact on the durability of adhesive bonds and little is known about how various adhesives behave in a marine environment or submerged in seawater. An additional difficulty is that the adhesive often loses strength first in regions which are difficult to access or inspect.

Adhesive bonds are non-reversible, i.e. they cannot be opened and closed in the same way as bolted connections. This has implications with respect to maintenance. For example, if one applies adhesive bonding to join the blade to the hub, it cannot be easily replaced.

In contrast, mechanical joints for composite blade connections are heavy and expensive, but are fast and easy to assemble. Furthermore, they are easier to inspect but require some maintenance.

The above difficulties related to adhesive joining also make it is difficult to know what strength and fatigue properties can be allowed in the design phase of adhesive joints. Under a complex fatigue loading condition, there are still a lot of questions on how the non-degraded adhesive behaves. Adding to that degradation due to environmental influences makes a correct estimation of design values even more challenging. The lack of understanding and limited research done on this topic so far, may be limiting the market uptake of adhesive bonding.

Not only the glue itself, but also the (mechanical) design of the components to be bonded should be carefully considered. The largest challenges are not necessarily at a technological level, but the fact that end-users, designers and customers are not familiar with how to design a good adhesive joint, especially for large hybrid connections (e.g. steel/composite).

3.3. Current application of adhesives in offshore

3.3.1. Wind turbine blade

The connections in a wind turbine rotor blade have the following characteristics:

- they are primary connections meaning that their failure would fail the blade and result in power loss;
- they are subjected to sever fatigue loading during the life time due to gravity, wind shear and gusts;
- blades and blade connections are designed to have minimal maintenance which highlights the importance of joints;
- joints and connections are often the first locations where crack initiates and grows and also where moisture can penetrate;
- connections increase the mass of the turbine blade;
- connections are not equipped with sensors;
- such connections are costly due to the use of additional materials, complex load transfer between different materials, uncertainty on behaviour of connection such as creep and fatigue, on-site assembly time, additional tooling and certification.

In the following sections the application of adhesive bonding in the internal structure of blades and possibility for the connection of the blade pieces together and to the hub will be presented [18].

Application of adhesive bonding joint in the wind turbine blades is well known. The blades consist of two aerodynamic shells upwind and downwind. Figure 15 shows a wind turbine blade and the cross section, which illustrate the material types and the location of the adhesive joints. The load is mainly carried by the three joints shown: the leading-edge, the trailing-edge and the web joints.

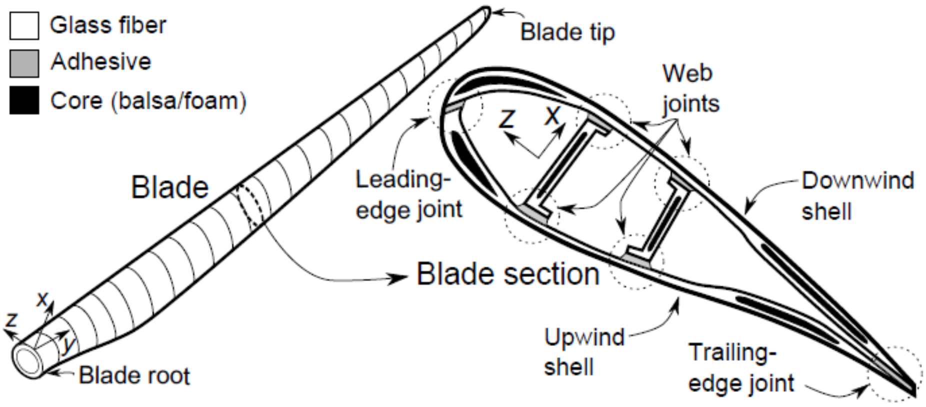


Figure 15: Wind turbine blade and a cross section showing the material type and inside design [19]

During the last years larger wind turbines have gained more attention. With larger wind turbine fewer units are required to generate the same level of energy, which is economically advantageous. Larger wind turbine means longer blades, and thus increase of the weight. Studies have shown that the weight of the blades measured in *kg*, has increased to the power of 2.1 times the rotor diameter in meters, see Figure 16 [20]. The aim is to build cost efficient light weight blades with a high strength to resist the wind load during the whole life time.

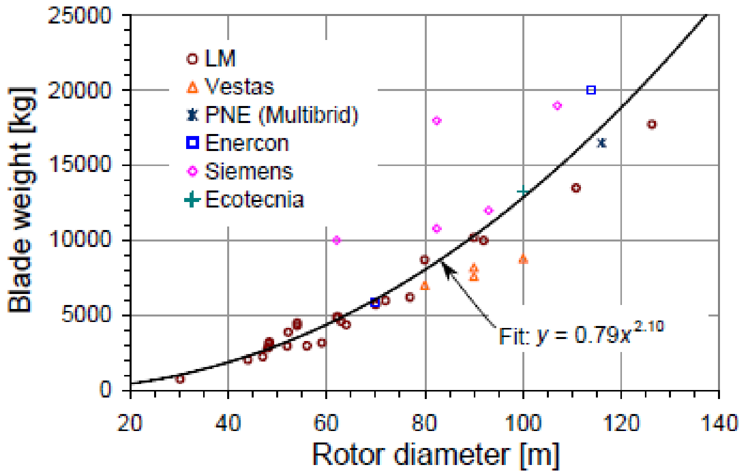


Figure 16: The trend in blade mass with rotor diameter [20]

3.3.2. Blade assembly

As mentioned earlier, wind turbine blade size increases and thus the manufacturing and transportation of long blades (>100m) to the site has become challenging. Segmented blade design is an approach to build the blade in multiple segments and transport them separately and assemble them onsite. Blade segmentation can be done to reduce the length, reduce the width/height or to reduce rotor loading. The designs, advantages and drawbacks are presented in Table 10 [21].

Table 10: Advantages and drawbacks of wind turbine blade segmentation [21]

Segmentation Strategy	Type of Division	Advantages	Drawbacks
Reducing length	Span-wise joint	Potential cost reductions	Goes against historical trend Slender blades reduce available space Optimal split transport/structure differs Division of structural spar
Reducing width/height	Chord-wise joint	Potential cost reductions	Transfer of edge-wise loads
Reducing rotor loading	Span-wise: telescopic blades	Variable swept area Reduced extreme loads.	Division of structural spar
	Chord-wise: trailing edge flaps	Variable blade shape Reduced extreme and fatigue loads	No need to divide structural spar Increased complexity

Adhesive bonding can be applied for joining blade segments, which offers low stress concentration and high damage tolerance. However, in practice the cost of installation of such joint type can be rather high. An overview of the challenges of adhesive bonding for segmented blades is presented in Table 11.

Lack of inherent self-alignment of adhesive joints is one of the installation issues. There are several remedies suggested in the literature such as laser positioning, brackets attached to spar cap, alignment pins and overlapping portions. Curing of the bonds is the other issue which requires experience and well trained man power. Ensuring high bond quality in on-site condition is also necessary. Bond quality can be affected by several factors e.g. surface preparation, temperature, humidity. Suggested remedies in the literature are applying bonding grid, meaning that the grid is incorporated into the joint to gain accurate bond thickness. Another suggestion is to obtain minimum constant distance between the parts is to use shims. Production of the segments in a single mold is the other suggestion. By folding in a vacuum bag with release agent, the two adjustment segments can be manufactured while they are in contact with each other. Later, they can be easily separated and fit well at the interface. Strength of adhesive joint can significantly reduce if air entrapment happens. One suggestion to avoid it is to put the connecting surface in place first, creating cavity to be flooded or infused to create the joint.

Table 11: An overview of the challenges and issues of adhesive bonding in segmented blades [21]

Adhesive Joint Issue		Suggested Remedies
Time of assembly	Alignment of the segments	-Alignment using laser-positioning -Brackets attached to spar cap -Alignment pins -Overlapping portions
	Curing of the bonds	-Resistance heated bonds
Bond-quality	Bond thickness	-Bonding grid -Shims -Producing the segments in a single mold
	Air entrapment	-Flooding of a cavity -Infusion

3.3.3. Blade root connection

Attachment of the blade root connection can be flange root, hub-type, T-bolt or stud root connection. Stud/ insert type is in fact longitudinal bolts attached to studs or inserts. Typically the inserts are made of steel causing a thermal and flexural mismatch. To avoid that, the studs are tapered on the outside or inside by using a thicker laminate. Often studs are glued into the blades. In case of wood composite blades the studs are located in the drilled holes. In glass fibre blades during the fabrication the holes are formed. Process of adhesive bonding and perfect positioning of the studs are of high importance to create a uniform bond layer and avoid local stress concentrations. Fixtures are often applied which facilitate the positioning and bonding process simultaneously. Injection of adhesive to the hole can be done via a second hole or through the gap between the laminate and the stud. The quality of the adhesive joint can be affected if there are macroscopic voids. A suggestion is to improve the tru-stud bonding method to allow vacuum infusion by adding a second channel to the stud. Another method is to embed the studs during the lamination process, which as a result less fabrication process steps are required. The advantage of this method is that compared to the T-bolt method about 35% more bolts and thus more strength can be obtained. Moreover the damage by drilling is avoided and that inserts can be prefabricated. A thorough literature review and research study on the stud/insert type and an example are reported in [21] [18].

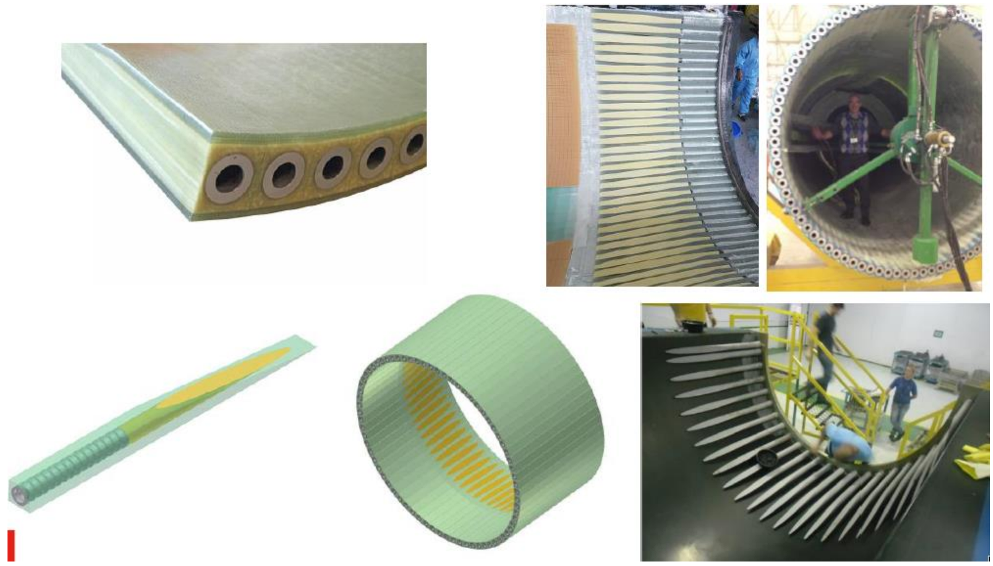


Figure 17: Illustration of the concept of inserts to connect composite blades to the hub [22]

3.3.4. Cold repair

Adhesive bonding attachment of a reinforcing plate, known as cold repair, is a suitable repair method for marine and offshore applications. A risk assessment study has suggested safer approach compared with welding method which is a hot repair technique [23]. Repairing the corroded parts can be time consuming and costly, especially if the repair requires a downtime. Moreover, the traditional hot repair work can cause risk of damage. The advantages of cold repair are listed as follows:

- Repair can be performed during the operation and without interrupting or lowering the production;
- In addition to the short repair time, less work is also required compared with the traditional methods. Only surface preparation and bonding needs to be done which can be handled by a small team;
- Patch repair offers mechanical reinforcement of the corroded surface. Not only it does not weaken the structural integrity but also can extend the life time of the structure;
- Cold patch repair is a safe method and low risk. It does not damage the paint, insulation, electrical equipment's and does not have a risk of fire or explosion as in hot repair.

Case study 5- ColdShield^{TM} solution

ColdShield^{TM}'s product ColdPad is a pad repair for marine and offshore applications. It comprises two layers: a top reinforcing plate made of a super duplex stainless steel and a layer made of composite material that ensures the load transfer between the hull and the steel plating, shown in Figure 18. In fact, the solution combines three technologies: vacuum-assisted resin injection, structural adhesion and assembly of high-performance metallic and composite materials. ColdShield^{TM} has been applied for

TOTAL FPSO vessel for the repair of the corroded surfaces. The prefabricated part is bonded to the FPSO's surface using a vacuum-assisted injection process that allows the resin to be spread evenly without any need to control atmospheric conditions. This is a solution for harsh environments since a peripheral fluorosilicone seal encapsulates the resin to protect it from seawater and hydrocarbons during the reinforcement's useful life [24], [25].

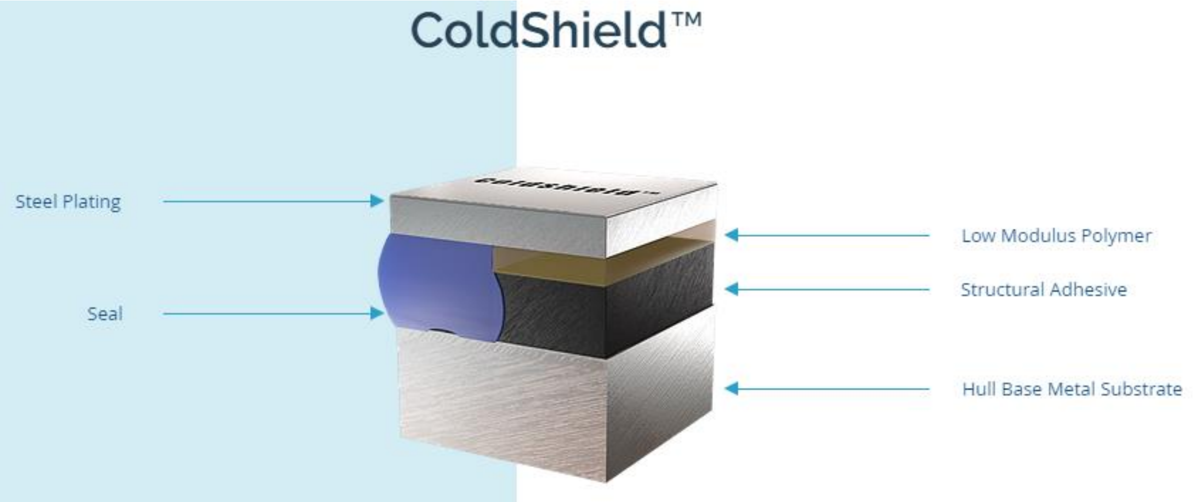


Figure 18: ColdShield™ solution of ColdPad [25]

3.3.5. Bonding fasteners

Several companies have made cold bonding fastener solutions suitable for marine and offshore harsh environment. Adhesive bonding solutions and fasteners reduces drilling holes, which as a result improves structural integrity of the structure and diminishes leak potential. It also reduces installation costs, prevent corrosion and eliminate hot work. The following case study presents an example of such bonding solutions. For more examples we refer to [7], [8], [9].

Case study 6- Fasteners

Click Bond studs and standoffs are products designed for several applications also in marine and offshore, which are resistant to fuel and oils, and optimized for durable, labour-saving attachments to structure. Adhesives are especially designed for Click Bond applications. They are fast cured adhesives which have passed IMO smoke and toxicity test. It is a two-part methacrylate adhesive designed for structural bonding of thermoplastic, metal, and composite assemblies. Figure 19 shows the studs installed in an offshore oil platform.

Figure 19: Studs for floor support post installation in an offshore oil platform [8]

3.4. Opportunities for hybrid materials in offshore

3.4.1. Platform

Fiberglass gratings are suitable solutions for oil rigs, wind farms and other offshore applications. They substitute aluminum or steel which lower the weight and require less maintenance and are corrosion resistance. This can especially help where the maintenance cost due to corrosive environment would be high [26], [27], [28]. The advantages of fiberglass reinforced plastic in the offshore industry are:

- chemical resistance: resistance to corrosive substances and acids;
- impact-resistance: such material is more impact-resistant than steel grating;
- nonskid and anti-slip: due the concave meniscus surface;
- maintenance-friendly: such material does not rust and therefore does not require maintenance;
- electrically and thermally non-conductive;
- lightweight;
- easy to process and install.

Figure 20: Fibreglass grating and handrails [26]

Figure 21: GRP grating application in offshore [28]

The composite grating could be installed with fixing clips and clamps. Application of adhesive bonding can be used as a valuable alternative for this case. Parkwind has studied such a potential which is presented in the next case study.

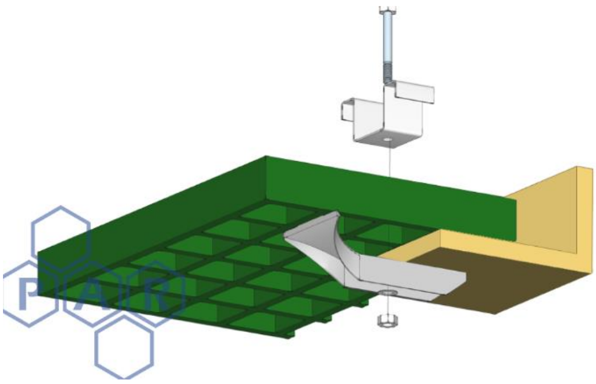


Figure 22: Installation of composite grating with fixing clips and clamps

Case study 7- Wind turbine transition platform in composite

Parkwind N.V. has previously studied a solution to replace the steel platform of wind turbines connected to the transition piece with an FRP platform. Parkwind is a pioneer in this research and there is no prototype made yet. Such platforms are subjected to heavy wave forces and especially wave run-ups. Current designs are steel platform welded. The first study considered an FRP platform connected with a hybrid joint, meaning combination of adhesive joining and bolt connection. The ultimate idea is however, to have an FRP platform adhesively bonded. For a platform six meter by seven meter the cost of the platform in steel would be around 120-180k €. If this platform is replaced by an FRP platform the CAPEX would be around 10% more expensive than the steel platform. So in fact the CAPEX for an FRP platform would be higher than conventional steel platforms. Regarding the OPEX however, the new solution would be relatively much less costly.
To this end, the main challenges are to come up with a design mechanically strong to resist the wave forces, with a rather easy installation process but the fire safety and life time performance need to be assured. Figure 23**Error! Reference source not found.** shows an initial idea however, further studies and researches are required.

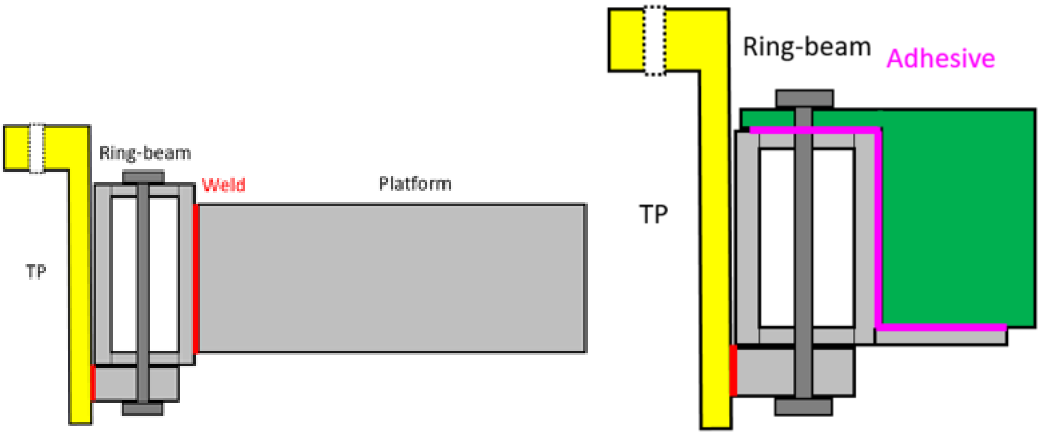


Figure 23: Steel platform welded (left), Parkwind case study proposing an FRP platform and hybrid joint (right)

3.4.2. Bonding of measurement equipment

Adhesive bonding has been previously applied for attachment of measurement equipment's for instance strain gauges. A novel application of adhesive bonding of entire equipment on impact-driven offshore monopile foundation in an offshore wind farm is presented here.

Case study 8- Bonding of sensors and cables in an offshore wind turbine

Due to certification issues conventional methods of fastening such as screwing or welding were not permitted in an offshore windfarm in the German north see. Instead, adhesive bonding of all parts (sensors, cables, shielding, recorder/computer) was successfully applied and withstood impact driving with several thousand blows of up to 1200 g (earth gravity).

Two main adhesive routes were implemented for the small sensors and all other components like cables, protection profiles and recording computer on the other hand. For the adhesive joint of small sensors thin structural layers of adhesives were applied for best coupling to the structure. Thin layers and rigid bonds are necessary to avoid mechanical damping of the layer between sensors and structure. This way correct measurements of dynamic deformation of the structure is assured. All other components including sensor protection, cables, monitoring equipment, etc. were installed using thick layers of semi-structural adhesive on a maximized area to provide elastic bedding with excellent adhesion, high damping factor and low failure growth [29]

Figure 24: Sensors below encapsulation, encapsulated sensors, cables embedded in adhesive and cable protection duct, driving shoe at end of cable protection duct near pile toe (from left to right) [29]

4. MARITIME INDUSTRY

4.1. Market status

Newbuilding

The aggregated EU-28 production value exceeds other maritime countries like Japan or USA and maintains a strong market share (~19%) [30]. This is mainly caused by a strong position in the building of Cruise vessels (~90% market share), Ferries (~50%) and naval vessels (~30%) and a small share in the (larger) container and offshore markets. Bulk carriers, oil or chemical tankers, LNG and LPG ships are almost exclusively produced in the far east (China, S. Korea and Japan). The shipbuilding market is highly export oriented with approximately 2/3 of its total production being exported.

Labour costs typically account for some 20% of the overall costs. Europe clearly shows higher labour costs in comparison to its Asian competitors, although low labour cost competition is mainly focused on China and emerging shipbuilding nations. Korea and Japan do not have significantly lower labour costs and have even higher labour costs than some European countries (such as Romania). Due to its specialisation in the high value-added segment of the market labour costs are less of an issue in shipbuilding in Europe [31].

Figure 25: Market overview [32]

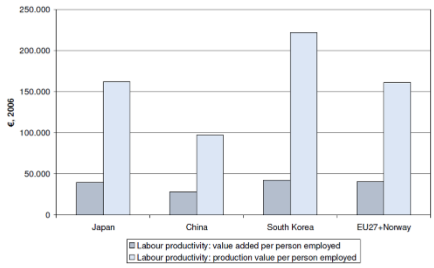


Figure 26: Labour productivity [31]

Repair

The European Ship Maintenance, Repair and Conversion market represents approximately €7.5 bn (see fig.25). Repair and maintenance is a short term activity. The dry dock period is generally 10 to 12 days. Conversions sector are in some aspects more similar to the newbuilding sector than to repair and maintenance. This sector is particularly important to countries on major trading routes, such as Greece and the UK, for whom repair represents more than 90% of the total shipbuilding turnover.

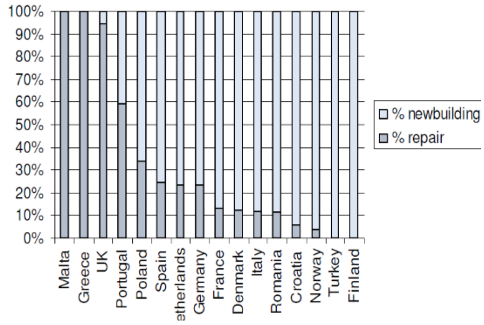


Figure 27: Share turnover 2007 [31]

4.2. SWOT analysis European shipyards

Framework Conditions	
S	• Strong European industry base in general, very good mechanical engineering and electrical engineering • Powerful research environment and educational system • Strong competitive environment with numerous flexible companies • Good infrastructure, reliable logistics
W	• Heterogeneous industry structure, few big, very many small companies • High wages and costly social system - High cost of production • Material cost comparatively high • Access to finance • Currency exchange rates • In comparison to other European industries, reluctant political support • Significant administrative burdens and cumbersome regulation
O	• Further harmonisation and standardisation of regulations in Europe to remove legislative barriers • High energy cost may trigger even more demand for energy efficient vessels • Further environmental regulations may lead to further increase of "green cost", but may drive technological markets for powerful systems and components
T	• Accelerated strategic expansion of the Asian maritime supplies industry mainly in Japan, South Korea and China, in conjunction with increasing export activities to the European market • Increasing activities by strategic investors from North America and Asia to acquire stakes in European global-acting companies. This may lead to accelerated exodus of companies or knowledge drain • Comparatively high (e.g. environmental) requirements cause high production costs in Europe • Subsidies in competing countries

Figure 28: SWOT EU maritime market [30]

4.3. Potential for hybrid joints in shipbuilding

4.3.1. Introduction

"Metals will still be the dominant bulk material used in ship structures, but there will be an increasing appetite for composites to replace steel in selected applications. The use of polymer matrix composites, from the traditional glass fibre and epoxy resin to the more recent carbon fibre-reinforced plastics, can offer lightweight, stronger, and tougher materials that do not corrode. Next-generation resilient mount materials will be explored to actively reduce the noise and vibration released from machinery." [32]. This statement is motivated by the presence of both a market pull as a technology push. "With the ever-tighter competition, shipping companies are driven to invest in new materials that offer better mechanical properties or versatile functionality, leading to improved operational efficiency and reduced operating expenditure (OPEX). Better fuel economy or more cargo-handling capacity can be achieved by introducing high strength-to-weight structural materials, such as advanced high-strength steel, aluminium, glass fibre, or carbon fibre composites. Self-repairing materials can reduce the need for maintenance. Meanwhile, material suppliers will continue to seek for sustainable sourcing." [32]

4.3.2. Market pull

Globally all industries are pressured to make efforts to reduce the greenhouse gas emissions as much as possible. The International Maritime "Marine Environment Protection Committee (MEPC)" has adopted the initial strategy during its 72nd session at IMO Headquarters in London, United Kingdom. The meeting was attended by more than 100 IMO Member States, copied from the IMO website [33].

1. carbon intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships:

   to review with the aim to strengthen the energy efficiency design requirements for ships with the percentage improvement for each phase to be determined for each ship type, as appropriate.
2. carbon intensity of international shipping to decline

   to reduce CO_2 emissions per transport work, as an average across international shipping, by at least **40% by 2030**, pursuing efforts towards **70% by 2050**, compared to 2008; and
3. GHG emissions from international shipping to peak and decline

to peak GHG emissions from international shipping as soon as possible and to reduce the **total annual GHG emissions by at least 50% by 2050** compared to 2008 whilst pursuing efforts towards phasing them out as called for in the Vision as a point on a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals.

The CO_2 –emissions can be reduced by more efficient propulsion, applying alternative fuels or by reducing the required power. However, for most ship types applying alternative fuels cannot compete with the specific energy or energy density of diesel, as illustrated in the left graph. and will either result in an unacceptable drop in space on the ships or range of the vessel. The graph below right is a conservative representation of the direct power reduction of lightweight ships.

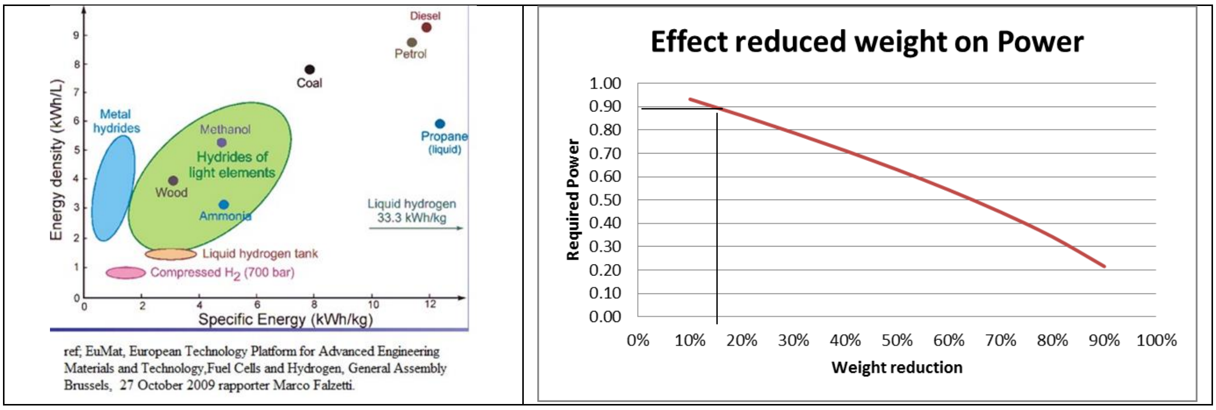


Figure 29: Left comparison fuel; Right fuel reduction

4.3.3. Technology push

In combination with the Horizon 2020 projects Fibreship & Ramsses the Qualify project will help the European maritime industry in developing the so called ‘fast track to innovation’, with specific attention to composites in this case. Where the Horizon 2020 projects focus on the performance and approval of large composite structures, the Qualify project will develop guidelines for the adhesive bonding.

The potential for composites in shipbuilding are well established. Looking at the participants of the above European projects is it clear that this well understood by most European shipbuilders, ship owners and governing bodies.

4.4. Bonding vs Bolting

In this chapter it is assumed both a bonded and a bolted connection meet all performance requirements. The comparison is made only with regards to production efficiency.

There are several disadvantages with bolting composite panels. First of all, it is not possible to put pre-tension on composites in a bolted connection since the resin will relax and most of the tension will be lost after 24h. If the tension is too high, e.g. to compensate the relaxation, too much tension can crush the resin causing small delamination cracks in the composite. Secondly, bolts in composites will transfer the load mostly as pinned connections, not by shear transfer of the surface. To carry the load, the thickness of composite structure needs to be doubled locally. Thirdly, during the machining of composites, it is possible small cracks are created in the hole and the holes should be sealed or a metal insert needs to be added. In comparison a composite panel prepared for bonding does not need structural reinforcement and the panels can be cut from long vacuum infused or even pultruded panels.

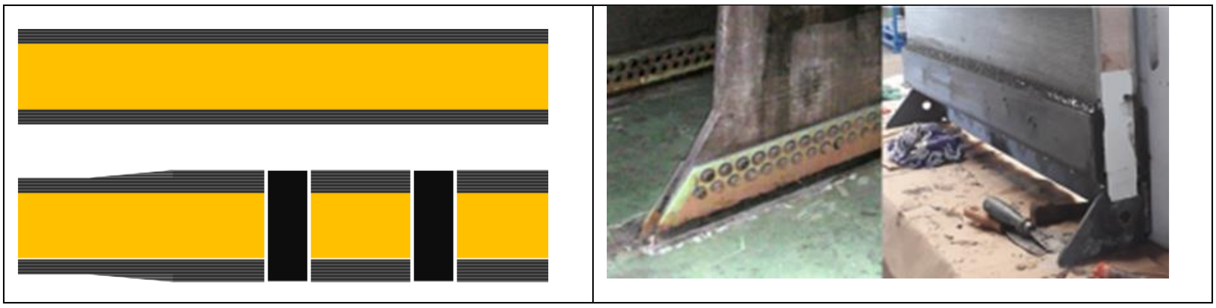


Figure 30: Bolted vs bonded composite structure

The assembly procedure depends on the type, size and amount of bolt and the viscosity of the adhesive but is assumed to be similar.

Case study 9- Adhesive bonding of passenger saloon

Adhesive bonding already has a noticeable presence in Damen products and its application is expanding – from cable trays and railings to bonded wheelhouses and windows. In one of the latest projects – FCS 7011 (Fast Crew Supplier) adhesive bonding was challenged even more. The first tier of the passenger saloon was part of the intact stability and therefore the bond line design of the windows was a special point of attention for Bureau Veritas (BV).

Figure 31: Windows of the passenger saloon of a fast crew supplier

In order to convince BV a test has been performed with the assistance of Sika – the adhesive supplier. The results of the test demonstrated the watertightness of the bonded joint and the ability to withstand a design pressure of 25 kPa and a maximum pressure of 100 kPa. The design and application of the joint was done in a way that guaranteed full required bonding width coverage of 30 mm and no air pockets inside the bond line. The soft spacers (inner – continuous and outer – intermittent) assisted in making sure that the above requirements are satisfied. [34].

Figure 32: Adhesive bonding joint process

Due to the accelerated curing the chosen Sika adhesive has minimized the waiting time for production to release the supporting clamps and proceed with other jobs around the windows.

4.5. *Adhesives in large shipbuilding*

Currently the use of adhesives in large ships is limited to appendages and foundations with little consequences in case of failure, and these are not regulated by class. Examples from naval shipping, such as the French “Lafayette” and the Singapore “Independence” class show that it is feasible to rely on adhesives in a primary structure without a redundant shape bound joint. However, these are still exceptions and there are no rules available that lead to approval of bonded joints.

Finally the table below summarizes the characteristics of adhesive bonding in the form of a SWOT analysis:

Table 12: SWOT Maritime adhesives

Strength	**Weakness**
• No damage to existing structure • Limited increase in temperature • Can join different materials • No stress concentrations • Joint thickness from 0.5 to +10 mm • Excellent surface finish	• Large spread in quality • Little to no inspection possible after production • Temperature & corrosion sensitive • Strength drops at increased thickness • Effect of fatigue + Ageing unknown • Different from standard process • High Material Cost (1.20 €/kg)
Opportunities	**Threats**
• Lightweight hybrid structures • Improved aesthetics • Joining at fatigue or corrosion critical locations • Reduced lead time for repair • If sufficient area can be bonded, the strength of the joint can be improved	• Loss of quality control • Insufficient guidelines to cover the risk • Excessive tests restrict the implementation of new adhesives • Frequent modifications and updates adhesive formula • Health and Safety Restrictions

5. COST ANALYSIS CASES

5.1. Offshore vessel

The ColdShield™ solution [25] applied for the repair of FPSO Girassol in Angola corroded structural part proved to be financially beneficial. In 2008, an inspection found 19 corroded areas covering a total of 250 square meters on the FPSO Girassol's deck plates. This threat to the vessel's structural and mechanical integrity was what led to the innovative cold repair solution, since no conventional method could provide a suitable response. The corroded surface was too large for buttering to be reliable, and replacing the damaged parts would have required shutting operations down completely to reduce the risks to the integrity of the deck and hull. This would have meant a production loss of 110,000 barrels per day, for 60 days. It was decided to innovate by preparing the FPSO Girassol's hull for cold repair. Structural bonding of the first reinforcements prefabricated specially for the project by Cold Pad (subcontracted to Hutchinson) was carried out in October 2018, in just 28 days, coming in on time and on budget. Although the remaining work will not be performed until the end of the year, the project's overall budget will remain below €10 million.

5.2. Corroded pipes

Cold pad solution of C-Claw™ [7] was applied for repair of 30 corroded pipe supports in offshore platform in Nigeria, as shown in Figure 33.

Figure 33: C-Claw™ solution

Compared with the conventional method of welding the direct cost of C-Claw™ application was higher. But considering the cost of business interruption of welding and the associated cost due to confined space entry C-Claw™ solution could offer a significant value saving. For this project the cost saving was reported as 400k €.

6. QUALIFY OUTPUT

The table below lists all deliverables from the qualify project that will be made public.
They are divided per workpackage.

The deliverables D.1. provide insight in the design and analysis of the joint. The deliverables cover production and design (D1.1.1), environmental influence such as temperature and salt water on small scale (D1.2.1, D1.3.1, D1.3.2) and large scale (D1.5.1, D1.6.1) and evaluation of fatigue of the joint (D1.4.1,D1.5.1 and D1.6.1).

Deliverables D.2. discuss the developments on Structural Health and Condition Monitoring, focussed on the training of the systems and their reliability both in lab as "in-situ" conditions.

Finally the findings are translated into guidelines in D3.3.1. These guidelines make use of all the work performed in D1 and D2 and the load analysis of the case study joint (D3.2.1) and build upon the current regulatory requirements in D3.1.1

#	Title		Responsible
D 1.1.1	Specifications of demonstrator cases		DAMEN /BAE
D 1.2.1	Model Predicting the mechanical performance of joint, based on loading and environmental input		Cambridge
D 1.3.1	Coupled model to predict the mechanical performance of a hybrid structure in operational conditions		Cambridge
D 1.3.2	Material properties as a function of environmental and operational conditions.		TUDelft/Cambridge
D 1.4.1	Fatigue properties as a function of joint geometry		UGent
D 1.5.1.	Fatigue properties of the substructural component in operational conditions (loading & environment)		UGent
D 1.6.1	Validated model predicting the lifetime of the hybrid structure in its operational environment		M2i
D 2.1.1	Structural integrity assessment of the hybrid structure		TUDelft
D 2.2.1	Reliability analysis of the in-situ monitoring system		Com&Sens
D 2.3.1	In-situ repair of the egress of embedded optical fibre sensor technology		Com&Sens
D 3.1.1	Overview of current regulatory requirements for adhesive bonding and hybrid connections		BV/Lloyds
D 3.2.1	Report documenting the load analysis for mechanical tests		BV/M2i
D 3.3.1	Guidelines for the qualification of hybrid joints		BV/Lloyds

7. CONCLUSIONS

A market study for the application of adhesive bonding in offshore and marine industries has been presented in this report. An overview of the common joining technologies is given and adhesive bonding pros and cons are presented.

Application of adhesive bonding in other sectors such as aerospace and automotive is a more a common practice. However, it is mostly in non-structural joints or applied as a hybrid joining technique. Some case studies are presented in this report.

The report focuses on the offshore wind and maritime industries, presenting current applications and the potential future applications of adhesive bonding.

A survey was developed and addressed to all sectors to reflect the current position and market potential for the application of adhesive bonding. It was concluded that the most critical criteria for selecting a joint method in marine environment was the lead time of assembly. The most common current roadblocks for the application adhesive bonding are unclear regulation and certification as well as risk of failure due to aging/thermal expansion. Lack of data raises concern for the durability of the joint. Structural requirements, fire safety and lack of reliable inspection protocols are the other concerns.

Harsh offshore environments and in some cases remote access to joints highlights the importance of good knowledge of the joint behaviour in the long term and the need for clear regulations and certifications.

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