Space Engineering
E-32 “Structures”

Presented by

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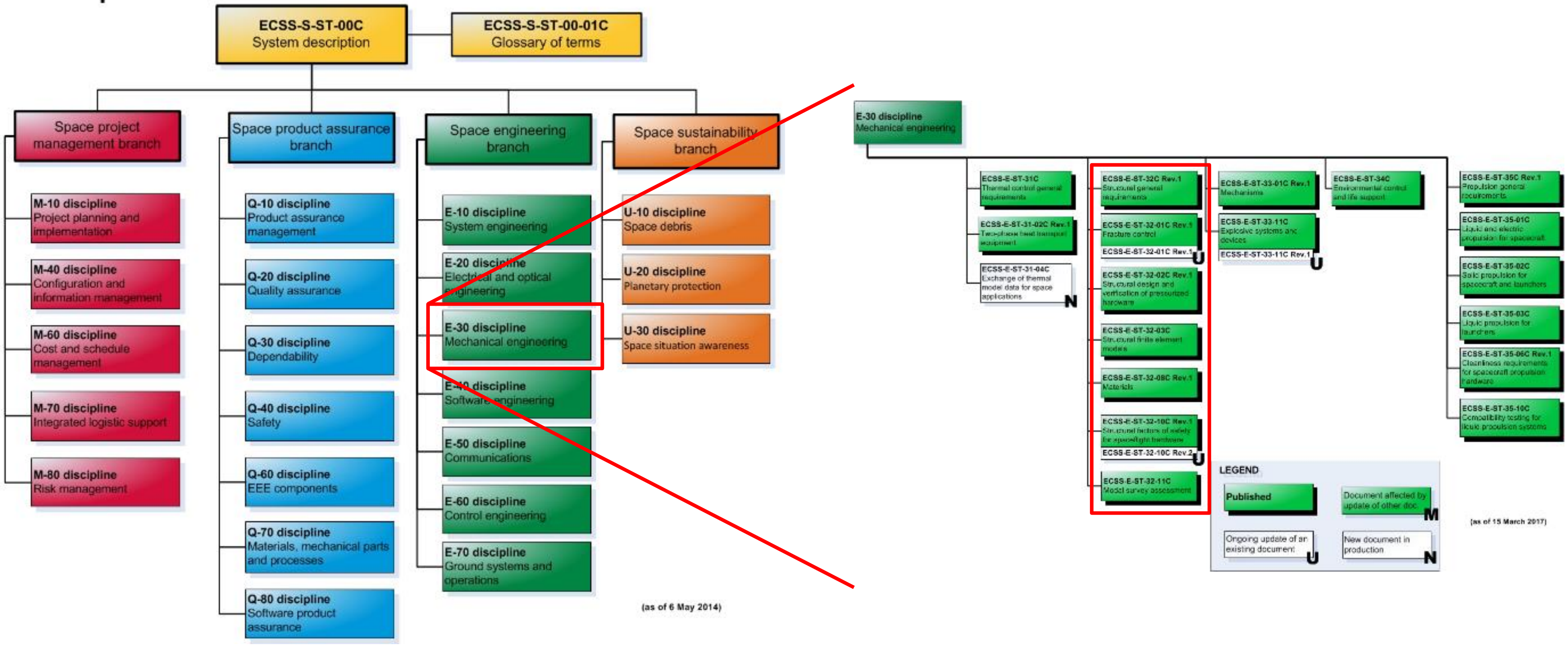
ESA- Retired

Objectives of the Course

To provide the attendants with a full insight of the spacecraft structural design, analysis and verification process related to the ECSS 32 Standards, Handbooks

Where to find our standards?

ECSS Disciplines



Overview

1. Definition of Space Structures
2. Function of a Spacecraft Structure
3. Structural General Requirements
4. Environment. Load types and derivation (*steady state, low frequency dynamics, high frequency acoustics and structure born vibrations, shock, thermal, constraints, micro-vibrations, …*)
5. Development Approach (*prototype, proto-flight, STM, …*), Structural Verification Cycle
6. Design of Structures (*material, processes, assembles, joints, allowable stress/load, …*)
7. Damage Tolerance (*hardware inspection, analytical verification, specific testing, …*)
8. Mechanical Analysis (*models, validation, static dynamic, acoustic, stability, thermo-elastic, micro-vibrations, sloshing, system, subsystem*) & Testing (*static, modal, sine, acoustic, random, thermal, micro-vibrations, pressures, …*)
9. Structural requirements flow down
10. Materials

Definition of Space Structures

- Set of mechanical components or assemblies designed to sustain loads or pressures, provide stiffness or stability or provide support or containment.
- Structures support spacecraft key components in desirable locations.
- Structures protect the spacecraft's components from dynamic environments during ground operations, launch, deployment and mission's operations.
- Structures vibrations must not interfere with launch vehicle's vibrations
- The materials must survive ground, launch and on-orbit environments. Also, if applicable it must de-orbit and demise.
- The structure must comply with the Space Debris requirements.

Function of a Spacecraft Structure

1. Provide Structural Integrity
    - Strength
    - Stability (buckling)
    - Stiffness
    - Damping
2. Provide Support to Equipment
3. I/F to launcher, internal I/Fs
4. Provide Alignment and Stability
    - Manufacturing and assembly tolerances
    - Thermo-elastic/moisture release deformations
    - Micro-vibration disturbances
5. Minimize debris creation when on orbit
6. After de-orbiting, ease break-up and demise-ability of the Spacecraft

Function of a Spacecraft Structure

- Structural integrity

- ❑ Strength
- ❑ Stability
- ❑ Stiffness
- ❑ Damping

Function of a Spacecraft Structure

Structural integrity

Two objectives:

- ❑ Mission success
- ❑ Safety

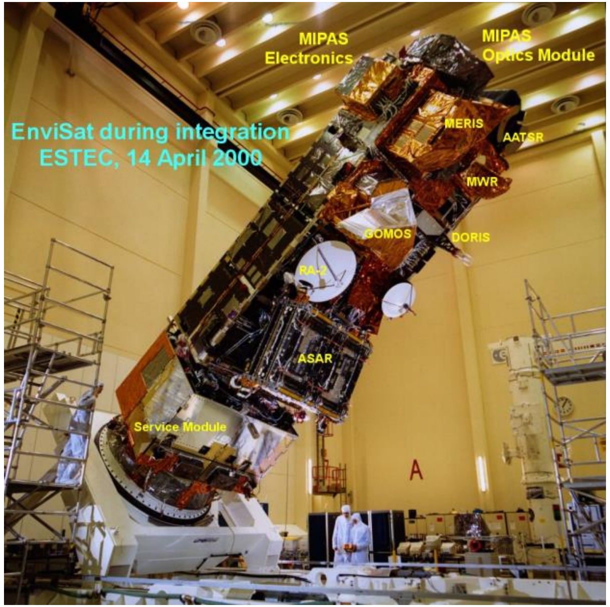
We want the S/C to work

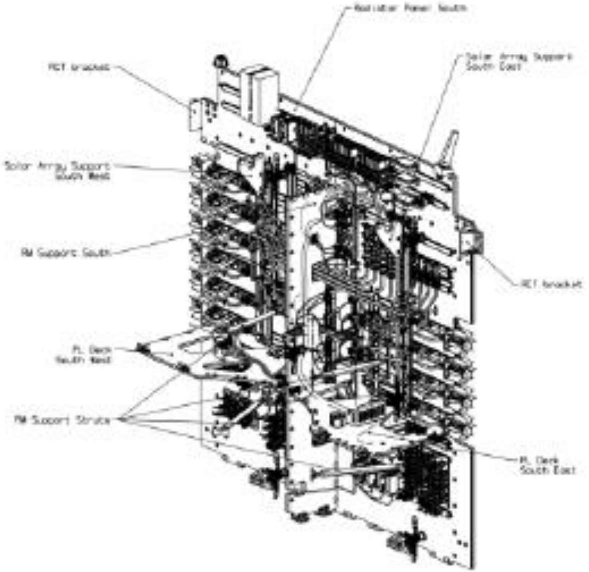
It's our responsibility

We do not harm people on ground and on orbit
We do not damage ground equipment and facilities
We do not damage other S/C or the launch vehicle

Function of a Spacecraft Structure

Support equipment



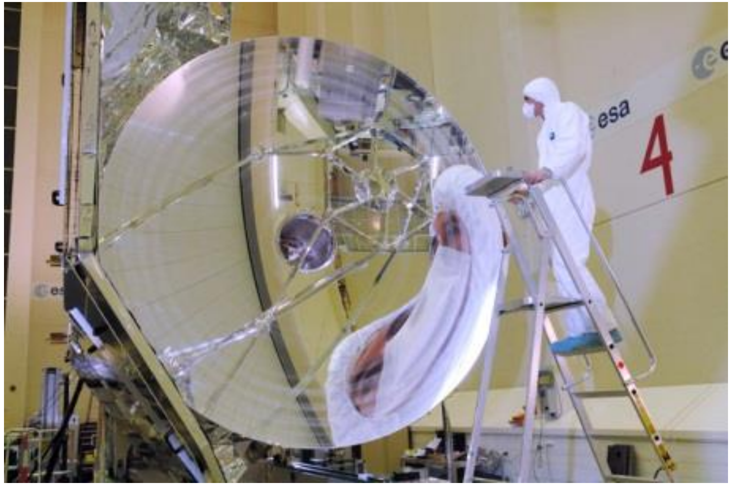


Function of a Spacecraft Structure

I/F to the launcher

Function of a Spacecraft Structure

Maintain alignment and stability



- ❑ Manufacturing and assembly tolerances
- ❑ Settlings
- ❑ Thermo-elastic/moisture release deformations
- ❑ Micro-vibration disturbances

Structural General Requirements

Hierarchy ECSS E-32 Standards

- ECSS-E-ST-32C — **Structural General Requirements**
  - ECSS-E-ST-32-01C — Fracture Control
  - ECSS-E-ST-32-02C — Structural Design and Verification of Pressurized Hardware
  - ECSS-E-ST-32-03C — Structural Finite Element Models
  - ECSS-E-ST-32-08C — Materials
  - ECSS-E-ST-32-10C — Structural Safety Factors
  - ECSS-E-ST-32-11C — Modal Survey Assessment

Structural General Requirements

- ECSS-E-ST-32C (Space engineering – Structural) defines the mechanical engineering requirements for structural engineering.
- This Standard specifies the requirements to be considered in all engineering aspects of structures: requirement definition and specification, design, development, verification, production, in service and eventual disposal.
- The Standard applies to all general structural subsystem aspects of space products including: launch vehicles, transfer vehicles, re-entry vehicles, spacecraft, landing probes and rovers, sounding rockets, payloads and instruments, and structural parts of all subsystems.
- This Standard may be tailored for the specific characteristics and constraints of a space project in conformance with ECSS-S-ST-00.

Structural General Requirements

Handbooks provide design and verification guidelines. The most relevant ECSS Handbooks related and supporting the E-32 standards are:

- ECSS-E-HB-32-21A, Adhesive Bonding Handbook
- ECSS-E-HB-32-24A, Buckling Handbook
- ECSS-E-HB-32-23A, Threaded Fasteners Handbook (*)
- ECSS-E-HB-32-22A, Insert Design Handbook
- ECSS-E-HB-32-26A, Loads Analysis Handbook (*)
- ECSS-E-HB-32-26A, Mechanical Shock Design and Verification Handbook
- ECSS-E-HB-32-20, Structural Materials Handbook
- ECSS-E-HB-32-20, Testing Guidelines (**)
- ESSB-HB-U-002, Space Debris Mitigation Guidelines

(*) Under revision

(**) In preparation

Structural General Requirements

- Terms, definition abbreviations
- Requirements

- Mission
- Functionality
- Interface
- Design
- Verification
- Production and manufacturing
- In-service
- Data-exchange
- Deliverables

Space engineering

Structural general requirements

ECSS-E-ST-32C Rev. 1
15 November 2008

Structural General Requirements

Space engineering

Structural general requirements

Mission

- Lifetime
- Natural and Induced Environment
- Mechanical environment
- Microgravity, audible noise and human induced vibration
- Load events
- Combined loads
- Limit Loads (Prob. 99%, CL 90%)
- Design Limit loads

Structural General Requirements

Mission - Environment

Manufacturing Assembly Storage

Ground Handling / Transportation Ground Test

Launch Orbit (Earth, Sun,…)

De-orbiting Fragmentation & Demise Re-entry

Structural General Requirements

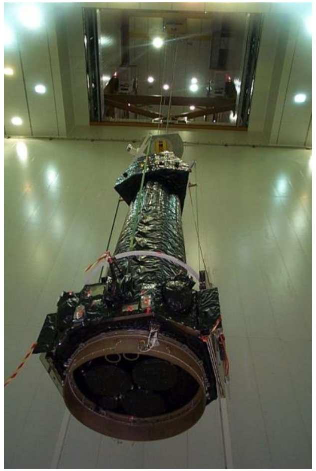
Mission – Environment – Ground

Ground environment

- Atmospheric conditions (contamination)
- Humidity (corrosion, deformations)
- Manufacturing processes (high temperatures, rapid cooling,…)

Loads

- Manufacturing/assembly (may induce also permanent stresses/deformations)
- Handling / Transportation
- Gravity



Structural General Requirements

Mission – Environment - Ground

Ground environment: test

- Non destructive inspections
- Mass, CoG, MoI measurement
- Functional
- Environmental tests
- Proof tests (static, pressure)

Tests may be the design condition for certain structural items

Structural General Requirements

Mission – Environment - Launch

Launch environment

- Rocket Motor Ignition Overpressure
- Lift-off
- Engine/Motor Generated Acoustic
- Engine/Motor Generated Structure-borne Vibration
- Engine/Motor Thrust Transients
- Pogo Instability, Solid Motor Pressure Oscillations
- Wind and Turbulence, Aerodynamic Sources
- Liquid Sloshing in Tanks
- Stage and Fairing Separation shocks
- Pyrotechnic Induced shocks
- De-pressurisation, Re-pressurization

Structural General Requirements

Mission – Environment - Launch

Launch environment

Usually inertial launch loads are classified according to their frequency content in:

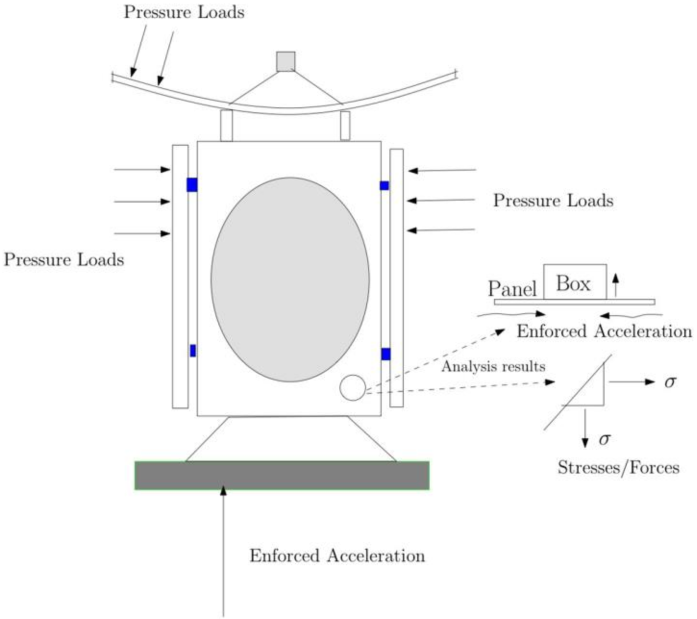
- Steady state accelerations
- Low frequency vibrations
- Broad band vibrations “Random vibrations”
- Acoustic loads
- Shocks

- Loads (vibrations) are transmitted to the payload (e.g. satellite) through its mechanical interface
- Acoustic loads also directly excite payload surfaces

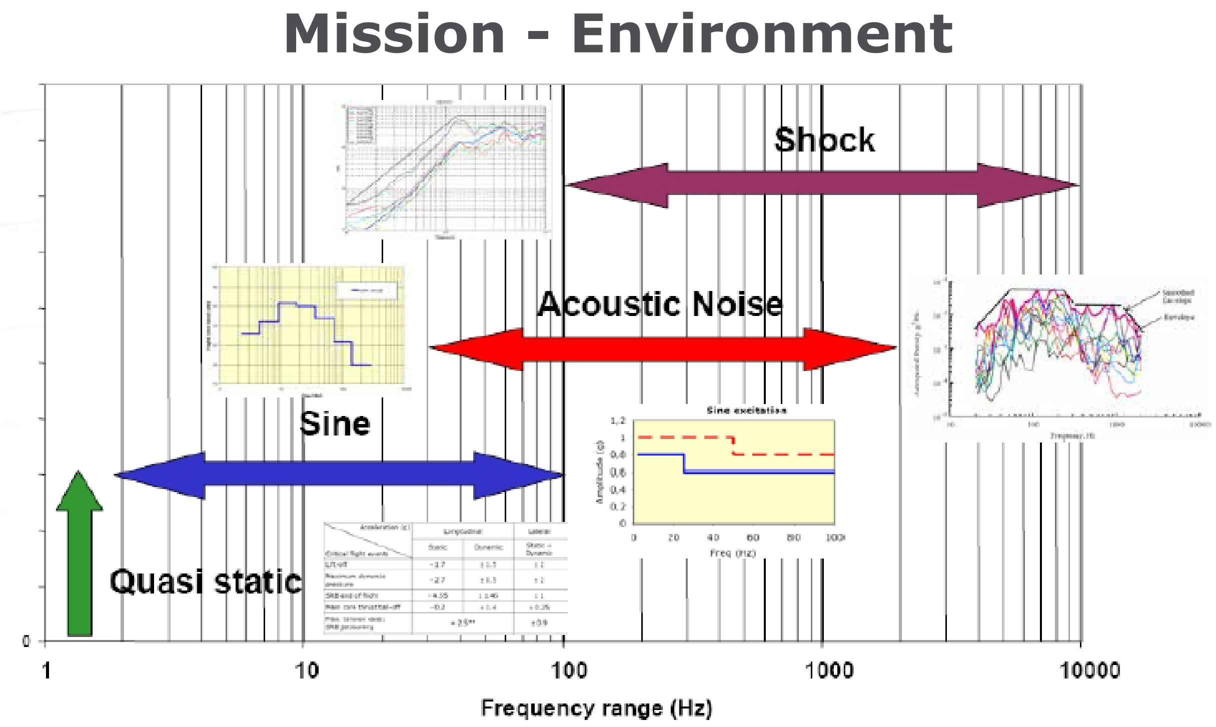
Structural General Requirements

Launch environment

Spacecraft loaded by pressure loads and enforced acceleration



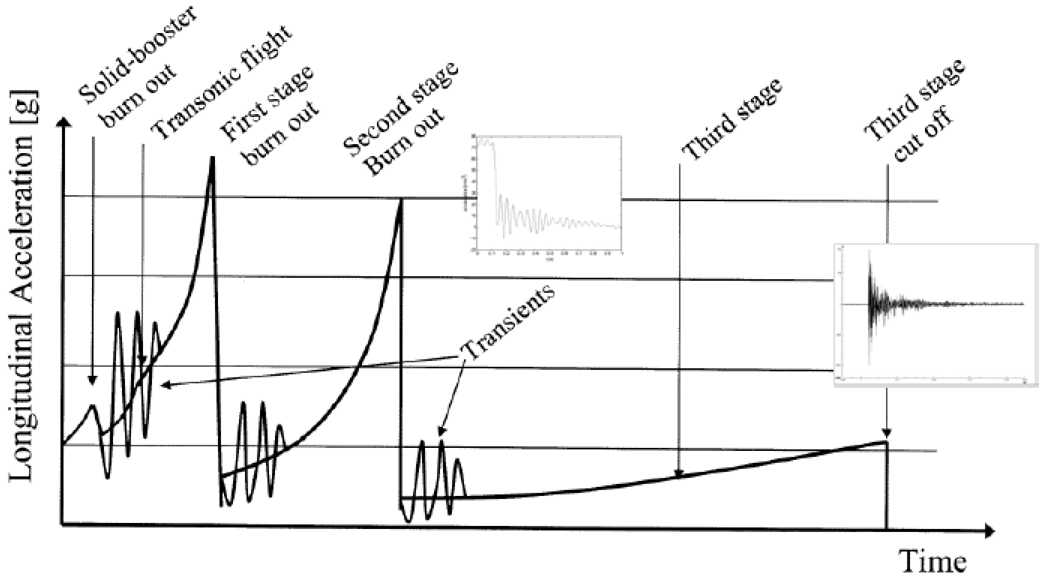
Structural General Requirements



Structural General Requirements

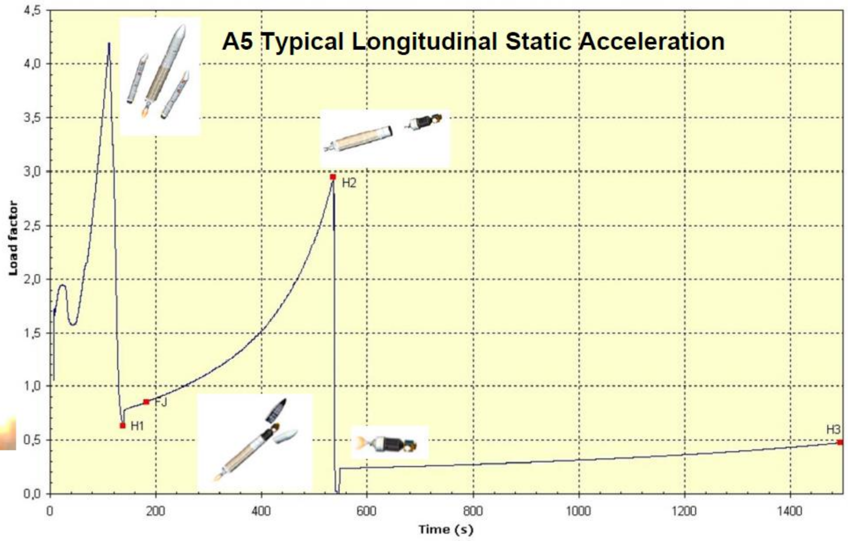
Mission – Environment - Launch

Launch loads: steady state and low frequency



Structural General Requirements

Mission – Environment - Launch



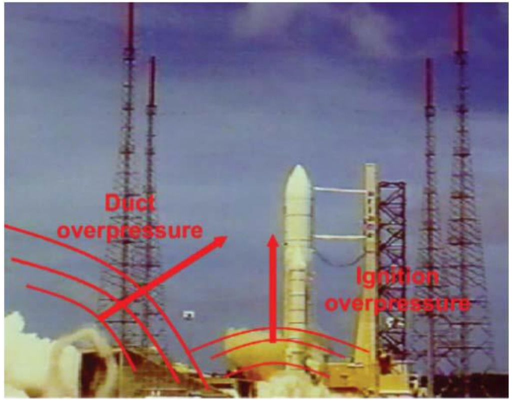
The axial acceleration on the launcher and the payload comes from the engines thrust. When the mass decreases due to consumption of the propellant, the acceleration increases.

Some launchers have a high static acceleration (more than 8g for Rockot).

Lateral accelerations come from wind gusts or changes in trajectory.

Structural General Requirements

Mission - Acoustic Environment - Launch



During the lift off and the early phases of the launch an extremely high level of acoustic noise surrounds the payload

The principal sources of noise are:
– **Engine functioning**
– **Aerodynamic turbulence**

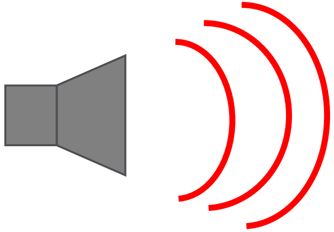
Acoustic noise (as pressure waves) impinging on light weight panel-like structures produce high response

Structural General Requirements

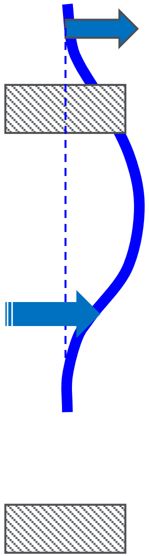
Mission – Environment - Launch

Acoustic loads:

Noise **Acoustic pressure varying with time**

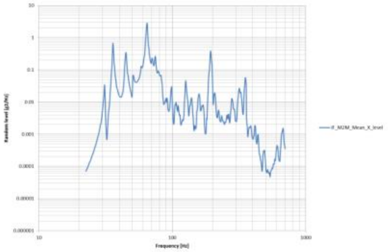


F = P x S



Loads acting on the structure

Dynamic / random response



Acoustic excitation ≈ random signal

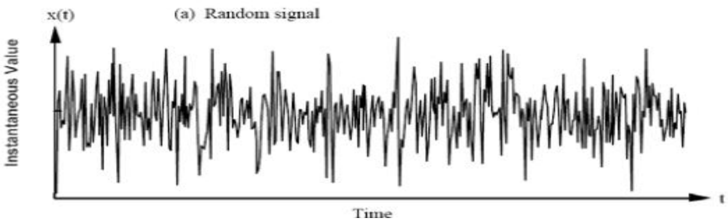
Structural General Requirements

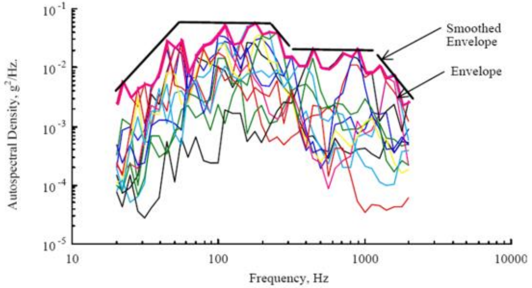
Mission – Environment - Launch

Launch loads: random vibration

The principal sources of random vibrations are:

- Engines functioning
- Structural response to broad-band acoustic loads
- Aerodynamic turbulent boundary layer





Structural General Requirements

Mission – Environment – Launch/On-orbit

Shocks

Mainly caused by the actuation of pyrotechnic devices:

- Release mechanisms for stage and satellite separation
- Deployable mechanisms for solar arrays etc.

Structural General Requirements

Mission – Environment – Launch/On-orbit

- Fairing jettisoning is still a sizing case for VEGA ➡ VESTA test

Release of clamp band holding the fairing ⇒ shock level not covered by SC separation

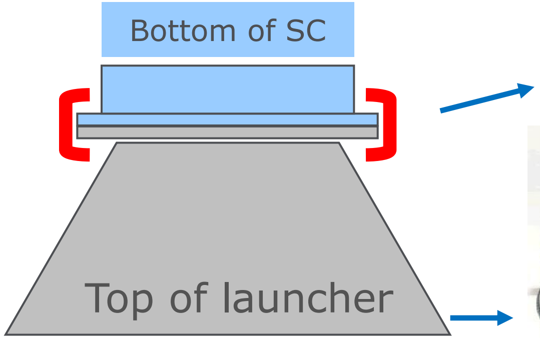
➡

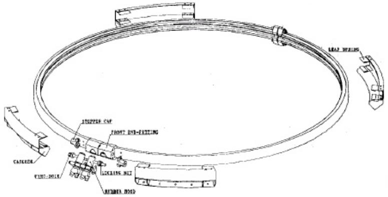
Specific test to reproduce the VEGA fairing separation shock.

Structural General Requirements

Mission – Environment – Launch/On-orbit

- Spacecraft separation shock:
- In most of the cases, the SC is attached to the launcher by a clamp band.

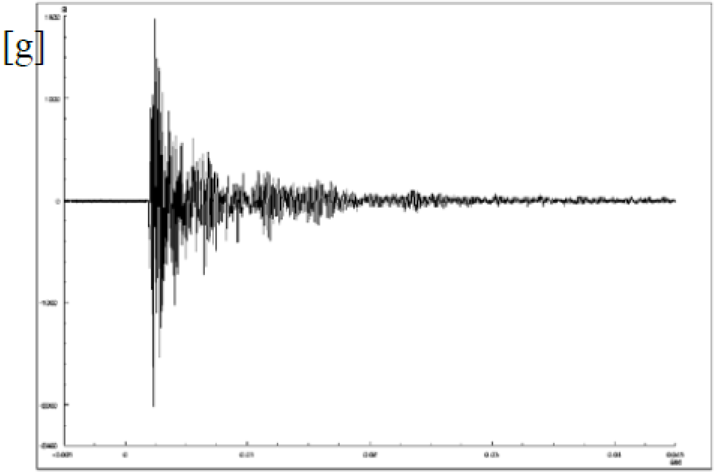


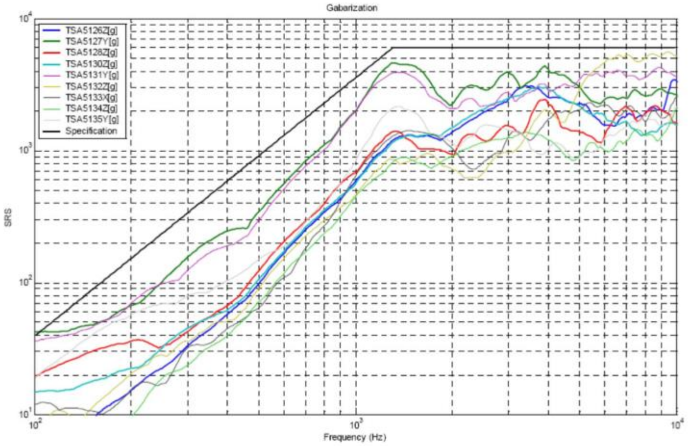


The shock is generated by the quick release of the clamp band and of the elastic energy stored in the system.

Structural General Requirements

Mission – Environment – Launch/On-orbit





Structural General Requirements

Mission – Environment – On-orbit

On-orbit environment

- (Almost) vacuum
- Residual oxygen
- Radiation
- Solar flux (including albedo)
- Micrometeorites and debris
- Thermal

Structural General Requirements

Mission – Environment – On-orbit

On-orbit loads:

- Thermo-elastic
- Manoeuvres
- Plume impingement
- Micro-vibrations
- Shocks
- Fragmentation & Demise

Structural General Requirements

Functionality

- Strength
- Local yielding
- Buckling
- Stiffness
- Dynamic behavior
- Thermal
- **Damage tolerance**
- Tolerances and Alignments
- Electrical conductivity
- Lighting protection
- Electro Magnetic Compatibility
- Dimensional Stability
- Demisability

Space engineering

Structural general requirements

Structural General Requirements

Interfaces

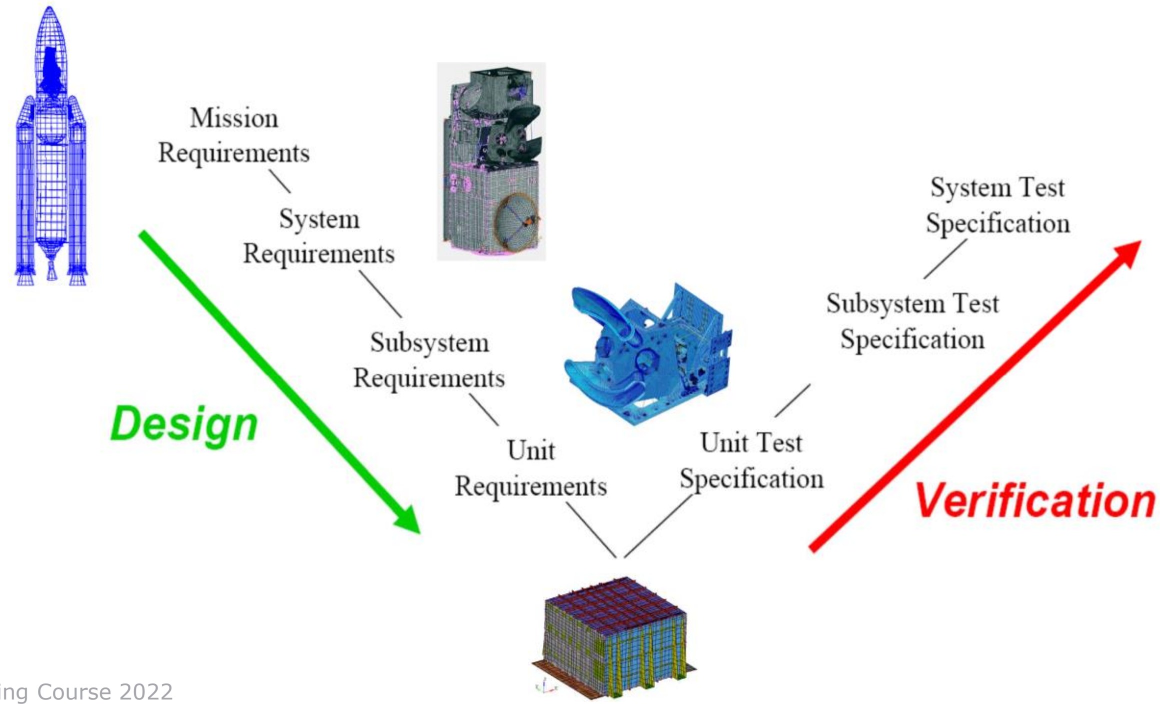
- Internal interfaces
  - Thermal control
  - Mechanisms
  - ECLS
  - Propulsion
  - Pyrotechnics
  - Mechanical parts
  - Materials
- External interfaces
  - Spacecraft-Launcher interface
  - Human factors and ergonomics
  - Interface with equipment, optics and avionics
  - Rendezvous and docking
  - Ground support equipment for pre-flight and post flight operations
  - Support equipment for in-orbit operations

Space engineering

Structural general requirements

Structural General Requirements

Design & Verification



Mechanical Requirements

Examples of (Mechanical) Requirements (1)

- The satellite shall be compatible with 2 launchers (potential candidates: VEGA, Soyuz in CSG, Rockot, Dnepr)...
- The satellite and all its units shall withstand applied loads due to the mechanical environments to which they are exposed during the service-life…
- Design Loads shall be derived by multiplication of the Limit Loads by a design factor equal to 1.25 (i.e. DL= 1.25 x LL)
- The structure shall withstand the worst design loads without failing or exhibiting permanent deformations.
- Buckling is not allowed.
- The natural frequencies of the structure shall be within adequate bandwidths to prevent dynamic coupling with major excitation frequencies…
- The spacecraft structure shall provide the mounting interface to the launch vehicle and comply with the launcher interface requirements.

Mechanical Requirements

Examples of (Mechanical) Requirements (2)

- All the Finite Element Models (FEM) prepared to support the mechanical verification activities at subsystem and satellite level shall be delivered in NASTRAN format
- The FEM of the spacecraft in its launch configuration shall be detailed enough to ensure an appropriate derivation and verification of the design loads and of the modal response of the various structural elements of the satellite up to 140 Hz
- A reduced FEM of the entire spacecraft correlated with the detailed FEM shall be delivered for the Launcher Coupled Loads Analysis (CLA)…
- The satellite FEMs shall be correlated against the results of modal survey tests carried out at complete spacecraft level, and at component level for units above 50 kg…
- The structural model of the satellite shall pass successfully qualification sine vibration Test.
- The flight satellite shall pass successfully acceptance sine vibration test.

Structural General Requirements

"Organizations" and "Levels of Assembly"… an example

• Launcher Authority	Spacecraft + launcher
• Spacecraft Authority (customer)	Spacecraft
• Spacecraft Prime Contractor	Spacecraft
• Payload Contractor	Instruments/sub-systems
• Other Contractors	Units/components/parts

Structural General Requirements

Design

- Inspectability
- Interchangeability
- Maintainability
- Dismountability
- Mass & Inertia properties
- Material selection
- Mechanical part selection
- Material design allowables
- Metals
- Non-metallic materials (Ceramics & Glass)
- Composite materials
- Adhesive materials in bonded joints
- Ablation and pyrolysis
- Micrometeoroid and debris collision
- Space Debris
- Venting
- Margins of Safety
- Factors of Safety
- Scatter factors

Structural General Requirements

Design

Design principles

Structure subsystem shall:

- Fulfill the mission objectives
- Ensure that no loss of alignment can jeopardize or degrade the mission objectives
- Be compatible with internal and external interfaces
- Withstand applied loads
- Be compatible with the natural and induced environments

Structural General Requirements

Design

Design principles

The structure of a spacecraft shall:

- Aim for simple load paths
- Maximise the use of conventional materials
- Minimise mass
- Simplify interfaces
- Providing easy integration
- Allow inspections
- Allow easy assembly, integration and repair
- Be verifiable

Structural General Requirements

Design

Classification: Primary structure

Part of the structure that carries the main flight loads and defines the overall stiffness

Structural General Requirements

Design

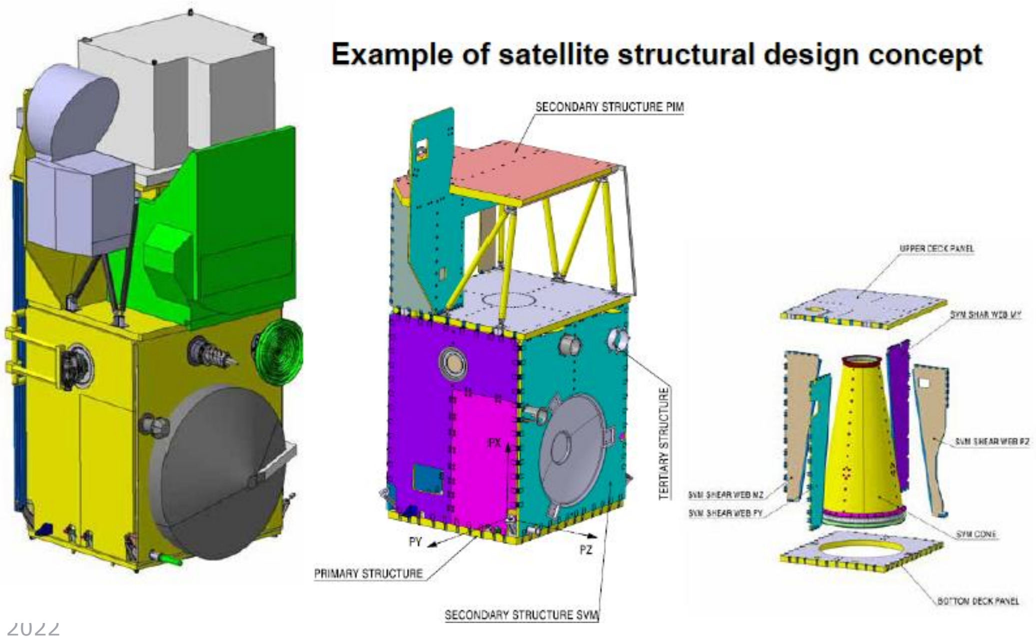
Classification: Secondary structure

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

Structural General Requirements

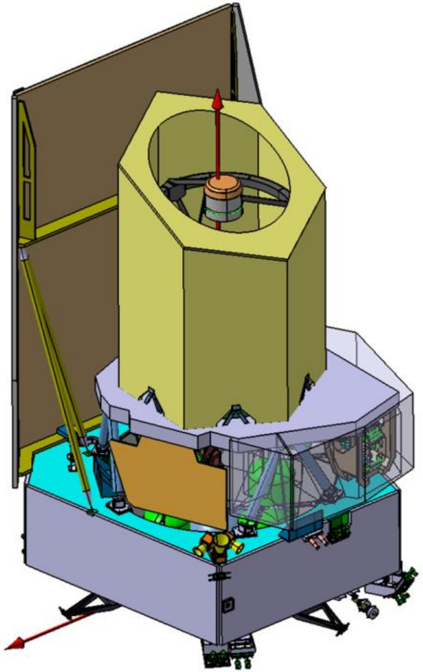
Design

Classification

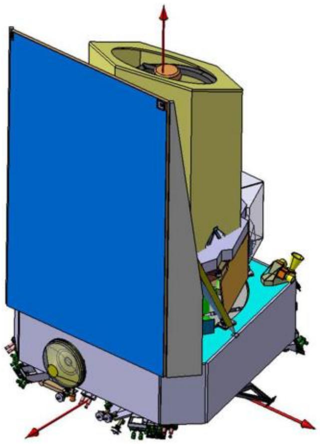


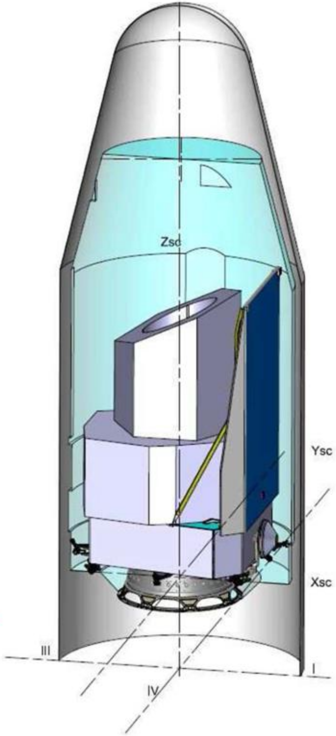
Structural General Requirements

Design



Euclid · Overall Configuration





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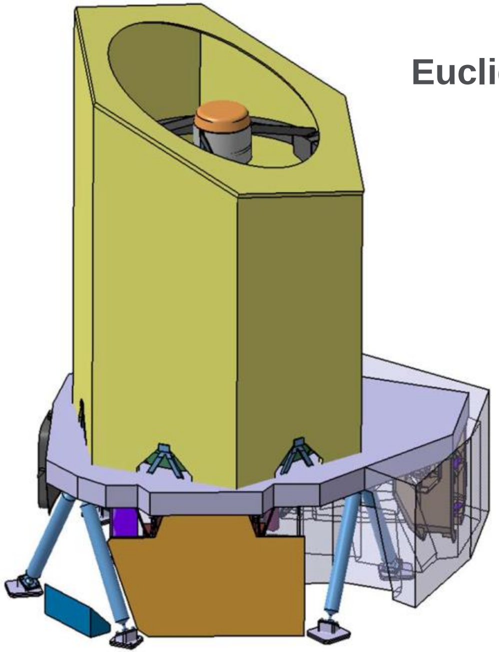
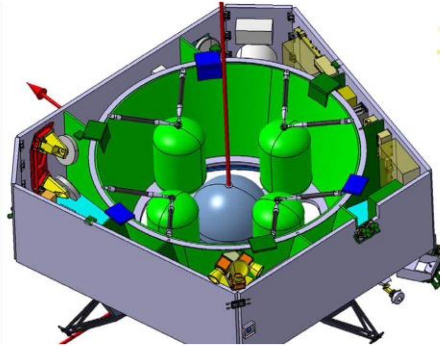
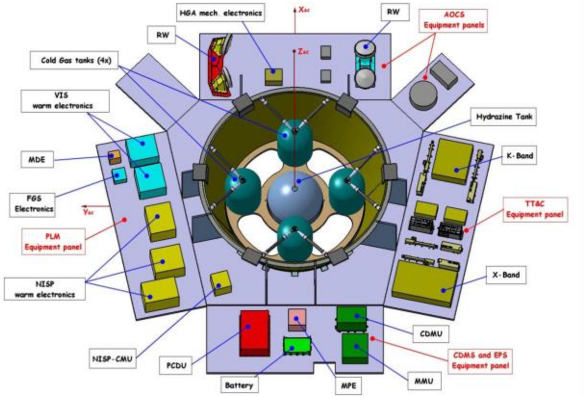
Structural General Requirements



Design

Euclid PLM & SVM

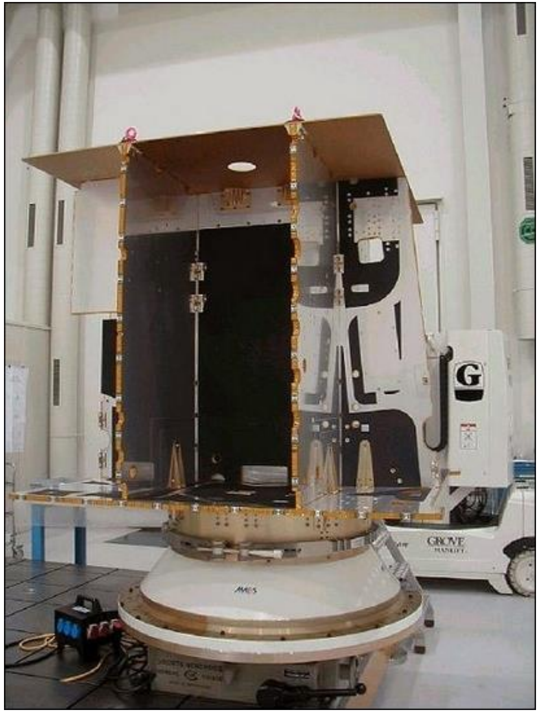




Structural General Requirements

Design

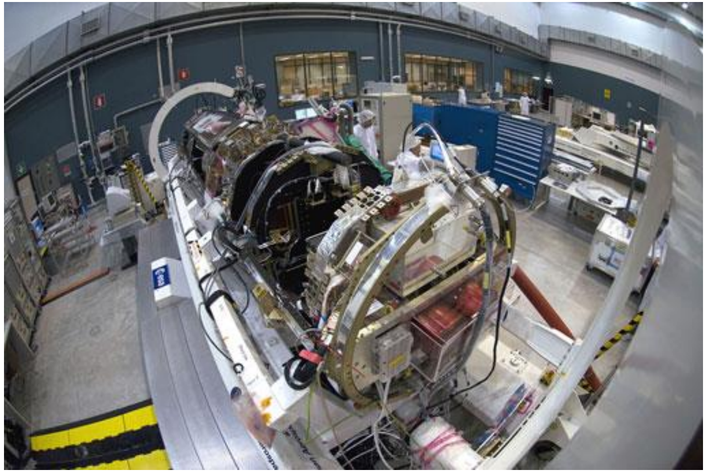
Typical architecture



Structural General Requirements

Design

Typical architecture



Structural General Requirements

Design

Materials

- Materials shall be compatible with all the encountered environmental conditions
- Material properties shall be well known (statistically derived)

Structural General Requirements

Design

Materials

Metallic alloys: aluminium, steel and titanium

- Easy to design metallic structures
- Well known properties / isotropic
- Easy to manufacture and assembly
- Good strength properties
- Cheap

Used for primary and secondary structures

Structural General Requirements

Design

Materials

Fibre reinforced materials: CFRP, GFRP

- Good strength/stiffness properties
- High strength to mass ratio
- High stiffness to mass ratio
- Good stability (low coefficient of thermal expansion)

Used for primary and sometimes secondary structures

Structural General Requirements

Design

Materials

Glass and ceramics

- Good stiffness properties
- Good stability (low coefficient of thermal expansion)

Used for optical benches

Allowable Loads or Stresses

Space engineering

Materials

ECSS-E-ST-32-08CRev.1
October 2014

- Metals
- Non-metallic materials
  - Glass & ceramics
  - Non Metallic materials other than Glass & Ceramics
- Composite Materials
- Adhesive materials in bonded joints

Design Allowable

- For structural material, design allowable shall be statistically derived covering all operational environments
- The scatter bands of the data shall be derived and design allowable defined in terms of fractions of their statistical distribution with A- basis or B- basis specified levels of reliability and confidence
- For each type of test the minimum number of test specimens shall be:
  - ten (10) to establish A- values, and
  - five (5) to establish B- values.
- If the material is delivered in several batches, the design allowable test program shall evaluate the variations from batch to batch by performing sample tests at regular intervals during the production sequence.

Definitions A- and B-Value

- A-basis design allowable (A-value)
  - mechanical property value above which at least 99 % of the population of values is expected to fall, with a confidence level of 95 %
- B-basis design allowable (B-value)
  - mechanical property value above which at least 90 % of the population of values is expected to fall, with a confidence level of 95 %

Metals

- All design allowable for metals shall be defined by their A-values.
- For unpressurized metal structures, B- values may be used in redundant structure in which the failure of a component can result in a safe redistribution of applied loads to other load–carrying structures.
- All other metal material properties shall be defined by average values.

Glass & Ceramics

- Design allowable for glass and ceramics shall be derived through a probabilistic approach, covering all size effects

Non-Metallics other than Glass & Ceramics

- Design allowable for other non- metals, (stress or strain) shall be defined by their A- values.
- For unpressurized non- metallic structures, B- values may be used in redundant structure in which the failure of a component can result in a safe redistribution of applied loads to other load–carrying structures
- The material properties other than those specified shall be defined by average values.

Composite Materials

- All design allowable for composite materials (stress or strain) shall be defined by their A- values.
- For unpressurized structures in composite materials, B-values may be used in redundant structure in which the failure of a component can result in a safe redistribution of applied loads to other load–carrying structures.
- All the material properties other than those specified shall be defined by their average values.

Adhesive Materials in Bonded Joints

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

Materials

Materials, ECSS-E-ST-32-08C Rev. 1, 15/10/2014

- ECSS-E-ST-32-08 defines the mechanical engineering requirements for materials. This Standard also encompasses the mechanical effects of the natural and induced environments to which materials used for space applications can be subjected.
- This Standard defines requirements for the establishment of the mechanical and physical properties of the materials to be used for space applications, and the verification of these requirements.
- Verification includes destructive and non-destructive test methods. Quality assurance requirements for materials (e.g. procurement and control) are covered by ECSS-Q-ST-70.
- This standard may be tailored for the specific characteristics and constrains of a space project in conformance with ECSS-S-ST-00.

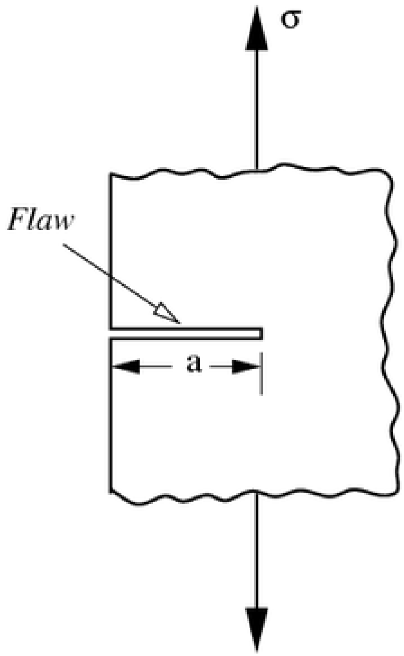
Structural Material Selection

Material	ρ (kg/m³)	E (GPa)	Fty (MPa)	E/ρ	Fty/ρ	α (µm/m K°)	κ (W/m K°)
Aluminum							
6061-T6	2800	68	276	24	98.6	23.6	167
7075-T651	2700	71	503	26	186.3	23.4	130
Magnesium							
AZ31B	1700	45	220	26	129.4	26	79
Titanium							
6Al-4V	4400	110	825	25	187.5	9	7.5
Beryllium							
S 65 A	2000	304	207	151	103.5	11.5	170
S R 200E	-	-	345	-	-	-	
Ferrous							
INVAR 36	8082	150	620	18.5	76.7	1.66	14
AM 350	7700	200	1034	26	134.3	11.9	40-60
304L annealed	7800	193	170	25	21.8	17.2	16
4130 steel	7833	200	1123	25	143	12.5	48
Heat resistant Non-magnetic							
A286	7944	200	585	25	73.6	16.4	12
Inconel 600	8414	206	206	24	24.5	-	-
Inconel 718	8220	203	1034	25	125.7	23.0	12

Damage Tolerance

- Damage tolerance capability of a structure to resist failure due to the presence of flaws, cracks, or other damage for a specified period of usage without inspection or repair.

- Characteristic of a structure for which the amount of general degradation or the size and distribution of local defects expected during operation, or both, do not lead to structural degradation below specified performance



Fault Tolerance

Fault tolerance is the property that enables a structure to continue operating properly in the event of the failure of (or one or more faults within) some of its components.

It is the ability of a structure to maintain functionality when portions of a system break down.

Fatigue & Fracture Control

Fracture control and fatigue life verification of spacecraft, launchers and their payloads and experiments is of paramount importance for the safety and reliability of manned and unmanned space operations.

ECSS-E-ST-32-01C Rev.1 6March 2009

Fatigue Analysis

- 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.
- Effects of stress concentrations shall be included in the analysis.
- The life of the structure shall be verified for the specified service life multiplied by the specified scatter factor considering the most unfavorable load sequence within each event.
- Design limit loads (multiplied by factors of safety specified by the customer for fatigue) shall be used for fatigue analysis.
- Alternate, permanent, and acoustic loads and their combination and sequence shall be used to perform the fatigue analysis.

Fracture Control

- For fracture control analysis requirements, see standard Fracture Control ECSS-E-ST-32-01C Rev. 1, 6/3/2009.

- Available Software
  - ESALOAD
  - ESACRACK
  - NASGRO

ESALOAD
User's Manual
Version 4.2.1a

ESACRACK
User's Manual
Version 4.3.0

NASGRO 6.x
User's Manual
Introduction to version distributed with ESACRACK

Structural General Requirements

Verification

- Verification by Analysis
- Verification by Test
- Verification by commonality

Space engineering

Structural general requirements

Structural General Requirements

Verification

Model philosophy:

- Prototype
  - Qualification model tested to levels higher than expected
  - Flight model tested for acceptance (quality screening)

- Proto-flight
  - The model tested at levels higher than expected (with some exception) is flown

  - STM (both prototype and proto-flight)

Structural General Requirements

Verification

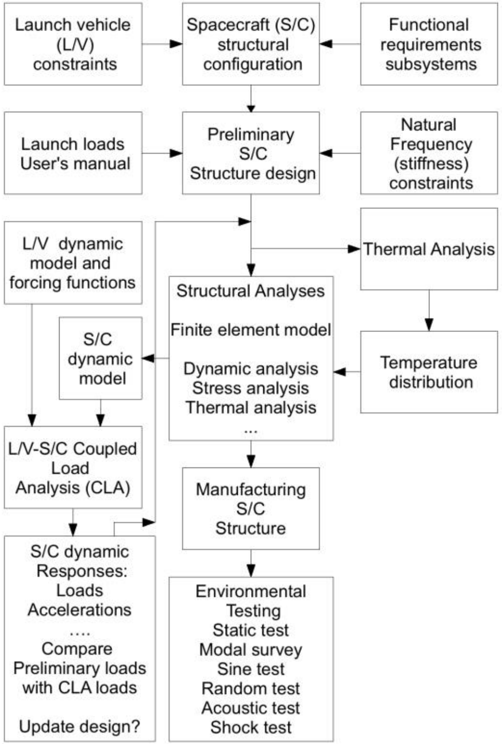
Verifiable low level requirements shall be flow down from high level requirements

the structure shall support the payload and spacecraft subsystems with enough strength and stiffness to preclude any failure (rupture, collapse, or detrimental deformation) that may keep them from working successfully

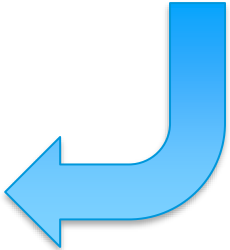
Margins of safety shall be higher than 0.0

Inserts strength properties shall be determined by test

Design & Verification



General introduction to Structural Design Verification cycle

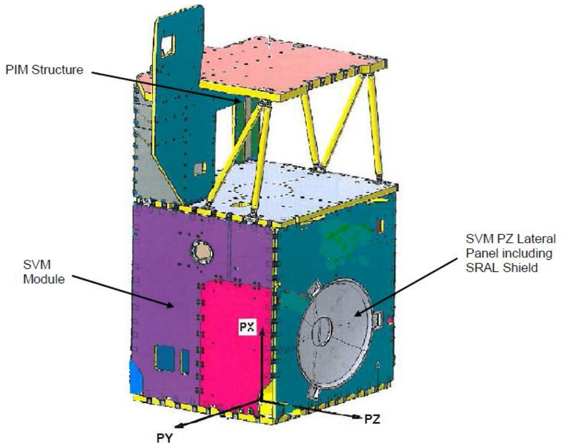


Agrawal, B.N. (1986) Design of Geosynchronous Spacecraft, Prentice Hall, ISBN 0-13-200114-4

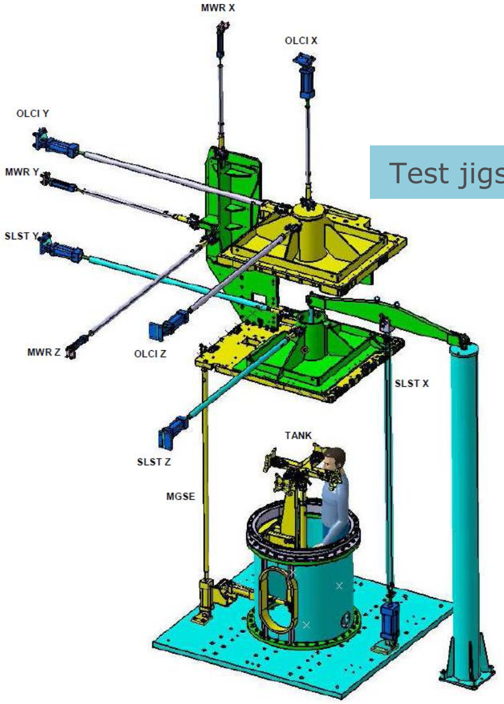
Mechanical testing on ground

- Example of static load test: Sentinel-3

Sentinel-3 primary structure



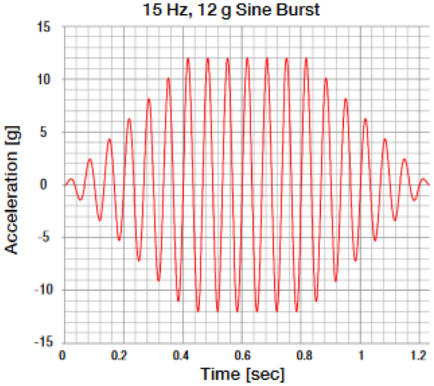
Test jigs and actuators



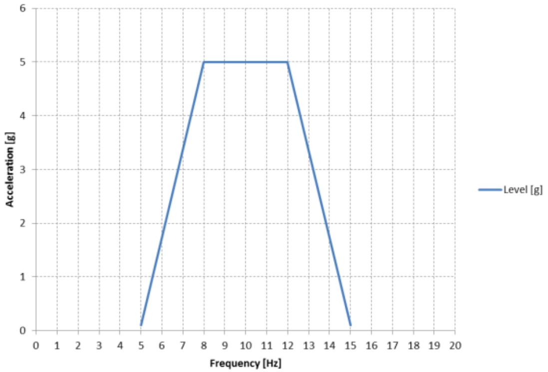
Mechanical testing on ground

- Qualification of main structure with respect to flight loads using a shaker:

Fixed frequency sine burst or dwell.

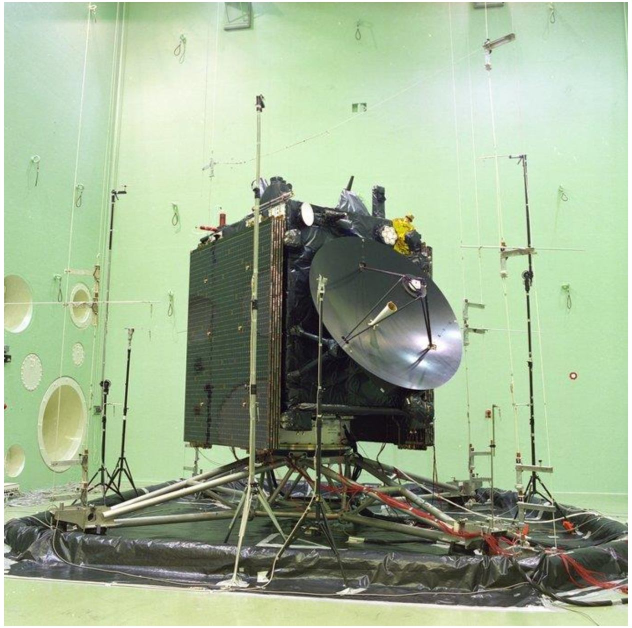


Low frequency sine sweep.



Acoustic Noise test

In a typical acoustic test, the test specimen is positioned in a reverberant acoustic chamber. The chamber is a large room with thick walls and a smooth interior surface that allows high reverberation



Rosetta in the ESTEC Large Acoustic Facility

Direct Field Acoustic Noise test

Design & Verification (Cont'd)

Remarks:

- CLA performed at least three times
  - Preliminary design cycle (PCLA). Phase B
  - Design cycle (DCLA). Phase C
  - Verification cycle (VCLA). Mathematical model test/analysis correlated. Phase D

- Shock test preferably performed on STM

Structural General Requirements

Final Verification consists of:

- **Making sure all requirements are satisfied ("compliance")**
- **Validating the methods and assumptions used to satisfy requirements**
- **Assessing risks**

Structural General Requirements

Criteria for Assessing Verification Loads (strength)

- Analysis: margins of safety must me greater that or equal to zero
- Test: Structures qualified by static or sinusoidal testing
  - Test loads or stresses "as predicted" (test-verified math model and test conditions) are compared with the total predicted loads during the mission (including flying transients, acoustics, random vibration, pressure, thermal effects and preloads).
- Test: Structures qualified by acoustic or random vibration testing
  - Test environments are compared with random-vibration environments derived from system-level acoustic testing.

Structural General Requirements

Final Verification (crucial points)

$$MOS = \frac{design\ allowable\ load}{design\ limit\ load \times FOS} - 1$$

- **To perform a Verification Loads Cycle for structures designed and tested to predicted loads**
  - **Finite element models correlation with the results of modal and static tests**
  - **Loads prediction with the current forcing functions**
  - **Compliance with analysis criteria (e.g. MOS>0)**

- **To make sure the random-vibration environments used to qualify components were high enough (based on data collected during the spacecraft acoustic test)**

- Note: in the verification loads cycle instead of identifying required design changes (design loads cycle) the adequacy of the structure that has already been built and tested is assessed

Structural General Requirements

Main inconsistencies of the loads verification process - 1

- Uni-axial vibration and shock test facilities while the dynamic environments for space vehicle hardware are typically multiple-axis. In practice, tests are performed axis by axis.
- Tests are performed environment by environment, even if they occur simultaneously. For this reason loads superposition techniques are applied and the verification of the structural integrity by analysis is normally required to prove the qualification of the spaceflight hardware.
- Low frequency transient often simulated at the subsystem and system assembly level using a swept-sine vibration test, mainly because of its simplicity in specification and testing.

Structural General Requirements

Main inconsistencies of the loads verification process - 2

- Infinite mechanical impedance of the shaker and the standard practice of specifying the input acceleration as envelope of the flight interface acceleration (despite the amplitude drop in the flight configuration). This is the major cause of over testing in aerospace vibration tests.
- Vibro-acoustic environment often simulated at the subsystem and units assembly level using a random vibration test.
- Test levels largely based on computational analyses. For this reason it is important to validate critical load analyses.

Structural General Requirements

Production and Manufacturing

- Manufacturing process
- Manufacturing drawings
- Tooling
- Assembly
- Storage
- Cleanliness
- Health and Safety

Space engineering

Structural general requirements

Structural General Requirements

In-Service

- Ground inspection
- In-orbit inspection
- Evaluation of damages
- Maintenance
- Repair

Space engineering

Structural general requirements

List of questions covering major concepts

- Design vs Verification. Differences in cost and duration.
- Diffeences between prototype and proto-flight approaches.
- Differences between damage tolerance and fault tolerance.
- List major mechanical tests during spcecraft development.
- Functions and types of a spacecraft structure.
- Typical materials used to build a spacecraft structure. Which materail to use if very high stability is required?
- What is flow down of requirements?
- What is tailoring?

Conclusions

- The slides presented provide a quick summary of the design and verification of space structures and the interrelation of the two activities with the related ECSS standards and handbooks.

- THANKS A LOT FOR YOUR ATTENTION!!

List of acronyms

STM	Short-Term Mission	Slide 4
I/F	Interface	Slide 6
S/C	Spacecraft	Slide 8
CL	Confidence Level	Slide 16
CoG	Centre of Gravity	Slide 19
MoI	Moment of Inertia	Slide 19
FEM	Finite Element Models	Slide 39
CLA	Coupled Loads Analysis	Slide 39
PLM	Payload Module	Slide 48
SVM	Service Module (Platform)	Slide 48
CFRP	Carbon Fiber Reinforced Plastic	Slide 53
GFRP	Glass-Fiber Reinforced Plastic	Slide 53
PCLA	Preliminary Design Cycle	Slide 77
DCLA	Design Cycle	Slide 77
VCLA	Verification Cycle	Slide 77
FOS	Factor of Safety	Slide 80
MOS	Margin of Safety	Slide 80

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