ECSS-Q-ST-70-16C DIR2
28 May 2018

Space product assurance

Adhesive bonding for spacecraft and launcher applications

This draft is circulated to the ECSS community for Public Review.
(Duration: 8 weeks)

Start Parallel Assessment: 29 May 2018

End of Parallel Assessment: 23 July 2018

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ESA-ESTEC
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Noordwijk, The Netherlands

Foreword

This Standard is one of the series of ECSS Standards intended to be applied together for the management, engineering and product assurance in space projects and applications. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining common standards. Requirements in this Standard are defined in terms of what shall be accomplished, rather than in terms of how to organize and perform the necessary work. This allows existing organizational structures and methods to be applied where they are effective, and for the structures and methods to evolve as necessary without rewriting the standards.

This Standard has been prepared by the ECSS-Q-ST-70-16C Working Group, reviewed by the ECSS Executive Secretariat and approved by the ECSS Technical Authority.

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Published by: ESA Requirements and Standards Division
ESTEC, P.O. Box 299,
2200 AG Noordwijk
The Netherlands

Change log

	Change log for Draft development
Previous steps	
ECSS-Q-ST-70-16C DIR1 1 May 2018	Parallel Assessment 2 May – 18 May 2018
ECSS-Q-ST-70-16C DIR2 25 May 2018	Update of DIR 1 with comments from Parallel Assessment and WG review
Current step	
ECSS-Q-ST-70-16C DIR2 28 May 2018	Public Review 29 May – 23 July 2018
Next steps	
	Draft with implemented DRRs
	DRR Feedback
	TA Vote for publication
	Preparation of document for publication (including DOORS transfer for Standards)
	Publication

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Introduction

Adhesive materials have a wide range of uses within the space domain however they are often qualified as a minor or negligible part of a large subsystem or system. This frequently results in unforeseen effects arising directly from the adhesive selection which impacts either the functionality, integrity or AIT activities. As a consequence whilst the adhesive is often the lowest cost element of the system it frequently has a high cost associated with the necessary recovery and delta qualification activities need to ensure the system level functionality. Both the system level qualification and any recovery actions are further complicated by the intrinsic relationship between the adhesive performance, the substrate and all the processes associated with the manufacture of the adhesive bond.

European space agencies and the space industry at present have a general handbook available for adhesive bonding (ECSS-E-HB-32-21) however there is no fixed scheme detailing the minimum requirements for verification of adhesive bonding process nor validation of an adhesive material.

Standardisation of the verification processes for adhesives and adhesive bonding across the European space industry is allowing a harmonised and consistent approach.

The generic approach facilitates the correct selection of data thus allowing streamlining of the industrial development activities and enabling the validation of adhesives and verification of adhesive bonding process at an early stage of a programmes lifetime.

The use of this standard allows a given programme technical focus to be emphasised onto specific functional requirements since generic testing is already defined.

The document is further justified because of the high level of non-conformances (NCR) identified across industry due to limited early programmatic qualification programmes related to adhesive bonding.

1 Scope

The scope of the document addresses the generic verification for all types of adhesive bonding for space applications including evaluation phases. It specifies all aspects of the adhesive bonding lifetime such as assembly, integration and testing, on-ground acceptance testing, storage, transport, pre-launch, launch and in-flight environments.

This standard does not cover requirements for:

- adhesive bonding used in EEE mounting on printed circuit boards (ECSS-Q-ST-70-61)
- adhesive bonding used in hybrid manufacturing (ESCC 2566000)
- adhesive bonding for cover-glass on solar cell assemblies (ECSS-E-ST-20-08)
- design of adhesive joint
- long term storage and long term storage sample testing
- performance of adhesive bond
- functional properties of adhesive joint
- co-curing processes

This standard may be tailored for the specific characteristics and constrains of a space project in conformance with ECSS-S-ST-00.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this ECSS Standard. For dated references, subsequent amendments to, or revision of any of these publications do not apply. However, parties to agreements based on this ECSS Standard are encouraged to investigate the possibility of applying the more recent editions of the normative documents indicated below. For undated references, the latest edition of the publication referred to applies.

ECSS-S-ST-00-01	ECSS system – Glossary of terms
ECSS-Q-ST-10	Space product assurance -Product assurance management
ECSS-Q-ST-20	Space product assurance -Quality assurance
ECSS-Q-ST-10-09	Space product assurance -Nonconformance control system
ECSS-Q-ST-40	Space product assurance - Safety
ECSS-Q-ST-70	Space product assurance – Materials, mechanical parts and processes
ECSS-Q-ST-70-02	Space product assurance - Thermal vacuum outgassing test for the screening of space materials
ECSS-Q-ST-70-09	Space product assurance - Measurements of thermo-optical properties of thermal control materials
ECSS-Q-ST-70-15	Space product assurance - Non-destructive inspection
ECSS-Q-ST-70-22	Space product assurance - Control of limited shelf-life materials
ECSS-Q-ST-70-71	Space product assurance - Materials, processes and their data selection
ISO 3696:1987	Water for analytical laboratory use - Specification and test methods

3 Terms, definitions and abbreviated terms

3.1 Terms from other standards

a. For the purpose of this Standard, the terms and definitions from ECSS-S-ST-00-01 apply.

b. For the purpose of this Standard, the terms and definitions from ECSS-Q-ST-70 apply, in particular for the following terms:

1. critical process
2. critical material
3. special process

3.2 Terms specific to the present standard

3.2.1 adhesion

state in which two surfaces are held together by interfacial forces which can consist of chemical or mechanical or physical interfacial forces

3.2.2 adhesive bonding process

material joining process where an adhesive material is added in order to maintain chemical, mechanical or physical interfacial forces between bonded parts

NOTE The joining mechanism between adhesive and bonded parts, also called "adherend", is adhesion-based. According to ECSS-Q-ST-70, adhesive bonding belongs to category of “special processes”.

3.2.3 adhesive material

substance with the capability of holding two surfaces together by either chemical, physical or mechanical interfacial forces or a combination of them

NOTE The concept of adhesive materials is addressed in ECSS-E-HB-32-21.

3.2.4 adhesive bonding procedure

detailed instructions, equipment and tools needed to perform the adhesive bonding

NOTE Refer to Annex A for the detailed content.

3.2.5 ambient humidity exposure in controlled environment

item is exposed to ambient air with temperature in the range of (22 ± 3) °C, and relative humidity (55 ± 10) %

NOTE 1 Long term exposure to this conditions can cause degradation of the adhesive joint's performance.

NOTE 2 Contributes to "intrinsic ageing" of the joints.

3.2.6 co-curing

earliest stage of manufacturing process, resulting in a fully integrated component

NOTE 1 The joining mechanism is chemical cross-linking. Both adherends are undergoing chemical reaction.

NOTE 2 This standard does not cover requirements for verification of co-curing processes.

3.2.7 co-bonding

intermediate stage of manufacturing process when uncured part is joined with one or more cured parts, typically with an additional layer of uncured adhesive

NOTE 1 The joining mechanism between the adhesive and the cured part is adhesion. Between the un-cured part and uncured adhesive layer chemical cross-linking is taking place.

NOTE 2 Further text refers only to adhesive bonding or co-bonding (uncured adhesive, cured substrate) or to bonding with pressure sensitive tapes (PSAs).

3.2.8 degradation

reduction of property of interest detected between two measurement points over period of time

3.2.9 hot-wet exposure

exposure where the test item is subjected to synergistic effect of gaseous water phase and temperature

NOTE 1 Typically the test item is exposed to conditions, where temperature and water vapour pressure are higher than humidity exposure in controlled environment (>25 °C and >65 % RH)

NOTE 2 Performed in frame of simulation of on-ground environment within adhesive bonding verification test sequence or as part of independent hot-wet testing

NOTE 3 Inspection and verification of the test item before and after hot-wet exposure is non-destructive and does not prevent test item to be submitted for further testing in frame of verification test sequence

NOTE 3 Also known as "humidity exposure"

3.2.10 hot-wet testing

test where the test item is subjected to hot-wet exposure and the effect of hot-wet exposure is verified after hot-wet exposure is performed

NOTE 1 Hot-wet exposure can be performed in combination with other additional stresses, e.g. mechanical, chemical or electrical

NOTE 2 Functional properties of test item can be verified during hot-wet exposure "in-situ" conditions

NOTE 3 In hot-wet testing of the adhesively bonded joints, hot-wet exposure is typically followed by mechanical test to verify degradation of the joint and reduction factor associated with hot-wet exposure

NOTE 4 Series of test item undergoing hot-wet testing are not following further the verification test sequence

NOTE 5 Also known as "damp-heat" testing or "humidity testing"

3.2.11 knock-down factor (KDF)

overall factor that is applied to the material property to account for variations in material composition, service environment and structural geometry

NOTE It can consist of several reduction factors.

3.2.12 reduction factor

ratio between mean value of given material property of reference test item and exposed test item sets

NOTE Can be expressed as fraction or as percentage of initial reference value (remaining percentage of the property of interest).

3.2.13 representativeness level of test item

definition of how well or accurately the test item reproduces the similarity to flight model configuration

3.2.14 test item

manufactured assembly undergoing verification test sequence

NOTE The test item can be standard test sample, component or part fully representative to the flight hardware.

3.2.15 test item population

group of test items sets manufactured to complete specific test sequence, including all reference test items, on-ground simulation test items, mission simulation test items and launch simulation test items and spare test items

NOTE Group of items with same manufacturing history.

3.2.16 test item set

test items that follow an identical test sequence

3.3 Abbreviated terms

For the purpose of this Standard, the abbreviated terms and symbols from ECSS-S-ST-00-01 and the following apply:

Abbreviation	Meaning
CME	coefficient of moisture expansion
CTE	coefficient of thermal expansion
DMA	dynamic mechanical analysis
DRD	document requirements definition
DSC	differential scanning calorimetry
MLI	multi-layer insulation
MMPP	materials, mechanical parts and processes
PA	product assurance
PSA	pressure sensitive adhesive
Tg	glass transition temperature
TGA	thermo-gravimetric analysis
TMA	thermo-mechanical analysis
TVC	thermal vacuum cycling
UV	ultraviolet

3.4 Nomenclature

The following nomenclature applies throughout this document:

a. The word “shall” is used in this Standard to express requirements. All the requirements are expressed with the word “shall”.

b. The word “should” is used in this Standard to express recommendations. All the recommendations are expressed with the word “should”.

NOTE It is expected that, during tailoring, recommendations in this document are either converted into requirements or tailored out.

c. The words “may” and “need not” are used in this Standard to express positive and negative permissions, respectively. All the positive permissions are expressed with the word “may”. All the negative permissions are expressed with the words “need not”.

d. The word “can” is used in this Standard to express capabilities or possibilities, and therefore, if not accompanied by one of the previous words, it implies descriptive text.

NOTE In ECSS “may” and “can” have completely different meanings: “may” is normative (permission), and “can” is descriptive.

e. The present and past tenses are used in this Standard to express statements of fact, and therefore they imply descriptive text.

4
Principles of adhesive bonding

4.1 Overview

Adhesive bonding for space hardware varies from bonding of for example cable ties, to the complex structural bonding of load bearing parts. Some adhesive bonds can be inside the space craft, while others are exposed to space conditions including sometimes large temperature variations and radiation. Therefore the lifetime of each adhesive bond is carefully assessed before starting the bonding process. An overview of the different factors affecting the adhesive bonding performance is given in Figure 4-1.

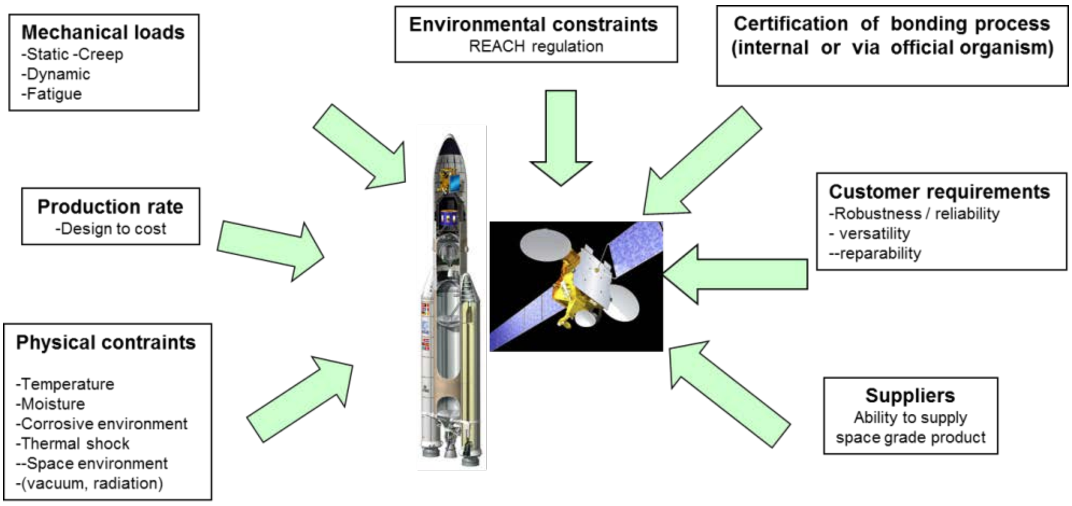

Figure 4-1: Overview of the constrains linked to adhesive bonds for space applications

4.2 Design of hardware

The design of bonded hardware involves parameters such as load directions, CTEs, bonding gaps, accessibility. A detailed overview on how to design an adhesive joint can be found in sections 8 to 11 of ECSS-E-HB-32-21.

Designers or sizing engineers have a good understanding of how stresses are distributed across the joint when loads (mechanical and thermal) are applied to it. Typically they consider the general guideline for thin adhesive bond (bond line thickness up to approx. 0,3 mm) to:

a. Maximize shear and minimize peeling and cleavage load

b. Maximize compression and minimize tension loads

c. Increase the joint width rather than the overlap length

NOTE 1 If the length is small, plasticization (yielding) the adhesive governs the failure.

NOTE 2 If the length is larger, it is important to take in to account adhesive crack with plasticization (yielding) or crack only governs the rupture.

NOTE 3 If the length is very large, the adhesive bond can be more resistant than the adherend which can break (case of composite).

d. In case of using composite adherends with unidirectional layup (0° being the best in accordance with maximum stress at failure) designers avoid for the first ply in contact with the adhesive 90° orientation ply and prefer a plain weave rather than unidirectional or ply with a lower stiffness (glass fabric for instance).

4.3 Performance of the adhesive bond

After having defined the basic design of the hardware and the parts that are bonded, the analysis of the adhesive bond is performed. This analysis can focus on joint design, adhesive material properties and environmental constraints, see Figure 4-2.

The needed performance of the adhesive bond has an influence on the choice of the adhesive itself, regarding for example strength, curing process, surface treatment of the adherend and temperature stability.

More information on surface treatments of the adherends can be found in section 12 of ECSS-E-HB-32-21.

In case the needed performance cannot be achieved with the adhesives and surface preparations available, the design is changed to generate a more bonding-friendly setup (see Figure 4-2) or change to another (for example mechanical) joining mechanism

4.4 Adhesive bonding process

The adhesive bonding process is generally taken into account in early stages of the project.

The amount of time and personnel needed to perform the bonding depends on parameters like, the overall surface area, type of surface treatment, possible primer application, pot life and curing of the adhesive.

The bonding process steps can be described in individual procedures. For example the adhesive bonding procedure can refer to sub- procedures.

Examples of adhesive bonding process steps:

a. Preparation of bonded parts (degreasing, cleaning, ultrasonic bath with organic solvents, drying condition)

b. Surface treatment (by mechanical, chemical and physical means)

c. Surface post-treatment (incl. final surface cleaning, preservation if not bonded immediately)

d. Surface activation (by mechanical, chemical and physical means)

e. Surface quality verification (for example surface energy, roughness, wettability)

f. Positioning and alignment of adherends

g. Adherend priming (if any)

h. Adhesive preparation (including mixing)

i. Adhesive application

j. Adhesive curing in bonded assembly

k. Bonded assembly verification (NDI inspection after cure – visual, dimensional check, mechanical load proof test)

NOTE The same process steps are applicable for in-process samples.

In case of adherends are sensitive to ageing in storage conditions (UV, humidity, temperature over time) specific surface preparation process can be applied to remove the affected surface layer.

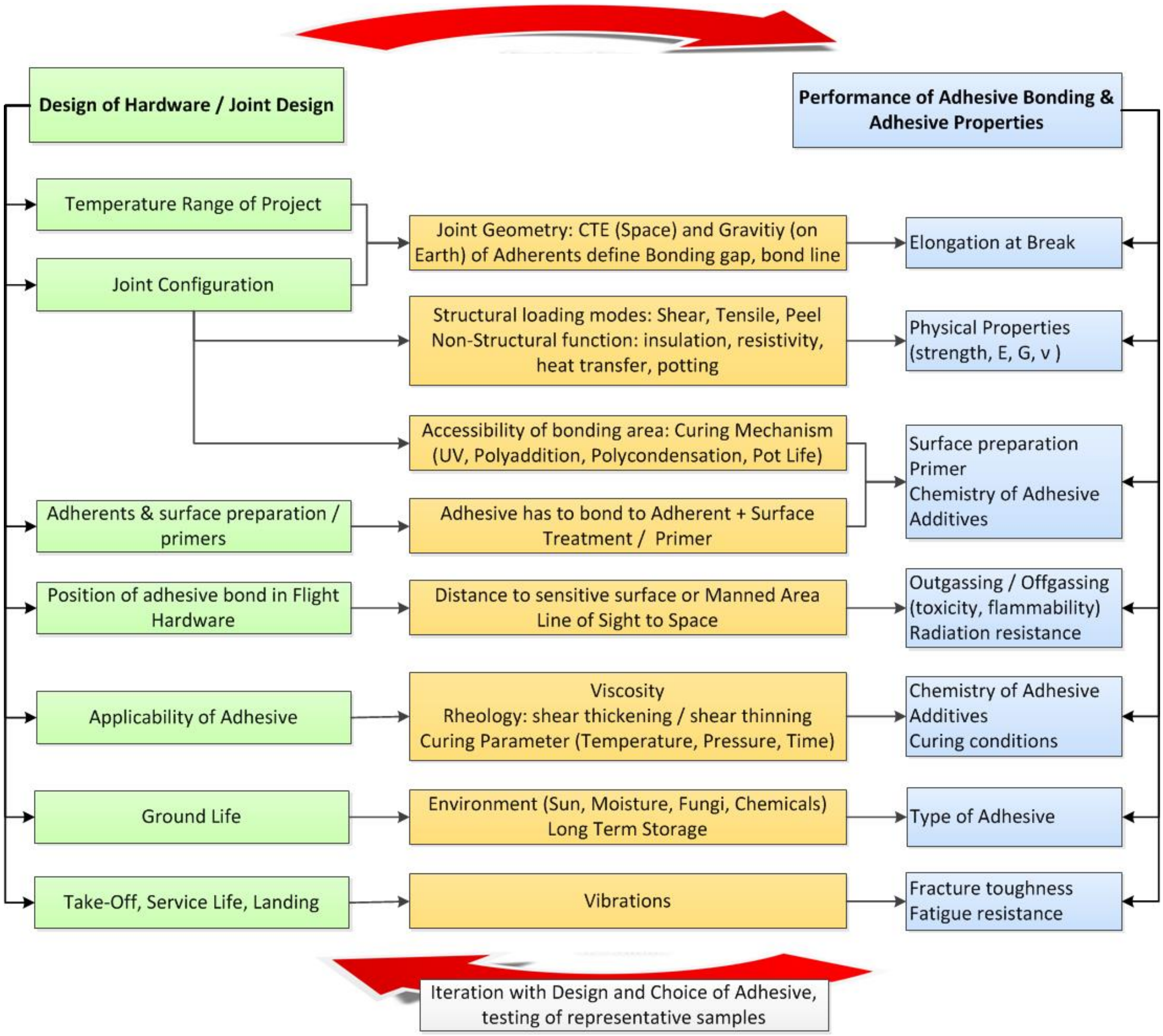

Figure 4-2: Overview on some parameters influencing the adhesive bond and its design

For more detailed design chart see Figure 10.16-1 in ECSS-E-HB-32-21.

5 Selection of adhesive

5.1 Overview

The selection of an appropriate adhesive depends on a wide range of factors from early stage of manufacturing over service life till the end of mission. The ECSS Adhesive Bonding Handbook ECSS-E-HB-32-21 gives information about adhesive characteristics and properties and adhesive selection.

5.2 Analysis of adhesive application

a. Selection of materials for adhesives shall be in compliance with requirements from clause 5 of ECSS-Q-ST-70.

NOTE Requirements from clause 5 of ECSS-Q-ST-70 include: for example: vacuum, radiation, moisture.

b. Selection of adhesives shall be in compliance with clause 4.2.11 of ECSS-Q-ST-70-71.

c. Depending on the cured adhesive properties, selection of adhesives shall be in compliance with requirements from clauses 4.2.17, 4.2.18 and 4.2.19 of ECSS-Q-ST-70-71.

NOTE Adhesive materials can be also grouped to elastomers (clause 4.2.17), thermoplastic (4.2.18) and thermosets (4.2.19).

d. Selection of adhesive tapes shall be in compliance with clause 4.2.12 of ECSS-Q-ST-70-71.

e. The outgassing characteristics of selected adhesive material in cured state shall be in compliance with requirements from clause 5 of ECSS-Q-ST-70-02.

NOTE For launcher applications when the adhesive material is not facing the spacecraft (for example lower stagers of launcher, ground segment support applications), the requirements on cleanliness and contamination and outgassing specified in clause 5 of ECSS-Q-ST-70-02 can be tailored.

f. An assessment of the bonding application shall be performed as basis for the adhesive selection.

g. The assessment should include, but is not limited to:

1. Joints design
   (a) Mechanical loads
   (b) Thermo-mechanical loads
   (c) Adherends
   (d) Geometrical Configuration
   (e) Shape of the bondline
2. Adhesives properties
   (a) Mechanical properties
   (b) Thermo-mechanical properties
   (c) Offgassing
   (d) Moisture sensitivity
   (e) Appearance
   (f) Specific properties
3. Processing
   (a) Surface preparation of adherends
   (b) Curing conditions: time to full cure, temperature, pressure, humidity, time to handling strength
   (c) Viscosity
   (d) Pot life
   (e) Manual or machine processing
   (f) Packaging
4. Ground, launch, and in-orbit environment
   (a) Radiation
   (b) Vacuum
   (c) Temperature range
   (d) Thermal cycling
   (e) Chemical compatibility
   (f) Storage time and storage conditions
5. Procurement
   (a) Cost factors
   (b) Lead time
   (c) Export control
   (d) Obsolescence risk
6. Health and safety

   NOTE 1 For requirement 5.2g.1(e): The shape of the bondline refers, for example, to the presence/absence of an outer fillet (excess glue)

NOTE 2 For requirement 5.2g.2(d): Sensitivity can be related to water absorption, water content in the adhesive, water desorption, CME, water diffusion.

NOTE 3 For requirement 5.2g.2(d): Accelerated hot-wet tests can be performed within screening activities in order to determine the moisture sensitivity of representative assembly.

NOTE 4 For requirement 5.2g.2(e): Optical applications can require either transparent or dark glues.

NOTE 5 For requirement 5.2g.2(f): Specific properties include electrical, thermal, optical, thermo-optical properties.

NOTE 6 Further information about selection of adhesives can be found in section 7 of ECSS-E-HB-32-21.

h. Adhesives properties should be analysed based on:

1. Supplier information

2. Materials data bases

3. Data of tests relevant to the specific application

NOTE 1 Examples of Materials databases are: MAPTIS (NASA), ESMAT (ESA), MATREX (CNES), Granta MI, ESMDB, MIL handbooks.

NOTE 2 Examples of tests can be found in Annex D, Annex E and section 15 of ECSS-E-HB 32-21.

NOTE 3 Further information on adhesive characteristics and properties can be found in a section 6 of ECSS-E-HB-32-21.

NOTE 4 Tests applied for generation of missing data are based on national or international standards, list of tests can be found in Annex D, Annex E.

i. Optical properties of adhesives inside the optical path should be tested on component level.

NOTE This is to demonstrate the suitability of adhesives optical properties with respect to optical design.

j. For application of adhesive tape for passive thermal control requirements from clause 4 of ECSS-Q-ST-70-09 shall apply for thermo-optical measurements.

NOTE Tape application procedure can have an impact on the tape thermo-optical properties.

k. For pressure sensitive tapes serving without polymerisation of adhesive layer, service temperature range should be verified.

6
Definition of adhesive bonding process

6.1 Adhesive bonding process requirements

a. The adhesive bonding process shall be in compliance with requirements specified as in clause 4.3.1 of ECSS-Q-ST-70-71.

b. Process control of adhesive bonding shall be performed in compliance with requirements from clause 7 of ECSS-Q-ST-70.

c. The adhesive bonding process shall be performed according to adhesive bonding procedure specified in DRD Annex A.

d. Adherends and adhesive materials shall have a same temperature as the processing environment in order to avoid condensation during the bonding process.

NOTE 1 This means conditioning to working temperature of materials taken from colder or warmer places than the bonding area.

NOTE 2 This can be described by an additional step: conditioning prior bonding.

6.2 Adhesive bonding procedure

a. An adhesive bonding procedure shall be issued by the supplier according to DRD Annex A.

NOTE 1 Preparation of bonding procedure is considered as a multidisciplinary task.

NOTE 2 The bonding procedure can be a single document or split into several documents.

b. The operators executing the bonding process shall proceed according to adhesive bonding procedure.

c. Training of the operators shall be done according to requirements in clause 8.9.

6.3 Adhesive bonding process traceability

a. For process traceability the requirements from clause 5.2.5 of ECSS-Q-ST-20 shall apply.

b. Date of the bonding process execution shall be recorded.

c. Batch or production lot number of primer and adhesive material used for bonding process shall be recorded.

d. Operator identification shall be recorded.

7 Verification of adhesive bonding

7.1 Overview

Constraints encountered on adhesive bonding on the flight hardware are important to be carefully analysed to determine the adequate test methods.

In order to make sure that the performance of the flight hardware is as expected, test methods on test item basis are selected accordingly. This means that for example the type and direction of load are the same.

7.2 Adhesive bonding test plan

a. The supplier shall issue an adhesive bonding test plan according to the DRD in Annex B for customer approval.

b. The adequacy and reliability of a bonding configuration and its associated process shall be demonstrated through a verification test sequence.

NOTE A bonding configuration is defined as a minimum by the adherends, the adhesive and the bonding process, see clause 7.9.

c. Adhesive bonding performance properties to be tested shall be selected according to application needs.

NOTE 1 The bonding application assessment as described in clause 5.2 can be used to determine these parameters.

NOTE 2 The test item configuration is linked to the properties to be characterized.

d. In the adhesive bonding test plan the supplier shall list all tests and inspections used during sub-sequential steps of verification test sequence in conformance with requirements from clause 7.9.

e. The pass-fail criteria of the verification test sequence shall be specified by the supplier and submitted as part of the adhesive bonding test plan for customer approval.

7.3 Adhesive bonding test report

a. The results of the test shall be documented in the adhesive bonding test report in conformance with the DRD from Annex C.

7.4 Test item bonding procedure

a. The bonding procedure shall be in compliance with the DRD from Annex A.

b. The bonding procedure used for test item shall be representative of flight hardware manufacturing.

c. Any deviation between test items and flight hardware bonding procedure shall be justified and submitted for the customer approval.

NOTE Deviations can be related to differences in adhesive application, tooling and manufacturing environment.

7.5 Test item configuration

a. Test items shall be representative of flight hardware configuration as a minimum for the following:

1. Adhesive preparation and curing
2. Adhesive application
3. Primer preparation and curing
4. Primer application
5. Adherend materials
6. Adhesive thickness
7. Surface finishing of adherends
8. Geometry
9. Dimensions
10. Surface preparation

NOTE to item 7.5a.5: for metallic alloy family the chemical composition can be important.

b. Any deviation between test items and flight hardware configuration shall be submitted for customer approval.

NOTE The justification rational can be included in the adhesive bonding test plan.

c. Deviations in test item from flight hardware shall be justified for following:

1. Adherends materials
2. Adhesive thickness
3. Curing cycle

4. Surfaces finishing of adherends
5. Geometry
6. Dimensions
7. Sandwich panel configuration
8. Surface preparation

d. Deviations in test item from flight hardware configuration shall not be allowed for following:

1. Mix ratios for multi-component adhesives including fillers
2. Mix ratios for multi-component primers
3. Primer application method

e. In case a standard repair process of adhesive bond exists, the test items shall be manufactured and tested according to verification sequence.

NOTE As an example can be debonding of MLI struts, additional fixtures in cabling.

7.6 Handling and storage

a. The conditions for handling and storage of materials used in adhesive bonding process shall be available to all operators and supervising staff.

b. The test item shall only be handled with clean, powder-free and lint-free gloves compatible with all compounds used.

NOTE For example the chemical compatibility between solvents, cleaning agents, adhesives, primer and manufacturing tools can play an important role.

c. Test items shall be stored in a controlled area, with an ambient temperature of (22 ± 3) °C and relative humidity of (55 ± 10) %.

d. When test items are handled, contamination shall be avoided.

e. Protective material may be used to avoid contamination on sensitive surfaces.

NOTE 1 Protective material can be polyethylene or polypropylene.

NOTE 2 Sensitive surface can be:

- surface treated prior priming,
- primed surface prior bonding,
- the fracture surface of analysed joint after functional or destructive test.

f. Use of a protective material is part of the handling procedure and shall be included in the verification sequence.

g. To avoid any damage the test items may be packed in clean, dust- and lint-free material.

h. Limited-life time materials shall be labelled with their shelf lives, dates of manufacture or date of delivery if date of manufacture is not known, and the lot number.

7.7 Test item identification

a. The supplier shall mark all test items with identification to maintain traceability in a way not to degrade the quality of the test item during testing.

NOTE This includes also untested spare test items.

b. The supplier shall maintain the traceability of the following details of the test items submitted for testing:

1. Identification code of the test item
2. Configuration control status
3. Details of supplier of the assembly
4. Type of product
5. Adherend and adhesive materials
6. Processing details, reference to adhesive bonding procedure
7. Batch numbers
8. Test item quantity
9. Test item manufacturing date
10. Prepared by

7.8 Hazard, health and safety precautions

a. The supplier shall identify, manage and process materials and parts with hazardous characteristic according to requirements from clause 5 to clause 8 of ECSS-Q-ST-40.

b. The supplier shall keep the health and safety precautions according to the supplier’s national safety regulations.

c. The details of hazards for each material used in the process shall be known to all personnel involved in the application.

d. Operators and supervising staff shall have access to Material Safety Data Sheets that are used in adhesive bonding process.

e. Hazards to personnel, equipment, environment and materials shall be controlled and reduced to the risk specified in supplier’s in-house procedures.

NOTE Hazard can be reduced by using protective clothing.

7.9 Verification test sequence

7.9.1 General

a. For the purpose of verification test sequence the supplier shall identify the parameters affecting the performance of adhesive bond within its life cycle.

NOTE Figure 4-2 shows some parameters from on ground-life phase, pre-launch, launch and early orbit phase and mission.

b. The verification test sequence shall be in accordance with the flow chart from Figure 7-1.

NOTE The verification sequence based on Flow chart from Figure 7-1 can be tailored depending on the application needs. For example it is not always necessary to have intermediate verification steps (Set of Test Items 2 tested after on-ground exposure simulation test and 3 tested after launch environmental exposure can be optional, represented by dashed lines with arrows Figure 7-1).

c. After each environmental exposure step inspection of the test item set should be performed.

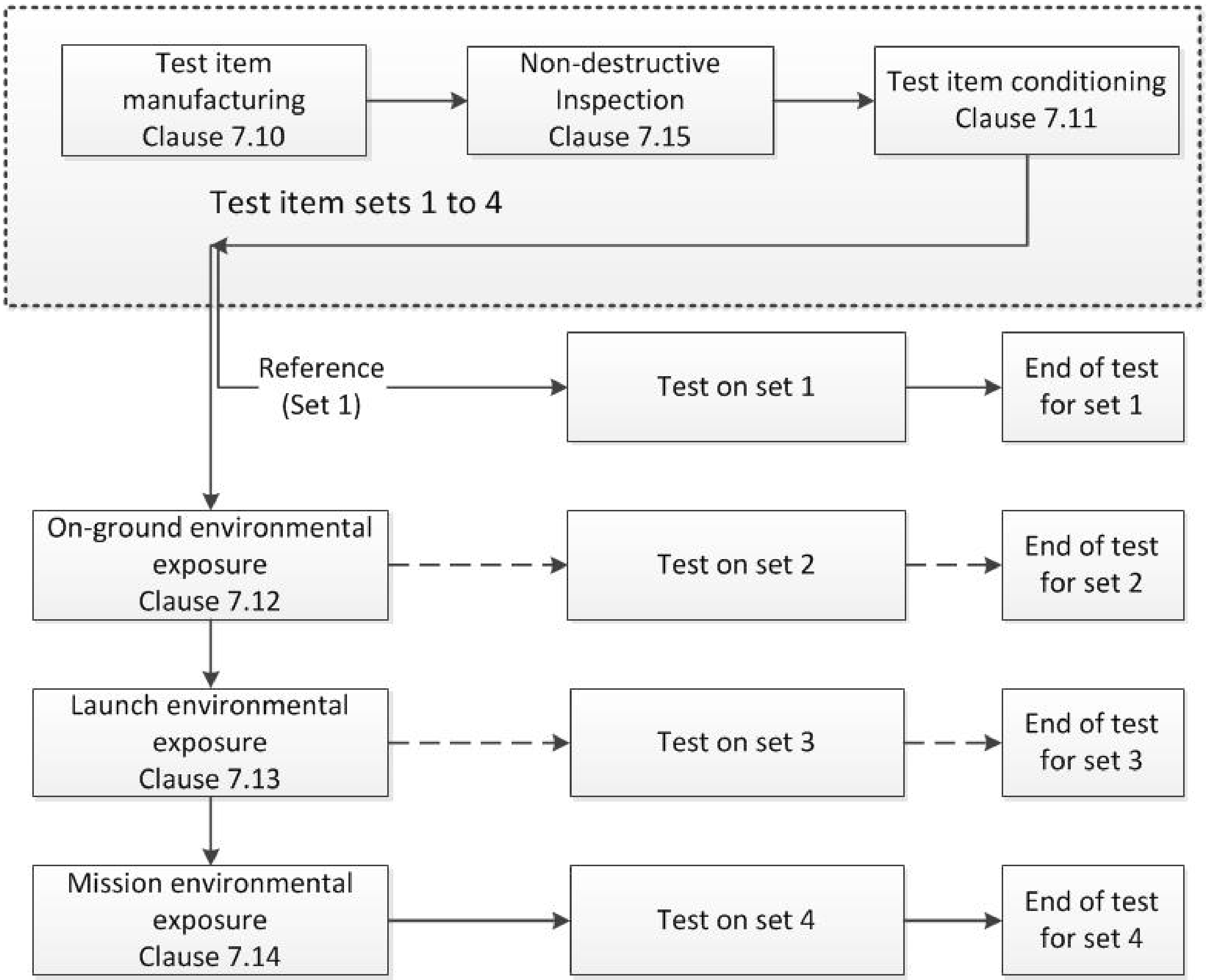

Figure 7-1 Flow chart with adhesive bonding verification sequence

7.10 Test item manufacturing

a. Test items shall be manufactured in accordance with requirements from clause 7.5.

b. The number of test items in a test item set shall be as a minimum five.

c. The number of test items may be reduced upon customer agreement.

d. The test items sets should originate from the same test item population.

7.11 Test item conditioning

a. Any conditioning step performed on flight hardware shall be applied to test items.

NOTE Examples of conditioning steps are:

- Heat treatments performed in manufacturing steps after bonding
- Bake-out

- Thermal cycling performed in screening activities
- Conditioning between environmental exposure and performance test

b. Thermal cycling tests performed as conditioning steps specified in requirement 7.11a may be combined with simulation of mission environmental exposure specified in requirements from clause 7.12.

7.12 Simulation of on-ground environmental exposure

a. The supplier shall demonstrate the robustness of adhesive bonding in relevant on-ground environment.

NOTE Relevant on-ground environment is the environment that the item is exposed to during entire duration between bonding and launch.

b. Demonstration may be based on experience, adhesive bonding process heritage or test.

NOTE The term heritage is defined in Table 5-1 of ECSS-E-ST-10-02.

c. For launcher applications the hot-wet exposure shall be part of the verification sequence of structural bonds.

NOTE 1 The list with examples of conditioning and durability standards see Table F-4 and Table F-5 respectively.

NOTE 2 Next to the humidity there can be other specific environments contributing to the degradation of the adhesive bond.

d. For spacecraft applications the sensitivity to atmospheric humidity shall be assessed.

NOTE 1 Sensitivity of adhesive bond performance to humidity can be interpreted as negative impact on the key property: for example mechanical, electrical, dimensional, thermo-optical properties.

NOTE 2 For criticality of the adhesive bonding application see Table F-1.

NOTE 3 For the sensitivity assessment of adhesive bond to humidity see Table F-2.

NOTE 4 Necessity to implement the hot-wet exposure into verification sequence can be found in Table F-3.

e. For spacecraft applications exposed to cleanroom-controlled environment the hot-wet exposure need not to be always performed.

NOTE 1 Cleanroom-controlled environment defined in ECSS-Q-ST-70-01, with temperature in the range of (22 ± 3) °C, and relative humidity (55 ± 10) %.

NOTE 2 The examples of humidity highly-sensitive, sensitive and non-sensitive applications are presented in Table F-2.

NOTE 3 The example of assessment for necessity to implement the hot-wet exposure into verification sequence can be found in Table F-3.

f. In case the hot-wet exposure is performed, the temperature, relative humidity and duration of the exposure shall be agreed with the customer.

NOTE The list with examples of conditioning and durability standards are given in Table F-4.

g. For the hot-wet exposure specified in 7.12f water condensation on the test item shall be prevented.

NOTE 1 An efficient way to avoid condensation is to increase the relative humidity only after the test items are at the given exposure temperature.

NOTE 2 A cover can prevent that accidentally condensed water drops down onto the test items from the ceiling of the test chamber.

h. For the hot-wet exposure specified in 7.12f purified water of a quality ISO Grade II, or better, as defined in ISO 3696:1987 or equivalent shall be used.

NOTE The detailed water purity requirements are also defined in ASTM D1193-06:2011.

7.13 Simulation of launch environmental exposure

7.13.1 Overview

Launch environmental exposure means mechanical loads, thermal exposure or a combination of both, that act on the flight hardware during launch.

Launch environment mechanical load testing at test item level is usually not necessary. It is generally performed when adhesive bonds are submitted to complex loads that are difficult to model.

7.13.2 Test definition

a. Launch environment test conditions shall be agreed with the customer.

b. Launch environment test conditions should be derived from system level requirements.

c. Thermal exposure relevant to launch phase may be combined with simulation of mission environmental exposure.

d. Mechanical load testing may consist of:

1. Vibration testing: quasi static, random, sinus, acoustic
2. Shock testing.

7.14 Simulation of mission environmental exposure

7.14.1 Overview

In-orbit environmental exposure is mainly related to thermal cycling of the adhesive bond.

In special applications, radiation (UV, electrons, protons) and ATOX tests can be necessary. Tests are generally performed in the frame of a dedicated verification test flow.

NOTE 1 Radiation testing is addressed in ECSS-Q-ST-70-06.

NOTE 2 Thermal cycling tests are not applicable for launchers except of in-orbit upper parts.

7.14.2 Thermal cycling test conditions

a. A minimum of 25 thermal cycles shall be performed.

NOTE 1 Generally 25 cycles cover acceptance or qualification thermal cycling at unit level with margin.

NOTE 2 ECSS-Q-ST-70-04 can be used as a guideline.

NOTE 3 The atmosphere in the test chamber can have an impact on adhesive joint performance.

NOTE 4 For ambient pressure chambers an inert gas can be used to reduce oxidation effects within thermal exposure.

b. As a minimum the first five thermal cycles should be performed in vacuum for vacuum sensitive configurations.

NOTE Vacuum sensitive configurations include but are not limited to:

- Adhesive tapes
- Foil heaters
- Thin or flexible adherends
- Radiator foils
- Solar reflectors
- Any assembly crossing *Tg* temperature of its adhesive material during the thermal cycling

c. In addition to requirement 7.14.2a additional thermal cycles shall be performed according to the project specification.

NOTE 1 The additional thermal cycles are typically performed to simulate ageing effects.

NOTE 2 The additional thermal cycles can contain long term thermal endurance exposure, for example cruise phases of probes.

d. For thermal vacuum cycles, the pressure level shall be less than 5 x 10^{-3} Pa.

e. For thermal vacuum cycling, the pressure shall be recorded.

f. The temperature range shall cover the mission qualification thermal requirements.

NOTE Mission specific qualification temperature for the bonding, taking into account all phases on ground, launch and during the mission

g. Temperature extremes shall be maintained during the dwell time within the intervals *Tmax* -0/+5 °C and *Tmin* +0/-5 °C.

h. The minimum dwell time at each temperature extreme shall be not less than five minutes.

i. The heating and cooling rate shall be less than 10 °C per minute.

NOTE Maximum rate is specified in order to avoid thermal shock.

j. The test item temperature shall be monitored to verify that the specified temperature is achieved.

k. The temperature sensor should be placed as close as possible to the adhesive bond.

NOTE An additional test item can be used if it is not possible to place a sensor directly on the qualification test item.

7.15 Inspection and testing before, during and after verification sequence

a. The supplier shall perform the inspection according to requirements in clause 8.8.

b. Test of test item set shall be performed according to adhesive bonding test plan specified in the 7.2.

8 Quality assurance

8.1 Overview

The role of quality assurance in adhesive bonding is to ensure that:

- Materials stipulated in the design are obtained, stored and used correctly; as stated in the procurement specification and confirmed by incoming inspection.
- Each joint made meets the materials and process specification(s) and is fully documented, test data are accumulated and that the bonded structure is qualified for space use,
- Bonded-joint data acquired from testing, inspection or in-service experience are 'fed-back' into manufacturing documentation. Previously accumulated data can aid the design process for all subsequent, similar, structures.

The performance of adhesive bonds is strongly linked to the application and strict control of every manufacturing process step. Adequate training, along with regular monitoring and documentation, of personnel involved in any bonding-related process is an essential part of the quality assurance system.

Besides all the materials and processes needed for the adhesive bonding, the training of personnel is a key factor for successful adhesive bonding. There are many possible causes for human error like for example bad mixing, exceeding of pot life, insufficient surface preparation and many more.

General information regarding quality control of adhesive bonding can be found in section 14 of ECSS-E-HB-32-21.

8.2 General

a. The quality assurance requirements specified in clause 5 of ECSS-Q-ST-20 shall apply.

8.3 Procurement

a. Procurement of all materials needed for the adhesive bonding shall be in conformance with clause 5.6.1 of ECSS-Q-ST-70.

NOTE Materials to be considered are for example raw materials, adhesives, filler materials, as well as adherends manufactured and pre-treated (for example plated, conversion coated) for bonding.

b. The supplier shall inform the customer upon request of any change of material composition, material testing and stop of production.

NOTE Further information on possible parameters to be checked can be found in section 14.4 of ECSS-E-HB-32-21.

8.4 Incoming inspection

a. All materials used in adhesive bonding process shall be submitted to an incoming inspection.

b. Incoming inspection shall be performed on each batch in compliance with clause 5.4.4. from ECSS-Q-ST-20.

c. In-coming inspection may include:

1. Surface finish of adherends
2. Expiry dates of adhesive components
3. Visual criteria
4. Chemical composition
5. Microstructural analysis of adherends
6. Crosscheck of relevant properties stated in certificate of analysis (CoA) of adhesive materials with results of in-house analysis.

NOTE Further information on possible parameters to be checked can be found in chapter 14.4 of ECSS-E-HB-32-21.

8.5 Traceability

a. Traceability of materials shall be handled in conformance with clause 5.7.2 of ECSS-Q-ST-70.

b. As adhesive materials have a limited shelf life the supplier executing bonding process shall establish a control system for verification of the validity of the material used in adhesive bonding process in compliance with requirements from clause 4 of ECSS-Q-ST-70-22.

NOTE This applies for surface treatment agents, adhesives, additives, primers, sealants or potting compounds.

c. Traceability of the bonding processes shall be performed in accordance with clause 6.3.

8.6 Tooling and equipment control

a. The supplier shall ensure that manufacturing equipment and tooling has no detrimental effect on the bonding process.

NOTE For example cleanliness provisions, no contamination with unwanted chemicals, no visual defects

b. Calibration control shall comply with requirement from clause 5.2.6 of ECSS-Q-ST-20.

c. The supplier shall ensure that all automated adhesive application systems are calibrated.

d. Selection of tooling and equipment shall conform to the requirements from clause 5.2.6 of ECSS-Q-ST-20.

8.7 Workmanship

a. The quality of the workmanship shall be monitored.

b. Bonded assemblies shall be free of defects that affect intended use.

NOTE For example cracks, entrapped air, discoloration, particles can affect bonding performance.

c. The supplier shall ensure quality of workmanship by implementing defined workmanship checks based on the dedicated bonding configuration.

NOTE For example check of visibility of adhesive at bond line edges, measurement of adhesive mass, control of temperature of the mixture, bond line thickness control, bonded area verification

d. The supplier shall specify adhesive bonding in-process control.

NOTE For example proof testing, in-process samples, visual inspection, adhesive cure check.

e. Adhesive bonding assembly shall not lose any macroscopic particles contributing to particulate contamination of the spacecraft.

NOTE The example of particulate release can be adhesives not covered by adherends after exposure to mechanical environment.

f. Cross-contamination between different chemical families shall be avoided.

NOTE 1 For example cross-contamination between silicones and other adhesives, between hardener and resin pots.

NOTE 2 Cross-contamination can be avoided for example by using dedicated tooling for different products, or by thoroughly cleaning tooling before using the next product.

NOTE 3 Change of gloves can be useful to avoid cross contamination.

NOTE 4 Separate rooms can be useful to avoid cross contamination between for example silicone adhesives and epoxy adhesives.

8.8 Inspection and bonding process control

a. Inspection procedure shall meet the requirements for inspection procedures from clause 4.3.16 of ECSS-Q-ST-70-71.

b. NDI inspection of adhesively bonded joints shall be in compliance with requirements of clauses 6, 8 and 9 of ECSS-Q-ST-70-15.

c. The supplier shall specify acceptability criteria for the inspection of bonded joints.

NOTE 1 Depending on the process and the configuration different acceptability criteria can be necessary.

NOTE 2 Supplier can introduce in-process samples.

d. Visual standards of bonded joint consisting of photos or drawings or other visual aids that clearly illustrate the quality characteristics needed should be available to each inspector.

NOTE The visual standards can be examples of acceptable and unacceptable bond lines.

e. The supplier shall perform an inspection on all qualification and flight hardware bonding.

f. The inspection shall not be performed only by the operator executing the bonding process.

NOTE 1 Four-eyes principle.

NOTE 2 For large number of identical bonded joints, inspection can be performed on a sampling basis.

NOTE 3 Typical defects can be reported in defect catalogue.

g. Personnel involved in the inspection and testing of adhesive bonds shall have an appropriate qualification and valid certificate.

NOTE 1 For example use of non-destructive testing equipment for defect detection (Visual inspection, Ultrasonic inspection, X-ray tomography, Microscopic inspection).

NOTE 2 Inspection can be part of bonding process but also an independent process.

8.9 Operator and inspector training

a. Operators performing adhesive bonding processes shall be trained and certified.

b. Inspectors for adhesive bonding shall be trained and certified.

c. Training shall be performed at an adhesive bonding school or by certified external bodies or by approved in-house instructors.

d. In-house instructors shall be nominated by the company with involvement of quality assurance responsible.

e. Training and certification may be performed according to in-house standards or external training and certification scheme

NOTE External certification scheme and certification bodies can be found in Annex G.

f. Training shall include at least the following points:

1. Adhesive bonding process
2. Complexity of configurations
3. Reproducibility
4. Handling of raw materials, process chemicals and equipment
5. Cleanliness and contamination control of environment, materials and equipment
6. Safety-related aspects of materials and process chemicals.

NOTE Examples of complexity of configurations are complex shapes, fragile or sensitive materials, multi-step integration processes.

g. Training specified in requirements 8.9f.4, 8.9f.5 and 8.9f.6 may be implemented in a dedicated training.

h. Skills status of all operators for adhesive bonding shall be traced in suppliers’ internal system.

i. The supplier shall specify the need for re-training and re-certification of operators.

NOTE For example in the event of a new process, modification to an existing process or a change of the equipment used.

j. The supplier shall specify the need for re-training and re-certification of inspectors.

NOTE For example in the event of a new inspection procedure, modification to an existing inspection procedure or a change of an existing one.

8.10 Nonconformance

a. Nonconformances shall be managed in conformance with requirements from the clause 5 and 6 of the ECSS-Q-ST-10-09 and clause 5.2 of ECSS-Q-ST-10.

Annex A (normative) Adhesive bonding procedure – DRD

A.1 DRD identification

A.1.1 Requirement identification and source document

This DRD is called from ECSS-Q-ST-70-16, requirements 6.1c and 6.2a.

A.1.2 Purpose and objective

The purpose of this document is to provide a detailed adhesive bonding procedure containing all steps necessary to perform adhesive bonding.

A.2 Expected response

A.2.1 Scope and content

a. The following adhesive bonding parameters shall be documented in the adhesive boding procedure:

1. List of adherend, adhesive and primer materials
2. List of equipment to be used during overall bonding process
3. Environmental working conditions
4. Positioning and blank mating of adherends to be bonded, dimensional verification
5. Surface preparation of adherends
6. Definition of time delay between surface preparation and execution of bonding
7. Storage conditions after surface preparation of adherends
8. Preparation of primer
9. Preparation of adhesive
10. Means of application of adhesive
11. Fixture load or pressure applied during curing
12. Curing schedule, including temperature, dwell time
13. Adhesive bonding process control

NOTE 1 to item A.2.1a.3: Examples of environmental working conditions are relative humidity, temperature, pressure and cleanliness of work place.

NOTE 2 to item A.2.1a.5: surface preparation include cleaning, sanding, chemical treatments, priming.

NOTE 3 to item A.2.1a.6: surface chemistry of adherend parts can evolve within few hours after surface preparation.

NOTE 4 to A.2.1a.8: preparation of primer includes mixing ratio, pot life, evaporation or curing time.

NOTE 5 to A.2.1a.9: preparation of adhesive includes mixing ratio, pot life, degassing of the mixture.

NOTE 6 to A.2.1a.10: means of application of adhesive are for example airbrush, foil adhesive roller or dispenser, brush, syringe, spatula, injector.

NOTE 7 to A.2.1a.12: heating and cooling rates can be key parameters for some type of adhesive systems.

NOTE 8 to A.2.1a.12: the minimum time for safe handling can be different compared to full curing.

NOTE 9 to A.2.1a.13: visual, dimensional verification, health monitoring (NDI, proof loads, witness samples).

A.2.2 Special remarks

None.

Annex B (normative) Adhesive bonding test plan - DRD

B.1 DRD identification

B.1.1 Requirement identification and source document

This DRD is called from ECSS-Q-ST-70-16, requirement 7.2a.

B.1.2 Purpose and objective

The purpose of this document is to provide a detailed adhesive bonding test plan containing all steps necessary to perform the verification of the adhesive bonding process.

B.2 Expected response

B.2.1 Scope and content

a. The adhesive bonding test plan shall contain the following information

1. Test objective
2. Test items
    - (a) Adhesive and adherend materials
    - (b) Representativeness of test items vs flight configuration
    - (c) Reference to the adhesive bonding procedure in conformance with DRD in Annex A
    - (d) Number of test sets and test items quantity in each set
3. Verification Test sequence
    - (a) List and designation of test item sets
    - (b) Applicable test procedures
    - (c) Applicable test standards
4. Pass-fail criteria

B.2.2 Special remarks

None.

Annex C (normative) Adhesive bonding test report -DRD

C.1 DRD identification

C.1.1 Requirement identification and source document

This DRD is called from ECSS-Q-ST-70-16, requirement 7.3a

C.1.2 Purpose and objective

The purpose of this document is to provide a detailed adhesive bonding test report containing all steps performed for the verification of the adhesive bonding process including all obtained results and conclusions of the test.

C.2 Expected response

C.2.1 Scope and content

a. The adhesive bonding test report shall contain the following information

1. Test objective
2. Reference to the applicable adhesive bonding test plan in conformance with DRD in Annex B
3. Test items
   (a) Adhesive and adherend materials
   (b) Representativeness of test items vs flight configuration
   (c) Reference to adhesive bonding procedure in conformance with DRD in Annex A
   (d) Number of individual test items and sets item sets tested during verification test sequence
4. Verification test sequence
   (a) List and designation of test item sets
   (b) Applicable test procedures
   (c) Applicable test standards
   (d) Sequence of consecutive exposures and inspections performed during verification sequence on each item set

5. Individual test item test results
6. List of nonconformances
7. Status of the process verification and definition of the process validity

NOTE Reference for adhesive bonding procedure can include the reference to record from manufacturing of bonded assembly or to manufacturing report.

C.2.2 Special remarks

None.

Annex D (informative) Examples of techniques used for adhesive material characterization (bulk)

D.1 Overview

This Annex presents a list of analytical methods and associated test standards which can be used to characterize bulk adhesive properties. These properties are suitable in order to select the best adhesives candidates for use at a dedicated bonding assembly.

The list of recommended test standards is given in the Table D-1 is not exhaustive. Relevant test standards can be found in ECSS-E-HB-32-21 Table 15.1-2 and the book written by G. Habenicht, 2009.

D.2 Rheology

Viscosity evaluation is of prime concern for manufacturing.

Viscosity of paste adhesive in uncured conditions can be evaluated by any appropriate means relevant to the bonding application.

NOTE 1 For bonding in vertical positions, the viscosity of adhesive can play an important role.

NOTE 2 If found relevant the injection capability can be evaluated.

Viscosity is useful to determine the ability of the adhesive to be injected or to be dispensed.

NOTE 1 For some dispensing systems it is important to take also the thixotropic characteristic into account.

NOTE 2 Some adhesive manufacturers determine the product's "pot life" as the duration after which the viscosity is twice the initial one.

NOTE 3 Determination of the viscosity is of primary concern w.r.t. manufacturing constraints.

NOTE 4 It is also important to determine gel point and pot life.

The following standards can be used for rheological measurements :

- EN 12092:2001 Adhesives. Determination of viscosity

- ASTM D 1824-16 Standard Test Method for Apparent Viscosity of Plastisols and Organosols at Low Shear Rates
- ISO 11443:2014 Plastics -- Determination of the fluidity of plastics using capillary and slit-die rheometers

Rheological test methods exist to determine the G′ G′′ crossing point to assess workability times, gel-points, evolution of complex viscosity during RT curing, thermally-accelerated curing (see Table D-1).

D.3 Outgassing

Outgassing test results provides the following values:

- Total Mass Loss (TML)
- Recovered Mass Loss (RML)
- Collected Volatile Condensable Material (CVCM)

These data are mandatory and need to be provided when an organic material is intended to be used for a space vacuum application (on orbit or in ground inside vacuum facilities).

The outgassing test method and acceptance criteria are covered in ECSS-Q-ST-70-02.

The adhesive materials are tested in such conditions which are representative to the flight hardware. For example two-component epoxy adhesive is tested after curing process representative to flight hardware application.

PSA tapes which do not undergo any deliberate curing step are tested as received.

D.4 Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) analysis can be used on non-polymerized product and on polymerized product.

On non-polymerized product, DSC analysis provides polymerisation enthalpy (generally exothermic). This can be useful:

- to compare or optimize curing schedule (temperature and duration),
- in case of extension of product shelf life.

On polymerized product, DSC analysis allows to:

- quantify potential residual polymerisation enthalpy (not fully cured product),
- determine glass transition temperature (Tg), melting temperature (Tm),
- evaluate the product degradation temperature.

The following standards can be used for DSC measurements:

- ISO 11357-2:2013 Plastics - Differential scanning calorimetry (DSC) - Part 2: Determination of glass transition temperature and glass transition step height
- ASTM D3418-15 Transition Temperatures of Polymers By Differential Scanning Calorimetry
- For other suitable standards see Table D-1

D.5 Thermogravimetric analysis (TGA)

To determine thermo-chemical stability of individual components in uncured state, mixed, multicomponent adhesives under curing conditions or cured adhesive materials.

Thermogravimetric Analysis (TGA) allows to measure:

- Product Mass loss
- Product degradation temperature
- Can be coupled with other analytical techniques (for example FTIR or GC-MS) to analyse thermally evolved products

The following standards can be used for TGA measurements:

- ASTM D3850–12 Standard Test Method for Rapid Thermal Degradation of Solid Electrical Insulating Materials by Thermogravimetric Method (TGA)
- ISO 11358-1:2014 Plastics - Thermogravimetry (TG) of polymers - Part 1: General principles
- For other suitable standards see Table D-1

D.6 Dilatometry and Thermomechanical Analysis (TMA)

Dilatometry or TMA is suitable for the determination of:

- Coefficient of Thermal Expansion (CTE)
- Glass transition temperature (*Tg*)
- Dimensional stability of the polymers

The following standards can be used for TMA measurements:

- ISO 11359-2:1999 Plastics - Plastics -- Thermomechanical analysis (TMA) -- Part 2: Determination of coefficient of linear thermal expansion and glass transition temperature
- ASTM D696 - 16 Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between −30°C and 30°C with a Vitreous Silica Dilatometer
- For other suitable standards see Table D-1

D.7 Dynamic Mechanical Analysis (DMA)

Dynamic Mechanical Analysis (DMA) typically can be performed under three mechanical loading modes :

- Tensile
- Compression
- 3 point bending

The following properties can be determined:

- Glass transition temperature (*Tg*)
- Young's Modulus
- Coulomb's Modulus (shear modulus)
- Damping Factor

The ASTM D4065-12 Standard Practice for Plastics: Dynamic Mechanical Properties: Determination and Report of Procedures, can be used for DMA measurements.

- For other suitable standards see Table D-1

D.8 Tensile strength and Young's modulus

Tensile strength testing on adhesive dog-bone shaped samples allow the measurement of:

- Young's modulus
- Yield strength (elastic limit)
- Ultimate tensile strength
- Elongation at break
- Poisson ratio

Suitable test standards: ISO 527-1 Plastics -- Determination of tensile properties -- Part 1: General principles, ISO 527-2 Plastics - Determination of tensile properties - Part 2: Test conditions for moulding and extrusion plastics, ASTM D638-14 Standard Test Method for Tensile Properties of Plastics

NOTE Other techniques for the determination of the tensile strength and modulus are often used, where the adhesive material is cured in test joint or assembly configuration, see in Table E-1 of Annex E.

D.9 Shear strength and shear modulus (adhesive material)

To address the shear properties in bulk, the materials are tested in non-bonded configuration. Dedicated tests serve to determine the bulk shear properties of the polymer:

- Shear elastic modulus
- Shear strength
- Elongation at break

ASTM E143-13 Standard Test Method for Shear Modulus at Room Temperature

NOTE Other techniques for determination of the shear strength and shear modulus are often used, where the adhesive material is cured in test joint or assembly configuration, see Table E-1 of Annex E

D.10 Compression strength and modulus

To address the compression properties in the bulk, the materials are tested in non-bonded configuration. Dedicated tests serve to determine the bulk compression properties of the polymer:

- Compression elastic modulus
- Compression strength
- Deformation at break

ASTM D 695-15 Standard Test Method for Compressive Properties of Rigid Plastics

Other techniques for determination of the compression properties can be used, where the adhesive material is cured in test joint assembly configuration, see in Table E-1 of Annex E

D.11 Electrical resistivity

Electrical resistance measurement allows to determine :

- Surface electrical resistance or resistivity and so respectively surface electrical conductivity
- Volume electrical resistance or resistivity and so respectively volume electrical conductivity

The following standards can be used :

- ASTM D257-14 Standard Test Method for DC Resistance or Conductance of Insulating Materials
- ASTM D4496-13 Standard Test Method for DC Resistance or Conductance of Moderately Conductive Materials

D.12 Thermal conductivity

Thermal resistance measurement allows to determine volume thermal resistance or resistivity and so respectively volume thermal conductivity

The following standards can be used:

- ASTM C177-13 Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus
- ASTM D5930-17 Standard Test Method for Thermal Conductivity of Plastics by Means of a Transient Line-Source Technique
- For other suitable standards see Table D-1

D.13 Thermo-optical properties

Thermo-optical properties are the following:

- Solar absorptance
- Infra-red emissivity

These properties are necessary in thermal analysis models if thermal radiative exchanges are not negligible. ECSS-Q-ST-70-09: Measurements of Thermo-Optical Properties of Thermal Control Materials provides different test method that can be used.

D.14 Transmittance

Transmittance measurement can be necessary for bonding in optical systems.

The following standards can be used :

- ISO 15368:2001 Optics and optical instruments -- Measurement of reflectance of plane surfaces and transmittance of plane parallel elements
- ASTM D1746–15 Standard Test Method for Transparency of Plastic Sheeting

D.15 Water absorption

Methods cover the determination of the relative rate of absorption of water by plastics when immersed. The following standards can be used:

- ASTM D570-98(2010)e1 Standard Test Method for Water Absorption of Plastics
- ASTM D5229/D5229M–14 Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials

D.16 Adhesive shrinkage

Adhesive volume shrinkage due to polymerisation can be evaluated by the difference of density between the uncured and cured adhesive.

Table D-1: Summary of relevant test standards for determination of bulk properties of adhesive material

Type of technique or material property	Relevant standards
Rheological measurements	EN 12092:2001, ASTM D1824-16, ISO 11443:2014, ISO 3219:1993, ISO 6721-10:2015
Outgassing	ECSS-Q-ST-70-02, ASTM E595-15
DSC techniques (Glass transitions, phase transition temperature)	ISO 11357-2:2013, ASTM D3418-15, ISO 11357-1:2016, ISO 11357-3:2018, ISO 11357-4:2014, ISO 11357-5:2013, ASTM D3418-15
Thermo-chemical stability (TGA)	ASTM D3850-12, ASTM E1131-08(2014), ISO 11358-2:2014, ISO 11358-1:2014
Thermo-mechanical (CTE by TMA or dilatometer)	ISO 11359-2:1999, ISO 11359-1:2014, ISO 11359-3:2002, ASTM D696-16, ASTM E831-03, ASTM E2113-04
Thermo-elastic properties (DMA)	ASTM D4065-12, ISO 6721-1:2011
Tensile properties	ISO 527-1:2012, ISO 527-2:2012, ASTM D638-14
Shear strength and modulus	ASTM E143-13
Compression strength and modulus	ASTM D695-15
Electrical Resistivity	ASTM D4496-13, ASTM D257-14
Thermal Conductivity	ASTM D5930-17, ASTM C177-13, ISO 22007-4:2017,
Thermo-optical	ECSS-Q-ST-70-09
Transmittance	ISO 15368:2001, ASTM D1746-15
Water absorption	ASTM D5229 / D5229M-14, ASTM D570-98(2010)e1

Annex E (informative) Characterisation of adhesive in bonded assembly configuration

E.1 Overview

There are a considerable number of test methods used to evaluate adhesive joints and to characterize the behaviour of adhesives in different loading configurations. Most of those that are of interest to the users are described in numerous test standards, for example from ASTM or ISO. The aim of this clause is to provide a brief overview of commonly evaluated properties and standardized test methods that can be applied in order to obtain comparable results.

To characterise individual adhesives, there are various test methods which assess fracture characteristics relevant to joint design.

Fracture mechanics concepts characterise the strength of adhesively bonded joints in terms of a critical value of an appropriate fracture parameter. This list is not exhaustive.

E.2 Adhesive bonding test

The properties of adhesives affect the static joint strengths and durability in fatigue. The fracture toughness of adhesives is important for long-life structures.

a. Adhesive bonding test includes:

1. Static joint strengths
2. Durability in fatigue
3. Fracture toughness
4. Environmental durability of the joints

NOTE 1 To characterise individual adhesives, there are various test methods which assess fracture characteristics relevant to joint design.

NOTE 2 Examples of standard tests for durability of the joints and test conditions can be found in Table F-4 and Table F-5 in Annex F.

E.3 Strength of bonded joints

E.3.1 Single Lap Shear Strength – thin adherends

This test is vastly used by adhesive bonding industry for the adhesive screening purposes, selection of adhesive, optimisation of bonding process. Due to its significant non-representativeness (thin adherents which deforms during the loading) this test is typically not used for definition of design allowables.

The list of relevant standards can be found in Table E-1.

- See single lap shear standards in Table E-1.

E.3.2 Lap shear –thick adherend test

In comparison to thin adherent test, this test method determines also shear modulus of the adhesive. The results are typically less affected by deformation of the adherend pieces and are of a lower scatter when compared with thin adherend test methods.

- ISO 11003-2:2001 Adhesives -- Determination of shear behaviour of structural adhesives -- Part 2: Tensile test method using thick adherends
- ISO 1827:2016 Rubber, vulcanized or thermoplastic -- Determination of shear modulus and adhesion to rigid plates -- Quadruple-shear methods

NOTE See standards listed in Table E-1.

E.3.3 Peel strength test

Peel strength depends on the definition of the test sample the loading configuration, strain rate and the nature of the materials. Therefore it is important to make the comparison between adhesive only if all the parameters are the same. This test is often used as in coming control of the product because it is cheap. This test allows to discriminate cohesive failure mode from adhesive one.

For the less flexible applications and for the peel strength determination of cured systems, other tests can be performed as for example

- Floating roller peel test according to EN 1464:2010, Adhesives. Determination of peel resistance of adhesive bonds. Floating roller method
- climbing drum test on bonded sandwiches, ASTM D1781 - 98(2012) Standard Test Method for Climbing Drum Peel for Adhesives

NOTE See standards listed in Table E-1.

E.3.4 Testing of peel strength on Pressure sensitive tapes (PSA)

There are certain types of standard tests dedicated to adhesive tape and can be performed under 2 directions:

- 90°
- 180°

NOTE Peel strength is the mean value of a measurement performed on a given length of a bonded tape.

The following standard can be used for bonded flexible foils, pressure sensitive tapes:

- ASTM D3330/D3330M-04(2010): Standard Test Method for Peel Adhesion of Pressure-Sensitive Tape
- EN 1939:2003 Self-adhesive tapes - Determination of peel adhesion properties, or equivalent

E.3.5 Tensile butt joint tests

Sometimes it is important to verify the behaviour of the bonded joints in tensile loading modes.

The following standards can be used :

- ASTM D897-08(2016): Standard Test Method for Tensile Properties of Adhesive Bonds
- ASTM D2095-96(2015) Standard Test Method for Tensile Strength of Adhesives by Means of Bar and Rod Specimens

E.3.6 Special tests

To address the performance of the joint under load modes which are representative to the foreseen application, it can be beneficial to design non-standard tests which fit the purpose of the application. Such test can be considered for example Arcan test approach, where both tensile and shear directions of the load can be applied on one type of the test specimen shape/assembly. Other standard test assemblies can exist with various loading modes:

- Cleavage modes
- Flatwise-tensile mode
- Torsion

E.4 Fracture mechanics of adhesively bonded joints

To address the fracture mechanics of adhesively bonded joint please see 15.1.4.1 of ECSS-E-HB-32-21.

The list of relevant standards can be found in Table E-1,

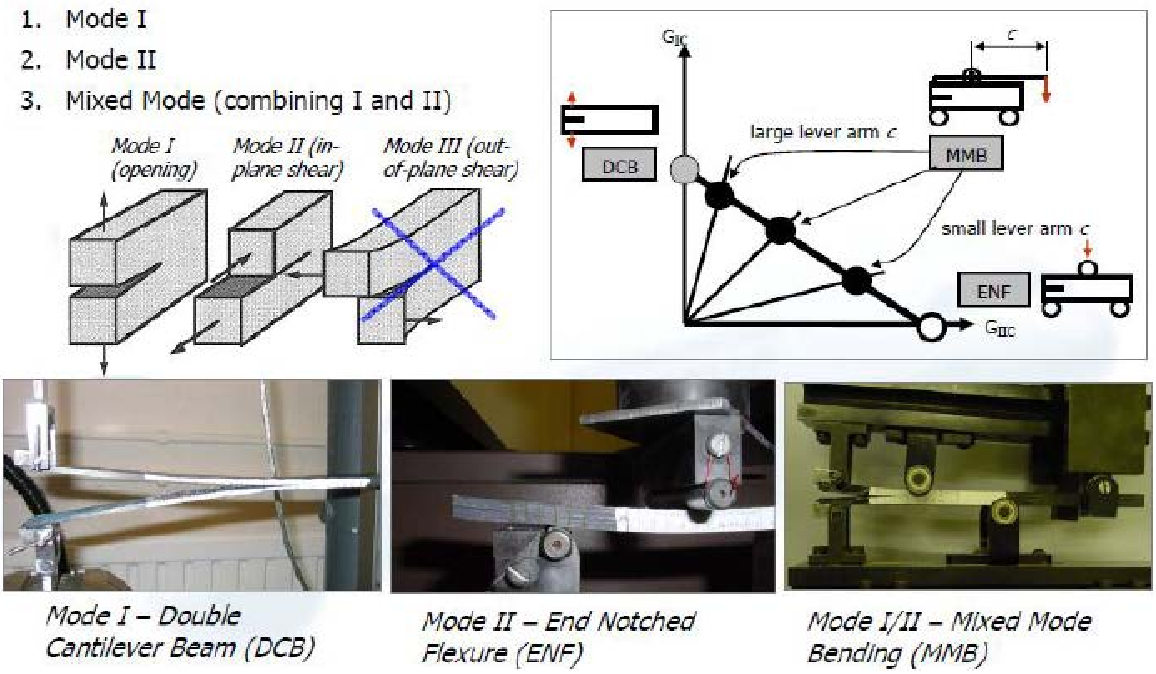

Figure E-1: Examples of fracture modes

E.5 Average stress criterion test methods

E.5.1 Overview

For adhesive tests using average stress criterion, there is an assumption that failure is controlled by the magnitude of the stress. Hence, tests are devised to measure the stress (generally an average) at which failure occurs. Most recognised standard tests are in the average stress criterion group.

E.5.2 Fracture mechanics test methods

a. Fracture mechanic test methods evaluate the quality of adhesives and design of bonded joints.

b. Fracture mechanics test methods evaluate presence of stress raisers in initiating failure.

E.5.3 Stress criterion test

a. The stress criterion test method includes:

1. Modulus
2. Strength
3. Fracture properties
4. Durability under tension
   (a) Purpose can be determination of design allowable under mechanical, thermal, or other relevant environment.

E.6 Adhesive characteristics to be verified by test (in bonded assembly)

Some of the commonly applied test methods are summarised, by specimen type, in Table E-1,. Test methods are often known by the name of the type of specimen used, rather than by their actual application. A detailed description of the test methods can be found in the related standards and the ECSS-E-HB-32-21 section 15.

Table E-1: Commonly applied test methods and related standards

Load mode	Test sample type	Key property	Standard number
Shear			
Shear by tension	Single-Lap	Tensile Lap Shear strength	ASTM D1002-10
			EN 1465:2009
			ASTM D2295-96(2016)
			ASTM D3163-01(2014)
			ASTM D5868-01(2014)
			ASTM D3165-07(2014)
			ISO 4587:2003
			BS 5350-C5:2002
			EN 2243-1:2005
	Single-Lap-thick adherends	Tensile Lap Shear strength & modulus	ISO 11003-2:2001
			EN 14869-2:2011
			ASTM D3983-98(2011)
			EN 2243-6:2005
			ASTM D5656-10(2017)
	Double-lap	Shear strength	ASTM D3528-96(2016)
Shear by compression	Pin-and-collar	Cylinder in cylinder compression shear strength	EN 15337:2007
			ASTM D4562-01(2013)
Shear in torsion	Butt-bonded hollow cylinders	Torsion shear strength & modulus	ISO 11003-1:2001
			BS EN 14869-1:2011
	Torsion butt joint	Torsional fatigue	Test described in: Prakash, V. et al., 1995
	Torsional shear test sample	Torque strength & modulus	DIN 54455:2016-09
		Torque strength and locking effect	ISO 10964:1993
			EN 15865:2009
Tensile			
Tensile	Tensile butt joint	Tensile strength	ASTM D897-08(2016)
			ASTM D2095-96(2015)
		Tensile strength and modulus	EN 15870 (2009)

Load mode	Test sample type	Key property	Standard number
Cleavage			
Cleavage	Wedge (cleavage)	Fracture energy, ageing proof, adhesion	DIN 65448 (1988-01)
	Compact tension	Cleavage strength	ASTM D1062-08(2015)
			BS 5350-C1:1986
	DCB - Flat, and DCB contoured	Fracture strength in cleavage, G1c and G1a	ASTM D3433-99(2012)
Peel			
Peel in roller	Thin to thick adherend plate	Peel strength	ASTM D3167-10(2017)
			EN 1464:2010
			EN 2243-2: 2005
			ISO 4578:1997
Peel, 90°	Flexible-bonded-to-rigid	Peel strength	EN 28510-1:2014
Peel, 90° and 180°	T-peel		ISO 8510-2:2006
Peel, 180°			ISO 11339:1993
			ASTM D1876-08(2015)e1
Peel (by hand)	Bead peel test	Qualitative test of adhesion	DIN 54457:2014-09
Bonded sandwich constructions			
Peel & Cleavage mix, 180deg	Laminated assembly, sandwich	Peel strength (average peel torque)	ASTM D1781-98(2012)
			EN 2243-3:2005
Tensile	Flat-wise tensile, laminated assembly, sandwich	Flatwise tensile strengths	ASTM C297 / C297M-16
			EN 2243-4:2005
Compression	Edgewise compression tests	Edgewise compressive strength	ASTM C364 / C364M-16
Bending	Long beam flexural	sandwich flexural stiffness, the core shear strength, and shear modulus	ASTM D7249 / D7249M-16e1

Load mode	Test sample type	Key property	Standard number
Tapes			
Peel, 90 and 180deg	PSA tapes, flexible thin foils, various configurations	Peel strength	ASTM D3330 / D3330M-04(2010)
Peel, 180deg	PSA tapes, flexible thin foils, various configurations	Peel strength	ASTM D903-98(2017)
Peel, 90 and 180deg	PSA tape, 180deg (its own adhesion) and 90deg to stainless steel panel	Peel strength	EN 1939: 2003
Shear by tension	PSA tape, Various configurations	Tape shear adhesion	ASTM D3654 / D3654M-06(2011)
Shear by tension	PSA tape, Various configurations	Tape shear adhesion	ISO 29863:2007
Static and dynamic, long-term stability			
Fatigue			
Shear by tension/compression (cyclic)	Single lap shear	Fatigue strength	ASTM D3166-99(2012)
			ISO 9664:1993
			EN ISO 9664:1995-08
Creep			
Shear by tension	Single lap shear	Creep strength in single lap shear	ASTM D2294-96(2016)
		Creep, time to rupture	EN 15336:2007
Impact resistance			
Shear in impact hammer	Shear impact test	Shear impact strength	ISO 9653:1998
			ASTM D950-03(2011)

Annex F (informative) Effects of the ageing on adhesively bonded joints

F.1 Introduction

Moisture ingress combined with temperature and mechanical loads is one of the main contributors of adhesive performance reduction. It is important to highlight that water is up to certain extent an active factor of ageing of bulk materials but also a powerful factor to reveal and to pronounce defects at the interface of the bond line between the adhesive and adherend.

F.2 Ageing of adhesively bonded joints

F.2.1 Natural ageing

The ageing process can be defined as gradual irreversible change in structure and function of a material that occur as a result of the passage of time in given environmental conditions.

Natural ageing is sometimes considered for specific case. For instance natural ageing in Kourou climate can be by exposing materials to the real conditions at the launch pad environment.

Realistic ageing can be achieved after exposure of flight hardware, unit or test item to workshop, clean room or other relevant environments. For both examples of natural ageing a significant period of time is typically needed to achieve noticeable degradation of adhesively bonded joints.

F.2.2 Accelerated ageing

To evaluate the resistance of joints against humid conditions, accelerated hot-wet tests are often employed for the process quality screening purposes.

Unfortunately, there is no exact analytical model that can accurately estimate the life degradation of complex adhesively bonded assemblies or systems. Following text further explains the complexity of the modelling of water diffusion trough polymers, its’ action in the bulk and life time prediction philosophy.

For critical adhesive bonds solicited for long-term service, it is recommended to determine the moisture diffusion kinetics which gives a better estimation of the moisture ingress inside the joint.

Materials that allows moisture absorption through Fickian diffusion are characterized by two key properties:

- diffusion coefficient of the penetrant and
- equilibrium concentration of penetrant (water molecules) in absorber (polymer)

F.2.3 Fick's law

The Fick's law (Equation 1) where *J* is the flux which gives the quantity of penetrant diffusing across unit area of medium per unit time and has units of mol.cm^{-2}.s^{-1}, *D* the diffusion coefficient, *c* the concentration, *x* the distance, and ∂c/∂x is called the gradient of the concentration along the axis [Karimi, M. 2011]. This relation is only applicable for steady state, where concentration is not varying with time (equilibrium conditions).

$$J = -D\frac{\partial c}{\partial x \partial}$$	Equation 1

F.2.4 Second Fick's law

Under unsteady state circumstance at which the penetrant accumulates in the certain element of the system, Fick's second law describes the diffusion process as given by Equation 2 [Karimi, M. 2011].

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial c}{\partial x}\right]$$	Equation 2

Concentration change ∂c of penetrant at certain element of the system with respect to the time (*t*), for one-dimensional diffusion per distance (∂x). Diffusion coefficient is D.

F.2.5 Water diffusion mechanisms and degradation models of adhesive joints

A review of the diffusion rates available in literature reveals that, in general, the diffusion rate along the interface of adhesive/substrate is faster than that of the bulk adhesive and it becomes more critical to the lifetime of the adhesive joints as the strength of the interface decreases [M.H. Shirangi and B. Michel].

Other authors [Vine et. al] reported faster diffusion in three-layer sandwich specimens than predicted based on mass-uptake experiments performed on bulk diffusion specimens. They attributed this behaviour to the presence of micro-cavities in the adhesive layer [M.H. Shirangi and B. Michel].

Moisture diffusion in adhesives and in carbon-epoxy composites is generally considered to be Fickian although some studies have shown that under certain conditions, diffusion can be non-Fickian (see Figure F-2)

Non-Fickian behaviour can be the consequence of a relaxation process in polymer molecules and/or the result of an irreversible reaction between polymer and moisture such as formation of hydrogen bonds [M.H. Shirangi and B. Michel].

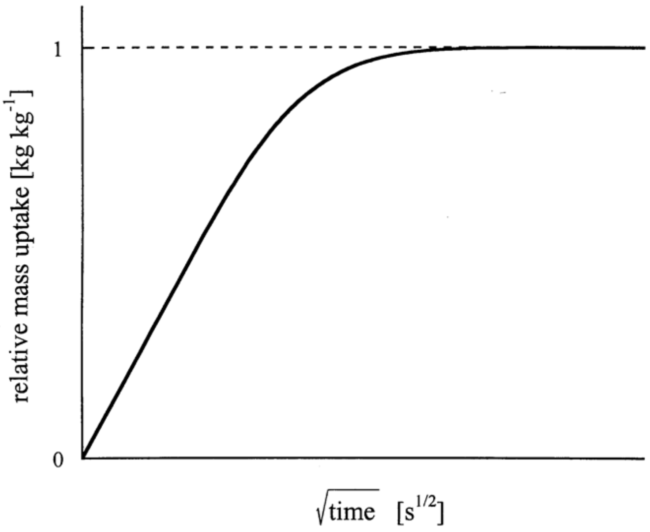

Figure F-1:Example of dependence of relative moisture content saturation ratio as a function of square root of time –Fickian behaviour [Gerben K. van der Wei and Olaf C.G. Adan, 2000]

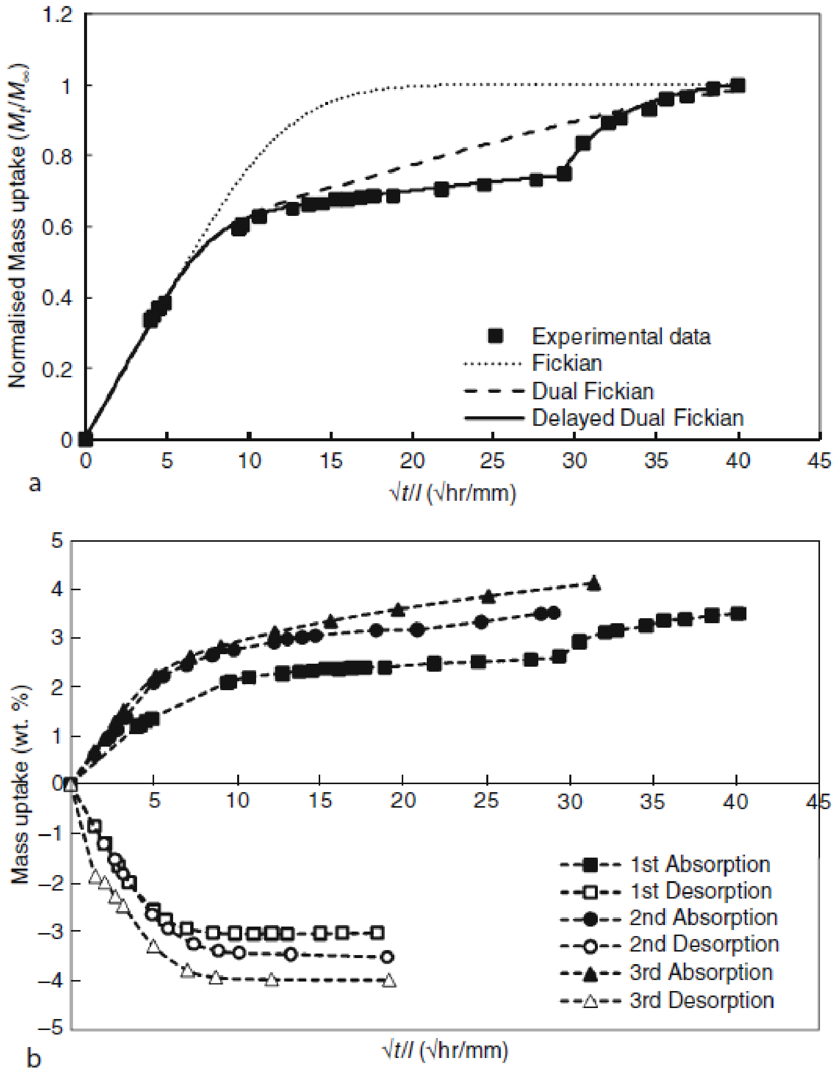

Figure F-2: Illustration of a non-Fickian behaviour and evolution with sorption cycles of one component epoxy adhesive, (up) normalised mass uptake –various models, (down) moisture uptake and de-sorption [Mubashar, I. A. et al., 2009]

In some cases, a pseudo-equilibrium stage is reached in the moisture uptake, which is then followed by a secondary uptake process. It can also be seen that the uptake behaviour can be different in absorption and desorption and can change with number of sorption cycles (see Figure F-2).

The diffusion coefficient is one of the material properties which controls the rate of absorption of moisture in a material. The diffusion coefficient is highly dependent on temperature and weakly dependent on relative humidity. This is the reason why the Arrhenius temperature acceleration model can be used Equation 3).

The activation energy for diffusion (Ea in J/mol) can be different for each damage mechanism and material.

$D = D_o \times exp\left(-\frac{E_a}{R \times T}\right)$	Equation 3

Where:

D = diffusion coefficient (at infinite temperature; in m/s)

D_0 = maximal diffusion coefficient (at infinite temperature; in m2/s)

Ea = activation energy for diffusion (J/mol)

T = temperature (K) and

R = gas constant 8,145 J/(mol·K).

Water concentration throughout the adhesive bond can be computed by solving Fick's law knowing for each material water concentration at equilibrium and diffusion coefficient. In the case adhesive joint with composite adherends, one can consider it is not necessary to know the coefficient of diffusion of the adhesive if the adhesive film is thin and in case the moisture diffusion is significantly faster throughout the adherend thickness.

a. In practice the coefficients of the model are commonly measured by gravimetric test method, which exposes a specimen to a controlled humid environment.

1. For each couple (HR, T) the two parameters of the Fick's law are determined:

(a) water concentration at equilibrium (asymptotic value of the moisture content curve

(b) and coefficient of diffusion (slope of the curve M/M∞ versus $t^{0,5}$).

2. By plotting D(T) in log scale versus 1/T, the D_0 and Ea is determined.

The "through-the-thickness" moisture diffusion coefficient can be determined for single-phase material by assuming Fickian diffusion behaviour with constant moisture absorption properties through the thickness of the test specimen [ISO 62:2008] or for more complex matrix [ASTM D5229 / D5229M – 14 and MIL-HDBK-17B 1988 respectively].

Other techniques for determination of diffusion coefficient in polymeric materials can be found in literature (M.H. Shirangi and B. Michel, 2010, Hallberg, Ö. and Peck, D. S. 1991, Karimi, M. 2011 or Vine, K et al. 2001 and many others).

The robustness of the model is based on a test campaign covering a different couples HR, T. It is recommended to perform for each material, 7 couples of conditions (HR,T) applied for each a minimum of 3 samples. A long period of ageing (more than one year or ambient conditioning) is needed to validate the model. Absorption and desorption tests are also needed to better identify the parameters of the model and long re-conditioning can be necessary to reach de-sorption equilibrium.

The determination of the knockdown factor of adhesion performance after accelerated ageing can be done experimentally with a minimum of 5 test samples for each point of measure.

A model developed to predict life of semiconductor (corrosion phenomena) encapsulated in epoxy packaging has been proposed by Hallberg, Ö. and Peck, D. S. 1991. The model is based on Arrhenius law a combining function of Temperature and Humidity. An important assumption of Hallberg-Peck's Temperature-Humidity model is that the effects of temperature and humidity are independent. The aim of Hallberg-Peck work was to derive model to be able to extrapolate results from HAST (Highly accelerated stress test), specifically 85 % RH/85 °C to estimate the time to failure in selected conditions ranging from (20 to 158) °C and (20 to 100) % RH. Note that empirical data were based on pass-fail criterion (qualitative) and not on severity or any other quantitative parameter.

$Life = \mathrm{A}(RH)^{-n}\, e^{\left(\frac{Ea}{kT}\right)}$	Equation 4

Where:

n = empirical factor

Ea = Activation energy for damage mechanism and material

$Life$ = time-to-failure

A = Constant

RH = Relative Humidity

K = Boltzmann constant = 8,615 × 10^{-5} eV/K

T = Temperature (Kelvin)

Equation for integrated circuits life time prediction as published by Hallberg, Ö. and Peck, D. S. 1991 [Equation 5]

$Rellife = \frac{85^3}{RH^3} - exp\left[\frac{0{,}9\ eV}{k}\left(\frac{1}{T = 273} - \frac{1}{358}\right)\right]$	Equation 5

with specific parameters 85 % RH and 85° C as test conditions, activation energy (0,9 eV) and empirical factor (n= -3)

Hallberg-Peck model approach is not to be used for lifetime predictions of adhesive joints nor for key property reduction estimation (shear, peel cleavage, tensile strength).

Suitable definition of the moisture sensitivity is problematic. One of the proposed approaches can be found in MIL-HDBK-17B, 1988 for composite materials. The approach is visualised in the Figure F-3.

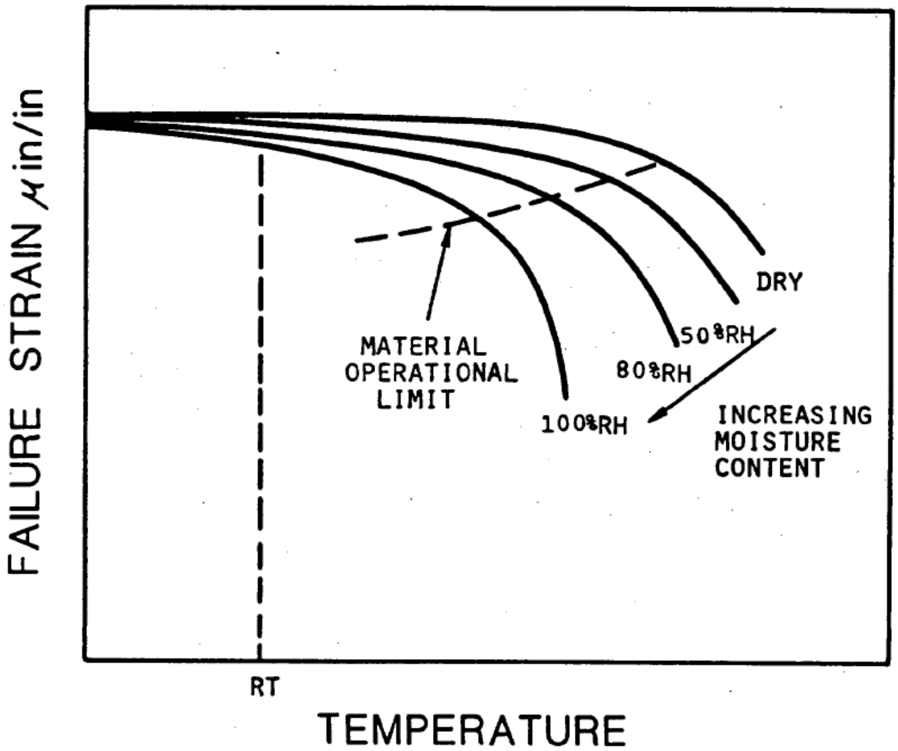

Figure F-3: Influence of temperature and moisture content on failure strain of epoxy matrix [MIL-HDBK-17B, 1988]

MIL-HDBK-17B is considering *Tg* as critical parameter for structural application of polymeric matrix and defines safety factor of 10 °C below Tg. ASTM D5229 / D5229M-14 recommends 25 °C below wet *Tg*.

F.2.6 Summary

Variety in bulk properties of adhesive materials due to their differences in polymer nature (silicones, epoxies, polyurethanes, cyanoacrylates), state (*Tg*, glassy vs. rubbery), crystallinity, degree of cure, curing mechanism, porosity, fillers and additives content on one hand and significant differences in quality and nature of the adhesive-adherend interface on other hand, make derivation of mathematical models for life time predictions in humid environments very complex. In practice it means that to determine the knock-down factors for adhesively bonded assembly it is much easier to perform harsh and often very conservative engineering tests (for example EN 2243-5:2005) aiming at saturation and steady state conditions with respect to absorbed water content in the exposed assembly.

In case of temperature humidity accelerated tests for ambient life time predictions it is important that adhesive material is not passing through its glass transition temperature (*Tg*) during the acceleration ageing test cycle.

F.3 Examples of hot-wet exposure conditions to be used in verification sequence for spacecraft and launchers

F.3.1 Satellites, in-orbit units, probes

The aim is not to simulate the equivalent life time degradation caused by atmospheric moisture but mainly to verify the sensitivity of the adhesive joint to atmospheric moisture in general.

For the cases when the flight hardware is exposed only to relative humidity equivalent to clean room controlled environment, the following conditions are recommended for hot-wet exposure:

Relative humidity range: No more than 70 % RH

Temperature:

- for adhesive materials with *Tg* below RT, the humidity exposure temperature is above *Tg*
- for adhesive materials with *Tg* above RT, the humidity exposure temperature is below *Tg*

  NOTE Close to *Tg* typical adhesive materials are rapidly changing their properties with temperature, therefore exposure to humidity at Tg can lead to highly scattered test results regardless the quality of the bonding process.

- Selected test temperature is not above the temperature range of thermal cycling used in verification sequence.

Duration of hot-wet exposure : typically 7 days or less

Based on experiences of many previous space programmes following tables contain some critical and less critical adhesive bonding applications (Table F-1) sensitivity to atmospheric moisture (Table F-2) and applicability of hot-wet exposure (Table F-3).

Table F-1: Example of the classification of adhesive bonding process in spacecraft and launcher applications based on its criticality

Criticality	Definition and examples
Highly critical	Any bonded joint, failure of which can lead to loss of mission, loss of spacecraft or loss of crew. Examples: Structural adhesive bonding with high dimensional stability or strength requirements on the joint (for example bonding of optical elements as lenses, mirrors). Structural adhesive bonding with high mechanical and static loads applied during on-ground, pre-launch, launch or mission phase. Primary structure joints without any redundancy (no extra riveting, bolts nor any other mechanical back up). Bonding of thermal protection systems (TPS) exposed to high thermal fluxes during on-ground, pre-launch, launch, mission, atmospheric entry or re-entry phase, facing significant mechanical or thermo-mechanical loads at the same time.
Critical	Any bonded joint, failure of which can lead to significant damage of the spacecraft or degradation of the mission or injury of the crew member. Examples: Primary structure joint with redundancy (bolted, secured with rivets). Secondary structure joint (for example bonding of stand-offs for MLI). Non-structural or semi-structural joints with other specific function (for example bonding of radiation shielding for electronics, shielding of crew capsule or both; electrically conductive bond.
Not critical	Any bonded joint, failure of which cannot cause any impact on spacecraft or mission and cannot cause injury of the crew member. Bonding of cable-tie bases with significant number of redundant measures (for example sensors, cable bundle potting or encapsulations). PSA tape marking, cable wrapping. Non-structural joints (e.g. without any other function than in place holding, marking etc.).

Table F-2: Examples of adhesive bonding applications and their sensitivity to on-ground humidity exposure (based on their failure occurrence)

Sensitivity	Definition and examples
Highly sensitive	Performance of the key property is reduced by more than 35% after exposure to moisture with respect to reference value Examples: Bonding to surfaces exposed to un-controlled environments, where molecular or particle contamination, humidity or temperature is not controlled. Bonded assembly with thin overlap areas without prevention of access of ambient humidity to the centre of overlap area for systems where diffusion rate of water trough adhesive/adherend interface layer is fast. Bonding of optical glasses, mirrors (fused silica,) or any similar adherend sensitive to moisture (for example CaF2, MgF2, lithium-aluminosilicate glass-ceramic). Bonding of adherend materials known to show signs of surface degradation already in ambient environments, (55 ±10) % RH and (22 ± 3) °C, for example low Fe-Ni alloys, low Cr-alloyed steels, carbon steels. Bonding with 2-c epoxy adhesive with Tg close to RT without option of post-cure process at elevated temperatures before exposure to on-ground environments, including controlled environments in clean rooms at (55 ±10) % RH and (22 ± 3) °C. Bonding to metallic surfaces with insufficient surface treatment (where proper surface treatment is prevented by application, for example AIT, repair on spot). Bonding with adhesive materials which are known to be moisture-sensitive when they are in their cured state.
Sensitive	Performance of the key property is reduced significantly (between 35 % and 10 %) after exposure to moisture with respect to reference value. Adhesive bonding applications with insufficient surface treatment of metallic adherends (absence of chemical etching, pickling, anodising processes). Adhesive bonding applications without stabilisation of adherend-adhesive interface (for example without use of protective primers, coatings, pyrolytical techniques). Bonding on thermo-optical coating layers or painted substrates without removal of paint or coating. Bonding to primed areas with longer exposures to humidity between priming and adhesive application.
Insensitive	Performance of the key property is not affected after exposure to moisture (less than 10 % reduction) with respect to reference value. The key property of the adhesive material in cured state is not sensitive to moisture. Bonded assembly with large overlapping areas limiting access to ambient humidity to the centre of overlap where diffusion rate of water trough adhesive/adherend interface layer is limited. Bonding to metallic surfaces which have enhanced endurance by corrosion inhibiting primers or similar protection systems.

The sensitivity level of the assembly can be assessed by accelerated hot-wet screening test in frame of adhesive selection process (see recommendation 5.2g.2(d)).

Recommendation on hot-wet exposure in verification sequence of spacecraft assembled and stored in controlled environment, an ambient temperature of (22 ± 3) °C and relative humidity of (55 ± 10) %, can be derived from Table F-3.

Table F-3: Example table with assessment for implementation of hot-wet exposure into the verification sequence (step: simulation of on-ground exposure)

		Sensitivity of the adhesive bond to moisture		
		Highly sensitive	**Sensitive**	**Non-sensitive**
Criticality of the bonding process application	**Highly critical**	Yes	Yes	Yes
	Critical	Yes	Yes	No
	Non-critical	Yes	No	No
NOTE: Yes: hot-wet exposure is recommended to be performed, No: hot-wet exposure need not to be performed				

F.3.2 The accelerated ageing of adhesively bonded assemblies for launcher applications

The purpose of this type of tests is to determine the resistance of structural adhesives and adhesively bonded joints against environmental influences. The aim is to quantify the reduction in the key property.

The destructive tests are typically focusing on reduction in the single lap shear strength, peel strength, shear strength/strain and reduction in shear modulus after the environmental exposure.

The exposed test items are typically followed by destructive testing performed after certain time since their exposure.

Typical hot-wet exposure conditions and compatible test standards for verification of key property are listed in the Table F-4.

Table F-4: Examples of standard test conditions for ageing tests and related test methods

Standard test reference	Test	Test conditions			Output
		T [°C]	Humidity [RH%]	Duration [Days]	
EN 2243-5:2005	Aerospace series - Non-metallic materials - Structural adhesives - Test method - Part 5: Ageing tests	50-70	95-100	30-90	Reduction factor – key property
ISO 9142:2003	Adhesives -- Guide to the selection of standard laboratory ageing conditions for testing bonded joints, Annex C	70	90-100	42	Ageing ratios
ASTM D618-13	Standard Practice for Conditioning Plastics for Testing, Procedure C	35	90	4	n/a
ISO 291:2008	Plastics - Standard atmospheres for conditioning and testing	23 - 27	50-65	Thickness dependent	n/a
*ASTM D5229 / D5229M – 14	Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials	Tg - 25	85-98	variable	Plot: mass vs. time, equilibrium moisture content, diffusivity
ASTM D1828 - 01(2013)	Atmospheric Exposure of Adhesive-Bonded Joints and Structures	natural atmospheric exposure (no acceleration)			Visual, Qualitative changes
NOTE: * Applicable for CFRP-core-CFRP sandwich structures					

Table F-5: Examples of standard durability tests (mechanical and humidity stress combined)

Standard test reference	Test	Test conditions			Output
		T [°C]	Humidity [RH%]	Duration [Days]	
ASTM D2919 - 01(2014)	Standard Test Method for Determining Durability of Adhesive Joints Stressed in Shear by Tension Loading	23-50	15-100	Not defined	Time to failure of single lap
ASTM D2918 - 99(2012)	Standard Test Method for Durability Assessment of Adhesive Joints Stressed in Peel	23-50	15-100	Not defined	Time to failure of peel sample
ASTM D3762 - 03(2010)	Standard Test Method for Adhesive-Bonded Surface Durability of Aluminum (Wedge Test)	23-70	15-100	Up to 30	Crack extension, fracture mode
ISO 14615:1997	Adhesives - Durability of structural adhesive joints -- Exposure to humidity and temperature under load (T-peel and single lap)	42-48	90-100	Not defined	Time to failure, cycles to failure

Annex G (informative) System for training and qualification of adhesive bonding personnel

EWF - The European Federation for Welding, Joining and Cutting, was created in 1992 by all the welding institutes of the European Union with the aim of updating and harmonizing training, education, qualification and certification in the field of joining technology. [Quintino L. et al.].

In terms of training of adhesive bonding personnel EWF has developed harmonized guidelines for the European Adhesive Engineer, the European Adhesive Specialist and the European Adhesive Bonder. [Quintino L. et al.]

The visualisation of Professional Qualification scheme is presented in the Figure G-1.

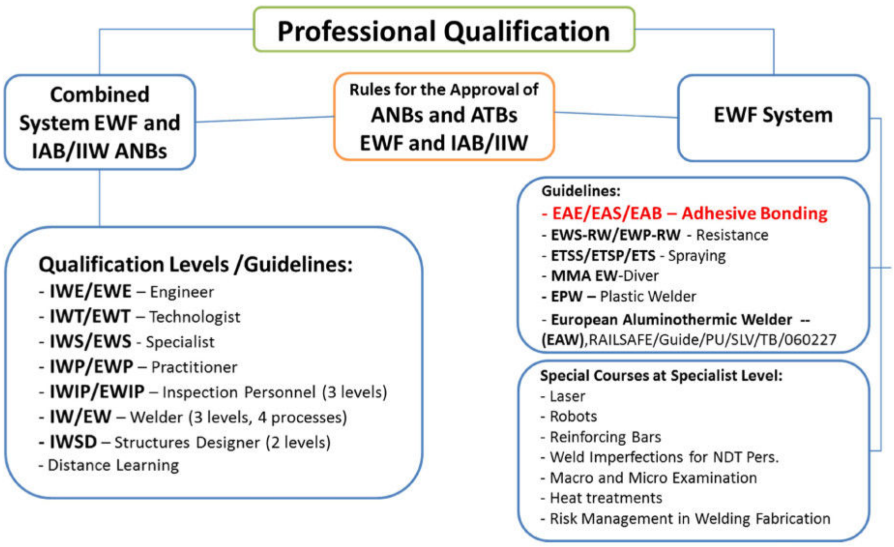

Figure G-1: The International Training and Qualification system for Personnel [Quintino L. et al.]

Entities providing training for adhesive bonding are listed below. The training is structured in three levels:

- European Adhesive Bonder (EAB), DVS® / EWF 3305 and EWF 515
- European Adhesive Specialist (EAS), DVS® / EWF 3301 and EWF 516
- European Adhesive Engineer (EAE), DVS® / EWF 3309 and EWF 517

Table G-1: The list of entities eligible to provide training for adhesive bonding*

Country	School	Contact details
Austria	OFI GmbH	OFI Technologie & Innovation GmbH, Franz-Grill-Straße 5, Objekt 213, 1030 Wien http://www.ofi.at/
Belgium	TECHNIFUTUR	Technifutur® asbl, Liège Science Park, Rue Bois Saint-Jean 15-17, B-4102 – Seraing http://www.technifutur.be/catalogue-des-formations-assemblage
Czech Republic	Centrum Lepení Brno	Centrum Lepení Brno, SVV Praha, s.r.o., Vídeňská 55, 639 00 Brno http://svv.cz/adhesive-bonding
France	Rescoll	Rescoll, 8 Allée Geoffroy Saint-Hilaire, 33600 Pessac https://rescoll.fr/rescoll/
Germany	IFAM	Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung IFAM, Wiener Straße 12, 28359 Bremen https://www.ifam.fraunhofer.de
Germany	TC Kleben GmbH	TC-Kleben GmbH, Carlstraße 50, 52531 Übach-Palenberg http://www.tc-kleben.de
Germany	SKZ Halle	Frankfurter Str. 15-17, 97082 Würzburg http://www.skz.de/
Italy	Istituto Italiano della Saldatura	Istituto Italiano della Saldatura, SEDE CENTRALE DI GENOVA, Lungobisagno Istria, 15A, 16141, Genova https://www.iis.it/
Netherlands	Adhesive Bonding Center	Adhesive Bonding Center, Vaartweg 81E, 8243 PD Lelystad http://adhesivebondingcenter.nl
Netherlands	Lijmacademie B.V. / IFAM	Lijmacademie B.V., Ericssonstraat 2, 5121 ML Rijen http://www.lijmacademie.eu
Poland	Instytut Spawalnictwa	Instytut Spawalnictwa, ul. Błogosławionego Czesława 16-18, 44-100 GLIWICE http://is.gliwice.pl/
Spain	CESOL	CESOL, C/ Condado de Treviño, nº 2 – Local F31, 28033 Madrid www.cesol.es
Spain	ITCS	ITCS - Ctra. de Molins de Rei a Sabadell, 79, Nau 8 bis NUEVO 08191 Rubí, Barcelona http://www.itcsoldadura.org/

NOTE: * The list in the table is not exhaustive and can change over time. Quoted entities often organise trainings also in other countries in collaboration with local universities or training institutes. For actual list of all Authorised Training Bodies (ATBs) consult your local Authorised National Body (ANB) or European Federation for Welding, Joining and Cutting (EWF).

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ECSS-E-HB-32-21	Space engineering – Adhesive bonding handbook
ECSS-E-ST-10-02	Space engineering – Verification
ECSS-Q-ST-70-01	Space product assurance - Cleanliness and contamination control
ECSS-Q-ST-70-04c	Space product assurance – Thermal testing for the evaluation of space materials, processes, mechanical parts and assemblies
ECSS-Q-ST-70-06	Space product assurance – Particle and UV radiation testing for space materials
ASTM D257-14	Standard Test Methods for DC Resistance or Conductance of Insulating Materials
ASTM D570-98(2010)e1	Standard Test Method for Water Absorption of Plastics
ASTM D618-13	Standard Practice for Conditioning Plastics for Testing, Procedure C
ASTM D638-14	Standard Test Method for Tensile Properties of Plastics
ASTM D695-15	Standard Test Method for Compressive Properties of Rigid Plastics
ASTM D696-16	Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between −30°C and 30°C with a Vitreous Silica Dilatometer
ASTM D897-08(2016)	Standard Test Method for Tensile Properties of Adhesive Bonds
ASTM D950-03(2011)	Standard Test Method for Impact Strength of Adhesive Bonds
ASTM D1002-10	Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)
ASTM D1062-08(2015)	Standard Test Method for Cleavage Strength of Metal-to-Metal Adhesive Bonds
ASTM D1746-15	Standard Test Method for Transparency of Plastic Sheeting
ASTM D1781-98(2012)	Standard Test Method for Climbing Drum Peel for Adhesives
ASTM D1824-16	Standard Test Method for Apparent Viscosity of Plastisols and Organosols at Low Shear Rates
ASTM D1876-08(2015)e1	Standard Test Method for Peel Resistance of Adhesives (T-Peel Test)
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ASTM D2294-96(2016)	Creep Properties of Adhesives in Shear by Tension Loading (Metal-to-Metal)

ASTM D2295-96(2016)	"Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading at Elevated Temperatures (Metal-to-Metal)"
ASTM D2918-99(2012)	Standard Test Method for Durability Assessment of Adhesive Joints Stressed in Peel
ASTM D2919-01(2014)	Standard Test Method for Determining Durability of Adhesive Joints Stressed in Shear by Tension Loading
ASTM D3163-01(2014)	Standard Test Method for Determining Strength of Adhesively Bonded Rigid Plastic Lap-Shear Joints in Shear by Tension Loading
ASTM D3165-07(2014)	Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies
ASTM D3166-99(2012)	Standard Test Method for Fatigue Properties of Adhesives in Shear by Tension Loading (Metal/Metal)
ASTM D3167-10(2017)	Standard Test Method for Floating Roller Peel Resistance of Adhesives
ASTM D3330 / D3330M-04(2010)	Standard Test Method for Peel Adhesion of Pressure-Sensitive Tape, (several methods)
ASTM D3418-15	Standard Test Method for Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry
ASTM D3418-15	Standard Test Method for Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry
ASTM D3433-99(2012)	Standard Test Method for Fracture Strength in Cleavage of Adhesives in Bonded Metal Joints
ASTM D3528-96(2016)	Standard Test Method for Strength Properties of Double Lap Shear Adhesive Joints by Tension Loading
ASTM D3654 / D3654M-06(2011)	Standard Test Methods for Shear Adhesion of Pressure-Sensitive Tapes
ASTM D3762-03(2010)	Standard Test Method for Adhesive-Bonded Surface Durability of Aluminum (Wedge Test)
ASTM D3850-12	Standard Test Method for Rapid Thermal Degradation of Solid Electrical Insulating Materials By Thermogravimetric Method (TGA)
ASTM D4065-12	Standard Practice for Plastics: Dynamic Mechanical Properties: Determination and Report of Procedures
ASTM D4496-13	Standard Test Method for D-C Resistance or Conductance of Moderately Conductive Materials
ASTM D4562-01(2013)	Standard Test Method for Shear Strength of Adhesives Using Pin-and-Collar Specimen
ASTM D5229 / D5229M-14	Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials
ASTM D5656-10(2017)	Standard Test Method for Thick-Adherend Metal Lap-Shear Joints for Determination of the Stress-Strain Behavior of Adhesives in Shear by Tension Loading

ASTM D5868-01(2014)	Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding
ASTM D5930-17	Standard Test Method for Thermal Conductivity of Plastics by Means of a Transient Line-Source Technique
ASTM D7249 / D7249M-16e1	Standard Test Method for Facing Properties of Sandwich Constructions by Long Beam Flexure
ASTM E143-13	Standard Test Method for Shear Modulus at Room Temperature
ASTM E595-15	Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment
ASTM E831-03	Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis
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