Report No.	**D3.1.1**	

Title of Report:	**Overview of current regulatory requirements for adhesive bonding and hybrid connections**

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EXECUTIVE SUMMARY

The project QUALIFY aims to remove the technological and regulatory barriers that currently prevent the widespread application of hybrid structures (metal/composite) in the industry.
The objective of this deliverable is:

- to provide a global overview of the regulatory requirements for adhesive bonding in marine and offshore industry applications,
- to compare adhesives using in other industrial sectors,
- to identify current regulatory barriers in marine and offshore.

This study has been performed conjointly by BV, LR and Parkwind and has been mainly focused on requirements for homologation on any specific plan appraisal. Concerning marine and offshore applications, some improvements are still necessary to accelerate the development of this joiningtechnique.

The comparison with other industrial sectors such as aeronautic, automotive, railway, etc, shows that the bonding is less developed in marine and offshore.

In addition, the following marine and offshore current regulatory barriers have been identified as contributing to the slow expansion of bonding joints:

- Short durability,
- Poor fire safety,
- Complex manufacturing,
- Few inspection control,
- Low training.

SUMMARY

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1. INTRODUCTION

Bureau Veritas and Lloyd's Register have compiled an overview of current industrial requirements for adhesive bonding in marine and offshore applications, such as rules, statutory, standards and codes applicable not only to the marine & offshore sectors, but also to other sectors e.g. aeronautic, automotive, railway, etc.

The document, produced by the two classification societies, reflects the current regulatory requirements for hybrid joints (adhesively bonded), including a mapping of current regulatory barriers to their application in primary structures in marine and offshore industries.

2. ADHESIVE REGULATORY REQUIREMENTS IN MARINE AND OFFSHORE

Requirements for classification of marine and offshore structures are laid down in by classification societies setting requirements for design, construction survey and testing of structures built under survey. In general, classification rules cover structural and watertight integrity and integrity of other essential service for safe operation. The rules also provide requirements for certification materials and components used in the fabrication of marine and offshore structures that come under class rules

All classification societies have rules regarding the certification and use of adhesive. The aim here is to review four classification societies rule set relating to adhesive, focusing primarily on requirements for homologation on any specific plan appraisal requirements. The four classification rule sets reviewed here are:

- BV: Guidance Note NI 613 DT R00 E – Adhesive Joints and Patch Repair
- LR: Rule for the Manufacture, Testing and Certification of Materials, Chapter 14
- ABS: Rules for Materials and Welding – Aluminium and Fibre Reinforced Plastic, Chapter 6 Material for Hull Construction – Fibre Reinforced Plastics
- DNVGL: Part 2 Materials and Welding, Chapter 3 Non-Metallic Materials
    - DNVGL-ST-0376: Rotor blades for wind turbines

2.1. ABS: Rules for Materials and Welding – Aluminium and Fibre Reinforced Plastic, Chapter 6 Material for Hull Construction – Fibre Reinforced Plastics

Requirements for structural application are provided in Part 2, Chapter 6, section 1-9 and need to comply with the following requirements:

a) Minimum shear strength of adhesive to be between 6.9N/mm^2 and 10.0N/mm^2 to be achieved in temperatures ranging from ambient to 49^{o}C using FRP substrate. Only cohesive or fibre failure modes are acceptable. Testing performed in accordance with ASTM D1002 or ASTMD3165
b) Adhesive to be tested in fatigue on either FRP or metallic substrate. Test to be conducted at 50% of ultimate tensile strength at 30 Hz, and to last for a minimum of one million cycles. Testing to be in accordance with ASTM D3166

c) Application process, including information on maximum bond line thickness, non-destructive testing and maximum creep to be submitted for review
d) Elastic modulus of the adhesive to be considerably less than that for the FRP skin to which it is being adhered
e) The strain to failure ratio of the adhesive is to be much larger than the surrounding structure
f) Mechanical properties of the adhesive are achieved rapidly so that mechanical fixing such as bolts or screws are not required to hold the substrate together while the adhesive cures
g) The adhesive is to be compatible with the lamination resin

Adhesives for structural application are to be used in accordance with manufacturer's recommendations. Details of proposed structural adhesive are to be specified on the Material Data Sheet and on the construction plans submitted. Builder process instructions are to be forwarded for review and to include details on handling, mixing and application of adhesive, identify level of training required for personnel undertaking the bonding process, and give particular attention to surface preparation and cleanliness of the adhered surfaces. And where bonding surfaces are uneven or fraying, a suitable gap filling adhesive or additional reinforcement to even out the surfaces.

2.2. BV: Guidance Note NI 613 DT R00 E – Adhesive Joints and Patch Repair

Guidance note NI613 DT R00 E gives requirement s and recommendations for the assessing adhesive joints and also applies to multiple-materials adhesive joints:
- Composite/Composite (secondary bonding)
- Metallic/Metallic
- Metallic/Composite

However, this guidance note only applies to adhesive joints or patch repairs, not participating in ship's structural, watertight and fire integrity.
The objective of the guidance note is to provide technical support to shipyards, designers and surveyors involved in bonding and patch repair activities

2.2.1. Adhesive joints risk level classification

Based on the level of risk, 3 types of bonding application are defined:

a) Class A (Low risk)

This covers all adhesive bonding application where failure of the bonded joint in service will not affect safe operation of the ship in any way. Class A bonding application would apply to fixtures and fitting weighing less than 5 kg.

b) Class B (Medium risk)

This covers all types of adhesive bonding application failure of the bonded joint in service has minor impact on ship's mission but without any consequence on ship's structural and watertight integrity, on passengers or crew safety and ability of the vessel to sail.

B class adhesive bonding includes fixtures and fittings weighing between 5 kg and 50 kg bonded on deck or on bulkhead located less than 1 m in height in space accessible to public.

c) **Class C (high risk)**

This covers all types of adhesive bonding application for which in-service failure of the bonded joint will compromise ship's essential services including primary and secondary services.

C class adhesive bonding includes fixtures and fittings weighing greater than 50 kg or on a bulkhead located greater than 1 m in height, in spaces accessible to public

However, although Class C covers all possible types of adhesive bonding application, project feasibility will remain subject to the Society's prior agreement due to the necessary consistency of design and durability justification.

2.2.2. Bonding process assessment

The assessment process consists of four main steps:

- Preliminary assessment of shipyard
- Bonding File assessment (BF assessment)
- Manufacturing, Testing and Inspection bonding plan (MTI bonding plan)
- Bonding final assessment

The overall process is summarized below in table 1 and figure 1:

Step	
Preliminary assessment of shipyard	The shipyard prepares the general documents on its organisation, quality system, personnel skill and qualification in bonding and previous experience in order to demonstrate its capacity to achieve reliable bonding operation
	The Society carries out preliminary inspection in order to establish an initial diagnosis at yard **(BV Surveyor at yard)**
Bonding File assessment	Further to the Bonding Specification phase, shipyard submits all necessary technical documents relative to the considered bonding application
	The Society assesses the conformity of the bonding application design to the requirements of its rules: validation of the bonded joints risk level classification, examination of associated drawings, bonded joints design properties, qualification tests… **(BV local plan office + BV Surveyor at yard)**
Manufacturing, Testing and Inspection bonding plan	The shipyard provides The Society its MTI bonding plan relative to the considered bonding application process
	The Society examines the MTI bonding plan and performs inspection of the bonding process **(BV local plan office + BV Surveyor at yard)**
Bonding final assessment	

Table 1: General bonding process assessment

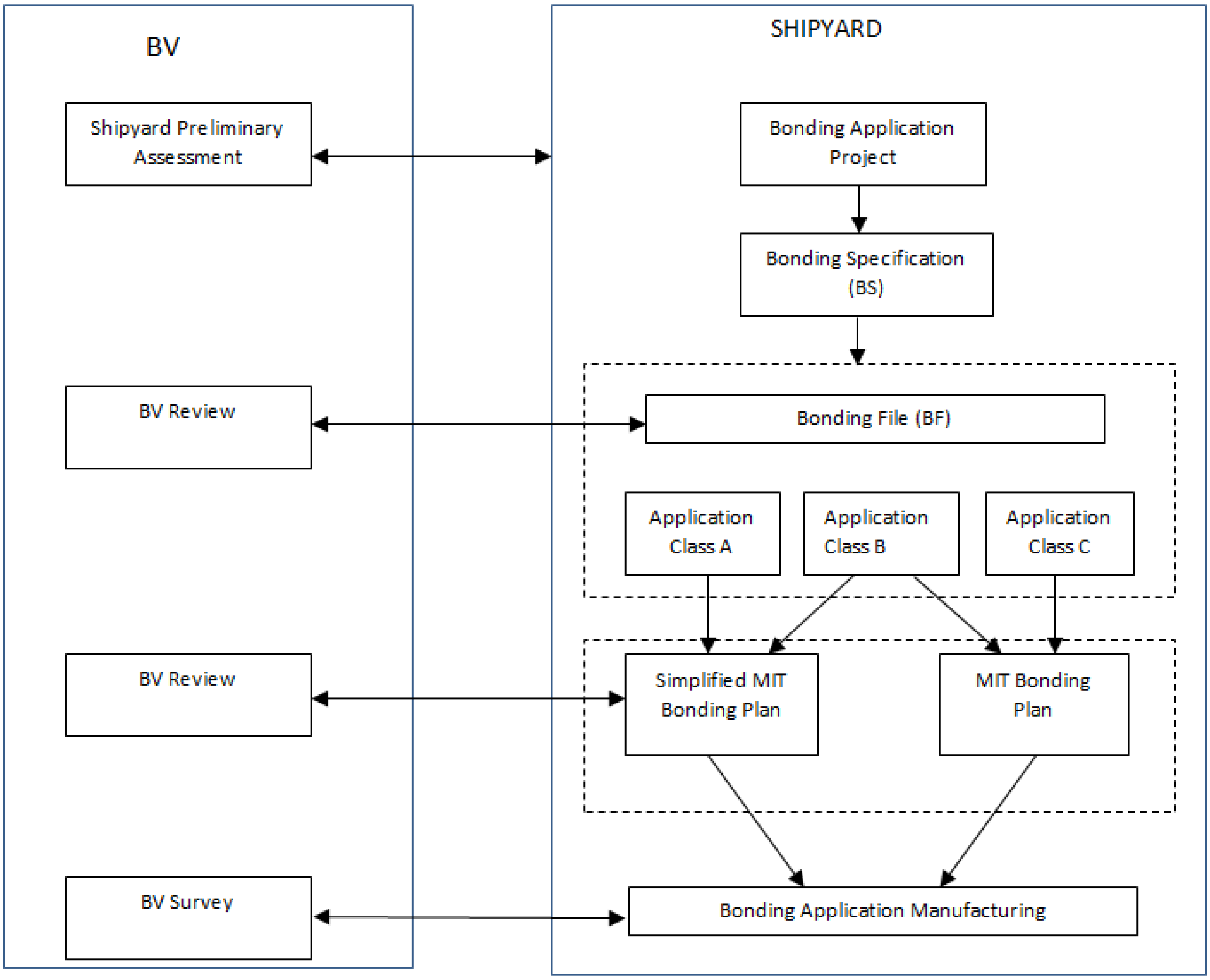


Figure 1: General Flow Chart for bonding process assessment

3.2.3 Bonding file review

The Bonding file (BF) prepared by the shipyard for the Society to review and accept will document the design out that can be verified against design requirements.

The design out file should consist of the following:

- Drawings, specifications, qualification tests and/or procedures necessary to achieve reliable in-service bonded joint performance
- Acceptance of bonding process to enable validation of bonded joint and establish requirements for safe and proper functioning of the bonded assembly
- Actions to address critical design item and to ensure key characteristics are controlled, with plans for verification and validation as needed.

Summary of the bonding file requirements are summarised as follows:

		Risk Class		
		A Low	B Medium	C High
BV check		SAY	LPO + SAY	LPO + SAY
General arrangement drawing / Associated drawing set		NA	X	X
Considered environmental service condition		X	X	X
Fire safety requirements for the considered bonding application		X	X	X
Design file	Considered design load	NA	X	X
	Considered material mechanical characteristics design values (E, G, nu, behaviour law)	NA	X	X
	Adhesive system breaking strength (σ,τ) measured on test samples representatives of real production conditions (environmental, surface treatments, polymerisation state…)	NA	(X)	X
	Durability assessment	NA	(X)	X
	Joint geometry specification	NA	X	X
	Calculation method justification	NA	X	X
Process specification file	Adherent surface condition specification before bonding	X	X	X
	Process description	X	X	X
	Process parameters to control / NDT	NA	(X)	X
Repair manual		X	X	X
Note 1: SAY: BV Surveyor at yard LPO: BV Local Plan Office NA: Not applicable X: Applicable (X): Applicable on case by case basis				

Table 2 Content of Bonding file

3.2.4 Adhesive Homologation

The procedure for homologation of the adhesive is given in NI 613 Appendix A, and document NR 320 - Certification Scheme of Materials and Equipment for the Classification of Marine Units.

Adhesive, as defined in NR 320, come under category $H_{BV,}$ such materials have to comply with design requirements assessed through type approval procedure, and manufactured by works recognised by the Society.

Products under category H_{BV} are not required to be certificated by the Society individually or per batch. Their compliance with the approved type is solely certified by the manufacturers using their own format of document and markings to allow traceability to the approved type

The homologation process is split into 2 stages;

- Design phase looking at technical documentation and type testing of the adhesive. The test programme is jointly drawn up by the adhesive manufacturer and the Society. The minimum tests required for type approval testing are given in table 3; however depending on the type and use of adhesive, some tests table 3 may be dropped or additional tests added to the approval test programme.

- Production phase concerning approval of facility where the adhesive is manufactured as per the provisions of NR320.

Adhesives properties/Characterisation	Comments	Test Methods/Standards
Glass transition temperature	Method used to be specified (DSC or DMA)	DSC: - ISO 11357-2 - ASTM E1356 - ASTM D3418 DMA: - ISO 6721-11 - ASTM D7028 - ASTM E1640
Curve of dynamic flexural modulus **(3)** as function of temperature	- Minimum 2 specimens **(1)** - Environmental and loading testing conditions to be specified **(2)**	DMA / dynamic test (see section
Tensile properties at room temperature **(5)** - Tensile stress / strain curve - Young modulus (MPa) - Poisson coefficient - Tensile strain at failure (%) Tensile strength at failure (MPa) - Tensile yield strength / strain **(4)**	- Minimum 10 specimens **(1)** - Loading and environmental testing conditions to be specified **(2)**	ISO 527 ASTM D 638
Shear properties at room temperature **(5)** - Shear stress / strain curve - Shear modulus (MPa) - Shear strain at failure (%) - Shear stress at failure (MPa) - Shear yield strength / strain **(4)**	- Minimum 10 specimens **(1)** - Loading and environmental testing conditions to be specified **(2)** - Min / max / average values, standard deviation and failure mode to be specified - Cohesive failure required	TAST methods: - ASTM D 3983 - ISO 11003-2 - NF EN 14869-2
Poisson coefficient	- Deduce from the measurement of the young's modulus and shear modulus at room temperature V = (G /2 .E) -1)	calculate
(1) Specimen manufacturing method and geometry of specimen to be specified; specimen curing state according to manufacturer's recommendations (2) Loading (test speed or constant strain rate, vibration frequency) and environmental testing conditions (T°, H%), to be specified. (3) Other dynamic moduli can be used (4) Determination of yield strength on case by case basis according to adhesive's mechanical behaviour. (5) Based on result measurement of dynamic moduli, additional testing in tensile and in shear, at other temperatures is required on case by case according to adhesive's type: - When adhesive's moduli are not constant (deviation less than 10% tolerated) between - Or when adhesive's glass transition temperature measured by DSC/DMA is close to (less than 20°C), environmental conditions stated in the present guidance note (see Sec 1, [4]). For instance, maximum additional testing in tensile and in shear at -20°C/0°C/40°C/60°C may be required. In case of additional testing at other temperature, reduced number of specimens (5) is required		

Table 3: Minimum tests for adhesive homologation

2.3. Lloyd's Register: Rule for the Manufacture, Testing and Certification of Materials, Chapter 14

Requirements for the approval of adhesives and sealant materials are provided in Part 2 Chapter 14 of LR Rules for the Manufacture, Testing and Certification of Materials. Essentially the following is required:

a) Materials of these types are to be accepted by LR before use.
b) The requirements for acceptance are dependent on the nature of the application.
c) In the first instance, the manufacturer is to submit full details of the product, procedure for method of use (including surface preparation) and the intended application. After review of these details, LR will provide a specific test schedule for confirmation of the material's properties.
d) Any acceptance granted will be limited to specific applications and will be contingent on the instructions for use being adhered to.

As in common with other Classification Societies, the approval process is divided into two phases; phase 1 - inspection of the site where the adhesive is manufactured, and phase 2 - approval testing of the adhesive.

Phase 1

LR Surveyor inspection of the site where the adhesive is manufactured is required. As part of the inspection process the attending Surveyor will verify review and verify the QA/QC procedures in place, check test equipment, personnel training records etc. In addition, the attending Surveyor will also verify selection of sample of adhesive from a batch previously manufactured in production (noting relevant batch numbers and expiry dates) for approval testing. The file site inspection report forwarded to the relevant support office for review.

Phase 2

The selected adhesive sample will need to be tested. The tests specified will depend on type of substrate specified by the adhesive manufacturer, and relevant manufacture specified surface preparation and cure/post-cure requirements to be followed. In the case of GRP/FRP or wood the following approval tests will be required:

1) Tensile lap-shear determination on minimum and maximum manufacture specified bondline thickness. Lap-shear samples to be tested at room temperature. Minimum of 5 specimens are to be tested. Testing in accordance with ASTM D1002 or ASTMD3165

2) Tensile lap-shear determination on minimum and maximum manufacturer specified bondline thickness. The prepared samples then immersed in distilled water at 35 degrees C for 28 day. After conditioning period the samples to be removed from water bath dried and tested within 2 hours.

In the case of metallic substrate, in addition to the lap-shear tests, the following tests would also be required:

3) Cleavage test on samples with typical bondline thickness, minimum of 5 specimens to be tested. Testing to be in accordance with ASTM D 1062

4) Fatigue evaluation on lap-shear samples with typical bondline thickness to determine load that will achieve a minimum of 1 000 000 cycles, test carried out between 2-5Hz, minimum of 5 specimens to be tested. Testing to be in accordance with ASTM D3166

5) In all case, in addition to failure loads, the mode of failure also to be reported

6) Specified approval testing can be undertaken by:

i) The adhesive manufacturer or any suitable non accredited test laboratory, but in this case the testing will need to be Surveyor witnessed and the report forwarded to the support office for review.

ii) Testing can be also undertaken by a nationally accredited test laboratory for the test specified above. In this case the accreditation certificate of the test laboratory will need to be verified by LR and if acceptable testing will not need to be Surveyor witnessed, but the final test report still needs to be submitted to design support office for review

7) Subject to satisfactory approval testing and site inspection, the relevant approval certificate for the adhesive/site of manufacture will be issued and will be valid for 5 years provided there is no change in formulation of the adhesive or the site of manufacture

2.4. DNVGL: Part 2 Materials and Welding, Chapter 3 Non-Metallic Materials

Part 2 Chapter 3, section 10 outlines the requirements for approval of three classes of adhesives:

- Rigid adhesive defined as having high strength adhesives with high stiffness
- Flexible adhesive defined as having low strength, low stiffness and high strain to failure
- Sealants defined as similar to flexible adhesives with the exception that they are not meant to transfer loads or moments

2.4.1. Requirements for rigid adhesive

For the un-cured adhesive, the following properties need to be forwarded:

- Density, according to ISO 1675
- Viscosity, according to ISO 3219

In addition, in the case of two-part adhesive curing at room temperature, the pot-life, according to ISO 10364 is to be stated.

Testing requirements of cured adhesive are summarised in table 4 below:

Property	*Test conditions*	*Test method* [1]	*Acceptance criteria, data format and unit*
Tensile lap-shear test [2]	At RT after 24 ± 1 h curing at 23°C and storage at 50% relative humidity [3]	EN 1465	12 MPA
Tensile lap-shear test after immersion in water [2]	At RT after 1000 ± 12 h storage in distilled water at 23°C	EN 1465	12 MPa
Tensile lap-shear test at elevated temperatures [2]	At 50°C	EN 1465	12 MPa
Long-term tensile lap-shear test [2]	At 23/50 at 60% of the mean tensile lap-shear strength for 192 ± 2 h	EN1465	- creep deformation ≤ 0.18 mm for a bondline thickness of 0.5mmm - creep deformation ≤ 0.1 mm for a bondline thickness of 3.0 mm
T-peel test [2]	At RT after 24 ± h curing at 23°C and storage at 50% relative humidity	ISO 11339	2 N/mm
T-peel test after immersion in water [2]	At RT after 1000 ± 12 h storage in distilled water at 23°C	ISO 11339	2 N/mm
Measurement of pH	Insert test specimen into test tube, filled with de-ionized water and close test tube. Store the test tube in a temperature chamber for 30 days at 40°C. Measure pH value using litmus paper	-	Document pH. If pH value is outside the allowed range, the adhesive joint must be protected against the impact of water. - Aluminium: pH 6 to pH 8 - Polycarbonate: pH 4 to pH 10 - Steel: always to be protected against the impact of water
Tensile modulus E_t and poisson's ratio	At 23/50, test specimen 1B	ISO 527-1,2	MPa
Shear modulus, G	Calculate	-	MPa
HDT test	At RT after 24 ± 1 h curing at 23°C and storage at 50% relative humidity [3]	ISO 75-1,2 method A	65°C
HDT test	At RT after 1000 ± 12 h storage in distilled water at 23°C	ISO 75-1,2 method A	65°C

1) Other standards may be agreed upon with the Society prior to testing
2) Specimens with an adhesive thickness of 0.5mm and 3.0mm shall be used and the substrate has to be agreed with the Society prior to testing
3) Other curing conditions may be agreed upon with the Society prior to testing

Table 4 Requirements for rigid adhesives

2.4.2. Requirements for flexible adhesive

The field of adhesive application is limited to bonding of structural components and load-bearing components which are integrated into the structure and relevant to safety of the ship, and depending on are of application the adhesive approval will either come under Class A or Class B.

Class A is defined bonded joints under increased mechanical stressing (high strength with medium compliance).

Class B is defined as bonded joints under medium mechanical stressing (high compliance with medium strength).

Testing requirements for cured flexible adhesives are summarised in the table below:

Property	Test method [1]	Acceptance criteria, data format and unit	
		Class A	Class B
Shore A	ISO 7619-1	≥ 45	≥ 30
Fracture strain at -20ºC	DIN 53504	≥ 50%	≥ 100%
Tensile stress at yield for +60ºC	DIN 53504	≥ 1.5 MPa	≥ 0.6 MPa
Tear propagation resistance	ISO34-1	≥ 4 N/mm	≥ 4 N/mm
Tensile lap-shear strength	DIN EN 1465	≥ 2 MPa	≥ 0.7 MPa
Values for the long-term tensile lap-shear test at: 23ºC/50% relative humidity at 60ºC	Based on DIN EN 1465	0.25 MPa [2] 0.15 MPa [2]	Specified by manufacturer
Relaxation test after 90 days conditioning	Based on DIN EN 1465 and ISO6270-2	Specified by manufacturer	30% ± 1%
Measurement of pH	Insert test specimen into test tube, filled with de-ionized water and close test tube. Store the test tube in a temperature chamber for 30 days at 40ºC. Measure pH value using litmus paper	Document pH. If pH value is outside the allowed range, the adhesive joint must be protected against the impact of water. - Aluminium: pH 6 to pH 8 - Polycarbonate: pH 4 to pH 10 - Steel: always to be protected against the impact of water	
Shear modulus, G	Calculate	MPa	
Glass transition temperature (T_g)	ISO 6721-2	ºC	

1) Other standards may be agreed upon with the Society prior to testing
2) No failure may take place within the long-duration shear tests. The strain-in creep values that are determined shall be specified versus the time

Table 5: Testing requirements of cured flexible adhesive

2.5. DNVGL-ST-0376: Rotor blades for wind turbines

Blades of wind turbines are generally made out of two composite shells, including internal stiffeners, connected with adhesive. This standard provides rules related to design, material selection and testing, manufacturing, inspections, maintenance and repairs.

2.5.1. Design

All requirements stated in the document assume that the temperature of the blades will remain between -30°C and +50°C. If it is expected that the extreme temperatures will exceed those boundaries, further testing is required. For the adhesive, this consists in demonstrating no change in structural properties of the adhesive and performing further adhesive static strength testing, and adhesive joints analyses.

Three (3) failure modes are identified for adhesive joints:

- *Adhesive/adherent interface failure*
  This failure is characterized by the failure at the adhesive and the adherent interface, i.e. interface failure. An interface failure is one of weakest failure modes and should be avoided. This failure mode is caused by poor adherent preparation and/or incompatible adhesive, among other causes. An interface crack may subsequently be loaded by a mix of shear and peeling stresses.
- *Adhesive failure*
  This failure is characterized by the failure at the adhesive, i.e. cohesive failure. Adhesives can have a nonlinear behaviour with large strains to failure, thus it may experience ductile failure.
- *Adherent failure*
  This failure is characterized by the failure of the adherent, i.e. the adhesive is stronger than the adherents. The failure modes are the same as for a composite laminate, matrix or fibre failure.

During design, it shall be demonstrated that the adhesive is compatible with the materials to be adhered, that the surface preparation is done according the relevant standards and that the adhesive is suitable for the extreme and operating temperatures and environmental conditions. The design verification shall be performed using either a stress or a combined stress – fracture mechanics approach (each method is associated with a different safety factor). The effect of creep shall be investigated through testing.

Design strength is equal to the characteristic strength lowered by safety factors, provided for both ULS and FLS:

- γ_{mc}: criticality of failure mode
- γ_{m1}: long-term degradation
- γ_{m2}: temperature effects
- γ_{m3}: manufacturing effect
- γ_{m4}: accuracy of analysis method
- γ_{m5}: accuracy of load assumptions

It is a requirement to perform intermediate level testing (component level) for each critical or highly loaded adhesive joint.

2.5.2. Material qualification and testing

The adhesive material shall be tested at a coupon level and the following physical and mechanical properties shall be tested and documented:

- thermal stability (e.g. glass transition temperature)
- ultimate and fatigue adhesive joint strength (appropriately considering shear; peel, and axial stresses)
- fracture toughness (mode I, mode II, and mixed mode), if used as basis for design verification analyses
- If the design verification of an adhesive joint against creep is based on material creep limits, material qualification testing of the adhesives shall include appropriate creep tests

For all static adhesive material qualification tests, a minimum of two adhesives batches should be used to manufacture the test joint pieces.

Full scale blades shall be similarly tested both at ULS and FLS. During and after the test, all non-reversible changes (for adhesive, cracks) shall be reported and compared to design values.

2.5.3. Manufacturing

For bonding, the following actions shall be performed:

- The bonding surfaces should be dry and free of release agents, impurities and solvents. It shall be ensured that the bonding surface is free of any material that can cause a negative effect on the bonding process.
- All bonding surfaces shall be roughened (e.g. mechanically or chemically).
  Note: Roughening is also required when peel ply is used. If alternative means are applied in order to avoid roughening, a verification of the procedure is required.
- Acceptance criteria for surface condition before bonding shall be specified.
- Adhesive shall be processed in accordance with the manufacturers' instructions. Adhesive shall be mixed in such a way that a homogeneous mixture is achieved. Any intrusion of air shall be avoided.
- Adhesive shall be applied properly for the adhesive system and shall meet the requirements for maximum allowable air content after application.
- After application of the adhesive, the bonding surfaces shall be brought together without delay and fixed in place.
- It shall be ensured that the application of adhesives, and final joining of components, is completed within a limited time after mixing. This time limit shall be properly specified, taking into account all relevant material and process characteristics (e.g. gel time).
- Adhesive joints shall not be loaded before the adhesive has cured sufficiently. For all adhesive joints with thermosetting adhesives, subsequent tempering of the joint is recommended.
- When FRP components are bonded, minimum and maximum curing levels before bonding shall be specified. Unless specified otherwise, FRP components should be totally cured before bonding if the bonding system is differing from the laminating system.
- Bond line thickness parameters shall be controlled by appropriate means (e.g. dry closure tests, visual inspections, ultrasonic scanning), in order to ensure consistency with the relevant design assumptions.

2.5.4. Material test methods and standards

Generally, the following test methods and standards are accepted.

- Ultimate adhesive joint strength
  - lap shear test on FRP substrates: ASTM D5868, ASTM D3528, EN 1465
  - lap shear test on metal substrates: ASTM D1002
  - peel: ISO 11339
  - it is strongly recommended to use test specimens that are more representative of the blade structure (i.e. component or sub-structure test specimens) for determining ultimate strength design properties in shear, peel, and axial direction.
- Fatigue adhesive joint strength
  - cyclic dynamic tests with sinusoidal loading for R=0.1
  - 3 specimens at a load level targeting 10^4 load cycles to failure
  - 3 specimens at a load level targeting 10^6 load cycles to failure
  - 3 specimens at a load level targeting 10^7 load cycles to failure
  - plus 3 specimens static test to failure
  - For this, single and double lap shear tests may be acceptable.
  - The test frequency shall be the same for all tests used for constructing an SN curve.
  - In addition, it is strongly recommended to use test specimens that are more representative of the blade structure (i.e. component or sub-structure test specimens) for determining fatigue strength design properties in shear, peel, and axial direction
- Fracture toughness
  - Mode I fracture (opening): ASTM D5528, DIN EN 6033
  - Mode II fracture (shearing): End notch flexural (ENF) specimens can be used to determine the fracture properties under mode II loading
  - Mixed mode I + II: ASTM D 6671 (recommended because it gives a clear indication of the interaction between mode I and mode II in the strength of the adhesive joint)
  - A stress based approach shall be used to identify those areas in adhesive joints where fracture mechanics considerations shall be applied. For the fracture mechanics considerations, a crack shall be considered and it shall be proven that it will not grow under the design loads, i.e. that the strain energy release rate is below the critical strain energy release rate for crack propagation (damage tolerance approach). Tests shall be performed in order to determine the critical strain energy release rate for crack propagation. Mode I fracture dominates over mode II, and designing a composite adhesive joint for mode I dominated loading is considered conservative.
- Creep

  If the design verification of an adhesive joint against creep is based on material creep limits, an appropriate creep test will consist of the following:
  - For coupon tests according to DIN EN 1465 with 0.5 mm and 3 mm bond line thicknesses, and at a specified load applied for 192 hours, the strain in creep shall be:

- o below 0.18 mm in the long-duration shear tension test for an adhesive layer thickness of 0.5 mm; and below 1 mm for an adhesive layer thickness of 3 mm.
- o If these requirements are met, the specified load can be considered the creep limit.

3. ADHESIVES USING IN OTHER INDUSTRIAL SECTORS

3.1. Air Sector

3.1.1. Materials used

With the huge civil aviation development after World War II, aluminium alloys, 2 000 and 7 000 series, had constituted the main material family used for civil aircraft. For example, 75% of the weight of an Airbus A320 is due to aluminium structure at the inaugural flight in 1987.
Over 30 years, the used of composite materials in aeronautic industry has been multiplied by 10, from 5% to 50% for the last generations of long-haul aircraft in Boeing with Dreamliner B787 and in Airbus with A350, see Figure 1 and Figure 2.

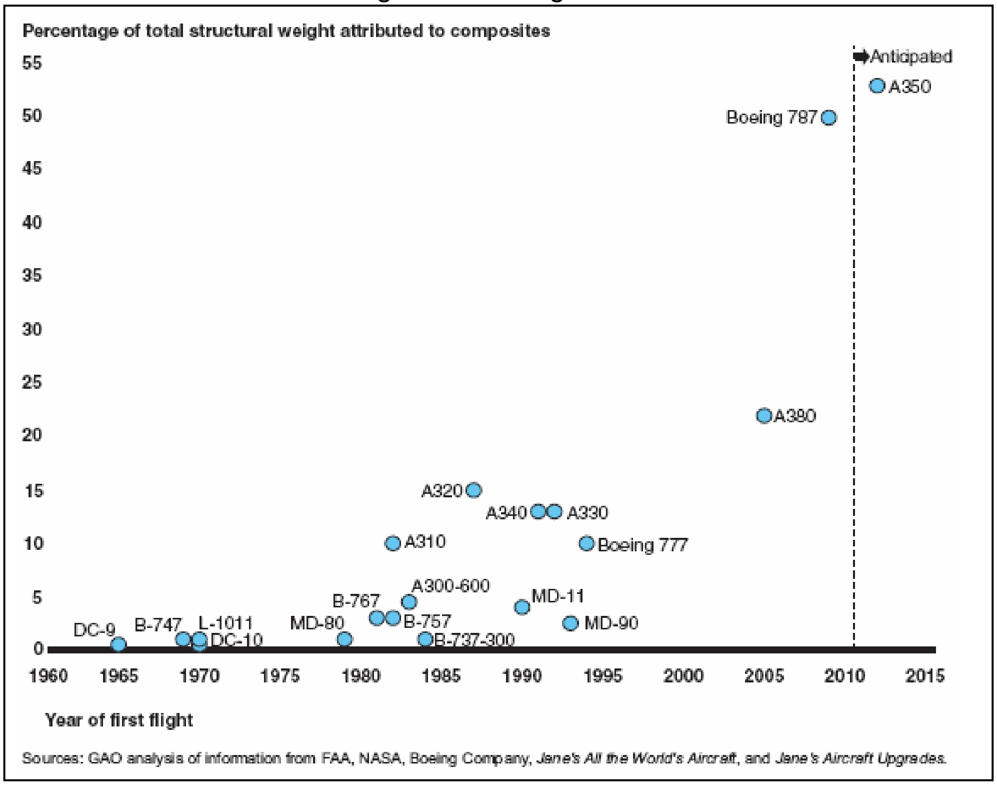


Figure 1: Commercial airplane models overtime by percentage of composites [2]

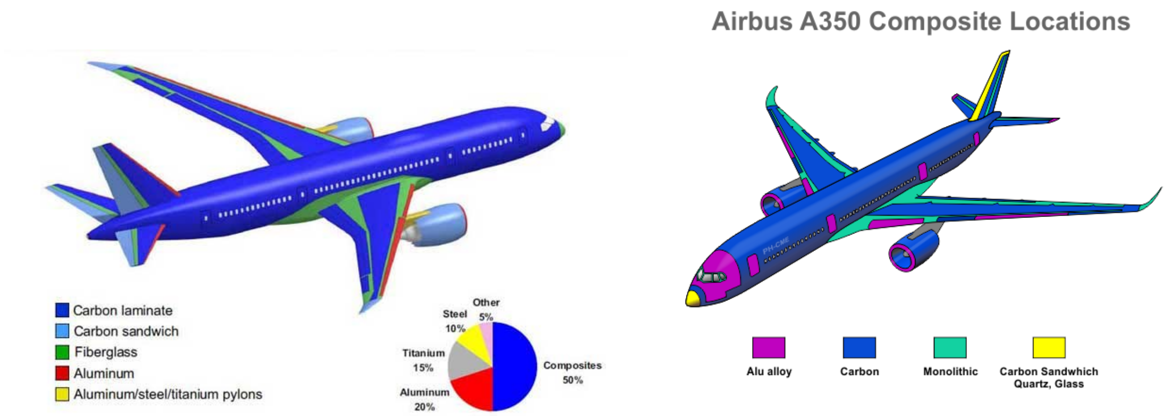


Figure 2: Materials distribution, Boeing B787 (left) and Airbus A350 (right)

3.1.2. Assembly technics

Due to a large amount of materials used in aeronautic industry, almost all assembly technics are used: riveting, screwing, welding, bonding… The selection of one technique in comparison with another one results in a compromise between different parameters: mechanical resistance, assembly constraints, reliability, reparability and economic aspect.
Riveting is the most common technique for aluminium aircraft structure. The advantage of riveting is that the mechanical properties of the metal are not affected by the temperature. However, a lot of developments on welding process by laser or friction are ongoing.

3.1.2.1Bonding

The bonding is largely used for arrangement elements, decoration, windows… Most of the adhesive families are represented on these application cases however it is not a structural application, see Figure 3.
For secondary structures, a number of pieces are produced in composite materials with the best ratio rigidity/mass, like front spar, nose, rudder,… see Figure 2. Most of the sandwich panels with aluminium honeycomb or Nomex are bonded to the skin with epoxy film.
For primary structure, bonding has only not been validated due to a lack of robust design tools, no reliable means of control and limited knowledge on long term fatigue life. Riveting and bolting are always predominant assembly methods for the connection of wings or to attach stiffeners to the fuselage. In the highest stressed areas, aluminium attachments are replaced by titanium alloy.

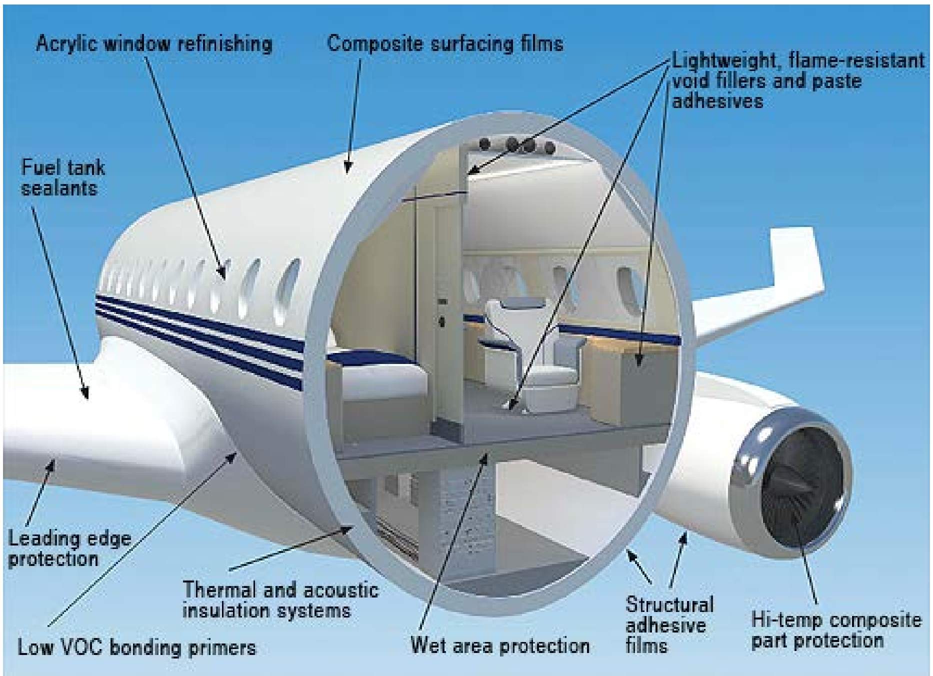


Figure 3: Bonding application in an aircraft (Courtesy of 3M Solutions)

To supplement rivets or bolts, joint sealant is added for the connection of fuselage blocks together, however the sealant has no structural role. More and more developments on hybrid connections, rivet / adhesive or bolts / adhesive, are ongoing in order to decrease the number of mechanical fasteners and to increase the ability of adhesive joints to support loads. The objective is to avoid holes in the structure, a cause of weakening and low fatigue life, and to increase production rate.

In the latest civil aircraft generation, co-curing and co-bonding have been developed in Airbus and Boeing industries for internal composite stiffeners with resin or epoxy film, see Figure 4. Nevertheless, the secondary bonding technique is not used because the control of surface defects and roughness is difficult especially for polymerized pieces.

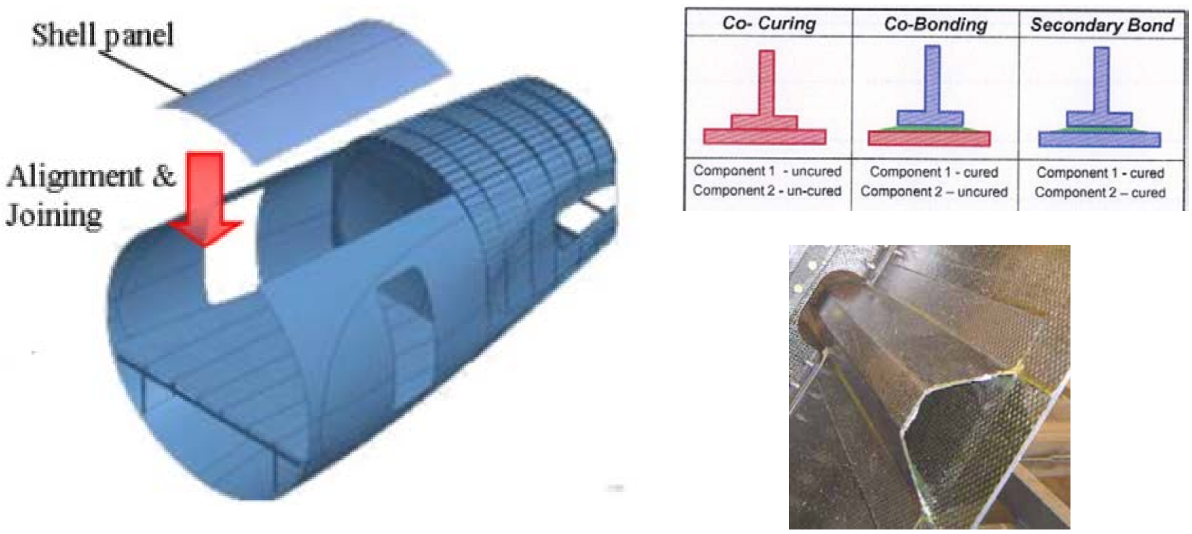


Figure 4: Examples of fuselage panel connection and composite stiffener assembly technics

3.1.3. Regulations

During the development of a new program, the aircraft is to be certified before the first commercial flight. The airworthiness certificate is issued by the Civil Aviation Authority (CAA), the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA) after a large series of static and dynamic tests up to full scale destructive tests.

In Europe, regulation CS-25 (Certification Specification for Large Aeroplanes [3]), equivalent to American regulation FAR 25 (Federal Aviation Regulation), applies for the structural design assessment of airliners. The sizing of the structure is based on 2 loading levels (CS-25 Subpart C - Structure):

- Limit loads: maximum loads to be expected in service.
- Ultimate loads: limit loads multiplied by prescribed factors of safety, in general 1.5.

Subpart D concerns requirements for the design and the construction and in particular the methodology to determine the mechanical properties of materials to be used in analytical and numerical computations. The resistance and durability of materials is to be demonstrated by tests or based on previous experience in environmental conditions (Temperature, humidity) having an influence on mechanical properties. Mechanical properties are to be evaluated according to international norms and standards (ASTM, ISO, …) or provided by military domain (Composite Material Military Handbook). Manufacturers are to ensure a high level of fabrication quality and assembly of pieces. The introduction of Subpart D highlights the importance of test in the certification process: “*The aeroplane may not have design features or details that experience has shown to be hazardous or unreliable. The suitability of each questionable design detail and part must be established by tests.”* In this context, the use of composite materials and new assembly technics imply a large quantity of tests and simulations to select, validate and produce new designs, see Figure 5.

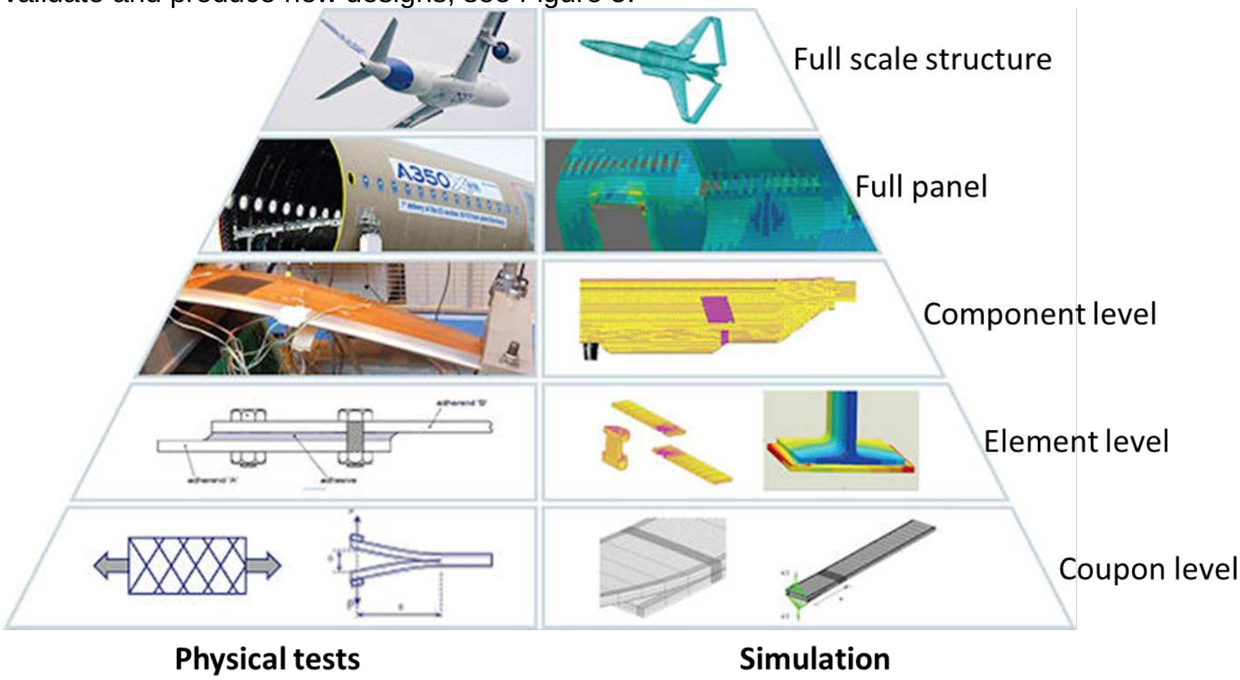


Figure 5: Tests pyramid in aeronautic industry

From the base to the top of the test pyramid, the price and the complexity of tests increase significantly. For example, the budget of the validation tests program of Airbus A380 was of €

1.4 billion including € 680 million for the structural part. Moreover, due to the experimental dispersion on the material mechanical properties, the regulation body imposes a statistic approach in order to reduce the properties variations by probability. Two statistical values have been provided by the regulation body:

- A: value such as 99% probability with 95% confidence
- B: value such as 90% probability with 95% confidence

A or B selection depends on the criticality of the tested piece. If the failure of the piece leads to the loss of the integrity of the structure, the criticality level of the piece is high and value A is chosen. In case of less criticality, failure leading to load redistribution to adjacent structure, value B is used. A and B values published in The Metallic Materials Properties Development and Standardization (MMPDS) handbook [5] are acceptable. Illustration of A and B-value according to normal distribution law is visible on Figure 6. A reduction coefficient is applied depending of the number of performed tests to ensure a high level of confidence.

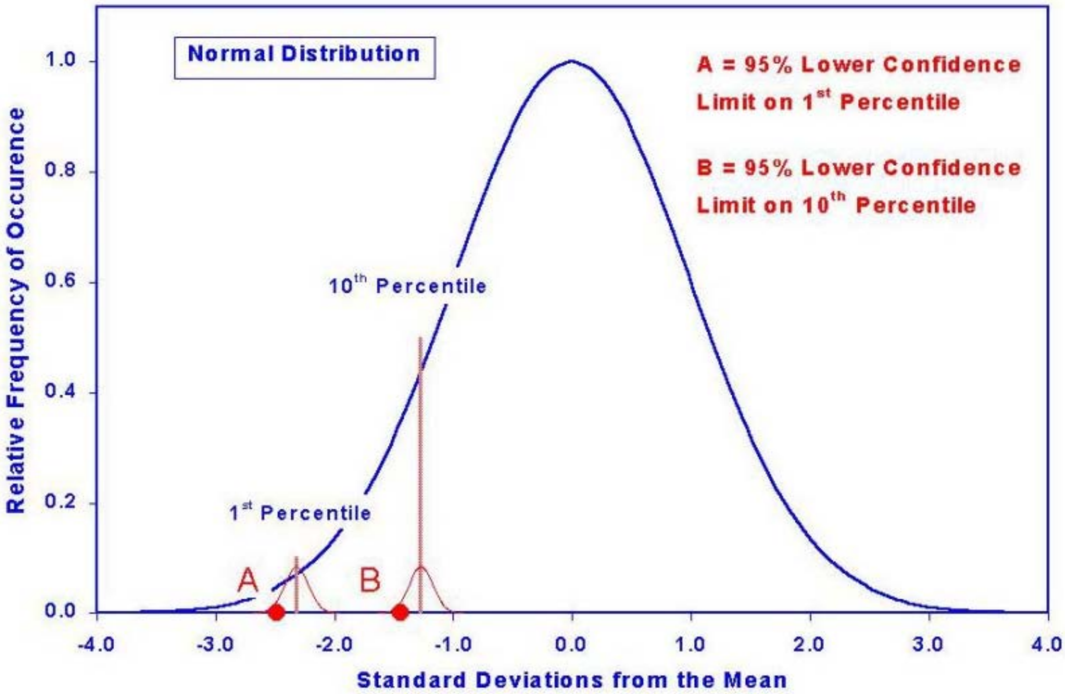


Figure 6: Illustration of A- and B-basis design allowable for a normal distribution [4]

3.2. Rail Sector

A major player in adhesive standard in the rail sector is the norm DIN 6701; "A*dhesive bonding of railway vehicles and parts*".

The DIN 6701 is made of 4 main parts:

- DIN6701-1 / 2004 - Part 1: Basic terms, basic rules
- DIN6701-2 / 2006 - Part 2: Qualification of manufacturer of Adhesive bonded materials, quality assurance
- DIN6701-3 / 2010 - Part 3: Guideline for construction design and verification of bonds on railway vehicles

- DIN6701-4 / 2010 - Part 4: Manufacturing controls and quality assurance

As is the case in other transportation sectors, lightweight research and introduction of multi-material structure led to a strong development of bonding as a mean of assembly. Designers also favour the multi-functional qualities of adhesives (phonic isolation, vibratory, thermal, etc…).
Nowadays, adhesives can be found mainly in the assembly of interior layout: floors, side wall stiffeners, doors, windows.
As an example, on Duplex TGV despite a doubled transportation capacity, the coupled use of aluminium and composites allowed the designers to maintain a load per axle adapted to high speeds.
Adhesives typically used are the same as in other transportation sectors (PU, acrylic, Epoxy…) and do not concern structural assembly. It rather answers the need for multi-material assembly not or weakly solicited in an environment less critical than the marine one.

The main players in of the rail sector (mainly the German SIEMENS, BOMBARDIER, and ALSTOM) were the starting point of the first standardization of bonding an industrial sector.
The norm DIN6701 aims at establishing a regulatory frame for the assembly operation in industrial bonding. It specifies the conditions to which subcontractors who produce parts with bonded assembly for rail equipment shall comply for providing parts for German rail companies. This norm is limited to Germany at the moment and to the rail sector but should be extended to other sectors in Europe. In 2019 the first European Norm on Railway component bonding is to be published paving the way to European regulation in the domain.

In this reference (DIN6701), bonded joints are classed in 4 categories:

- A1 failure of the joint might lead to a non-avoidable hazard threatening lives or physical integrity of people or compromising security of operation of the rail vehicle.
- A2 failure of the bonded joint may imply a risk and physical damage to people, or lead to a degradation of the global operation of the rail vehicle.
- A3 failure of the bonded joint lead in the worst case to a lack of comfort, physical damage on person weakly probable.
- Z Failure of the joint does not lead to physical damage nor degradation of the operations.

Then DIN 6701 requires that German projects shall be designed and produced by certified companies (as per EN ISO/TEC 17065 by DIN 6701 authorized bodies). Thus for a joint A1 the certification requires:

- Qualification of operators, and ruled delegation;
- Robust process: Design, qualification, entry control, production, production follow-up, expedition;
- Certified production site (temperature, humidity, cleanliness, air flow…).

This impacts directly the organisation of the company with transversal supervision of bonding process.
The validation occurs at several steps:

- Calculations

- Tests
- Operational feedback
- …

Latest norm in the field is the DIN 2304 which gathers requirements on quality published in 2016.

3.3. Civil Engineering Sector

In civil engineering, bonding is mainly used for repair and reinforcement of concrete construction work: rigid external reinforcements are bonded on damaged structures in order to reconstitute or increase their mechanical capacity and lengthen their lifespan for a minor cost. Epoxy adhesives are by far the most commonly used adhesives in civil constructions (90% in tonnage). Considering dimensions of the constructions and external installation condition, specially formulated bi-component epoxies are used. These harden at ambient temperature, with a low glass transition temperature.
Bonding is also used for the connection of steel / concrete of bridges and for assembly of prefabricated elements of reinforced concrete.
However, in this sector too, barriers exist to the generalization of this assembly technique due to lack of guarantee of the long term durability (100 years), and the absence of reliable modelling tools allowing predicting lifespan of bonded assemblies.

3.4. Construction Industry

In the construction industry, we find numerous applications of bonding for cladding, lining, and insulation in internal and external use. They are not in the direct scope of our study. We notice a generalization of the use of bonding for external window glass on metallic frame (Stainless steel, Aluminium). The term adhesive mastic is generally used.

The following references are used:
For EOTA (European Organisation for Technical Approvals) published the ETAG n° 002 Structural Sealant Glazing Kits
It contains rules for evaluation of strength, initial and after artificial ageing, resistance to fire with reference to EN 13501-1, -2 and -5. A series of mechanical test is defined.
The mechanical tests described are as per Figure 7 and Figure 8.

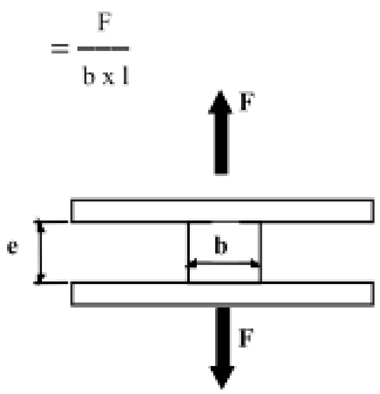


Figure 7 Test set-up for tensile test evaluation

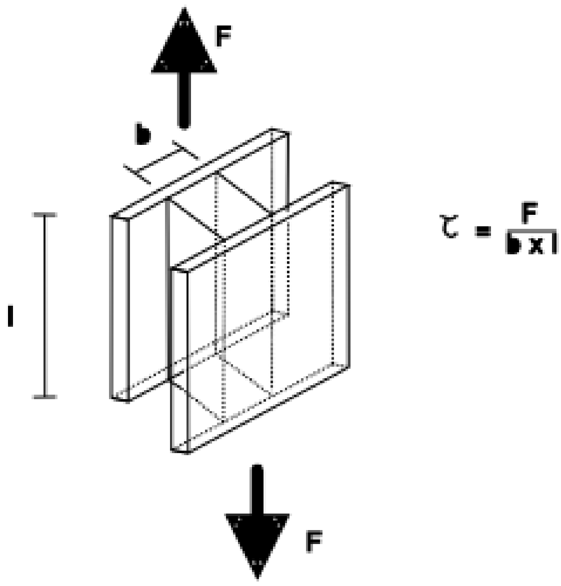


Figure 8 Test set up for Shear strength evaluation

A fatigue test procedure is also detailed.

In some countries but not all Europeans states, retaining devices are required in case of failure of the bonded joint.

We note that the type of adhesive is limited to silicones. Other adhesives are disregarded unless a dedicated approval process has been undertaken. 3M has recently had a double sided adhesive tape made of acrylic foam certified.

Figure 9 3M certified adhesive tape

The certification bodies have agreed the use of silicone adhesive due to their superior UV resistance compared to other types of adhesive and as there is 30 years history since the first applications (without major incident).

Only the anodized aluminium, thermo-coated aluminium or stainless steel frames are allowed since there are standardized surface treatments for those materials.

Generally, the windows are bonded on the associated frames directly in factories and sold as a window kit by a society granted for Technical European Agreement.

The lifespan considered by this norm is 25 years.

3.5. Automotive Sector

The first use of bonding in automotive as a means of assembly can be found back in the 60's. It was metallic stiffeners on the internal face of engine hoods.

Nowadays, bonding has become as a routine assembly technique and is part of the options examined by design offices during vehicle conception.

This technique allows appropriate solutions to the current challenges faced by the industry: difficult agreement between security aspects, comfort, cost and production reductions, energy savings, and environment care.

Within a highly competitive market with strong production cadence, the design of vehicles goes through a weight saving of structures leading to multi-material solutions and as a consequence requires mastering of specific assembly techniques.

Actually, technological and economic studies led in the past few years by the industry conducted to the spreading of adapted multi-material structures allowing taking advantage of all the properties of the assembled materials. It must be emphasized that mono-material solutions are no more economically competitive (on the large series segment in particular).

Adhesive bonding appears then as a booming technique for this sector and still concerns principally assembly of parts that are non-critical for the structure of vehicles as for example a variety of plastic part inside the car or for the installation of windshields.

Given the diversity of the material present in the vehicle, numerous adhesive families are used to answer each specific needs:

- Solvent adhesives: mechanical seals
- PU mono component without solvent: windows, body of industrial vehicles
- PU bi-component without solvent: assembly of different material for body element (composite / steel)
- MS polymers for the windshield
- Double sided adhesive tape acrylic based sensible to pressure: internal seals, external protection band, wheel cover
- Anaerobe: mirrors, thread brakes
- Acrylic: plastic parts, mirrors, lights
- Resins base on phenol-formaldehyde: brake lining

Applications for structural parts are however limited to high-end segments and only concern hybrid assembly techniques such as welded-bonded, rivet-bonded, bolted-bonded. Structural bonding is not yet completely current even though numerous studies and project are on-going.

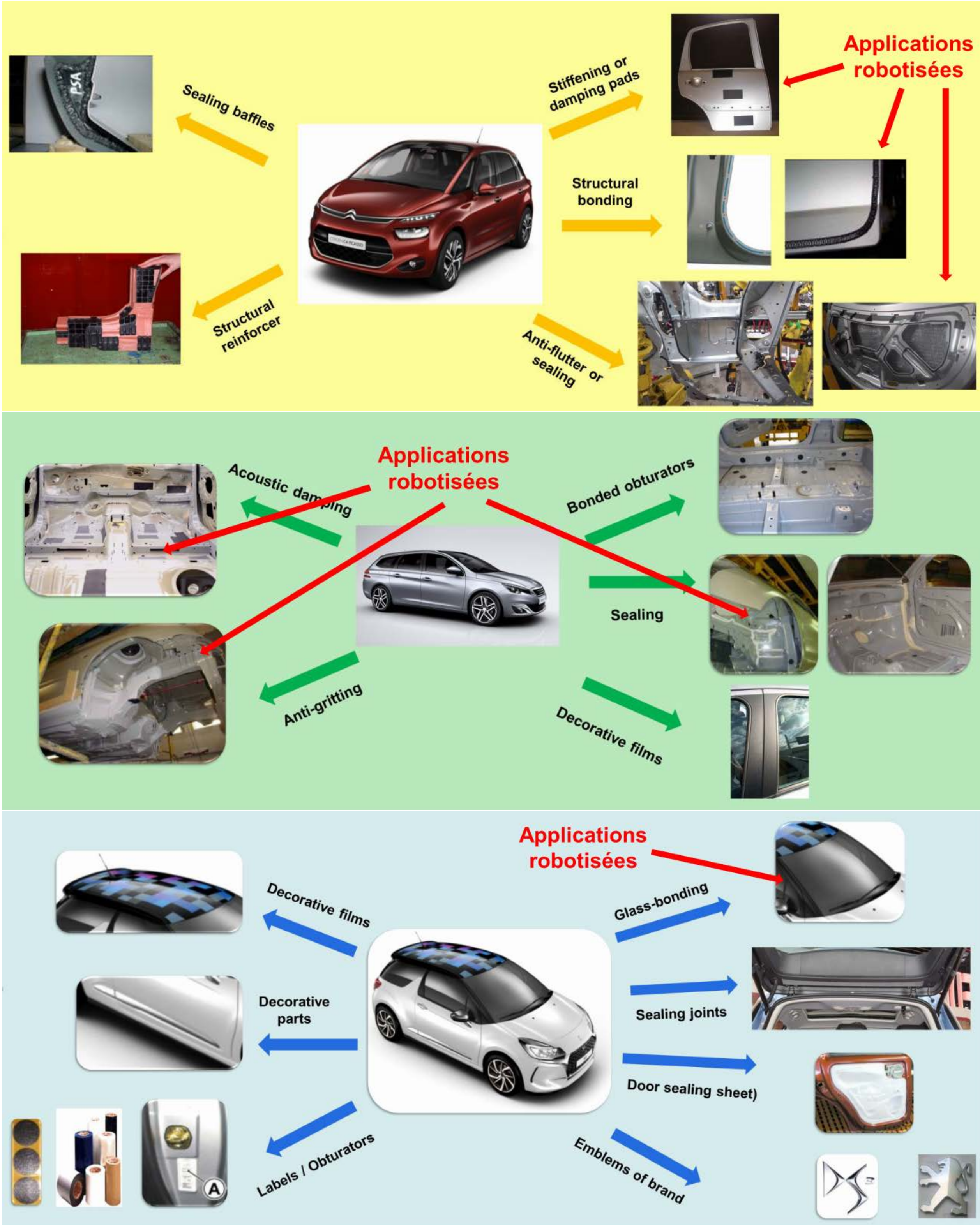


Figure 10 Examples of bonding applications in the automotive sector

Actually, in the absence of guaranty on bonding strength, scantling or sizing (design verification for strength) is realised on local fixtures that only ensure the geometric or dimensional tolerances. Stiffeners, dampers, anti-flutters are also added using bonding. We note that each type of bonded assembly is realised in different workshop depending on its location in the assembly chain of course, but also on its criticality.

Weld-bonding is nowadays widely used by top range specialised manufacturer (BMW 7 series, Mercedes Class S, E, Vito, Audi) and in more specific cases in the generalist brand (Renault, PSA…). The case of the Lotus Elise is noticeable with a riveted-bonded aluminium chassis.

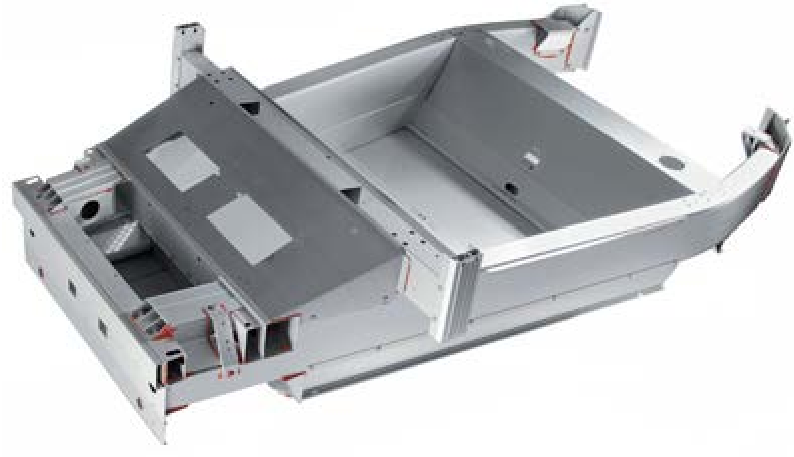


Figure 11 Bonded-riveted Lotus Elise chassis

If elastomer mastics are used for setting or cushioning, Epoxy based adhesive are mostly used for more stringent applications.

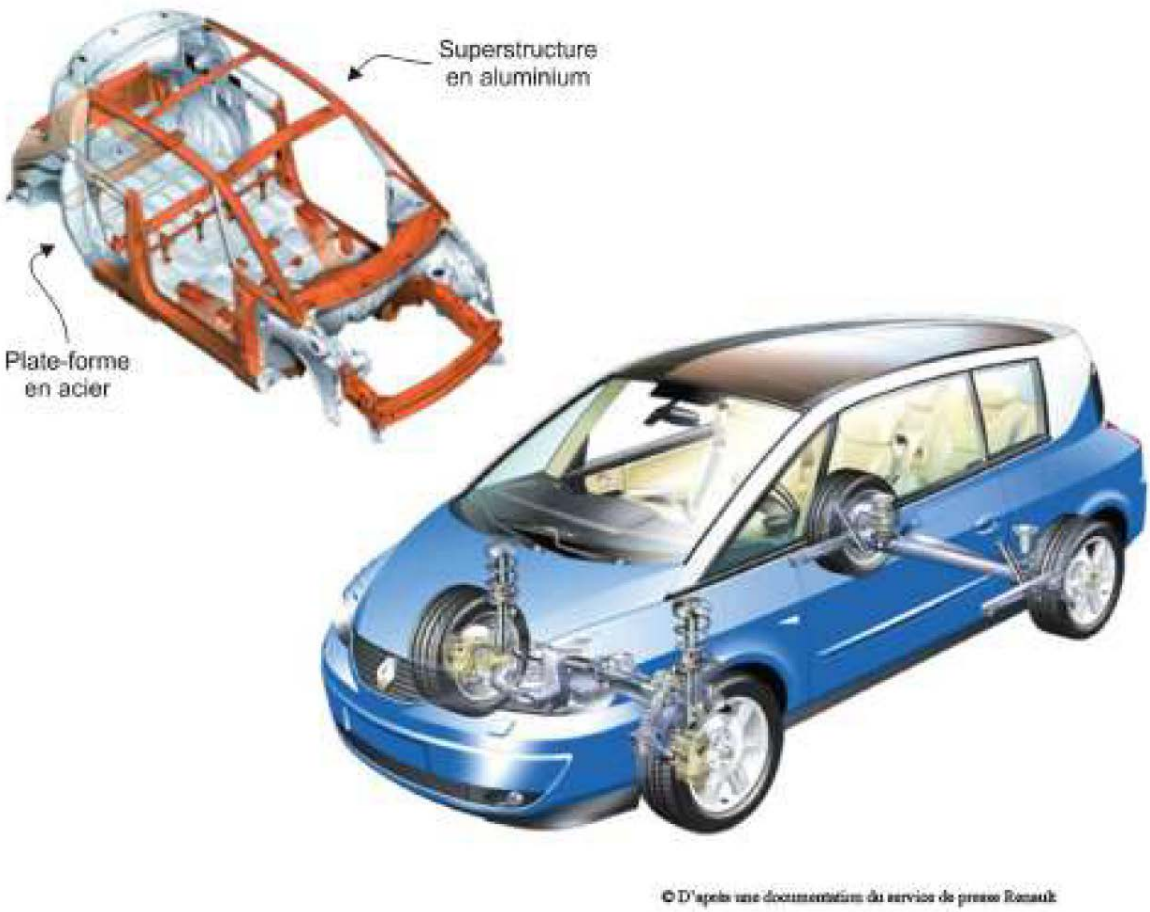


Figure 12 Assembly of aluminium superstructure to steel structure by bonding on the Renault Advantime

Builders are also working on integrating to bonded joints the function of energy absorber in the case of crash (a major issue for builders).

The identified constraints to the development of bonding in the automotive industry are similar to other sectors:

- Constraints related to the production rates versus adhesive reticulation duration (an additional fixture is used in some cases to guaranty the geometry)
- Constraints related to surface condition of the elements to be assembled and the environment of the workshops (anti corrosion treatment, grease, dust…)
- Availability of adapted design tools and methods for the design offices (static analysis or fatigue)
- Lack of feedback on long term behaviour (ageing in humid environment)
- Psychological factor of builders and clients

4. CURRENT REGULATORY BARRIERS INSTALLATION, DURABILITY, FIRE SAFETY, INSPECTION...

We should recognize that in the marine and offshore domain, bonding is largely non permitted. Thus the barriers are not easily identified by themes, but by generic ban. In specific cases such as yachts, small vessels, national voyage vessels, composites are employed and adhesive bonding is wide-spread, but in larger units or in multi-material bonding, there is quite a ban despite some initiative (BV NI613 [1] or Bondship [7] for instance). Therefore, the current barriers shall be found in a general engineering reflexion rather than in a specific rule.
Firstly, adhesive bonding is a complex process implying mechanics, chemistry, and master of process. Disciplines such as:

- design and calculations,
- surface treatment,
- thermal performance,
- mechanical performance,
- durability,
- implementation,
- control (destructive or not).

are necessary steps to be mastered for a successful bonding project. The main words are robustness and reliability.

Adhesive bonding is a so called “special process”, which is defined by a process that cannot be entirely verified by non-destructive test after manufacture, and for which deficiencies may only appear during use of the product. The performance of such a process can only be reached by the mastering of the process, means, methods, and qualification of the teams.
This creates the need for a standardization of the process.

In classical process, riveting, bolting, welding, quality is a backing of the final controls, were in adhesive bonding quality shall substitute this final control in a large proportion.

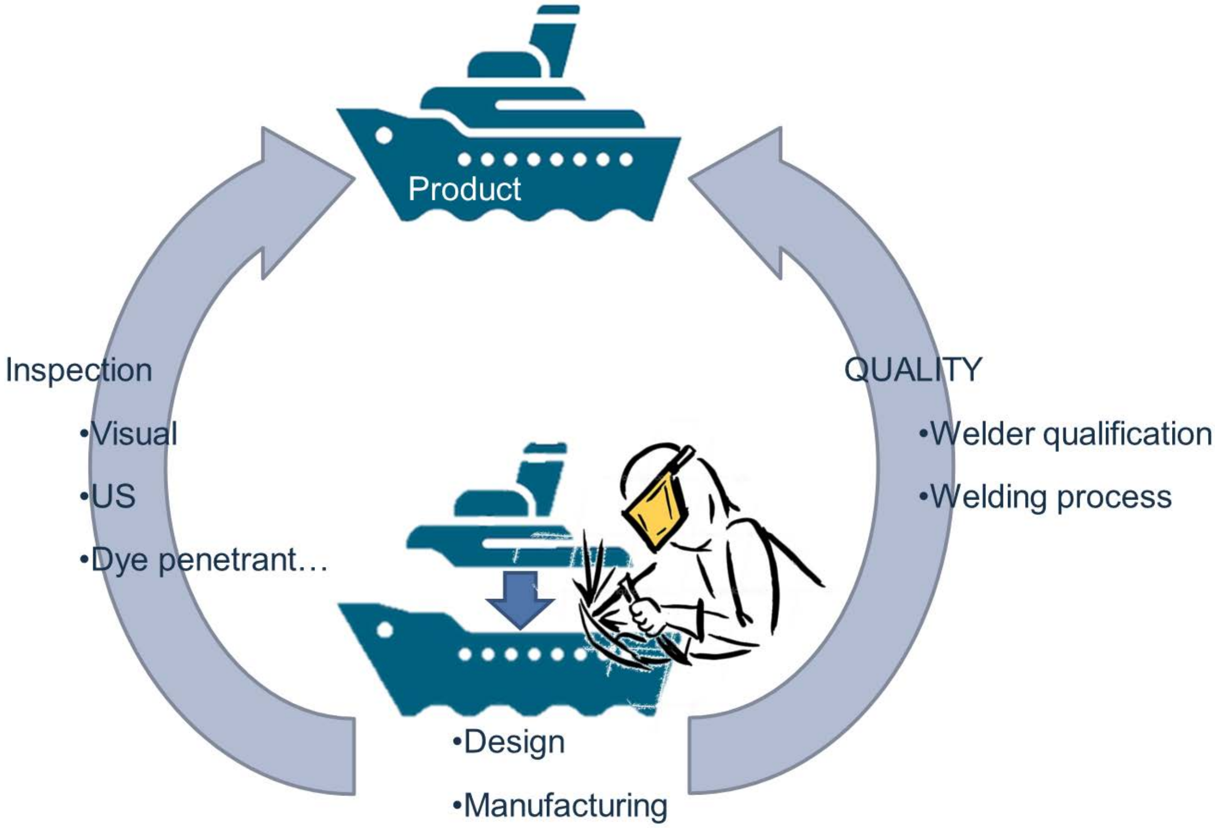


Figure 13 Typical scheme of production for welded product

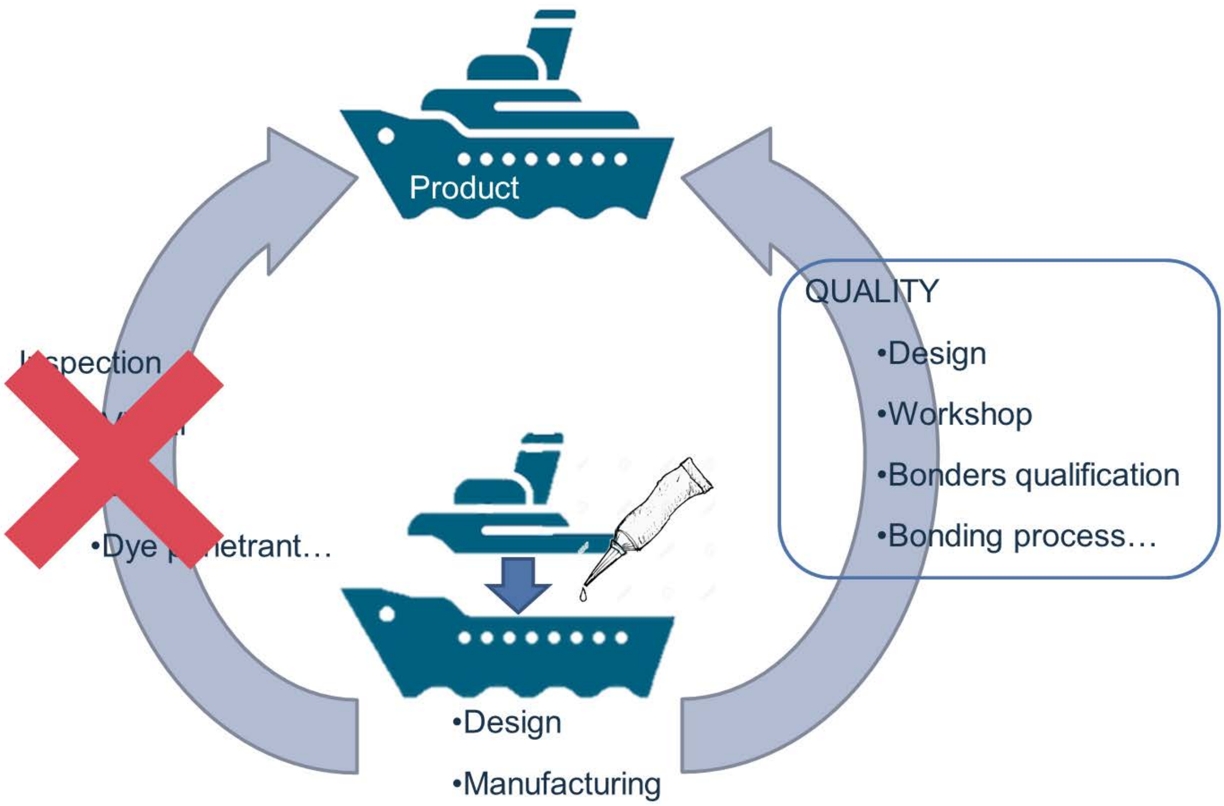


Figure 14 Scheme of production in the case of uses of bonded joints

This is a schematic view of course, and there are means of control, but they are partial, and cannot allow 100% validation of the accurate performance of the bonded joint. Indeed the first barrier stands in the mastering of the complete process, from integration of the bonded joint in the design, to the selection of adhesive, the qualification of operators, adequacy between the state of the workshop and the bonding methods, the surface preparation, control, quality, etc,…

4.1. Durability

Composite and adhesive are sensible to the environment, and particularly to water absorption. The loss of property may be an important proportion of the initial state as it is illustrated in the Figure 15 (extracted from [8]).

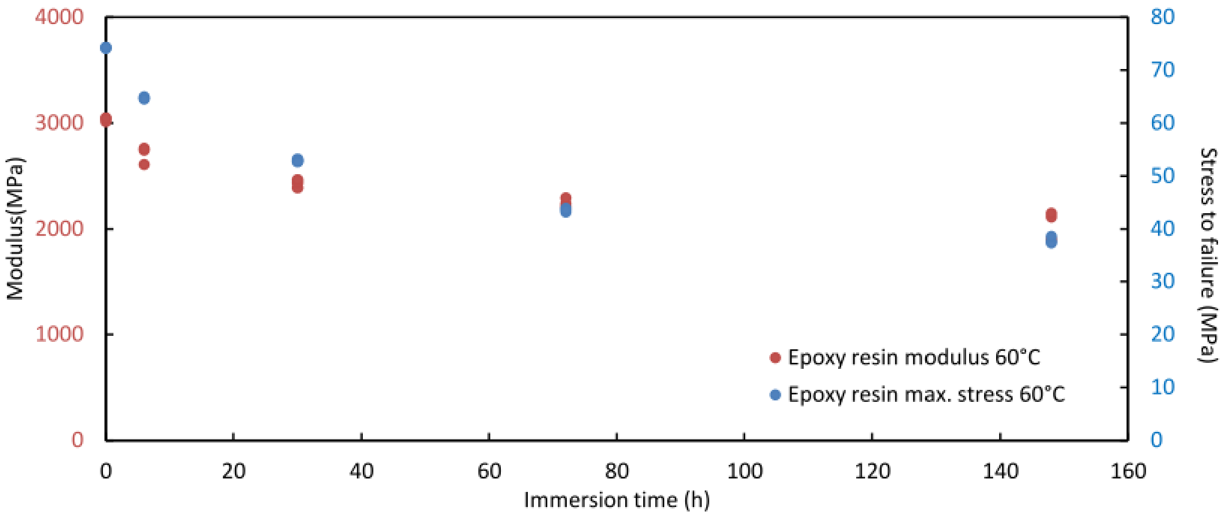


Figure 15 Evolution of epoxy resin tensile properties during sea water ageing at 60° (strength and modulus)

However, there are no regulatory frame allowing extrapolations of ageing tests to real lifespan. Thus it is necessary to define tests as representative as possible of the real operation of the joint, with design, process of the ageing sample representative from the industrial joint. The ageing methodology and accelerated process shall be investigated understood, and discussed by the actors of the industry, designer, users, shipyard, academics, laboratories, certification bodies. It is necessary to qualification of bonded joints on the durability side.

As stated in [7], polymeric material such as adhesives primers, paints, etc are likely to absorb water that will induce swelling and plasticizing. Thus the properties of the polymer are not maintained.

Temperature, chemicals, cyclic loads also affect the polymers.

Various polymers have various degrees of absorption and degradation, thus a screening shall be done to select the polymer prone for success in the define application. However those tests do not allow conclusion on the viability of a joint in real environment for a full lifespan.

4.2. Fire safety

Being viscoelastic materials, adhesives are very sensitive to factors such as the environmental effects, temperature, humidity and the long-term loading. The loss of strength and durability of adhesives materials as a result of these factors needs to be taken into considerations as part of any design evaluation. For example, in the case of a bonded joint, increase in temperature will lead to decrease in elastic (E) and (G) moduli, cohesive and adhesive forces within the joint and maximum stresses that can be carried by the bonded joint see figure 2 below.

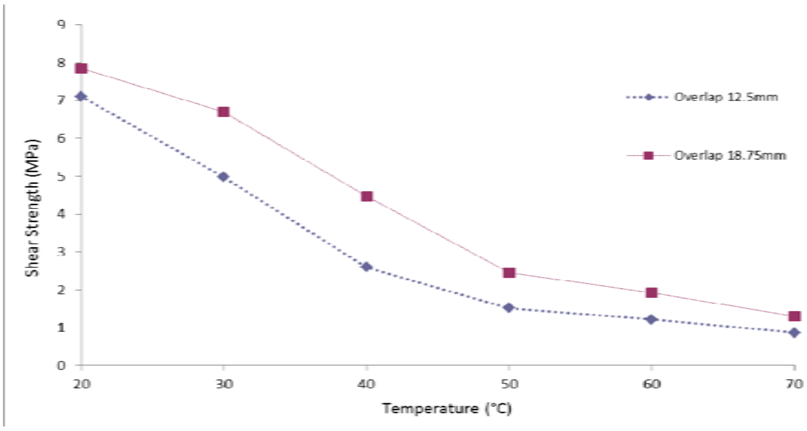


Figure2. Diagram of shear strength versus temperature (extracted from [8])

Also, at elevated temperatures adhesive will be susceptible to creep; hence the failure will happen in a shorter time. In addition to loss in strength, at extreme temperature, adhesives will burn and release toxic fumes and smoke; hence statutory requirements are out by International Maritime Organization

Generally requirements in SOLAS Chapter II-2 Regulation 5.3.1.1 for the approval of adhesives that are to be used in internal manned spaces in ships apply.
The above regulation requires adhesives to be tested to FTP Code Annex 1 Part 5 Paragraph 4.5 to demonstrate “Low Flame Spread Properties” in order to be considered for use in conjunction with either the surface finish materials or as part of A, B and C Class fire divisions. In addition, for use in A and B Class divisions, the proposed adhesive is required to be fire tested in a representative specimen of such fire divisions to FTP Code Annex 1 Part 3, to demonstrate that the final construction, in particular, the joint arrangements are suitable to provide the required fire integrity and insulation for the minimum fire protection duration.
Additional testing requirements may also be applicable for all other applications where such adhesives are proposed to be used and LR can provide guidance on such testing, after review of the proposal on a case-by-case basis.

4.3. Manufacturing

4.3.1. Composite fabrication

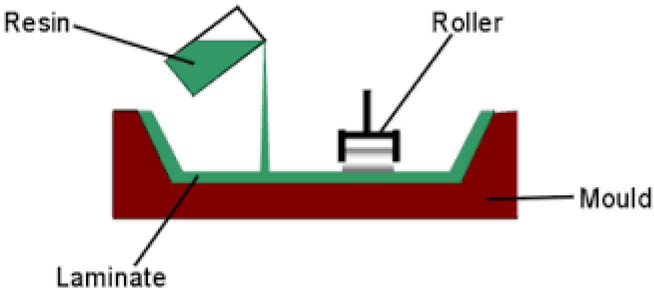
The most common manufacturing methods used in the fabrication of composite components in the marine sector include:

- Manual lamination
- Filament winding
- Resin infusion

And to a certain extent quality and structural performance of the final component will be influenced by the fabrication technique selected i.e. some techniques are highly operator dependant, which can impact on quality and consistency of the fabricated composite components. Poor manufacturing can lead to high defect levels, fibre distortion, incorrect fibre alignment, low fibre volume fractions, inability to achieve expected mechanical performance, in-service failure. This then leads on to the issue training personnel carrying out the fabrication process and inspection of the final component.

4.3.2. Manual lay-up

Alternatively known as the wet lay-up, single mould, or open mould process, hand lay-up is the most commonly used process for moulding reinforced plastics. The process imposes little limitation on the size of moulding which is produced and is particularly applicable to the production of such large mouldings as boat hulls and car bodies.



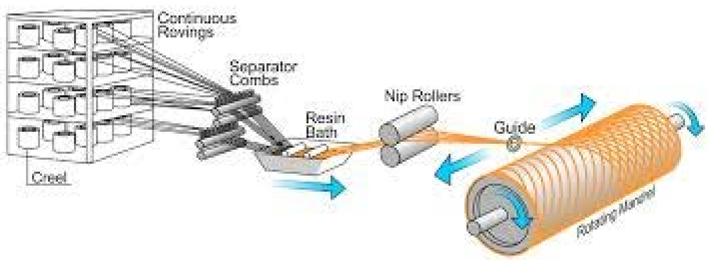
Before lay-up is started, the mould is treated with a release agent to promote easy removal of the final moulded component. The relevant reinforcement material is cut to size and impregnated with the laminating resin and consolidated using a roller to ensure the even distribution of the resin and remove entrapped air. More fibre reinforcement is added and impregnated and consolidated in similar manner until the require part thickness has been built up.

In the case of polyester lamination, the fabricated component shall be cured for a minimum of 48 hours at a minimum air temperature of 18ºC. Where other laminating resin systems curing/post-curing is to be carried out according to resin manufacturer's recommendation

There is no limitation on the size of component that can be fabricated, but the process is highly operator dependant and quality of fabricated part will depend on the skill of the operator

4.3.3. Filament Winding

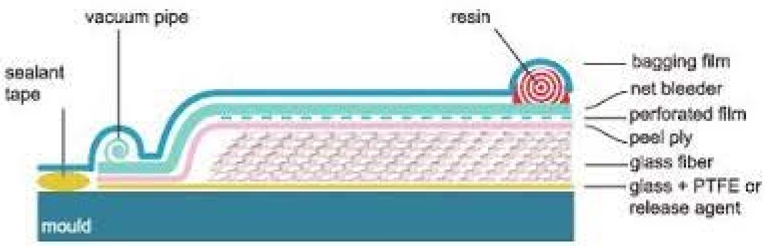
Tubes, tubular vessels and spherical vessels can he manufactured by the filament winding process. In its basic form, as in the case of the production of tubing, the mould takes the form of a rod or cylinder rotating on its longitudinal axis. Reinforcement in the form of rovings or tape passes from a holder through a bath of catalysed resin, through nip rolls set to squeeze out excess resin and on, under tension, to the rotating mandrel forming the mould where, after completion of winding, the component is cured.



The filament winding process lends itself to a high degree of mechanisation. The angle at which the filaments are wound on to the mandrel affects the ratio of tensile (longitudinal) strength to the hoop strength of the tubing formed and winding angles in the first layers of reinforcements may differ from those subsequently placed. The winding angle may be varied either by rotating the mandrel at different speeds as the carriage holding the reinforcement and resin bath moves forwards and backwards along the mandrel axis, or by varying the speed of the reinforcement carriage whilst the mandrel rotates at constant speed. In either case the whole winding operation may be controlled by a programmer. Resin to glass ratio can be controlled by variation of the separation of the nip rollers through which the resin impregnated fibre tapes passes.

4.3.4. Resin Infusion

In this technique the fibre layup is pre-stacked and laid into a mould in one process. The fibre stack is then covered with a peel ply and resin distribution media. A vacuum bag is then enclosed around the assembled fabric stack and placed under vacuum and vacuum drop test undertaken to ensure there are no leaks in the vacuum bag. Then by opening relevant valve, resin is allowed to flow into the vacuum bag and over infuse into the dry fibre stack with the aid of the distribution media



Heat can be applied for higher temperature resins such as epoxies but it can be used for any resin system with a low enough viscosity. The ability to pre-degas the resin and the elimination of resin agitation leads to much lower void percentages. Fibre volume fractions can be increased from hand layup (even under vacuum consolidation) as the pack is under continuous compaction pressure.

Key points that need to be considered when it comes to resin infusion are:

a) Resin formulation should be such that it has adequate viscosity and gel-time to allow the component under vacuum to be fully infused and maximum temperature during cure is kept within acceptable limits
b) Pressure levels during the infusion process should be specified, and should be adequate to ensure consolidation of fibre stack and specified mechanical properties are achieved
c) The pressure shall be maintained throughout cure cycle of the laminate

d) The vacuum to be monitored with the aid of pressure gauges to get a reliable indication of pressure distribution over the composite fabrication, but the positioned far away from vacuum suction point

Advantages of resin infusion:
1) Compared to hand lay-up, much higher fibre to resin ratio
2) Low quantity of voids
3) Consistent laminates with good process control
4) Good surface finish
5) Cleaner process with no VOC air pollution

Draw backs of resin infusion
1) Set-up can be complicated depending on part
2) Cost of scrappage if there is a leak or incomplete infusion
3) Tooling costs
4) Additional consumable costs

4.4. Inspection Control

Many types of defaults might appear in an adhesive joint manufacture. A general picture is given below with the associated potential cause.

- Cracks
  Thermal tensions during reticulation
- Porosities, Cavity (in the bulk, at an interface or joining the interfaces)
  Origin = evaporation of volatile component, air bubbles, lack of pressure
  Size of critical default depending on its localisation
  Disrespect of mix proportion
  Insufficient mix
  Disrespect of cure conditions (duration, temperature)
- Interfacial bad bonding, (kiss bonding)
  Incorrect choice of surface preparation
  Deviation in surface preparation
  Pollution of the surface after preparation
  Foreign body

This is a non-exhaustive list.

NDT Technique	Lack of adhesive	Cohesion	Adhesion
Ultrasonic Echography Transmission	YES	NO	NO
Sonic resonance	YES	Some cases	NO
Radiography	YES	NO	NO
Infrared Thermography	YES	NO	NO
Holographic Interferometry	YES	NO	NO
Acoustic emission	?	?	Some cases

At the moment, there are no really reliable techniques applicable in the production facility to control a bonded assembly. Ultrasonic and infrared thermography techniques are promising even if a lot of work is still to be done to enhance reliability and possible use in yards.

4.5. Training

The defects initiated during the manufacture can evolve, aggregate, allow water to enter the adhesive, and lead to a very important decrease in the lifetime a bonded joint. As detailed above, the NDT techniques available to inspect a bonded joint are weak to none on some types of defaults.

Thus, and as per the introduction of this part 9, the quality of the bonded joint can only be captured by a rigorous control of the production process all along the manufacture of the bonded joint.

Operators have a tremendous impact on the fabrication process. Above that all the persons involve in the process shall have minimum of knowledge. Thus the question is raided about a common referential allowing attesting the competences of the workers involved in bonding activities.

A number of organisatons offer on the market training relative to bonding, however the content of those training is unequal. In France, the only training course considered as qualifying is the course given by RESCOLL; it is required in some industrial domains.

4.5.1. RESCOLL

Following the same objective as what was done in welding 10 years ago, and answering the demand of some stakeholders, the EWF (European Federation for Welding) reference European organisation for assembling activities created a common referential that guarantee competency of the person.

Those training programs ensure a mastering of bonding processes at three levels:

- EWF European Bonding operator (EWF 515)
- EWF European bonding specialist (EWF 516)
- EWF European bonding engineer (EWF 517)

RESCOLL is the only French organisation authorised to teach the 2 first levels. The engineer level is only taught in Germany.

In the air sector, variations of the two first levels exist; "bonding assembly for operators in aeronautics", and "specialist in bonding assembly in aeronautics".
In the rail industry, main actors request already to their sub-contractors that their teams employed in the implementation of bonding operations are granted with a diploma, attesting their mastering of the various techniques.
Germanischer Lloyd has the same requirements for the windmill manufacture.

4.5.2. CNAM

The CNAM offers a teaching unit (UE) called "adhesive, adhesion and bonding assembly". This unit rather dedicated to technicians aims at giving the theoretical and practical tools necessary for the apprehension of adhesion mechanism in bonding assembly, to be able to define and control the properties of the bonded product.

Note that other organism offer training in this illustration based on the French offer, CETIM, some private organism, and some producer (3M, Epotechny).

All trainings offer generally the same basis with an approach rather mechanical or rather chemical depending on the entity delivering the training. On the basis of the content of the various offered programs, and of the experience feedback, a minimal content of the training course that could be proposed in naval application is suggested below:

- Bonding assembly fundamentals
  - Introduction to bonding
- Vocabulary, normalised terminology (EN 923)
- Advantages and limitations of bonding assembly technologies
- Interest of surface preparation methods
  - Interest of the preparation and treatment of the surfaces
  - Various types of surface treatment
  - Typical substrate surface treatment: thermoplastics, elastomers, metals, various coatings
- Notions of geometry and sizing (scantling) of bonding assemblies: main encountered efforts
- Bonding a special process
  - Special process and imposed process
  - Implementation of a bonding process
- Application possibilities and use of adhesives
- Control of realised bonded assembly: notions of non-destructive control
- Rules of storage of adhesives
- Health and safety rules to be followed

As results of the training the staff shall be able to:

- Understand and realise specific bonding processes and methods
- Achieve an operation as per the current state of the art
- Apply an imposed process
- Guaranty the quality of the produced assemblies
- Apply the fundamental rules of health and safety

5. CONCLUSION

This study, performed by BV, LR and Parkwind, allows to have a global overview of the regulatory requirements for adhesive bonding in marine and offshore industry applications. Some rules and standards, developed by Classification Societies, have been identified as relevant for certain application types. The study has been focused on requirements for homologation on any specific plan appraisal requirements on ABS, BV, DNVGL and LR. Some improvements are still necessary to accelerate the development of this joining technic.

The comparison with other industrial sectors such as aeronautic, automotive, railway, etc, shows that the bonding is less developed in marine and offshore. Indeed; these sectors have a long experience of the bonding using but it is mainly for non-structural assembly or by using hybrid connections mixing two assembly methods. Moreover, for marine and offshore, current regulatory barriers have been identified as contributing to the slow expansion of bonding joints. Identified barriers are:

- Short durability,
- Poor fire safety,
- Complex manufacturing,
- Few inspection control,
- Low training.

Based on this study, the Qualify test plan has been defined in collaboration with all partners. Dedicated requirements provided by Classification Societies and also from other sectors have been taken into account for testing. Moreover, barriers identification allows to concentrate project strength on specific topics.

6. REFERENCE DOCUMENTS

6.1. Rules and Guidance Notes

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6.2. Other references

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