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# Space systems — Fracture and damage control

*Systèmes spatiaux — Maîtrise des fissurations et des dommages*

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# Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 21347 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

# Introduction

To prevent premature structural failure due to the propagation of cracks or crack-like defects during a structure's service life, fracture control policy is being imposed on space systems. These systems include civil and military space vehicles, launch systems, and their related ground support equipment. For manned space flight systems, most procurement agencies consider fracture control a mandatory human safety related requirement. For example, the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) require fracture control for all payloads using the NASA Space Shuttle (Shuttle) and all equipment items installed on the International Space Station (ISS). These systems have established specific fracture control requirements. These requirements are being implemented on all the payloads and equipment items using the Shuttle and ISS.

Recently, many procurement agencies and range safety authorities have imposed fracture control requirements on critical hardware items such as main propellant tanks of expendable launch vehicles (ELVs) and high-pressure gas bottles used in unmanned spacecraft in order to prevent loss of life and/or launch site facilities. Mechanical damage control is also being required by many range safety authorities on impact damage prone composite-overwrapped pressure vessels (COPVs). This International Standard provides uniform fracture and mechanical damage control requirements to the non-Shuttle and non-ISS hardware. It can be applied to safety and mission critical structures and other hardware items.

**INTERNATIONAL STANDARD** **ISO 21347:2005(E)**

# Space systems — Fracture and damage control

## 1 Scope

This International Standard establishes general requirements for the application of fracture control technology to fracture-critical items (FCIs) fabricated from metallic, non-metallic or composite materials. It also establishes mechanical damage control requirements for mechanical-damage-critical items (MDCIs) fabricated from composite materials. These requirements, when implemented on a particular space system, can assure a high level of confidence in achieving safe operation and mission success.

The requirements set forth in this International Standard are the minimum fracture control and mechanical damage control requirements for FCIs and MDCIs in general space systems, including launch vehicles and spacecraft. With necessary modifications, these requirements may also be applicable to reusable launch vehicles (RLVs). This International Standard is not applicable to the Shuttle and its payloads or the ISS and its equipment, since they already have a set of specific requirements suitable for their special applications.

This International Standard is not applicable to processing detected defects.

## 2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 14623:2003, *Space systems — Pressure vessels and pressurized structures — Design and operation*

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

**3.1**
**burst strength after impact**
**BAI**
actual burst pressure of a pressure vessel after it has been subjected to an impact event

**3.2**
**catastrophic hazard**
potential risk situation that can result in loss of life, life-threatening or permanently disabling injury, occupational illness, loss of an element of an interfacing manned flight system, loss of launch site facilities, or long-term detriment to the environment

**3.3**
**composite material**
combination of materials which differ in composition or form on a macro scale

NOTE The constituents may retain their identities in the composite. Normally, the constituents can be physically identified, and there is an interface between them. A bonded structure such as metallic honeycomb sandwich is not considered as a composite structure in this International Standard.

### 3.4
**composite-overwrapped pressure vessel**
**COPV**
pressure vessel with a fibre-based composite system fully or partially encapsulating a liner

NOTE 1 The COPV containing a metallic liner is referred to as a metal-lined COPV while the COPV containing a nonmetallic liner is referred to as a nonmetal-lined COPV.

NOTE 2 The liner serves as a fluid permeation barrier and may or may not carry substantial pressure and external loads. The composite overwraps generally carry pressure and environmental loads.

### 3.5
**critical flaw**
specific shape of flaw with sufficient size such that unstable growth will occur under the specific operating load and environment

### 3.6
**critical hazard**
potential risk situation that can result in temporarily disabling but not life-threatening injury, or temporary occupational illness; loss of, or major damage to, flight systems, major flight system elements or ground facilities; loss of, or major damage to, public or private property, or short-term detrimental environmental effects

### 3.7
**damage tolerance**
ability of a material/structure to resist failure due to the presence of flaws for a specified period of unrepaired usage

### 3.8
**damage tolerance threshold strain level**
strain level below which no crack or damage propagation will occur when subjected to expected load or environmental conditions

### 3.9
**design safety factor**
design factor of safety
factor of safety
multiplying factor to be applied to the limit load and/or maximum expected operating pressure (MEOP), or maximum design pressure (MDP), for the purpose of analytical assessment and/or test verification of structural adequacy

EXAMPLE The design burst factor applied to the MEOP is the required design burst pressure for analysis or test.

### 3.10
**fail-safe structure**
structural item for which it can be shown by analysis or test that, as a result of structural redundancy, the structure remaining after the failure of any element of the structural item can sustain the redistributed limit loads with an ultimate safety factor of 1,0

NOTE It also can be shown that the structural item can withstand the fatigue loads for all the mission life for multi-mission applications.

### 3.11
**flaw**
local discontinuity in a structural material

EXAMPLES Crack, delamination or debonding.

**3.12**
**fracture control**
application of design philosophy, analysis method, manufacturing technology, verification methodology, quality assurance, and operating procedures to prevent premature structural failure caused by the propagation of cracks or crack-like flaws during fabrication, testing, transportation, handling and service

**3.13**
**fracture-limited life item**
any hardware item that requires periodic re-inspection or replacement to comply with damage tolerance requirements

**3.14**
**fracture mechanics**
engineering discipline that describes the behaviour of cracks or crack-like flaws in materials under stress

**3.15**
**impact damage indicator**
means for indicating the occurrence of an impact event

**3.16**
**impact damage protector**
physical device which can be used to prevent impact damage

**3.17**
**initial flaw size**
maximum flaw size, as defined by non-destructive evaluation (NDE), that is assumed to exist for the purpose of performing a damage tolerance (safe-life) analysis or testing

**3.18**
**leak-before-burst**
**LBB**
design concept which shows that, at maximum expected operating pressure (MEOP), potentially critical flaws will grow through the wall of a metallic pressurized hardware item or the metal liner of a composite-overwrapped pressure vessel (COPV) and cause pressure-relieving leakage rather than burst or rupture (catastrophic failure)

**3.19**
**limit load**
maximum expected external load or combination of loads that a structure can experience during the performance of specified missions in specified environments

NOTE When a statistical estimate is applicable, the limit load is that load not expected to be exceeded at 99 % probability with 90 % confidence.

**3.20**
**maximum design pressure**
**MDP**
highest pressure, as defined by maximum relief pressure, maximum regulator pressure and/or maximum temperature, including transient pressures, at which a pressure vessel retains two-fault tolerance without failure

**3.21**
**maximum expected operating pressure**
**MEOP**
highest differential pressure which a pressurized hardware item is expected to experience during its service life and retain its functionality, in association with its applicable operating environments

**3.22**
**mechanical damage**
induced flaw in the composite hardware item that is caused by surface abrasions, cuts or impacts

**3.23**
**mechanical damage control**
use of mechanical damage protection and/or indication system and appropriate inspection procedure to assure that no mechanical damage has been induced on a composite hardware item or if it has, the residual strength of the item still meets the minimum design ultimate load/pressure requirements for the required life

**3.24**
**metal-lined COPV**
composite-overwrapped pressure vessel which has a metallic liner

**3.25**
**non-destructive evaluation**
**non-destructive examination**
**NDE**
process or procedure for determining the quality or characteristics of a material, part, or assembly without permanently altering the subject or its properties

NOTE For the purposes of this International Standard, this term is synonymous with non-destructive inspection (NDI), and non-destructive testing (NDT).

**3.26**
**pressure vessel**
container designed primarily for the storage of pressurized fluid, which fulfils at least one of the following criteria:

a) contains gas or liquid with high energy level;

b) contains gas or liquid which will create a mishap (accident) if released;

c) contains gas or liquid with high pressure level

NOTE 1 **Pressurized structures** (3.27), pressure components and pressurized equipment including batteries, heat pipes, cryostats, and sealed containers are excluded.

NOTE 2 Energy and pressure level are defined by each project, and approved by the procuring authority (customer); if appropriate values are not defined by the project, the following levels are used:

- stored energy is 19 310 J or greater based on adiabatic expansion of perfect gas; or
- maximum expected operating pressure (MEOP) is 0,69 MPa or greater.

**3.27**
**pressurized structure**
structure designed to carry both internal pressure and vehicle loads

EXAMPLES Launch vehicle main propellant tanks, crew cabins and manned modules.

**3.28**
**pressurized hardware**
hardware items that contain primarily internal pressure

NOTE For the purposes of this International Standard, this term covers all pressure vessels and **pressurized structures** (3.27).

**3.29**
**proof factor**
multiplying factor applied to the limit load or maximum expected operating pressure (or maximum design pressure) to obtain proof load or proof pressure for use in the acceptance testing

**3.30**
**residual strength**
maximum value of load and/or pressure (stress) that a cracked or damaged structural item is capable of sustaining, considering appropriate environmental conditions

**3.31**
**rotational machinery**
device with a spinning part such as a fan and a rotor that has a high kinetic energy

EXAMPLES Control momentum gyroscopes and energy storage flywheels.

NOTE The energy level is defined by each project. If an appropriate value is not defined by the project, the value taken is 19 310 J or greater, based on 0,5 $I\omega^2$, where $I$ is the moment of inertia (kg·m$^2$) and $\omega$ is the angular velocity (rad·s$^{-1}$).

**3.32**
**safe life**
required period during which a metallic hardware item, even containing a large undetected crack, is shown by analysis or testing not to fail catastrophically in the expected service load and environment

**3.33**
**safe-life analysis**
fracture mechanics-based analysis that predicts the flaw growth behaviour of a flawed hardware item which is under service load spectrum

NOTE For the purposes of this International Standard, safe-life analysis is synonymous with damage tolerance analysis.

**3.34**
**safe-life test**
test that determines experimentally the flaw growth behaviour of a flawed hardware item which is under service load spectrum

NOTE For the purposes of this International Standard, safe-life test is synonymous with damage tolerance test.

**3.35**
**service life**
period of time (or cycles) that starts with item inspection after manufacturing and continues through all testing, handling, storage, transportation, launch operations, orbital operations, refurbishment, re-entry or recovery from orbit, and reuse that may be required or specified for the item

NOTE For a metal-lined COPV, the service life starts with the autofrettage process during manufacturing.

**3.36**
**stress-corrosion cracking**
mechanically and environmentally induced failure process in which sustained tensile stress and chemical attack combine to initiate and propagate a crack or a crack-like flaw in a metal part

**3.37**
**structural item**
hardware item which is designed to sustain load and/or pressure or maintain alignment

EXAMPLES Spacecraft trusses, launch vehicle fairings, pressure vessels and pressurized structures; also fasteners, instrument housing and support brackets.

### 3.38
**ultimate load**
product of the limit load and the design ultimate safety factor

NOTE It is the load which the structural item must withstand without rupture or collapse in the expected operating environments.

### 3.39
**visual damage threshold**
**VDT**
impact energy level shown by a test or tests that creates an indication barely detectable by a trained inspector using an unaided visual inspection technique

## 4 Symbols and abbreviated terms

For the purposes of this document, the following symbols and abbreviated terms apply.

| | |
|---|---|
| $a$ | crack depth |
| $c$ | half crack length |
| BAI | burst strength after impact |
| COPV | composite overwrapped pressure vessel |
| DBF | design burst factor |
| FCI | fracture-critical item |
| Gr/Ep | graphite /epoxy |
| ISS | international space station |
| $K_{\mathrm{c}}$ | plane stress fracture toughness |
| $K_{\mathrm{Ic}}$ | plane strain fracture toughness |
| $K_{\mathrm{ISCC}}$ | stress intensity factor threshold for stress corrosion cracking |
| $K_{\mathrm{max}}$ | maximum stress intensity factor |
| LBB | leak-before-burst |
| LEFM | linear elastic fracture mechanics |
| MDCI | mechanical-damage-critical item |
| MEOP | maximum expected operating pressure |
| NDE | non-destructive evaluation or examination |
| POD | probability of detection |
| PTC | part-through crack |
| $T$ | wall thickness |

| | |
|---|---|
| VDT | visual damage threshold |
| $\Delta K$ | stress intensity factor range |
| $\Delta K_{\mathrm{th}}$ | fatigue crack growth threshold |

# 5 Fracture and mechanical damage control requirements

## 5.1 Fracture control requirements

### 5.1.1 General

A fracture control program shall be implemented for hardware items when structural failure due to the growth of undetected flaws can result in a catastrophic or critical hazard. Structural items that can be verified as fail-safe structures may be exempted from fracture control. Fail-safe demonstration requirements are specified in 5.4.1.

### 5.1.2 Fracture-critical item (FCI) classification

A hardware item is classified as an FCI if it is one or more of the following items:

a) pressure vessel;

b) pressurized structure which exhibits brittle (non-LBB) failure mode or which contains hazardous fluid;

c) uncontained rotational machinery which has a high kinetic energy;

d) composite or non-metallic structural item.

Other hardware items may be classified as an FCI if it is deemed necessary by the procuring authority for mission success.

### 5.1.3 Fracture control plan

All FCIs shall be placed under fracture control following a fracture control plan. The plan shall provide detailed hardware-specific fracture control methodologies and procedures for the prevention of catastrophic or critical failures associated with the propagation of flaws during fabrication, testing, handling, transportation and operational life. The plan shall identify organizational elements and their responsibilities for activities required for the implementation of the fracture control plan. The plan shall also include the following data and information:

a) description of each structural item that is classified as an FCI;

b) overall review and assessment of the fracture control activities and results;

c) information concerning non-FCIs that could cause catastrophic/critical hazard (e.g. fail-safe or contained items).

Any change to the fracture control methodologies and procedures shall be incorporated into the revised fracture control plan.

### 5.1.4 Damage tolerance requirements

#### 5.1.4.1 General

An FCI shall be demonstrated to possess the ability to resist failure due to the presence of flaws during the period of its entire service life multiplied by the required life factor. Unless otherwise specified, the life factor shall be four (4). Damage tolerance demonstrations shall be performed on all FCIs by analysis or testing.

#### 5.1.4.2 Damage tolerance (safe-life) analysis

Damage tolerance analysis (also referred to as safe-life analysis) based on linear elastic fracture mechanics (LEFM) shall be conducted to demonstrate the damage tolerance capability of a metallic FCI stressed within the elastic range. In a damage tolerance analysis, it shall assume that crack(s) exist at critical location(s) and in the most unfavourable orientations with respect to the applied stresses and material properties. The most critical location of the assumed crack shall be identified first. Stress-concentration and environmental effects shall be considered during this process. In a case where the most critical location or orientation of the initial crack is not obvious, the analysis shall consider a sufficient number of locations and orientations such that the criticality of the item can be determined.

Unless otherwise specified, average values of fracture toughness ($K_{\text{Ic}}$ or $K_{\text{c}}$) and fatigue crack growth rate ($\text{d}a/\text{d}N$) data associated with each alloy, temper, product form or process, and thermal and chemical environments shall be used in the damage tolerance analysis. If proof test logic is used to establish the initial crack sizes, an upper bound fracture toughness value shall be used in determining both the initial crack size and the critical crack size at fracture. When the upper bound value is not available, a value that is 1,3 × average $K_{\text{Ic}}$ or $K_{\text{c}}$ shall be used.

A metallic FCI which experiences sustained stresses shall also show that the corresponding maximum stress intensity factor ($K_{\text{max}}$) during sustained load in service is less than the stress intensity threshold for stress corrosion cracking ($K_{\text{ISCC}}$) data in the appropriate environment. Detrimental tensile residual stress shall be included in the analysis.

In the damage tolerance analysis, the flaw shape ($a/2c$) changes for part-through cracks (PTCs) (including surface cracks or corner cracks) shall be accounted for. Retardation effects on crack growth rates from variable amplitude loading shall not be considered without the approval of the procuring authority.

The results of damage tolerance analysis shall be documented in a report that contains the following at a minimum:

a) description of the item with identification of material (alloy and temper), grain direction, and a sketch showing the size, location and direction of all assumed cracks; and

b) description of the analysis performed, including

   - reference to the stress report, if it is separated from the damage tolerance analysis report;
   - description of loading/environment spectrum and how it has been derived;
   - material data and how they have been derived;
   - stress intensity factor solutions and how they have been derived;
   - initial crack sizes and NDE method(s) used;
   - analytical-life and critical crack size; and
   - summary of significant results.

For composite FCIs, damage tolerance analysis is only acceptable when the methodology used to conduct the analysis is supported by test evidence. The use of damage tolerance analysis for damage tolerance demonstration needs to be approved by the procuring authority.

#### 5.1.4.3 Damage tolerance (safe-life) test

The damage tolerance (safe-life) test is an acceptable option for performing the required damage tolerance demonstration for metallic FCIs. It shall be conducted on flight-like elements of the FCI, with the controlled crack(s) prefabricated at the critical location(s). Coupons shall only be allowed when the stress field is well defined and material properties are representative of that of the flight hardware. The size and shape of crack(s) shall correspond to the detection capability of the NDE to be imposed on the flight hardware. A successful damage tolerance test for a metallic FCI is one in which, after the application of four (4) service-life load spectra, the hardware item may still perform its designed function.

For composite FCIs, damage tolerance testing shall be conducted only on flight-like elements of the composite FCI, with controlled flaws (such as delaminations). Their initial sizes shall be based on the resolution of the NDE to be imposed on the flight part. The type of flaws considered shall be representative of those that could occur on the flight part. A successful damage tolerance test for a composite FCI is one in which, after the application of four (4) service-life load spectra, there is no measurable growth of the prefabricated flaws in the critical locations. If there is measurable growth, assessment for accept/reject shall be performed on a case-by-case basis. The residual strength of the composite FCI shall not be degraded below its ultimate load.

A test report that documents the damage tolerance test shall be prepared with the following information:

a) test specimen configuration and initial crack size/shape;

b) test equipment and test set-up;

c) test load spectrum and corresponding environmental condition;

d) crack size measurements;

e) test results; and

f) conclusions.

#### 5.1.4.4 Service-life load (pressure) spectrum

All events experienced by the FCI in its service life shall be considered in the development of the service-life load (pressure) spectrum to be used in the crack growth damage tolerance (safe-life) analysis or test. The service-life load (pressure) spectrum shall be clearly defined, in order to identify all cyclic and sustained load events. The following events shall be considered as appropriate (if they are after relevant NDE):

a) manufacturing/assembly;

b) acceptance tests (e.g. proof testing, vibration testing);

c) handling, e.g. by a dolly or a hoist;

d) transportation by land, sea, or air;

e) lift-off and ascent;

f) stay in orbit (for spacecraft);

g) descent (for reusable systems);

h) landing (for reusable systems).

The most unfavourable expected load/pressure values and their combinations shall be taken into account for load/pressure spectrum development.

#### 5.1.4.5 Stress spectrum

For the critical locations where flaws are assumed to exist, stresses including loads, pressure and temperature shall be generated in three orthogonal directions. For pressure vessels, both primary membrane and secondary bending stresses resulting from internal pressure shall be calculated to account for the effects of geometric discontinuities. Where applicable, rotational accelerations shall be considered in addition to linear accelerations. Residual stresses due to fabrication, assembly, testing or preloading shall be included.

Various types of load, including axial loads, shear loads and bending loads, shall be transferred to stresses through corresponding stress transfer functions.

### 5.1.5 Special provision

For composite structural items that are used in a single mission system, the required damage tolerance (safe-life) demonstration may be replaced by a proof test option as follows:

a) conduct a proof test on each flight article to no less than 110 % of its limit load for unmanned systems and 120 % of its limit load for manned systems;

b) the test may be accomplished at the component or subassembly level if the loads on the test article duplicated those that would be seen in a fully assembled test article;

c) caution shall be exercised when proof testing the flight article to prevent detrimental yielding to the metallic fittings and fasteners in the flight assembly and damage to the composites;

d) post proof NDE shall be conducted to detect proof test induced damage.

## 5.2 Mechanical damage control requirements

### 5.2.1 General

Mechanical damage control shall be applied to composite structural items where structural failure due to the undetected mechanical damage can result in a catastrophic or critical hazard. COPVs shall meet damage control requirements specified in ISO 14623:2003, 3.4.3.

### 5.2.2 Mechanical damage critical item (MDCI) classification

A composite hardware item shall be classified as an MDCI if it is a COPV, a composite pressurized structure or a composite solid rocket motor case. Other composite structural items may be classified as MDCI when it is deemed necessary by the procuring authority for safety or mission success reasons.

### 5.2.3 Mechanical damage control plan

#### 5.2.3.1 General

A mechanical damage control plan shall be prepared for a MDCI. It shall contain a threat analysis that shows source and magnitude of the threat under which mechanical damage can occur in service life. For COPVs, the pressure levels at potential impact events shall also be included in the threat conditions.

The mechanical damage control plan shall describe all events and inspection points from the time at which the MDCI is fabricated to the end of its service life. NDE and/or visual inspection shall be conducted prior to

a) each pressurization, when rupture of the vessel could create a hazardous condition, and

b) closeout, after which inspection is impossible or impractical, or mechanical damage is no longer credible.

The mechanical damage control plan shall identify the approach to be taken for the specific MDCI.

Two approaches may be adopted in order to meet mechanical damage control requirements:

- use of mechanical damage protection and/or indication with proper procedures; and
- demonstration of mechanical damage tolerance abilities.

#### 5.2.3.2 Mechanical damage protection and indication

When this approach is adopted, the following requirements shall be met.

a) Mechanical damage protection device

The damage protection device shall be designed to protect the MDCI completely under the worst credible threat defined in the mechanical damage control plan. For COPVs having stored energy level in excess of 19 310 J or containing hazardous fluids, protective covers or standoffs which isolate the pressure vessels are required when personnel will be exposed to pressurize the vessel. The effectiveness of protective covers shall be demonstrated by test. Protective covers shall not be removed until the latest possible time prior to launch.

b) Mechanical damage indicators

For MDCIs, the effectiveness of the damage indicators to provide positive evidence of a mechanical damage event shall be demonstrated by test. The use of the damage indicator as the sole means of mitigating threats for MDCIs is allowed except for pressurized COPVs during personnel workaround.

c) Scheduled/regular inspections

Appropriate inspections to detect any damage shall be scheduled at intervals. The effectiveness of inspection shall be demonstrated as specified in 5.3.

#### 5.2.3.3 Mechanical damage tolerance demonstration

For MDCIs, mechanical damage tolerance demonstration is another approach to satisfy the mechanical damage control requirement. This approach may be used to complement a damage protection device. The mechanical damage considered shall include surface abrasions, cuts and impacts.

Impact damage tolerance of a MDCI shall be demonstrated by test only. Impact damage shall be induced using a drop type impactor. A pendulum type arrangement is allowed if an analysis substantiates energy levels equivalent to a drop test. The minimum impact energy levels shall be the greater of the worst-case threat or VDT. The damage shall be induced at the most impact damage critical condition (e.g. fully charged vs. empty for a COPV). After inducing impact damage to the MDCI, the test article shall be tested to failure to show that the specific impact damage level will not degrade the ultimate strength of the MDCI to less than its design ultimate strength. For MDCIs with many missions, a life test shall be conducted. A successful life test is one in which, after the application of four (4) service-life load spectra, there is no structural failure.

Mechanical damage tolerance with respect to surface cuts may be demonstrated by analysis using the proven analytical methodology. Testing is an acceptable alternative.

### 5.3 Non-destructive evaluation (NDE)

Non-destructive evaluation (NDE) shall be performed on all FCIs to establish their initial conditions, especially the flaw types and sizes. The NDE techniques used shall be those most suitable for metallic or composite hardware respectively. The crack detection capability for NDE technique(s) applied to metallic FCIs shall demonstrate a 90 % probability of detection at a 95 % confidence level.

Proof testing of a flight item made of metallic materials is an acceptable NDE method for flaw screening. It requires the approval of the customer prior to testing.

For all metallic pressure vessels and pressurized structures, NDE shall be performed before and after proof test on the weld joints as a minimum. For COPVs and other composite FCIs, NDE shall be performed after the proof tests.

## 5.4 Other special requirements

### 5.4.1 Fail-safe demonstration

A structural item shall meet the following requirements to be demonstrated as a fail-safe part.

a) It can be shown by analysis or test that, due to structural redundancy, the structure remaining after any single failure can sustain the redistributed limit loads with an ultimate safety factor of 1,0 without losing limit-specified performance. The change of dynamic loading caused by failure of structural members shall be taken into account.

b) Failure of the item shall not result in the release of any part or fragment which results in an event having catastrophic or critical consequences.

c) It shall be shown that no cracks or other defects will initiate and cause failure within the service life or inspection interval where appropriate scatter factor is used.

### 5.4.2 Leak-before-burst (LBB) failure mode demonstration

Leak-before-burst (LBB) failure mode for all elastic response metallic pressure vessels, pressurized structures and the elastic-response metallic liners of COPVs shall be demonstrated by analysis or test. For plastic-response pressure vessels or metallic liners of COPV, LBB failure mode shall be demonstrated by test only.

When LBB failure mode is demonstrated by analysis, linear elastic fracture mechanics (LEFM) principles shall be employed. It shall be shown that, at MEOP, an initial surface crack (part-through crack) with a crack aspect ratio ($a/2c$) ranging from 0,1 to 0,5 will meet the following conditions:

a) it will not fail as a surface crack; and

b) it will grow through the wall of the metallic pressure vessel or the liner of a COPV to become a through crack with a length equal to or greater than ten (10) times the wall thickness, thereby leaking out the contents before catastrophic failure (burst) can occur.

When LBB failure mode is demonstrated by test, coupons or full-scale articles with prefabricated surface crack(s) shall be used as test specimens. Coupons shall duplicate the materials (parent metals, weld joints, and heat-affected zones) and the thickness of the metallic hardware items. When the full-scale article is used, it shall be representative of the flight hardware. The crack shape of the prefabricated surface crack(s) shall range from 0,1 to 0,5. Stress (or strain) cycles shall be applied to the test specimens with the maximum stress corresponding to the MEOP level and minimum stress kept to zero, or actual minimum stress, whichever is most conservative, until the surface crack grows through the specimen's thickness to become a through crack. LBB failure mode is demonstrated if the length of the through crack becomes equal to or greater than 10 times the specimen's thickness and still remains stable.

### 5.4.3 Traceability and documentation

Traceability of materials shall be implemented on all FCI and MDCI to provide assurance that the materials used in the manufacture of these items have properties fully representative of those used in the analysis or verification test.

Traceability shall also provide assurance that structural hardware is manufactured and inspected in accordance with the specific requirements necessary to implement the fracture/mechanical damage control programs.

The following traceability and documentation requirements apply.

a) All associated drawings, manufacturing and quality control documentation shall identify that the item is an FCI or MDCI.

b) An FCI and MDCI list shall be compiled. Each of the FCI or MDCI shall be traceable by its own unique serial number.

c) Each FCI or MDCI shall be identified as fracture-critical or mechanical-damage-critical on its accompanying tag and data package.

d) Damage tolerance (safe-life) analysis or test results shall be documented. Other fracture control related analyses or testing such as fail-safe analysis or test shall be documented as well.

e) For each FCI or MDCI, a log which documents the environmental and operational aspects (including fluid exposure for pressurized hardware) of all storage conditions during its service life shall be maintained.

f) For each FCI or MDCI, a log which documents all applied loads due to testing, assembly and operation shall be maintained.

# Annex A
(informative)

# Fracture control implementation guidelines

## A.1 Fracture control plan

Implementation of fracture control requirements on FCI made of metallic materials should start with the development of a fracture control plan. The extent of the control plan depends largely on the complexity of the space system. A fracture control plan should include the following information:

a) list of the FCIs with simple descriptions of their functions, configurations and materials;

b) NDE techniques to be used in the determination of the initial conditions of those FCIs;

c) description of analytical tools and methodologies to be used in the damage tolerance (safe-life) analysis;

d) description of damage tolerance (safe-life) test procedures when damage tolerance capability of a specific FCI is to be demonstrated by testing;

e) procedures and methodologies to be used in the generation of the load/environment spectrum for damage tolerance (safe-life) analysis or testing;

f) procedures to be used for raw material inspection, fabricated parts inspection and disposal of discrepant parts;

g) procedures to be used to control design changes, load/environment spectrum modifications.

For a large space system, a fracture control plan should include the following information in addition to the above list:

- the entity responsible for fracture control implementation; and
- its organization, including names and functions of responsible individuals.

## A.2 Damage tolerance demonstration

### A.2.1 General

For FCI made of metallic materials such as steel, aluminium, titanium or nickel-base alloys, damage tolerance demonstration should be accomplished by conducting damage tolerance analyses (safe-life analyses). When the material properties are not readily available, or when crack geometry or the loading conditions are very complex, or when the stress states are in the elastic-plastic region, safe-life analyses may be replaced by safe-life tests. The following sections provide guidelines for safe-life analysis and test in the areas that usually need clarification.

### A.2.2 Damage tolerance (safe-life) analysis methodology

#### A.2.2.1 General

Crack growth analysis methodology based on linear elastic fracture mechanics (LEFM) should be employed as the analytical tool to perform the safe-life analysis. A proven crack growth computer software package should be used. For a new computer code, known crack growth test results should be used to check against its safe-life prediction capability.

### A.2.2.2 Service-life load spectrum development

A load spectrum may be presented as either a variable-amplitude or an equivalent constant-amplitude format. When necessary, load spectra for sinusoidal sweep tests, random vibration tests, and acoustic tests may be converted into an equivalent constant-amplitude format. It should be noted that this conversion is material dependent.

The equivalent number of cycles, $N_{\mathrm{eq}}$, for a random vibration test or acoustic test is given by

$$N_{\mathrm{eq}} = f_{\mathrm{n}} \Delta t \left\{ (0{,}471)^{n} \, \Gamma\left[ \frac{(n+2)}{n} \right] \right\}$$

where

$f_{\mathrm{n}}$ is the resonant frequency, in hertz;

$\Delta t$ is the duration of test, in seconds;

$\Gamma$ is a gamma function; and

$n$ is the Paris crack growth rate exponent for a specific metallic material.

Table A.1 gives the equivalent number of limit cycles for random vibration and acoustic tests. For a given material, $n$ is determined experimentally.

**Table A.1 — Equivalent number of limit cycles for random vibration and acoustic tests**

| $n$ | $N_{\mathrm{eq}}$ |
|---|---|
| 2 | $f_{\mathrm{n}}\Delta t$ (0,222) |
| 3 | $f_{\mathrm{n}}\Delta t$ (0,139) |
| 4 | $f_{\mathrm{n}}\Delta t$ (0,099) |
| 5 | $f_{\mathrm{n}}\Delta t$ (0,077) |
| 6 | $f_{\mathrm{n}}\Delta t$ (0,066) |

### A.2.2.3 Stress spectrum generation

For the critical location, stresses including temperature and pressure should be generated in three principal directions. For pressure vessels, both primary membrane and secondary bending stresses resulting from internal pressure should be calculated to account for the effects of geometric discontinuities. Where applicable, rotational accelerations should be considered in addition to linear accelerations. Residual stresses due to fabrication, assembly, testing or preloading should be included.

Various types of loads including axial loads, shear loads and bending loads should be transferred to stresses through corresponding stress transfer functions. State-of-the-art software packages usually have algorithms that can perform the needed conversions automatically. Loads that do not cause the crack to grow should be omitted. Any load that induces a tensile stress to produce the stress intensity factor range ($\Delta K$) below its crack growth threshold ($\Delta K_{\mathrm{th}}$) should be eliminated through a pre-processor.

An easy but conservative approach is to use the critical crack size in the calculation of the stress intensity factor range:

$$\Delta K = (1-R) K_{\mathrm{max}} = (1-R) \left[ \beta \sigma_{\mathrm{max}} \left( \pi a_{\mathrm{cr}} \right)^{0{,}5} \right]$$

where

$R = \sigma_{\mathrm{min}}/\sigma_{\mathrm{max}}$ is the stress ratio of a stress cycle,

$\beta$ is the geometric correction function, and

$a_{\mathrm{cr}}$ is the critical crack size.

If the calculated $\Delta K$ is less than $\Delta K_{\mathrm{th}}$, the corresponding stress cycle could be deleted from the stress spectrum.

A stress spectrum should be generated for each critical location analyzed and should include stresses for all loading events which occur throughout the service life. Each stress step in the stress spectrum should contain the number of cycles in the step, and the maximum and minimum values of the stress amplitude.

### A.2.2.4 Initial crack size and shape assumption

In most cases, initial crack sizes assumed in the crack growth analysis are based on specific NDE technique(s) that is (are) imposed on flight hardware. Minimum detectable initial crack sizes for specific NDE methods are given in Table A.2 for common crack geometry. These are so-called “standard NDE”-detectable crack sizes. In general, the NDE method is selected for a specific location and then the corresponding crack sizes are used in the safe-life analyses or tests. However, when the analysis shows that the use of standard NDE sizes for one specific NDE method can not meet the requirement, sizes corresponding to other NDE methods should be tried. Otherwise, “special NDE” by a special inspector with specific technique(s) should be performed. The probability of detection (POD) of a special NDE should be demonstrated with a 90 % reliability with a 95 % confidence. NDE should screen for both internal and surface cracks.

**Table A.2 — Minimum detected crack size versus NDE method**

| **Crack location** | **Part thickness,** $t$ mm | **Crack type** | **Crack depth,** $a$ mm | **Half crack length,** $c$ mm |
|---|---|---|---|---|
| **Eddy current NDE** | | | | |
| Open surface | $t \leqslant 1{,}27$<br>$t > 1{,}27$ | through<br>PTC | $t$<br>0,5<br>1,27 | 1,27<br>2,5<br>1,27 |
| Edge or hole | $t \leqslant 1{,}9$<br>$t > 1{,}9$ | through<br>corner | $t$<br>1,9 | 2,5<br>1,9 |
| **Penetrant NDE** | | | | |
| Open surface | $t \leqslant 1{,}27$<br>$1{,}27 < t \leqslant 1{,}9$<br>$t > 1{,}9$ | through<br>through<br>PTC | $t$<br>$t$<br>0,63<br>1,9 | 2,5<br>$3{,}8 - t$<br>3,2<br>1,9 |
| Edge or hole | $t \leqslant 2{,}5$<br>$t > 2{,}5$ | through<br>corner | $t$<br>2,5 | 2,5<br>2,5 |
| **Magnetic particle NDE** | | | | |
| Open surface | $t \leqslant 1{,}9$<br>$t > 1{,}9$ | through<br>PTC | $t$<br>1,0<br>1,9 | 3,2<br>4,6<br>3,2 |
| Edge or hole | $t \leqslant 1{,}9$<br>$t > 1{,}9$ | through<br>corner | $t$<br>1,9 | 6,3<br>6,3 |
| **Radiographic NDE** | | | | |
| Open surface | $0{,}8 \leqslant t \leqslant 2{,}7$<br>$t > 2{,}7$ | PTC | $0{,}7\,t$<br>$0{,}7\,t$ | 1,9<br>$0{,}7\,t$ |
| **Ultrasonic NDE** | | | | |
| Open surface | $t \geqslant 2{,}5$ | PTC | 0,76<br>1,65 | 3,8<br>1,65 |

### A.2.2.5 Material data

Material properties used in the crack growth analysis should be valid for the grain direction, material thickness, and load ratio $R$ (minimum stress/maximum stress) and the anticipated environment. Unless otherwise specified, mean values of the following material data should be used for LEFM crack growth analysis:

a) cyclic crack growth rate, $\mathrm{d}a/\mathrm{d}N$ vs $\Delta K$;

b) sustained load crack growth rate, $\mathrm{d}a/\mathrm{d}t$ (for glass);

c) threshold stress intensity range, $\Delta K_{\mathrm{th;}}$

d) plane strain fracture toughness, $K_{\mathrm{Ic}}$;

e) plane stress fracture toughness, $K_{\mathrm{c;}}$ and

f) stress corrosion cracking plane strain fracture toughness, $K_{\mathrm{ISCC}}$.

## A.2.3 Damage tolerance (safe-life) testing

Testing is a viable option to demonstrate the damage tolerance capability for an FCI made of metallic materials. Full-scale, flight-like elements of the FCI with controlled flaws should be used as test articles. These flaws should be placed in the critical locations and in the most unfavourable orientation with respect to the applied load and material fracture characteristics. Usually, the primary reason to perform testing in lieu of analysis is when a new material and/or a new product form is used to construct the FCI, and the material's fracture properties are not readily available to perform the required analysis. When a service loading condition is very complex and the analysis tool is not very reliable, testing is a preferred alternative.

In a safe-life test, there are a few important procedures and precautions.

a) The shape and size of the initial flaws prefabricated in the test article should be consistent with the NDE that will be applied to the flight hardware. Usually, the initial flaws are prefabricated by an electric discharge machining (EDM) process. The width of flaws formed by EDM should be approximately 0,1 mm. The test article should be subjected to fatigue pre-cracking before the application of the service load spectrum.

b) The load/environment spectrum used in the test should be developed by the methods described in 5.1.3.3. To avoid the non-representative load interaction effects on the crack growth, the service loads should be applied to the test article in sequence.

c) If a component-level specimen is used as the test article, one test is sufficient for damage tolerance demonstration unless the test result is doubtful. In such a case, a duplicate test should be performed.

d) For metal-lined COPV, damage tolerance (safe-life) testing shall be performed on the metallic liners. Coupons can be used as the test specimens in lieu of the full-scale vessels. Since the test coupons do not have beneficial residual stresses introduced by the autofrettage (sizing) process, the test results are generally conservative.

e) It is desirable to perform safe-life tests on a closed loop electro-hydraulic test machine. If test spectrum includes variable amplitudes, a computer-controlled system is highly recommended. The test spectrum should be verified independently before the test is conducted.

f) If chemical environments present are known to cause stress corrosion cracking, sustained loads should be maintained for their full duration. An accelerated test should not be permitted unless the acceleration scheme to be used has been substantiated with test results. Temperature effects should be accounted for by conducting the test at a specific temperature. Otherwise, temperature compensation factors should be applied to the test results.

g) The crack growth should be monitored during the safe-life test. The crack size should be measured occasionally using an optical device that has been pre-calibrated. If for any reason a direct measurement is not feasible, an electron fractography study should be performed. Measured crack lengths versus fatigue cycles should be documented in a chart format for easy interpretation.

h) Unless otherwise specified, a life factor of four (4) should be applied on damage tolerance (safe-life) tests. After damage tolerance capability is demonstrated, the test article should be brought to failure to observe the residual strength margin.

### A.2.4 Test report

A test report that documents the damage tolerance test should be prepared with the following information:

- test specimen configuration and initial crack size/shape;
- test equipment and test set-up;
- test load spectrum and corresponding environmental condition;
- crack size measurements;
- test results;
- conclusions.

# Annex B
(informative)

# Guidelines for mechanical damage control of COPV

## B.1 Mechanical damage control plan

A mechanical damage control plan should be prepared for COPVs that are placed under mechanical damage control. A system threat analysis is needed to clearly indicate the potential mechanical damage sources and the magnitude of the threat. Examples are the types of tool that will be used in the manufacturing environment, shipment area and assembly facilities. Sensitivities of NDE including visual inspection should be addressed. Selection of an impact control approach should be delineated.

## B.2 COPV impact damage tolerance demonstration

**B.2.1** COPV mechanical damage is generally caused by improper handling or impacts associated with work about or above the vessel. Most plausible damage events affect the encapsulating composite overwrap of the pressure vessel. The impact damage should be assessed by evaluating the burst strength after impact (BAI) of the pressure vessel. The overall approach for the impact damage tolerance demonstration is as follows.

**B.2.2** An assessment should be made that includes credible impact conditions, impact locations, pressurization levels, and environmental conditions. The assessment should identify drop heights, velocities of potential impacts, masses of objects, and the shape of each object. The threat analysis of the post-fabrication handling damage of the pressure vessel design performed in the system analysis should be used for impact damage tolerance assessment. This assessment may make use of similarity data from prior programs using similar metal liner materials, metal liner diameter to thickness ratio, composite materials, composite thickness, and laminate design, or by development test data for the COPV.

**B.2.3** After the completion of the assessment, the results should be used to establish the visual damage threshold (VDT) of a specific COPV design. This may be done by the application of an impact event on the vessel at the pre-selected locations and impact conditions. The visual inspection should be performed following the impact event. The inspection should be performed by a technician or technicians having formal training in impact damage of COPVs. Multiple impacts may be applied on the same test article. Full scale COPV should be used to avoid any scaling effect concerns. Multiple impacts at different conditions may be applied on the same test article provided a minimum distance is kept. The minimum distance should be ten times the impactor size.

**B.2.4** After the establishment of VDT for a specific COPV design, an undamaged vessel should be used as the test article for impact damage tolerance demonstration. The impact at VDT level should be applied on the test article at the most critical location at the worst-case pressure level. The stress analysis results should be used to select the locations. Visual inspections should be performed to verify that the impact is indeed not visible or barely visible. After the visual inspection, the test article should be placed in a burst test chamber and pressurized to failure.

**B.2.5** The criterion for a successful impact damage tolerance test is

$$\mathrm{BAI} \geqslant \mathrm{DBF} \times \mathrm{MEOP}$$

The impact damage tolerance may be demonstrated by applying a) to e).

a) Drop the pressure vessel 25,4 cm onto a wooden table. For cylindrical COPV, drops should occur so the cylindrical section, then the closure dome section, strikes the wooden surface. For spherical COPV, the impact region should be at the minimum thickness zone of the overwrap, or at the most highly stressed region of the composite and at the location of the final tie-off.

b) Drop the pressure vessel 15,24 cm so the polar boss regions strike the wooden surface. Conduct the test after removal of porting features including transition tubes.

c) Strike the pressure vessel with an impact energy level of 6,8 J using an impactor 12,7 mm in diameter. The point of impact should be at the location of greatest damage sensitivity of the vessel. For cylindrical COPV, this includes the cylindrical section in the region of final tie-off and the highest stress region on the closure dome. For spherical COPVs, the impacted location should be at the final tie-off, and at the predicted failure location for an undamaged vessel, based on the results of the stress analysis.

d) Inspect the vessel by the methods defined by the manufacturer at vessel acceptance. Record all detectable conditions.

e) Subject the vessel to the following hydrostatic pressure test.

    1) Fill at a rate less than or equal to the maximum fill rate to 110 % of MEOP.

    2) Hold for 10 min at 110 % of MEOP.

    3) Fill, at a rate less than or equal to maximum fill rate, to proof pressure level (125 % of MEOP).

    4) Hold at proof pressure for 5 min.

    5) Fill, at a rate less than or equal to maximum fill rate, to minimum design burst pressure.

    6) Hold at minimum burst for 30 s.

    7) Pressurize to rupture. The pressure transducer should be mounted as close as possible to the vessel inlet port during pressure testing. Document the results including description of initiation, location, and deviation of behaviour from undamaged burst test specimen.

## B.3 COPV impact damage protection

For flight COPV, the following impact damage protection procedures should be followed.

a) The vessel should be stored in a rigid container when not actively being fabricated or inspected.

b) Coatings that are applied to the composite after cure should not degrade the ability to detect surface damage. The enhancement of detection capability of surface damage should be a consideration in selecting surface coatings.

c) Transportation containers should be foam-lined and protect the vessel from impact damage during shipping.

d) The manufacturer should inspect the vessel just prior to shipment, and map and record all indications that could be interpreted as damage sites during subsequent incoming inspection at the integration or launch facility. The mapping of indications should be part of the vessel data package provided to the user of the pressure vessel.

e) The COPV should be inspected upon receipt at the facility for damage that may have occurred during shipping.

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