INTERNATIONAL STANDARD

ISO 10786

First edition
2011-07-15

Space systems — Structural components and assemblies

Systèmes spatiaux — Composants et assemblages de structure

Reference number
ISO 10786:2011(E)

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Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 10786 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

Structures are the backbones of all spaceflight systems. A structural failure could cause the loss of human lives for manned space systems or could jeopardize the intended mission for unmanned space systems. Currently, there is no International Standard that covers all the aspects that can be used for spaceflight structural items such as spacecraft platforms, interstage adaptors, launch vehicle buses and rocket motor cases.

The purpose of this International Standard is to establish general requirements for structures. It provides the uniform requirements necessary to minimize the duplication of effort and the differences between approaches taken by the participating nations and their commercial space communities in developing structures. In addition, the use of agreed-upon standards will facilitate cooperation and communication among space progammes.

Space systems — Structural components and assemblies

1 Scope

This International Standard establishes requirements for the design; material selection and characterization; fabrication; testing and inspection of all structural items in space systems, including expendable and reusable launch vehicles, satellites and their payloads. This International Standard, when implemented for a particular space system, will assure high confidence in achieving safe and reliable operation in all phases of its planned mission.

This International Standard applies specifically to all structural items, including fracture-critical hardware used in space systems during all phases of the mission, with the following exceptions: adaptive structures, engines and thermal protection systems.

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 14622:2000, *Space systems —Structural design — Loads and induced environment*

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

ISO 14953:2000, *Space systems — Structural design — Determination of loading levels for static qualification testing of launch vehicles*

ISO 14954:2005, *Space systems — Dynamic and static analysis — Exchange of mathematical models*

ISO 15864:2004, *Space systems — General test methods for space craft, subsystems and units*

ISO 16454:2007, *Space systems — Structural design — Stress analysis requirements*

ISO 21347:2005, *Space systems — Fracture and damage control*

ISO 21648:2008, *Space systems – Flywheel module design and testing*

ISO 22010:2007, *Space systems — Mass properties control*

ISO 24638:2008, *Space systems — Pressure components and pressure system integration*

ISO 24917:2010, *Space systems — General test requirements for launch vehicles*

MIL-STD-1540, *Revision D Test Requirements for Space Vehicles*

3 Terms and definitions

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

3.1
A-basis allowable
A-basis design allowable
A-value
mechanical strength value above which at least 99 % of the population of values is expected to fall, with a confidence level of 95 %

[ISO 16454:2007]

3.2
acceptance test
required formal test conducted on flight hardware to ascertain that the materials, manufacturing processes, and workmanship meet specifications and that the hardware is acceptable for intended usage

[ISO 14623:2003]

3.3
adaptive structures
autonomous structural systems which incorporate sensors, processors, and actuators to enable adaptation to changing environmental conditions, thereby enhancing safety, stability, vibration damping, acoustic noise suppression, aerodynamic performance and optimization, pointing accuracy, load redistribution, damage response, structural integrity, etc.

3.4
allowable load
maximum load that can be accommodated by a structure or a component of a structural assembly without potential rupture, collapse, or detrimental deformation in a given environment

NOTE 1 "Allowable loads" commonly correspond to the statistically based ultimate strength, buckling strength, and yield strength, or maximum strain (for ductile materials).

NOTE 2 "Allowable load" is often referred to as just "allowable".

3.5
assembly
combination of parts, components and units which forms a functional entity

3.6
B-basis allowable
B-basis design allowable
B-value
mechanical strength value above which at least 90 % of the population of values is expected to fall, with a confidence level of 95 %

[ISO 16454:2007]

3.7
buckling
failure mode in which an infinitesimal increase in the load could lead to sudden collapse or detrimental deformation of a structure

EXAMPLE Snapping of slender beams, columns, struts and thin-wall shells.

3.8
catastrophic failure
failure which results in the loss of human life, mission or a major ground facility, or long-term detrimental environmental effects

3.9
collapse
failure mode induced by quasi-static loads (compression, shear or combined stress) accompanied by irreversible loss of load-carrying capability

3.10
composite material
combination of materials different in composition or form on a macro scale

NOTE 1 The constituents retain their identities in the composite.

NOTE 2 The constituents can normally be physically identified, and there is an interface between them.

[ISO 16454:2007]

EXAMPLE Composites include

— fibrous (composed of fibres, usually in a matrix),

— laminar (layers of materials), and

— hybrid (combination of fibrous and laminar).

3.11
composite overwrapped pressure vessel
COPV
pressure vessel with a fibre-based composite system fully or partially encapsulating a liner

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

[ISO 14623:2003]

3.12
composite structure
structural components that are made of composite materials

3.13
damage tolerance
ability of a structure or a component of a structural assembly to resist failure due to the presence of flaws, cracks, or other damage for a specified period of unrepaired usage

[ISO 21347:2005]

3.14
design parameter
physical feature which influences the design performance of the design of structural items

NOTE According to the nature of the design variables, different design problems can be identified such as:

— structural sizing for the dimensioning of beams, shells, etc.;

— shape optimization;

— material selection;

— structural topology.

3.15
design safety factor
factor by which limit loads are multiplied in order to account for uncertainties and variations that cannot be analysed or accounted for explicitly in a rational manner

NOTE Design safety factor is sometimes referred to as design factor of safety, factor of safety or just safety factor.

3.16
detrimental deformation
structural deformation, deflection or displacement that prevents any portion of the structure or some other system from performing its intended function or that jeopardizes mission success

3.17
development test
test to provide information that can be used to check the validity of analytic techniques and assumed design parameters, uncover unexpected system response characteristics, evaluate design changes, determine interface compatibility, prove qualification and acceptance procedures and techniques, check manufacturing technology, or establish accept/reject criteria

[ISO 16454:2007]

3.18
dynamic load
time-dependent load with deterministic or stochastic variation

3.19
failure mode
rupture, collapse, detrimental deformation, excessive wear or any other phenomenon resulting in an inability to sustain loads, pressures and corresponding environments, or that jeopardizes mission success

NOTE This definition applies to structural failure.

3.20
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 load, with an ultimate safety factor of 1,0

[ISO 21347:2005]

3.21
fatigue life
number of cycles of stress or strain of a specified character that a given structure or component of a structural assembly can sustain (without the presence of flaw) before failure of a specified nature could occur

3.22
failure mode effects and critically analysis
FMECA
analysis performed to systematically evaluate the potential effect of each functional or hardware failure on mission success, personnel and system safety, system performance, maintainability and maintenance requirements

NOTE It is also used to rank by the severity of its effect.

3.23
flaw
local discontinuity in a structural material

EXAMPLES Crack, cut, scratch, void, delamination disbond, impact damage and other kinds of mechanical damage.

[ISO 21347:2005]

3.24
fracture control
application of design philosophy, analysis methods, manufacturing technology, verification methodology, quality assurance, including non-destructive evaluation (NDE) and operating procedures to prevent premature structural failure caused by the presence and/or propagation of flaws during fabrication, testing, transportation, handling, and service events such as launch, in-orbit operation, and return

3.25
fracture-critical item
fracture-critical part
structural part whose failure due to the presence of a flaw would result in a catastrophic failure

3.26
full scale article
full-size test article which represents the whole flight structure or a part of the flight structure with representative loading and boundary conditions

3.27
hydrogen embrittlement
mechanical-environmental process that results from the initial presence or absorption of excessive amounts of hydrogen in metals, usually in combination with residual or applied tensile stresses

[ISO 14623:2003]

3.28
human vibration
vibration transmitted to and/or induced by the crew members

3.29
life factor
coefficient by which the number of cycles or time is multiplied in order to account for uncertainties in the statistical distribution of loads and cycles, as well as uncertainties of the methodology used in the life related analyses

NOTE 1 Life factor and scatter factor are interchangeable terms in some documents.

NOTE 2 Life factor is sometimes referred to as scatter factor when uncertainties are material uncertainties.

EXAMPLE Factors used in fatigue (life) analysis and damage tolerance life (crack growth safe-life) analysis.

3.30
limit load
LL
maximum expected load, or combination of loads, which a structure or a component in a structural assembly is expected to experience during its service life in association with the applicable operating environments

NOTE 1 Load is a generic term for thermal load, pressure, external mechanical load (force, moment, or enforced displacement) or internal mechanical load (residual stress, pretension, or inertial load).

NOTE 2 The corresponding stress or strain is called limit stress or limit strain.

NOTE 3 Limit load is sometimes referred to as design limit load. See informative Annex A.

3.31
loading case
combined loading case
particular condition of single (or combined) mechanical load, pressure and temperature, which can occur for some structural components or a structural assembly at the same time during their service life

3.32
loading spectrum
representation of the cumulative loading levels and associated cycles anticipated for the structure or component of a structural assembly according to its service life under all expected operating environments

NOTE Significant transportation, test, and handling loads are included in this definition.

3.33
margin of safety
MS
measure of a structure's predicted reserve strength in excess of the design criteria

NOTE 1 For a single loading condition, MS is expressed as:

MS = { [Allowable Load (Yield or Ultimate)] / [Limit Load x Factor of Safety (Yield or Ultimate)]} -1

NOTE 2 Load may mean force, stress, or strain, if the load-stress relationship is linear.

NOTE 3 The relation also can be expressed for a combined loading case, when the load-stress relationship remains linear for all the contributors of the loading case. Also see alternative methods in Annex D.

3.34
mass and inertia properties
mass and inertia properties of a structure comprise its mass, the location of its centre of gravity, its moments and products of inertia, and, where applicable, its balancing masses

3.35
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

NOTE 1 MEOP includes the effects of temperature, transient peaks, relief pressures, regulator pressure, vehicle acceleration, phase changes, transient pressure excursions, and relief valve tolerance.

NOTE 2 Some particular project may replace MEOP by Maximum Design Pressure (MDP), which takes into account more conservative conditions.

3.36
metallic structural item
structural item made of metals

NOTE In this document, load bearing metallic liners of COPVs are also referred to as metallic structural items.

3.37
moving mechanical assembly
MMA
mechanical or electromechanical device that controls the movement of one mechanical part of a vehicle relative to another part

EXAMPLES Gimbals, actuators, despin and separation mechanisms, motors, latches, clutch springs, dampers, or bearings.

3.38
POGO
instability due to the coupling between the vehicle axial motion and the dynamic response characteristic of the propulsion system

3.39
pressure component
component in a pressurized system, other than a pressure vessel, pressurized structure that is designed largely by the internal pressure

[ISO 24638:2008]

EXAMPLES Valves, pumps, lines, fittings, hoses and bellows.

3.40
pressure vessel
container designed primarily for storage of pressurized fluid that (1) contains gas or liquid with an energy level of 19,310 joules (14,240 foot-pounds) or greater, based on adiabatic expansion of a perfect gas; or (2) contains gas or liquid that will create a mishap (accident) if released; or (3) will experience a MEOP greater than 700 kPa (100 psi)

NOTE Pressurized structures, pressure components and pressurized equipment are excluded from this definition.

3.41
pressurized equipment
special pressurized equipment
piece of equipment that meets the pressure vessel definition, but for which it is not feasible or cost effective to comply with the requirements applicable to pressure vessels

EXAMPLES Batteries, heat pipes, cryostats and sealed containers.

3.42
pressurized hardware
pressurized hardware includes pressure vessels, pressurized structures, pressure components and pressurized equipment

3.43
pressurized structure
structure designed to carry both internal pressure and vehicle structural loads

[ISO 14623:2003], [ISO 24638:2008]

EXAMPLES Main propellant tanks and solid rocket motor cases of launch vehicles, and crew cabins of manned modules.

3.44
primary structure
part of a structure that carries the main flight loads and defines the overall stiffness of the structure, thus influencing its natural frequencies and mode shapes

3.45
proof factor
multiplying factor applied to the limit load or MEOP to obtain proof load or proof pressure for use in the acceptance testing

3.46
protoqualification test
test of the flight-quality article to a higher load level and duration than the acceptance test applied to flight units under prototype qualification strategy

NOTE The testing consists of the same types and sequences as used in qualification testing.

3.47
qualification test
required formal contractual test conducted at load levels and durations to demonstrate that the design, manufacturing, and assembly of flight-quality structures have resulted in hardware that conforms to specification requirements

NOTE In addition, the qualification test may validate the planned acceptance progamme including test techniques, procedures, equipment, instrumentation, and software.

3.48
random load
vibrating load or fluctuating load whose instantaneous magnitudes are specified only by probability distribution functions giving the probable fraction of the total time that the instantaneous magnitude lies within a specified range

NOTE A random load contains non-periodic or quasi-periodic constituents.

3.49
residual strength
maximum value of load and/or pressure (stress) that a flawed or damaged structural item is capable of sustaining without further damage or collapse, considering appropriate environmental conditions

3.50
residual stress
stress that remains in a structure after processing, fabrication, assembly, testing or operation

EXAMPLE Welding-induced residual stress.

[ISO 14623:2003]

3.51
S-basis allowable
mechanical strength value specified as a minimum by the governing industrial specification, or a particular contractor's specification

EXAMPLES Properties given in MMPDS (Metallic Materials Properties Development and Standardization).

3.52
safe life
(1) design criterion under which failure does not occur in the expected environment during the service life

(2) required period during which a structural item, even containing the largest undetected flaw, is shown by analysis or testing not to fail catastrophically under the expected service load and environment

NOTE 1 An equivalent definition is “period during which the structure is predicted not to fail in the expected service life environment”.

NOTE 2 Safe life is also referred as damage tolerance life or fatigue life.

3.53
safe-life structure
structure designed according to the safe-life design criterion

3.54
scatter factor
coefficient by which the number of cycles or time defined in service life is multiplied in order to account for uncertainties in material properties when performing fatigue and/or crack growth analysis

NOTE Scatter factor is sometimes referred to as life factor, which is usually used for just the difference in material data used in the analysis; for example, S-N data used in fatigue life analysis, or da/dN data used in crack grow analysis.

3.55
secondary structure
structure attached to the primary structure with negligible participation in the main load transfer and overall stiffness

3.56
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, retesting, re-entry or recovery from orbit, and reuse that can be required or specified for the item

3.57
shock load
special type of transient load, where the load shows significant peaks and the duration of the load is well below the typical response time of the structure

3.58
stiffness
ratio between an applied force and the resulting displacement

3.59
stress-corrosion cracking
mechanically and environmentally induced failure process in which sustained stress and chemical attack combine to initiate and/or propagate a crack or a crack-like flaw in a metal part

[ISO 21347:2005]

3.60
stress-rupture life
minimum time during which a non-metallic structural item maintains structural integrity, considering the combined effects of stress level(s), time at stress level(s), and associated environments

3.61
structural component
mechanical part(s) in a functional hardware item designed to sustain load and/or pressure or maintain alignment

EXAMPLES Antenna support structure, instrument housing, and pressure vessel.

3.62
structural design
process used to determine geometries/dimensions and to select materials of a structure

3.63
structural item
structure, structural subsystem (assembly), or structural component

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

3.64
structural mathematical model
analytical or numerical representation of a structure

NOTE It is advisable that the model provides an adequate description of the structure's response under loads/pressures/temperatures.

[ISO 16454:2007]

3.65
structure
structural assembly
set of mechanical components or assemblies designed to sustain (carry) internal and/or external loads or pressures; provide (maintain) stiffness, alignment, and/or stability; and provide support or containment for other systems or subsystems

NOTE The space vehicle structure is usually categorized into primary and secondary structures.

3.66
system threat analysis energy level
maximum expected energy level due to an impact resulting from a credible threat event determined in a system threat analysis

3.67
static load
quasi-static load
load which is independent of time or are varying slowly with time, so that the dynamic response of the structure is insignificant

NOTE Quasi-static loads comprise both static and dynamic loads and are applied at a frequency sufficiently below the natural frequency of the considered part, thus being equivalent to static loads in their effects on the structure.

3.68
transient load
load whose magnitude or direction varies with time and for which the dynamic response of the structure is significant

[ISO 14622:2000]

NOTE These loads can be induced by transportation, gusts, engine ignition or shutdown, separation, orbital docking, physical impact, or deployment of appendages.

3.69
ultimate load
UL
maximum design load that the structure shall withstand without rupture or collapse, which is expressed as a limit load multiplied by an ultimate design safety factor

NOTE The corresponding stress and/or strain is called ultimate stress and/or strain.

3.70
ultimate strength
maximum load or stress that a structure or material can withstand without incurring rupture or collapse

3.71
vibroacoustic
environment induced by high-intensity acoustic noise associated with various segments of the flight profile

NOTE It manifests itself throughout the structure in the form of transmitted acoustic excitation and as structure-borne random vibration.

3.72
visual damage threshold
VDT
impact energy level shown by test(s) to create an indication that is barely detectable by a trained inspector using an unaided visual inspection technique

[ISO 21347:2005]

3.73
yield load
YL
maximum design load that the structure shall withstand without detrimental deformation, which is expressed as a limit load multiplied by a yield design safety factor

NOTE The corresponding stress and/or strain is called yield stress and/or strain.

3.74
yield strength
maximum load or stress that a structure or material can withstand without incurring a specified permanent deformation or yield

NOTE The yield is usually determined by measuring the departure of the actual stress-strain diagram from an extension of the initial straight proportion. The specified value is often taken as an offset unit strain of 0,002.

4 Symbols and abbreviated terms

The following abbreviated terms are defined and used within this document:

ε - N	fatigue strain-life data
$\sum n/N$	Miner's rule
AIT	assembly, integration and tests
AOCS	attitude and orbit control system
BIT	built-in testing
CAD	computer aided design
CAE	computer aided engineering
CAM	computer aided manufacturing
COPV	composite overwrapped pressure vessel
da/dN	fatigue crack growth rate
DDF	design definition file
DJF	design justification file
DOF	degree(s) of freedom
DSF	design safety factor
ECLS	environment control and life support
EMC	electromagnetic compatibility
EVA	extra-vehicular activity
FCI	fracture critical item
FEA	finite element analysis

FE	finite element
FM	flight model
FMECA	failure mode effects and criticality analysis
FOS	factor of safety
FSI	fluid structure interaction
HDBK	handbook
Hz	hertz
ICD	interface control document
K_c	fracture toughness
KPP	key process parameter
LBB	leak-before-burst
LCDA	launcher coupled dynamic analysis
LL	limit load
MDP	maximum design pressure
MEOP	maximum expected operating pressure
MEOS	maximum expected operating speed
MMPDS	Metallic Materials Properties Development and Standardization
M/OD	meteoroid and orbital debris
MS	margin of safety
NASA	National Aeronautics and Space Administration
NDE	non-destructive evaluation (examination)
NDI	non-destructive inspection
NDT	non-destructive test
PFO	particle fall out
RMS	root-mean-square
SEP	system engineering plan
S-N	fatigue stress-life data
VDT	visual damage threshold

5 Tailoring

For a specific progamme or project, the requirements defined in this International Standard may be tailored to match the actual requirements of the particular progamme or project. Tailoring of requirements shall be undertaken in agreement with the procuring authority where applicable.

Tailoring is a process by which individual requirements or specifications, standards, and related documents are evaluated and made applicable to a specific progamme or project by selection, and in some exceptional cases, by modification and addition of requirements in the standards.

Requirements for a human-rated progamme or project can be adjusted for a specified use by a procurement agency.

6 Requirements

6.1 General

Clause 6 presents the general requirements for the design; material selection and characterization; fabrication and process control; quality assurance; storage and transportation; repair and refurbishment for all structural items.

6.2 Design requirements

6.2.1 Static strength

6.2.1.1 Ultimate strength

All structural items shall have the strength and stiffness in all necessary configurations to support the ultimate loads, pressure and operating environments throughout their respective service lives without catastrophic failure or collapse.

6.2.1.2 Yield strength

All structural items shall have the strength and stiffness in all necessary configurations to support the yield loads, pressure and operating environments throughout their respective service lives, including the expected tests without detrimental (excessive or permanent) deformation, yielding, gapping, sliding, or losing rigidity that can jeopardize the mission objectives.

NOTE 1 For functional requirements (e.g. no excessive deformation, gapping, sliding, loss of rigidity) some projects may consider limit loads only instead of yield loads.

NOTE 2 For metal structural components, local yielding may exist. This local yielding is acceptable if it does not cause overall permanent set instability or fatigue failure of the structure, and remains compliant with the functional requirements.

6.2.2 Buckling strength

Buckling shall not cause structural failure when ultimate loads are applied, nor shall it cause excessive deformations to degrade functioning of any system or produce changes in any loads that shall be accounted for. All structural items subjected to significant in-plane stresses (compression and/or shear) or external pressure under any combination of ground loads, flight loads, or loads resulting from temperature changes, shall be analysed or tested for buckling failure. Buckling evaluation shall address local or global instability, crippling, and creep. Design loads for buckling shall be ultimate loads, except that the minimum anticipated value shall be used for any load component that tends to alleviate buckling.

Local buckling shall be prevented unless:

a) the buckling is reversible;

b) the resulting stiffness and deformations still conform to the structural and functional requirements.

6.2.3 Margin of safety (MS)

The MS for every structural strength or buckling calculation shall be positive under single or combined loads, pressures, and accompanying environments such as temperature for each design condition.

NOTE "Positive" means equal to or greater than the margin specified in the margin policy for the structural item.

6.2.4 Stiffness

All structural items shall possess adequate stiffness to preclude detrimental deformations due to loads corresponding to the expected test and operating environments throughout their respective service lives.

They shall also possess adequate stiffness to preclude collapse at design ultimate load. The cumulative elastic, permanent, and thermal deformations shall not degrade structural capability or adversely affect aerodynamic characteristics. In addition:

a) the structure shall be designed to conform to required stiffness under the specified load and boundary conditions, and

b) the stiffness of subassemblies and components and interfaces shall be such that the structural and functional performance requirements are met.

NOTE Stiffness is often expressed in terms of a minimum natural frequency requirement.

Deformations leading to the following failure modes shall be avoided: violations of specified envelopes, gapping at joints, the creation of inefficient load paths and dynamic coupling with other subsystems, e.g. Attitude and Orbit Control System (AOCS).

6.2.5 Dynamic behaviour

The natural frequencies of a structure shall be within specified bandwidths to prevent dynamic coupling with major excitation frequencies (e.g. launch vehicle fundamental frequencies).

Spacecraft structures shall be designed to avoid coupling with the launch vehicle control system. The stiffness of each structural item shall be consistent with the minimum required stiffness to ensure structural adequacy under transient dynamic loads. In addition, the body-bending frequencies shall be within the limits imposed by the vehicle flight control system.

The spacecraft shall be designed to avoid load-inducing dynamic coupling of flexible modes during launch, in-orbit operations, and landing. When avoiding such coupling is not practical, careful evaluation of the resulting dynamic loads, and their simulation by analysis or test, shall be required.

Structural components and assemblies shall be capable of performance within specification after exposure to sinusoidal vibration, random vibration, vibroacoustic and shock environment as appropriate.

6.2.6 Dimensional stability

Structural materials shall remain dimensionally stable under given environments during ground, flight, landing, and post-landing operations. The structural item shall not lose alignment that would impact the mission under the action of applied loads, including the effects of temperature, humidity, and venting. In addition:

a) Dimensional stability of the structure shall conform to mission specified system and payload requirements.

b) The design of a structure shall ensure that no loss of alignment which jeopardizes or degrades the mission objectives can be caused by the action of applied loads (e.g. launch loads, deployment loads, thermal stress and moisture release).

c) Selected materials shall take into account the stability of the material under the specified environment in-service.

NOTE Dimensional stability requirements address the short, medium and long-term alignment stability of a space structure under the operational environment.

6.2.7 Tolerances and alignments

The accuracy of the system of tolerances applied to the mechanical design shall guarantee conformance to geometrical interface requirements.

The angular and position tolerances shall be consistent with the alignment or pointing accuracy of the assembly to achieve the mission objectives.

In cases where alignment adjustability is specified, either at assembly level or at spacecraft level, these provisions shall be included in the mechanical design together with the devices (e.g. alignment cubes) and procedures required for measurement or checking of the alignment.

6.2.8 Thermal

The design of space structures shall conform to the constraints imposed by thermal design to meet the mission objectives.

The temperatures and temperature variations and gradients during all phases of a mission, including manufacturing and storage, shall be taken into account, both in the material selection and in the design in order to achieve the specified functional and structural performance.

6.2.9 Thermal distortion

Detrimental distortion of structural items due to thermal loading shall be prevented during transfer orbit, in orbit, or in safe mode operation including the effects of the molecular heating.

It is necessary that thermal distortion effects for spacecraft pointing and/or co-alignment of sensors be reduced.

6.2.10 Interface requirements

Interfaces of structural parts that include joints and connections shall be taken into consideration in the structural design. The structural integrity of bond joints, weld joints, and other forms of joints and connections shall be assessed, including the potential interaction among failure modes.

The design of bolted joints shall include sufficient thread engagement.

6.2.11 Electromagnetic compatibility

Structural requirements imposed by electromagnetic compatibility (EMC) of the equipment and payload structures shall be taken into account.

6.2.12 Lightning protection

The structure of launch vehicles shall be designed to:

a) dissipate static electrical charges;

b) provide electromagnetic protection; and

c) provide means of diverting electrical current arising from lightning strike so as not to endanger the vehicle.

6.2.13 Mass and inertia properties

Mass, centre of gravity and moment of inertia properties shall be compliant with the mass budget allocation. During the development, fabrication and system test phases continuous refinement of mass, centre of gravity and moment of inertia shall be performed. ISO 22010 specifies the mass properties control.

6.2.14 Fatigue life

All non-fracture-critical structural items shall have adequate fatigue life in order to achieve mission success. Unless otherwise specified, fatigue life shall be at least four times the service life with no assumed initial damage or defects.

6.2.15 Fracture control

A fracture control progamme shall be established and implemented for structural items when their failure due to the growth of undetected flaws can result in a catastrophic or critical hazard. The fracture control progamme shall be integrated in the design and verification process. This progamme shall include the following activities as a minimum:

a) hazard analysis and structural screening to identify fracture critical items (FCIs);

b) fail-safe analysis/or test for the structural assembly exempting from fracture control;

c) formulation of a nondestructive evaluation (NDE) policy;

d) demonstration of damage tolerance life for metallic FCIs; and

e) demonstration of impact damage tolerance for composite FCIs.

Unless specified by the procuring agency, other requirements set forth in ISO 21347 shall be met.

6.2.15.1 Fail-safe

A structural item/assembly shall meet the following requirements to be qualified as a fail-safe item:

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

   For other structural items except attachments, requiring basic fail-safe design is not recommended to avoid unnecessary increases in the mass of these items

b) Failure of the structural item shall not result in the release of any part or fragment which could lead to any 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 an appropriate life factor is used.

6.2.15.2 Damage-tolerance life (safe life)

Each fracture-critical item (FCI) shall be damage tolerant, i.e., have an adequate damage tolerance life (safe life). For metallic structural items, it is required that the largest undetected crack (consistent in size with the proof test limits or sensitivity of the applied NDE) that could exist in the FCI will not grow to failure when subjected to cyclic and sustained loads in a specified number of service life times. For composite structural items, except composite overwrapped pressure vessels (COPV), the broader range of flaws shall be considered. If some attachment is single, and if it is FCI, then it shall take into account safe-life requirements.

Loads to be considered include testing, launch and/or landing, and normal operational cycles and durations encountered in service. Unless otherwise specified, the required damage tolerance life (safe life) shall be at least four times the service life. For structural items of a reusable launch vehicle and multi-mission spacecraft, or payloads which have scheduled inspection intervals, the required damage tolerance life (safe life) shall be at least four times the inspection interval.

Detailed damage tolerance requirements shall be specified by the procuring authority. ISO 21347 shall be used for the appropriate applications. For pressure vessels and other pressurized hardware, damage tolerance requirements set forth in ISO 14623 shall be met.

6.2.16 Impact damage

The residual strength of composite structural items after impact shall not be degraded below a predetermined level, as specified by the procuring authority for the specific application. For COPVs, the residual strength shall not be degraded below their ultimate load requirements after being subjected to the lesser of a system threat analysis energy level or visual damage threshold (VDT) level impact. Detailed impact damage tolerance requirements shall be specified by the procuring authority. ISO 21347 may be used if appropriate for the specific application. For COPVs, impact damage tolerance requirements set forth in ISO 14623 shall be met.

6.2.17 Stress-rupture life

Composite and other nonmetallic structural items shall be designed to meet the service life requirement considering the time they are under sustained load. These items shall be designed such that there is no credible stress-rupture failure mode based on stress-rupture data for a specified probability of survival. Unless otherwise specified, the minimum probability of survival associated with catastrophic failure shall be 0.999.

6.2.18 Corrosion and stress corrosion control

The effects of the following factors on material properties over the service life of the structural item shall be considered:

a) corrosive or incompatible environments;

b) galvanic corrosion; and

c) stress-corrosion cracking.

6.2.19 Outgassing

The selection of structural materials and processes shall consider the effects of outgassing on the structural items and the surrounding elements or systems.

6.2.20 Meteoroid and orbital debris protection

When required, the space vehicle primary structures, pressurized hardware, thermal radiators, battery cells, and electronic boxes, etc., shall be protected from meteoroid and orbital debris (M/OD) impact in order to prevent risk of catastrophic failure. The selection and design of material and M/OD protection systems shall be based on a defined probability of survival, which may be influenced by the probability of impact, critical M/OD size, and material response to hypervelocity impacts. The magnitude and characteristics of M/OD flux, as well as methods of calculating the probability of penetration, shall be determined in accordance with the requirements specified by government or industry standards.

Furthermore, the space vehicle structural item shall be designed in a manner that complies with international guidelines that are in place to limit the amount of debris created from the item disintegrated during its mission.

6.3 Material requirements

For all the materials in structural items, mechanical properties at room temperature and at the operating temperatures expected over the service life of the item shall be considered in selection, evaluation, and characterization of the materials. Mechanical properties shall include but not be limited to stiffness, strength allowable, fatigue data, fracture toughness and crack growth data. The stress-strain curve shall be included when the material exhibits nonlinear-elastic behaviour.

6.3.1 Metallic materials

6.3.1.1 Metallic material selection

Material selection for metallic structures shall be based on well documented material strengths, physical properties, and fatigue/fracture characteristics consistent with overall system requirements.

6.3.1.2 Metallic material evaluation

Selected metals shall be evaluated for material processing, fabrication methods, manufacturing operations, refurbishment procedures and processes, and other factors that affect the resulting strength and fatigue/fracture properties of the material in the fabricated and refurbished configurations.

Metals susceptible to stress-corrosion cracking or mechanisms such as hydrogen embrittlement shall be evaluated by performing sustained load fracture tests when applicable data are not available.

6.3.1.3 Metallic material characterization

Allowable mechanical properties of all metals selected for structural items shall be characterized in sufficient detail to permit reliable and high-confidence predictions of their structural performance in the expected operating environments, unless these properties are available from reliable sources.

Where material properties are not available, they shall be characterized by tests. Uniform test procedures shall be used to determine material strength and fracture properties as required. These procedures shall conform to recognized standards.

NOTE The following publications are examples of such recognized standards: ASTM E-399, ASTM E-647, and ASTM E-740, developed by the American Society for Testing and Materials (ASTM).

Test specimens and procedures utilized shall provide valid test data for the intended application.

For fracture-critical items, sufficient tests shall be conducted so that meaningful nominal values of fracture toughness, fatigue data, and crack growth rate data, corresponding to each alloy system, temper, product form, thermal and chemical environments, and loading spectra, can be established to evaluate compliance with strength, fatigue life and damage tolerance life (safe life) requirements.

6.3.1.4 Metallic material strength allowables

For all primary metallic structures that are not fail-safe, A-basis strength values shall be used for margin of safety calculations. As a minimum, B-basis values shall be used for fail-safe or secondary structures. In special circumstances where design data at the required statistical level are not established, limited data acquisition tests to establish S-basis allowables may be conducted.

For fracture-critical items, the calculation shall be based on the material's A-basis allowable.

6.3.2 Glass and ceramics materials

For glass and ceramics, the lack of ductility results in very low failure strains. The large scatter is primarily caused by the variable severity of embedded flaws or surface flaws. The different nature of the flaws results in dissimilar failure response to identical external loading conditions. Due to the random distribution of flaws in these materials, the failure of a complex structural part can be initiated at any point, and not just at the location in the part experiencing the highest stress or possessing the weakest strength.

6.3.2.1 Glass and ceramics material selection

Material selection for glass or ceramic structures shall be based on well documented material properties appropriate for the intended application. Key characteristics to be considered shall include fracture toughness, hardness, Weibull parameters, dimensional tolerances, environmental compatibility, elastic properties, thermal properties, electrical properties, surface finish, and surface quality (presence of surface defects caused by impurities). For each type of glass or ceramic component, temperature and stress distributions shall be determined for steady-state and transient operating conditions. These data shall then be used in conjunction with accepted life-prediction progammes to make initial assessments of the probability of survival of the component over its intended lifetime. The minimum acceptable probability of survival shall be set on the basis of mission requirements.

6.3.2.2 Glass and ceramic material evaluation

Selected glass or ceramics materials shall be evaluated with respect to material processing, manufacturing robustness, inspection protocols, refurbishment procedures and processes, and other factors that affect the functional performance of the material in fabricated and refurbished configurations.

Materials which are susceptible to time-dependent or (temperature or stress) cycle-dependent failure shall be evaluated by performing stress-rupture and/or cyclic fatigue tests when applicable data are not available.

6.3.2.3 Glass/ceramic material characterization

Mechanical and thermal properties of all glass or ceramic materials selected for structural items shall be characterized in sufficient detail to permit reliable and high-confidence predictions of operating stresses and temperatures for steady-state and transient conditions. The Weibull and slow crack growth/cyclic fatigue parameters required to predict probability of survival also shall be characterized. Potential sources of these data include material suppliers, technical publications, and established databases.

Where material properties are not available, they shall be characterized using established testing procedures. When possible, these procedures shall conform to recognized standards, such as standard test methods developed by the ASTM. If no standards exist, adopted test procedures shall be based on the best available methods as defined in the current technical literature. Sufficient tests shall be conducted so that statistically meaningful data corresponding to each material type, manufacturing method, product form and size, thermal and chemical environments, and operating spectra can be established to evaluate compliance with strength, safe-life, and/or fatigue requirements.

6.3.2.4 Strength allowables for glass and ceramic materials

Strength allowables for glass and ceramics shall be selected on a statistical basis. The allowables to be used with the predicted design limit stresses shall be such that the probability of failure of the structural item is consistent with the reliability requirements for this kind of material set by the procuring authority. In the absence of an allocated reliability to the structural item, the probability of failure shall not be greater than 1×10^{-6}.

6.3.3 Composite materials

The strength and stiffness of composite fibre reinforced materials are functions of fibre properties, matrix properties, fibre content and orientation of fibres, and the processes used to construct the composite material.

The properties of composites are determined by both fibres and matrix. By placing fibres in different directions, the material properties can range from highly anisotropic to quasi-isotropic.

6.3.3.1 Composite material selection

At a minimum, composite materials used for fabricating structural items shall be selected on the basis of environmental compatibility, material strength and modulus, stress-rupture, and outgassing properties. The effects of fabrication process, temperature and humidity, load spectra, and other conditions, which can affect strength, stiffness, and dimensional stability of the material in the fabricated configuration, shall be included in the rationale for selecting the composite materials.

6.3.3.2 Composite material evaluation

Materials selected for a composite structure shall be evaluated with respect to the material processing, fabrication methods, manufacturing operations and processes, operating environments, service life, and other pertinent factors that affect the material properties including strength and stiffness in the fabricated configurations.

6.3.3.3 Composite material characterization

Strength and other mechanical properties of composite materials shall be sufficiently characterized for all critical failure modes and expected environmental conditions unless these properties are available from reliable sources such as MIL-HDBK-17, the DOD/NASA Advanced Composites Design Guide, and other sources.

Test methods using samples representative of the geometry, layup, and manufacturing processes involved in hardware fabrication shall be used to determine material properties as required. The anisotropy of laminated composite structural elements shall be accounted for when establishing material properties and failure modes. Test specimens and procedures shall follow standardized test methods whenever available in order to provide valid test data for the intended application.

6.3.3.4 Strength allowables for composite materials

Strength allowables for composite materials shall be determined from testing of coupons, or sub-scale or full-scale composite parts. When sub-scale and coupon data are used in the database, the correlation between coupon/sub-scale data and full-scale data shall be established.

A-basis allowables shall be used for non-fail-safe primary and/or fracture-critical composite structures.

For fail-safe primary structures and all secondary structures, B-basis allowables shall be used as a minimum. For secondary structures only, S-basis allowables may be used with the approval of the procuring authority.

Design development tests shall be conducted to evaluate materials and joint behaviour. The tests may range in complexity from coupon tests and sub-scale tests to full-scale structures.

Design allowables shall be established for each anticipated failure mode using coupons or test specimens taken from a part fabricated using the same process and similar geometry as the full-scale structure. The tests shall develop relationships between strength/temperature and strength/moisture for the entire range of storage, transportation, and operational environments for each critical area of the structure. A series of test specimens of increasing complexity from coupons, sub-scale, to full-scale shall be used to establish allowables for full-scale structures.

6.3.4 Polymeric materials

6.3.4.1 Polymeric material selection

Adhesives and other polymeric materials used for a structural item shall be selected on the basis of environmental compatibility, adjacent materials, material strength and modulus, fatigue, creep deformation and relaxation, and stress-rupture properties as dictated by the application. Effects of fabrication processes, temperature and humidity, load spectra, and other conditions that can affect strength, stiffness, and dimensional tolerance of the material in the fabricated configuration shall also be included in the rationale for selecting polymeric materials. Other material selection considerations shall include flammability, toxicity, and outgassing.

6.3.4.2 Polymeric material evaluation

Materials selected for a polymeric structural item shall be evaluated with respect to the material processing, manufacturing operations and processes, operating environments, service life, and other pertinent factors that affect resulting strength, stiffness, and dimensional tolerance properties of material in fabricated configurations.

6.3.4.3 Polymeric material characterization

Properties of the polymeric materials selected shall be characterized in their expected configurations and operating environments. Test methods using samples representative of manufacturing processes involved in structural hardware fabrication shall be used to determine material properties as required. Test specimens and procedures shall follow standardized test methods whenever available in order to provide valid test data for the intended application.

EXAMPLE ASTM also publishes standardized test methods.

6.3.4.4 Strength allowables for polymeric materials

Strength allowables for polymeric materials shall be determined from testing of coupons, sub-scale, or full-scale parts. When sub-scale and coupon data are used in the database, the correlation between coupon/sub-scale data and full-scale data shall be established.

The bases for design allowables for primary and secondary structural components shall correspond to A-basis and B-basis values, respectively. For fail-safe primary structural components, the B-basis allowables may be used. In special circumstances where design data at the required statistical level are not established, special limited data acquisition tests to establish S-basis allowables may be conducted.

6.3.5 Adhesive materials in bonded joints

All design allowables for adhesive materials in bonded joints (stress or strain) shall be defined according standards agreed upon with the customer.

6.4 Manufacturing and interfaces requirements

The production engineering shall ensure that all structural components and assemblies can be manufactured in the way intended to conform to the quality, reliability and reproducibility requirements.

The production of space structures includes the following:

a) fabrication of structural components (parts) in the factory;

b) integration of structural assemblies in the factory; and

c) integration of structural subsystems either in the factory or at the launch site.

6.4.1 Manufacturing requirements

Design of structural items shall use well characterized fabrication processes and procedures. The fabrication processes of each structural item shall be controlled and documented and all such fabrication processes and operators shall have all required certifications. Proven processes and procedures for fabrication and repair shall be used to preclude damage or material degradation during material processing and manufacturing operations. In particular, special attention shall be given to ascertain that the thermal treatment, machining, drilling, grinding, and other operations are within the state of the art and appropriate for the application.

For fracture-critical structures, fracture toughness, fatigue crack growth rate, mechanical, and physical properties shall be within established design limits after exposure to the intended fabrication processes. Fracture control requirements and procedures shall be defined in applicable drawings and process specifications. Detailed fabrication instructions and controls shall be developed and used to ensure proper implementation of fracture control requirements.

For composite structures, coupon tests and manufacturing process checks shall be performed to show that the as-built flight articles satisfy design and analysis assumptions and are representative of the verification test articles.

Materials shall have certifications that demonstrate acceptable variability in material properties to ensure repeatable and reliable performance. The fabrication processes shall control or eliminate detrimental conditions in the fabricated article.

An inspection plan shall be developed to identify all key process parameters (KPP) essential for verification. In-process inspection or process monitoring shall be used to verify the setup and acceptability of critical parameters during the fabrication process/procedure.

6.4.2 Manufacturing process

The selected manufacturing process shall be demonstrated to be reliable and repeatable, and have been qualified beforehand. In case a new technology is implemented, a development and qualification plan shall first be established.

6.4.2.1 Manufacturing activities

Manufacturing activities to be developed include:

a) samples for evaluation and testing;

b) prototypes, components, representative sections or whole structures in order to prove manufacturing processes and procedures, test and evaluate, and determine and prove inspection procedures; and

c) flight hardware, components and structure for use.

6.4.2.2 Manufacturing drawings

Manufacturing drawings derived from design drawings and established in accordance with the functional requirements shall be used.

Manufacturing drawings shall take into account the quality requirements, the manufacturing process and the manufacturing steps.

6.4.2.3 Tooling

Requirements for tooling, including assembly jigs and fixtures, shall take into account the following:

a) materials used in manufacture;

b) thermal conditions required for the process;

c) geometry of the parts; and

d) serial numbers of parts.

Tooling design shall cover the acceptability of the finished components quality, size, shape and surface finish.

6.4.2.4 Component manufacturing

During design development, component manufacturing requirements shall be taken into account through inputs from the production engineering evaluation.

The component manufacturing techniques shall be taken into account in the evaluation of competitive designs.

All component manufacturing operations shall conform to product assurance requirements.

6.4.3 Integration requirements and procedures

The integration covers both component integration and assembly integration. Component integration is the activity of joining together of individual parts to form a structural component. Assembly integration is the connection of either components, e.g. launcher stage assembly, or final construction of the launch vehicle and its payloads.

Component integration procedures shall include at least:

a) specifications of parts and materials;

b) inspection and test; and

c) integration instructions that include

   1) preparation,

   2) equipment,

   3) parts and materials,

   4) preload specification (bolt torque, clam-band tension and so on),

   5) method, and

   6) cleaning.

Major integration operations shall be accompanied by inspection and tests.

6.5 Quality assurance

6.5.1 General

A quality assurance or inspection progamme based on a comprehensive study of the product and engineering requirements shall be established in accordance with 6.9.2 and 6.9.3 to ensure that necessary NDE and acceptance proof tests are performed effectively. The progamme shall ensure that no damage or degradation occurs during material processing, fabrication, inspection, acceptance tests, shipping, storage, assembly, and operational use and refurbishment, and such defects that could cause failure are detected or evaluated and corrected. Quality assurance data for all structural items shall be maintained throughout the service life. As a minimum, inspection, acceptance proof test and traceability shall be included in the quality assurance progamme. Details are specified in 6.5.2 and 6.5.3.

NOTE The inspection progamme can be linked with fracture control and impact damage analysis.

6.5.2 Inspection

6.5.2.1 Inspection plans

An inspection master plan shall be established before fabrication begins. The plan shall specify appropriate inspection points, and inspection techniques for use throughout the progamme, beginning with material procurement and continuing through fabrication, assembly, acceptance proof test, shipment, assembly, and operation as appropriate. In establishing inspection points and inspection techniques, emphasis shall be placed on verification of key analysis parameters. Consideration shall be given to the material characteristics, fabrication processes, design concepts, presence of corrosion such as pitting and crevice cracking, and accessibility for inspection of defects.

6.5.2.2 Inspection techniques

For fracture-critical metallic structural items, selected inspection techniques shall be able to determine the size, geometry, location, and orientation of a crack or a crack-like defect. Inspection techniques, such as dye penetrant, magnetic particle, eddy current, radiography, and ultrasound, shall be used to detect cracks as appropriate. NDE techniques used shall have a demonstrated 90 % probability of detection at a 95 % confidence level as a minimum.

Inspection techniques for composite materials shall include visual inspection performed in conjunction with appropriate state-of-the-art NDE techniques. Inspections shall be performed to look for flaws such as nonuniform or broken fibres, delaminations, fibre wrinkles and waviness, dry fibres (i.e., fuzzing or “brooming”), machining damage, impact damage, and uniformity of surface coatings, if applicable. When required, inspections shall be augmented by use of optical magnification or solvent wipe techniques (i.e., for detection of cracks or delaminations). Proven NDE techniques, such as ultrasound, radiography, thermography, computed tomography, and shearography, shall be used to identify and characterize critical defects as appropriate. The appropriateness and ability of the NDE methods selected to detect and characterize critical defects shall be established. NDE shall be performed in accordance with applicable published industry or government standards.

6.5.2.3 Teardown inspection

For structural items in reusable launch vehicles or multi-mission payloads, a teardown inspection shall be performed as appropriate when damage tolerance demonstration is based on the inspection interval.

6.5.2.4 Inspection data

Inspection data for the structural items shall be maintained throughout the service life. These data shall be periodically reviewed and assessed to evaluate trends and anomalies associated with the inspection procedures, equipment and personnel, material characteristics, fabrication processes, design concept, and structural configuration. The result of this assessment shall form the basis of any required corrective action.

6.5.3 Acceptance proof test

Unless otherwise specified, all fibre-reinforced composite and bonded primary structures shall be proof tested. When the proof tests are conducted at temperature and humidity conditions other than the worst-case design environment, the change in material properties at the test conditions shall be accounted for in the test. The test configuration shall simulate structural interfaces in order to replicate launch and flight external load distributions.

Unless otherwise specified, all glass and ceramic material primary structures shall be proof tested.

6.6 Traceability

Traceability of design and development processes and the relationship between each other shall be ensured.

Traceability shall be maintained on all fracture-critical structural items throughout their development, manufacturing, testing, and service. As a minimum, serialization shall be required on all fracture-critical items and they shall have traceability to material heat treat lot or composite manufacture and cure lot. A log shall be maintained for each fracture-critical item to record all significant manufacturing assembly processes, load cycles, inspections, and tests occurring during the time period from fabrication to the end of service life. Engineering drawings for fracture-critical items shall contain notes that label the hardware item as “fracture critical” and specify the appropriate inspections or flaw screening methods to be used. Computer aided design (CAD), computer aided engineering (CAE) and computer aided manufacturing (CAM) models, structural analysis and test documentation shall be included.

6.7 Deliverables

All products (e.g. hardware, software, models and documents) to be delivered during the course of a project shall be specified at the beginning of a project. See Clause 9 for documentation requirements.

6.7.1 Packing, handling, transportation

When structural items are transported, they shall be packaged in a manner that will provide protection against damage from physical or environmental sources. These sources include, but are not limited to, exposure to adverse environmental conditions (e.g., temperature extremes, humidity, water, prolonged exposure to sunlight, etc.), physical impact, vibration, and shock during transport.

Critical environmental and transportation conditions that pose a threat to the integrity of the structural item such as temperature extremes, excessive vibration, or shock loading shall be recorded. The nature of recording (i.e. continuous vs. maximum) and parameters to be monitored shall be commensurate with the threat assessment for the method of transportation and the consequences of these transportation parameters on the structural item.

As a minimum, records documenting transportation events, packaging used, method of conveyance, person or company responsible for transport, dates of shipment and receipt, and a written report including photographs of visual inspection results of the package and its contents shall be kept. Any adverse events or observations shall be recorded and assessed for implications about the integrity of the structural item.

6.7.2 Storage

When structural items are stored, they shall be protected against exposure to adverse environments (e.g. temperature, humidity, etc.). In addition, they shall be protected against damage (e.g. abrasion, cutting, impact, etc.). Critical environmental conditions shall be recorded.

a) Storage conditions shall prevent the degradations of the structural material or its geometric configuration

b) To avoid all hazards to personnel or equipment, items that contain hazardous materials or those with specific storage requirements shall be marked according to specific procedure

c) For parts or components, which cannot be inspected prior to flight and for which the structural degradation during storage is uncertain, representative specimens (witness specimens) shall be stored together with the flight hardware.

d) Prior to acceptance for flight, the samples shall be inspected or tested for any structural degradation.

6.8 In-service requirements

6.8.1 Ground inspection

Ground inspection of integrated structures shall be performed prior to launch. Ground inspection shall be performed after the return of a recoverable structure.

6.8.2 In-orbit inspection

6.8.2.1 General

An in-orbit inspection is performed to ensure that a structure has not deteriorated while in use such that further operation would render it unsafe.

In-orbit inspection equipment is designed in such a way that:

a) it is able to detect damage in a reliable and cost-effective way;

b) it is easy to use; and

c) it can be used without the need for specialist personnel, extensive resources and expert interpretation.

6.8.2.2 Provisions

Built-in-testing (BIT) systems shall be developed for continuous monitoring of long-term deployed structures, where access is limited or the area is critical to the integrity and safety of the structure. Such systems shall identify damaged areas as the damage occurs.

In case damage is identified, other techniques agreed upon with the customer shall be used to investigate local damage sites, as directed by the global monitoring system.

6.8.3 Evaluation of damage

When a defective or damaged area is located, its criticality with regard to the operations and safety shall be assessed. The defect size, location and potential propagation rate shall be determined.

The following factors shall be taken into account in determining the criticality of the damage:

a) operational conditions (loading and environment);

b) maintenance schedules;

c) as-designed structural requirements; and

d) service life of the structure.

Depending on the outcome of the evaluation of the damage, a decision shall be made and justified to repair, replace or use as is the affected parts of the structure.

6.9 Maintenance requirements

6.9.1 General maintenance requirements

All maintenance actions shall be documented, including:

a) the specification of inspection methods;

b) recording of results;

c) category of damage;

d) repair methods; and

e) compilation of service history documents.

The maintenance schedules shall be determined during the design process, and procedures shall be specified for all of the actions to be performed.

6.9.2 Preventive maintenance

Preventive maintenance shall be performed on parts classified as:

a) critical to the safety and function of the structure;

b) identified parts with low service life;

c) parts experiencing high or low temperature use;

d) moving parts experiencing wear;

e) access points of structures (doors and hatches); and

f) surfaces experiencing general “wear-and-tear”.

NOTE 1 Preventive maintenance includes the replacement of parts approaching the end of their stated lives, repainting parts as needed and adequately lubricating moving parts, where relevant.

NOTE 2 “Wear-and-tear” refers to the gradual deterioration of an asset which results naturally from usage.

6.9.3 Corrective maintenance

Corrective maintenance shall be performed on parts incurring damage and those undergoing higher than expected rates of deterioration.

Depending on the criticality of the damage or deterioration, procedures shall be specified for what actions are to be taken for both in-orbit and on-ground cases.

NOTE Corrective maintenance includes replacing or repairing parts and assemblies which have been damaged, either by accident or as a result of a higher than expected rate of deterioration.

As corrective maintenance involves the repair or replacement of damaged parts, the decision to repair or replace shall be justified based upon at least an evaluation of the following considerations for the damaged parts:

a) damage sustained;

b) possibility to repair (i.e. to restore the as-designed mechanical and environmental performance for the remaining designed service life, by known and proven techniques);

c) capability to replace; and

d) remaining service life.

6.10 Repair and refurbishment

When inspections reveal structural damage or defects exceeding permissible levels, nonconforming hardware shall be assessed by a material review board. All repairs and refurbishments shall use an approved repair process. All repaired or refurbished hardware shall be re-verified after each repair or refurbishment by the applicable test procedure for new hardware to verify structural integrity and establish suitability for continued service.

Special care and verification shall be focused on the boundary section between the repaired portion of the structural item and un-repaired portion, as this boundary section could become the weakest location of the structural item (due to the possibility of unfavorable load transfers caused by rigidity changes and local geometric disturbances).

The internal load transfer behaviour of the repaired item shall be re-analysed, taking into account the effect of localized changes on the resulting margins of safety.

The following considerations shall apply to repair and refurbishment procedures.

a) On-ground and in-orbit repair procedures shall be specified.

b) All repair procedures shall take into account the following factors:

   1) structural classification,

   2) damage category,

   3) repair procedure supported by mechanical and environmental testing progamme,

   4) accessibility to damaged parts (e.g. one or both sides), and

   5) availability of equipment (e.g. repair material and services, and qualified personal).

c) Additionally, in-orbit repair procedures shall take into account the following factors:

   1) requirements for extra-vehicular activity,

   2) transportability of materials to space (e.g. stability and outgassing properties of adhesives, hazardous cleaning and preparation chemicals),

   3) preparation of surfaces or damage removal (e.g. availability of appropriate hand-tools, control of dust, and contamination, and avoidance of space debris generation), and

   4) repair manufacture difficulties.

d) All repair procedures shall be adequately qualified (i.e. with respect to their expected application mode and environment).

7 Verification of general requirements

7.1 General

Clause 7 presents the general means for verifying that the requirements set forth in Clause 6 are satisfied. Requirements for acceptance test requirements for flight hardware items, as well as qualification test requirements for the new design are also presented.

7.2 Verification of design requirements

Verification methods appropriate to establish compliance with the design requirements specified in 6.2 are summarized in a verification matrix shown in Table 1. Detailed requirements and discussion are presented in 7.2.1 to 7.2.20. In general, the verification methods rely on analysis, testing or some appropriate combination of analysis and testing. Verification by similarity is an option for heritage structural designs. This option shall be applied on a case-by-case basis and is therefore not listed in the verification matrix shown in Table 1.

7.2.1 Verification of static strength

Static strength of a specific structural item shall be verified by structural analysis and tests, considering environments such as mechanical loads, pressure, and temperature soak and gradients. Verification may be performed by analysis only if the conditions defined in 7.2.1.3 are met.

7.2.1.1 Structural (stress) analysis

Structural analysis shall be performed for all loads and environments to determine critical internal loads (forces, stresses, and/or strains). Requirements set forth in ISO 16454 for the determination of maximum stresses and corresponding margin of safety (MS) shall be met. As appropriate, effects of deformations, temperatures, and geometric nonlinearities shall be included in calculating internal loads. Structural analysis for flight conditions shall be performed based on test-correlated analytical models.

Analysis of laminated composite structures shall address ply-by-ply stress (strain) response to applied loads and environments to determine minimum margins of safety for each applicable failure mode such as fibre fracture, in-plane shear failure, and delamination.

Table 1 — Design requirements verification matrix

Requirement subclause	Subclause title	Verification method	Verification subclause
6.2.1	Static strength	Analysis and test	7.2.1
6.2.2	Buckling strength	Analysis and test	7.2.2
6.2.3	Margin of safety	Analysis and test	7.2.3
6.2.4	Stiffness	Analysis and test	7.2.4
6.2.5	Dynamic behaviour	Analysis and test	7.2.5
6.2.6	Dimensional stability	Analysis and test	7.2.6
6.2.7	Tolerances and alignments	Analysis and test	7.2.7
6.2.8	Thermal	Analysis and test	7.2.8
6.2.9	Thermal distortion	Analysis	7.2.9
6.2.10	Interface requirements	Analysis and/or test	7.2.10
6.2.11	Electromagnetic compatibility	Test	7.2.11
6.2.12	Lightning protection	Analysis and test	7.2.12
6.2.13	Mass and inertia properties	Analysis and test	7.2.13
6.2.14	Fatigue life	Analysis and/or test	7.2.14
6.2.15.1	Fail-safe	Analysis and/or test	7.2.15.1
6.2.15.2	Damage tolerance life (safe life)	Analysis and test	7.2.15.2
6.2.16	Impact damage	Test	7.2.16
6.2.17	Stress-rupture life	Analysis and test	7.2.17
6.2.18	Corrosion and stress corrosion control	Analysis	7.2.18
6.2.19	Outgassing	Analysis and test	7.2.19
6.2.20	Meteoroid and orbital debris protection	Analysis and test	7.2.20

7.2.1.2 Static load test

Results of the qualification tests specified in 7.4 shall be used to verify rigidity and strength requirements.

7.2.1.3 Static strength verification by analysis only

Static strength of a specific structural item may be verified by analysis only if the following conditions are met and approval is granted by the procuring authority:

a) The item is metallic, or a secondary non-metallic structure.

b) The structural design is simple with easily determined load paths (e.g., statically determinate) and well defined failure modes, it has been thoroughly analysed for all critical load conditions, and there is a high confidence in the magnitude of all significant loading events.

c) The structure is similar in overall configuration, design detail, and critical load conditions to a previous structure which was successfully test-verified, with good correlation of test results to analytical predictions.

d) Development and/or component tests have been successfully completed on critical elements of the structure, for which it had been difficult to analyse, and good analytical model correlation to test results has been demonstrated.

7.2.2 Buckling strength verification

7.2.2.1 Buckling analysis

Evaluation of buckling strength shall consider the combined action of primary and secondary stresses and their effects on general stability, local or panel instability, crippling, and creep. Analysis shall include consideration of the relative deflection of adjoining structures. Bifurcation buckling and/or nonlinear analysis procedures as appropriate shall be used to predict the loads at which the onset of structural instability occurs. Defects and geometrical imperfections in the structures shall be adequately taken into account. The buckling strength shall be the predicted buckling load times an appropriate knockdown factor to account for unknown defects, geometrical imperfections, and the structural item's configuration. Knockdown factors shall be based on relevant test data or experiences that provide a lower bound for the buckling strength.

In addition:

a) For cases where elastic fully reversible buckling is accepted, post-buckling behaviour shall be analysed.

b) Boundary conditions, defects and geometrical imperfections in the structure shall be taken into account.

   NOTE Geometrical imperfections refer to any deviation from the nominal shape including effects due to assembly tolerances.

c) Minimum gauge shall be used for buckling analysis.

7.2.2.2 Buckling test

Buckling strength verification can be accomplished by a buckling test. Representative structural items shall be tested under the conditions cited in 6.4.3. As a minimum, development tests for primary structures shall be conducted simulating compressive and/or shear load and/or external pressure when any of the following apply:

a) configurations are shells of complex shape,

b) coupling between various modes of failure is possible, and

c) no theory or test correlation factor exists.

7.2.3 Margin-of-safety (MS) verification

The MS shall be determined by analysis using the appropriate statistically based material allowable. Test data shall be used to validate results when necessary. Selection of factors of safety in MS determination shall be predetermined by the procurement agency. Annex C contains factors of safety used by different regional documents. Additional design factors for the following special situations shall be established based on prior experience or test data:

a) personnel safety when the structural item contains stored energy;

b) highly localized stresses at locations such as holes, corners, or fillets;

c) stresses in complex joints and fittings; and

d) stresses along discontinuities in composite structures.

MS calculations for reusable structural items shall consider degradation of material properties, if any, after being subjected to the service life.

7.2.4 Stiffness verification

7.2.4.1 Stiffness analysis

Stiffness analysis shall be performed to verify structural response to quasi-static loads. Analysis shall determine required displacements and internal forces under representative applied loads and boundary conditions.

7.2.4.2 Stiffness test

When required, structural tests shall be conducted under maximum expected loads to determine structural stiffness and other responses including displacements and internal load distribution.

7.2.5 Verification of dynamic behaviour

7.2.5.1 Dynamic (response) analysis

Dynamic (response) analysis shall be performed for various flight events such as lift-off, engine ignition, aerodynamics, maneuvering, staging, reentry, and landing. Structural dynamic mathematical models and associated load transformation matrices shall be developed to support the loads analysis. Models used in dynamic analyses shall represent structural assemblies by characterization of dynamic parameters (natural frequencies and mode shapes) and associated effective masses and damping. Dynamic models shall be updated to reflect changes in design and the loads environment as a progamme matures and more data from ground test and flight test become available.

Low-frequency dynamic analysis shall be performed on an integrated spacecraft and launch vehicle model to verify frequency requirements and determine associated modal characteristics including natural frequencies and mode shapes.

Loads analysis shall provide structural accelerations, internal member loads and stresses, deflections and rotations, and interface forces at various components in sufficient detail to allow verification of structural integrity. The analysis shall provide accelerations, velocities, and displacements at specified locations to a certain probability level.

NOTE Some standards may currently use probability of 99,7 % with 90 % confidence, unless specified otherwise by the procuring authority.

Verification loads analysis shall be performed to provide final definition of loads using structural dynamic models and forcing functions verified by modal survey and other applicable tests. These analyses, including analysis methodologies, shall be verified by an independent organization when such requirements are specified by the procuring authority.

a) Dynamic response analysis shall be used to verify the structural response due to excitations (e.g. force or motion inputs via mechanical interfaces, thermal input such as eclipse transitions, spinner centrifugal forces, and possible combinations thereof) either in the frequency domain (e.g. sine and random) or time domain (transient) according to the definition of loads and information specified.

b) Coupled-load analyses shall be performed to verify the loads resulting from dynamic behaviour of structural assemblies as follows:

   1) The mathematical models applied in coupled analyses shall represent the structural assemblies by characterization of the dynamic parameters, namely natural frequencies, mode shapes, associated generalized and effective masses, and damping.

   2) It is not necessary to characterize natural frequencies with small effective masses (e.g. multilayer insulation or small equipment) if it can be shown that these modes do not significantly influence the overall dynamic behaviour.

7.2.5.2 Modal survey

7.2.5.2.1 Modal analysis

Modal analysis shall be performed 1) to verify that the structure conforms to the natural frequency requirements, and 2) to determine associated modal characteristics (e.g. natural frequencies, mode shapes, and generalized and effective masses).

Pretension and spin effects shall be included.

For large lightweight structures (e.g. solar arrays, antenna reflectors), the effect of the surrounding air shall be taken into account.

7.2.5.2.2 Modal survey test

Modal survey tests of flight-quality structures shall be conducted to verify mathematical models of dynamically complex structures such as spacecraft, upper stages, and fairings.

All significant equipment components shall have an accurate dynamic representation in the test.

All significant modes of vibration, mode shapes, frequencies, and associated damping over the frequency range of interest for loads analyses specified by the launch vehicle contractor shall be measured. Modal correlation requirements shall be specified by the procuring authority. Modal survey test results shall be certified by an independent organization that validates analytical models, when required by the procuring authority.

7.2.5.3 Vibration, acoustic and shock verification

7.2.5.3.1 Vibration, acoustic and shock analysis (dynamic analysis: sine, random, shock)

Vibration, acoustic and shock analysis and/or survey shall be performed by the launch vehicle organization using the launch vehicle environment to verify the acoustic spectrum and level in the payload bay/shroud or external spacecraft location.

Vibroacoustic loads analysis shall provide structural accelerations, internal member loads and stresses, deflections and rotations, and interface forces at various components in sufficient detail to allow verification of structural integrity for the different structural parts including equipment supports.

Shock analysis shall be performed on all shock-inducing events, including pyrotechnic initiation and separation, to define environments at spacecraft locations where hardware sensitive to shock damage is located.

7.2.5.3.2 Vibration, acoustic and shock tests (dynamic tests: sine, random, shock)

Vibration, acoustic and shock tests shall be conducted in accordance with the requirements of MIL-STD-1540 or as specified by the procuring authority. Dynamic tests shall be performed to verify the following objectives:

a) the dynamic behaviour, in terms of accelerations and interface forces (including units and appendages),

b) the compliance to the stiffness requirements,

c) the strength and alignment stability under dynamic loads, which include sinusoidal vibration loads, random vibration loads and shock loads when appropriate,

d) the compliance of the levels on equipment, considering their individual qualification levels,

e) the levels on equipment supports,

f) the validity of the lay out (e.g. the arrangement of equipment items and their supports to a structural item), and

g) the behaviour of various elements for which analysis is almost unpractical (e.g. flexible items or cables).

Acoustic tests shall verify the ability of the structure and its equipment to withstand the vibrations induced by the specified acoustic field.

Acoustic tests shall confirm the random dynamic design environment for subsystems and equipment.

7.2.5.4 Verification of microgravity, audible noise and human vibration

Verification of the microgravity, audible noise and human vibration requirements shall be performed by analysis.

The conformance of equipment to requirements of vibration and audible noise sources of equipment shall be verified by test.

Structure-to-structure acoustic transmissibility shall be validated by test.

7.2.5.5 Fluid structure interaction (FSI)

The structure shall be verified against the effects of the interaction with fluids (e.g. sloshing, POGO, cavitations effects and pressure fields).

Demonstration shall be performed by tests, or by analysis supported by tests if multi-physical tests are not possible or practical.

7.2.5.6 Aero-thermodynamic test

Aero-thermodynamic tests shall be performed to verify the behaviour of the vehicle or a part of it during flight in the atmosphere.

Tests performed with subscale models shall be verified to be representative of the flight structure.

7.2.5.7 Aeroelasticity verification

Aeroelasticity analysis shall be used to assess the interaction between the aerodynamic flow and the structure.

Aeroelasticity tests shall be performed to verify the analytically predicted behaviour for each flight configuration and to determine application limits.

Aeroelasticity tests shall be performed on subscale and full-scale models and on flight vehicles on the ground and in flight, if necessary.

7.2.6 Dimensional stability verification

As appropriate, dimensional stability shall be verified by material testing to determine changes in structural dimensions and material properties due to environment influences such as moisture release and absorption, aging, and creep.

a) Short, medium and long term effects of structural dimensional stability shall be analysed.

b) A stability budget shall be established and the contributors shall be identified, analysed and allocated.

NOTE Examples of contributors affecting dimensional stability are thermo-elastic effects, moisture release, in-orbit loads, zero-gravity environment, micro-vibrations, material ageing (material property changes), material dimensional instability, setting effect and spin effect.

c) The dimensional stability of the structure in operational environments shall be verified by test.

d) The conformance of material properties to specification in spite of long-term effects (e.g. moisture release, ageing and creep) shall be verified by test.

7.2.7 Verification of tolerances and alignments and geometric control

The verification analysis shall assure that the design tolerances conform to the alignment requirements.

Alignment checks shall be performed in order to verify the relative position and movements between parts during manufacturing, assembly and verification testing.

Dimensions and tolerances shall be controlled during and after manufacturing to conform to the functional requirements.

7.2.8 Verification of thermal stress

7.2.8.1 Thermal stress test

The survival of the structure subjected to significant thermal loads (compared to the effect of the other loads) without failure shall be verified by thermal stress tests.

7.2.8.2 Thermal cycling test

Thermal cycling tests shall verify that the structure is able to survive without failure due to all of the thermal cycling loads expected during its service life.

Thermal cycling temperature ranges shall be increased to account for uncertainties in the thermal analysis.

The following scatter factor should be applied for the thermal cycling tests, if necessary:

a) for launchers, re-entry vehicles and spacecraft subject to a low number of operational thermal cycles (e.g. geostationary orbits):

   1) a scatter factor of 4, for cycling within flight temperature ranges;

   2) a scatter factor of 2 for cycling within the qualification temperature ranges.

b) a scatter factor of 1,5 for other spacecraft subjected to a large number of operational thermal cycles.

7.2.8.3 Thermo-stress analysis

Thermo-stress analysis shall be performed to compute stresses and deformations due to occurring temperatures.

NOTE To perform thermo-stress analysis, temperature distributions defined by thermal analysis are usually mapped on the structural model.

Hydro-thermal analysis shall be performed to compute deformations due to occurring moisture release or absorption according to the mission.

7.2.9 Verification of thermal distortion

A thermal distortion analysis shall be performed to ensure critical thermal distortion is not exceeded. The analysis shall be based on appropriate thermal and structural mathematical models that shall be of sufficient fidelity to predict displacement and rotation at critical parts of the structure. The analysis shall be based on the worst-case flight temperature gradient or maximum and minimum model temperature. Unless otherwise specified, the structure model shall incorporate normal gauge dimension and account for the effects of material properties at the corresponding maximum and minimum temperatures.

7.2.10 Verification of interface joints and connections

7.2.10.1 Bonded joints (adhesive connections)

The evaluation of bonded joints shall be performed in accordance with standards or procedures agreed upon with the customer.

For the mechanical characteristics of the bonded joints, the following items are usually taken into account:

a) influence of the characteristics of the adhesive,

b) material of the adherents,

c) process (heating, pressure applied),

d) any surface treatments,

e) dimensions of the bonded area, and

f) relative stiffness of the parts.

7.2.10.2 Bolted joints (connections)

Bolted joints shall be verified according to standards or procedures agreed upon with the customer.

The sufficiency of thread engagement shall be verified.

Minimum preload shall be considered for functional verification (no gapping, no sliding) and maximum preload shall be considered for strength verification of the bolts or flanges.

NOTE Generally, it is not necessary to apply a safety factor to preload in bolts when preload is defined considering simultaneously conservative assumptions for the applied torque and its dispersion, the friction coefficients between the different parts, and other pertinent factors.

7.2.10.3 Welded joints (connections)

Welded joints shall be verified according to standards or procedures agreed upon with the customer.

The analytical verification of welded joints shall take into account the following:

a) stress concentrations,

b) type and quality of the weld,

c) local maximum allowable geometrical defects (e.g. mismatch and peaking),

d) residual stresses and material characteristics changes due to local heating and cooling, and

e) welding processes and procedures.

7.2.10.4 Riveted joints (connections)

Riveted joints shall be verified according to standards or procedures agreed upon with the customer.

7.2.10.5 Joints with inserts (connections)

Inserts shall be verified according to standards or procedures agreed upon with the customer.

NOTE Inserts are generally used in sandwich constructions with cores of low strength.

7.2.10.6 Inspection and fit check

Interface verification shall be performed by inspection (including geometrical control) of the manufacturing drawings and parts with respect to the interface requirements, and with the aid of fit checks of interfacing structural components.

7.2.11 V erification of electromagnetic compatibility (EMC)

The electromagnetic interference characteristics (emission and susceptibility) of a structural component shall be demonstrated by EMC test. Radiated emissions shall be performed on all structural components capable of generating emissions.

7.2.12 Verification of lightning protection

The lightning protection system shall be inspected and its function shall be tested.

7.2.13 Verification of mass and inertia properties

The inertia properties shall be computed to the specified accuracy using the inertia matrix of individual components.

The quantities shall be monitored and presented in a mass budget report issued on a regular basis; a breakdown of mass to component level shall be given together with mass contingency estimates based on the design maturity.

The mass and inertia data shall include mass, co-ordinates of the centre of mass with respect to a specified co-ordinate system, moments of inertia with respect to a specified co-ordinate system, and the principal moments of inertia and their orientation with respect to a specified coordinate system.

The mass and inertia properties of the structure shall be measured within the specified accuracy.

ISO 22010 specifies the mass properties control.

7.2.14 Verification of fatigue life

As appropriate, fatigue life shall be verified for non-fracture-critical structural items by fatigue analysis or test. Fracture-mechanics-based damage tolerance (safe-life) analysis or test may be used as a substitute for fatigue analysis or test.

7.2.14.1 Fatigue analysis

When a fatigue analysis is used to verify the fatigue life of a structural item, nominal values of fatigue characteristics, including fatigue stress-life data (S-N) and/or fatigue strain-life (ε-N) data of the material shall be used. These data shall be taken from reliable sources such as MMPDS-01 and the Aerospace Structural Metal Handbook. Analysis shall account for the spectra of expected operating loads and environments.

Miner's Rule ($\sum n/N$) is an acceptable method for predicting the effects of variable amplitude fatigue cyclic loading. The following requirements shall be met as a minimum:

a) Fatigue analysis shall be performed to verify that fatigue defect (crack or delamination) initiation or propagation resulting in structural failure or functional degradation cannot occur throughout the service life of the structure;

b) Effects of stress concentrations, stresses due to assembly, and/or residual stresses due to fabrication shall be taken into account;

c) The life of the structure shall be verified for the specified envelope life multiplied by the specified scatter factor; and

d) Design limit loads (without any safety factor) shall be used for fatigue analysis: all loads (alternating loads, permanent loads and acoustic loads) and their combination and sequence shall be taken into account.

NOTE Fatigue analysis normally uses a cumulative damage approach which estimates fatigue life from stress spectra and fatigue material allowables (S-N curves).

7.2.14.2 Fatigue test

Testing of specimens in a representative environment to demonstrate fatigue life of a specific part, together with stress analysis, is an acceptable alternative to analytical prediction.

The number of tests shall be sufficient to form a statistically meaningful database. In addition:

a) fatigue tests shall verify that the structure can survive, without degradation, at least the predicted service life cycles with the specified scatter factor, and

b) fatigue tests shall verify that the cyclic loads do not cause cracks or crack-like defects that endanger the integrity of the structure or change the behaviour significantly.

7.2.15 Verification of fracture control

7.2.15.1 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 an appropriate scatter factor is used.

7.2.15.2 Verification of damage-tolerance life (safe-life)

7.2.15.2.1 Damage-tolerance life (safe-life) analysis

For all metallic, glass, and ceramic fracture-critical parts, damage-tolerance life analysis (also referred to as safe-life fracture mechanics analysis) shall be performed to verify that the parts meet the damage-tolerance (safe-life) requirements specified in 6.4.15. Undetected crack(s) shall be assumed to be in critical location(s) and in the most unfavorable orientation(s) with respect to the applied stress and material properties.

The size of the crack(s) shall be based on crack-screening proof test-limits or the detection capability of appropriate NDE technique(s) used in the acceptance tests. Nominal values of fracture toughness and fatigue crack growth rate ($\mathrm{d}a/\mathrm{d}N$) data shall be used in the analysis.

7.2.15.2.2 Damage-tolerance life (safe-life) test

Damage-tolerance verification for fracture-critical metallic, glass, and ceramic parts may be performed by testing flight-quality parts with pre-fabricated crack(s) of controlled size(s) in a representative environment. Coupons may be allowed in lieu of full-scale, flight-quality articles only for metallic parts when the stress field is well defined and the material properties are representative of the flight parts. The size and shape of crack(s) shall correspond to the detection capability of the NDE to be imposed on the flight parts.

Damage-tolerance verification for fracture-critical composite parts shall be performed by test only. The test spectrum shall adequately represent all cycles, time, and environments associated with part history.

Proven accelerated test techniques may be used. Damage-tolerance test(s) for fracture-critical composite parts shall be performed by using full-scale, flight-quality articles, with pre-fabricated flaw(s). The size of the flaws shall be based on the detection capability of the NDE to be imposed on the flight parts.

NOTE 1 Analysis in order to reduce the number of cases to be performed by test may be acceptable, providing a good correlation exists between results obtained using the proposed analysis method(s) and previous tests. However, some minimum amount of testing remains mandatory.

NOTE 2 “Full-scale” means using either a full-size example of the whole specimen or a representative full-size part with representative boundary conditions and loading.

For components where neither damage-tolerance analysis nor damage-tolerance testing is appropriate, such as for some composite material failure modes, proof testing of each flight hardware item may be used to establish confidence in a part's damage tolerance, provided it is approved by the procuring authority.

7.2.16 Verification of impact damage

Testing in a representative environment is the only acceptable method to demonstrate impact damage tolerance of fracture-critical composite parts. Impact damage tolerance is verified when it is shown that residual strength does not degrade below the predetermined level. Full-scale articles, which are representative of the flight part, with induced impact damage shall be used as the test specimens. For COPVs, either system threat analysis energy levels or verified VDT energy levels, whichever is less, shall be used to determine the impact energy level in the impact damage tolerance tests.

NOTE Some margin on the size of initial damage should be considered in such a case that the size of the defect decreases during time before the following NDE.

7.2.17 Verification of stress-rupture life

Stress-rupture life for composite and other non-metallic structural items shall be verified by analysis supported by test data. If an alternative way of demonstration is used (such as maintaining the structure under the load taking into account some factor on the load or on the time), the equivalence with the probability of failure as specified in 6.2.17 should be stated.

7.2.18 Verification of corrosion and stress-corrosion cracking control

A corrosion control plan shall be developed for structural items that are prone to stress-corrosion cracking or corrosion due to environmental or galvanic effects. The corrosion control plan shall be reviewed for adequacy and tracked for effectiveness.

7.2.19 Outgassing verification

Outgassing levels of structural materials for the specified operating conditions shall be shown to be less than the specified allowable by analysis, test, or documented engineering practice. The effects of outgassing on material properties, dimensional characteristics, and residual stresses shall be established and included in the determination of material properties, analytical evaluations, and/or experimental validations for all structural items.

7.2.20 Verification of meteoroid and orbital debris shielding

When required by the procuring authority, mission-critical components that are vulnerable to M/OD impacts should be tested for M/OD damage at representative velocity levels.

7.3 Acceptance tests

Acceptance tests shall be performed on the flight hardware to demonstrate that no workmanship defect prevents a structure item from fulfilling specification requirements.

Acceptance tests shall include the following types of tests:

a) proof pressure tests of pressurized hardware,

b) static load tests of composite structures,

c) proof tests on sandwich inserts, and

d) vibration tests or other dynamic tests on structural components that are prone to experience dynamic environments.

NOTE Acceptance tests may include structure-related functional tests when mechanisms are included.

7.3.1 Non-destructive inspection (NDI)

Each structural item shall be subjected to inspection if required by the inspection plan of 6.5.2. NDI can be conducted either at the component level, or at the assembly level for some structural items.

For fracture-critical parts, NDI shall be performed to verify that no defect (crack or delamination) larger than the size specified by requirements are present.

7.3.2 Proof load and/or pressure test

Metallic structural components such as pressure vessels, pressurized structures, and heat pipes, shall be subjected to an acceptance proof test using minimum proof test factors shown in Table 2.

Composite and bonded primary structures shall be subjected to an acceptance proof test at a minimum level of 1.1 times the limit load.

Glass structures shall be subjected to an acceptance proof test with a specific level provided by the procurement agency.

During acceptance proof testing, the test item shall not rupture, experience severe damage, or exceed specifications on linear and/or nonlinear deformation. If necessary, the proof-test parameters, such as load, pressure, and temperature, shall be suitably adjusted to account for the environmental effects on material properties and stress fields in order to make the proof test representative of the critical condition. Before and after each proof test, appropriate NDI shall be performed to ensure that no damage has been induced during the proof test. For pressure components including pressure vessels, a leak check shall be conducted to establish preflight condition.

For non-pressurized structures, in cases where such acceptance testing is not practical, deviation may be granted by the procuring authority, provided the manufacturer of the composite/bonded structural item demonstrates that:

a) certified and controlled specifications are used,

b) personnel are properly trained and certified,

c) mechanical properties of each component are verified by tag end tests, and

d) NDI is adequate to validate the quality and integrity of the hardware.

7.3.3 Vibration and shock test

Vibration and shock tests on structural items shall be conducted in accordance with the requirements specified by the procuring authority.

7.4 Qualification progamme (qualification tests)

Qualification tests shall be performed to verify that the structure design and manufacturing technique fulfil specification requirements.

The general test requirements for spacecraft or launch vehicle are specified by ISO 15864 and ISO 24917.

NOTE Qualification tests can include static tests, dynamic and acoustic tests, and other tests as appropriate. (e.g. thermal stress test).

Every structural item (new design or redesign) shall be verified by a qualification progamme in accordance with the test options shown in Annex C. Qualification tests shall be conducted on a flight-quality structural item all of whose parts have been subjected to NDI and an acceptance proof test as described in 7.3.

Tests can be conducted either at the component level, assembly level, or at a higher level of integration. The following tests shall be conducted on all new or substantially modified structural items as appropriate:

a) inspection,

b) proof load and/or pressure tests,

c) vibration and shock tests, and

d) ultimate load and/or burst tests.

A fatigue life and/or damage tolerance test may also be a part of the qualification test progamme, if required.

In general, a damage tolerance test shall be conducted on a separate test article. However, it may be conducted on the qualification test article whenever feasible.

7.4.1 Proof load and/or pressure tests

The qualification test article shall be subjected to proof load and pressure tests if required in accordance with 7.3.2.

7.4.2 Vibration and shock tests

A structural item shall undergo appropriate acceptance- and qualification-level vibration and shock test(s) in accordance with requirements specified by the procuring authority.

7.4.3 Inspection

Inspections of the qualification test article shall be performed in accordance with the requirements of 6.5.2 to ensure that the qualification hardware conforms to applicable drawings and specifications for functional performance.

7.4.4 Qualification load and/or pressure tests

A qualification load test shall be conducted on a flight-quality article to verify compliance with the design qualification factor of safety requirement established for each type of structural item. The qualification load test parameters such as load and temperature shall be suitably adjusted to account for environmental effects on material properties and stress fields in order to make the test representative of the lowest margin condition.

The test article shall be held at the qualification load level for at least the period required by the procuring authority. The test article shall not exhibit catastrophic failure at or prior to the end of the hold time.

One of the following test approaches shall be used for composite/bonded structures to account for degradation of material properties due to combined temperature and moisture effects:

a) Perform the qualification test on the test article which has been environmentally preconditioned under the worst-case combination of temperature and moisture conditions.

   The evaluation of qualification test results or data shall account for the worst hardware characteristics which can be present in a flight unit but are not present in the test unit.

b) Perform the qualification test at ambient conditions where the actual applied load shall be adjusted by the appropriate environmental and statistical knockdown factors derived from the design allowable test results for the same failure mode. If thermal loads are low, ISO 14953 gives some formal procedures to take thermal loads into account for static qualification test by increasing mechanical loads.

For all pressure vessels, pressurized structures, and pressure components, all qualification test requirements shall be demonstrated in accordance with the appropriate ISO standards listed in 8.2.

8 Special structural items

8.1 General

Clause 8 presents additional requirements for special structural items, including pressure vessels, pressurized structures, special pressurized equipment, heat pipes, flywheel rotors, beryllium structural items, cryo structures, hot structures, and sandwich structures. For items that already have published standards, the standard is identified. For items without published standards, specific requirements are defined in 8.3.

8.2 Special structural items with published standards

Table 2 provides a list of special structural items that shall be designed, fabricated, verified, qualified, and accepted based on a set of requirements specified in the corresponding published standards.

Table 2 also summarizes important requirements contained in these standards.

Table 2 — Published specific requirements for special structural items (minimum values)

Hardware type	Design ultimate load/ Pressure	Acceptance proof load/ Pressure	Fatigue life/ Failure mode	Damage tolerance (safe life)	Post-proof NDE	Corresponding published standard
Metallic pressure vessel	1, 25x LL, 1,5x MEOP	1,25x MEOP	Required for LBB failure mode, 4x service life	Required for non-LBB failure mode, 4x service life	Required on welds	ISO 14623
Metallic pressurized structure	1,25x LL, 1,25x MEOP	1,1x MEOP	Required for LBB failure mode, 4x service life	Required for non-LBB failure mode, 4x service life	Required on welds	ISO 14623
Composite over wrapped pressure vessel	1,5x MEOP	1,25x MEOP	Required for non-hazardous LBB liner, 4x service life	Required for hazardous LBB liner, 4x service life	Required visual inspection	ISO 14623
Battery case	1,5x MEOP	1,25x MEOP	Required for LBB failure mode, 4x service life	Required for hazardous LBB case, 4x service life	Not required	ISO 24638
Sealed container	1,5x MEOP	1,1x MEOP	Required for LBB failure mode, 4x service life	Required for hazardous LBB, 4x service life	Not required	ISO 24638
Cryostat shell	1,5x MEOP	1,25x MEOP	Required for LBB failure mode, 4x service life	Required for non-LBB failure mode, 4x service life	Not required	ISO 24638
Heat pipe	2,5x MEOP	1,5x MEOP	Not required	Not required	Not required	ISO 24638
Flywheel rotor	1,25x MEOS	1,1x MEOS	Required for unmanned system, 4x service life	Required for manned system, 4x service life	Not required	ISO 21648
NOTE LBB applies only to metallic or metallic part of COVP.						

8.3 Special structural items without published standards

This subclause addresses special structural items that shall be designed, fabricated, and tested in accordance with a specific set of requirements in addition to the general requirements specified in Clauses 6 and 7.

8.3.1 Beryllium structural items

All beryllium primary and secondary structural items shall undergo a proof load test to 1.4 times limit load.

No detrimental permanent deformation shall be allowed to occur as a result of applying the loads, and applicable alignment requirements shall be met following the test. In addition, the following requirements shall apply.

a) When using cross-rolled sheet, the design shall preclude out-of-plane loads and displacements during assembly, testing, or service life.

b) In order to account for uncertainties in material properties and local stress levels, an ultimate design safety factor of 1,6 shall be used in margin of safety analysis.

c) Stress analysis shall properly account for the lack of ductility of the material by rigorous treatment of applied loads, boundary conditions, assembly stresses, stress concentrations, thermal cycling, and possible material anisotropy. The stress analysis shall take into account worst-case tolerance conditions.

d) All machined and/or mechanically disturbed surfaces shall be chemically milled to ensure removal of surface damage and residual stresses.

e) All parts shall undergo inspection for surface flaws in accordance with 6.5.2.2.

8.3.2 Cryo structures and hot structures

In cases where a primary load condition on the structure is due to large thermal gradients or extreme temperature ranges, testing shall be performed in accordance with requirements specified by the procuring authority. As appropriate, testing shall include simulation of the temperatures and gradients on the structure, validation of analytical models at the component or subassembly level, and qualification of flight-quality hardware at higher levels of assembly.

A comprehensive test plan shall be developed and approved by the procuring authority. The test plan shall define what tests are required, the fidelity of the simulations, and the stages of development at which the tests are performed.

8.3.3 Sandwich structures

Sandwich structures shall normally use a vented core. The design shall utilize perforated core fitted with either perforated face sheets and/or panel edge members that allow gases present within the sandwich structures to vent safely during ascent into orbit.

In exceptional cases where venting is not acceptable, use of a non-vented design shall be approved by the procuring authority. The structure shall withstand pressure buildup without violating strength and stability requirements. For these cases, the integrity of each flight-quality article or flight article, if necessary, shall be demonstrated by specially tailored proof tests, including high rate depressurization, to simulate the critical ascent environment. In addition, the face sheet-to-core bondlines shall be examined for debonds per the requirements of 6.5.2.2.

9 Documentation requirements

9.1 Interface control documents

All interface control documents (ICD) related to structural items shall be recorded and subjected to review by the procuring authority.

9.2 Applicable (contractual) documents

All applicable documents shall be listed and a summary shall be prepared to show compliance with requirements. Deviations from the applicable documents shall be identified. Justifications for deviations shall be submitted to the procuring authority for review and approval. Approvals and denials of requested deviations shall be provided in written format as part of the documentation package.

9.3 Analysis reports

When analysis is part of the verification of compliance with the requirements specified in Clause 6, a corresponding report shall be prepared and submitted to the procuring authority for review and approval.

The specific requirements for the analysis reports are specified in 9.3.1 to 9.3.5.

Reports shall include sufficient information describing the structural mathematical models and analyses performed to demonstrate the verification and validation of the results generated. Supporting analyses shall be documented and shall be traceable to engineering drawings, material data, and loading.

9.3.1 Stress analysis report

A stress analysis report documenting the analysis results shall be prepared. As a minimum, the report shall consist of the following sections:

a) analysis inputs and assumptions, including:

   1) structure configuration and geometry,

   2) structure materials and their properties,

   3) limit loads, pressures, and temperatures for every loading case considered,

   4) safety factors for every loading case and structure element considered,

   5) structural mathematical model description, including:

      i) assumptions and supporting justification,

      ii) boundary conditions;

b) structural mathematical model checks and results;

c) failure modes considered;

d) failure criteria applied;

e) description or references for methods and software applied;

f) summary of significant analysis results;

g) references.

The analysis shall be revised whenever changes of basic data occur and the revised results shall be documented.

9.3.2 Fatigue or damage tolerance life (safe- life) analysis reports

A fatigue or damage tolerance analysis report shall include the following as a minimum.

a) fatigue stress-life (S-N) data or fracture mechanics data, including fracture toughness (Kc) and fatigue crack growth rates (da/dN);

b) loading spectrum and environments;

c) NDE methods and corresponding initial flaw sizes for damage tolerance analysis;

d) analysis assumptions and rationale;

e) calculation methodology, including software description;

f) summary of significant results; and

g) references.

9.3.3 Fracture/impact damage control plan/report

As a minimum, the organization with primary responsibility for hardware development shall provide a fracture control plan and/or impact damage control plan. The plan shall provide detailed hardware-specific fracture and/or impact damage control methodologies and procedures for testing, inspecting, handling, transportation, and operational life. The plan shall identify organizational elements and their responsibilities for activities required to implement the plan, including review of design and structural analyses, configuration control, and generation of required documentation such as a fracture/impact damage control summary report, etc.

The fracture/impact damage control summary report shall certify fracture control compliance, and the report shall be submitted to the procuring authority.

9.3.4 Inspection reports

The inspection report is a compilation of inspection sheets used by the inspector to record results. As a minimum, the inspection sheet shall identify the following:

a) structural item by name and part number;

b) material and condition;

c) type of NDE and sensitivity level;

d) sketch of the item showing the area inspected and type of defects for which inspection was performed; and

e) results of the inspection and the inspector's signature, date, and stamp.

9.3.5 Dynamic analysis

The dynamic analysis report shall include loads analysis methodologies, analysis models, forcing functions, modal frequencies, and results of analysis/test correlations.

10 Data exchange

10.1 Data set requirements

The International system of units (SI) shall be used for all drawings, specification and engineering data.

The data shall include the delivery of datasets in both:

— the native data format of the software or facility used to produce the data, and

— a neutral data format complying with an open international standard or traceability matrix provided by the procurement authority.

All data, regardless of the format, shall be accompanied by documentation containing detailed descriptions of the data, including the following:

a) native data format, and open international data format (name and version);

b) date and time stamp when the data were produced;

c) status of data;

d) responsible organization and person who produced the data;

e) name and version of the software or facility used to produce the data; and

f) format of media (e.g. tape, back-up, and operating system).

During the development process, it is important to exchange data safely and quickly within the project. This includes data exchange between all engineering disciplines and sub-disciplines including design, analysis, manufacturing and test, as well as geographically distributed teams and between different subsystems, such as the management of project information and documentation.

10.2 System configuration data

Data for the system configuration should be exchanged in a computer sensible format through interfaces complying with open International Standards or through direct interfaces agreed upon with the customer.

10.3 Data exchange between design and structural analysis

Geometrical data shall be exchanged between CAD and CAE software tools through interfaces complying with open International Standards or through direct interfaces agreed upon with the customer.

Other data for design and structural analysis (e.g. material definitions and their properties) should be exchanged in a computer sensible format through interfaces complying with open international standards or through direct interfaces agreed upon with the customer.

10.4 Data exchange between structural design and manufacturing

Data for structural design and manufacturing should be exchanged in a computer sensible format through interfaces complying with open international standards or through direct interfaces agreed upon with the customer.

10.5 Data exchange with other subsystems

The transfer of data and interfacing software between structural and other subsystems (e.g. thermal control and optical) can be achieved by means of standard-based or direct electronic interfaces where available or by using applicable documents.

NOTE The exchange of data with other subsystems can imply a mapping of entries or results between the different models and the use of extrapolation methods.

10.6 Tests and structural analysis

Exchanges of test and structural analysis data shall be based on standard-based electronic interface formats or in the format of tables or files.

10.7 Structural mathematical models

Exchange of structural mathematical model data is made at three levels:

a) For physical models (e.g. finite element models and finite difference models)

   1) the same software shall be used,

   2) the same version of the software should be used,

   3) for model transfer between different codes, translation problems and differences in capabilities of different software shall be considered, and

   4) accompanying documents shall clearly describe the model, the software, the version or release, any parameters being used and the results of the performed model checks.

b) For mass and stiffness matrices: the model is reduced in size and restitution matrices shall be used.

c) For mode components: the definition may depend upon the method used (e.g. clamped or free).

Detailed numbering (nodes and elements) and modelling requirements shall be specified in a finite element model requirements document.

For LCDA between launchers and its payloads, ISO 14954 specifies the exchange of mathematical models for static and dynamic analyses.

Structural engineering can use the practices given in Annex A to perform an adequate design of a structural item which conforms to the functional and performance requirements of this International Standard.

Annex A
(informative)

Recommended best practices for structural design

A.1 Structural design

Structural design is an iterative process. The process starts with the conceptual design of possible alternatives which can be considered to satisfy the general performance requirements and are likely to meet the main mission constraints (e.g. mass, interfaces, operation and cost). The various concepts are then evaluated according to a set of prioritized criteria in order to select the designs to develop in further detail. The main purpose of the evaluation is to identify the main mission requirements and to establish whether the selected concepts meet the requirements. The selected concepts are evolved and evaluated in more detail against a comprehensive set of mechanical requirements and interface constraints which are “flowed down” from the main mission and functional requirements.

NOTE Structural engineering can satisfy this requirement more easily by aiming for simple load paths, maximizing the use of conventional materials, simplifying interfaces, and providing easy integration.

A.2 Mission requirements

A.2.1 Life

a) The service life of a structural item should be defined taking into account all phases including at a minimum the following phases:

   1) transportation, handling, testing and storage; and

   2) all phases of pre-launch, launch, operation and descent.

b) The phases, applicable loads and duration should be determined based on the following:

   1) requirements of service life (i.e. single mission, expendable, re-usable or long-term deployment);

   2) effect of all degradation mechanisms upon materials used in the construction (i.e. both terrestrial and space environments and all expected loading regimes); and

   3) experience with similar structural items (e.g. qualification and problems identified in-service).

c) Service life evaluations should be applied to determine the following:

   1) inspection and maintenance requirements;

   2) when an item should be replaced (preventive maintenance); and

   3) inspection and repair procedures and intervals (corrective maintenance).

d) When the methodology is linked with fatigue and damage tolerance analysis or tests, the service life should be an envelope life, consisting of the most unfavorable sequence of events (e.g. loading cycles, thermal cycles) to which the structure can be subjected during its defined service life. Then the service life will:

   1) include also manufacturing phases (as the proof test);

2) be an envelope of all real phases and durations, retaining the most severe variants if there are several ones;

3) take into account, for each phase, the maximum number of cycles; and

4) consider, for each phase, the limit level of the loads.

This service life is associated with the “life factor” (or “scatter factor” defined mainly for material dispersion), as defined in 3.29 or 3.54.

A.2.2 Mass and inertia properties

Change of mass and inertia properties of the structure during the service life should be taken into account.

A.2.3 Loads and pressure

Anticipated loads and pressures throughout the service life of a structural item should be used to define the load/pressure spectra for design, analysis, and testing. Updates to the design spectra should be evaluated.

ISO 14622 specifies loads and induced environment during the service life of a space flight vehicle and its components.

A.2.3.1 Load events

Typical loading conditions relevant to the pre-launch, launch, and ascent phases which should be considered include transportation, ground operations, operational pressures, engine ignition, thrust, aerodynamic loads, heat flux, pyrotechnic shock, maneuvering, and separation. Loading conditions for the in-orbit phase should include operational loads and pressures, thrust, pyrotechnic and deployment shock, temperature, vibration, and meteoroid and debris impact. Loading relevant to reentry, descent, and landing should include aerodynamic loads, temperatures, deployment, landing (including contingency), and post-landing heat soak.

a) All relevant structural and thermal load events expected throughout the service life of a structure should be identified and considered.

b) Loads should be defined according to their nature, (i.e. static or dynamic) and their levels, occurrence time and durations during service life.

c) As a minimum the following load events should be considered:

1) Ground and test loads:

i) handling, transportation and storage loads;

ii) assembly and integration loads;

iii) ground test loads; and

iv) ground environment (wind, earthquake, friction, etc.).

2) Launch loads as defined by the launcher authority including:

i) launch preparation,

ii) operational pressures,

iii) engine ignition,

iv) thrust built-up,

v) aborted launch,

vi) lift-off,

vii) thrust (constant or varying slowly),

viii) aerodynamic loads,

ix) heat flux from engine and aerodynamics,

x) gust,

xi) dynamic interaction between the structure and propulsion system,

xii) thrust decay,

xiii) acoustic noise,

xiv) maneuvers,

xv) pyrotechnics

xvi) separation of parts (e.g. stage, fairing and spacecraft), and

xvii) depressurization.

3) In-orbit loads:

i) operational pressures,

ii) static and dynamic loads induced by thrusters,

iii) shocks due to pyrotechnical operation and deployment of appendages,

iv) thermo-elastic loads induced by temperature variations,

v) hygroscopic-induced loads due to variations in moisture content,

vi) micro-vibrations induced by moving elements (e.g. momentum wheels) and thrusters,

vii) micrometeoroids and debris,

viii) docking,

ix) berthing,

x) crew-induced loads (e.g. on handles, rails and by movements),

xi) plume impingement,

xii) momentum gyro or control momentum gyro attitude adjustment, and

xiii) solar array pointing mechanism-induced loads.

4) Re-entry, descent and landing:

i) aerodynamic loads and thermal fluxes,

ii) parachute ejection and deployment shocks,

iii) operational pressures,

iv) landing loads, and

v) impact loads.

A.2.3.2 Ground handling, transportation, and post-landing loads

As appropriate, the structural item should be instrumented during ground handling and transportation to ensure that critical design loads and thermal and humidity levels are not exceeded. Loading conditions for all logistic, ground handling and post-landing operations should be developed and considered in designing the structural item.

A.2.3.3 Flight and orbital loads

The principal source of design loads for the structural item is the loads generated by the quasi-static and transient phenomena occurring during the various operational phases of launch, flight, and orbit (such as docking and extra-vehicular activity (EVA) related loads, where applicable). All loads should be considered in the combinations that yield the specified statistical basis.

Loads in the low-frequency regime should be determined by analysis utilizing simulations and coupled system flexible body structural dynamic models, as appropriate for the event and the nature of the applied external environment. Other significant low-frequency loads may occur due to in-orbit operations by moving mechanical assemblies, such as appendage deployment, vehicle slewing.

The frequency range for loads analyses should be supplied by the launch vehicle organization up to an upper frequency, depending on the resolution and fidelity of the launch vehicle and satellite models and forcing functions. The payload dynamic model should have sufficient fidelity to capture the dynamic behaviour of the payload in this frequency range.

NOTE The typical upper frequency required to verify decoupling from launch vehicle or spacecraft structure sources is up to 70 Hz for spacecraft structures, and up to 100 Hz for equipment structures.

A.2.3.4 Pressure

All pressure vessels, pressurized structures, and other pressure components should withstand limit pressure applied simultaneously with other limit loads in a loading case without experiencing detrimental deformation. They should withstand ultimate pressure applied simultaneously with relevant ultimate loads in a loading case without failure in the critical environment.

Pressure vessels and pressurized structures should be able to withstand ultimate external pressures (destabilizing) and other loads without collapse or rupture when internally pressurized to the minimum anticipated operating pressure.

Provisions should be made for venting, as required, to preclude damage due to over-pressurization of the launch vehicle and spacecraft during service life.

A.2.3.5 Differential pressure

For structural components whose strength could be affected by the differential pressure (internal/external) during flight ascent or descent, then the differential pressure should be considered depending on the failure mode (minimum differential pressure for relieving differential pressure).

A.2.3.6 Combined loads

Load combination rules should be defined according to specified load events by establishing the loads to be combined, their level and mathematical combination procedures (e.g. linear superposition or root of the sum of the squares).

Load application sequence should be defined.

To account for any load-interaction effect depending on load application sequence:

— Factors of safety for combined loads should be defined at yield and ultimate level, and for the tests.

— Rules to be applied for relieving loads should be defined.

Usually design safety factor should not be used for relieving loads, if they are statistically independent from other loads, otherwise the same safety factor should be used. However, sometimes no safety factor is used for relieving loads.

Annex D shows examples.

A.2.3.7 Limit loads

The limit loads are derived as follows.

a) For cases where a representative statistical distribution of the loads is known, the limit load should be defined as the load level not being exceeded with a probability of 99 % and a confidence level of 90 % during the service life.

b) For cases where a statistical distribution of the loads is not known, the limit loads should be based on conservative assumptions.

c) For pressurized systems, the MEOP should be part of the limit loads.

For Gaussian-distributed random loads for verification, with a zero mean value, the limit load contribution should be derived as the standard deviation multiplied by three, i.e. 3 × root-mean-squares (RMS).

NOTE For long-time application, the relevant factor may be greater than 3.

A.2.3.8 Design limit loads

"Design Limit Loads" are introduced when explicitly separating both the design safety factor and design system factor as follows.

a) Design safety factors:

Some projects define only limit loads, and then (design) yield loads and (design) ultimate loads, taking account, respectively, of the (design) yield safety factor and (design) ultimate safety factor.

The word "design" is associated with using a design safety factor (also called in a condensed term as a "safety factor" or a "factor of safety").

b) Design system factors:

Other projects may refer to "limit loads" as "design limit loads", which are derived by multiplying the limit loads by design system factor.

The word "design" is associated with using a design system factor (also called in a condensed term a "system factor" or "design factor").

Design system factors are put on top of design safety factors and are different from them.

When separating design system factors from design safety factors, safety factors will normally take into account statistically the dispersion for loads and materials, while system factors will take into account uncertainties for poorly understood phenomena.

When not separating design system factors from design safety factors, only one set of terms is used: “design safety factor” (see 3.15) and “limit load” (see 3.30), as in this International Standard. Tailoring of this International Standard may separate these terms.

NOTE The design system factors may be defined due to project progammematic aspects (e.g. uncertainty in launcher environments, maturity of design and other design considerations, protoflight approach or qualification philosophy).

EXAMPLE The European Cooperation for Space Standardization (ECSS) defines two kinds of design system factors to be considered:

— the project factor KP, mainly for maturity of design or further evolution of specification, and

— the model factor KM, for uncertainties in the model used for computing loads (as dynamic response), or in the model for derivation of loads from global launcher or spacecraft till individual structural element (hyper-staticity).

In this philosophy, as design system factors should normally be conservative, loads given at a lower level (individual structural element) have a lower probability to be reached than at an upper level. In any event, some projects may use a different approach, in which loads given at a lower level could have a higher probability to be reached than at an upper level (depending on the required failure probability at each level).

A.2.4 Environments

A.2.4.1 Natural and induced environments

All structural assemblies and components should be able to withstand the environment loads and conditions to which they are exposed both during manufacture and their complete service life.

Components and assemblies for space applications should be compatible with the operational environment conditions and with the atmospheric conditions on earth in which they are manufactured and tested.

Consideration should be given to the effects of gravitation and exposure of sensitive materials to manufacturing and atmospheric environments; suitable provisions (e.g. gravitational compensation and purging) should be made where necessary for the protection of sensitive equipment or components.

The sensitivity of materials to the environment on earth can stipulate the requirements for quality control procedures.

NOTE 1 The natural environment generally covers the climatic, thermal, chemical and vacuum conditions, required cleanliness, levels of radiation and the meteoroid and space debris environment.

NOTE 2 The induced environments cover the mechanical loads induced by ground handling and pre-launch operations, launch, maneuvers and disturbances, re-entry, descent and landing. Additional induced environments include static pressure within the payload volume, temperature and thermal flux variations and the electromagnetic and humidity environments.

A.2.4.2 Mechanical environment

The mechanical environment should be defined by static, thermal and dynamic environment loads. The static and dynamic environment loads should be defined in terms of constant acceleration, transient, sinusoidal and random vibration, acoustic noise and shock loads.

All loads should be considered in the worst combinations in which they can occur.

NOTE The severest load is experienced during launch, ascent and separation, and, where relevant, during re-entry, descent and landing.

All loads which can affect the performance in an operational mode should be taken into account in the definition of the mechanical environment.

A.2.4.3 Thermal environment

Effects of steady-state and realistically extreme transient thermal conditions should be considered in the structural design. Thermal effects on the structural item, including heat transfer rates, temperature levels and cycles, thermal stresses and deformations, and mechanical and physical property changes, should be based on critical design and test thermal environments. Thermal effects due to contingency operations should be considered.

A.2.4.4 Vibroacoustic environment

Combined effects of the mechanically induced transient and random vibration environments and acoustic environment should be accounted for by analysis of the dynamic response to the environment.

A.2.4.5 Pyrotechnic shock environment

Shock loads induced by pyrotechnic shock events should be considered, when appropriate.

A.2.4.6 Space flight environment

The material degradation effects of atomic oxygen, ionizing radiation, solar ultraviolet, plasma or spacecraft charging effects should be considered in designing the structures, when required.

A.2.4.7 Micrometeoroid and orbital debris environments

The effect of the micrometeoroid and orbital debris environment should be considered in designing the structures, including shielding, when required.

a) Pressurized structures, tanks, battery cells, pipes, electronic boxes and other specified equipment should be protected from micrometeoroid and orbital debris impact in order to prevent the risk of catastrophic failures.

b) The selection and design of material and debris protection systems should be based on a specified probability of survival.

NOTE The probability of survival is influenced by the probability of impact, critical debris size, material response to hypervelocity impacts, impact face, back face (spalling), mission duration, spacecraft orientation and multiple impacts.

A.2.4.8 Microgravity, audible noise and human vibration

Structural requirements imposed by microgravity, audible noise and human vibration system level requirements should be taken into account.

A.2.4.9 Corrosion effects

Corrosion can be regarded as any deterioration in the physical and chemical properties of a material due to the environment.

a) The selection of a material for corrosion resistance should take into account the specific environment, the design, fabrication and storage of individual and assembled components, compatibility of dissimilar materials, and susceptibility to fretting and crack initiation.

b) In cases where the behaviour of a material in a specific environment is not known, corrosion tests of representative materials (composition and condition) should be performed, either under the service conditions, or in more severe conditions (accelerated testing).

c) Metals, their alloys and weld joints when used in structural applications should be selected from those materials known to have a high resistance to stress-corrosion cracking, as follows:

   1) materials which have been tested and demonstrated to have a high resistance to stress-corrosion cracking, and therefore may be used for this purpose;

   2) metals, alloys and weld joints which may be approved for structural applications by means of the stress-corrosion evaluation; and

   3) new alloys and their weld joints whose characteristics and susceptibility to stress-corrosion cracking have been demonstrated by test.

A.2.4.10 Ablation and pyrolysis

The structural design should take into account the material changes due to ablation and pyrolysis.

In cases where the behaviour of a material in a specific environment is not known, ablation and pyrolysis tests of representative materials (composition and condition) should be performed, either under the service conditions, or in more severe conditions (accelerated testing).

A.2.4.11 Venting and purging

a) Venting should be provided in order to prevent a build-up of excess pressure and to reduce the time to evacuate the structure.

b) In case provision a) is not conformed to, the structure should withstand build-up pressure.

c) The openings for venting (e.g. to prevent contamination or risk of explosion) should be compatible with the purging system gas supply pressure and flow rate.

A.3 Other recommended good practices

A.3.1 Inspectability

To ensure structural integrity, the requirement to inspect a component, assembly or structure should take into account 1) at various stages throughout manufacture, 2) at various stages during assembly, 3) after testing, and 4) in service.

An NDI policy should be defined and incorporated into the design process taking into account the inspectability of parts and access for inspection equipment and personnel.

For structures subject to fracture control, the NDI policy should be consistent with the assumption made for the fracture control verification specified in ISO 21347.

The need to provide access for inspecting various structural items should guide the formulation of design criteria early in the design phase of the structure and its layout.

A.3.2 Interchangeability

All parts or subassemblies identified by an item number should be functionally and dimensionally interchangeable with items which are identically numbered.

A.3.3 Maintainability

The mechanical design should be performed in such a way that assembly, integration, repair and maintenance activities can be carried out with a minimum of special tools and test equipment.

The design should minimize the maintenance during storage and ground life.

The maintenance progamme should do the following:

a) include a maintenance protocol; and

b) define measurable parameters for all operations, and during all project phases, including at least the following:

   1) mean-time-to-repair,

   2) limited-life,

   3) fault detection and isolation capability,

   4) spares requirements, and

   5) ground storage requirements.

The results of the maintenance progamme evaluation should:

— influence the design and avoid costly, late alterations, or replacement of parts; and

— form the criteria with which various concept designs are evaluated.

Structures that are not accessible should be maintenance free during service life.

A.3.4 Dismountability

The mechanical design should enable removal and replacement of secondary structures, equipment and payload.

A.3.5 Interface

The design of structural assemblies should be compatible with all internal and external interfaces which can affect, or can be affected by adjacent systems, subsystems or assemblies. The following factors should be taken into account:

a) spacecraft-launcher interface;

b) human factors and ergonomics;

c) interfaces with equipment, optics and avionics;

d) rendezvous and docking, and robotics;

e) ground support equipment for pre-flight and post-flight operations; and

f) support equipment for in-orbit operations.

Interfaces should be explicitly defined with respect to the following:

— design requirements, i.e. areas, volumes, alignments, surface finishing and properties, tolerances, geometry, flatness, fixations, conductibility, constraints imposed by the launcher (e.g. geometric, static and dynamic envelopes) and by design concepts (e.g. thermal and optical design), mass and inertia properties;

  NOTE Cut edges of carbon fibre reinforced plastics (CFRP) have unprotected carbon which might be a corrosion element with the metallic surface coating. Therefore, it is recommended to protect cut CFRP edges (e.g. with resin).

- external loads applied to the interfaces, including temperature effects;
- global and local stiffness;
- electrical, magnetic and radio frequency aspects, when applicable.

A.3.6 Material design allowables

For all structural materials, design allowables used in the MS calculation method should be statistically derived, taking into account all operational environments.

The scatter bands of the data should be derived and design allowables defined in terms of fractions of their statistical distribution with specified levels of reliability and confidence.

For each type of test, the minimum number of test specimens should be:

a) ten (10) to establish A-values, and

b) five (5) to establish B-values.

If the material is delivered in several batches, the design allowables test progamme shall take into account the variations from batch to batch.

In the cases specified above, preliminary design allowables may be based on an initially small sample size, and upgraded as the sample size increases by tests of newly arriving batches.

Probabilistic descriptions of the strength distribution of materials are usually based on the normal, log-normal or the Weibull distribution. Regardless of the kind of distribution, distribution curves and fractal's cannot be uniquely identified due to the data scatter. The values are assumed to lie within an interval bounded by upper and lower confidence limits. When design allowables are deduced from a regression line based on a small number of test specimens, the confidence in such allowables is low. Larger numbers of test specimens generally do not change the shape of the regression line, but the confidence in the statistical evaluation increases.

Annex B
(informative)

Design requirements verification methods

B.1 Verification by analysis

B.1.1 General

Analysis should be based on qualified methods and input data derived from tests. Different analysis methods are available, such as handbook-based calculations, analytical closed-form solutions or numerical solutions.

A mathematical model (e.g. finite element model) should be developed for primary and secondary structures.

It should be developed and delivered for launcher coupled dynamic analysis (LCDA) also.

It should be demonstrated that the analysis tools used are adequate for the intended purpose. A justification of the assumptions made in developing tools, methods and models should be provided.

Nominal structure gauge (thickness) as specified in the design drawings should be applied for analysis.

NOTE Some projects may use minimum structure gauge or some intermediate value.

The influence of tolerances (including overall dimensions and thickness) should be assessed whenever potentially critical.

The mathematical models should be correlated with data from the available tests (ground or flight tests) foreseen in the general test plan.

B.1.2 Modelling aspects

All mathematical models should be checked, according to the mathematical model requirements and mathematical model description and delivery, for the following aspects:

a) validity of the numerical structural model;

b) validity within the expected application range; and

c) applicability of the assumptions and boundary conditions with respect to the real physical behaviour being modelled.

In addition:

— Analysis is based on mathematical models which are representative of the structural behaviour. These models help the designer to assess how the design fulfils structural requirements and gives insight on how to improve the design.

— The mathematical models enable preparation of experimental testing and verification of requirements not demonstrable by tests, e.g. through coupled analysis.

— The mathematical models help in defining load cases or combination of load cases.

— The mathematical models can also give designers insight on sensitivity of the design with respect to uncertainties.

B.2 Verification by test

The test objectives and success criteria should be specified. The adequacy of the test procedure with regard to the test objectives should be verified before the test.

Checking of the test conformance with regard to the test procedure should be performed after the test. The impact of deviations on the adequacy of the test with respect to the test objectives should be evaluated.

Differences between test conditions and expected operating conditions (e.g. boundary conditions, gravity and atmosphere) should be identified and their effect with respect to operating conditions should be evaluated.

NOTE Test-analysis correlation is performed to validate the mathematical model.

The validated mathematical model should be used to check the adequacy of the tests.

The test results should be evaluated with respect to the requirements to be verified.

B.2.1 Model philosophy

One of the following test model philosophies should be applied:

a) prototype approach;

b) protoflight approach; or

c) hybrid approach

Detail discussion on each philosophy can be found in MIL-STD-1540.

The chosen approach should be approved by the procuring authority.

B.2.2 Development tests

For unconventional materials, new design concepts or expected critical parts, development tests should be performed to:

a) evaluate design choices;

b) support and check analysis methods;

c) determine the failure modes; and

d) support the definition of qualification and acceptance tests.

NOTE 1 Development tests can be performed on specimens (e.g. to test material properties), or structural parts or components, or the whole structure.

NOTE 2 Development tests can include static tests and other tests (e.g. fracture mechanics test, thermal distortion test).

B.3 Verification by similarity

Verification by similarity is an option for heritage structural designs. This option may be applied on a case-by-case basis provided the hardware verification test conditions are shown to be applicable and encompass the new application conditions by an approved analysis. This option is not listed in Table 1 as it is a special case.

If component “A” is to be considered a candidate for qualification by similarity to component “B” that has already been qualified, then all of the following should apply.

a) Component “B” was not qualified by similarity or analysis.

b) Component “B” was a representative flight article.

c) The environments, both amplitude and duration, encountered by component “B” during its qualification are equal to or more severe than the qualification environment intended for component “A”.

d) Components “A” and “B” were produced by the same manufacturer using identical tools, manufacturing processes, and quality control procedures.

e) Supporting documentation for component “B” is available and includes specifications, drawings, qualification test procedures, qualification and acceptance reports, problem failure reports, if any, with closure history, test waivers, and a flight history summary.

Annex C
(informative)

Design requirements verification methods

C.1 General

Minimum design factors of safety used in margin-of-safety calculations for structures in different regional documents are listed in the following tables. They are for information only. Each progamme should select the appropriate values suited for the specific applications.

Table C.1 contains the design factor of safety required in the structure standard issued by the American Institute of Aeronautics and Astronautics (AIAA), AIAA S-110. Tables C.2, C.3, and C.4 contain the design factors of safety required in the structure standard, developed by the European Cooperation for Space Standardization (ECSS), ECSS-E-ST-32C.

Special factors, also called “additional factors”, specified in Table C.2 and Table C.3 (e.g. for joints and inserts), should be applied in addition to other factors of safety.

NOTE 1 As opposed to the empirical approach applied in the definition of deterministic factors of safety, a probabilistic approach is allowed in some space progammes. Factors of safety are calculated based on a statistical description of loads, materials and geometry, combined with a failure probability requirement.

NOTE 2 Table C.1 is not related to pressurized hardware,

NOTE 3 The factors in Table C.1 are for the design process, and different factors may be used for qualification tests,

Table C.1 — Minimum design factors of safety (AIAA S-110)

Design and test strategy	Design factor of safety on limit loads			Typical application
	Yield[a]	Ultimate		
		Unmanned	Manned	
Qualification test dedicated unit(s) to ultimate	1,10	1,25	1,40	Fleet
Protoqualification test single flight unit	1,25	1,40	1,40	Small fleet
Proof test all flight units	1,10	1,25[a]/1,40[b]	1,40	Few
No qualification or protoqualification test[c]	1,60	2,00	2,25	One-of-a kind, or modification to existing structure

[a] Applies to metallic structural items only.

[b] Applies to non-metallic structural items only.

[c] Applies to metallic and secondary non-metallic structural items.

Table C.2 — Minimum factor of safety for unmanned spacecraft (ECSS-E-ST-32C)

Structure type and sizing case	FOSY	FOSU	FOSY for verification by analysis only	FOSU for verification by analysis only	Additional factors
Metallic structures	1,10	1,25	1,25	2,0	
Composite structures, Uniform material		1,25		2,0	
Composite structures discontinuities		1,25		2,0	1,2
Sandwich structures: — Face wrinkling — Intracell buckling — Honeycomb shear		1,25		2,0	1,2
Joints and Inserts		1,25		2,0	1,2
Glass structures		2,5		5,0	
NOTE FOSY: Factor of safety for yield, FOSU: Factor of safety for ultimate.					

Table C.3 — Minimum factor of safety for pressurized manned modules (ECSS-E-ST-32C)

Structure type and sizing case	FOSY	FOSU	FOSY for verification by analysis only	FOSU for verification by analysis only	Additional factors
Metallic structures: — Launch and landing — In orbit loads	 1,25 1,1	 1,4 1,5			
Composite structures Uniform material — Launch and landing — In orbit loads		 1,5 2,0			
Composite structures discontinuities		2,0			1,2
Sandwich structures: — Face wrinkling — Intracell buckling — Honeycomb shear		1,4			1,20
Joints and Inserts		1,4			1,20
Glass structures		3,0			
Pressurized manned compartments: — Pressure only — Pressure and inertia	 1,65 1,1	 2,0 1,5			

Special factors, also called “additional factors”, specified in Table C.2 and Table C.3 (e.g. for joints and inserts), should be applied in addition to other factors of safety.

Table C.4 — Minimum factor of safety for expendable launchers (ECSS-E-ST-32C)

Structure type and sizing case	FOSY	FOSU
Structural pressurized tanks for liquid propellants and solid propellant stage boosters	1,10	1,25
Pressure vessels and small solid propellant boosters:		
— Pressure	1,50	2,00
— Other loads	1,10	1,25
Engine feed pipes and main tank pressurization pipes	1,10	1,25
Other pipes:		
— Pressure	1,50	2,50
— Other loads	1,10	1,25
Elastomer and elastomer/structure interfaces		2,00
Other structures	1,10	1,25

C.2 Factor of safety (FOS)

Factors of safety are highly experience dependent. The selection of appropriate factors of safety for a specific structural element depends on parameters which are related to loads, design, structural verification approach, model philosophy, and manufacturing aspects. Such aspects include the following:

— pressurized structures,

— human presence,

— flight hardware or ground support equipment,

— material type,

— joints, bearings, welds,

— verification by test,

— verification by analysis only,

— thermal loads,

— ageing effects,

— emergency loads,

— fail-safe structure verification, and

— dimensional stability.

Annex D
(informative)

Margin of safety for combined loads

The margins of safety for combined loads may be computed by the following process.

METHOD 1

The most severe combination of thermal, mechanical and pressure loads occurring at the same instant in time should be used in a rational manner according to the following equation.

$K_1 L_{\text{mechanical}} + K_2 L_{\text{thermal}} + K_3 L_{\text{pressure}}$ = Total (Yield or Ultimate) Load, and

MS [Allowable (Yield or Ultimate) Load/ (Total (Yield or Ultimate) Load)] - 1

K_i design factor of safety on yield or ultimate in Annex C, as applicable, when term is additive to the algebraic sum, $\sum L$

K_i 1,0 when term is subtractive to the algebraic sum, $\sum L$

$L_{\text{mechanical}}$ internal loads (forces, stresses, and/or strains) due to externally applied mechanical limit loads; e.g. inertial loads, aerodynamic pressure

L_{thermal} internal loads (forces, stresses, and/or strains) due to thermally-induced loads at the maximum and minimum predicted temperatures including modelling uncertainty margins

L_{pressure} internal loads (forces, stresses, and/or strains) due to design limit pressures

METHOD 2

“Interaction Equation” or “Load Ratios” method can be applied to compute λ for combined loads.

— Define the load combination applied at a certain design level (limit, yield or ultimate), according to the specified FOS for combined loads.

— With reference to an examined failure mode, for each ith load of the combination which can cause the failure, compute the ratio R_i between the applied and the allowable load (which causes the failure if the ith load is applied alone).

— Solve the following interaction equation, to find the minimum significant value of the load multiplier λ at the failure:

$$\lambda^{\alpha} R^{\alpha}{}_1 + \lambda^{\beta} R^{\beta}{}_2 + \lambda^{\gamma} R^{\gamma}{}_3 + \lambda^{\delta} R^{\delta}{}_4 .... = 1$$

where the exponents α, β, γ, and δ are real numbers in the most general case, known from tests or theory.

— Calculate the margin of safety as MOS = λ – 1.

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ICS 49.140

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