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Space systems — Structural design — Stress analysis requirements

Systèmes spatiaux — Conception des structures — Exigences relatives à l'analyse des contraintes

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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 16454 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

From the beginning of the space age, structural integrity verification has been one of the main fields of mechanical specialists' activity. Mission failure and potential danger to human life, expensive ground constructions and other public and private property are the most probable consequences in the case of space structural integrity failure. Static strength is one of the most important critical conditions for structural integrity analysis. It is usually the main criteria for space structure weight evaluation. If the space structure is too heavy, the mission could be extremely expensive or impossible to achieve. If the space structure is underdesigned, it could result in structural failure, leading to high risk associated with safety of life, and loss of expensive hardware and other property. It is therefore necessary to specify unique requirements for static strength analysis in order to provide cost effective design and light-weight, reliable and low risk structures for space application.

The analysis and design of space structures has a long history. This International Standard establishes the preferred requirements related to these techniques for static strength critical condition.

Space systems — Structural design — Stress analysis requirements

1 Scope

This International Standard is intended to be used for the determination of the stress/strain distribution and margins of safety in launch vehicles and spacecraft primary structure design. Liquid propellant engine structures, solid propellant engine nozzles and the solid propellant itself are not covered, but liquid propellant tanks, pressure vessels and solid propellant cases are within the scope of this International Standard.

This International Standard provides requirements for the determination of maximum stress and corresponding margin of safety under loading, and defines criteria for static strength failure modes, such as rupture, collapse and detrimental yielding. Critical conditions associated with fatigue, creep and crack growths are not covered. Notwithstanding these limitations in scope, the results of stress calculations based on the requirements of this International Standard are applicable to other critical condition analyses.

In accordance with the requirements of this International Standard, models, methods and procedures for stress determination can also be applied to the displacements and deformation calculations, as well as to the loads definition, applied to substructures and structural members of structures under consideration. When this International Standard is applied, it is assumed that temperature distribution has been determined and is used as input data.

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, *Space systems — Structural design — Loads and induced environment*

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

3 Terms and definitions

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

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

3.2
allowable load
allowable stress
allowable strain
maximum load (stress, strain) that can be accommodated by a material/structure without potential rupture, collapse or detrimental deformation in a given environment

NOTE Allowable loads (stresses, strains) commonly correspond to the statistically based minimum ultimate strength, buckling strength and yield strength, respectively.

3.3
basic data
input data required to perform stress analysis and to determine margins of safety

3.4
B-basis allowable
mechanical strength value above which at least 90 % of the population of values is expected to fall, with a confidence level of 95 %

3.5
collapse
failure mode induced by quasi-static compression, shear or combined stress, accompanied by very rapid irreversible loss of load resistance capability

3.6
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.

3.7
creep
process of a permanent material deformation resulting from long duration under constant or slowly altered load

NOTE The ultimate creep deformation, corresponding to the loss of material integrity is often much larger than ultimate deformation in the case of short time loading.

3.8
critical condition
most severe environmental condition in terms of load and temperature, or combination thereof, imposed on a structure, system, subsystem or component during service life

3.9
critical location
structural point at which rupture, local buckling or detrimental deformation will first lead to structural failure

3.10
design safety factor
coefficient by which limit loads are multiplied in order to account for the statistical variations of loads and structure resistance, and inaccuracies in the knowledge of their statistical distributions

3.11
destabilizing load
load that produces compressive stress at critical location

3.12
detrimental yielding
⟨metallic structures⟩ permanent deformation specified at the system level to be detrimental

3.13
development test
test to provide design information that can be used to check the validity of analytic technique and assumed design parameters, to uncover unexpected system response characteristics, to evaluate design changes, to determine interface compatibility, to prove qualification and acceptance procedures and techniques, to check manufacturing technology, or to establish accept/reject criteria

3.14
flight-type hardware test
test of a flight structure article, a protoflight model, a representative special model or a structural element fabricated with the same or close to flight hardware technology

3.15
gauges
thickness and other structure dimensions which relative scattering could result in significant effect on stress levels and/or margin of safety

3.16
knockdown coefficient
empirical coefficient, other than design safety factor, which is used to determine analytically in a simple way actual or allowable loads or stresses, and which is defined on the basis of test results of flight-type structures, model structures or structural members as compared with corresponding stress analysis data

3.17
limit load
maximum that can be expected during service life and in the presence of the environment

NOTE For stabilizing loads, the limit load is the minimum load.

3.18
loads
volume forces and moments, concentrated and/or distributed over the structure surfaces or structure, caused by its interaction with environment and adjacent parts of vehicle, and accelerations

NOTE This includes pressures, external loads and enforced displacements acted at considered structural element, pretension, inertial loads caused by accelerations and thermal gradients.

3.19
loading case
particular condition described in terms of loads/pressures/temperatures combinations, which can occur for some parts of structure at the same time during its service life

3.20
local buckling
failure mode, which occurs when an alternative equilibrium mode of a structural member exists, and which could lead to detrimental deformation or rupture of that member if it occurs under loading

3.21
margin of safety
M_S
expression of the margin of the limit load multiplied by design safety factor against the allowed load

Another representation of the concept:

$$M_\mathrm{S} = \left(\frac{F_\mathrm{AL}}{f_\mathrm{DS} \times F_\mathrm{LL}} \right) - 1 \qquad (1)$$

where

F_AL is the allowable load under specified functional conditions (e.g. yield, rupture, collapse, local buckling);

F_LL is the limit load;

f_DS is the design safety factor.

NOTE Load can imply corresponding stress or strain.

3.22
minimum allowable
minimum material mechanical properties warranted by the supplier

3.23
pressure
external load caused by fluid action on a structural surface

NOTE The terms “pressure” and “load” are sometimes referred to simultaneously in this International Standard.

3.24
primary structure
part of a vehicle that carries the main loads and/or defines the fundamental resonance frequencies

3.25
rupture
loss of integrity by structure material differed from fatigue and ultimate creep deformation attainment, which could prevent the structure from withstanding load combinations

3.26
semi-finished item
product that is used for structure manufacturing or assembling

EXAMPLE Sheets, plates, profiles, strips, etc.

3.27
stabilizing load
load which decreases compressive stresses if applied in conjunction with destabilizing loads

3.28
static strength
property of a structure, characterized by its capability to withstand loads and temperature combinations without rupture, collapse, detrimental local buckling and detrimental deformation

3.29
strength failure mode
condition of a structure or a structural member considered as a critical condition in accordance with stress analysis results

3.30
stress analysis
analytical procedure to determine structure stress/strain distribution, deformations and margins of safety

3.31
structure
primary structure, unit attachments, pressure/loads carrying elements of pressure vessels, loads carrying elements of appendages

3.32
structural mathematical model
analytical or digital presentation of a structure

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

3.33
ultimate load
limit load multiplied by ultimate design safety factor

3.34
unit
part of a vehicle which is designed mainly to provide vehicle functioning and which differs from a structure

4 Requirements

4.1 General

For structures used in space systems, such as launch and space vehicles, the stress analysis and corresponding determination of margin of safety for various static strength failure modes shall meet the requirements specified in this International Standard.

Basic data, structural models, methods for stress analysis and strength criteria are considered critical for the successful completion of these procedures.

Unless otherwise noted below, there are no limitations set out in this International Standard that restrict the use of results from stress calculations for other applications.

4.2 Basic data

4.2.1 General

Basic data used for space structure stress analyses shall meet the requirements included in 4.2

Basic data shall include all the following information:

— structural configuration, geometry and gauges,

— structural materials and their properties, and

— loading case list, load and temperature combinations, and corresponding design safety factors for every loading case.

4.2.2 Structural configuration, geometry and gauges

4.2.2.1 Structural configuration, geometry and gauge data (with tolerances) used for stress analyses shall correspond to drawings representing a relevant design stage.

4.2.2.2 The choice of particular thickness (minimum or nominal) for stress analyses shall be subject to national regulatory requirements. Otherwise, the following factors shall be taken into account:

— conservatism of applied safety factors and knockdown coefficients;

— correspondence between applied thickness and procedure for knockdown coefficient determination;

— stress analysis results dependence on and sensitivity to thickness;

— simplification of stress analysis procedure application;

— linear or non-linear behaviour.

4.2.2.3 Structural configuration, geometry and gauge data (with tolerance) shall be sufficient to substantiate a given structural analytical model and to determine the corresponding parameters.

4.2.3 Structural materials and their properties

4.2.3.1 This entire subclause (4.2.3) refers to individual material properties for any individual part of the structure (junctions) for which the stress analyses require allowable values.

4.2.3.2 A list of materials used for the fabrication of the structure and its members shall correspond to the design and technology documentation. The information about types of materials, semi-finished items and technology processes shall be sufficient to evaluate possible variations of their properties used for stress analysis and determination of margin of safety.

4.2.3.3 Material properties used for stress analysis and determination of margin of safety shall take into account manufacturing processes, temperature and other significant environmental effects, including possible aging during lifetime.

If appropriate data are not available, special development tests shall be conducted to evaluate corresponding properties.

4.2.3.4 Appropriate ultimate and yield strength (for metal only) material properties shall be used for margin of safety calculations. "A-basis allowable" values shall be used where failure of a single load path would result in loss of structural integrity. "B-basis allowable" values may be used for redundant structural elements where failure of one element would result in a safe redistribution of applied loads to other elements. When it is difficult to obtain "A-basis allowable" and "B-basis allowable" values, it is permissible to use the minimum values warranted by the material supplier and approved by the procuring agency.

Nominal modulus of elasticity and Poisson's ratio shall be used for the stress analysis.

4.2.3.5 If inertia loads are applied and corresponding basic data are described in terms of accelerations or gravity constant, inertia material properties and masses of units and appendages data shall be sufficient to determine those inertia loads adequately.

Nominal material inertia properties and nominal units and appendages masses and parameters of their arrangements shall be used for stress analyses. When an attachment can be used for different types of units or appendages, nominal values for the most unfavourable type of equipment shall be taken into account.

When equipment inertia scattering is considered significant, the most unfavourable combinations of units and appendages masses and parameters of their arrangements shall be used for local stress analyses in areas near corresponding attachments.

4.2.3.6 Temperature effects on material and physical properties and thermal stresses shall be considered.

When appropriate, it is permissible to take into no account thermal stresses for materials with high ultimate deformation (as compared with thermal expansion) and low yield strength.

4.2.3.7 When loading which exceeds an elastic limit is permitted and loads values are sufficient to cause significant nonlinear material behaviour, then corresponding stress-strain dependencies shall be used for stress analyses.

4.2.4 Loading data

Load data shall include:

- list of loading cases;
- load and temperature combinations for every loading case.

Load data shall include the ranges in which loads and temperatures can vary simultaneously for every loading case and every loading combination. Maximum loads values shall be limit loads.

Unless otherwise specified, load data shall meet the requirements of ISO 14622. Unless otherwise specified, load/pressure data for metallic pressurized systems and composite overwrapped pressure vessels shall meet the requirements of ISO 14623.

Unless otherwise specified, design safety factors shall meet the requirements of ISO 14622, where only their minimum values are established. Design safety factors used for stress analysis and determination of margin of safety may be higher, in which case their values shall be specified by a contract, taking into account national industry specifications, relevant experience and other design and verification requirements. Unless otherwise specified, design safety factors for metallic pressurized systems and composite overwrapped pressure vessels shall meet the requirements of ISO 14623.

Subject to ISO 14622, the following types of external loads shall be taken into account, which can be generally classified as:

— mechanical loads (quasi static or equivalent quasi-static loads for stresses analysis);

— pressure loads (or equivalent quasi-static pressure);

— thermal loads;

— pretension loads;

— other preloads.

4.3 Analysis methodology and software

4.3.1 Analysis methodology

4.3.1.1 Either closed form structural analysis techniques or numerical methods, such as finite element, boundary element methods, etc., may be used for stress analyses and determination of margin of safety separately or in combination (e.g. stresses are calculated with a numerical method and margins of safety corresponding to structural member local buckling are determined as closed form solutions).

4.3.1.2 When numerical methods are applied, the required accuracy shall be demonstrated.

4.3.1.3 Commonly used stress analysis methods shall be verified by comparing calculation results and known test data.

NOTE Verification is not required by current international standard methods.

4.3.2 Software verification

4.3.2.1 Software used for stress analyses shall be verified by comparing the results of calculation with analytical results and/or results obtained by using another verified software.

NOTE Verification is not required for current international standard software.

4.3.2.2 Verification procedures shall take into account typical structural models, boundary conditions, loading conditions, materials applied, convergence and stability of numerical methods used.

When knockdown coefficients are used as input data for a software application, the software verification shall be conducted without accounting for the comparison with purely analytical results.

4.4 Structural mathematical model

4.4.1 General

When applied for stress analyses, the structural mathematical model shall generally be developed using appropriate experience based on the results of flight-type hardware tests.

If such experience is not available or considered not applicable to a particular case, special development tests shall be conducted for structural model validation.

The structural mathematical model shall be developed to take into account the structural configuration, materials applied, loading, environmental conditions and type of analysis.

Structural mathematical models shall be checked for correlation with available test data.

4.4.2 Boundary conditions

Boundary conditions are an integral part of the structural analytical model. The adjacent structures which influence load transmission, stress distribution and collapse mode shall be evaluated to provide adequate loading conditions for the structure under consideration. When any applied boundary conditions do not represent the actual stress distribution, the analytical model of the adjacent structure or sufficiently large part of the adjacent structure shall be developed and incorporated into the model of the structure under consideration.

Notwithstanding that requirement, simplification of boundary conditions is permitted, such as reducing to conservative conditions or to effective stiffness; however, it shall be demonstrated that those simplifications provide a conservative result.

In general, the adjacent structure model shall be developed to be the same as the one for the structure under consideration, except that only stiffness and its load transmission should be modelled properly.

4.5 Structure mathematical model check

When computerized numerical methods are used for stress analyses, the structural mathematical model checks shall be conducted. It is recommended to follow the model in Annex A to as far as possible.

4.6 Failure modes

4.6.1 General

The strength criteria application shall be based on the appropriate experience, including flight-type hardware testing with accounting for basic data, structural model, knockdown coefficients and fabrication technology. When appropriate experience is not available or in case of doubt, special development tests shall be conducted for criteria validation.

4.6.2 Detrimental yielding

The margin of safety for detrimental yielding failure mode shall be determined for prescribed load combinations presented in loading data. It shall be taken into account that a detrimental yielding failure mode occurs when stress (strain) levels in the prescribed locations are equal to, or exceed, the corresponding yield material properties.

4.6.3 Rupture

Margins of safety for rupture failure mode shall be determined for any load combination presented in the loading data.

It shall be taken into account that a rupture failure mode occurs when stress (strains) levels in any location of the structure are equal to, or exceed, the corresponding ultimate material properties.

4.6.4 Collapse

Margins of safety shall be determined for the collapse failure mode if compressive and/or shear stresses can occur, when loads are varied in specified ranges.

Criterion for this failure mode is the result of an appropriate buckling analysis application that collapse occurs for a given load combination. For collapse analyses, the initial deformations due to manufacturing operations and thermal deformations due to temperature gradients shall be taken into account. It is permissible to take them into account by the application of corresponding knockdown coefficients.

4.6.5 Local buckling

When not detrimental, post buckled structures are acceptable. Margins of safety for local buckling of all structural parts shall be determined if compressive and/or shear stresses can occur in these parts, when loads are varied within specified ranges. If the margin of safety is below zero for a part (or parts) of the structure and local buckling is not considered as failure mode, and if it is acceptable at system level, margins of safety for other failure modes shall be determined with buckled elements accounted for.

Criterion for this failure mode is the result of an appropriate buckling analysis application, that local buckling occurs for given stresses combination. For local buckling analyses, the initial deformations due to manufacturing shall be taken into account. It is permissible to take them into account by applying corresponding knockdown coefficients.

4.7 Critical location analysis

Loading conditions and stress distribution analysis shall be carried out to define critical locations where material or structural members are most sensitive to a failure mode attainment.

When margins of safety are determined for every critical location, the most unfavourable combinations of loads, pressures and temperatures in frames of specified ranges shall be accounted for.

4.8 Determination margins of safety

4.8.1 Margins of safety (M_S) shall be calculated according to Equation (1) (see 3.21), where F_AL shall be determined in accordance with the criteria stated in 4.6 and the requirements of 4.2.

The application of design safety factors is based on the integral accounting of many different issues, such as loads statistical distributions, accuracy of loads and stress analysis models, manufactory technology level, capabilities of test methods and facilities to provide adequate loading conditions, etc.

Margins of safety express the margin of the design load ($f_\mathrm{DS} \times F_\mathrm{LL}$) against the allowed load. Load may mean corresponding stress or strain. In the case of significant influence of residual stress, this stress shall be taken into account when the margin of safety is determined.

4.8.2 For collapse and local buckling, failure mode stabilizing loads shall be accounted for in conjunction with design safety factor of 1,0. If not otherwise specified, minimum values of stabilizing loads (in the prescribed ranges) shall be used instead of maximum ones in these cases.

4.8.3 Margins of safety, calculated in accordance with Equation (1), shall be non-negative for every loading case and loading combination specified in basic data to demonstrate that a structure meets strength requirements.

4.8.4 As an alternative approach, a reserve factor, η, may be determined according to Equation (2).

$$\eta = \frac{F_\mathrm{AL}}{\left(f_\mathrm{DS} \times F_\mathrm{LL}\right)} = M_\mathrm{S} + 1 \qquad (2)$$

The requirement $\eta \geqslant 1{,}0$ is mathematically equivalent to the requirement formulated in 4.8.3.

4.9 Report

As a result of the stress analysis activity, a stress analysis report shall be issued. The report shall consist of:

- basic data, including:
  - status of structure configuration, geometry, gauges, materials;
  - structural configuration, geometry and gauges;
  - structure materials and their properties;
  - limit loads/pressures/temperatures for every loading case considered;
  - safety factors for every loading case and structure elements considered;
- structural mathematical model description, including:
  - rationales for its choice;
  - boundary conditions;
- structural mathematical model checks and their results;
- foundation of closed form solutions applied;
- failure modes considered;
- strength criteria applied;
- description or references related to methods and software applied;
- summary of significant analysis results including:
  - information on structural element considered;
  - loading case;
  - failure mode;
  - safety factor corresponding to failure mode;
  - margin of safety (or reserve factor); and
  - contribution of main loads in the margin of safety (if applicable).

Any additional margins applied shall be clearly indicated in the report.

Annex A
(informative)

Structural mathematical model check

A.1 General

When computerized numerical methods are used for stress analysis, the following structural mathematical model checks are recommended as far as possible.

A.2 Mass check

It is recommended to check that the total mass of the mathematical model does not differ from mass indicated in approved system documentation by more than 1,0 %.

A.3 Centre of gravity check

It is recommended to check that the centre of gravity of the mathematical model does not differ from that indicated in approved system documentation by more than 1,0 % of a maximum dimension in an analysed structure, as measured along any Cartesian system axis.

A.4 Inertia check

It is recommended to check that inertia tensor elements values of the mathematical model do not differ from values indicated in approved system documentation by more than 1,0 % of maximum inertia tensor elements value.

A.5 Free-free check

To conduct this check, lower frequencies of the mathematical model are determined via an unconstrained modal analysis. It is recommended to check that at least six frequencies are present with absolute values not exceeding 0,005 Hz. More than six quasi-zero frequencies are present when additional mechanisms are used in the structural model. The presence of additional rigid body modes should be explained by specific structure configuration.

A.6 Strain energy check

To conduct this check, rigid body modes corresponding to quasi-zero frequencies (see Clause A.5) are determined for the mathematical model with free-free boundary conditions. Modes are normalized such that displacements are equal to 1 m and rotations are equal to 1 rad. The strain energy matrix, E, is defined as follows:

$$E = 0{,}5\Phi^{\mathrm{T}} \cdot K \cdot \Phi \qquad \text{(A.1)}$$

where

Φ is a matrix with rigid body modes as columns;

Φ^{T} is the transformed Φ matrix;

K is a stiffness matrix of the mathematical model.

It is recommended to check that diagonal elements of matrix E are sufficiently small according to the state of the art. A critical value of 10^{-3} N·m can be applied.

A.7 Gravity load check

Gravity load of 1 g value is applied successively along each axis of the used Cartesian coordinate system for the mathematical model, with boundary conditions corresponding to a required stress analysis. It is recommended to check that total reaction for a corresponding direction is equal to the mathematical model weight. It is also recommended to check that at any boundary point desirable reactions occur in desirable directions. Output of all reaction forces should be checked to ensure that only the intended constraint points restrain the model, and that no unconditional restraints are present.

A.8 Thermal check

This check is conducted for the mathematical model with free-free boundary conditions and in the absence of rigid links between nodes, which prevent any relative deformation of these nodes. A uniform temperature field of $\Delta T = 100$ K is applied to the mathematical model. The Poison's ratio of 0,3 and a thermal expansion coefficient of $\alpha = 10^{-5}$ are used for this check. It is recommended to check that resulting stress is negligible at any structure location.

A.9 Artificial stiffening check

If artificial stiffening is used in the mathematical model for specific purposes, it should be checked that it does not cause unrealistic vibration modes.

A.10 The node ratio check

To conduct this check, maximum and minimum diagonal elements of stiffness matrix are determined for each node of the mathematical model. It is recommended to check that the ratio of minimum value to maximum one exceeds 10^{-8} for any node.

A.11 Maximum ratio check

To conduct this check, the mathematical model stiffness matrix, K, with boundary conditions is decomposed as follows:

$$K = L \cdot D \cdot L^{\mathrm{T}} \tag{A.2}$$

where

L is a triangle matrix with unit diagonal elements;

L^{T} is the transformed L matrix;

D is a diagonal matrix.

The ratio of (K diagonal element)/(corresponding D diagonal element) is determined for each row of stiffness matrix. It is recommended to check that the ratio is below 10^{7} for any row of stiffness matrix.

A.12 Rigid body check

To conduct this check, attach the main structural interface rigidly to one point and displace that point 1 unit in each axis of the Cartesian direction of the enforced displacement. Verify that the displacements are 1 unit in the enforced displacement and 0 unit in the other directions. Then rotate that point 1 unit about each axis of the Cartesian coordinate system. Verify that the rotations are 1 unit about the axis of rotation. Finally, verify that the forces are 0 in all elements for all cases.

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