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BONDED ASSEMBLIES

NR613 – FEBRUARY 2025

RULE NOTE

BUREAU VERITAS

BUREAU VERITAS
RULES, RULE NOTES AND GUIDANCE NOTES

NR613 DT R01 February 2025 takes precedence over previous revision.

The PDF electronic version of this document available on the Bureau Veritas Marine & Offshore website https://marine-offshore.bureauveritas.com/ is the official version and shall prevail if there are any inconsistencies between the PDF version and any other available version.

These rules are provided within the scope of the Bureau Veritas Marine & Offshore General Conditions, enclosed at the end of Part A of NR467, Rules for the Classification of Steel Ships. The latest version of these General Conditions is available on the Bureau Veritas Marine & Offshore website.

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NR613

RULES FOR BONDED ASSEMBLIES

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Appendix 7 Surface Preparation

Section 1 General

1 Application

1.1 Scope

1.1.1 This Rule Note provides the requirements for structural bonded assemblies of composite materials used in the construction of ships or equipment to be surveyed for classification or certification purposes.

Bonded assemblies for other structural materials are to be considered on a case-by-case basis by the Society.

1.2 Compliance with other Society Rules

1.2.1 The requirements of this Rule Note are in addition to the applicable Society's Rules for the classification and/or certification of ships. In particular, reference is made to the followings:

- NR206 Wind Propulsion Systems
- NR217 Rules for the Classification of Inland Navigation Vessels, Part A Classification and Surveys
- NR500 Rules for the Classification and the Certification of Yachts, Part A Classification and Surveys
- NR546 Hull in Composite, Plywood and High Density Polyethylene Materials
- NR600 Hull Structure and Arrangement for the Classification of Cargo Ships less than 65 m and Non Cargo Ships less than 90 m.

The requirements given for design assessment, procedures and products in the other relevant Society's Rules or specified by the Society on the reviewed drawings, are also applicable, where appropriate.

1.3 Compliance with Statutory requirements

1.3.1 Attention is drawn to any specific requirements that may be required by the Flag Administration with regard to structural fire protection and the use of structural bonded assemblies.

2 Definition and abbreviations

2.1 Abbreviations

2.1.1 The following abbreviations are used in this Rule Note

DCB : Double Cantilever Beam
ENF : End Notched Flexure
MMB : Mixed Mode Bending
MTI : Manufacturing, Testing and Inspection
SERR : Strain Energy Release Rate (kJ/m^2)
SHM : Structural Health Monitoring
SLB : Single Leg Bending
TAST : Thick Adherend Shear Test, corresponds to standard shear test for adhesive
T_g : Glass transition Temperature (°C)
NDT : Non Destructive Test

2.2 Definitions

2.2.1 Adhesive

Adhesive is the material used for bonding two substrates (or adherends).

General information on adhesives and the main features of the polymers are given in App 2.

2.2.2 Adhesive failure

Failure of a bonded assembly at the interface between one of the substrate and the adhesive.

2.2.3 Bonded assembly

Two substrates connected together by an adhesive.

2.2.4 Bondline

The bondline refers to the whole length of the 1D model (with no variation in the thickness and width of the assembly) where nominal stress (see Sec 4, [1.8]) is calculated.

2.2.5 Bulk
Bulk refers to only one constituent, a raw material.

2.2.6 Cohesive failure
Failure of a bonded assembly by cracking, damage or delamination of one or more substrate or within the adhesive.

2.2.7 Creep
Phenomenon that induces an increase of strain under a constant stress loading. This phenomenon can be destructive as the strain may increase until a limit state, causing failure of the creeping element.

2.2.8 Delamination
Delamination is a shear failure mode between two plies in composite materials.

2.2.9 Relaxation
Phenomenon that induces a decrease of the stress state under a constant imposed strain. Relaxation is not destructive as the stress decreases over time.

2.2.10 Structural adhesive
A structural adhesive is an adhesive designed to transfer a load from one substrate to another one.

2.2.11 Substrate (or adherend)
The substrate or adherend means the material to which the adhesive is to be applied.

2.2.12 Test set-up
Configuration used for the test campaign defined by the type of test and associated loading, geometry, material and process.

Section 2 Bonded Assembly Methodology Assessment

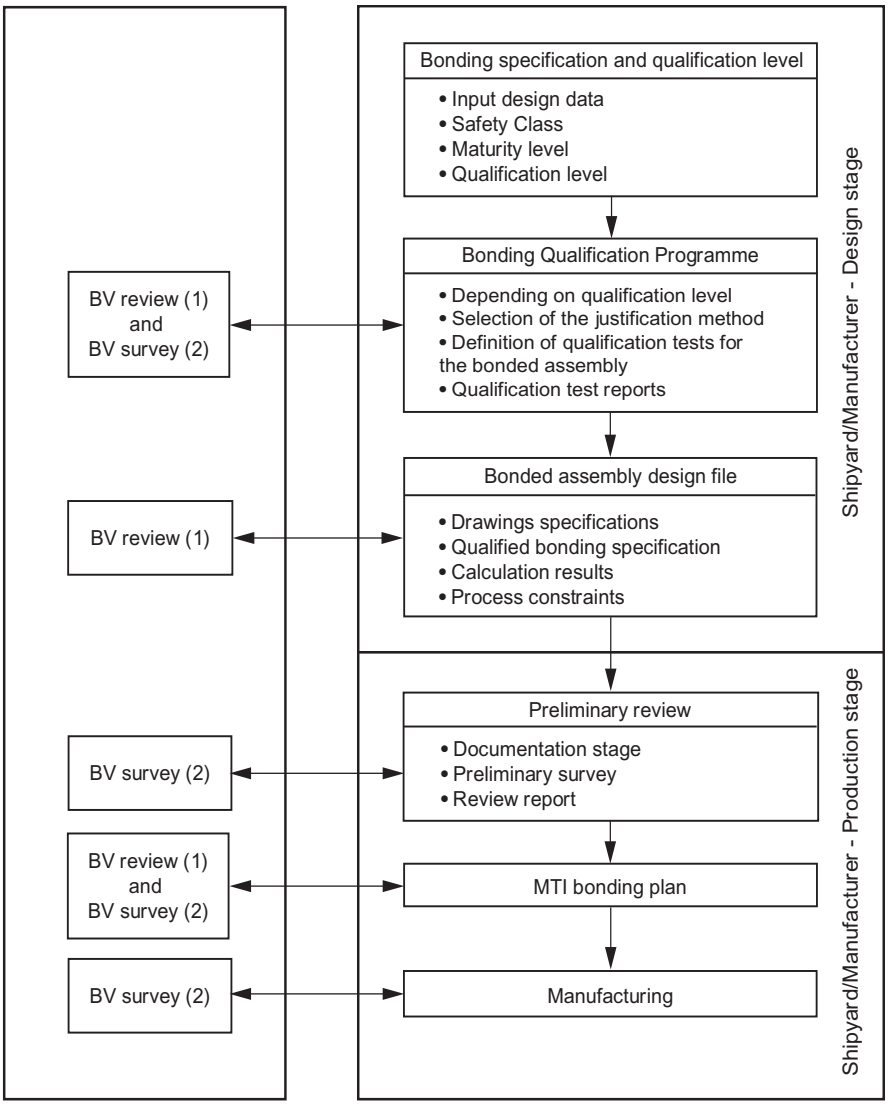
1 General

1.1 Methodology

1.1.1 Structural bonding is a special process. This Section outlines the methodology for assessing a bonded assembly in six main steps (see Fig 1):

- Bonding specification and qualification level: defining the bonded assembly
- Bonding qualification programme: based on qualification levels
- Bonded assembly design file: gathering all design information
- Shipyard/Manufacturer preliminary review: including documentation stage, preliminary survey, review report
- Manufacturing, Testing and Inspection (MTI) Bonding plan
- Manufacturing.

Figure 1 : Flowchart of Bonding Process Assessment



(1) BV review means an action by BV plan office surveyor

(2) BV survey means an action by BV field survey.

2 Bonding Specification and Qualification Level

2.1 General

2.1.1 The Bonding specification is to define the main input data to be considered in the design steps of the bonded assembly. The bonding specification is to be submitted to the Society. The following technical items are to be considered:

- Description of the considered assembly
- Application and function of the assembly
- Location of the bonded assembly on-bard
- Loads to be withstood by the assembly
- Bonded assembly maturity
- Safety class
- Qualification requirement level
- Characteristics of the adhesive
- Surface conditions of materials to be assembled
- Production process and limitations
- Bonder qualification
- Operations after curing that could impair bonding application
- Location of the bonding operations.

For more details, see App 1.

2.2 Safety class

2.2.1 The safety class of the bonded assembly is to be determined in accordance with the Tab 1.

Table 1 : Safety Class

Safety class	Definition	
SC1	Low level	Failure of the bonded assembly will result in a failure of a function: • which will not affect an essential service • which will not lead to dangerous situations for human safety, safety of the ship and/or threat to the environment
SC2	Medium level	Failure of the bonded assembly will result in a failure of a function: • which could eventually affect an essential service • which could eventually lead to dangerous situations for human safety, safety of the ship and/ or threat to the environment
SC3	High level	Failure of the bonded assembly will result in a failure of a function: • which could immediately affect an essential service • which could immediately lead to dangerous situations for human safety, safety of the ship and/or threat to the environment

2.3 Bonded assembly maturity level

2.3.1 The bonded assembly maturity level is to be determined in accordance with Tab 2, taking into account the bonded assembly configuration, materials, processes and shipyard/manufacturer experience.

As a rule:

- a bonded assembly maturity level of 1 will require few additional testing or qualifications, other than those detailed in the ship type rules set
- a bonded assembly maturity level of 3 will require all the aspects of qualification described in this Rule Note.

The maturity of a bonded assembly could be evidenced by a design of joint that has been already used on-board a ship with the same design, material, multiple conditions of application and for a period of more than 5 years so that in service feedbacks can be documented and submitted to the Society.

Table 2 : Bonded assembly maturity level

Bonded assembly maturity level	Proof of maturity	
1	Proven	Documented operational references with the applicable conditions of operation
2	Limited reference	Few or short operational references
3	Unproven	New bonded assembly without any reference

2.4 Qualification level

2.4.1 The qualification level Q of the bonded assembly is to be determined from Q1 to Q5 in accordance with Tab 3.

2.4.2 The qualification level Q is to be agreed by the Society.

Table 3 : Qualification level Q depending on safety class and bonded assembly maturity

			Bonded assembly maturity level		
			Proven	Limited reference	Unproven
			1	2	3
Safety class	Low level	SC1	Q1	Q2	Q2
	Medium level	SC2	Q2	Q3	Q4
	High level	SC3	Q3	Q4	Q5

3 Bonding Qualification Programme

3.1 General

3.1.1 A bonding qualification programme specifying the qualification requirements is to be submitted to the Society Tab 4 defines the qualification requirements depending on the qualification level.

Bonding qualification requirements are detailed in:

- Sec 3 for the adhesive and bonded assembly characterisation
- Sec 4 for the strength validation depending on the justification method A, B or C
- Sec 5 for the manufacturing and survey.

Bonded assembly ranked Q5 has at least Q4 qualification requirements. Additional justifications will be required on a case-by-case basis.

4 Bonded Assembly Design File

4.1 General

4.1.1 The Bonded assembly design file is to specify the following information and is to be submitted by the shipyard/ manufacturer or adhesive supplier to the Society:

- bonding specification as defined in Article [2]
- bonded assembly drawings
- environmental service conditions (temperature, humidity, exposure to chemical agents)
- design loads in accordance with applicable Rules and/or other if relevant
- qualification requirements as defined in Tab 4.

Table 4 : Qualification requirements as a function of the qualification levels

Qualification requirements	Reference	Qualification level			
		Q1	Q2	Q3	Q4
Adhesive Type Approval Certificate	Sec 3, [3]	–	–	X	X
Bonded Assembly characterisation (physicochemical and mechanical) **(1)**	Sec 3, [4]	–	X	X	X
Ageing **(2)**	Sec 3, [4]	–	–	X	X

(1) The content depends on the qualification level and operational conditions
(2) Depends on the environmental condition of the bonded assembly
(3) If the joint is subjected to sustain permanent loads
(4) Fatigue is required in case of applicable Rules indicating fatigue validation, or if the joint is subjected to high number of cyclic loads, or upon specific requirement of class
(5) In some case, fatigue and ageing coupling might be required, See App 5. The method selected is to be agreed with the Society
(6) Specific inspection or SHM might be required
(7) A, B, C refers to Method A, B and C defined respectively in Sec 4, [2.2], Sec 4, [2.3] and Sec 4, [2.4]

Qualification requirements		Reference	Qualification level			
			Q1	Q2	Q3	Q4
Adhesive protection		Sec 3, [3]	–	–	X	X
Strength validation by justification method		Sec 4	A, B or C **(7)**	A, B or C **(7)**	A or C **(7)**	A or C **(7)**
Creep **(3)**		Sec 4, [4.1]				X
Fatigue **(4)** **(5)**		Sec 4, [4.2] and App 5	–	–	–	X
Manufacturing	Control of the environmental conditions	Sec 5, [4]	X	X	X	X
	Traceability of materials	Sec 5, [4]	–	X	X	X
	Traceability of process	Sec 5, [4]	–	–	X	X
	Qualification of bonders	Sec 5, [5]	–	–	–	X
Survey/SHM **(6)**		Sec 5, [4]	–	–	X	X

(1) The content depends on the qualification level and operational conditions
(2) Depends on the environmental condition of the bonded assembly
(3) If the joint is subjected to sustain permanent loads
(4) Fatigue is required in case of applicable Rules indicating fatigue validation, or if the joint is subjected to high number of cyclic loads, or upon specific requirement of class
(5) In some case, fatigue and ageing coupling might be required, See App 5. The method selected is to be agreed with the Society
(6) Specific inspection or SHM might be required
(7) A, B, C refers to Method A, B and C defined respectively in Sec 4, [2.2], Sec 4, [2.3] and Sec 4, [2.4]

5 Shipyard/manufacturer preliminary review

5.1 General

5.1.1 The shipyard/manufacturer preliminary review consists of two main stages:

- documentation phase
- survey at shipyard/manufacturer premises.

The aim of these stages is to verify shipyard/manufacturer capability to operate a bonding process. Details of these stages are given in Sec 5.

6 Manufacturing, Testing and Inspection Bonding Plan and Survey

6.1 General

6.1.1 Manufacturing, testing and inspection (MTI) bonding plan and survey requirements are defined in Sec 5**.**

Section 3 Characterisation and Adhesive Type Approval Certification

1 General

1.1 Scope

1.1.1 The purpose of this Section is to specify the requirements regarding:

- characterisation of adhesive materials
- type approval certification of adhesive materials
- characterisation of the bonded assembly.

1.2 Testing

1.2.1 Overview of testing methods

An extensive range of test methods exists for characterising adhesives and bonded assembly and might be:

- based on standard or not
- with qualitative or quantitative purpose
- performed on bulk specimens or/and on bonded assembly specimens.

The usefulness and limitations of testing methods should be clearly understood before starting a testing program.

1.2.2 The testing is composed of 3 categories of tests, see Tab 1

a) Test for the characterisation of the adhesive, see Article [2]

b) Tests for the type approval certification of the adhesive, required for Qualification level Q3, Q4 and Q5, see Article [3]

c) Tests for the characterisation of the bonded assembly whatever the qualification level, see Article [4].

Test specimens are to be adapted to the justification method applied:

- Justification method A: see Sec 4, [2.2]
- Justification method C: see Sec 4, [2.4].

Table 1 : Adhesive and bonded assembly characterisation testing matrix

	Adhesive and bonded assembly characterisation		Adhesive certification
Qualification level	Justification Method A	Justification Method C	
Q1 or Q2	Bonded Assembly characterisation	Adhesive characterisation + Bonded assembly characterisation	Not applicable
Q3, Q4 or Q5	Bonded Assembly characterisation	Adhesive characterisation + Bonded assembly characterisation	Type approval Certification / Approval test program

2 Adhesive characterisation

2.1 General

2.1.1 The aim of adhesive testing is to characterise the adhesive itself and provide values that can be used for:

- calculation purpose (elastic coefficients, breaking stress and strain, …) in case of method C as described in Sec 4, [2.4] or method B when material data are missing (see Sec 4, [2.3] is used
- certification purpose in case of qualification level of bonded assembly is Q3, Q4 or Q5.

Tests may be physicochemical or mechanical tests as per Tab 3 and Tab 4. Other tests may be requested by the Society depending on the conditions in which the adhesive will be applied and used.

2.2 Tests samples

2.2.1 Test samples are to be prepared in accordance with chosen test standards with the following considerations:

- exothermic reactions for thick adhesive specimens can cause overheating and residual thermal stress
- defect content may affect adhesive failure behaviour such as porosity.

Other preparation precautions may be necessary depending on the type of polymer constituting the adhesive. In such a case, preparation procedure is to be submitted to the Society for information.

A minimum of 5 samples are to be tested for mechanical testing. For physicochemical testing, depending on the reliability of the test method, a lower number of tests may be accepted.

2.3 Tests to be performed

2.3.1 The tests program is to be submitted to the Society for agreement before carrying out the tests.

For bonded assemblies having a qualification level Q1 or Q2, the testing program of the adhesive is to include the tests prescribed in Tab 2 including glass transition temperature, tensile and shear testing at room temperature.

2.4 Test report

Technical reports, issued in the forms stipulated in the standards used for testing as chosen in Tab 3 and Tab 4 are to be submitted to the Society.

3 Adhesive Type Approval

3.1 General

3.1.1 The requirements for the certification scheme of materials are given in NR320 Certification Scheme of Materials and Equipment. In the absence of adhesive type approval certificate, mechanical tests on the adhesive are to be performed as defined in Tab 2.

3.2 Type approval scheme

3.2.1 Adhesives to be type approved are adhesives used for structural bonded assemblies that fall in the scope of qualification levels Q3, Q4 and Q5 as detailed in Sec 2, [2.4.1].

Other products used in conjunction with structural adhesives, granting environmental protection such as sealant ensuring watertightness or UV protection, will only be used in the characterisation of the bonded assembly as per Article [4].

3.2.2 Scheme

As a rule, adhesive materials manufactured in series correspond to HBV product as per NR320 Certification Scheme of Materials and Equipment.

HBV products correspond to products manufactured in series, having to comply with design requirements assessed through type approval procedure, and manufactured by works recognised by the Society.

Such products are not required to be certified by the Society individually or per batch. Their compliance with the approved type is solely certified by the manufacturer using his own format of document and marking to allow traceability to the approved type.

The type approval process of adhesives requests the two following successive phases:

- design type approval: To review the technical documentation and mechanical characteristics proposed by the adhesive's manufacturer in compliance with [3.3]
- work's recognition: To assess the compliance of the adhesive materials manufactured in series with the design type approval (see [3.4]).

3.2.3 Certificate and responsibilities of adhesive's manufacturer

Upon satisfactory completion of the two phases, a type approval certificate and a recognition certificate are issued by the Society under conditions defined in NR320 Certification Scheme of Materials and Equipment.

3.3 Design type approval of structural adhesives

3.3.1 Documentation to be submitted

The following informations are to be submitted for design review phase of the type approval:

a) product name type designation, i.e. product name (grade) to be stated on the type approval certificate

b) type/family of adhesive with information on curing system (mixing ratio, pot life, open time)

c) physical characteristics including: Density, viscosity, operating temperature, T_g

d) mechanical characteristics of the adhesive considered as manufacturer specified values used as a basis for the approval with:
   - applicable standards, which the product shall comply
   - nature of substrate used to obtain those values
   - surface preparation details.

e) limitations on the use of the adhesive:
- environmental conditions such as: humidity, temperature
- chemical sensitivity to hydrocarbons, oils, water, etc
- if applicable viscosity, thixotropy.

f) in-service feedback, if available

g) other type approval procedure engaged, if applicable.

3.3.2 Approval test program

The review of the technical documentation and the type test program are to be carried out within the scope of the design type approval, as defined in NR320 Certification Scheme of Materials and Equipment.

The test program is to be drawn up by the adhesive's manufacturer, submitted to the Society for review and is to be based at least on Tab 2.

Additional tests may be required by the Society. Some additional tests may be requested, and, depending on the particular use, or experience acquired, with the materials under approval test program according to Tab 2.

3.3.3 Report and certificate

Technical reports, issued in the forms stipulated in standards indicated in Tab 2, are to be submitted to the Society.

Upon satisfactory completion of the procedure, a Type Approval Certificate is issued by the Society as per the provision of the NR320 Certification Scheme of Materials and Equipment.

3.4 Work's recognition

3.4.1 The requirements for the work's recognition schemes are given in NR320 Certification Scheme of Materials and Equipment.

Table 2 : Minimum test requirement for adhesive

Raw material	Property / Characteristics	Required value	Test methods /Standard
Structural adhesive	Glass transition temperature (T_g) (°C)	≥ to manufacturer values	DSC: ISO 11357-2:2020 DMA: ISO 6721-11:2019 or equivalent
	Tensile properties at several temperatures **(1)**: • Young modulus (MPa) • Tensile strain at failure (%) • Tensile stress at failure (MPa)	• Manufacturer nominal value ± 10% **(2)** • Minimum 5 specimens tested for each temperature	ISO 527-2:2012 or equivalent
	Shear properties at several temperatures **(1)**: • Shear modulus (MPa) • Shear strain at failure (%) • Shear stress at failure (MPa)	• Manufacturer nominal value ± 10% **(2)** • Minimum 5 specimens tested for each temperature	ISO 11003-2:2019 NF EN 14869-2:2011 or equivalent
(1) 3 minimum required temperatures: –20°C, 23°C and 60°C (or T_g – 20° for thermoset) **(2)** At room temperature			

4 Bonded assembly characterisation

4.1 General

4.1.1 Scope

Structural assessment of bonded assembly is to be carried out in accordance with the present Rule Note and the applicable requirements of the Society Rules (see Sec 1). Tests to be carried out are defined in [4.2].

Depending on bonded assembly qualification level as described in Sec 2, [4] of the present note, tests are to be performed in order to determine characteristics of the materials (adhesive, substrates,...) and the bonded assembly.

4.1.2 Application

Mechanical and physicochemical tests are to be performed on bonded assembly components and assembly produced by the shipyard/manufacturer and submitted to the Society for agreement as representative of the final assembly, in accordance with the justification method A or C, see Sec 4, [2.2] and Sec 4, [2.4] respectively.

The results of the mechanical tests are to be used in accordance with the requirements of the present Rule Note and considered for the bonded assembly assessment.

In order to be representative of the production methods and of the final bonded assembly to be used on board, each bonded assembly intended for testing is to be:

- manufactured with the same raw materials and components as the final adhesive assembly: substrate, adhesive and interfaces
- manufactured with the same methods intended for the final assembly and in the same environmental conditions, and particularly with the same surface preparation and curing cycle, when applicable.

4.2 Tests

4.2.1 Characterisation test program

In accordance with Sec 2, Tab 4 bonding qualification requirements characterisation test program is to be submitted to the Society covering strength, ageing and protection if applicable. Complementary characterisation may be requested on case by case by the Society.

Test lists provided in Tab 3, Tab 4 and Tab 5 are to be used as guidance for the complete set of tests to be performed, rather than a test list to be complied with.

Technical reports, issued in the forms stipulated in standards used for testing are to be submitted to the Society. Failure patterns are to be included according to ISO 10365:2022.

4.2.2 Standardized tests / non standardized tests

Standardized tests are mainly requested for comparing materials' properties and determining the consistency of materials and processes. They are less valuable in accurately predicting the strength of bonded assemblies. Modified standardized tests or specific prototype tests often need to be designed for this purpose and agreed with the Society such as:

- tests where no dedicated standard exists but are deemed necessary by the Society in order to assess bonded assembly
- combined tests with the aim to assess, for example, the effect of an environmental parameter on mechanical characteristics like immersion and shear strength.

Tests are to be submitted and witnessed by the Society.

4.2.3 Tests on bonded assembly specimens

Determination of reliable mechanical properties could be performed through testing on bonded assembly specimens.

The other approach is to use specially designed joint / prototype tests. These tests more closely reflect joint design but with some problems associated to bonded assembly configuration:

- stress distribution is most of the time non uniform due to stress concentration at bondline ends
- accuracy and reliability of displacement measurements as magnitude is often small.

4.2.4 Durability tests

Assessment of bonded assemblies involves knowledge of interaction between particularly complex ageing mechanisms and mechanical loading.

Parameters which can decrease lifetime of bonded assemblies are mainly mechanical loading combined with environmental factors such as temperature and moisture.

Some standardized test methods described in Tab 3 and Tab 4 may be used for Q3 and Q4. Due to the variety of application cases and specific behaviour of each type of adhesive, other test methods might be used in agreement with the Society.

Repeated long-term testing under the expected environmental conditions is generally considered to be the most efficient method, but for practical reasons this type of testing is not always possible.

Alternative approach may be to use accelerated tests methods.

The determination of accelerated tests will be based on the following four steps:

a) definition of the environment in which the bonded application will evolve (temperature, moisture, UV, other chemical media, mechanical load, water, etc)

b) identification of degradation mechanisms (physical, chemical, combined)

c) identification of accelerating factors: combined loads (fatigue, static); temperature (isothermal, cyclic); hydrothermal; etc.

d) identification of indicators (residual strength, stiffness, fatigue life, etc.)

Once these steps have been performed, a level of application of accelerating factors and a duration of accelerated test representative of the product lifetime is defined.

The methods development to determine the time reduction in function of the level of application of the accelerating factor could be either empirical using as input the environmental factors in tests protocols or analytical using as input the controlling variables (geometry, loading history, material properties, etc.).

The procedure used is to be agreed with the Society before application.

Table 3 : Physico-chemical tests

Properties / Standard and test methods	Comments
T_g or other transition temperatures • Differential Scanning Calorimetry: ISO 11357-2:2020, ASTM E1356:2023, ASTM D3418:2021 • Dynamic Mechanical Analysis: ISO 6721-11:2019, ASTM D7028:2024, ASTM E1640:2023	
Density • ISO 1675:2022, ISO 1183-1:2019, ISO 1183-2:2019, ISO 1183-3:1999, NF EN 542:2003, NF EN 543:2003	As a rule, density of adhesives may vary from 0,8 to 1,5
Viscosity • NF EN 12092:2002, ASTM D2556:2018, ASTM D1084:2021, ISO 2555:2018, ISO 3219-1:2021, ISO 3219-2:2021	Essential factor linked to the processability of the adhesive
Pot life • ISO 10364:2024	Time during which the adhesive may be used after components mixing (related to two component adhesives)
Water absorption • ISO 62:2008, ASTM D570:2022	Permit to know the mass of water absorbed by a sample and to determine the water content at saturation and the wet diffusion coefficient using a Fick's law
Coefficient of thermal expansion • ASTM D696:2024, ISO 11359-2:2021	Parameter to be considered in the case of assembly of different materials
Hardness • ISO 868:2003, ASTM C661:2022, ASTM D2240:2021	Comparative method measurement can give an indication of the degree of cure of the adhesive
pH • NF EN 1245:2011, ASTM D3310:2023, ASTM D1583:2018	Some adhesives can be acidic or alkaline under influence of moisture with the time. Corrosion of metallic substrate and decrease durability of bonded assembly could be generated. pH can be measured only on water dispersion or solutions depending on the type of adhesive formulation
Resistance to UV • ASTM D904:2021, ISO 4892-1:2016, ISO 4892-2:2013, ISO 4892-3:2016	For UV exposed bonded assembly
Resistance to chemicals • ASTM D896:2017	Adhesive resistance against aggressive media commonly encountered in operating environment is to be specified by adhesive supplier
Filler content • NF EN 1246:1998, NF EN 827:2006, ASTM D5040:2021, ASTM D1489:2021	• Method used to measure content of mineral fillers or other solid raw material in adhesives • According to their shape, for example, fillers may even induce anisotropy in the behaviour of the adhesive. Their interaction with moisture and / or metal substrates may also cause effects on ageing of bonded assemblies

Table 4 : Mechanical tests

Properties / Standard and test methods	Comments	Limitations
Tensile • ISO 527-2:2012, ASTM D638:2022	• Specimen fabrication and testing easy • Pure stress state • Ok for design data	• Fabrication: caution for exothermic reaction in thick specimens • Strain to failure dependent on the presence of defects (porosity, cracks)
Compression: • Soft adhesives: ISO 7743:2017, ASTM D575:2024 • Rigid adhesives: ISO 604:2002, ASTM D695:2023	• As a rule, it is assumed that compressive and tensile properties are the same, except when hydrostatic stress component influence adhesive's yield and failure	• Test different for soft and rigid adhesives
Shear • Single Lap Joints (SLJ) and Double-Lap Joints (DLJ): ASTM D1002:2019, ASTM D3163:2023, ASTM D3164:2017, ASTM D3165:2023, ASTM D3166:2020, ASTM D3528:2016, ASTM D5868:2023, NF EN 1465:2009, ISO 4587:2003, ISO 9664:1993	• Specimen fabrication and testing easy • Ok for comparative assessment, adhesive selection, quality control • Ok for fatigue/creep/environmental test	• Not suitable for generating design data (Yields “apparent” shear strength only) • Geometry dependent (adhesive thickness, overlap length…) • Caution of failure mode for proper analysis (peel, substrate yielding…) Limited to rigid substrates • SLJ: loading misalignment: elevated shear / peel stresses at bondline ends • DLJ: reduce peel stresses but do not ensure uniform shear stress • Measurement reproducibility
Shear • V-Notched Beam (Iosipescu): ASTM D5379:2021	• Bulk or joint specimen • Ok for design data • Ok for environmental testing	• Bulk Resin: 2 biaxial strain gauges required • Bonded assemblies: difficulties with small deformation measurement • Accurate machining required • Special test fixture required • Unsuitable for fatigue / creep testing
Shear • Arcan (V-Notched plate) and Modified Arcan: No standard	• Versatile testing method (tensile / shear loading combination) • Bulk or joint specimen • Stress state uniform (improved with modified arcan test) • Ok for design data • OK for fatigue /creep /environmental test	• Difficulties with small strain measure • Strain gauges/extensometer required • Accurate machining required • Special test fixture required • No existing standard
Shear • Torsion Rod/Butt: No standard	• Bulk or joint specimen • Ok for design data • Ok for fatigue /creep /environmental test	• Torsion facility required • Exothermic reaction Bulk specimens • Bonded assemblies • Small strains difficult to measure
Shear • Napkin Ring : ISO 11003-1:2019, NF EN 14869-1:2011	• Stress state relatively uniform • Ok for design data • Ok for fatigue /environmental test	• Torsion facility required • Accurate machining required • Small strains difficult to measure • Bondline thickness difficult to control
Shear • TAST: ASTM D3983:2019, ISO 11003-2:2019, NF EN 14869-2:2011 • Modified TAST: no standard	• Stress state uniform over bondline. • Ok for design data • TAST specimen fabrication and testing relatively straightforward • Ok for environmental testing	• Small strains difficult to measure (two extensometers required) • Accurate stress analysis difficult / concentrations present at bondline ends (reduced with Modified TAST- special test fixture required or spew fillet) • Limited fatigue capability

Properties / Standard and test methods	Comments	Limitations
Shear • End Notched Flexure (ENF): ASTM D7905:2019	• Mode II fracture toughness • Specimen fabrication and testing straightforward • Ok for fatigue/environmental testing	• Limited to rigid substrates and adhesives • Special test fixture required • Not ok for generating design data • Results analysis difficult • Measurements reproducibility
Peel • T peel: ASTM D1876:2023, ISO 11339:2022, ISO 8510-2:2006	• Specimen fabrication and testing easy • Ok for comparative assessment, adhesive selection, quality control • Possible for environmental testing	• Limited to thin flexible substrates • Not ok for generating design data • Measurement reproducibility • Not ok for fatigue / creep testing
Peel • Climbing Drum: ASTM D1781:2021	• Testing straightforward • Ok for comparative assessment, adhesive selection, quality control for sandwich skins	• Special test fixture required • Specimen fabrication • Not ok for generating design data • Not ok for fatigue /creep / environmental test
Peel • Floating Roller Method: ASTM D3167:2017, ISO 4578:1997, NF EN 1464:2010	• Specimen fabrication and testing relatively easy • Ok for comparative assessment, adhesive selection, quality control	• Special test fixture required • Limited to rigid-to-flexible substrates • Not ok for generating design data
Cleavage • Wedge Cleavage (Boeing Wedge): ISO 15107:1998, ISO 10354:1992	• Mode I fracture toughness • Specimen fabrication and testing easy • Ok for environmental testing • Effective comparative method for durability assessment of adhesive and substrates surface preparation • Accurate and reproducible data • Variant method (chip test) for brittle materials	• Limited to rigid adhesives and substrates • Not ok for fatigue / creep loading
Cleavage • Cleavage Strength (Compact Tension): ASTM D1062:2023	• Mode I fracture toughness • Specimen fabrication and testing easy • Ok for comparative assessment, adhesive selection, quality control • Ok for environmental /fatigue test	• Special test fixture required • Limited to rigid substrates • Not ok for generating design data
Cleavage • Double Cantilever Beam (DCB): ASTM D3433:2020, ASTM D5528:2022, ISO 25217:2009	• Mode I fracture toughness • Specimen fabrication and testing straightforward • Ok for fatigue / environmental test	• Limited to rigid substrates • Fracture energy vary with length of failure • Special test fixture required • Limited for generating design data • Results analysis difficult • Measurements reproducibility
Cleavage • Tapered Double Cantilever Beam (TDCB): ASTM D3433:2020, ISO 25217:2009	• Mode I fracture toughness • Specimen fabrication and testing relatively straightforward • Ok for fatigue / environmental test	• Limited to rigid substrates • Large specimens required • Not ok for generating design data • Special test fixture required • Measurements reproducibility
Mixed mode • Mixed mode bending: ASTM D6671:2022	Mixed mode fracture toughness mode I and II	

Properties / Standard and test methods	Comments	Limitations
Dynamic test • ISO 6721-1:2019, ISO 6721-2:2019, ISO 6721-3:2021, ISO 6721-4:2019, ISO 6721-5:2019, ISO 6721-6:2019, ISO 6721-7:2019, ISO 6721-8:2019, ISO 6721-9:2019, ISO 6721-10:2015, ISO 6721-11:2019, ISO 6721-12:2022, ASTM D4065:2020, ASTM D4092:2021, ASTM D5023:2023, ASTM D5024:2023, ASTM D5026:2023, ASTM D5279:2021, ASTM D5418:2023	• Alternative and versatile methods (tensile, flexural, compression, torsion) might be used for determining T_g or generating mechanical properties relatively close from those obtained with static tests • Modulus (E, G) may be obtained as a function of frequency or temperature • Non-destructive methods • Specimen fabrication and testing easy • Bulk or joint specimen • Methods which may use specimens prepared for other static tests. (tensile bulk, TAST) • Suitable for R&D, adhesive characterisation and selection, quality control	• Unsuitable for soft adhesive • High vibration frequencies may generate self-heating of test specimens, which may lead to biased results

Table 5 : Tests on the substrates

Properties / Standard and test methods	Comments	Limitations
Surface preparation wettability • NF EN 828:2013	Determination by measurement of contact angle and critical surface tension of solid surface	
Wetting tension • ASTM D2578:2023	Standardized test method for wetting tension	
Pull off test • ASTM D4541:2022	• Pull tests are to be performed in the same condition that the bonding • Ok for comparative assessment	
Coefficient of thermal expansion • ASTM E831:2024, ASTM D696:2024, ISO 11359-2:2021	Linear Thermal Expansion used to determine the rate at which a material expands as a function of temperature	
Surface roughness • ISO 21920-1:2021, ISO 21920-2:2021, ISO 21920-3:2021	Method for measuring surface roughness R_a	
Substrate surface quality • ISO 8296:2003, Pull off test, ASTM D3808:2021, Rugosity	Comparative methods to be used for substrate surface preparation before bonding	
Tensile • ISO 527-2:2012, ASTM D638:2022	• Specimen fabrication and testing easy • Pure stress state • Ok for design data	• Fabrication: caution for exothermic reaction in thick specimens • Strain to failure dependent on the presence of defects (porosity, cracks)

Section 4 Bonded Assembly Design Requirements

1 General

1.1 Application

1.1.1 This Section defines the design requirements for a bonded assembly.

1.2 Design loads

1.2.1 Design loads to be considered are defined in the Society Rules listed in Sec 1, [1.2].

1.3 Environmental conditions

1.3.1 Without specific definition of the environmental service conditions in the applicable rules, or specifications of the bonded assembly, the following may be considered:

- temperature: –25°C to 55°C
- humidity: 95% at 55°C
- salt mist content: 1 mg/m^3.

Other values may be considered upon specifications.

The correspondence between the specification of a bonded assembly and its intended use is subject to the agreement of the Society who may require additional justifications.

1.3.2 The strength of the bonded assembly is to be demonstrated at room temperature (RT) for all joints, or at the relevant operating temperature.

Upon Society's agreement, it may be possible to lower the severity of the extreme temperatures when it clearly appears that design load cannot occur at the maximum temperatures.

The temperature design range is to exclude the range of temperature [T_g –20°C ; T_g+20°C]. For a bonded assembly with a temperature design range below T_g, this gap may be reduced to 15°C if T_g onset E is considered and measured using DMA test (see characterisation tests in Sec 3).

1.3.3 The effects of UV light and/or chemical aggression are to be considered and characterised, or the absence of such environmental factors is to be evidenced.

1.4 Joint geometries

1.4.1 As a rule, the joint geometry of a bonded assembly is to be designed in a way that in plane shear load will be prevalent.

Joint geometry leading to other type of loading as defined in Fig 1 may be considered on a case-by-case basis by the Society.

Typical bonding edge geometries of bonded assemblies leads to a smooth stress transition, as presented in Fig 2.

1.4.2 Adhesive thickness

A range of thicknesses is to be defined, submitted and once agreed by the Society used in the design considering bonding thickness tolerance that can be manufactured and controlled.

The strength of the joint considering the design range thickness is to be checked according to methodology developed in [2.2] to [2.4].

Figure 1 : Illustration of peel modes of loading range from uniform peel to various peel (cleavage) and finally local peel

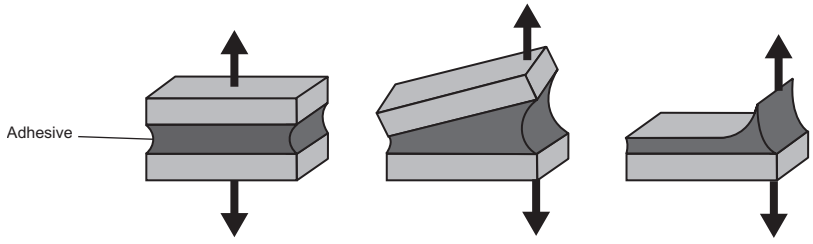
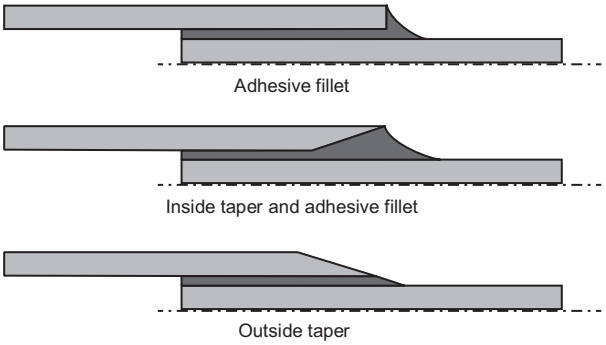


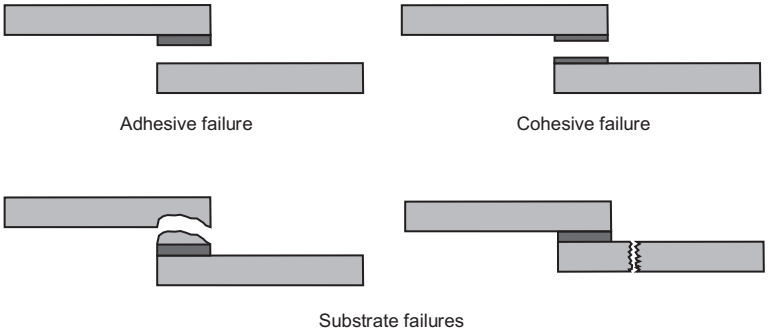
Figure 2 : Typical bonding edges



1.5 Failure modes of bonded assemblies

1.5.1 The most frequent failure modes of a bonded assembly are presented in the Fig 3. Combination of these failure modes may happen.

Figure 3 : Representation of the main modes of failure of bonded assemblies



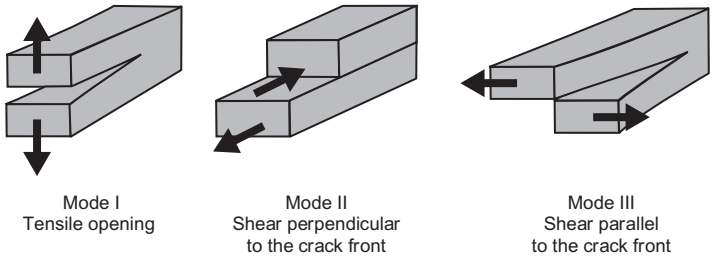
1.6 Crack propagation modes

1.6.1 In presence of a crack in the adhesive or at the interfaces, crack propagates following 3 modes, as presented in Fig 4:

- Mode I - Opening mode (a tensile stress normal to the plane of the crack),
- Mode II - Sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front), and
- Mode III - Tearing mode (a shear stress acting parallel to the plane of the crack and parallel to the crack front).

As a rule, bonded assemblies are to be designed so as to minimize the peel internal loads, and to avoid local peel load, or loading in mode I.

Figure 4 : Illustration of the 3 basic loading modes in presence of a crack within the plane of the bondline



1.7 Type of failure

- A guidance to determine the following type of failure is provided in App 3:
- Ductile failure: a ductile failure is a failure with plastic deformation of the failed part.
- Brittle failure: a brittle failure is a failure of an overloaded part with no distortion and no plastic deformation.
- Tough or ductile assembly: specific considerations on brittle / ductile assembly are to be considered. For those assemblies a guidance for sorting brittle joints from ductile joints is given in App 3.
- Brittle assembly: high stress points are likely to drive the design strength in brittle assembly. Hence for brittle adhesives and when the maturity is not proven, joints design is to be assisted by tests (method C). Additionally, specific care is to be taken on the manufacturing quality so as to lower as much as possible the risks of defects mostly in the vicinity of singularities, and the shapes of the edges of the bondline is to be specifically defined (see Fig 2). In any case, the tests for validation are to be representative of the actual edge shapes in production.

1.8 Type of stress

1.8.1 The following type of stresses of a bonded assembly may be calculated:

a) The average stress assumes the substrates to be fully rigid and the stress, (out of plane) or (in-plane), to be constant throughout the adhesive:

$$\sigma = \frac{F}{S}$$

$$\tau = \frac{T}{S}$$

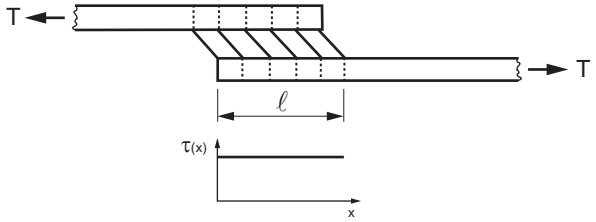
where:

F : Out of plane load, in N, acting normal to the bondline.

T : Shear load, in N, acting parallel to the bondline, see Fig 5.

S : Area of the bonding overlap, in mm^2.

Figure 5 : Average stress illustration



b) The nominal stress considers the stiffness in the substrates, and the stiffness of the adhesive, without considering the stress concentrations through the adhesive thickness. In such models, the stress in the adhesive can vary along the bondline but is considered constant across the adhesive thickness, see Fig 6.

Plastic deformation shall not appear for calculation models using nominal stress.

Alternatively, the nominal stress may be derived from a Finite Element Analysis (FEA) where only one element is present in the adhesive thickness (one linear element), see Fig 7.

Figure 6 : Nominal stress illustration

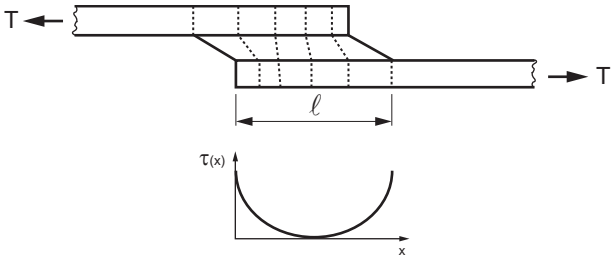
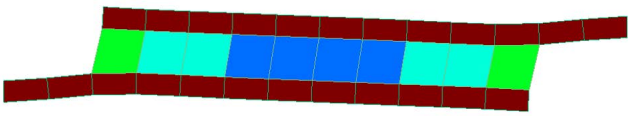


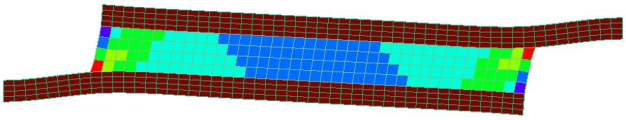
Figure 7 : Illustration of nominal stress in FEA



c) The hot spot stress is the stress within the adhesive considering stiffness of substrates and adhesive and the actual representation of the joint in the thickness and shape at edge (see Fig 2).

This stress can be determined using FEA, where the thickness of the joint is defined using a number of elements across the adhesive thickness, sufficient to represent the stress gradient, see Fig 8.

Figure 8 : Illustration of hot spot stresses in FEA



2 Strength validation

2.1 General

2.1.1 General

Strength of the bonded assembly is to be demonstrated in all combinations of loads described in the applicable Rules, effects of the load cases i is noted L^i_{design}.

Based on explanation provided to the Society, if an envelope loading case can be identified as the most severe loading cases, only the envelope loading case may be assessed.

2.1.2 Justification methods

Assessment of bonded assembly is to be carried out using one of the three justification methods that are proposed below for the qualification of the bonded assembly without considering the impact of ageing, fatigue, and creep. For fatigue and creep, see specific cases in Article [4].

The strength of the bonded assembly is to be demonstrated on the basis of one of the following:

- Method A - Design justified by tests only

  All parameters (materials, shape, loading point) of the designed assembly part are always the same. The method A can be applied whatever the qualification level.
- Method B - Design justified by calculations only

  Method B can be only used for qualification levels Q1 and Q2 with a justification of adhesive properties.
- Method C - Design justified by tests and calculations

  Method C can be applied whatever the qualification level.

2.1.3 Design methodology

A design methodology, is to be defined for justification method B and C (see App 4). It corresponds to the combination of a calculation model and a failure criterion. The methodology is to be defined clearly, with all influencing parameters, and those should be applied systematically in justification methods B and C.

Other methodologies than those presented in App 4 may be accepted on a case-by-case basis.

2.2 Method A - Assembly justified by testing

2.2.1 Method A is applied when:

- the design is fixed (i.e. no thickness variation, no geometry variation, no material variation), and
- whatever the qualification level.

The strength is to be demonstrated by representative tests of bonded assembly, as mentioned in Sec 3, performed at full scale or in representative configuration agreed with the Society. For the assembly validation, all load cases are to fulfil the following formula:

$$L^i_{design} \cdot SF_i \leq F^i_A$$

L^i_{design} : Loads as defined in the applicable Rules for load case i

SF_i : Safety factor associated with load case i, see Article [3].

F^i_A : Characteristic failure load of a representative set of tests performed at most severe temperature under the testing configuration i.

The characteristic failure load obtained by testing, which is given for a specific level of confidence, represents the level of load below which a small specified proportion of the specimens are expected to fail.

It can be expressed as:

$$F^i_A = F^i_{average} - k_m \cdot S^i$$

with:

k_m : Coefficient function of the total number m of specimens tested in the configuration i for 5% characteristic value. The value of k_m is defined according to Tab 1.

S^i : Standard deviation of failure load of tests in the testing configuration i.

$F^i_{average}$: Average failure load of the tests in the testing configuration i.

Table 1 : Value of k_m as a function of the total number of considered tests for 5% characteristic value

m	3	4	5	6	8	10	20	30	infinite
k_m	3,37	2,63	2,33	2,18	2,00	1,92	1,76	1,73	1,64

The test program is to be defined in order to take into consideration all loading configurations and their combinations.

The parameters affecting assembly strength such as substrate material, adhesive thickness, surface preparation, manufacturing, curing are to be representative of the actual production. These parameters are to be settled in a way to perform tests in the most severe condition. As a rule, a minimum of 5 specimens is recommended. Testing configurations are to be agreed with the Society.

2.3 Method B - Assembly justified by calculations

2.3.1 Method B is dedicated to bonded assemblies with qualification levels Q1 and Q2. For instance, bonded assemblies:

- presenting a proven and referenced maturity
- integrated in a known environment
- subject to loadings similar as the one for which the shipyard/design office has experience (which is to be documented).

Evidences that the assembly system complies with the above conditions are to be provided to the Society, as well as the description of the design methodology and its associated calculations.

Average stress method is excluded for method B.

In such case, recognized calculation models may be used, see App 4.

Standard characterisation tests may still be needed for parameters such as modulus and strength, see Sec 3.

Strength is to be demonstrated for all load cases i. Strength validation corresponds to the validation of:

$$L^{i}_{design} \cdot SF_i \leq F^{i}_{B}$$

L^{i}_{design} : Loads as defined in the applicable Rules for load case i.

SF_i : Safety factor associated with testing load case i, see Article [3].

F^{i}_{B} : The predicted failure load as calculated by the applied design methodology for the load case i.

2.4 Method C - Assembly justified by calculations combined with testing

2.4.1 Method C can be applied for Q2 all qualification levels.

The strength of the bonded assembly is to be demonstrated by adjusting predicted results from design methodologies with the help of a strength test campaign. The output of the method C is the correlated failure load F^{i}_{C} obtained by evaluating:

- the experimental sensitivity of the joint to design parameters
- the robustness of the design methodology.

The overall process of this method is to:

- perform an experimental campaign at small to medium scale only
- model these tests using an appropriate design methodology
- determine the correlated failure load of these tests applying formulas from [2.4.4] to [2.4.6] that are based on EN1990:2003 Annex D “design assisted by tests”
- determine the correlated failure load for design load case using only the design methodology and applying the factors determined at previous step.

2.4.2 Validation of design strength

The design is to be validated in all most severe loading conditions i by confirming the following formula:

$$L^{i}_{design} \cdot SF_i \leq F^{i}_{C}$$

L^{i}_{design} : Loads as defined in the applicable Rules for load case i.

SF_i : Safety factor associated with load case i, see Article [3].

F^{i}_{C} : The correlated failure load for the load case i as determined by method C.

A methodology to calculate F^{i}_{C} is given in [2.4.3] to [2.4.7].

2.4.3 Strength test campaign

a) Strength tests requirements:

The strength test is to be representative (not only based on lap shear tests) of the actual design of a bonded assembly, with representative substrates materials and stiffness, adhesive material, thickness and edges, and type of loading. In order to perform strength tests, manufacturing of test pieces is to be representative as results may be strongly affected by the manufacturing conditions - those are to be defined clearly and documented in the bonding specification. If any, impacts of the evolution of manufacturing process which may occur during qualification phases are to be evaluated and considered.

b) Establishment of the test plan:

Assessment of strength is to be carried out on a minimum of 4 representative test set-ups to investigate the design envelope (temperature, thickness, overlap, loading type…). Each defined test set-up is to be tested with at least 5 specimens.

When large scale specimens are tested, they are to be included in this test database, however, large scale test objective is rather to confirm design and manufacturing parameters at once. The number of specimens may be reduced if a large scale test set-up is tested.

Loading speed of the strength tests is to match the order of magnitude of the actual loading.

In any case, the test plan is to be agreed with the Society.

c) Test instrumentation and records:

Joints may be instrumented as precisely as possible in order to

- enable cross comparison of results and models
- bring better understanding
- validate the models.

Failure load is to be recorded for each specimen k of the test set-up j, $F^j_{exp\_k}$.

Tests data may reveal several modes of failures, which are to be duly defined, recorded and treated independently.

d) Post treatment of strength test - Experimental versus predicted failure diagram

A graph gathering data of test results and design methodology results, is to be drawn out:

- horizontal axis being the predicted failure loads F_{pred} from design methodology
- vertical axis the experimental failure loads F_{exp}

Note 1: No j or k indices when simply referring to abscissas and ordinates.

By comparing experimental data to the perfect resistance model, that is represented by a curve with 1/1 ratio slope as shown in Fig 9, the robustness of the design methodology is assessed.

Two types of dispersion may be identified:

- tests dispersion, vertical spreading of each group of dots
- limited accuracy of the design methodology, misalignment of the group of dots.

2.4.4 Determination of the best linear fit

Predicted results are to be corrected to the experimental results by applying a constant ratio. It corresponds to the best linear fit between the experimental failure loads and the predicted failure loads. The slope of this best linear fit is referred to as “b”.

$$b = \frac{\Sigma_j[F^j_{pred} \cdot \Sigma_k F^j_{exp\_k}]}{\Sigma_j[n_j \cdot (F^j_{pred})^2]}j$$

The best linear fit equation is:

$b \cdot F^j_{exp\_k}$

The ratio b is calculated in the following manner (least squares theory):

where:

n_j : Number of specimens in the test set-up j

F^j_{pred} : Predicted failure load of test set-up j calculated with the design methodology chosen

$F^j_{exp\_k}$: Failure load for each specimen k of the test set-up j.

The use of a corrected model enables to make further error evaluation without considering a proportionality error in the model. Fig 9 illustrates this, as the model, in this case, is systematically predicting a lower strength than experimentally measured.

$b \cdot F_{pred}$ corrects the proportionality error of the model.

The error between the corrected model and the experimental results is therefore minimized and represents:

- the actual experimental dispersion
- the model error in predicting the impact of a change in the design parameter.

2.4.5 Determination of the coefficient of variation

For each specimen k of the test set-up j, the error δ_k can be expressed as follows:

$$\delta^j_k = \frac{F^j_{exp\_k}}{F^j_{pred} \cdot b}$$

where:

F^j_{pred} : Predicted failure load of test set-up j calculated with the design methodology chosen

$F^j_{exp\_k}$: Failure load for each specimen k of the test set-up j

b : ratio defined in [2.4.4].

The use of the natural logarithm of this ratio enhances the weight of the non-conservative results so that the error is majored when the result is non-conservative:

$$\Delta^j_k = \ln(\delta^j_k)$$

The average log of the ratio, is:

$$\bar{\Delta} = \frac{1}{N}\Sigma_j \Sigma_k \Delta^j_k$$

with

N : Total number of tested specimens whatever the test set-up.

The variance is to be considered as follows:

$$s_{\Delta}^2 = \frac{\Sigma_j \Sigma_k (\Delta_k^j - \bar{\Delta})^2}{N-1}$$

The coefficient of Variation, COV, is to be taken as:

$$COV = \sqrt{\exp(s_{\Delta}^2) - 1}$$

2.4.6 Determination of the correlation coefficient

Using COV as defined in [2.4.5], the correlation coefficient β_C of the assessed joint j is to be estimated through:

$$\beta_C = (1 - k_N \cdot COV) \cdot b$$

where:

k_N : Coefficient function of the total number N of specimen tested whatever the configuration for 5% characteristic value. The value of k_N is defined according to Tab 2

As per EN1990:2003, the choice of the value k_N depends on the knowledge of the COV associated to the basic variables. In the case of bonded assembly, it is difficult to estimate the coefficient of variation of all the parameters implied in the joint, material, material transformation, surface preparation, application, environment during application, etc. Thus it is recommended to use the table of k_N representing an unknown coefficient of variation of the different factors.

b : Ratio defined in [2.4.4].

Table 2 : Values from the EN1990:2003, of k_N as a function of the total number of considered tests for 5% characteristic value.

N specimens	3	4	5	6	8	10	20	30	unlimited
k_N	3,37	2,63	2,33	2,18	2,00	1,92	1,76	1,73	1,64

Note 1: An application case is presented on the Fig 9. In this case, the model systematically gives lower results than observed in the experimental tests i.e the best linear fit curve (green curve) is above the perfect model curve (red curve). However, the correlated failure load curve (blue curve). is closer to the perfect model and below all experimental results in this case.

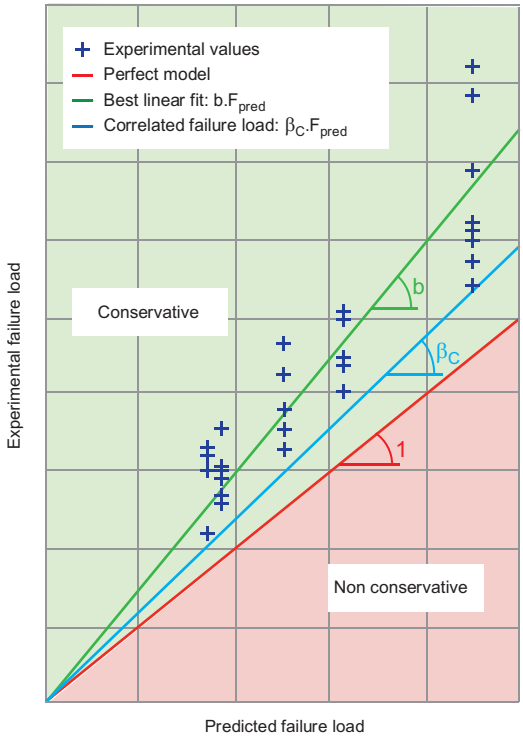
2.4.7 Determination of correlated failure load F^i_C

Using β_C as defined in [2.4.6], the correlated failure load F^i_C is to be determined using:

$$F^i_C = \beta_C F^i_{pred}$$

where F^i_{pred} is the predicted failure load for load case i.

Figure 9 : Method C application case example



3 Safety factors

3.1 General

3.1.1 Safety factors are provided as a function of the justification method A, B, C defined in Article [3].

The safety factor is considered as being the ratio between the characteristic failure load of the bonded assembly, depending of the justification method, and the maximal design load combination. This ratio is to fulfil the following condition:

$SF \geq \alpha\ C_t\ C_v\ C_F\ C_\theta\ C_b$

where:

α : Coeficient taken equal to:

- for method A (see [2.2]): $\alpha = 1,5$
- for method B (see [2.3]): $\alpha = 2$
- for method C (see [2.4]): $\alpha = 1,5$

C_t : Safety factor considered for the failure criteria:

- $C_t = 1,2$ if failure criteria is determined by mechanical tests of the assembly (Method A or C)
- $C_t = 1,5$ if failure criteria is determined on the basis of data sheets for appropriate substrates (Method B)

C_v : Factor taking into account the ageing effect:

- $C_v = 1,2$ when joint considered as protected.

Note 1: When the joint is directly exposed to UV and/or water, the value of C_v can be adjusted by performing ageing tests.

C_F : Factor taking into account the bonding process and generally taken as:

- $C_F = 1,25$ in case of manual process
- $C_F = 1,15$ in case of a vacuum process, infusion, injection or equivalent

C_θ : Factor taking into account the temperature in service condition, to be taken equal to:

- $C_\theta = 1$ when the joint is tested in laboratory with the min/max temperature provided in service
- $C_\theta = 1,2$ when the mechanical characteristics of the joint at the min/max temperature provided in service are deduced from technical data sheets submitted by the adhesive supplier.

C_b : Factor taking into account the type of failure:

- $C_b = 1,0$ for ductile failure
- $C_b = 1,15$ for brittle failure or in absence of justification

In order to determine if the failure is brittle or ductile, a guidance is provided in App 3

When predicted failure load is determined by using a Finite Element Model in method B, SF can be reduced by 10%.

4 Specific cases

4.1 Creep

4.1.1 Creep may happen in bonded assemblies subjected to sustained loads, with duration above a few hours. One shall differentiate the relaxation phenomenon from creep phenomenon.

Relaxation will tend to lower and smoothen the stress concentrations, while creep will lead to large deformations and failure of the joint.

Bonded assemblies that sustain a long term load are very prone to creep as a bonded support under permanent gravity tensile or shear load. Bonded assembly design where stress redistribution is possible (with a peak stress on the edge and no stress in the central area of the assembly) might be less sensitive to creep due to relaxation.

Creep characterisation of the adhesive may demonstrate that the assembly is able to sustain the maximum duration of the loads:

- at the level of loading of the adhesive in the assembly (accounting for safety factors)
- at the maximum temperature of the design range.

If bonded assembly is prone to creep (long duration, isostatic, low redistribution possibilities, high temperature), representative tests shall be defined to demonstrate the creep strength of the actual device. Testing temperature and load might be increased in order to shorten the test duration. However, the design duration is to be demonstrated as validated. Time-temperature equivalence can be used in such objective. Test conditions are to be agreed with the Society.

4.2 Fatigue

4.2.1 For Q4 qualification level, if adhesive joint is subjected to high number of cyclic load, or when deemed necessary by the Society, fatigue analysis of the bonded assembly, based on recognised method, is to be submitted for examination, or full scale testing may be required.

As a guidance, two main methodologies are detailed in App 5:

- S-N curves fatigue analysis, or other damage accumulation assessment
- full scale representative test validation.

The validation by full scale test requires to manufacture specimens at full scale representing a part of the assembly which is critical for the fatigue loading. The manufacturing process, material and design is to be representative of the actual design and construction. The loading histogram applicable to the bonded assembly is to be submitted to the Society.

Section 5 Manufacturing of bonded assemblies

1 General

1.1 Application

1.1.1 The purpose of this Section is to specify requirements for manufacturing of bonded assembly within the scope of this Rule Note.

Methodology review and surveys of bonded assemblies are in accordance with survey mode performed on the structure or equipment subject to this kind of assembly.

2 Shipyard/manufacturer quality system for bonding and BV preliminary survey

2.1 General

2.1.1 The shipyard/manufacturer preliminary survey aims at assessing that the general requirements for manufacturing bonding assemblies are satisfied. The application for this preliminary survey is to be made by the shipyard/manufacturer. For composite shipyards/manufacturer, when a shipyard/manufacturer preliminary survey has been performed for composite parts survey for bonding process is included.as per described in NR546, Sec 12, [5].

2.1.2 As a rule, the shipyard/manufacturer appoints a Bonding Coordinator who is the person responsible for the supervision and the coordination of all bonding activities at the shipyard/manufacturer's. He is the main contact of the Society and ensures the quality of bonding operations.

2.2 Documentation review stage

2.2.1 The shipyard/manufacturer is to submit the relevant quality system documentation, as per Tab 1, covering the following items:

- general shipyard/manufacturer's organization and specific facilities for bonding operation
- quality system and traceability management
- personnel skills and qualification in bonding
- previous shipyard/manufacturer's experience in bonding relevant for the application.

Any other necessary informations on shipyard/manufacturer installation or manufacturing process specificities are to be submitted to the Society.

At preliminary stage, influential manufacturing parameters may be only partially defined. However, the following main characteristics are to be submitted to the Society:

- manufacturing tolerances
- environment of manufacturing
- temperature and range of estimated relative humidity during manufacturing (climate-controlled workshop, open shed…)
- curing cycle of adhesive and associated means of control
- process of adhesive application
- foreseen level of automation of adhesive application
- adhesive pot life
- adhesive working life
- post curing requirements.

2.3 Quality system

2.3.1 The Quality system implemented by the shipyard/manufacturer is to be documented. Quality system documentation is to define shipyard/manufacturer quality policy, its organisation and responsibilities. It also stipulates practice means and the sequence of activities involved in bonding in order to ensure the level of quality that the yard has set itself. Those documents must include the information required in Tab 1 and in NR320 Certification Scheme of material and equipment, as amended.

The Bonding Coordinator will ensure the quality assurance system.

Table 1 : Quality documentation to be submitted

General shipyard/manufacturer's organization and specific facilities for bonding operation	Shipyard/manufacturer references: name, address, size and distribution of workforce (e.g. design office, production work staff…)
	Production capacity (total number of assemblies already built, number of units per year, number of types, sizes)
	Shipyard/manufacturer lay-out showing area assigned to different material preparation, storage site for raw materials (adhesives and all bonded related material, substrate …), assembly / bonding unit and hull construction operations and organizational links among them
	Existing equipment related to bonding (process tooling, control and testing equipment, NDT…)
Quality system / traceability management Shipyard/manufacturer quality policy (existence of a quality system / ISO certification or equivalent)	Shipyard/manufacturer organization
	Document control management
	Purchasing management
	Material, products, equipment identification and traceability management
	Production means and process control management
	Inspection, measuring and test equipment management
	Handling of non-conformity
	Corrective and preventive action
	Internal quality audit
Personnel skills and qualification in bonding	Shipyard/manufacturer's personnel training policy
	Identification of Shipyard/manufacturer's bonding coordinator and shipyard bonding operator
	Specific qualification in adhesive technology of shipyard/manufacturer's personnel (e.g. certification EWF adhesive bonder / specialist / engineer or equivalent qualification level)
	Training program from adhesive's supplier
Previous shipyard's experience in bonding	Compilation, as exhaustive as possible of bonding applications carried out previously by the shipyard/manufacturer describing type of adhesive used, surface preparation and bonding process
	Operating feedback of bonding applications in service

2.4 Survey on site

2.4.1 On-site survey is carried out by the Society to review the implementation of the quality system documentation.

2.5 Shipyard/Manufacturer survey report

2.5.1 Upon completion of the survey, a report is issued by the Society to conclude on the survey results with or without comments. Alternatively, the preliminary survey results may be included in existing classification processes (manufacturer's recognition schemes or shipyard review reports).

3 Manufacturing, Testing and Inspection Bonding Plan (MTI Bonding Plan)

3.1 General

3.1.1 The MTI bonding plan is to describe the process steps and parameters to be checked by shipyard/manufacturer (from adhesives purchase, storage, substrate preparation, to adhesive application and final assembly) during bonding operations involved in a product surveyed by BV for classification purpose.

This plan is to describe:

- examination and tests to be carried out before, during and after bonding operations
- the role of stakeholders, including the Society's interventions, at each step (e.g. Review, Witness, Hold)
- procedures or instructions to be complied with
- acceptability criteria

The MTI bonding plan is to be submitted to the Society for review.

3.2 Type of MTI bonding plan

3.2.1 The MTI bonding plan may be adapted in accordance with qualification level. For low qualification levels, Q1 and Q2, a simplified MTI bonding plan may be accepted, based on previous shipyard/manufacturer experience for similar applications. Such arrangement is subject to prior agreement by the Society.

As a rule, an MTI bonding plan is drawn up for each different type of bonding application in each ship under Society's survey within the scope of this present Rule note.

However, single MTI bonding plans may be established in order to gather similar bonding applications in one or different ships. In this case, the MTI bonding plan must contain any specific procedures that have to be respected according to each type of bonding application.

3.3 Content of MTI Bonding Plan

3.3.1 The typical content of the MTI Bonding Plan is detailed in App 6.

4 Bonding Manufacturing

4.1 General

4.1.1 Manufacturing of bonded assembly is to be performed in line with the MTI bonding plan.

4.1.2 It is the responsibility of the shipyard/manufacturer to ensure that effective process and production controls are adhered to in operation to achieve the bonding according to the bonding assembly design file and the qualified bonding specification.

4.2 Traceability

4.2.1 Shipyard/Manufacturer procedure is to ensure traceability on the following aspects:

- Material:

  Data to ensure traceability of raw materials and equipment covered by Rule Note from purchase to final use / fitting on a vessel (see also Article [3]).
- Process:

  Data to ensure traceability of production means describing different steps such as inspection or recording, during the production.
- Recording of environmental conditions.

4.3 Bonding process

4.3.1 In addition to the information provided through steps described the MTI bonding plan in App 6, [3], special care should be taken by Shipyard/manufacturer on surface preparation, adhesive preparation application and assembly, final control, non-destructive tests and testing.

4.3.2 Surface preparation

The surface preparation is to be according to the specification of the adhesive supplier specification. Any deviation will be subject to agreement of the Society and adhesive supplier. Batch number of product used for preparation purposes such as cleaner, degreasing agent, which may interfere with bonding are to be recorded in the traceability file.

As a rule, preparation of bonding surface consists of the following iterative phases:

- cleaning and degreasing
- surface abrasion
- cleaning and degreasing.

Appropriate means for preparing surfaces of substrate are to be used prior to bonding. Supplementary information is given in App 7.

Checks during and after surface preparation are to be performed. Surface preparation may be tested according to one of the following methods:

- Method 1 - Wettability - NF EN 828:2013

  Determination by measurement of contact angle and critical surface tension of solid surface.
- Method 2 - Wetting Tension - ASTM D2578-23

  Standard test method for wetting tension.
- Method 3 - Pull test:

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

4.3.3 Adhesive preparation, application and assembly

Process parameters are to be controlled and traced and are subject to the issuance of a written procedure that is detailed in App 7.

Preparation and application of bonding adhesives are to be performed in accordance with the MTI bonding plan with focus on the following aspects to be checked:

- humidity and temperature records from preparation to application of adhesives. Records are to be kept for traceability purpose
- procedures for dosing, preparing, and mixing the adhesive are to be documented. Each prepared adhesive is to be recorded with its batch number on an accompanying data-sheet for traceability purpose
- matching pot life with procedure written in the MTI bonding plan. If several batch numbers of adhesives are used, a layout plan showing position of batch is to be annexed in the traceability file
- positioning: perimeter of adhesive application area is to be clearly delimited on the substrate
- means of dispensing of adhesive are to be in accordance with the validated Bonding Specification and the MTI bonding plan
- assembly performed in accordance with procedure describe in the MTI bonding plan in App 6, [3.6].

4.3.4 Final Control

Once bonded assembly is cured, checks are to be carried out in accordance with the MTI bonding plan. Final checks may be based on a combination of tests among which there will be:

- metrology
- non-destructive tests
- testing.

4.3.5 Non-destructive tests

Non-Destructive Tests (NDT) are to be performed in order to confirm that bonding manufacturing process has not produced defects which could impair the structural integrity.

A specification booklet is to be issued by shipyard/manufacturer and submitted to Society containing following details:

- tested pieces
- calibration
- means of tests (see Tab 2) and operator qualification
- testing procedure and report
- list and description of searched non conformities/defects (see Tab 3)
- acceptance criteria.

Defects which are not detectable should be prevented by alternative and suitable quality control methods.

A special attention is to be drawn at the design stage to ensure accessibility of inspection equipment.

4.3.6 Testing

Controls are to be carried out in accordance with MTI bonding plan and bonding specification.

Table 2 : NDT methods

NDT methods	
Visual inspection	First NDT method to implement prior any other methods Highlight of surface defects (cracks / disbond), lack / excess of adhesive
Taping	Analysis of the acoustic response of a material to a mechanical shock • manual or automated methods • highlighted of large volume defects (few mm)
Ultrasonic	Based on the principle of ultrasonic wave propagation (emission / reception) Highlight of small volume defects
Acoustic emission	Acoustic analysis of the tested component response by mechanical straining
Mechanical Impedance	Various methods where the structure is excited with relatively low frequency mechanical vibrations and its response to these excitations is measured
Radiography	An image is formed following differential absorption of X-ray energy by elements present in the component Enables the volumetric inspection of components
Thermography	Heating of the element to check / Analysis of emitted temperature • any discontinuities affect the rate of heat conduction • highlight of medium volume defects

Table 3 : Type of defects probable cause

Defects type	Main probable cause
Porosity	Loss of volatile product, occurrence of gas bubble, insufficient pressure during curing of adhesive
Voids or cavities	Concentration of porosity, lack of adhesive during application
Debonds between substrates and adhesive	Poor surface preparation, occurrence of solid form contaminant as grit, swarf, or peel ply…
Poor adhesive polymerisation	Homogeneous adhesive (poor mixing), non-respect of curing specifications of adhesive (time, temperature)
Cracks	High thermal stress not controlled during curing of adhesive
Inclusion	Forgotten foreign body not specified in the manufacturing process.

5 Bonder qualification

5.1 General

5.1.1 Bonded assemblies are to be performed by qualified personnel. A list of qualified bonders and their training records are to be made available to the surveyor on request.

For automated bonded assembly, the qualification of the process ensuring consistent quality is to be carried out on a case by case basis by the Society.

Appendix 1 Bonding Specification Detailed Items

1 General

1.1

1.1.1 A list of items to be addressed in the bonding specification is provided in Tab 1.

Table 1 : Bonding specification detailed items

No.	Items	Comments
1	Description of the considered assembly	General arrangement / Principle scheme
2	Application and function of the assembly	Loads transfer or sealing only
3	Location of the bonded assembly on-board	Location inboard, outboard, AC space, machinery space, etc In service environmental conditions of the assembly Temperature, humidity, immersion, UV, chemicals agent exposition Maximum, minimum, average, peak values Type of exposition (permanent, variable, intermittent...) Location on-board subject to Fire safety requirements Accessibility for survey and in service survey
4	Loads to be withstood by the assembly	Loading nature: shear / tensile / compressive / bending / torsion / peeling Load type: static, dynamic, permanent, variable, intermittent. fatigue / vibration / shocks Load intensity: Min, Max, frequency Creep behaviour to consider
5	Bonded assembly maturity	Availability of operating feedback of similar bonding applications in service shipyard/manufacturer experience 1, 2 or 3, defined in Sec 2
6	Safety class	SC1, SC2 or SC3, defined in Sec 2
7	Qualification requirements level	Q1, Q2, Q3, Q4 or Q5, defined in Sec 2
8	Characteristics of the adhesive	Adhesive's form: films, pastes, one component / multi components adhesive Rigid or flexible adhesive Gap filling properties Adhesive storage consideration Adhesive pot life
9	Surface condition of materials to be assembled	Polluted surface, coated surface, flatness, roughness Possibility of cleaning the surfaces before bonding Possibility to carry out a surface preparation prior to bonding Mechanical or chemical surface preparation Possibility of applying a primer or adhesion promoter prior to bonding
10	Production process and limitations	Methods for adhesive application: Manual, automatic Surface to be bonded Variability in the thickness of the bonded assembly Adhesive curing mode consideration (T°, H%, pressure, curing time...) Pressure applied during curing Tool used to maintain for assembly
11	Bonder qualification	Specific training program
12	Operation after curing that could impair bonding application	Machining / handling / storage / transport Other environmental conditions and/or mechanical loading to consider
13	Location of the bonding operation	In dedicated shipyard's area, outdoor, in board… Controlled atmosphere (T°, H%, dust…) / non controlled atmosphere

Appendix 2 For Information only - Adhesives and Polymers Generalities

1 Adhesive materials

1.1 General

1.1.1 A large number and variety of adhesives have been developed by manufacturers to provide solutions for joining a wide variety of materials. Therefore, it should be understood that no universal adhesive exists.

Adhesive materials are not to be considered alone but as part of an adhesive system where final mechanical characteristics of the assembly depend on the following parameters:

- type of adhesive family
- type of the components to be bonded as well as their surface preparation
- geometry and thickness of the bonded assembly
- curing process of the bonded assembly.

Adhesives are generally divided in two categories as:

- structural, where load-bearing properties are needed
- non-structural or semi structural used for low load-bearing applications. Potting materials and sealants material are also included in this class.

Other categorisation could be considered for adhesives as:

- the curing mode like reaction adhesives, solvent adhesives or melt adhesives
- the strain capability of the joint after curing (rigid, flexible)
- the adhesive form: film, liquid, paste, single or two components
- the chemical family of the adhesive, even if it should be noted that some hybrid products exist, sharing properties of different polymer families.

It is the latter categorisation which was retained in this note with following main families:

- epoxy-based adhesives
- polyurethane-based adhesives
- acrylic-based adhesives
- silicon
- MS polymer (Modified Silane polymer)
- others.

2 Adhesive families

2.1 General

2.1.1 Tab 1 gives general information about the main adhesives generally used in marine environment in order to ensure a permanent connection between substrates.

Other families like polyester, vinylester or phenolic adhesives with properties similar to resin used in composite building could be considered.

3 Adhesive properties

3.1 General

3.1.1 For general guidance only, some adhesive's properties are described in:

- Tab 2 for epoxy-based adhesives
- Tab 3 for Polyurethane-based adhesives
- Tab 4 for Silicon and MS Polymer
- Tab 5 for Acrylic and Anaerobic.

Table 1 : Adhesive families

Adhesive families	Main features
Epoxy-based adhesives	• this thermoset family is one of the most common and one of the most efficient in the range of structural adhesives • rigid bond and strong mechanical properties depending on formulation (mainly hardener type) and curing mode • available in single, two components or film form • good adhesion to many different substrates (composite, metallic substrates, wood…).
Polyurethane-based adhesives	• large family with different properties • flexible or semi flexible bond with moderate mechanical properties depending on product form (single, two components or melt).
Acrylic-based adhesives	• very large family with very different properties. They could be thermoset or thermoplastic polymers • structural acrylic adhesives are thermosets with two main sub-families: - modified acrylic range (basic polymethylmethacrylate resin grafted with elastomers) - anaerobic adhesives mainly used for fastener locking braking applications of threaded metallic pieces and metallic cylindrical assembly.
Silicone adhesives	• family characterised by basic poly-siloxane structure (Si-C and Si-O linkage) which is responsible for their unusual combination of organic and inorganic chemical properties • used primarily as elastomeric adhesives and sealants, silicone adhesives are now known for their ability to withstand large variations in temperature and to resist to UV • different curing mode as poly-condensation (RTV: Room Temperature Vulcanizing) or poly-addition (HTV: High Temperature Vulcanizing).
MS polymer	• MS Polymer is Modified Silane polymer which represents a compromise between the polyurethanes and the silicones • single component curing mode: after applying, curing at room temperature with air humidity • two components curing mode: mixing of single component and activator.

Table 2 : Adhesive properties - Epoxy

Properties	Epoxy-based adhesives		
Form available	Single component: Pastes or liquids	Two components: Pastes or liquids	Film supported (fabrics, frames which allowed thickness calibration) / Film Unsupported (no thickness calibration)
Hardening mode	Adhesive in liquid or paste form and already contains the hardener which reacts by the action of heat (T° from 100°C to 200°C)	Mixing a base and a hardener which hardens at room temperature (or accelerated by heating cycle)	• Similar to the chemistry of single component epoxy • Curing cycle conveniently performed in an autoclave or oven + vacuum (T° from 90°C to 180°C and pressure from 1 to 7 bars, vacuum up to –0,9 bars)
Parameters influencing the hardening	Temperature	• Temperature • Component ratio • Quantity mixed	• Temperature • Pressure
Handling time		Few minutes to few hours at RT	
Complete hardening time	Few minutes to few hours	Few hours by heating cycle to several days at RT	Few minutes to few hours
Service temperature	–75°C to + 150°C	–75°C to + 120°C	–75°C to + 220°C
Shear strength	20 to 35 MPa	15 to 30 MPa	25 to 45 MPa
Joint flexibility	Rigid (strain < 5%)	Rigid (strain from 5 to 10%)	Rigid (strain < 5%)
Peel strength	2 to 10 N/mm	2 to 10 N/mm	2 to 15 N/mm
Optimum joint thickness	0,05 to 1 mm	0,05 to 1mm	0,1 to 0,2 mm
Maximum Joint thickness	Few mm	Few mm	0,5 mm
Viscosity	5000 to 1000000 mPa.s	2000 to 1000000 mPa.s	
Note 1: The values given in this table are for general guidance only **Note 2:** T° = temperature, RT = Room temperature			

Properties	Epoxy-based adhesives		
Form available	Single component: Pastes or liquids	Two components: Pastes or liquids	Film supported (fabrics, frames which allowed thickness calibration) / Film Unsupported (no thickness calibration)
Advantages	• High mechanical strength • Hardening time • No mixing temperature • Environment and chemical agents resistance	• High mechanical strength • Hardening at RT • Environment and chemical agents resistance • Gap filing properties	• High mechanical strength • Very low shrinkage • Thermal strength
Disadvantages	• Hardening by heating (> 100°C) • Risk of allergies • Storage at T° < 20 °C	• Hardening time • Harmfulness of some hardener	• Hardening by autoclave or oven + vacuum • Risk of allergies • Storage to T° < –20°C • Cutting time
Applications	Structural	Structural	Structural
Note 1: The values given in this table are for general guidance only **Note 2:** T° = temperature, RT = Room temperature			

Table 3 : Adhesive properties - Polyurethane

Properties	Polyurethane-based adhesives		
Form available	Single component Pastes	Two components: Pastes or liquids	Melt polyurethane solid (Granules, sticks.)
Hardening mode	At RT, pasty adhesive which hardens by the action of humidity in the air after application	Mixing a base and a hardener which hardens by heating or at RT after application	By heating the adhesive becomes liquid. After application and cooling, the adhesive becomes solid and hardens under the action of air humidity
Parameters influencing the hardening	• Air humidity • Temperature • Adhesive joint width	• Temperature • Component ratio • Quantity mixed	• Air humidity • Temperature
Handling time	Few hours at RT	Few minutes to few hours at RT	Few seconds to few minutes at RT
Complete hardening time	Several days at RT	Several days at RT	Several days at RT
Service temperature	- 70°C to + 90°C	- 50°C to + 100°C	- 50°C to + 100°C
Shear strength	1 to 5 MPa	5 to 15 MPa	5 to 15 MPa
Joint flexibility	Very flexible (strain > 200%)	Flexible (strain from 30 to 200%)	Very flexible (strain > 300%)
Peel strength	4 to 15 N/mm	5 to 15 N/mm	5 to 15 N/mm
Optimum joint thickness	0,5 to 5 mm	0,5 to 3 mm	0,1 to 1 mm
Maximum Joint thickness	Few mm	Few mm	Few mm
Viscosity	>1000000 mPa.s	5000 to 1000000 mPa.s	
Advantages	• No mixing • Hardening at RT • Joint flexibility • Gap filing properties	• Hardening at RT • Joint flexibility • Mechanical strength	• Handling time • Joint flexibility • Mechanical strength
Disadvantages	• Hardening time • Storage • UV resistance • Harmfulness of iso cyanate • Do not allow bonding large surfaces	• Harmfulness of iso cyanate • Components mixing	• Store away from humidity • Harmfulness of iso cyanate • Do not allow bonding large surfaces
Applications	Sealant / semi structural / glazing	Semi structural / structural	Semi structural / structural
Note 1: The values given in this table are for general guidance only **Note 2:** T° = temperature, RT = Room temperature			

Table 4 : Adhesive properties - Silicone and MS Polymer

Properties	Silicone	MS Polymer
Form available	Single or two components	Single or two components
Hardening mode	• For RTV silicone, by poly-condensation at RT and with air humidity (could be accelerated by heat T°<80°C) • For HTV silicone, by poly-addition with heating cycle (T° from 120°C to 200°C)	• For single component, at RT and with air humidity (could be accelerated by heating T°<80°C) • For two components, at RT after mixing (could be accelerated by heating T°<80°C)
Parameters influencing the hardening	• Temperature • Air humidity	• Temperature • Air humidity
Handling time	• Few minutes to few hours for RTV silicone • Few minutes to 1 hour for HTV silicone	• Few hours for single component • Few minutes to 1 hour for two components
Complete hardening time	• Several days for RTV silicone • 30 minutes to 1 hours for HTV silicone	Several days for single component
Service temperature	- 75°C to + 250°C	- 40°C to + 100°C
Shear strength	0,5 to 4 MPa	1 to 4 MPa
Joint flexibility	Very flexible (strain > 200%)	Very flexible (strain > 100%)
Peel strength	5 to 15 N /mm	4 to 15 N /mm
Optimum joint thickness	0,5 to 5 mm	0,5 to 5 mm
Maximum Joint thickness	Few mm	Few mm
Viscosity	• >1000000 mPa.s for single component • 3000 to 350000 mPa.s for two components	>1000000 mPa.s
Advantages	Thermal resistance	• Joint flexibility • Tolerance to the surface cleanness • UV resistance paintable seal
Disadvantages	• Metallic corrosion for single component with acetic base • Hardening time	Hardening time
Applications	Sealant / semi structural / glazing	Sealant / semi structural / glazing
Note 1: The values given in this table are for general guidance only **Note 2:** T° = temperature, RT = Room temperature		

Table 5 : Adhesive properties - Acrylic and Anaerobic

Properties	Acrylic-based adhesives	Anaerobic adhesives
Form available	Two components or “No-mix”	Single component liquid
Hardening mode	• For two components, at RT after mixing base and hardener (could be accelerated by heating T°<80°C) • For no mix, at RT, hardening by contact further application of the base on one face and activator on the other face (could be accelerated by heating T°<80°C)	• Hardening at RT, without oxygen and only on metallic surface (catalytic effect of metal ions). Could be accelerated by accelerator or heated T°<100°C)
Parameters influencing the hardening	Temperature	• Temperature • Joint thickness • Metal type
Handling time	Few minutes at RT	Few minutes
Complete hardening time	Few hours at RT	Few hours
Service temperature	- 40°C to + 120°C	- 50°C to + 150°C
Shear strength	15 to 30 MPa	10 to 30 MPa
Note 1: The values given in this table are for general guidance only **Note 2:** T° = temperature, RT = Room temperature		

Properties	Acrylic-based adhesives	Anaerobic adhesives
Joint flexibility	Flexible (strain from 30 to 150%)	Rigid (strain from 5 to 10%)
Peel strength	5 to 10 N / mm	Low
Optimum joint thickness	0,5 to 1mm	< 0,1mm
Maximum Joint thickness	0,3 mm (No-mix) to few mm (two components)	0,2mm
Viscosity	5000 to 500000 mPa.s	50 to 3000 mPa.s
Advantages	• Mechanical strength • Hardening time at RT • Gap filing properties for two components • Tolerance to the surface cleanness	• Mechanical strength • Hardening time at RT
Disadvantages	Strong odour	• Thin joint • Need metal ions
Applications	Structural	Structural / metallic fastener locking
Note 1: The values given in this table are for general guidance only **Note 2:** T° = temperature, RT = Room temperature		

4 Basic knowledge on polymers

4.1 General

4.1.1 Scope

This Article gives an overview of the main features of the polymers. Indeed, all adhesives considered in the present Note are part of the family of polymeric materials.

Compared to metallic materials, the mechanical behaviour of polymers is much more complex. This is due to the variety of constituent structures of these materials on the one hand but also of behaviour's diversity of one same material according to its terms of use on the other hand.

4.2 Polymer microstructure

4.2.1 General

Polymers consist of long chains of molecules: macromolecular chains. These macromolecules are composed of one or several chemical units (monomers) that are repeated throughout the chain of the polymer. Polymers mechanical behaviour will depend on how macromolecular chains are linked together and their arrangement. Polymers always contain some various additives, plasticizers, mineral charges… in order to modify their initial properties or to facilitate their implementation. According to their microstructure, polymers can classically be classified in 3 different classes: Thermosets, Elastomers and Thermoplastics.

4.2.2 Thermosets

Thermosets consist of macromolecular chains which are linked together by nodes with high energy forces (covalent type) created during polymerization. They form a 3D network where the chains are disordered (amorphous structure) and have very little mobility.

Because of this cross-linked structure, thermosets are rigid and they cannot melt. As a rule, structural adhesives are thermoset polymers (e.g. epoxy).

4.2.3 Elastomers

The elastomers are constituted of linear chains linked together by more spaced nodes than for thermoset polymers and which forms an amorphous structure.

Because of this arrangement, the elastomers have a very high deformation capacity. They do not melt but soften with heat. As a rule, elastomers are non-structural adhesives (e.g. MS polymer or silicone) and mainly used for sealant application.

4.2.4 Thermoplastics

Thermoplastic materials are made of macromolecular chains (linear or branched) that are tangled and linked together by weak energy forces (van der Waals forces or hydrogen type).

Thermoplastics materials can take different microstructure: amorphous structure only or semi-crystalline structure with coexistence of amorphous and crystalline phases in varying proportions. In amorphous structure, polymer chains are disordered.

This type of microstructure does not melt but softened with heat. In crystal structure, polymer chains acquire an ordered structure. This type of microstructure melts with heat.

Typical example of thermoplastic adhesives are those called “hot-melts” and which are used in packaging. As a rule, thermoplastic adhesives are non-structural and with very few applications in shipbuilding.

4.2.5 Adhesives and polymers

The polymers microstructure of the main adhesive families is indicated in Tab 6.

It should be noted that due to the possible large variety of formulation and the existence of hybrid products, some adhesives may contain phases whose microstructure belongs to one or the other type of polymer (e.g. epoxy adhesive which contain elastomer phases in order to provide a greater toughness).

Table 6 : Adhesive class

Thermoset	Elastomers	Thermoplastics
Epoxy, polyester, vinylester adhesives Anaerobic adhesives Some Polyurethane adhesives Some Acrylic-based adhesives	Silicone adhesives MS Polymer adhesives Some polyurethane adhesives	Some Polyurethane adhesives Some Acrylic-based adhesives

4.3 Polymer basic mechanical behaviour

4.3.1 Mechanical behaviour of polymers

The mechanical behaviour of polymers is characterised by a very high apparent diversity.

The main parameters that can affect the mechanical behaviour of polymers are:

- type of microstructure polymer (see [4.2])
- temperature (see [4.4])
- loading time / loading speed / loading frequency
- others: high pressure, environment (moisture mainly).

4.3.2 Visco-elastic behaviour of polymers

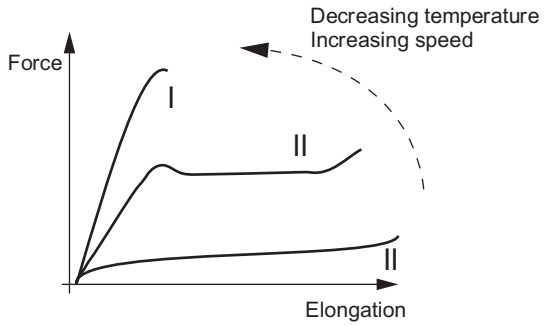
Due to its macromolecular nature, polymer exhibits a visco-elastic behaviour. Visco-elastic behaviour is an intermediate behaviour between an elastic response and viscous response and characterised by a time/temperature dependence.

When a load is applied to the material, chains will be able to stretch and to slide relatively to each other. The higher the temperature or the lower the strain rate, the more chains will be able to slide relatively to each other. The stretching of the molecular network gives the elastic response of the material that does not depend on time or temperature. The sliding of the chain gives the viscous behaviour of the material. Increasing the strain rate or decreasing the temperature prevents the sliding of the chains and the stiffness of the material is increased.

These effects depend on the nature of the macromolecular arrangement. The elastic behaviour of polymer is preponderant when chains are highly cross-linked as for thermoset. The viscous behaviour of polymer is particularly marked for networks weakly or not cross-linked as elastomer or thermoplastic polymers.

Example: Typical evolution of polymers tensile behaviour according to the temperature or the speed of traction, see Fig 1.

Figure 1 : Typical evolution of polymers tensile behaviour according to the temperature or the speed of traction



- Curve n°I: rigid / brittle behaviour:

  This behaviour may be considered characteristic for thermoset highly cross-linked or others polymers at high speed or low temperature. Mechanical behaviour is mainly elastic type, more or less linear, and characterised by high modulus and low deformation capacity.

- Curve n°II: ductile behaviour:

  Mechanical behaviour more or less ductile (plastic deformation may be possible).

  This behaviour may be considered characteristic for semi-crystalline thermoplastics and for amorphous thermoplastics at intermediate temperature and speed.

- Curve n°III: rubbery behaviour:

  This behaviour may be considered characteristic for elastomers and for amorphous thermoplastics at high temperature or low speed. Mechanical behaviour is hyperelastic type and generally highly nonlinear.

4.4 Temperature effect on polymers

4.4.1 Glass transition temperature

Polymers exist in different states according to the temperature where they are used, see Fig 2.

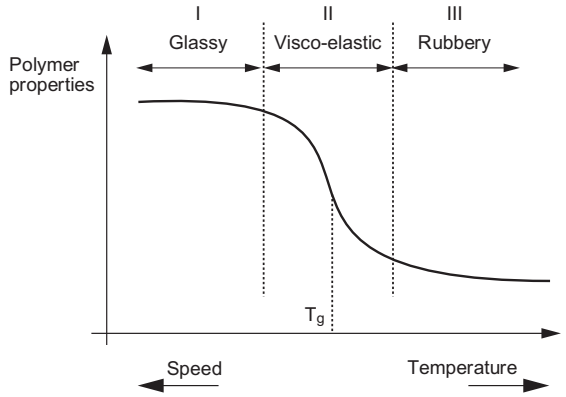
At low temperatures, the mobility of polymer chains is limited. When temperature increases, chains movement become possible according to the polymer nature. Mechanical properties may then evolve more or less abruptly in a gap where is defined the glass transition temperature (T_g).

T_g is one of the most important features that define a polymer. In this gap, polymers change from a glassy state to a rubbery state, with a visco-elastic type behaviour.

T_g only relates to amorphous microstructure (thermosets and elastomers) or amorphous phases of the semi-crystalline thermoplastics.

When passing this transition, the module can for example decrease by a factor 10 for thermosets or 1000 for some elastomers.

Figure 2 : Polymer properties vs speed and temperature



Two test means commonly used to measure the glass transition temperature are DSC (Differential Scanning Calorimetry) and DMA (Dynamic Mechanical Analysis). When T_g is measured, it is necessary to indicate the reference of the test method, since the measured value of T_g may vary from one method to another.

For thermosets, the more polymerized is the polymer, i.e. the greater is the number of chemical links between macromolecules chains, the higher is the value of T_g.

The glass transition temperature may be elevated using curing process at elevated temperature.

The glass transition temperature can be significantly reduced by moisture absorption.

4.4.2 Glassy state

All polymers in this glassy state are solid and their behaviour is more or less rigid and brittle.

In glassy state, mechanical behaviour is mainly elastic type characterised by high modulus and low deformation capacity.

Thermosets are mainly used in their glassy state as their T_g is above the room temperature.

Polymers properties are more or less stable in glassy state but some secondary transitions may modify chains arrangement which can slightly affect some polymers mechanical properties.

4.4.3 Rubbery state

In rubbery state, polymers are characterised by a low modulus and a high deformation capacity.

Elastomers are mainly used in their rubbery state as their T_g is below the room temperature.

Amorphous microstructures (thermosets and elastomers) cannot melt if temperature increases but they decompose with heat. Only crystal phases of thermoplastics can melt.

4.5 Ageing of polymers and bonded assemblies

4.5.1 General

In marine environment, polymers may degrade under the effect of the oxygen in the air, UV rays, temperature, water or other solvents and mechanical stress.

Assessment of bonded assemblies ageing involves knowledge of particularly complex phenomenon. Different mechanisms can interact with each other, each with their own kinetic. Furthermore, these mechanisms may be reversible or not.

4.5.2 Moisture influence

Moisture is the main factor that decreases bonded assembly strength. The different mechanisms that can appear may be:

- Plasticization of the adhesive (reversible phenomenon): the water that has penetrated the polymer network can bind onto hydrophilic sites of the macromolecular chains and break the bonds between chains or the chain itself. This causes an increase in the mobility of the chains and may decrease the glass transition temperature. Plasticization of the adhesive generally leads to a significant decrease in mechanical properties (modulus and breaking strengths) and an increase in ductility.
- Swelling of the adhesive (reversible phenomenon): the breaking of the bonds between the chains results in a loosening of the whole network. This promotes the absorption of new water molecules and an overall swelling of the polymer. For a bonded assembly, the swelling may not be homogeneous and may lead to additional internal stresses.
- Hydrolysis of the adhesive (irreversible phenomenon): this is a chemical degradation reaction induced by water. This results in deep modification of macromolecular chains either by cuts of chains or by creation of new bonds between chains or appearance of degradation products. These phenomena generally operate from the exposed surface to the center of the material, which may result as a heterogeneous character of the ageing through thickness of polymers.
- Interface degradation: the interfacial area is a special area where are established physical or chemical bonds between the polymer and the substrate. Water may condensate in this area by migration from the adhesive and by capillary along the interface. It should be noted that the diffusion of water at the interface is much faster than in the solid adhesive.
- The presence of impurities on the substrate surface and the existence of differential swelling phenomena between the adhesive and the substrate may cause water concentration gradients and a high osmotic pressure between the interface and the adhesive. For metallic substrates, water can degrade the strength of the bonded assemblies through hydration of metal oxyde layers. Corrosion products at the interface are considered a post failure phenomenon. For composite substrates, water can also migrate in the composite itself through the fibres.

For information, distilled water effect is generally considered more severe than fresh water and sea water.

4.5.3 Temperature influence

An increase in temperature activates the diffusion of the water inside the adhesive and promotes the wet ageing and the interfacial degradation of the bonded assembly.

In an environment where the relative humidity is stable, the temperature does not significantly alter the maximum rate of water absorption of an adhesive. The higher the relative humidity in a medium, the higher the rate of water absorption of an adhesive.

Temperature also affects mechanical behaviour of the adhesive as described in Article [3].

4.5.4 Other chemicals influence

Other media as solvent or chemicals (fuel, mineral oil, hydraulic fluid, grease, acid and alkaline solutions, etc…) may have similar influence than water according to the nature of adhesives.

4.5.5 UV influence

Ultraviolet radiations can break macromolecular chains. In almost all bonded assemblies, substrates are opaque. Only the free edges are exposed to light. As the adhesive layer is most of the time thin, influence of UV radiation may be considered negligible.

Only when substrates are transparent (glazing for instance), influence of UV has to be investigated. For such applications, adhesives specially formulated with UV stabilizers are to be selected.

Appendix 3 For Information only - Guidance for Sorting Brittle Joints from Ductile Joints

1 General

1.1 Identification of brittle assembly and ductile assembly

1.1.1 As a guidance, the identification between brittle assembly and ductile assembly might be done as follows:

Evaluation of the characteristic plastic zone length r_p:

$$r_p = \frac{EG_C}{3\pi\sigma_y^2}$$

with :

E : Bulk adhesive modulus in MPa.

G_c : Toughness in mode I of the assembly, or interface in kJ/m² (see Sec 3).

σ_y : Yield stress of the bulk adhesive in tension in MPa;

Note 1: reference: Askarinejad S., Thouless M.D. , Fleck N.A. (2021) Failure of a pre-cracked epoxy sandwich layer in shear - in European Journal of Mechanics - A/Solids Volume 85

As a rule, the yield stress may be determined on the basis of a stress-strain curve as the intersection of a line tangent to the linear elastic region and a line tangent to the non linear plastic region of the curve, as defined in Fig 1. This curve is to be defined taking into account the maximum air temperature provided in service.

A comparison of the characteristic plastic zone length r_p to the thickness of the bonded assembly t_a in mm, is shown in Tab 1.

Figure 1 : Adhesive stress/strain curve

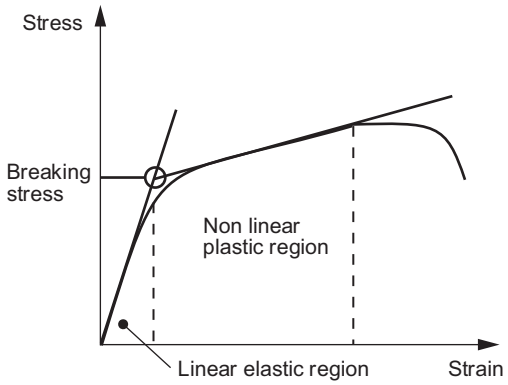


Table 1 : Comparison of the characteristic plastic zone length r_p to the thickness of the bonded assembly t_a in mm

r_p «0,1 t_a	$r_p \equiv 0,1\ t_a$
Assembly should be considered as brittle	Assembly should be considered as ductile
Linear Elastic Fracture Mechanic (LEFM) law is fully available	LEFM law is not applicable or only for large defects
Strength of the joint is driven by the singularities and stress concentrations	Strength is driven by ductility of the adhesive
Specific care is to be provided to master the shape on the edges of the bondline, and discontinuities, and/or edge of the bondline is to be unloaded by design	Shape of the edge is less important, even though it should preferably be smoothen, and constantly manufactured
Assembly will be sensitive to cracks and flaws, protection is to be adapted, specific care is to be taken to avoid defects in loaded areas of the joint	A tolerance in cracks and flaw might be expected

Appendix 4 For Information only - Predicted Failure Loads - Design Methodologies

1 General

1.1 Objective

1.1.1 The objective of this Appendix is to present different design methodologies used for the design assessment of bonded assembly. The design methodology must not be confused with the justification method described in Sec 4 with methods A, B or C where the design load and the failure load are inputs to justify the resistance of the bonded assembly. Here, the design methodology only goal is the predicted failure load as an output.

The design methodology is defined by a combination of a calculation model and a failure criterion.

Note 1: For example, with an analytical model such as Volkersen (identified as the calculation model), it is possible to obtain the distribution of the shear nominal stress in the bondline. However, to identify the failure load, the calculation model is not enough. It must be combined to a failure criterion, for example a maximum shear stress of 20 MPa, to determine the failure load. This failure criterion is usually based on the characterisation part that determines a maximum stress, toughness or strain.

The calculation models will first be described, followed by the failure criteria.

2 Calculation models

2.1 Analytics

2.1.1 Different analytical formulas can be found in the literature (See references in Article [5]). Some of these models are presented in the following sections. The variables used for each model are different as the formalism of the original papers was kept as much as possible.

In general, those models provide a value of the shear stress and in some cases peel stress along the bondline. They take into account the stiffness of the adhesive (shear modulus and thickness), stiffness of the substrates (modulus, thickness,…) in different predefined configuration of the joints. The advantage is to provide for a very little investment an insightful view of the behaviour of the joint nominal stress.

Main drawback is that the configurations are defined in advance, and unless entering into a non-trivial theoretical work, it is not possible to adapt the calculation exactly to each configuration (tapering, scarfed joint, joint edge, varying bondline thickness, etc.). Moreover, they are mostly available in linear domain.

For a ductile assembly, it is relevant to use such approach with a yield stress of the adhesive as limit stress. Adhesive thickness, modulus of the adhesive and yield stress are to be adapted to the design case temperature as per Sec 4.

2.1.2 Average stress model

Regarding single lap joints, the simplest analysis that can be applied considers that the shear stress is constant over the entire bonded surface. For that case, only the shear stress is considered and the substrates are considered as rigid (see Fig 1). For information, this method cannot be applied in method B.

This rigidity involves the adhesive shear stress τ to be constant over the overlap length, and it can be expressed by the equation:

$$\tau(x) = \frac{P}{bc}$$

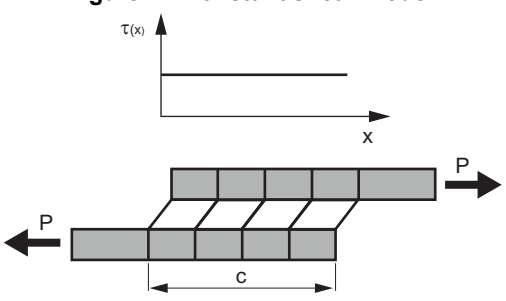
where

P : Load, in N, applied to the substrate

b : Joint width, in mm

c : Overlap length, in mm.

Figure 1 : Constant shear model

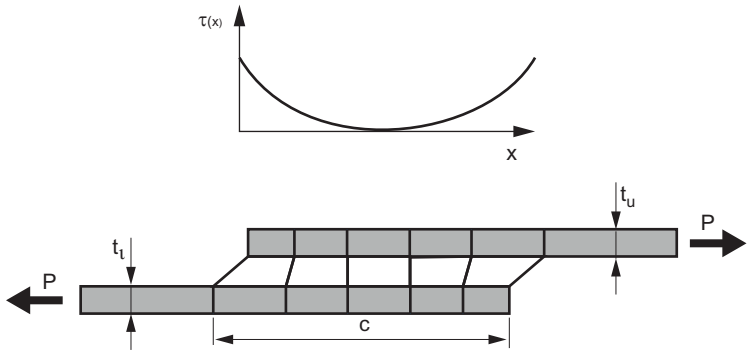


2.1.3 Volkersen Model

From Volkersen (1938), using a 1D model of pure shear (see Fig 2, it assume that the adhesive layer is loaded only in shear and that the substrates follow a purely longitudinal strain. It also assumes that the behaviour of the adhesive is linear elastic.

The shear stress τ, in MPa, in the adhesive is maximum at x = 0, x = c (where c is the overlap length).

Figure 2 : Volkersen's model for the single lap joint



An expression of the shear stress distribution along the adhesive layer can be obtained. For a single lap joint, with the following boundary conditions:

$$\sigma_l(x = 0) = -\frac{P}{bt_l}$$

$$\sigma_l(x = c) = 0$$

$$\sigma_u(x = 0) = 0$$

$$\sigma_u(x = c) = -\frac{P}{bt_u}$$

the unique solution of this expression is given by:

$$\tau(x) = \frac{G_a}{\omega t_a}\frac{P}{bE_l t_l}\left(\frac{\cosh(\omega c)}{\sinh(\omega x)}\left(\cosh(\omega c) + \frac{k_l}{k_u}\right) - \sinh(\omega x)\right)$$

with:

ω : Coefficient, in mm^{-1}, equal to:

$$\omega = \sqrt{\frac{G_a}{t_a}\left(\frac{1}{t_l E_l} + \frac{1}{t_u E_u}\right)}$$

E_u, E_l : Young modulus of the upper and lower substrate, in MPa

G_a : Shear modulus of the adhesive, in MPa

t_u, t_l, t_a : Thicknesses, in mm, of respectively the upper substrate, lower substrate and the adhesive.

k_u, k_l, k_a : Stiffness, in MPa, of respectively the upper substrate, the lower substrate, the adhesive expressed by unit length with:

$$k_u = \frac{t_u E_u}{c}$$

$$k_l = \frac{t_l E_l}{c}$$

$$k_a = \frac{G_a c}{t_a}$$

If the lower and upper substrates have an equivalent stiffness ($k_u = k_l$), the bonded assembly is balanced and a simplified equation is obtained as follow:

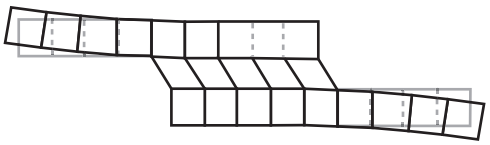
$$\tau(x) = \frac{k_a}{\omega k_l c}\frac{P}{bc}\left(\frac{\cosh(\omega c)(1 + \cosh(\omega c))}{\sinh(\omega x)} - \sinh(\omega x)\right)$$

2.1.4 Goland and Reissner Model

To improve the Volkersen model on the stress analysis of bonded assemblies, Goland and Reissner (1944) proposed another approach, based on plates theory, to express the stress state along the bondline for linear elastic material, including the effect of the bending of the substrate resulting in shear and peel stresses along the bonded length (see Fig 3). Their analysis was only developed for the case of balanced joints (similar top and bottom substrates).

Goland and Reissner model is the first to consider the peel stress as an important phenomenon that can cause the failure of a bonded assembly.

Figure 3 : Deformed state of a single lap joint in the case of the Goland and Reissner model



The single lap joint problem defined by Goland and Reissner is divided into two different studies:

- the analysis of the bending moment and the rotation of the substrates out of the bonded area, following the plate theory
- the analysis of the bonded area.

For the overlap region, the authors obtained two equations, one for the adhesive shear stress, and another one for peel stress distributions:

a) The adhesive shear stress is given by:

$$\frac{\tau(x)}{\tau_s} = -\frac{1}{8}\left[(1+3k)\frac{\delta}{\sinh(\delta)}\left(\cosh\frac{\delta x}{c}\right)+3(1-k)\right]$$

b) The adhesive peel stress distribution is given by:

$$\frac{\sigma_y(x)}{Ft_u}\left(\frac{c}{2}\right)^2 = \frac{1}{\Delta}(A+B)$$

where:

τ_s : Average shear stress, in MPa:

$$\tau_s = \frac{2F}{c}$$

F : Applied tensile load per unit width, in N/mm:

F = P / b

b : Width of the bondline

$$\delta = \frac{c}{t_u}\sqrt{\frac{8G_a t_u}{Et_a}}$$

P : Applied tensile load, in N

c : Overlap length.
Thus, c/2 is the distance from the middle of the bondline to the extremity of the bonded assembly

k : Dimensionless bending moment factor expressed as:

$$k = \frac{\cosh\Lambda}{\cosh\Lambda + 2\sqrt{2}\sinh\Lambda}$$

$$\Lambda = \frac{c}{2t_u}\sqrt{\frac{3F(1-\nu^2)}{2t_u E}}$$

ν : Poisson coefficient of the substrate

$$\Delta = \frac{1}{2}(\sinh(2\lambda)+\sin(2\lambda))$$

$$\lambda = \frac{c}{2t_u}\cdot\sqrt[4]{\frac{6E_a t_u}{E_u t_a}}$$

$$A = \left(K_2\lambda^2\frac{k}{2}+\lambda k'\cosh(\lambda)\cosh(\lambda)\right)\cosh\left(\lambda\frac{2x}{c}\right)\cos\left(\lambda\frac{2x}{c}\right)$$

$$K_2 = \sinh(\lambda)\cos(\lambda)-\cosh(\lambda)\sin(\lambda)$$

k' : Transverse factor equal to:

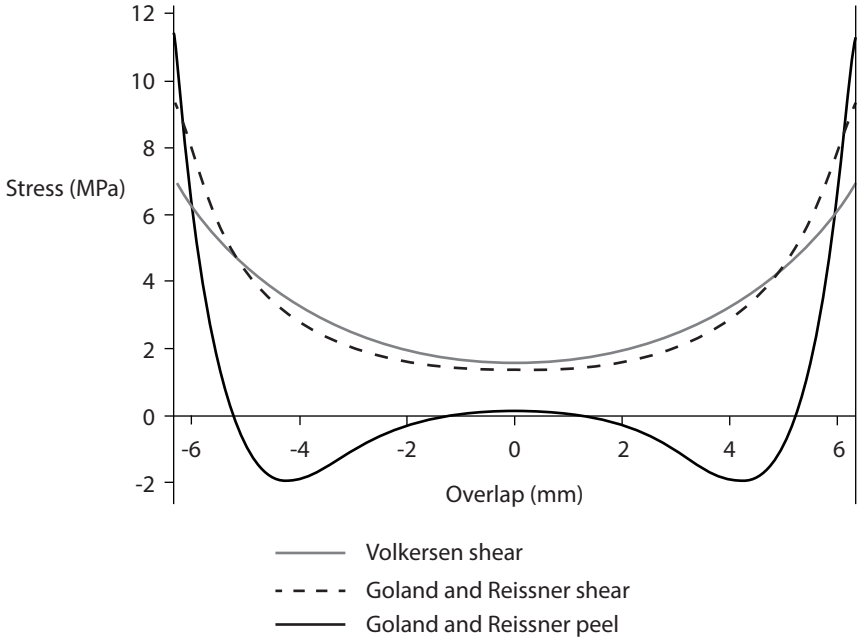
$$k' = kF\sqrt{\frac{3(1-\nu^2)Ft_u}{E_u t_a}}$$

$$B = \left(K_1\lambda^2\frac{k}{2}+\lambda k'\sinh(\lambda)\sin(\lambda)\right)\sinh\left(\lambda\frac{2x}{c}\right)\sin\left(\lambda\frac{2x}{c}\right)$$

$$K_1 = \cosh(\lambda)\sin(\lambda)+\sinh(\lambda)\cos(\lambda)$$

The obtained shear profile is closed to the one from Volkersen. The peel is in tension at the edge and compression in the central part. It is much more complete than the previous model derived from the Volkersen's approach but remains limited to linear elastic adhesives. As it can be seen in Fig 4, the Goland and Reissner model predicts higher adhesive shear stresses at the end of the overlap, mainly because of the peel stresses that cause additional shear stress.

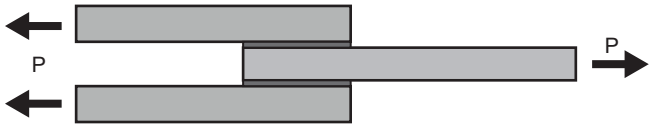
Figure 4 : Stresses predicted by Volkersen, and Goland Reissner models



2.1.5 Hart-Smith model

Hart-Smith (1973) proposed an improvement of the Volkersen's theory including the elasto-plastic (with perfect plasticity) behaviour of the adhesive. As in Volkersen's model, the adhesive is supposed to remain in pure shear strain and the substrates in pure tensile strain. Historically, this development was carried out on symmetric double lap joints (see Fig 5).

Figure 5 : Application case of the Hart-Smith model



Based on these assumptions and equilibrium, two differential nonlinear equations can be obtained:

- one specific equation for the shear stress in the elastic zone, which is the same than the one from Volkersen
- another one for the adhesive shear strain, γ_p in the plastic zone of length:

  $(c-d)/2$

  where:

  d : Plastic zone length, in mm.

As for the Volkersen's model, the expression of the parameter ω remains similar:

$$\omega = \sqrt{\frac{G_a}{t_a}\left(\frac{1}{t_l E_l}+\frac{1}{t_u E_u}\right)}$$

with:

$$\gamma(\xi) = \left(\frac{\omega^2}{2G_a}\right)\tau_p\xi^2 + C\xi + H$$

$$\xi = x - \frac{d}{2}$$

τ_p : Adhesive yield shear stress, in MPa (see Fig 6).

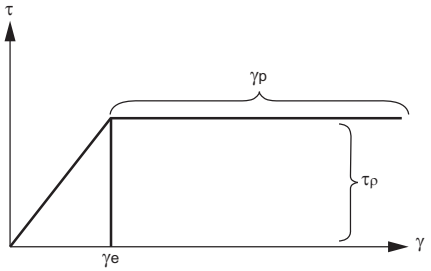
$$C = \frac{\omega\tau_p}{G_a}\tanh\left(\frac{\omega d}{2}\right)$$

$$H = \frac{\tau_p}{G_a} = \gamma_e$$

γ_e : Adhesive elastic shear strain at yield, in MPa

$\gamma_e = \gamma$ at $x = \frac{d}{2}$

Figure 6 : Perfect plastic law of the adhesive



The strain continuity condition and the overall force equilibrium allow obtaining two equations that need to be solved to get access to the final shear stress state:

$$\left(\omega\frac{(c-d)}{2}\tanh\left(\frac{\omega d}{2}\right)\right)^2 = \tanh\left(\frac{\omega d}{2}\right) + 2\frac{\gamma_p}{\gamma_e}$$

$$\gamma_e + \gamma_p = \gamma\left(\xi = \frac{c-d}{2}\right)$$

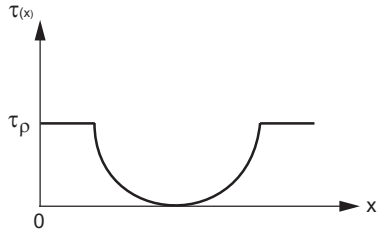
$$\frac{\tau(x)}{\tau_p} = \left(1 - \frac{d}{c}\right) + \frac{\tanh\left(\frac{\omega d}{2}\right)}{\frac{\omega c}{2}}$$

with:

γ_p : Plastic part of the shear strain, in MPa

A common shape of the typical solutions for the shear stress along the lap length is described in Fig 7.

Figure 7 : Hart-Smith's shear stress distribution



The plateau corresponds to the plasticity around the edges of the bondline. The Hart-Smith model solved the main problem of the Volkersen and Goland Reissner models, as it accounts for the plastic reduction of stresses around the free edges (see Fig 8).

Considering a longer bondline, the behaviour is different as described on Fig 8. For a low load level, the response is elastic within the bonded length. With the load increase, the yield stress is reached at one end first and a plastic zone starts to develop before the second end reaches the yield stress. Then, the plastic zone will develop on each side of the assembly. As the plastic zone continues to grow, the adhesive strain increases at the edges up to a maximal allowable strain value and a crack initiate near the border of the overlap. If the load remains constant, the crack propagates and leads to failure. It can thus be observed that above a certain length, the ultimate strength and the overlap length are independent (see Fig 9). Any bond defect in the centre area (adhesion, material defect), where the stresses are equal to zero, should therefore have a limited impact on the overall strength of the patch.

Figure 8 : Relation between the overlap length and the adhesive shear stress distributions for Hart-Smith model, (left) for short overlap - (right) for long overlap

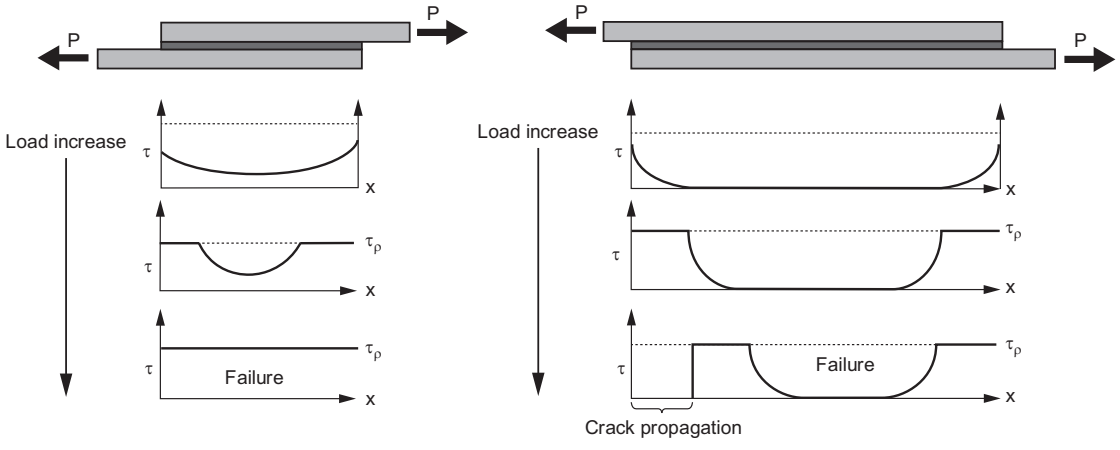
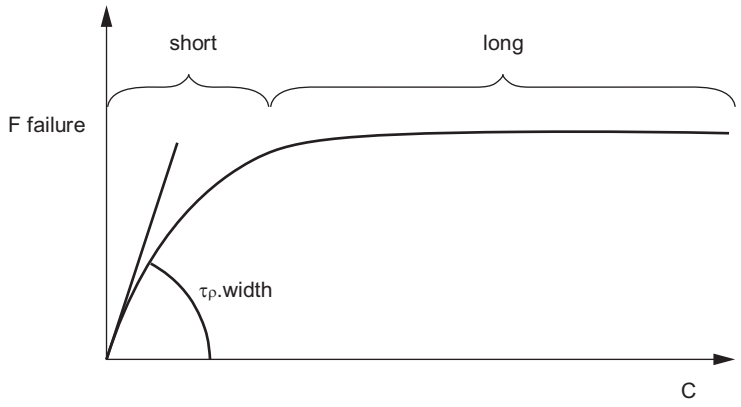


Figure 9 : Scheme presenting the relationship between the ultimate capacity and the bonded length

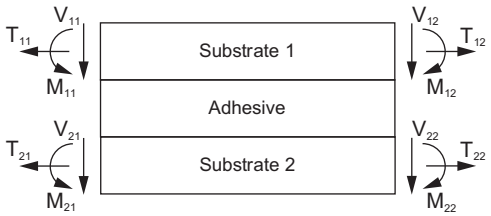


2.1.6 Bigwood and Crocombe model

Bigwood and Crocombe model was developed in order to predict the shear and peel stress in a bonded joint subject to general loading, with shear, tensile forces and bending moments at the substrates ends as shown in Fig 10. It considered the substrates (that can be dissimilar) to act as cylindrically bent plates joined by a layer adhesive which can transmit shear and tensile loadings.

Simplified expressions for the shear and peel can be found. The general elastic analysis though produces two uncoupled seventh and sixth order differential equations for the shear and peel stress respectively. Thus a system with 13 equations constants must be solved. The boundary conditions and equations are described in Bigwood and Crocombe (1989).

Figure 10 : The general substrate-adhesive sandwich



2.2 Main analytical models summary

2.2.1 A non-exhaustive list of analytical models and their comparison in terms of characteristics is given in Tab 1 for indication.

Table 1 : Main analytical models summary (from Lucas et al. (2009))

	Material linearity				Adherend					Adhesive stresses			Solution	
	Adhesive		Adherend					Dissimilar						
	Linear	Non linear	Linear	Non linear	Isotropic	Composite	Similar	Thickness	Material	σ_x	σ_y	τ_{xy}	Closed form	Only numerical
Volkersen (1938)	X		X		X		X	X				X	X	
Goland and Reissner (1944)	X		X		X		X				X	X	X	
Wah (1973)	X		X		X	X	X	X			X	X	X	
Hart-Smith (1973)	X	X	X		X		X				X	X	X	
Privics (1974)	X		X		X		X	X	X	X	X	X		X
Grimes and Greimann (1975)	X	X	X	X	X	X	X	X	X	X	X	X		X
Renton and Vinson (1975)	X		X		X	X	X	X	X		X	X	X	
Srinivas (1975)	X		X		X	X	X	X	X		X	X	X	X
Allman (1977)	X		X		X	X	X				X	X		X

	Material linearity				Adherend					Adhesive stresses			Solution	
	Adhesive		Adherend					Dissimilar						
	Linear	Non linear	Linear	Non linear	Isotropic	Composite	Similar	Thickness	Material	σ_x	σ_y	τ_{xy}	Closed form	Only numerical
Cheng et al (1991)	X		X		X		X	X	X	X	X	X	X	
Bigwood and Crocombe (1992)	X	X	X	X	X		X	X	X		X	X		X
Adams & Mallick (1992)	X	X	X		X	X	X	X	X		X	X		X
Yang and Pang (1996)	X		X		X	X	X	X	X		X	X	X	
Frostig et al (1999)	X		X		X	X	X	X	X		X	X		X
Sawa et al. (2000)	X		X		X		X	X	X	X	X	X		X
Mortensen and Thomsen (2002)	X	X	X		X	X	X	X			X	X		X

3 Finite element analysis

3.1 Generalities

3.1.1 Finite Element models can be composed of:

- plate elements model substrates with adequate modelling of the bonded assembly with solid elements
- volumetric model of the structure with volumetric representation of the adhesive, potentially modelling of different non-linearity, great displacements, large strain, material non-linearity plasticity, hyper elasticity, etc.

3.2 Meshing

3.2.1 The mesh is to be defined using shell elements and/or solid elements for the substrates and solid elements for the adhesive, with or without mid-side nodes.

Meshing is to be carried out following uniformity criteria among the different elements.

Most of quadrilateral elements are to be such that the ratio between the longer side length and the shorter side length does not exceed 2. Some of them may have a ratio greater than 2, but not exceeding 4. Their angles are to be greater than 60° and less than 120°. The triangular elements angles are to be greater than 30° and less than 120°.

The number of nodes and elements is to be such that the stiffness and inertia of the model properly represent those of the structure, and the distribution of loads among the various load carrying members is correctly taken into account.

The structural modelling is to be accurate; the mesh dimensions are to be such as to enable a faithful representation of the stress gradients.

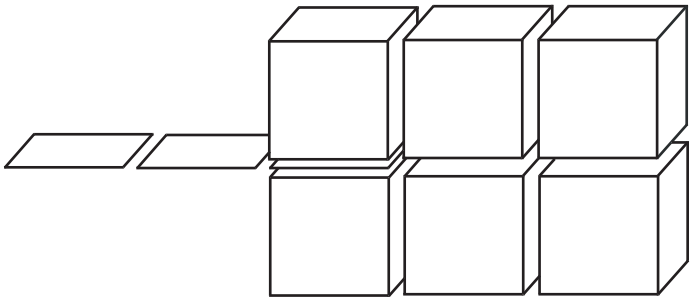
In case of local meshing, the mesh area is to be extended and not reduced to the computed part.

The two main reasons for extending the finite elements model are the following:

- the extension of the 3D mesh
- how to model the transition between the shell elements and the solid ones. As shown in Fig 11, shell elements must be extended inside the solid mesh in order to correctly transfer the rotation degree of freedom of the shell elements to the solid elements.

Adhesive is to be modelled using at least 3 solid elements in the thickness for linear finite elements. If quadratic elements are used, less than 3 elements could be considered.

Figure 11 : Shell/solid connections



3.3 Stress approach

3.3.1 In finite element analysis, peak stress shall always be associated to mesh size unless a mesh sensitivity study has been carried out. It is required to use constantly a similar mesh size across qualification calculations (to analyse experiments) and design calculations.

When considering stress, several parameters can be monitored: shear, maximum principal stress and most importantly peel. Stress can be monitored at the interface to compare with assembly test from characterisation, or in the adhesive bulk, to be compared with results from component characterisation.

3.4 Analysis

3.4.1 Linear approach

Linear approach means that materials used are defined by a linear elastic law. In linear elastic model, the material's behaviour is defined by Hooke's law. Linear hypothesis should be verified during the post-process.

3.4.2 Non-linear approach

Non-linear analysis means that the sources of non-linearity are:

- material (hyperelasticity, etc)
- geometry (large displacements, etc)
- contact, etc.

Adhesives are to be modelled with an appropriate adhesive law but if this law is not available, the adhesives can be modelled with an equivalent elastic law.

This assumption is to be justified by tests on the strain range to be used for the application.

When the classical stress approach cannot be used, for example due to stress concentration at the bond edges, other methods can be performed such as fracture mechanics or cohesive elements, based on energy criteria.

3.5 Fracture mechanics approach

3.5.1 Crack propagation techniques allow to simulate the propagation of a crack. It is usually used in FEM software but can also be analytical. This approach implies the calculation of the Stress Energy Release Rate (SERR) when propagating a crack of length "a" to a length "a + da".

Virtual crack extension (VCE) techniques enables to evaluate the SERR of a structure as a crack propagates on a known path. This technique remains accessible in 2D but becomes difficult in actual 3D structure and bonded assemblies. Specialized software are to be used and calibrated.

Virtual Crack Closure Technique (VCCT) allows to assess the propagation of a crack, without knowing the crack path. Specialized software are to be used and calibrated.

For characterisation it is necessary to measure the weakest interface where the crack is propagating, or to determine it by test fully representative of the manufacturing, design, and loading. It should be verified that for the main loadings to happen in service, the mode of failure remains identical.

3.6 Cohesive elements

3.6.1 Cohesive zone modelling or cohesive elements

Cohesive zone (CZ) modelling is a technique within finite element modelling. In this approach, an adhesive bond or an interface is modelled with non-linear elements - both small and zero thickness elements are possible - that are calibrated on specific dedicated tests for the characteristic traction-separation relationship between the two connected bodies. Such elements present an initially elastic behaviour up to a critical traction or sliding level with a subsequent progressive stiffness reduction characterising the damage, until the connection fails. The energy consumed to separate the connecting media corresponds to the fracture toughness.

Advantages and drawbacks of the cohesive zone method are presented in Tab 2.

Table 2 : Advantages and drawbacks of the Cohesive Zone method

Advantages of the CZ method	Drawbacks of the CZ method
Most bonding configurations and loadings can be modelled with a high accuracy	Computational and characterisation costs are high
Both, non-damaged and damaged joints, can be modelled	Characterisation effort is important because the number of parameters to be defined is important
	Moreover, the crack path is to be defined to place cohesive elements

3.6.2 Interface modelling

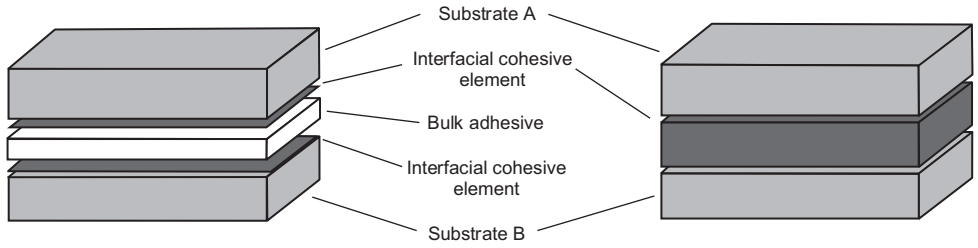
For modelling interfaces, cohesive elements of zero thickness are commonly chosen. Initially coinciding nodes of the two connecting bodies will separate upon loading, following the specified traction-separation behaviour.

Theoretically, the initial element stiffness is infinite until the point of damage initiation is reached in the element. Practically, this would be impossible to solve numerically. Thus, a high enough stiffness is usually used to not influence the overall stiffness of the adhesive layer, already taken into account by adhesive volume elements, see Fig 12 (left).

Such modelling may be used in parallel with solid elements representing the thickness of adhesive and associated elasticity (and/or plasticity, hyper elasticity etc…). It allows to represent a cohesive law adapted to each interface for hybrid joints:

- composite to adhesive
- adhesive to composite.

Figure 12 : Interface element (left) and adhesive layer cohesive element (right)



3.6.3 Adhesive layer modelling

Cohesive element might not represent only the interface, but also the adhesive layer of finite thickness itself, see Fig 12 (right). In such case the elements have a geometrical thickness, and combine both, the material behaviour of the adhesive and the damage behaviour, in the cohesive law.

The characterisation of such element could be done by direct measurements of toughness and cohesive law of bi-material specimens, but no standards exist for such approach. Alternatively, symmetrical standard (identical substrates) tests might be performed, such as composite to composite. Then the cohesive law can be entered into the cohesive elements. Symmetrical tests standards can be found in the characterisation in Sec 3. It shall be checked that the failure happening in the representative tests is the same as the one used to characterise the cohesive law. For example, if in the real case the failure is happening cohesively within the composite, the cohesive law should be calibrated using toughness tests, comprising a composite substrate where the failure is located.

3.6.4 Cohesive laws

Cohesive elements are defined by a cohesive law which describes the traction-separation relationship between the two connected media. This is to be done for mode I and mode II (and mode III often taken equal to mode II), see Sec 4, Fig 6.

Mode I characterisation is generally done by a Double Cantilever Beam (DCB) test. Note that the standard test gives the critical energy release rate or fracture energy of an assembly in mode I (noted G_{IC}). For mode II the most common test is End Notched Flexure (ENF) test measuring G_{IIC}. For mixed mode the total strain energy release rate G_t is measured relatively through the ratio of G_I/G_{II} using MMB (Mixed Mode Bending), SLB (Single Leg Bending) or other tests. Standards tests do not provide the cohesive law but the toughness or critical strain energy release rates in kJ/m² which corresponds to the energy necessary to fully separate an element of surface of the bonded bodies - the integral of the cohesive law. Those tests are presented in Fig 13 and Fig 14.

Those tests measure critical SERR at which crack propagates. By varying the crack length over several specimens or monitoring the crack length along a non-brittle crack propagation, the fracture mechanic allows derivating the value of the fracture energy. Parameters of the law such as stress level at damage initiation, or initial stiffness are to be calibrated by specific methods such as engineering approach, optimization or others.

Other approaches concentrate on the opening (respectively sliding) of a very local portion of the adhesive at one location within the specimen. Specific measurement tools such as Digital Image Correlation (DIC) methods enable the use of J-integral method closed form expressions which allow to compute the J-integral of the adhesive at the location of application. On this basis, cohesive parameters can be derived.

J-integral expressions are formulated for ENF and DCB (see Leffler (2007) and Högberg (2007)).

Figure 13 : Double Cantilever Beam (DCB) and End Notched Flexure (ENF) test set-ups for characterisation of toughness in mode-I and mode-II

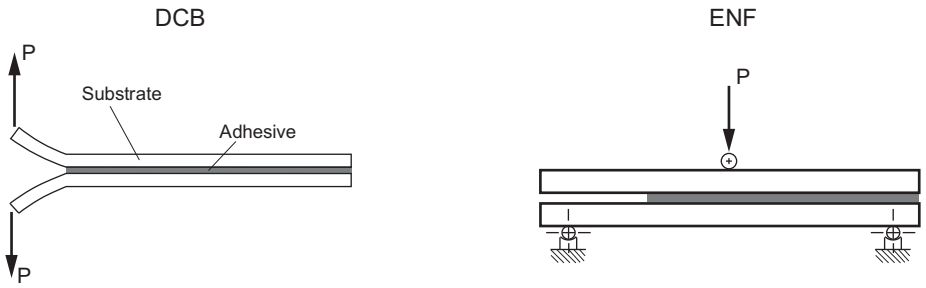
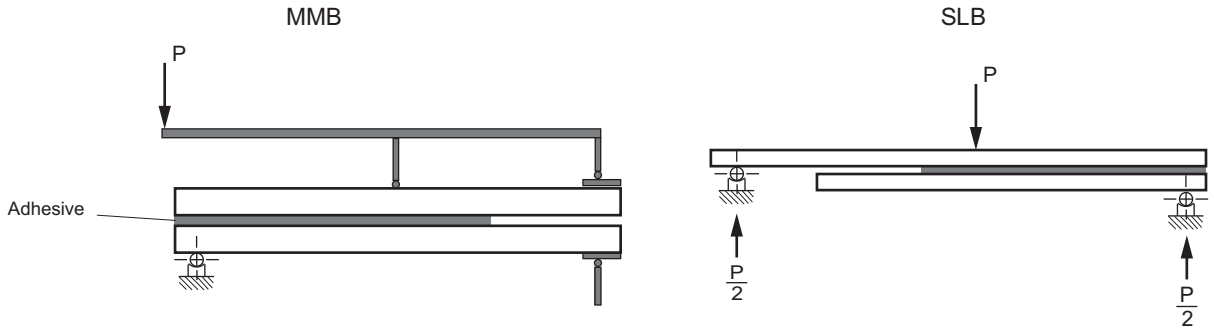


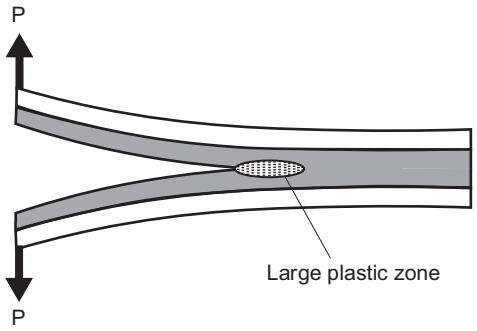
Figure 14 : Mixed Mode Bending (MMB) and Single Leg Bending (SLB) test set-ups for mixed mode



3.6.5 Plastic adhesive

It should be noted that the standard tests such as DCB, ENF, MMB, etc. are developed for adhesives with no or a low plasticity. Hence, these set ups might not be compatible with high plasticity adhesives especially on thick joints, see Fig 15. The formulas presented to compute the toughness are valid within the hypothesis that the cohesive zone size and bulk adhesive plastic dissipation zone are small compared to the crack size and specimen dimension in the load direction. Thus extreme care is to be taken with such standard when applied to very ductile adhesives (with large plastic zones), especially if the thickness is large (as a guidance a value of 1 mm may be given).

Figure 15 : Illustration of large plastic zone



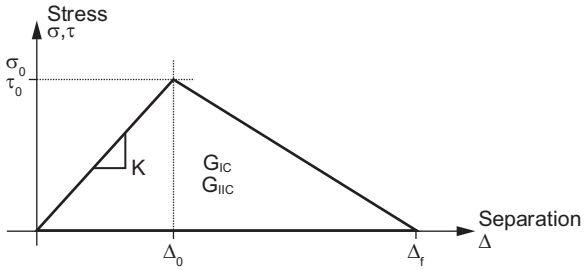
3.6.6 Cohesive law shapes

Several cohesive laws are suggested in literature and implemented in commercial finite element codes. The most simple and mostly spread is the bilinear cohesive law with an initial linear elastic part characterised by the pseudo stiffness K, followed by a linear decline until the critical separation (or strain) is reached, see Fig 16. The linear part is usually defined using mechanical parameters with numerical considerations, whereas the toughness can be measured by DCB, ENF,… tests.

For the full calibration of the bilinear cohesive law additional parameters need to be defined:

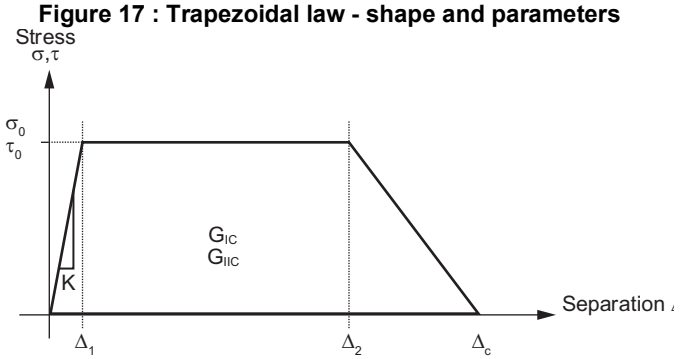
- stiffness K
- interfacial strength σ_0, τ_0
- separation at final failure, or critical SERR G_c.

Figure 16 : Bilinear cohesive law with associated parameters



Other common laws are the exponential law, and the trapezoidal cohesive law which enables the inclusion of plasticity of the interface within the cohesive law, see Fig 17. The various parameters of the trapezoidal law are to be fitted to the results of dedicated experiments. No standard tests exist at this point to calibrate such laws.

Figure 17 : Trapezoidal law - shape and parameters



3.6.7 Parameters settings guidelines for bilinear laws

Guidelines for tuning the bilinear law can be found in the literature. A summary of the work implemented by Turon (2006) is detailed in the specific context of brittle adhesives:

a) Pseudo stiffness K

A zero-thickness interface is characterised by an infinite stiffness. However numerically it is necessary to present a stiffness low enough to allow convergence of the models. It is suggested to use a multiple of the joined substrate's stiffness:

$$K = \alpha \frac{E_{33}}{t}$$

where:

E_{33} : Out-of-plane modulus

t : Thickness of the softest adjacent substrate,

α : Factor taken as $\alpha >> 1$ to obtain an accurate out of plane stiffness of the assembly ($\alpha > 50$ is recommended). This parameter is to be refined in order to allow correct convergence of the models.

b) Interfacial strength σ_0, τ_0

The interfacial strength corresponds to the maximum stress that can be supported by the interface in a test set-up that does not allow geometrical stress redistribution, i.e. a test set-up where the stress is constant within the section where the failure will occur, TAST, tensile tests, ARCAN tests… Typically, for composite UD delamination the interfacial strength is related to the failure stress of a UD laminate at 90° of the load direction (transverse strength).

c) Element size

To capture the crack initiation and/or crack propagation well, a sufficiently refined mesh is of importance. A recommended practice here is to use a mesh size such that 2 to 5 elements lie within the process zone - the zone between the crack tip and the point where the interfacial strength is reached.

3.6.8 Mixed mode loading

In real structures, on the contrary to specific test configurations such as ENF or DCB, the loading of the adhesive layer is mixed: presenting mode I and mode II simultaneously. Several laws exist for mode-mixity which can be found in commercial finite element codes. They present different mixing law parameters which should be characterised using dedicated test set-ups where the ratio of mode-mixity is known, e.g. MMB (Mixed Mode Bending), SLB (Single Leg Bending), or others.

3.6.9 Validation

As the number of parameters for such a cohesive law is large (damage initiation criterion, fracture energy, shape of the cohesive law, and the mode-mixity parameter(s)), their characterisation is not an easy task and validation of the results shall be done systematically on several specimens' configurations. They will be calibrated on dedicated mode I and mode II tests for the mode-individual properties, and then on mixed mode test for the mode-mixity. Accuracy and robustness of the results are to be confirmed on a variety of at least 3 configurations within the actual design envelop of the bonded assembly.

3.6.10 Mesh sensitivity

The mesh sensitivity of cohesive element modelling should be performed. One should remember that the model used for characterisation of the cohesive law shall be representative (in terms of mesh size) of the models that might be used for design assessment. Thus, a mesh size "a" is to be determined which is compatible with design assessment in the project phase (usually rather coarse). Then calibration of the cohesive laws is to be performed using systematically this mesh size "a". When assessing the robustness of the strength prediction, the mesh size is to be constantly equal to "a".

3.6.11 Documentation to be submitted to the Society

Following justifications are to be provided to the Society:

- ENF and DCB results, with details of specimens manufacturing (curing, lay-up, products, adhesive, primer, surface preparation, quality controls…)
- calibration of cohesive parameters, method and results with modelling details and results of DCB and ENF (including mesh size, mesh sensitivity analysis if any, …)
- robustness validation depending on requirement level.

4 Failure Criteria

4.1 Stress criterion

4.1.1 All the above-mentioned models can predict the stress and strain fields with variable precision. The stress criteria limit the use of the joint to a level of load leading to a predefined stress level.

Bonded assembly generally induces stress concentration on the edges where two (or more) different materials join. This stress concentration commonly leads to yielding of the material and crack initiation which can lead to the ultimate material failure. Those phenomena might be complex to model in a design process. Thus, the often used linear models represent stresses (if the linear-elastic limits are breached) that are non-realistic.

In such case, the robustness of the stress criteria needs to be demonstrated.

In a finite element model without plasticity or other stress limiting behaviour, the stress in the bondline at the vicinity of the edge singularity will highly depend on the mesh size.

4.2 Strain criterion

4.2.1 In the case of ductile adhesive, the stress criterion may not be appropriate anymore, where failure is governed by strain. A criterion may thus be based on the maximal strain in the adhesive. The main limitation of this approach is the necessity to determine the plastic strain.

The predicted failure load will be the minimum load for which the critical strain is reached.

4.3 Energy criterion

4.3.1 The energy criterion supposes an initial crack and use crack propagation technique to calculate the SERR $G_{(a,F)}$ of a crack length a.

Propagation occurs if:

$$G_{(a,F)} > G_C$$

With $G_{(a,F)}$ being the SERR of the bonded assembly subject to a crack of size a at a load F. If the inequality is fulfilled, the crack propagates and the predicted failure load is the minimum load F for which this inequality is fulfilled.

This criterion is easily defined in pure mode (either only mode I or only mode II), as the critical toughness is directly linked to standard tests such as DCB in mode I and ENF in mode II. However in mixed mode, the SERR calculated in the model with classic tensile or bending loading will have a mode ratio in the range between 0 and 1 (which is generally the case) so the critical toughness must defined over that entire range. A common model used to define the SERR in this range is the Benzeggagh-Kenane (B-K) criterion (see M.L. Benzeggagh 1996).

It takes values based on tests with mode I, mode II and mixed mode and interpolates the values with a power law as shown in Fig 18. The function used for the interpolation is:

$$G_C = G_{IC} + (G_{IIC} - G_{IC}) \cdot \left(\frac{G_{II}}{G_t}\right)^n$$

where n is the only parameter that needs to be characterised. In the presence of mode III the last term with the power would be

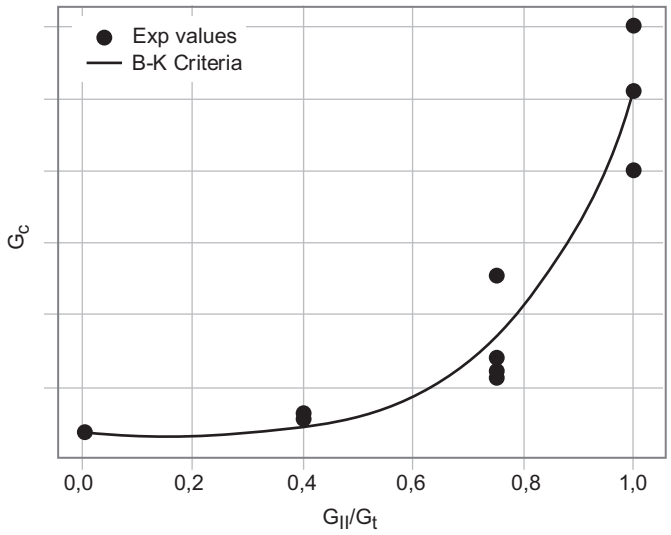
$$\left(\frac{G_{II} + G_{III}}{G_t}\right)^n$$

with:

$$G_t = G_I + G_{II} + G_{III}$$

It may be defined already in FEM software but in case it is not, the SERR must be extracted from the software and then compared in a little script for example.

Figure 18 : Illustration of the critical toughness based on the B-K criterion



4.4 Coupled stress-energy criterion

4.4.1 In this approach the stress along the bondline is characterised for the design (extreme) load. Thus the safety factor is expressed along the bondline.

Another calculation assumes a crack from the edge to each location along the joint. For each length the energy release rate is calculated and the ratio of the strain energy release rate to the adhesive toughness is plotted along the joint. The comparison of the two curves gives the identification of the part of the joint which is damaged (safety factor below 1) and the length above which the crack will propagate (SERR larger than the adhesive toughness). It enables to confirm if the design is valid for the design load or not.

4.5 Cohesive element failure

4.5.1 When using cohesive elements, the failure of an element can be defined when the damage parameter reaches 1, which is equivalent to the stiffness of the element reaching 0. The predicted failure load is thus defined as the load where the first cohesive element damage reaches 1, which is illustrated by the start of the crack propagation.

5 References

5.1

5.1.1 The Following documents are used for reference in this Appendix:

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Appendix 5 For Information only - Fatigue Assessment

1 General

1.1 Methodologies

1.1.1 For Q4 qualification level, if joint is subjected to high number of cyclic load, or upon specific requirement of class, fatigue is to be justified.

As a guidance, two main methodologies can be identified and are presented in what follows:

- S-N curves fatigue analysis, or other damage accumulation assessment
- full scale representative test validation.

In either case, it is important to define the loading histogram applicable to the bonded assembly. In any case the testing should be representative of the actual design in terms of design, manufacturing process and, of course for the loading. Fatigue results are highly dependant on the type of load, and may not be extrapolated to sensibly different loading configurations such as peel shear ratio very different from the tests.

When possible, the two steps can be performed:

- One to define the S-N curves, and
- One for the validation of the design and the evaluation of the accuracy of the hypothesis used with S-N curves.

1.2 Fatigue Load histogram

1.2.1 The first step of the validation is to establish the loading histogram on the joint. The methodology here should follow an engineering process defining the number of cycles, and their amplitudes. When requiring fatigue, the relevant applicable Rules provide in most cases the methodology for this assessment.

For instance, considering hull girder strength, NR467, Part B prescribes a deterministic wave fatigue approach. In brief, it consists in calculating the loading cases with a probability of 10^{-5} (classical storm), in the wave crest and wave trough condition for a variety of loading conditions (full load, ballast, …) and wave conditions (beam seas, quartering seas, head seas…). This provides in each case a range of loads/stress with a probability of 10^{-2}.

The ranges of load are transferred into a histogram using a Weibull law, for the design period, 20-25 years. A pondered summation of the different loading configurations might be needed (50% of the time in ballast condition, 50% in full load condition, etc…). This is in general defined in the applicable Rules.

For any other applications, fatigue load histogram is to be submitted and agreed by the Society.

1.3 Design validation using S-N curves

1.3.1 Establishment of S-N curves

In the first method based on S-N Curves, a calculation model of the joint may be established: design methodology from strength analysis is foreseen or finer.

If a calculation model is developed (corresponding to design methodology from strength validation part, or finer), the results will constitute a proper Stress to Number of cycles: S-N Curves. In general, the stress to be considered is the nominal stress as defined in Sec 4.

If no calculation model is developed it is preferable to use load or average stress for the curve obtained. It shall be clearly mentioned that it is an averaged stress results S-N curves. It is not accurate for design except when the joint is subject to the same loading and presents the same substrate stiffness, same area of bonding and same adhesive thickness.

All interfaces, adhesive, and substrates failures shall be considered for the establishment of the S-N curves.

The bonding edge will modify the fatigue results specifically when the adhesive or assembly is brittle. A simplified model of the bonded assembly edge might be done, for example not considering the actual shape, but the same model needs to be used for design fatigue evaluation, in any case, the tests specimens need to correspond to the actual joint in particular for the edge.

The lay-up of the test specimens is to be representative of the actual design: process, type of fibres, orientation, especially for the first plies in contact with the adhesive.

Also the curve expresses the relation between a stress level and a number of cycle to failure. It is necessary to define what type of stress is considered:

- average stress
- nominal stress.

Ideally, the specimens used for the tests should present a repartition of nominal stress as per the typical design.

The level of peel stress should be comparable to the actual design.

As creep, relaxation or damage softening may occur during the test, it is necessary to take good care on the type of control that is applied to the joint, and monitor stiffness, displacements and loads during tests.

The level of mean stress applied in the specimen testing should be representative of actual conditions or higher. Loading ratio R (Min load/ Max load) of R = 0,1 is to be applied in general for the tests.

Specific care should be taken regarding the adequacy between the stress definition used to build the S-N curves and the stress post-processed from the calculation model.

The statistical analysis of the specimen testing results should be carried out using a recognized standard, e.g. ISO 12107:2012. Unless a different fatigue model is implied by the data, a Basquin model can be considered to represent the relationship between the stress range level and the number of cycles to failure. This model assumes a linear relationship between the logarithm of the stress range ΔS and the logarithm of the number of cycles to failure N:

$$N = \frac{K}{\Delta S^m}$$

$$\log N = \log K - m \cdot \log \Delta S$$

K, m : Parameters of the S-N curve depending on the material.

For the design, the S-N curve considered should correspond to a survival probability of 95%.

1.3.2 Damage calculation

Using a load histogram, the stress can be derived, and the damage estimated using Miner's rule:

$$d = \sum_i \frac{n_i}{N_i}$$

with

n_i : Number of cycles from the histogram at the i^{th} level of load.

N_i : Number of cycles from the S-N curve at the i^{th} level of load.

Damage should verify:

$$d \leq \frac{1}{SF}$$

SF being the fatigue safety factor defined on a case by case basis.

1.3.3 Frequency of loading

Fatigue tests are long to perform. To shorten the tests, frequency of loading might be increased. However, because of the visco-elastic or visco-plastic nature of adhesive, self-heating might occur. Values of 4 Hz may be considered as far as practicable temperature measurements (e.g. using infrared camera) may be used to ensure that the heat generated by the loading stays stable. When the frequency used for the fatigue tests is much higher than the actual loading, it may be necessary to evaluate the level of stress reached within the bondline by a calculation using elastic properties of the adhesive in line with the speed of solicitation. A monotonic test up to failure might be performed using the same speed as the fatigue test to verify the strength under fatigue solicitation speed.

1.3.4 Fatigue model validation

In order to confirm that the design procedure based on a fatigue model and small-scale testing is adequate, a validation can be carried out against a destructive full-scale test. The fatigue model should be able to conservatively predict the fatigue life obtained in the full-scale testing.

1.4 Validation by full scale tests

1.4.1 The validation by full scale test requires to manufacture specimens at full scale representing a part of the assembly which is critical for the fatigue loading. The manufacturing process, material and design should be representative of the actual design and construction.

1.4.2 Loads cycle grouping

The specimen should be loaded in a representative manner by a histogram of load that is equivalent to the in-service life of the actual joint. Simplifications to the histogram might be performed. To do so the loading histogram should be divided in groups of loading levels called bins. Within each bin all occurrences are to be summed, and represented by the maximum level of the group.

The order of application of the load level should be preferably random. A possible pseudo-randomisation method is to consider a reference load sequence with the number of cycles of each bin being computed as:

$$N'_i = \frac{N_i}{p}$$

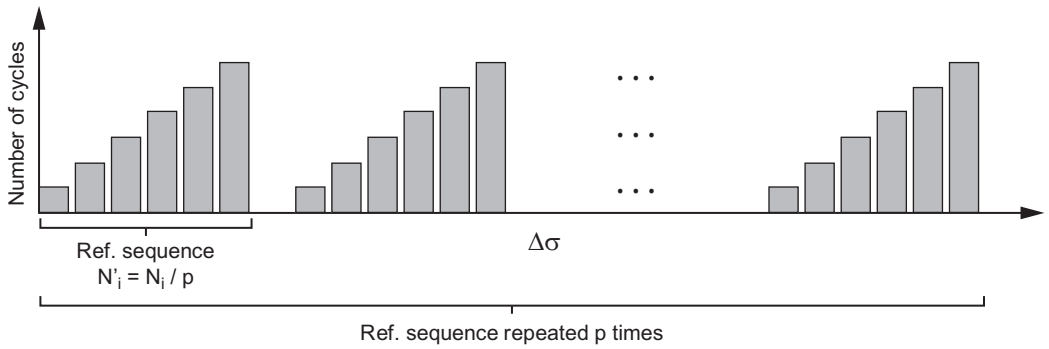
where:

N'_i : Number of cycles of the i^{th} bin of the reference sequence

N_i : Total number of cycles of the i^{th} bin of the original loading and p is the number of blocks to be considered, for instance p=10 (see Fig 1).

Other relevant loading arrangement can be proposed and discussed with the Society.

Figure 1 : Loads cycle grouping example



1.4.3 Load clipping

The total number of cycles may be prohibitive for testing (in terms of load duration). Thus load clipping might be performed. This requires an evaluation of the fatigue threshold for the joint.

In order to determine the threshold, small scale tests are to be performed, which is to be representative of:

- substrates material(s)
- overlap length in the main direction of the load
- adhesive thickness (or the minimum of the adhesive thickness range, if no clear change in joint failure is noted within this range)
- loading configuration
- substrate stiffness
- manufacturing
- joint edge design (especially in brittle adhesive or failure)
- (potentially others, to be agreed with the Society)

In the case where it is difficult to maintain the overlap length and substrate stiffness, it is mandatory to maintain an equivalent shear stress repartition using a nominal stress approach such as Bigwood & Crocombe or Volkersen, see App 4. This is specifically important when brittle failure occurs or brittle adhesive is used, see App 3.

Existence of a fatigue threshold is to be investigated with these small scale specimens. For instance, constant amplitude fatigue load tests might be performed, lowering the load level until runout of the fatigue tests (at least 10^6 cycles, to be agreed with the Society depending on the application case). It is necessary to obtain several specimens which do not fail. Three specimens is a minimum and to be agreed with the Society.

In the case where a fatigue threshold does exist, the load cycles below the threshold in the load histogram might be disregarded. A factor of 2 at least shall be considered between the actual established threshold and the clipping level. Specific care should be taken regarding the adequacy between the stress definition considered to define the endurance limit and the stress definition post-processed from the fatigue model.

1.4.4 Coupling with ageing

For Q4 requirement level and in agreement with the Society, a coupling is to be done with ageing of the joint. Coupling a fatigue test with ageing is a really difficult task which is more a research topic than a qualification test. However, it might be possible to combine the tests, with an ageing of the full scale specimen prior to perform a fatigue validation. For the definition and performance of the ageing test, refer to Sec 3, [4.2.4].

Appendix 6 Typical Content of the MTI Bonding Plan

1 General

1.1

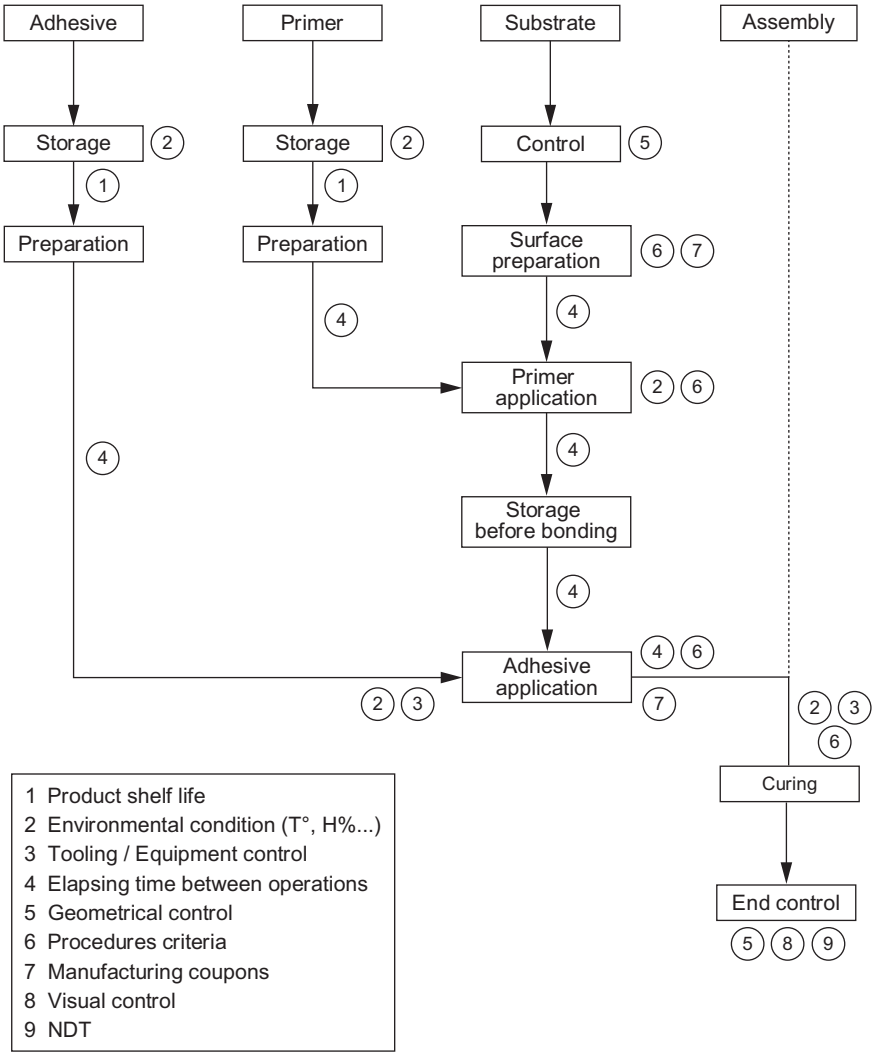
1.1.1 An exhaustive list of all related materials and various tools and equipment used in bonding process is to be drawn-up by the shipyard/manufacturer.

This includes:

- adhesives and constituent parts (base resin, hardener, catalyst…)
- substrates
- solvents, chemicals, primers, substrate promoter, various consumables and equipment for cleaning and surface preparation of substrates (peel plies, grit blasting, bristle blaster, sandpaper, wipes, gloves, various tools…)
- tools and equipment for applying adhesives
- tools and equipment for assembly operations

An example of principle scheme for process control is given in Fig 1.

Figure 1 : MTI bonding plan: example of principle scheme for process control



2 Action prior to bonding operations

2.1 References

2.1.1 Shipyard/manufacturer's documentation shall contain the following information for each type of material:

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

2.2 Storage conditions

2.2.1 Shipyard/manufacturer's procedures shall contain the following information on storage sites:

- Location (or locations):
  - geographical position in relation to bonding units, stating variations of temperature and hygrometry that products must undergo when transiting from one to another
  - ventilation conditions, particularly air-replacement rates
  - heating conditions, stipulating means of temperature measurement, recording means, and expected maximum variation (i.e. minimum to maximum temperature)
  - arrangements for measuring hygrometry, giving at least the same information as for temperature, as well as the intended method of calibration of instruments
- Recording means available on storage sites:
  - listing documents related to storage conditions and stored products available on the storage site, and means deployed to ensure that stock managers are informed of arrangements to be made
  - listing documents available on measures to be taken by stock managers, if irregularities occur during storage (e.g. excessive storage temperature or hygrometry)
  - listing documents (and methods for updating such documents) to record arrival and departure dates for consignments, with description of any special event that could affect a consignment during storage.

2.3 Reception of raw materials

2.3.1 Shipyard/manufacturer's procedures shall state arrangements for incoming materials, in particular:

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

2.4 Supply of materials to bonding units

2.4.1 Shipyard/manufacturer's procedures shall cover the following points:

- conditions and precautions to be taken when preparing each material for use
- precautions taken in preparing materials when subject to wide temperature variations before use
- methods adopted to prevent use of products that are exceeded their use-by or fail to conform to supplier or shipyard/ manufacturer requirements.

2.5 Traceability

2.5.1 Shipyard/manufacturer's procedures must ensure traceability of materials, from the time of reception until the end of production operations.

3 Bonding operations

3.1 General

3.1.1 Site procedures dealing with methods of preparation of adhesives and substrates materials for the bonding operation phase shall provide information indicated in [3.2] to [3.8].

3.2 Bonding environment

3.2.1 Shipyard/manufacturer's procedures shall describe the following environmental conditions for bonding environment:

- minimum and maximum temperatures and hygrometry in air
  - minimum dew point deviation
- means of measuring, controlling and recording these values
- procedures provided by the shipyard/manufacturer to halt or alter the bonding process when temperature or hygrometry reading exceed limits
- positions of various workstations in relation to one another, in particular precautions taken to prevent the presence of dust at some sensitive workstation caused by other operations.

3.3 Substrate surface preparation

3.3.1 The procedure for surface preparation of the substrates shall describe:

- method of checking before surface preparation that the substrates have been stored in accordance with procedures
- methods, tools and various agents necessary for mechanical and / or chemical surface preparation
- methods, tools and various agents necessary for cleaning surface preparation
- description of each cleaning and surface preparation sequence with minimum and maximum time elapsing between each step
- method for checking after surface preparation that the substrates have been prepared in accordance with procedures.

3.4 Adhesive preparation

3.4.1 The procedure for adhesive preparation shall describe:

- method of checking before preparation that the various technical components of the adhesives have been stored in accordance with manufacturer's specifications and shipyard/manufacturer procedures
- process of preparation of adhesives, defining methods and equipment used to measure various ingredients, component mixing, check viscosity, etc…
- list of criteria for pursuing or halting application after preparation
- precautions taken to comply with manufacturer's specifications on the maximum time elapsing between preparation and application of adhesives.

3.5 Adhesive application

3.5.1 The procedure for application of the adhesive shall describe:

- methods, tools and equipment for application of adhesive (manual or automatic application devices…)
- positioning with traceability
- amounts (weight/surface), thickness of adhesive to be applied, and tolerances
- means of respecting this thickness
- various inspection procedures (e.g. physical examination, measurement of thickness), carried out after bonding operation, and the shipyard/manufacturer reference document for common defects, stating causes and remedies.

3.6 Assembly

3.6.1 Shipyard/manufacturer's procedure for assembly shall describe:

- description of all assembly stages with methods, tools and equipment necessary
- means of ensuring contact pressures, immobility of components
- minimum and maximum time elapsing between application of adhesive and assembly stage
- methods of checking dimensions of components and their positioning.
- method to control bond line thickness, shape of adhesive bead and tolerance (flatness of substrates)
- method for removal of excessive adhesive
- method to control that bonding will occur on full surface (removal of bubbles, good spreading of adhesives…)
- procedures provided by the shipyard/manufacturer when bond line thickness exceeds tolerance limits.

3.7 Curing

3.7.1 Shipyard/manufacturer's procedure for curing shall describe:

- methods, tools and equipment necessary to maintain assembly parts in position during polymerisation of the bonded assemblies
- condition specification and control methods to achieve required curing rate (T°, H%, pressure...)
- method and equipment for air porosity elimination
- method for heating if relevant with curing cycles specification
- inspection methods and criteria for checking the curing of the adhesive.

3.8 End control of the assembly

3.8.1 Shipyard/manufacturer's procedure shall describe:

- intended inspection methods and NDT after assembly, acceptability criteria for the assembly, as well as remedies for any defects found, means of handling any non-conformities found
- dimensional checks after assembly
- storage conditions specification for the assembly.

Appendix 7 Surface Preparation

1 General

1.1 Scope

1.1.1 This Appendix gives main requirements for preparing the surface before bonding.

Surface preparation is an important process in the quality scheme of bonded assemblies. Surface preparation needs careful attention to ensure reliability and appropriate properties of the bonded assembly.

2 Means of preparation

2.1 Cleaning and degreasing

2.1.1 The characteristics of a cleaner must comply with:

- cleaner must be able to remove all that is soluble in water (dirt, salts, etc..) and also insoluble in water (dirt, oil, grease, etc...) from the surface
- cleaner should evaporate or be removed quickly without any residue
- cleaner must not damage the materials to be bonded
- cleaning product is to be harmless to health and environment

There are two major families of cleaners:

- organic: alcohols (isopropyl) and acetone are the most common
- aqueous: Alkaline (pH> 9) cleaners are recommended because they can remove hydrocarbon derivatives, soaps and metal salts. Non-ionic detergents also give good results.

Cleaning and degreasing is to be made with a lint-free cloth and the wiping action should be applied only in one direction, without rubbing. After each wipe the cloth should be refolded to expose another clean area ready for wiping the surface.

2.2 Surface abrasion

2.2.1 As a rule, surface of composite structure is prepared with sandpaper.

The method used for the preparation of a surface will depend on:

- state of the surface
- dimensions of the surface to be prepared
- specific readiness required
- requirements relating to particular operating conditions.

Surface abrasion can be carried out wet or dry. The following sequence is recommended:

- perform abrasion in one direction, until the entire surface has been slightly and uniformly scarified
- perform abrasion in the direction perpendicular to the last, until all traces of the process are eliminated
- perform abrasion by means of a circular movement until removed, again, all traces of the previous point, and until surface looks uniform
- remove loose material, cleaning with solvent and a clean lint free cloth
- glue or perform other processing of surface modification.

2.3 Primers

2.3.1 Primers are products, mostly liquids, which are applied to a substrate prior to application of an adhesive, paint or sealant. The reasons for using them are the following:

- protection of the surface after a treatment
- modifying the surface free energy by providing a more easily wettable surface than the original substrate
- promoting chemical reaction between the adhesive and the substrate
- dissolving low levels of organic contamination that otherwise would remain at the interface as a weak boundary layer
- serving as an intermediate layer to enhance the physical properties of the joint and improve bond strength
- penetrating porous or rough surfaces to provide better mechanical interlocking
- sealing surfaces from the environment.

Usually, a primer is needed when the adhesive or sealant cannot be applied immediately after surface preparation, when a surface is weak or porous, or when the joint interface requires additional protection from service environments, which is the case in marine environment.

Primers are to be applied quickly after surface preparation and result in a dry or slightly tacky film. It is usually recommended that they have a dried coating thickness range of tenths of a millimetre. It is necessary to control the primer thickness, since if the primer layer becomes too thick its bulk properties may predominate, and the primer could become the weakest part of the joint.

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