esa

Space engineering

ECSS E-32 “Structures”

J.J. Wijker

EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

European Space Agency

Objectives of the Course

To get insight in the spacecraft structural design, analysis and verification process related to ECSS standards, handbooks and other literature (books & papers).

Overview of Sub-Course E-32 Structures

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

Bibliography

- **ECSS E-32 Standards**
  - Structural General Requirements ECSS-E-ST-32C Rev. 1, 15/11/2008
  - Fracture Control ECSS-E-ST-32-01C Rev. 1, 6/3/2009
  - Structural Design and Verification of Pressurized Hardware, ECSS-E-ST-32-02C Rev. 1, 15/11/2008
  - Structural Finite Element Models, ECSS-E-ST-32-03C, 31/7/2008
  - Materials, ECSS-E-ST-32-08C Rev. 1, 21/7/2008
  - Structural Factors of Safety for Spaceflight Hardware, ECSS-E-ST-32-10C Rev. 1, 6/3/2009
  - Modal Survey Assessment, ECSS-E-ST-32-11C Rev. 1, 21/7/2008

  - Verification, ECSS-E-ST-10-02C, 6/3/2009
  - Testing, ECSS-E-10-03A, 15/2/2002 (superseded)
  - Testing, ECSS-E-ST-10-03C, Draft 12.5, 4/3/2011 (in review)

Related ECSS E-32 Standards

- Space Product Assurance, Data for selection of space materials and processes ECSS-Q-70-71A, Rev 1, 18 June 2004
- Space Product Assurance, Materials, mechanical parts and processes ECSS-Q-ST-70C, 6 March 2009
- Space Product Assurance, Material selection for controlling stress-corrosion cracking, ECSS-Q-ST-70-36C, 6 March 2009
- Space Product Assurance, Safety, ECSS-Q-ST-70-40C, 6 March 2009
- Space Product Assurance, Standard methods for mechanical testing of metallic materials ECSS-Q-ST-70-45C, Rev 1

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

Bibliography (Cont'd)

- **Handbooks**
  - Adhesive Bonding Handbook, ECSS-E-HB-32-21A, 20/3/2011
  - Insert Design Handbook, ECSS-E-HB-32-22A, 20/3/2011
  - Threaded Fasteners Handbook, ECSS-E-HB-32-23A, 10/4/2010
  - Buckling of Structures, ECSS-E-HB-32-24A, 24/3/2010
  - Spacecraft Load Analysis, ECSS-E-HB-32-26, TBD issue date
  - Structural Acoustics Design Manual, ESA PSS-03-204, March 1996
  - Mechanical Shock Design and verification Handbook, ESA Contract No 20503/06/NL/Sfe, 15/9/2011 (will be issued as ECSS Handbook)

Bibliography (Cont'd)

- **(ESA) Launch Vehicle User's Manuals**
  - VEGA User's manual, Issue 3, rev. 0, Arianespace, March 2006
  - Soyuz (from Guiana Space Centre) User's manual, Issue 1, rev. 0, Arianespace, June 2006
  - ARIANE 5 User's manual, Issue 5, rev. 1, Arianespace, July 2011
  - Rockot User's Guide, EHB0003, Issue 5, Revision 0, August 2011, EUROCKOT
  - Atlas Launch System Mission Planner's Guide, Revision 10, 2007, Lockheed-Martin
  - …

Bibliography (Cont'd)

- **Textbooks**

  - T.P. Sarafin, Spacecraft Structures and Mechanisms, From Concept to Launch, (1995), Space Technology Series, ISBN 0-7923-3476-0
  - Agrawal, B.N. (1986) Design of Geosynchronous Spacecraft, Prentice Hall, ISBN 0-13-200114-4
  - J.J. Wijker, Mechanical Vibrations in Spacecraft Design, (2004) Springer, ISBN 3-540-40530-5
  - J.J. Wijker, Spacecraft Structures, (2008) Springer, ISBN 978-3-540-75552-4
  - J.J. Wijker, Random Vibrations in Spacecraft Structures Design, (2009) Springer, ISBN 978-90-481-2727-6
  - D.S. Steinberg, Vibration Analysis for Electronic Equipment, third edition, (2000), John Wiley, ISBN 0-171-37685-x
  - R.D. Cook. D.S. Malkus, M.E. Plesha, Concepts and Applications of Finite Element Analysis, (1989), John Wiley, ISBN0-471-84788-7
  - T.H.G. Megson, Aircraft Structures for Engineering Students, third edition, (1999), Butterworth Heinemann, ISBN 0-340-70588-4
  - Gere, J.M., Timoshenko, S.P., Mechanics of materials, third edition, Chapman & Hall, 0-412-36880-3
  - …

Definition of Structures

- 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, on-orbit environments.

Scope

- 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, inservice and eventual disposal.
- The Standard applies to all general structural subsystem aspects of space products including: launch vehicles, transfer vehicles, reentry 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 ECSS-E-ST-32C, Rev. 1, TOC

- Terms, definition abbreviations
- Requirements
  - Mission
  - Functionality
  - Interface
  - Design
  - Verification
  - Production and manufacturing
  - In-service
  - Data-exchange
  - Deliverables

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

Space engineering

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

Space engineering

Structural general requirements

Interfaces (E-32)

- 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

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
- Venting
- Margins of Safety
- Factors of Safety
- Scatter factors

Space engineering

Structural general requirements

Verification

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

Space engineering

Structural general requirements

Production and manufacturing

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

Space engineering

Structural general requirements

In-Service

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

Space engineering

Structural general requirements

Data Exchange

- System configuration data
- Data exchange between design and structural analysis
- Data exchange between structural design and manufacturing
- Data exchange with other subsystems
- Tests and structural analysis
- Structural mathematical models
- Data traceability

Space engineering

Structural general requirements

Deliverables (Normative)

- Computer aided design model description and delivery (CADMDD)-DRD
- Design Loads (DL)-DRD
- Dimensional Stability Analysis (DSA)s-DRD
- Fatigue Analysis (FA)-DRD
- Fracture Control Analysis (FSA)-DRD
- Fracture Control Plan-DRD
- Fracture Control Items Lists (PFCIL, FCIL, FLLIL)-DRD
- Materials and Mechanical Part Allowables (MMPA)-DRD
- Mathematical Model Description and Delivery (MMDD)-DRD
- Modal and Dynamic Response Analysis (MDRA)-DRD
- Stress and Strength Analysis (SSA)-DRD
- Structural Alignment Budget (SAB)
- Structure Buckling (SB)-DRD
- Structure Mass Summary (SMS)-DRD
- Test-Analysis Correlation (TAC)-DRD
- Test Evaluation (TE)-DRD
- Test Predictions (TP)-DRD

Space engineering

Structural general requirements

E-32 Discipline Documents Delivery per Review

Document Title	Phase												DRD Ref.
	0	A		B	C	D			E				
	MDR	PRR	SRR	PDR	CDR	QR	AR	ORR	FRR	LRR	CRR	ELR	
Computer aided design model description and delivery				X	X								ECSS-E-ST-32, Annex A
Design loads			X	X	X	X							ECSS-E-ST-32, Annex B
Dimensional stability analysis				X	X	X							ECSS-E-ST-32, Annex C
Fatigue analysis					X	X							ECSS-E-ST-32, Annex D
Fracture control analysis					X	X							ECSS-E-ST-32, Annex E
Fracture control plan				X	X								ECSS-E-ST-32, Annex F
Fracture control items lists				X	X	X							ECSS-E-ST-32, Annex G

Space engineering

Structural general requirements

E-32 Discipline Documents Delivery per Review (Cont'd)

Document Title	Phase												DRD Ref.
	0	A		B	C	D			E				
	MDR	PRR	SRR	PDR	CDR	QR	AR	ORR	FRR	LRR	CRR	ELR	
Material and mechanical part allowables				X	X								ECSS-E-ST-32, Annex H
Mathematical model description and delivery				X	X	X							ECSS-E-ST-32, Annex I
Modal and dynamic response analysis				X	X	X							ECSS-E-ST-32, Annex J
Stress and strength analysis				X	X	X							ECSS-E-ST-32, Annex K
Structure alignment budget				X	X	X							ECSS-E-ST-32, Annex L
Structure buckling				X	X	X							ECSS-E-ST-32, Annex M
Structure mass summary			X	X	X	X							ECSS-E-ST-32, Annex N
Test-analysis correlation						X	X						ECSS-E-ST-32, Annex O
Test evaluation						X	X						ECSS-E-ST-32, Annex P
Test prediction					X	X							ECSS-E-ST-32, Annex Q

Overview of Sub-Course E-32 Structures

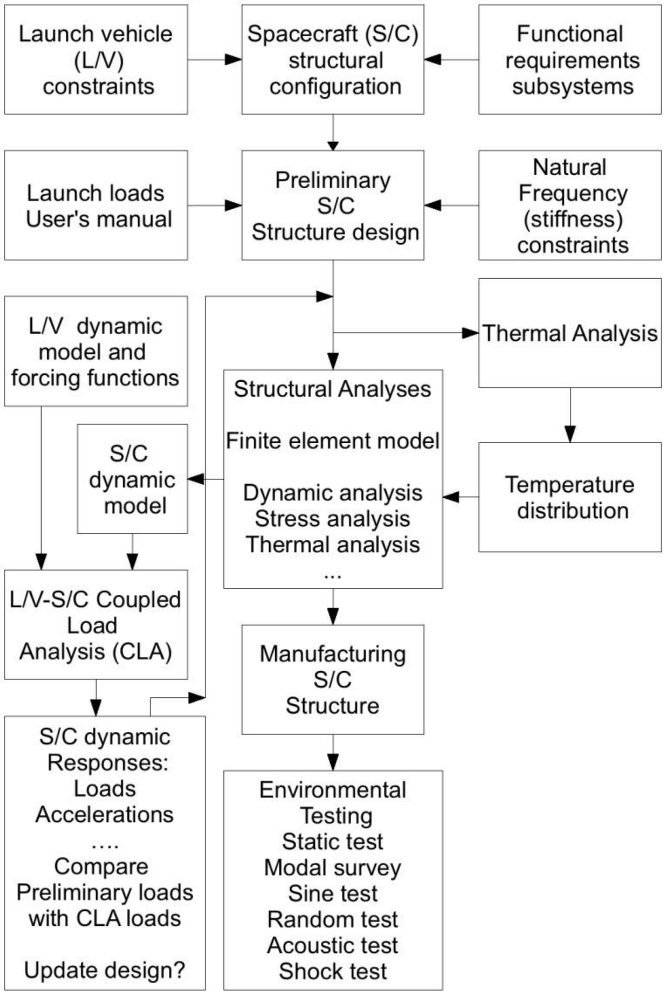
1. **General introduction to Structural Verification Cycle**
2. Load types and derivation (*steady state, low frequency dynamics, high frequency acoustics and structure born vibrations, shock, thermal, constraints, micro-vibrations, …*)
3. Development Approach (*prototype, proto-flight, STM, …*)
4. Design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

General Introduction Structural Verification Cycle

- Design
- Manufacturing
- Test

European Space Agency

Design & Verification



General introduction to Structural Design Verification cycle

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

Design & Verification (Cont'd)

Remarks:

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

- Shock test only performed on STM

Overview of Sub-Course E-32 Structures

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

Space engineering

Structural general requirements

Loads

Ground, Launch, on Orbit and Descent (re-entry & landing)

Load Events

- Relevant mechanical and thermal loads expected through the service life of the structure is to be identified
- Loads are to be defined according to their nature (i.e. static or dynamic) and their level, occurrence time and duration
- ECSS-E-ST-32C
    - Ground loads
    - Test Loads
    - Launch Loads
    - In-Orbit Loads
    - Re-entry, descent and Landing

Load Events (Cont'd)

Ground Loads

- Handling Loads
- Transportation Loads
- Storage Loads
- Assembly & Integration Loads

Ground Test Loads

- Static
- Shaker test
- Acoustic Test
- Shock Test

Launch Loads

- Launch preparation
- Operational pressures
- Engines ignition
- Thrust built-up
- Aborted Launch
- Lift-off
- Thrust
- Aerodynamic Loads
- Heat flux
- Wind & gust
- Dynamic interaction L/V and Engines (POGO)
- Thrust decay
- Maneuvers
- Pyrotechnics
- Depressurization

Load Events (Cont'd)

Ground In-orbit loads

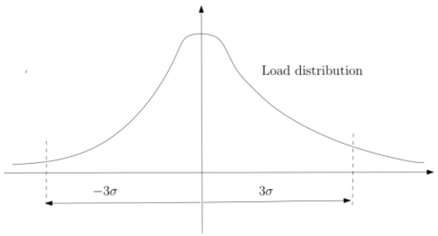
- Operational pressures
- Static and dynamic loads induced by thrusters
- Shocks (pyrotechnics, deployment)
- Thermo-elastic loads
- Hygroscopic-induced loads
- Micro-vibrations
- Micrometeoroids & Debris
- Docking
- Berthing
- Crew induced loads

Re-entry, descent and Landing

- Aerodynamic Loads
- Thermal fluxes
- Parachute ejection and deployment shocks
- Operation pressures
- Land loads
- Impact Loads

Spacecraft Environmental Load Conditions Mechanical Environment(e.g. ARIANE 5)

esa



- Probability loads will be exceeded is 1% (90% CL, Rockot)
- Overall Loads
  - Static Acceleration (steady-state)
    - Launch direction <=4.55g
    - Lateral direction <=0.25g
  - Static pressure under the fairing (on ground, in flight (depressurization)
  - Sine-equivalent dynamics (derived from SRS)
  - Random vibration (covered by sine and acoustics at system level)
  - Acoustic vibration (lift-off, aerodynamics)
  - Shocks
    - Spacecraft separation
    - Fairing jettison
    - Upper stage separation (cryogenic stage)
  - Thermal environment

Stiffness Requirements

- Dynamic decoupling spacecraft from launch vehicle

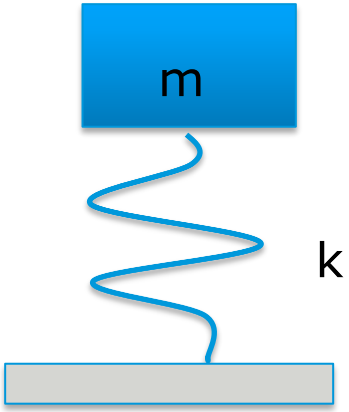
Stiffness Requirements A5 User's Manual

Lateral frequencies

The fundamental (primary) frequency in the lateral axis of a spacecraft cantilevered at the interface must be as follows (provided that a off the self adapter will be used for flight):

S/C mass (kg)	Launcher interface diameter (mm)	1st fundamental lateral frequency (Hz)	Transverse inertia wrt separation plane (kg.m²)
< 4500	< ⌀2624	≥ 10	≤ 50,000
	⌀2624	≥ 9	
4500 ≤ M M ≤ 6500	≤ ⌀2624	≥ 8	≤ 90,000
M > 6500	⌀2624	≥ 7.5	≤ 535,000
	< ⌀2624	TBD	TBD

No secondary mode should be lower than the first primary mode.



$$f = \frac{1}{2p}\sqrt{\frac{k}{m}}\,(\mathrm{Hz})$$

Longitudinal frequencies

The fundamental frequency in the longitudinal axis of a spacecraft cantilevered at the interface must be as follows (provided that an off-the-self adapter will be used for flight):

≥ 31 Hz for S/C mass < 4500 kg
≥ 27 Hz for S/C mass ≥ 4500 kg

No secondary mode should be lower than the first primary mode.

Quasi-Static Loads

- Loads independent of time or which vary slowly, so that the dynamic response of the structure is not significant (Definition ECSS-E-ST-32C)
- Combination of static and dynamic loads into an equivalent static load specified for design purposes
  - Note 1: quasi static loads are equivalent to (or interpreted by the designer as) static loads, typically expressed as equivalent accelerations at the C.o.G
  - Note 2: In some contexts the quasi static loads are understood as "Loads associated to a quasi static event" (LV/SC CLA terminology)
- Quasi Static Event: Event generated by external forces which change slowly with time so that the dynamic response of the structure is not significant (Definitions ECSS-32-HDB-26, draft)

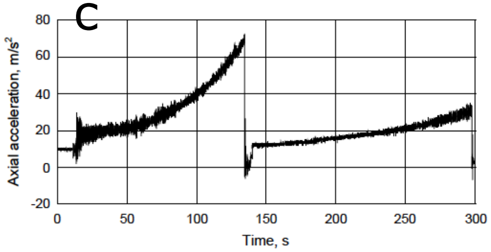
- Typical definition: Combination of steady-sate-acceleration plus low frequency dynamic (transient or pressure oscillations) response

Quasi-Static Loads (A5 User's manual)

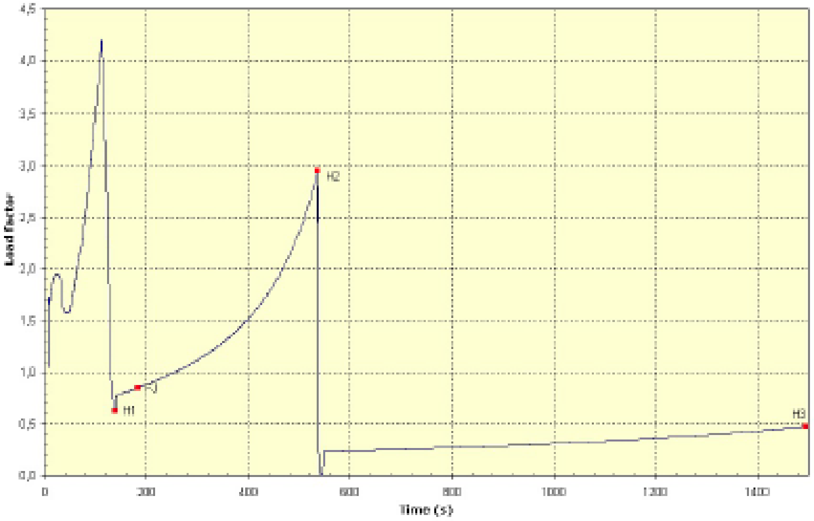
Acceleration (g) / Critical flight events	Longitudinal		Lateral	Additional line load (N/mm)
	Static	Dynamic	Static + Dynamic	
Lift-off	- 1.8	± 1.5	± 2	26
Aerodynamic phase	- 2.7	± 0.5	± 2	23
Pressure oscillations / SRB end of flight	- 4.40	± 1.6	± 1	37
SRB jettisoning *	-0.7	± 3.2	± 0.9	0

* This flight phase leads to a 2.5 g tension case, except for a spacecraft with first longitudinal frequency above 40 Hz where the tension value is the following:

Rockot QSL+dynamic



Flight Limit Loads



A5 Longitudinal

European Space Agency

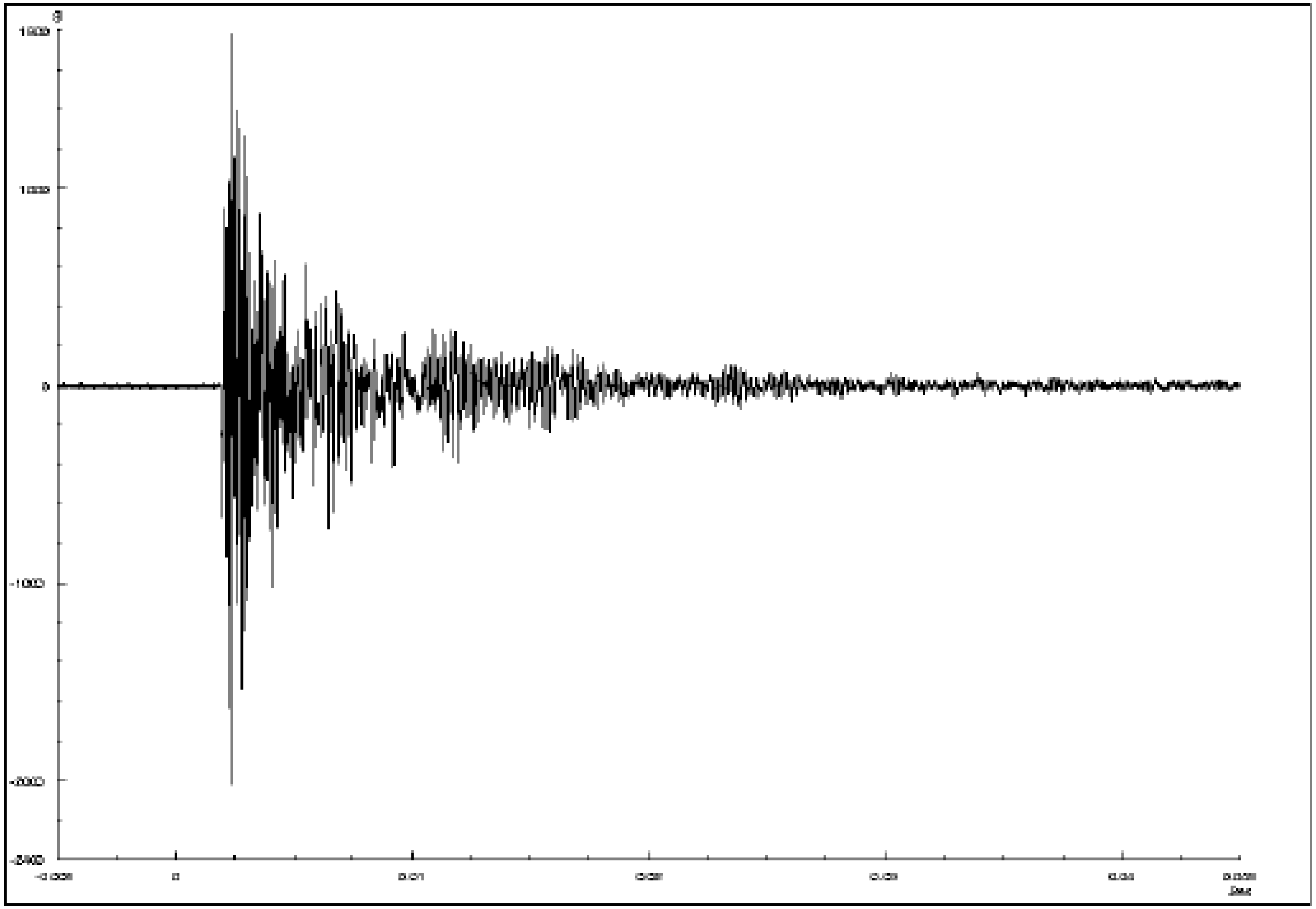
High Frequency Transients, Shocks

- Staging
- Jettison of fairing
- Separation spacecraft from Launch vehicle
  - Clamp band
  - Bolted connection
- Release appendices (Solar array wing, antenna dishes, …)

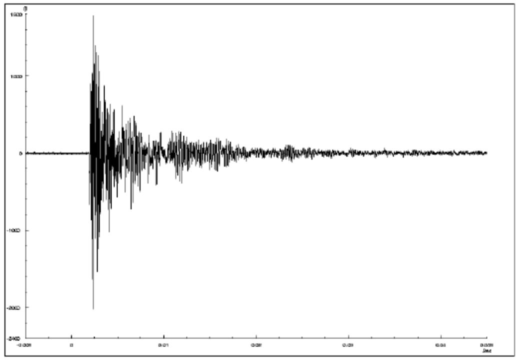
Mechanical Shock Design and Verification Handbook

ESA-Contract No 20503/06/NL/SFe
ESA study manager: S. KIRYENKO, ESA/ESTEC, Noordwijk

High Frequency Transients

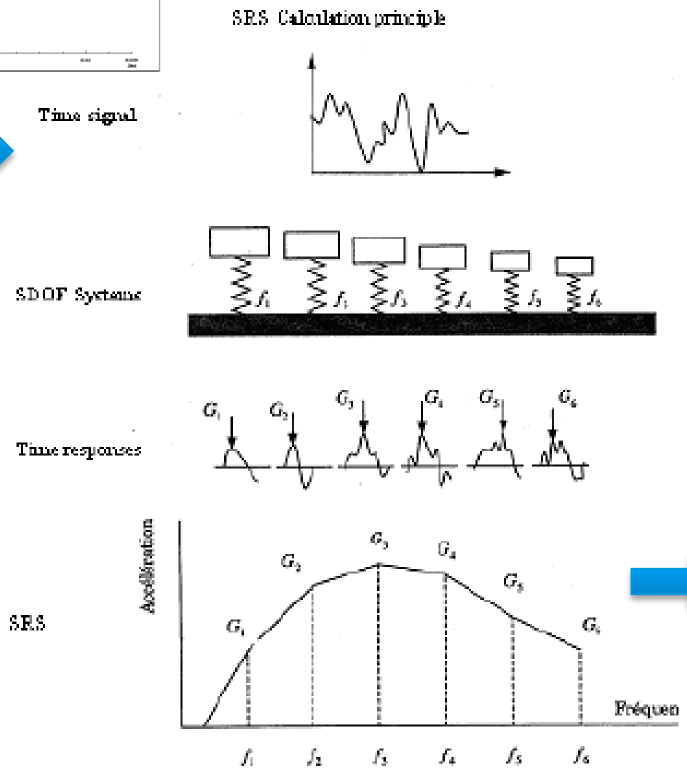


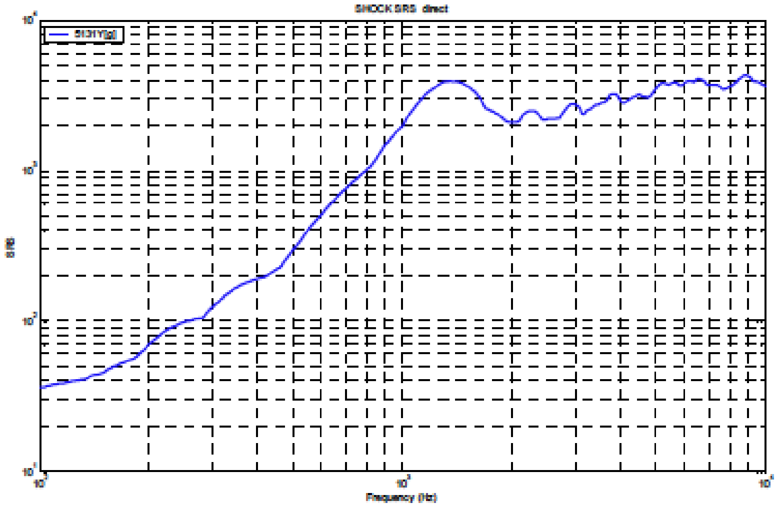
Shock Response Spectrum (SRS)



Mechanical Shock Design and Verification Handbook

ESA-Contract No 20503/06/NL/SFe
ESA study manager: S. KIRYENKO, ESA/ESTEC, Noordwijk





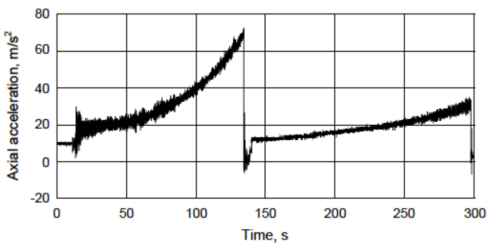
Sine Vibration Loads

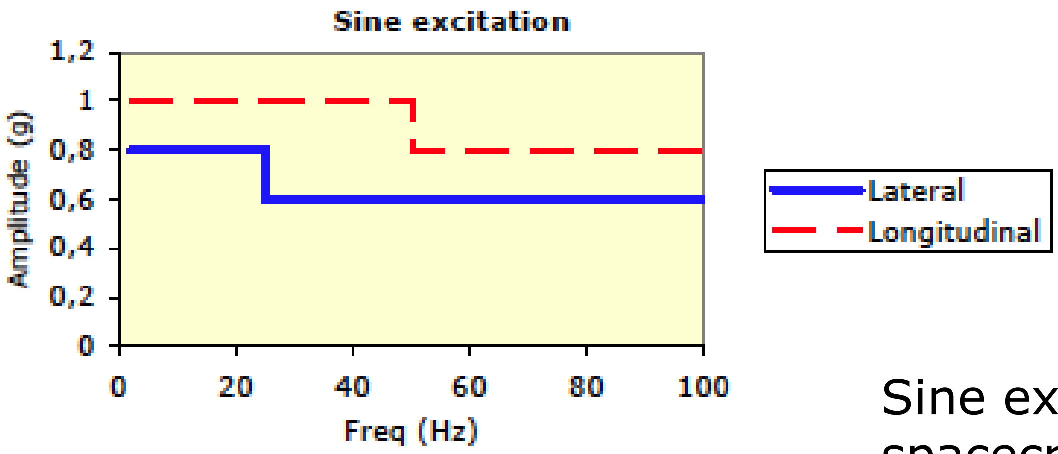
- Powered Atmospheric flight
- Staging

Sine Equivalent Dynamics (A5 User's manual)

Direction	Frequency band (Hz)	Sine amplitude (g)
Longitudinal	2 – 50	1.0
	50 - 100	0.8
Lateral	2 – 25	0.8
	25 – 100	0.6

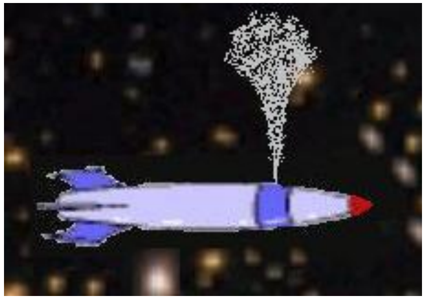
Rockot QSL+dynamic

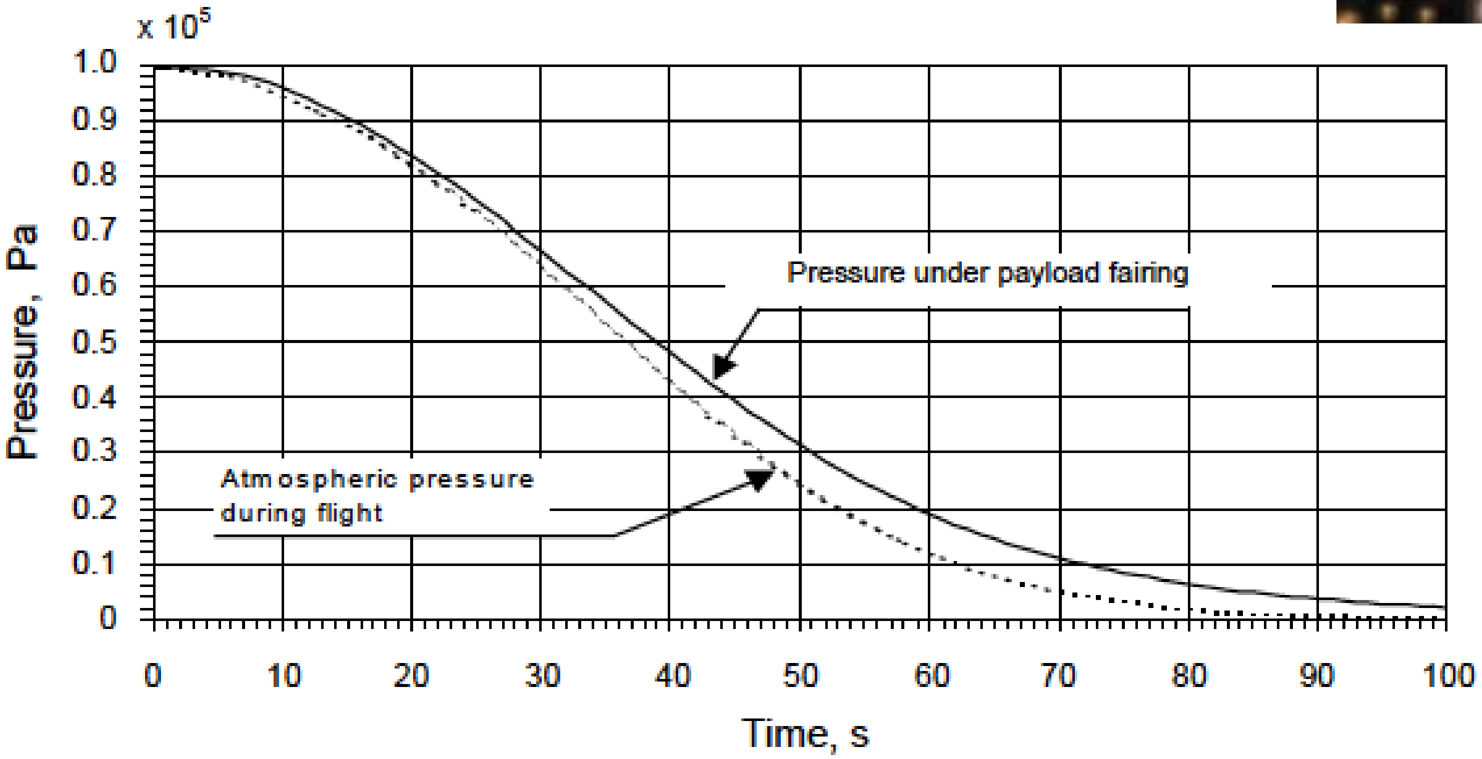




Sine excitation at spacecraft base (Limit Loads)

Depressurization under the fairing (Venting)





Venting

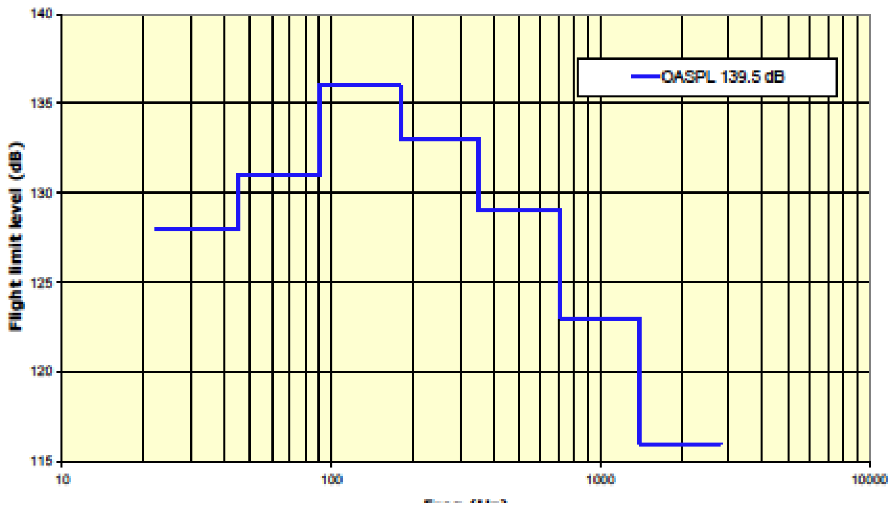
- Provision shall be made in the design of the structure for venting in order to prevent a build- up of excess pressure and to reduce the time to evacuate the structure, a minimum ratio of venting- area to enclosed- volume is usually needed for venting.
- In case that provision is not made, the structure shall withstand buildup pressure (including safety factors).
- The openings for venting shall be compatible with the purging system gas supply pressure and flow rate.

- Examples
  - Create Venting holes in closed structures
  - Perforated honeycomb in sandwich structures

Acoustic Loads (Noise)

- Lift-Off, Atmospheric Flight
- One-third, Octave bands
- Sound Pressure Levels
  - dB
  - OASPL

Octave center frequency (Hz)	Flight limit level (dB) (reference: 0 dB = 2 x 10^{-5} Pa)
31.5	128
63	131
125	136
250	133
500	129
1000	123
2000	116
OASPL (20 – 2828 Hz)	139.5

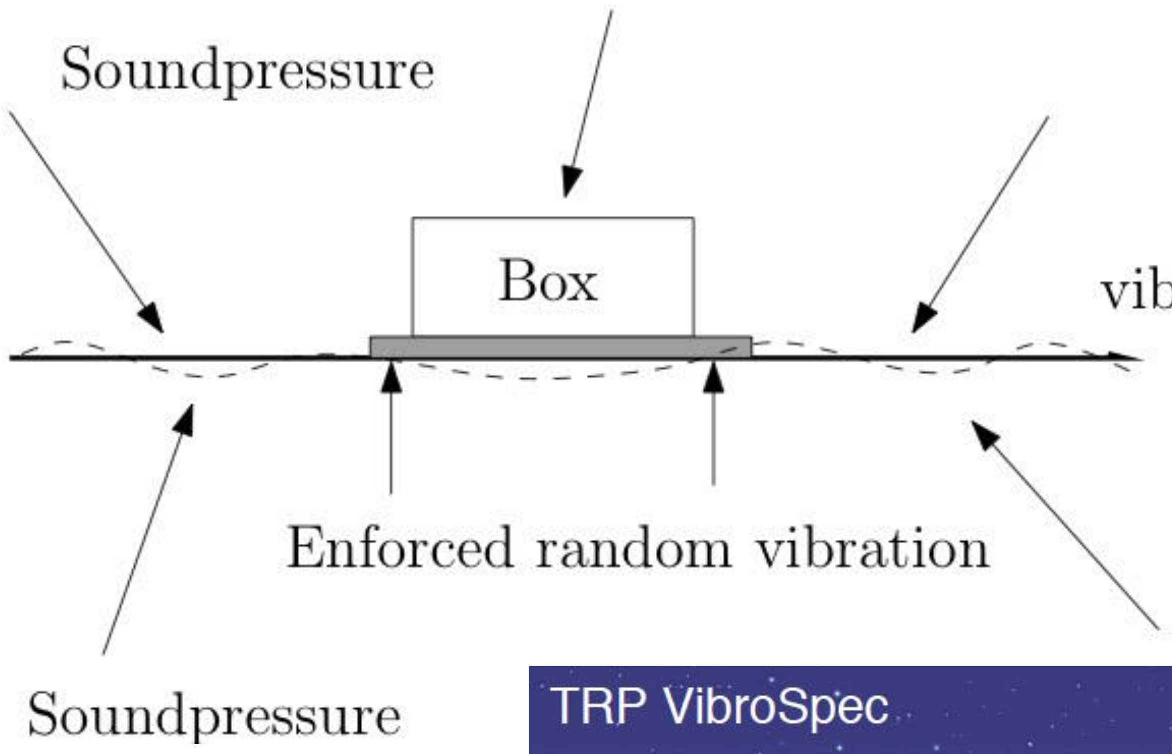


Acoustic noise spectrum(SPL) under the fairing (A5 User's manual)

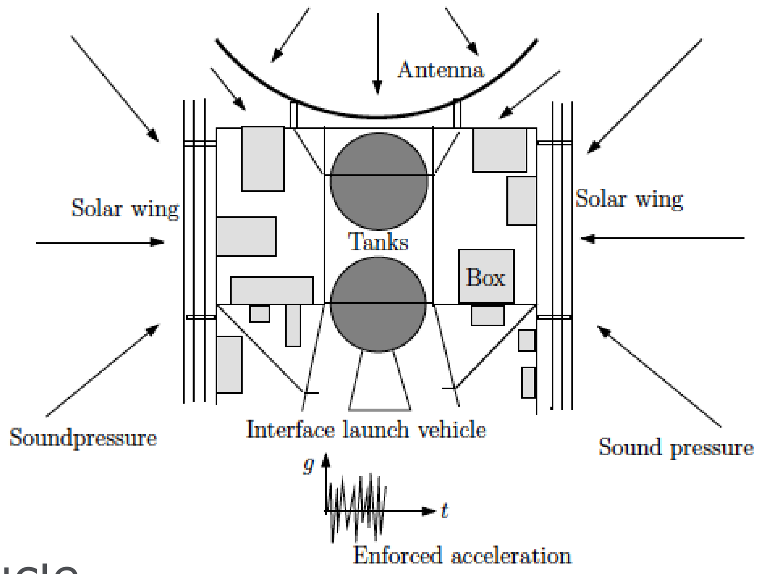
$$SPL(f) = 10 \log \left(\frac{p_{rms}^2(f)}{p_{ref}^2} \right) (dB) \qquad p_{rms}^2(f) = p_{ref}^2 10^{\frac{SPL(f)}{10}} \left(Pa^2 \right)$$

$$W_p(f) = \frac{p_{rms}^2(f)}{\Delta f} \left(\frac{Pa^2}{Hz} \right)$$

Structure Born Random Vibrations



Random Vibration



- Structure born
- Via interface spacecraft/Launch Vehicle

Definition: vibration 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.

Random Vibration via interface Spacecraft/Launch Vehicle (Soyuz)

Event	Frequency Band (Hz)						G_{RMS} (g)	Duration of application (s)
	20 – 50	50-100	100-200	200-500	500-1000	1000-2000		
	PSD, Power Spectral Density(1) (g^2/Hz)							
1st stage flight	0.0050	0.0050 0.0100	0.0100 0.0250	0.0250	0.0250 0.0100	0.0100 0.0050	4.94	120
2nd stage and 3rd stage flight	0.0025	0.0025 0.0050	0.0050 0.0100	0.0100	0.0100 0.0050	0.0050 0.0025	3.31	480
FREGAT flight	0,0020	0,0020	0,0020	0,0020	0,0020 0,0010	0,0010	1,63	875

Maximum flight levels of random vibration at spacecraft base

$$\ddot{X}_{rms} = \sqrt{\int_0^{f_{max}} W_{\ddot{x}}(f)\,df}$$

Structure Born Random Vibrations (Cont'd)

esa

Space engineering

ECSS-E-10-03A

15 February 2002

Testing

Location	Duration	Levels	
Equipment located on "external panel [a] or with unknown location	Vertical [b] 2,5 min/axis	(20 – 100) Hz	+3 dB/octave
		(100 – 300) Hz	PSD(M) [c] = 0,12 g^2/Hz × (M + 20 kg)/(M + 1 kg)
		(300 – 2 000) Hz	–5 dB/octave
	Lateral [b] 2,5 min/axis	(20 – 100) Hz	+3 dB/octave
		(100 – 300) Hz	PSD(M) [c] = 0,05 g^2/Hz × (M + 20 kg)/(M + 1 kg)
		(300 – 2 000) Hz	–5 dB/octave
Equipment not located on "external" panel [a]	All axes 2,5 min/axis	(20 – 100) Hz	+3 dB/octave
		(100 – 300) Hz	PSD(M) [c] = 0,05 g^2/Hz × (M + 20 kg)/(M + 1 kg)
		(300 – 2 000) Hz	–5 dB/octave

a Panel directly excited by payload acoustic environment.

b Equipment vertical axis = perpendicular to fixation plane.
Equipment lateral axis = parallel to fixation plane.

c M = equipment mass in kg, PSD = Power Spectral Density in g^2/Hz.

Example random vibration specification

Space engineering

ECSS-E-HB-32-26
TBD Issue Date

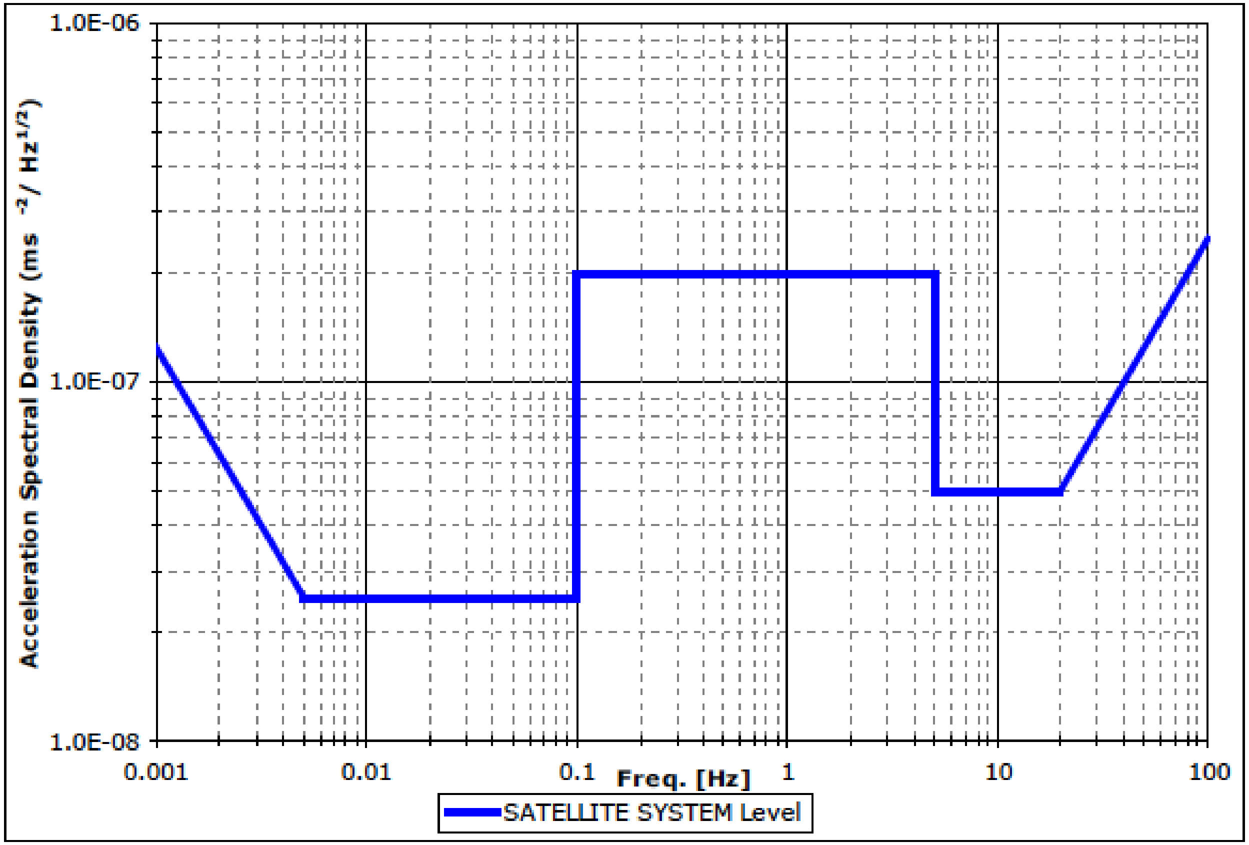
Spacecraft loads analysis

Micro-Vibrations

- International Space Station
- GOCE

European Space Agency

GOCE Micro-Vibration Requirement

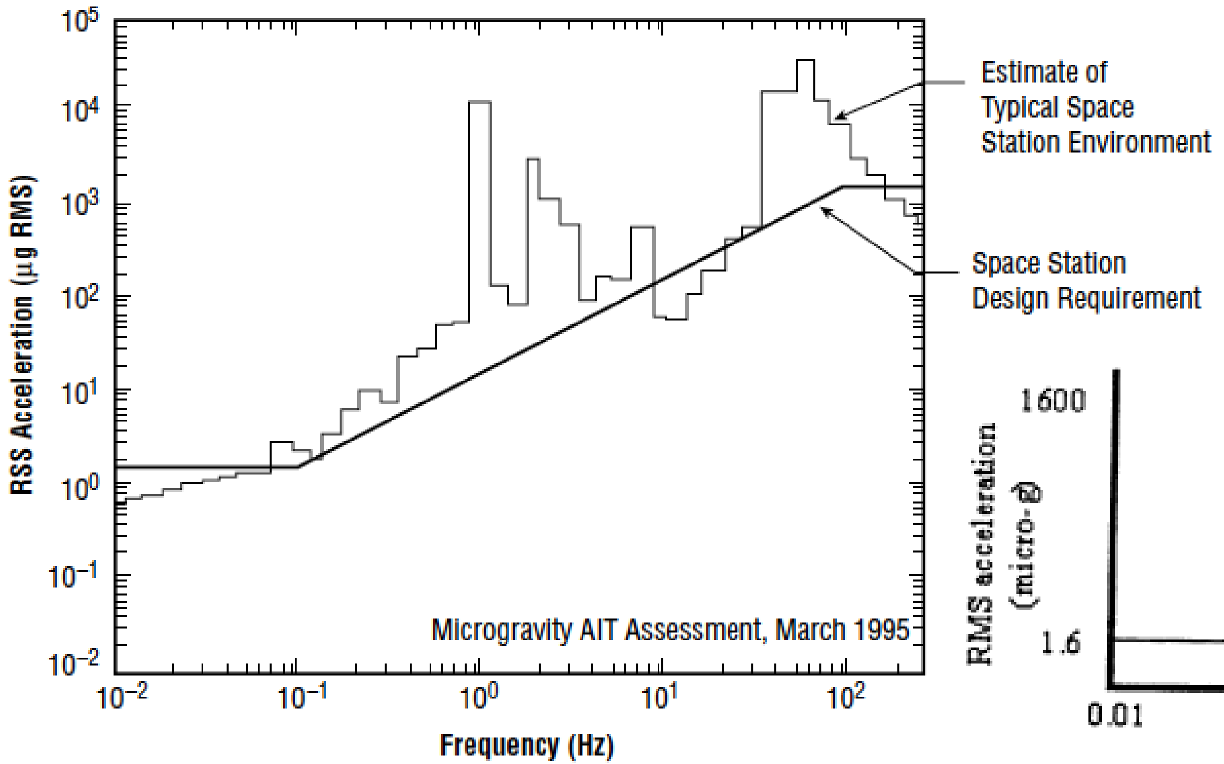


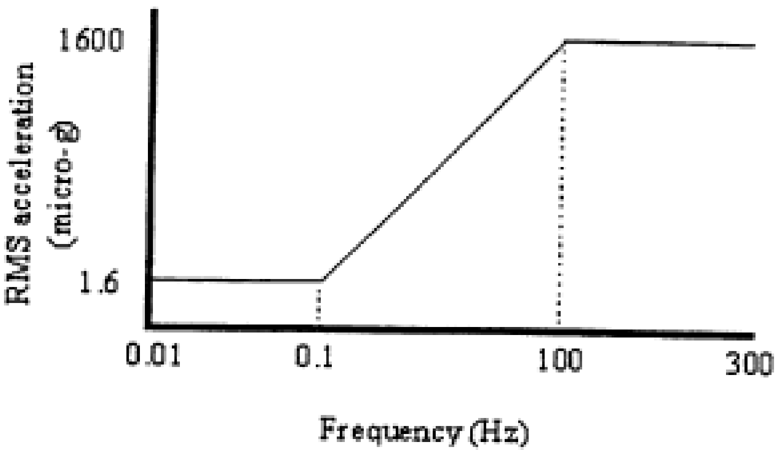
Space engineering

Spacecraft loads analysis

GOCE Satellite Micro-Vibration requirement during measurement mode – Linear Acceleration Spectral Density Profile

Micro-Vibration Environment (ISS)





THE INTERNATIONAL SPACE STATION AS A MICROGRAVITY RESEARCH PLATFORM†

Acta Astronautica Vol. 50, No. 11, pp. 691–696, 2002

Space engineering

ECSS-E-HB-32-26
TBD Issue Date

Spacecraft loads analysis   Chapter 13

Micro-Vibrations Disturbances

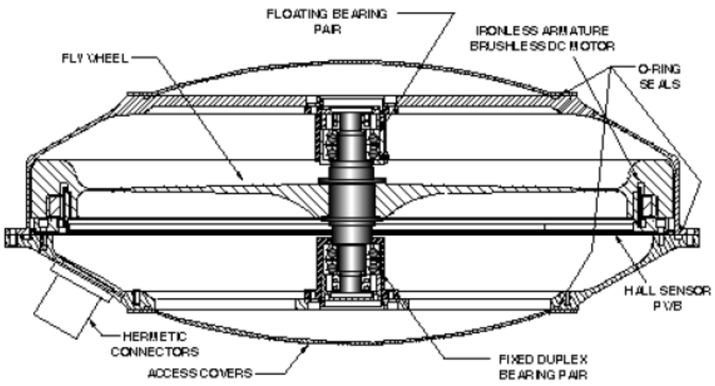
Pressurized Payloads
Interface Requirements Document

International Space Station Program

November 1, 2000

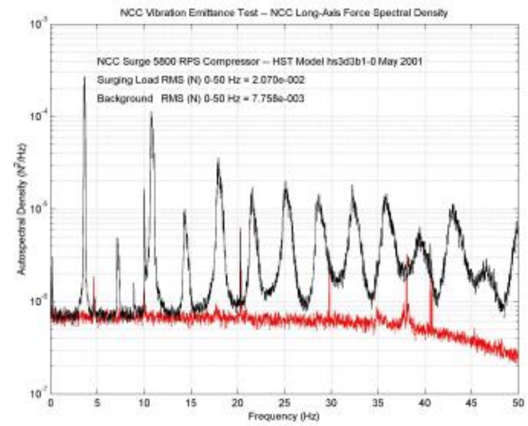
Revision E

SSP 57000, Revision E

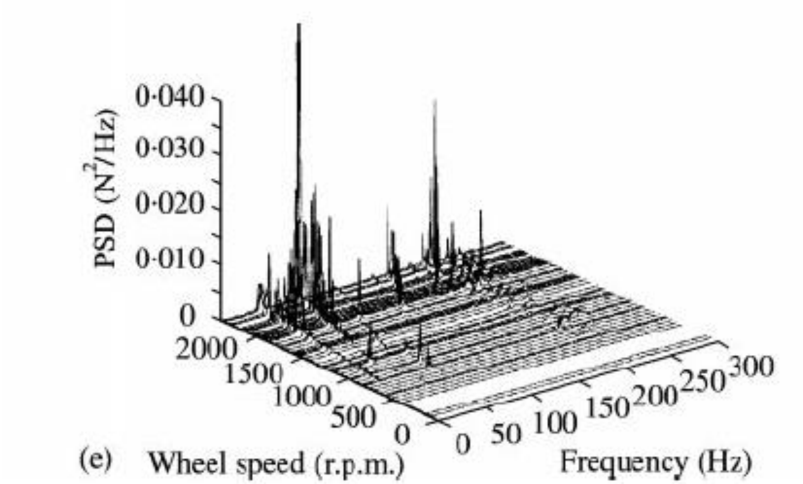


Dynamic Disturbance Sources
Some Examples

- **Cryo-cooler**
- **Reaction wheel assemble**
- **Audible Noise**
- Human induced vibration



Rack Noise Limits Measured At 0.6 Meters Distance From The Test Article	
Frequency Band Hz	**Integrated Rack Sound Pressure Level (SPL)**
63	64
125	56
250	50
500	45
1000	41
2000	39
4000	38
8000	37



Design of Instruments/Equipment

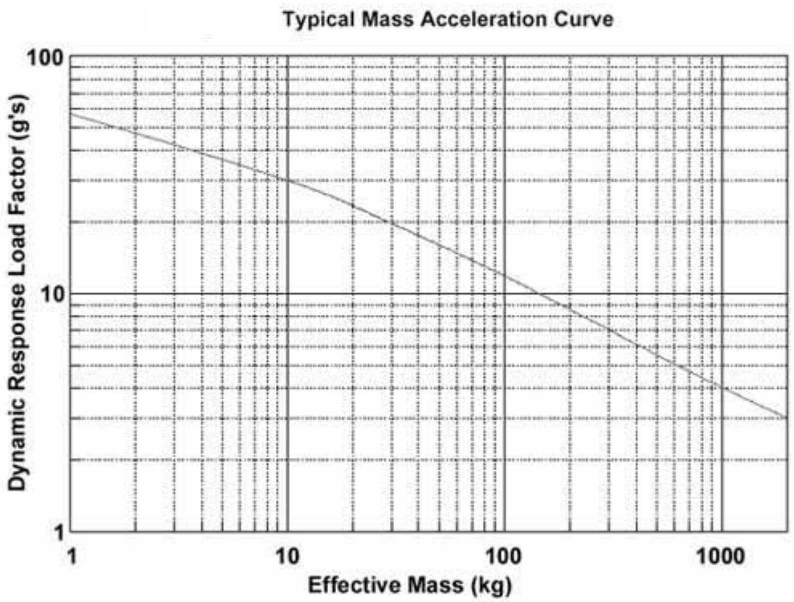
- Mass Acceleration Curve (MAC)
- Preliminary design instruments, Units, ..

Mass Acceleration Curve

- The MAC is an upper bound acceleration level for all components of a given mass, regardless of location, orientation, or frequency. Applicability is limited to appendage masses up to 500 kg, with frequencies up to approximately 100 Hz. Such a curve can be derived based on analytical and flight data, and includes the effects of both transient and mechanically transmitted random vibration. That is, the load predicted by the curve is already a combination of transient and random vibration.

Not mentioned in ECSS-E-ST-32C

NASA PD-ED 1211 Combination methods for Deriving Structural Design Loads …



European Space Agency

Statically Indeterminate Structures

The structure is called statically indeterminate when the number of reaction forces is more than the number of available 6 equations of equilibrium (3 translations and 3 rotations)

Statically Indeterminate Structures

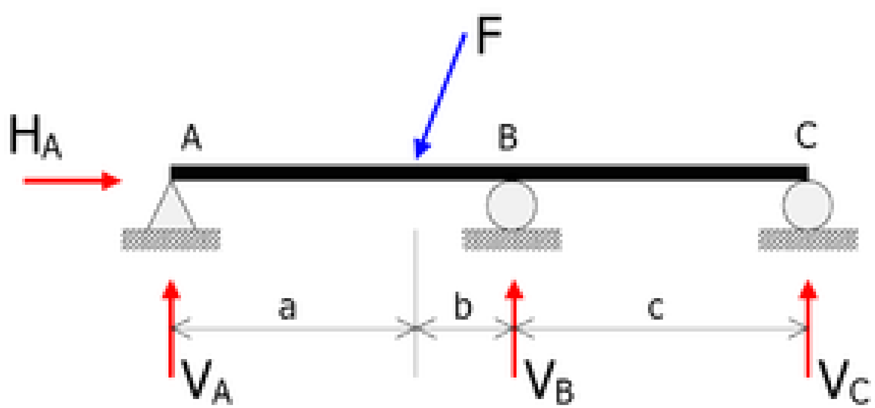
Definition:
The structure is called statically indeterminate when the number of reaction forces is more than the number of available 6 equations of equilibrium (3 translations and 3 rotations)

$$\sum_{k=1}^{3} F_k = 0,$$

$$\sum_{k=1}^{3} M_k = 0,$$

Example

- 2 equations of equilibrium
- 4 reaction forces
- 1 Degree of statically indeterminacy
- 1 equation of compliancy needed



http://www.youtube.com/watch?v=q0_piF4-eNc&feature=related

Statically Indeterminate Structures (Cont'd)

- Indeterminate Structures
  - Advantages
    - Smaller stress
    - Greater stiffness
    - Redundancies
  - Disadvantages
    - Stress due to support settlements
    - Stresses due to temperature changes and fabrication errors

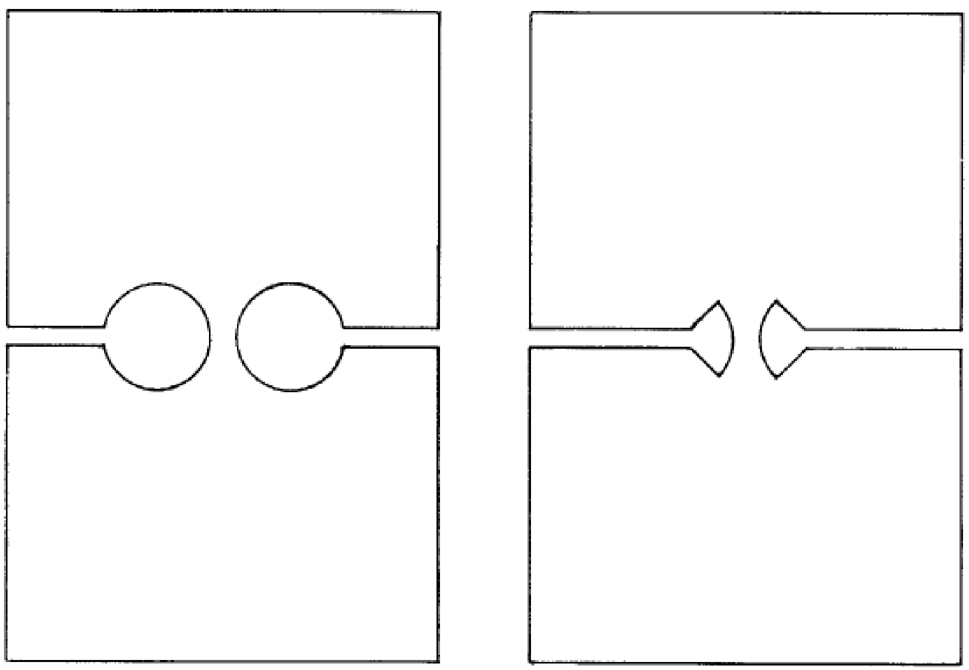
Statically Indeterminate Structures (Cont'd)

- Determinate Structures (Stress free thermal expansion)
  - Optical benches
  - Suspension system of instruments (Kinematic mounts)
  - Simple interfaces
  - Not fail-safe
- Indeterminate Structures
  - Load carrying structures
  - Complex interfaces
- Bibliography

  - Gere, J.M., Timoshenko, S.P., Mechanics of materials, third edition, Chapman & Hall, 0-412-36880-3
  - Den Hartog, J.P., Strength of Materials, Dover, 1961, ISBN 0486607550
  - http://en.vinksda.nl/software-toolkit/calculating-flexure-hinges

Statically Indeterminate Structures (Cont'd)

Flexure Hinges (Kinematic mounts)

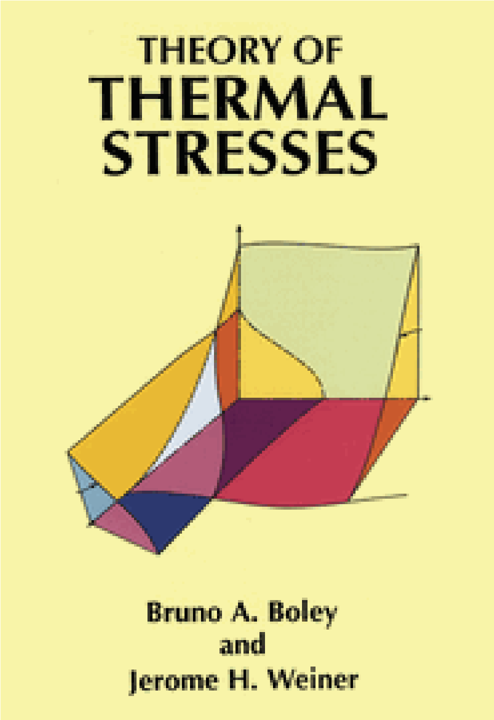


Calculation Flexure hinges

http://en.vinksda.nl/software-toolkit/calculating-flexure-hinges

Thermal Distortion/Stress

- Coefficient of Thermal Expansion
- Temperature Gradient
- Reference temperature



Dover Publications (1985)
ISBN 0486695794

Thermal Effects

- Temperature difference $\Delta T = T - T_{ref} \left({}^{o}C \right)$
- Coefficient of thermal expansion (CTE) $\alpha \left(m / {}^{o}C \right)$
- Characteristic Length/Cross section $L\,(m),\ A\left(m^{2}\right)$
- Thermal strain $\alpha \Delta T \,(-)$
- Thermal distortion $\alpha \Delta T L \,(m)$
- Thermal stress $E \alpha \Delta T \,(Pa)$
- Thermal Load (virtual) $E A \alpha \Delta T \,(N)$

European Space Agency

Overview of Sub-Course E-32 Structures

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

Space engineering

Structural general requirements

Development Approach

- Prototype Approach
- Protoflight Approach
- Hybrid Approach

Definitions

- Prototype Approach
  - The qualification testing can be conducted on one or more qualification model (QM), according to the project requirements and objectives, always with qualification levels and duration.
  - For tests on more than one QM, the tests shall be performed on the different models according to their representativeness (e.g. functional qualification is performed on EQM) and the test sequences for each model shall be adapted accordingly.
  - The FM shall be subjected to complete acceptance testing.
  - Qualification of systems
- Protoflight Approach
  - All the qualification tests shall be performed on the same model to be flown, normally with qualification levels and reduced duration.
  - The protoflight model (PFM) should be subjected to a test program defined on a case-by-case basis.
  - The test program combines both qualification and acceptance tests to satisfy the qualification and the acceptance objectives

Definitions (Cont'd)

- Hybrid Approach
  - A combination of the prototype and protoflight rules shall be applied.
  - Specific qualification testing in the critical areas can be conducted on dedicated models (e.g. STM, QM, EQM or others).
  - In critical areas acceptance testing shall be performed only on the PFM.

  - STM =Structural Thermal Model
  - QM = Qualification Model
  - EQM = Electric(Engineering?) Qualification Model
  - FM = Flight Model
  - PFM = Protoflight model

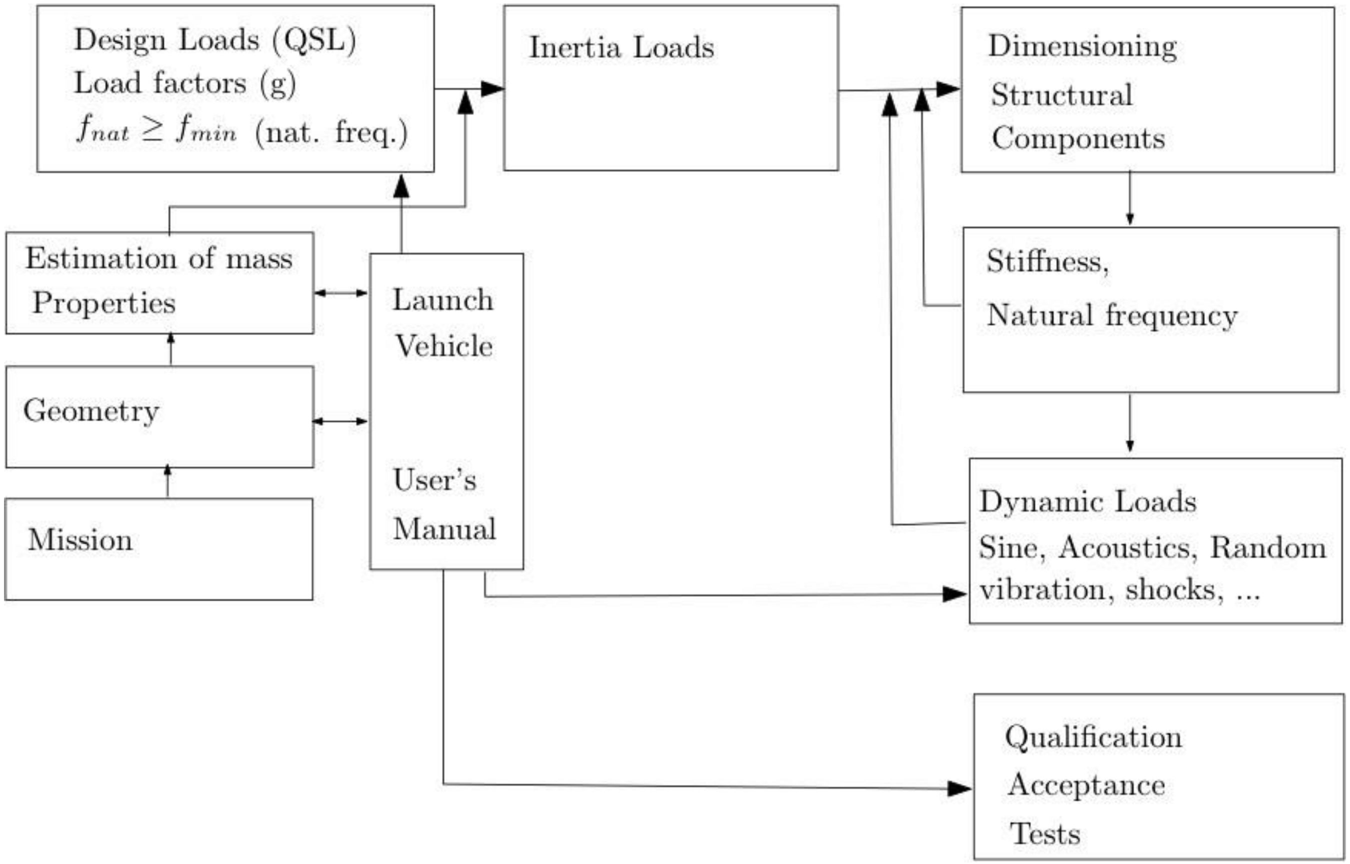
Overview of Sub-Course E-32 Structures

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

Design of Structures

- Preliminary Design
- Factors of Safety / Margin of Safety
- Allowable Stress/Load

Preliminary Design of Spacecraft Structure



Reference, J.J. Wijker
Spacecraft Structures, Springer, ISBN 978-3-540-75552-4, 2008

Space engineering

Structural factors of safety for spaceflight hardware

ECSS-E-ST-32-10C Rev.1
6 March 2009

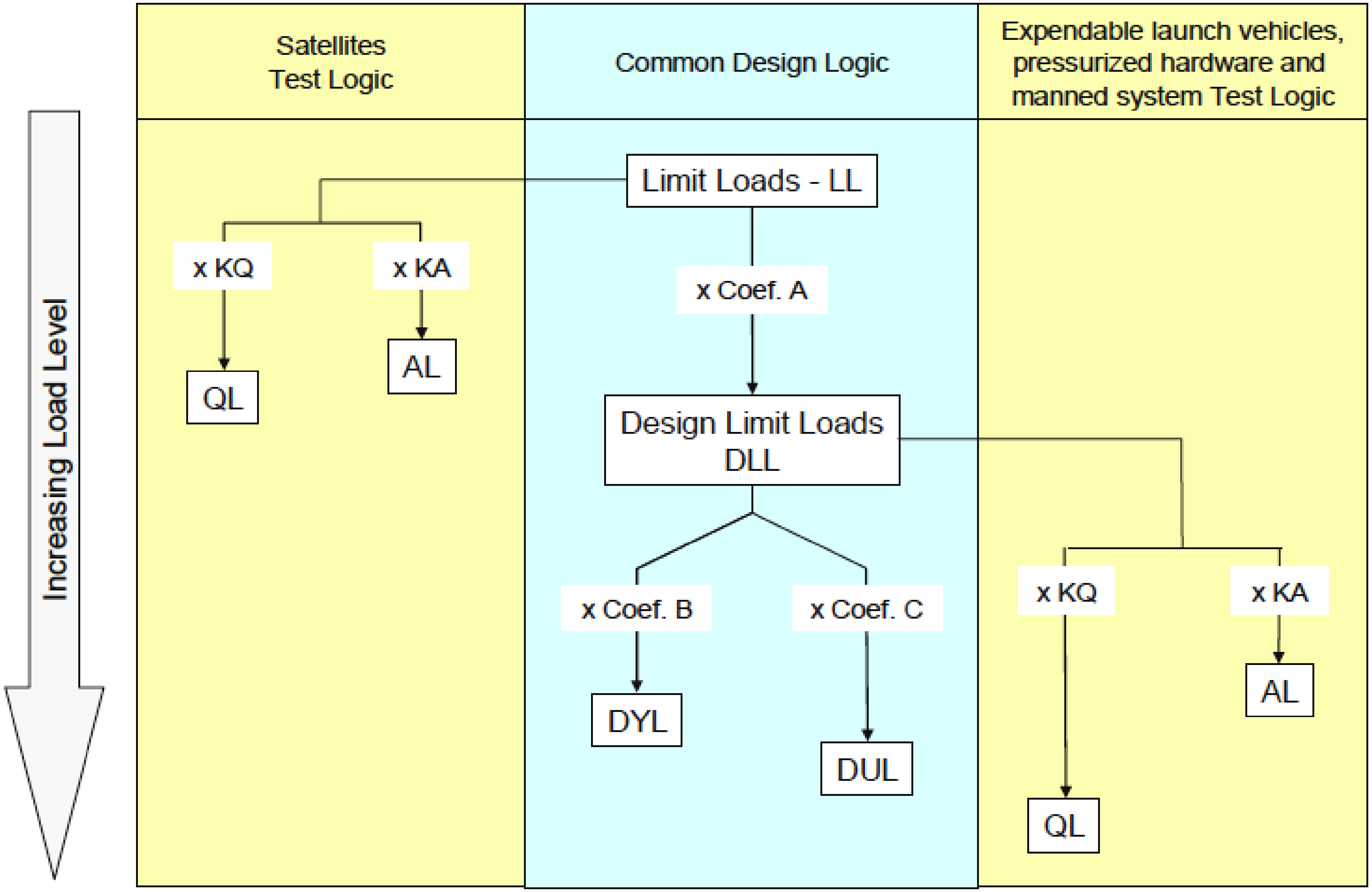
Structural Factors of Safety

- Spacecraft
- Launch vehicles
- Pressurized hardware
- Man-rated spacecraft

- Design Load Factors for Loads
- Additional factors for design
- Test factors

Test Factors/Factors of Safety

Logic of Factor of Safety Application



Test Factors/Factors of Safety (Cont'd)

Relationship among structural factors of safety, design factors and additional factors

Coefficient	Satellite	Launch vehicles and pressurised hardware	Man-rated systems
Coef A or Design factor	$KQ \times K_P \times K_M$	$K_P \times K_M$	$K_P \times K_M$
Coef B	$FOSY \times K_{LD}$	$FOSY \times K_{MP} \times K_{LD}$	$FOSY \times K_{LD}$
Coef C	$FOSU \times K_{LD}$	$FOSU \times K_{MP} \times K_{LD}$	$FOSU \times K_{LD}$

Test Factors

KQ and KA provided by ECSS-E-ST-32-10C

- Spacecraft
- Launch Vehicle
- Man-rated Spacecraft

Type of Load

- Internal pressure
- Dynamic Loads
- Hoisting Loads
- Storage and Transportation Loads
- Thermal Loads

Factors of Safety FoSY and FoSU

FoSY and FoSU provided for ECSS-E-ST-32-10C

- Spacecraft
- Launch Vehicle
- Man-rated Spacecraft

Type of structural material, failure mode, ..

- Metallic Structures
- FRP structure; undisturbed, disturbed (hole, joints, ...)
- Sandwich structures
- Glass & Ceramic structures
- Joints (gapping, sliding) inserts,
- Buckling (global, local)
- Pressurized hardware

Margin of Safety (MoS)

- Margins of Safety (MoS) are to be calculated by the following formula

$$\text{MoS} = \frac{\text{Design Allowable Load}}{\text{Design Limit Load x FoS}} - 1 > 0$$

- Factors of Safety (ECSS-E-ST-32-10C)
- Load may replaced by stress
- Significance MoS values (not mentioned in ECSS-E-ST-32C)

$$\text{MoS} < 0 \text{ Failure}$$

$$0 < \text{MoS £ } 0.5 \text{ Optimal design}$$

$$0.5 < \text{MoS £ } 1.5 \text{ Good design}$$

$$\text{MoS} > 1.5 \text{ Design can be easily improved}$$

Space engineering

ECSS-E-ST-32-08C
31 July 2008

Materials

Allowable Loads or Stresses

- 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:
    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 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.

Design of Structures (2)

- Structural General Requirements ECSS-E-ST-32C Rev. 1, 15/11/2008

- Materials (see ECSS-E-ST-32-08C)
- Processes (see ECSS-E-ST-32C)
- Assembles (see ECSS-E-ST-32C)
- Joints (bolts, bonding, welding, soldering, brazing)

Materials

1. Materials, ECSS-E-ST-32-08C Rev. 1, 21/7/2008

- 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

Overview of Sub-Course E-32 Structures

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

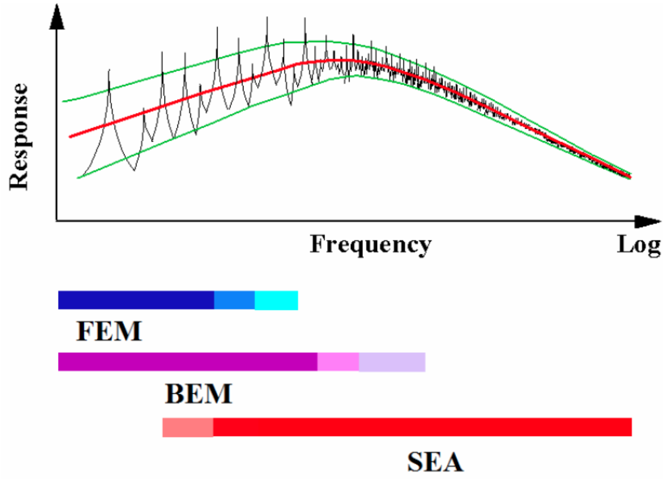
Verification by Analyses

- Mathematical Models
- Numerical Analysis (FEA, BEA, SEA)

Analysis Methods

Analysis Methods to calculate Structural Response of Spacecraft Structures loaded by static, dynamic and acoustic loads

- Analytical methods "Hand calculation"
  - Closed form solutions
- Finite Element Analysis (FEA)
  - Analysis of complex structures
  - Multi-Body dynamics
- Boundary Element Analysis (BEA)
  - Fluid structure interaction
- Statistical Energy Analysis (SEA)
  - High modal density
- Hybrid Analysis (FEA/SEA)
  - Coupling FEA/SEA



Solution strategy as a function of the modal response

Courtesy University Madrid (UPM)

Hand Calculations

- Why? To get a feeling for more detailed analysis

- Strength Stiffness Basic Structural Elements
- Approximate Natural Frequency
- Approximate Dynamic Response Analysis

Hand Calculations (Cont'd)

- **Strength & Stiffness Analysis Basic Structural Elements**
  - Truss frames
  - Rod/Bar/Beam/Rings
  - Plate (Shear panel, Sandwich, …)
  - Shells of Revolution (cylinder, cone, sphere, …)
  - Joints (bolted, bonded, ..)
- Books about Strength of Materials
- NASA SP-8019 Buckling of Thin-Walled Truncated Cones
- NASA SP-8007 Buckling of Thin-Walled Circular Cylinders

- **Failure modes**
  - Yield stress
  - Ultimate stress
  - Local global buckling
  - Fracture mechanics
  - Fatigue
  - …

Hand Calculations (Cont'd)

- Approximation Natural Frequencies
  - Static Displacement
  - Rayleigh Quotient
  - Dunkerley's equation

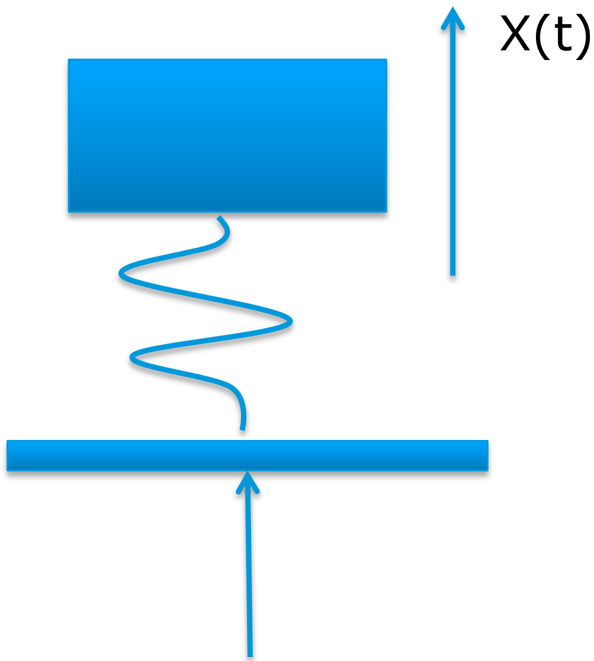
- Rayleigh's Principle and Its Applications to Engineering, Temple, G, Bickley, W.G., Dover, 2004, ISBN 048643902x
- Formulas for Natural Frequencies and Mode Shape, Blevins, R.D. Krieger Publishing, 1995, ISBN 0-89464-894-2

Hand Calculations (Cont'd)

- **Approximation Dynamic Response Analysis**
  - Sine/transient
    - Assumed mode approach
  - Random
    - Assumed mode approach, Miles equation
  - Acoustic
    - Assumed mode approach, Miles equation, Blevins approach

- Miles, J.W. (1954) On Structural Fatigue Under Random Loading, Journal of the Aeronautical Science, November, pages 753-762
- Cunningham, P.R. Langley, R.S., P.R., White, R.G. (2003), Dynamic Response of Double Curved Honeycomb Sandwich Panels to Random Acoustic Excitation. Part 2 Theoretical Study, Journal of Sound and Vibration, Vol. 264, pages 605-637
- Blevins, R.D. (1989) An Approximate Methods for Sonic Fatigue Analysis of Plates and Shells, Journal of Sound and Vibration, **129** (1), pages 51-71

Hand Calculations (Cont'd) Miles' Equation (One Mode Representation)

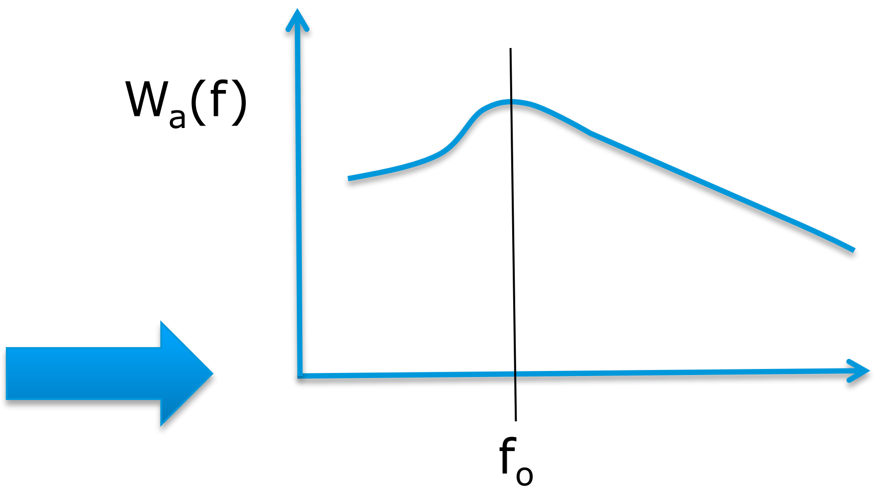


$$\ddot{X}_{rms} » \sqrt{\frac{p}{2} f_o Q W_a(f_o)}$$

$$Q = 1/2z \qquad \text{Q not to low}$$

$$f_o = \frac{1}{2p}\sqrt{\frac{k}{m}}$$

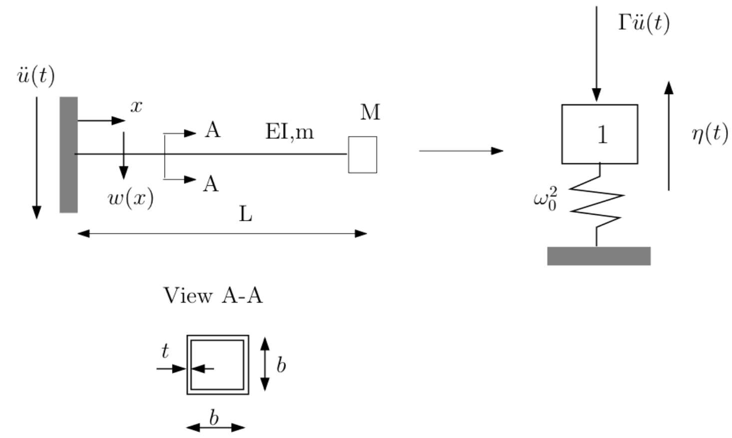
Random Enforced acceleration
$W_a(f)$ (g^2/Hz)



European Space Agency

Hand Calculations (Cont'd)

- Example



$$\phi(x) = \frac{3}{2}\left(\frac{x}{L}\right)^2 - \frac{1}{2}\left(\frac{x}{L}\right)^3$$

$$w(x,t) = \phi(x)\eta(t)$$

$$U = \frac{EI}{2}\int_0^L \left(\frac{\partial^2 w(x,t)}{\partial x^2}\right)^2 dx,$$

$$T = \frac{m}{2}\int_0^L \left[\dot{w}(x,t) + \dot{u}(t)\right]^2 dx + \frac{1}{2}M\left[\dot{w}(L,t) + \dot{u}(t)\right]^2.$$

$$\ddot{\eta}(t) + \omega_1^2\eta(t) = -\Gamma\ddot{u}(t)$$

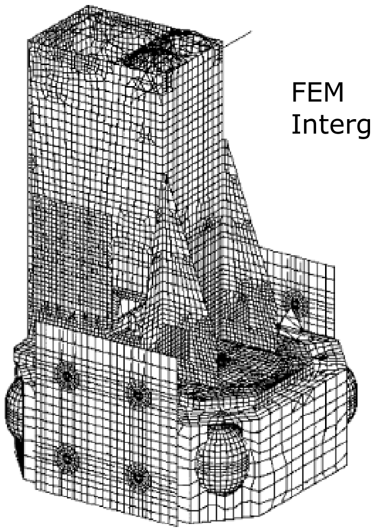
$$\omega_1^2 = \frac{420EI}{L^3(33mL + 140M)},$$

$$\Gamma = \frac{35(3mL + 8M)}{2(33mL + 140M)}.$$

- Wijker, J.J. (2009) Random Vibrations in Spacecraft Structures Design, Springer, ISBN 978-90-481-2727-6

Finite Element Analysis

- Structural Finite Element Models, ECSS-E-ST-32-03C
- Structural General Requirements ECSS-E-ST-32C Rev. 1
  - DRD’s
    - Modal and dynamic response analysis
    - Stress and strength analysis
    - Structure buckling analysis
    - Test- analysis correlation
    - Mathematical model description and delivery
    - …



FEM
Intergral

Reference:
Adriano Calvi, Uncertainty-based loads analysis for spacecraft: Finite element model validation and dynamic responses, Computer and Structures, Vol. 83, 2005, pages 1103-1112

Finite Element Analysis (Cont'd)

- The elastic-dynamic behavior of structural elements (rod, beam, plate, cylinder,) can be described with the aid of partial differential equations (PDE). PDE are difficult to solve.
- The PDE's can be converted into sets of linear equations applying variational methods in combination of assumed functions (shapes); Theorem of minimum potential and complementary energy, Rayleigh-Ritz method, Galerkin method, … The finite element method is based on variational techniques and is the major numerical analysis method.
- The finite element method requires division of the problem into many subdomains and each domain is called a finite element. The problem domain consists of may elements.
- The set of many linear equations is solved by numerical schemes on very high performance computers (Gauss elimination, Cholesky decomposition, …)

- The Finite Element method Using MATLAB, Kwon, Y.W., Bang, H. CRC Press, 2000, ISBN 0-8493-0096-7

Finite Element Analysis, NAFEMS (Cont'd)

NAFEMS is an independent not-for-profit body with the sole aim of promoting the effective use of engineering simulation methods such as finite element analysis, multibody system dynamics and computational fluid dynamics.

Dr. Costas Stavrinidis- Chairman
Head Mechanical Engineering Department, ESTEC

NAFEMS Council of management

Finite Element Analysis (Con'd)

- The finite element analysis (FEA) method one the most applied numerical tools to solve mechanical static and dynamic problems in launch vehicle and spacecraft structural engineering
    - Static analysis
        - Inertia and pressure loads
        - Thermal-elastic analysis (deformation & stress)
        - Buckling Analysis (bifurcation and limit load)
        - Non-linear (Geometrical, material, ..)
    - Dynamic analysis
        - Modal analysis
        - Frequency response analysis
            - Sine and random vibrations
            - Acoustic response analysis
        - Transient Analysis (CLA, shocks)
            - CLA, Shocks
            - Non-linear analysis
        - Micro-vibrations
        - …

Finite Element Analysis (Cont'd)

Finite Element Analysis flow chart

- Number of nodes
- Boundary Conditions
- Material properties
- Forcing functions
- Selection finite element type
- Damping

- Static analysis
- Modal analysis
- Dynamic analysis
- Buckling analysis
- …

CAD

→ Geometry

FEA Pre-processor

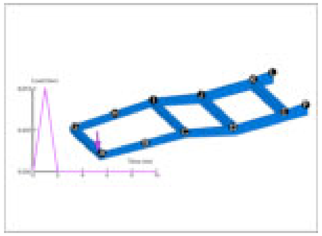
→
- Finite element model (FEM)
- Mass matrix (6x6)

FEA Solver

→
- Nodal displacements
- Element stresses/forces

FEA Post-processor

- Plots
- Fatigue life
- …



Finite Element Analysis (Cont'd)

esa

- Finite Element Model (FEM) validation,
  - Structural Finite Element Models, ECSS-E-ST-32-03C (Focus on MSC.Nastran)

- Use SI system: m, N, kg, s
- Modeling requirements
  - Permitted type of element and aspect ratio's
  - Numbering schemes
  - Guidelines (Do, Don't)
- Model checks
  - Model geometry check
  - Element topology check
  - Rigid body mass matrix check
  - Rigid body strain energy check
  - Stress-free thermo-elastic deformation check
  - Free-free modal analysis check

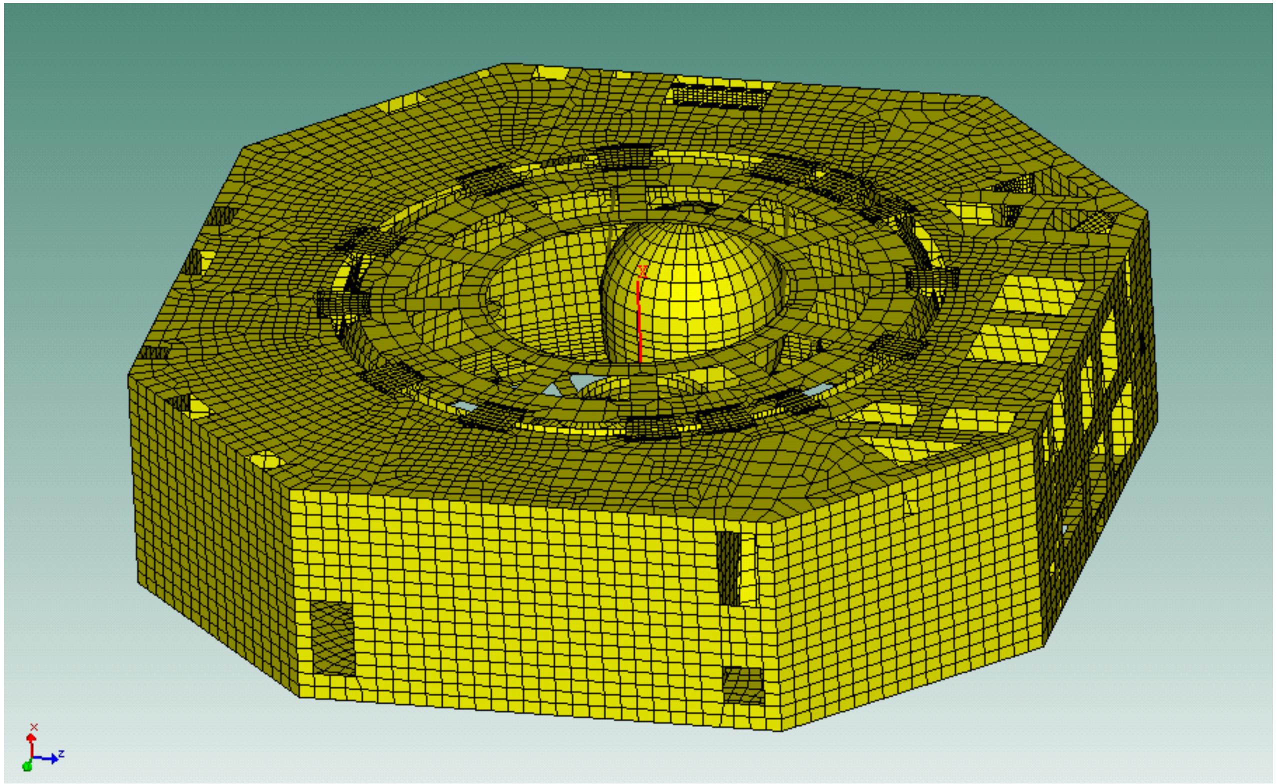
EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

Space engineering

Structural finite element models

Finite Element Analysis (Con't)

Finite Element Model
Service Module
Herschel



FEA Static Analysis

- Inertia and pressure loads
- Thermal-elastic analysis (deformation & stress)
- Buckling Analysis (bifurcation and limit load)
- Non-linear analysis (implicit or explicit)
    - Geometric
    - Material
- …

FEA Buckling Analysis

Buckling of Structures, ECSS-E-HB-32-24A

Space engineering

Buckling of structures

- Not stable equilibrium of a structure under loads applied statically or dynamically

- Linearized Pre-buckling/Bifurcation analysis
- Nonlinear Pre-buckling/Bifurcation Analysis

Buckling

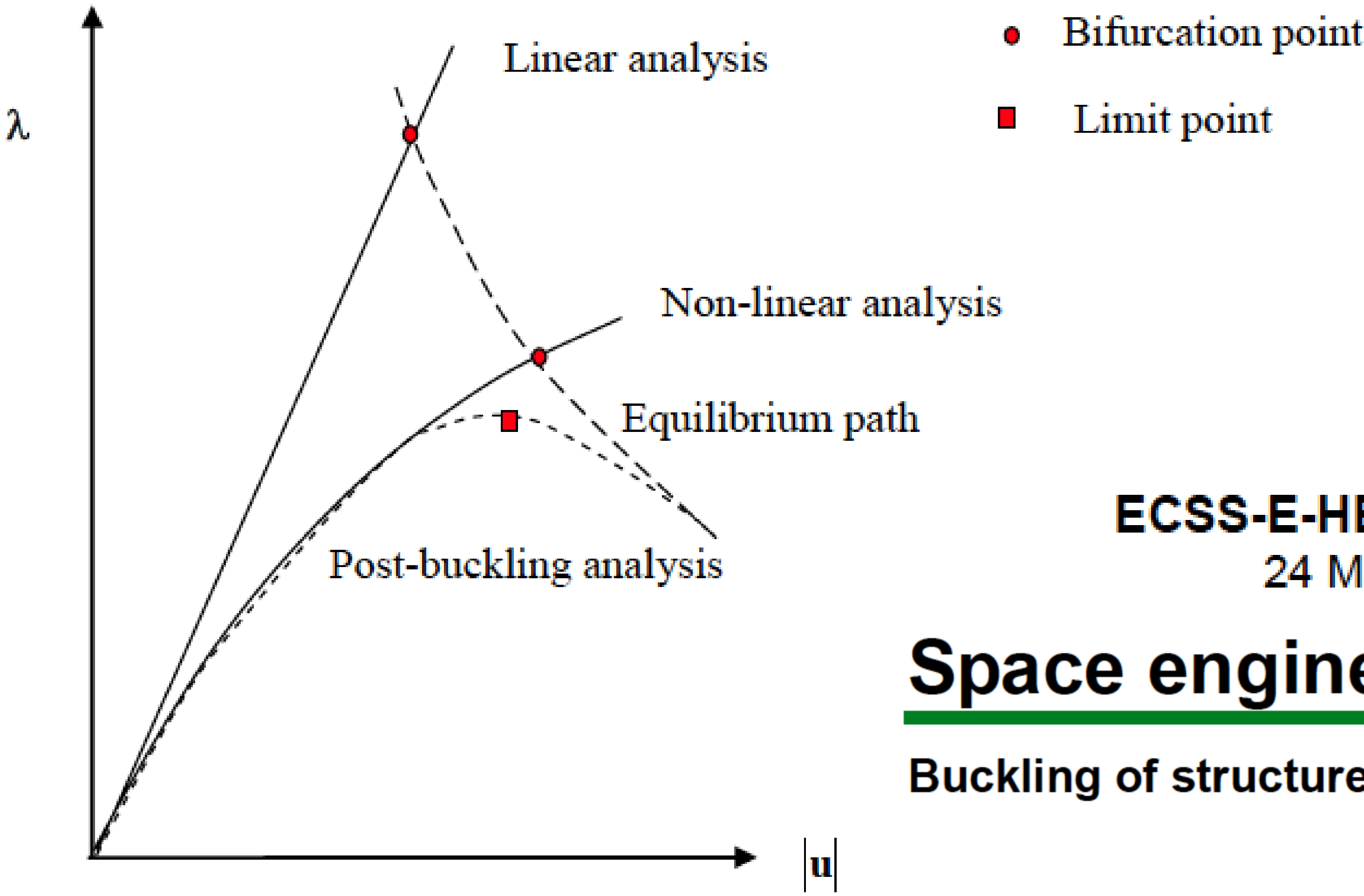
- The stability (i.e. no buckling) of the structure shall be verified for the design loads.
- Local buckling shall be prevented unless:
    - the buckling is reversible, and
    - the resulting stiffness and deformations still conform to the structural and functional requirements, and
    - a post- buckling investigation (by analysis or test) demonstrates positive margins against failure.

Buckling Analysis

- Buckling analysis shall be used to predict the loads at which the onset of structural instability occurs.
- For cases where elastic fully reversible buckling is accepted, post- buckling behavior shall be analyzed.
- Effects on stability of boundary conditions, defects and geometrical imperfections in the structure shall be included in the buckling analysis.

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

Post-Buckling Analysis



ECSS-E-HB-32-24A

24 March 2010

Space engineering

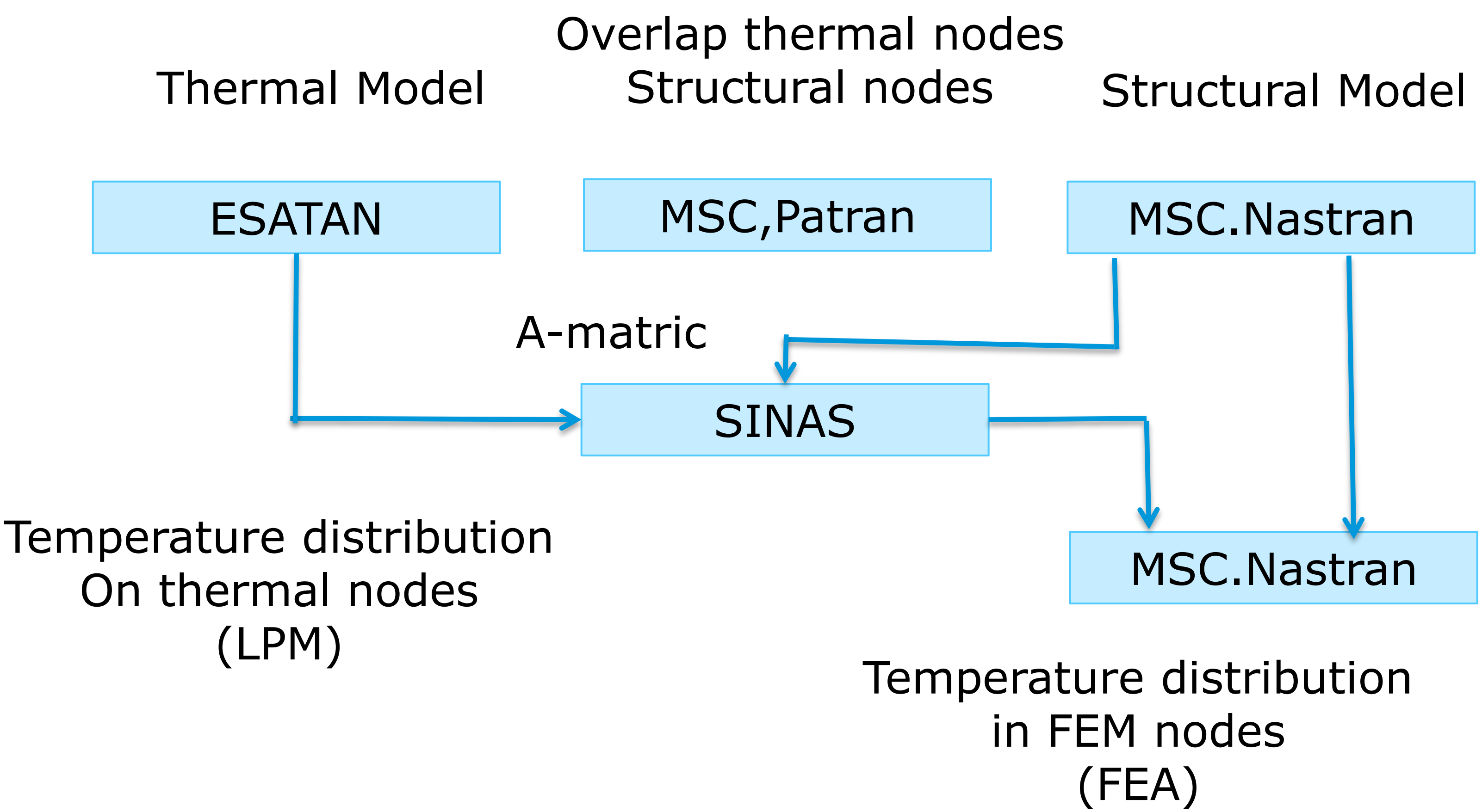
Buckling of structures

Thermal Load Analysis

- Thermal Analyzer (ESATAN, ESARAD, ...)
- Temperature interpolation (PAT)
- Thermal Distortions/stress (FEA) (Thermal distortions on-orbit)

- Constraints imposed by the thermal design and impacting the structure shall be identified.
- The temperatures and temperature variations and gradients during all phases of a mission, including manufacturing and storage, shall be used, both in the material selection and in the design in order to achieve the specified functional and structural performance.

Prescribed Average Temperatures
Temperature interpolation



Prescribed Average Temperatures Temperature interpolation (Cont'd)

Thermal Model

Prescribed Average Temperatures

Structural Model

$$\{T_{TM}\} \qquad \{T_{TM}\} = [A]\{T_{FEM}\} \qquad [C]$$

Temperature interpolation

$$\begin{bmatrix} C & A^T \\ A & 0 \end{bmatrix} \begin{Bmatrix} T_{FEM} \\ q_{LM} \end{Bmatrix} = \begin{Bmatrix} 0 \\ T_{TM} \end{Bmatrix}$$

FEA Dynamic Analysis

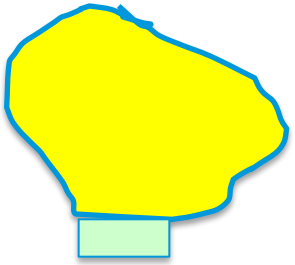
- Modal analysis
- Frequency Response Analysis
  - Sine and random vibrations
  - Acoustic response analysis
- Transient Analysis
  - CLA, shocks, Acoustics, non-linear (implicit & explicit)
- Micro-vibrations
- …

FEA Modal Analysis

- Natural frequency
- Real vibration modes
- Stress/force modes
- Rigid body modes
- Generalized mass and Stiffness
- Modal Participation factor, Effective Mass
- Residual Flexibility/Mode acceleration
- Damped vibration modes
- …

Eigenvalue problem (elastic problem)

$$\left(-\omega_i^2[M]+[K]\right)\{\Phi_1\}=\{0\},\ i=1,2,\ldots,n$$

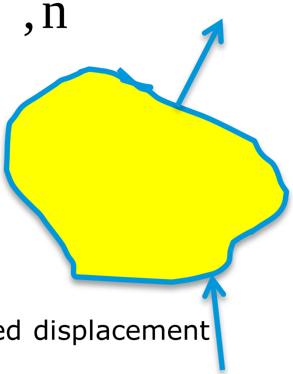


Generalized mass and stiffness

$$\{\Phi_i\}[M]\{\Phi_j\}=\delta_{ij}\mu_i,\ \{\Phi_i\}[K]\{\Phi_j\}=\delta_{ij}\omega_i^2\mu_i,\ i,j=1,2\ldots,n$$

Rigid body mode (Determinate boundary conditions)

$$[K]\{\Phi_{R,j}\}=\{0\},\ j=1,2,\ldots,6$$



Modal participation

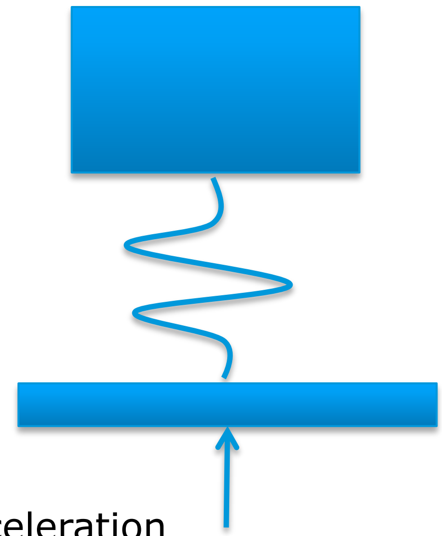
$$\{\Phi_i\}^T[M]\{\Phi_{R,j}\}=\{L_{ij}\},\ i=1,2,\ldots n,\ j=1,2,\ldots,6$$

Modal effective mass

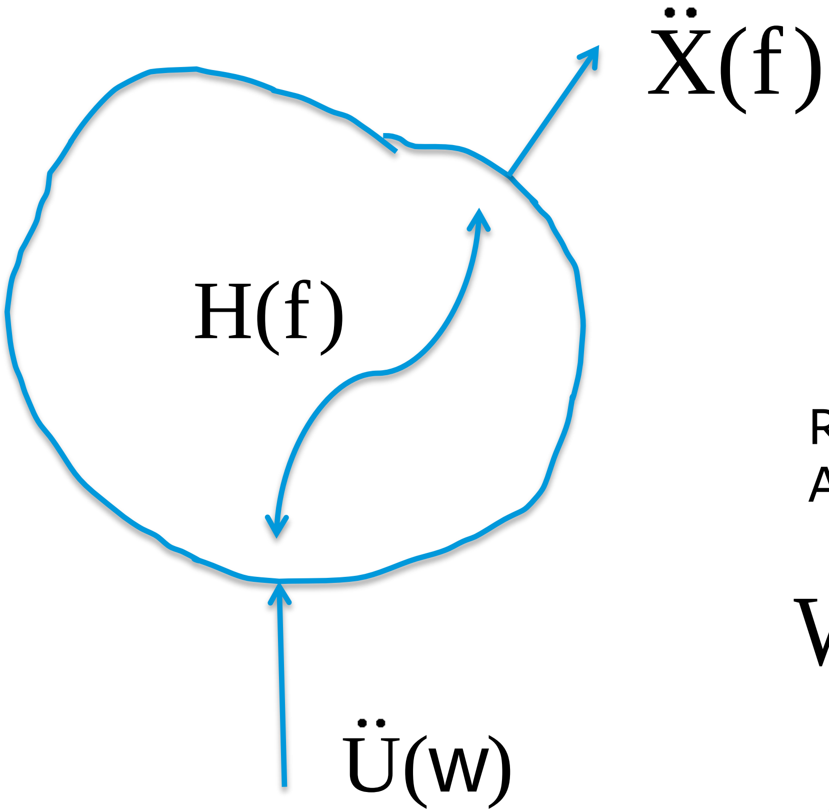
$$\left[M_{em,ij}\right]=\frac{\{L_{ij}\}^T\{L_{ij}\}}{\mu_1},\ i=1,2,\ldots n,\ j=1,2,\ldots,6$$

FEA Sine and Random Response Analysis (Frequency Domain)

- Enforced Accelerations
- Damping properties very important



FEA Sine and Random Response Analysis



Sinusoidal Response Analysis

$$\ddot{X}(f) = H(f)\ddot{U}(f)$$

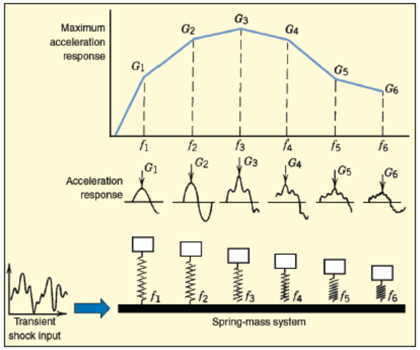
Random Response Analysis

$$W_{\ddot{X}}(f) = \left|H(f)\right|^2 W_{\ddot{U}}(f)$$

$$\ddot{X}_{rms} = \sqrt{\int_0^\infty W_{\ddot{X}}(f)df}$$

Mechanical Shock Design and Verification Handbook

ESA-Contract No 20503/06/NL/SFe
ESA study manager: S. KIRYENKO, ESA/ESTEC, Noordwijk



FEA Shock (SRS)

- Shock Response Spectrum (SRS)

- Mechanical Shock Design and verification Handbook, ESA Contract No 20503/06/NL/Sfe, 15/9/2011
- NASA STD-7003 Pyro shock Test Criteria, 1999

Transient Response Analysis (Time domain)

- Shocks (High frequency transients)
- Non-linear Analysis
- Fluid Structure Interaction

Finite Element Analysis Software

- FEA Software Applied by ESTEC TEC-MSS Department
  - MSC.Nastran (Nastran=**NA**SA **Str**uctural **An**alysis)
    - MSC.Software
  - Abaqus/CAE
    - Simulia
  - VA-ONE
    - ESI Group
  - SAMCEF
    - SAMTECH
  - SINAS (Dutch Space development) Interface between ESATAN and MSC.Nastran

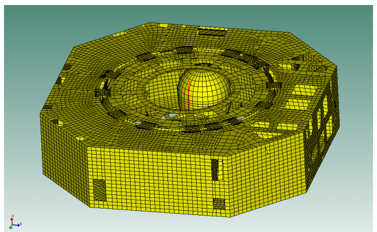
Boundary Element Analysis

- Low frequency domain
- Combined FEA/BEA approach

- Modal description of Structure by finite element analysis (FEA)
- Fluid Structure Interaction by boundary element analysis (BEA)

FEA/BEA Analysis Flow

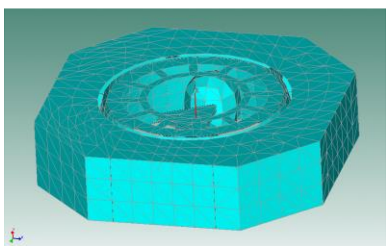
CAD



Reverberant sound field (set of plane waves)
- Frequency range (1-1/3 octave band)
- SPL (dB) 0dB=2x10^{-5} Pa

Finite Element Model (FEM)

Boundary Element Model (BEM)



Modal Properties
- Natural frequencies
- Vibration Modes
- Generalized Mass/Stiffness
- Modal damping

Coupled FEA/BEA Solver

Modal properties
- Added mass
- Radiation loss

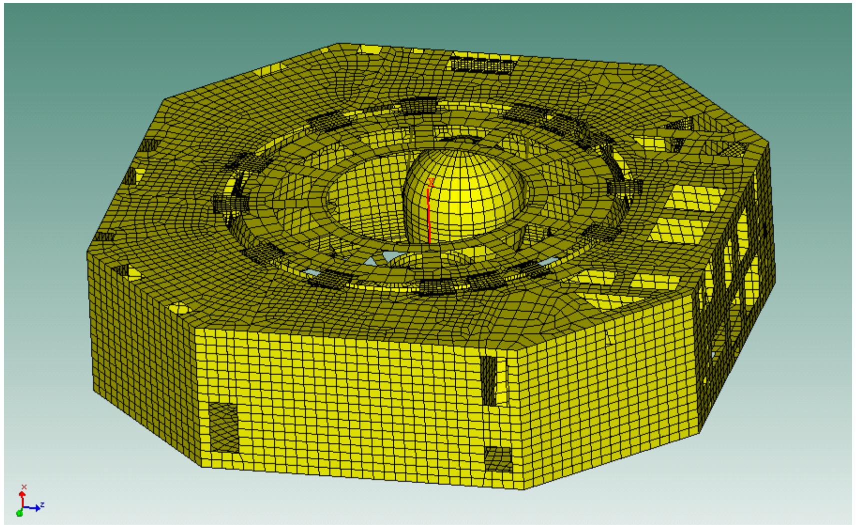
Pressure fields
- Blocked pressure
- Radiated pressure
- Absolute pressure

Structural/field Responses
- PSD/rms Accelerations
- PSD/rms Stress/Loads
- PSD/rms Pressure Field/Jump
- …..

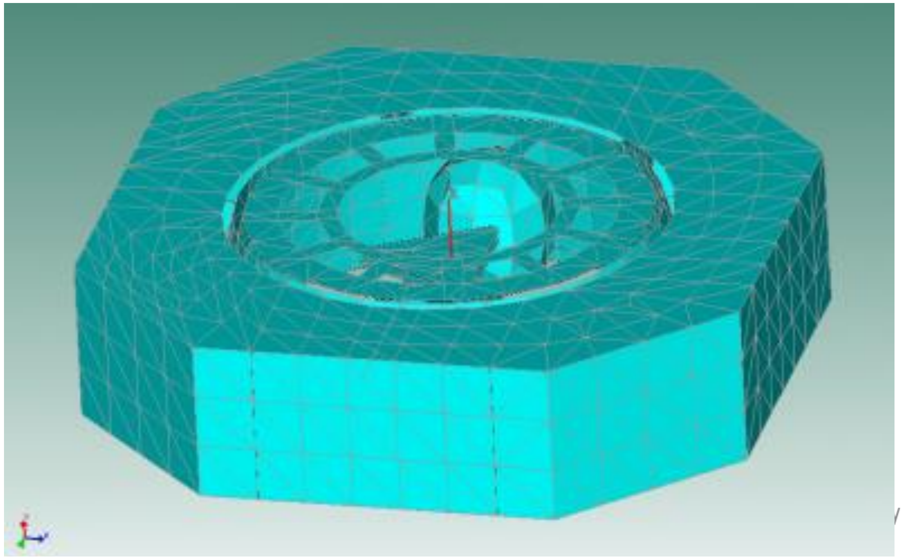
FEA/BEA Analysis Software In ESTEC

- FEA MSC. Nastran
  - Modal Properties
- BEA Rayon (VA-One)
  - Fluid Structure Interaction

Finite Element Model
SVM Herschel



Boundary Element
Model SVM Herschel



Mid & High Frequency Structural Response Analysis

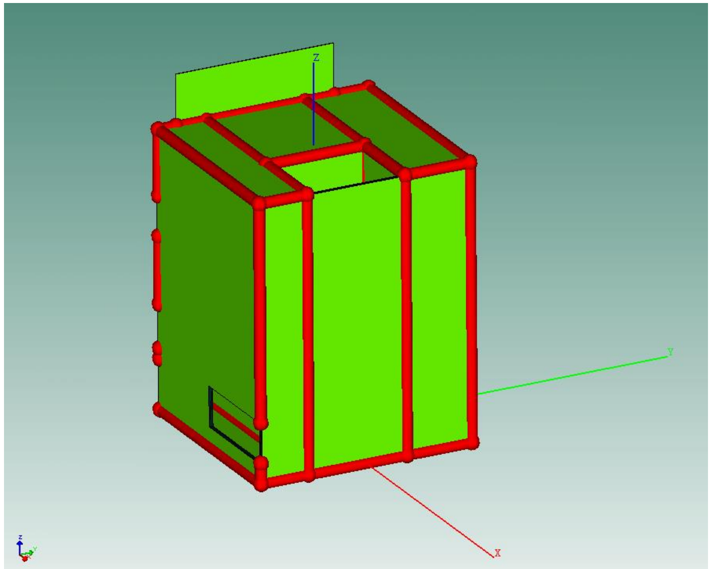
- Hybrid method (FEA/SEA)
- Statistical Energy Analysis (SEA)
- Approximate methods

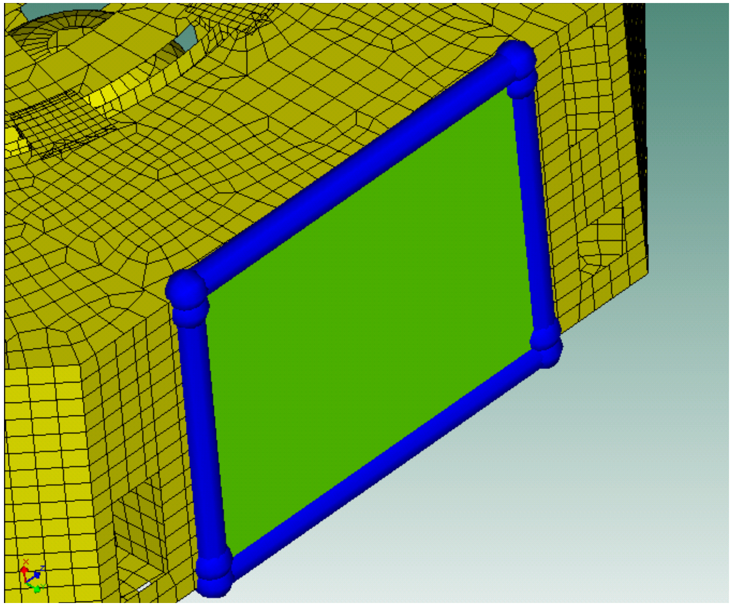
Lyon, R. H., and DeJong, R. G., Theory and Application of Statistical Energy Analysis, 2nd ed., Butterworth-Heinemann, Boston, 1995.

Finite Element Analysis (Con't)

Hybrid FEA/SEA Model
SVM Herschel

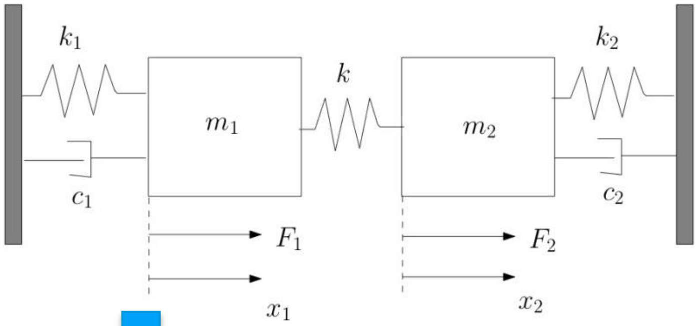
Statistical Energy
Analysis Model Proba-2



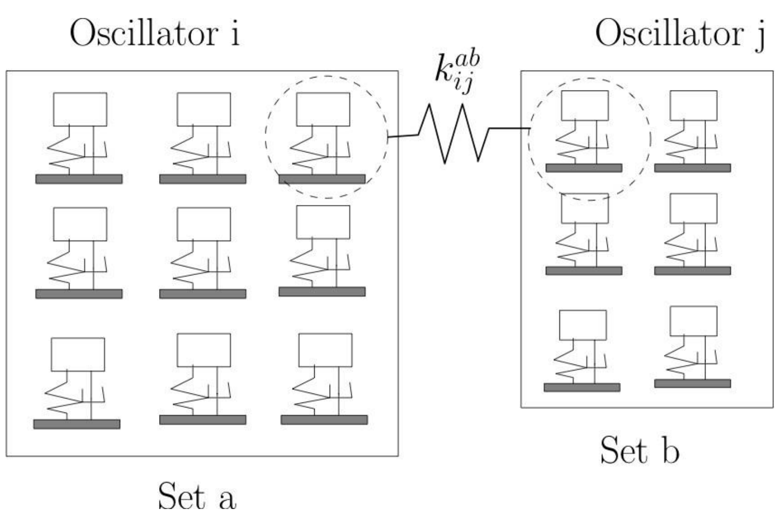


European Space Agency

Statistical Energy Analysis (Cont'd)

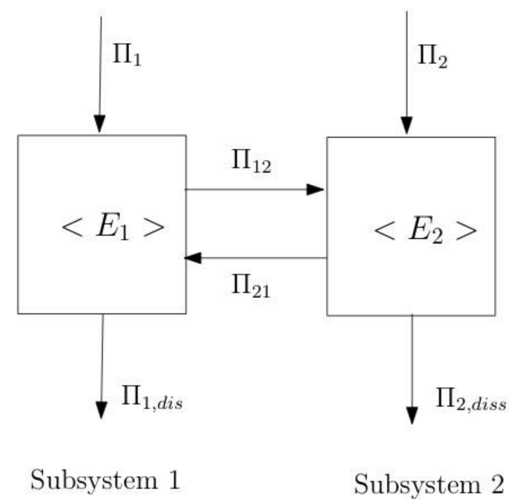


Two spring-coupled oscillators



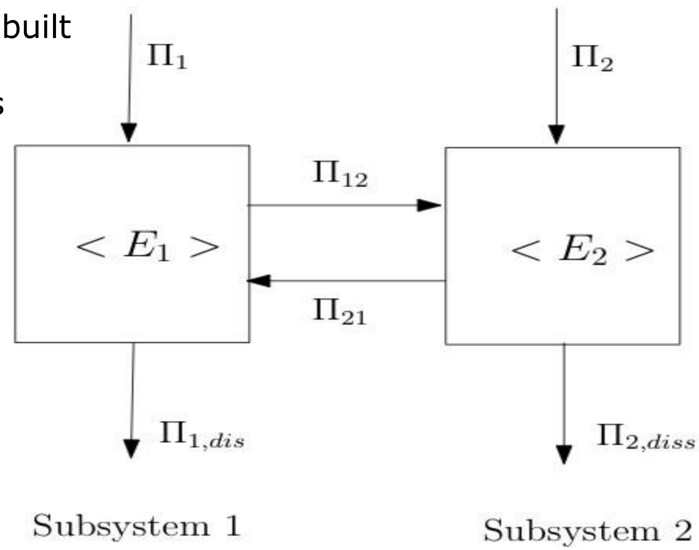
Two sets of spring-coupled oscillators

Fundamental SEA model built up by two subsystems



Statistical Energy Analysis (Cont'd)

Fundamental SEA model built up by two subsystems



ω Radian frequency

n_1 Modal density subsystem i

η_1 Loss factor (LF) subsystem i

η_{1j} Coupling loss factor (CLF) subsystem i to subsystem j

Energy balance equations

$$P_1 = \omega\eta_1 < E_1 > + \omega\eta_{12} n_1 \left(\frac{< E_1 >}{n_1} - \frac{< E_2 >}{n_2} \right)$$

$$P_2 = \omega\eta_2 < E_2 > + \omega\eta_{21} n_2 \left(\frac{< E_2 >}{n_2} - \frac{< E_1 >}{n_1} \right)$$

European Space Agency

Statistical Energy Analysis (Cont'd)

Aproximate method (References)

VibroSpec

Derivation of Satellite Equipment Design and Test Specifications from Random Vibration Environments

ESA Contract No.: 20502/06/NL/SFe

Based on measurements
No SEA

Shi, Q., S. Ando, M. Tsuchihashi, M. Saitoh, "Introduction of JAXA Tool for Random Vibrations Prediction and Its Recent Upgrading," 1st CEAS European Air and Space Conference, 2007

M.E. McNelis, "A Modified VAPEPS Method for Prediction Vibro-Acoustic Response of Unreinforced Mass Loaded Honeycomb Panels", NASA Technical Memorandum 101467, 1989

Conlon, S.C., and S.A. Hambric, " Predicting the vibro-acoustic response of satellite equipment panels," JASA, vol. 113, no. 3, 2003, pp. 1455-1474

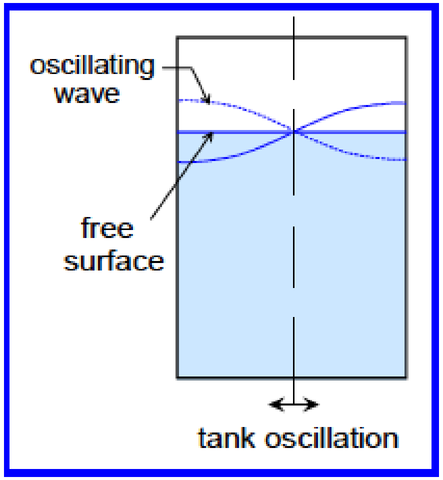
Sloshing Effects

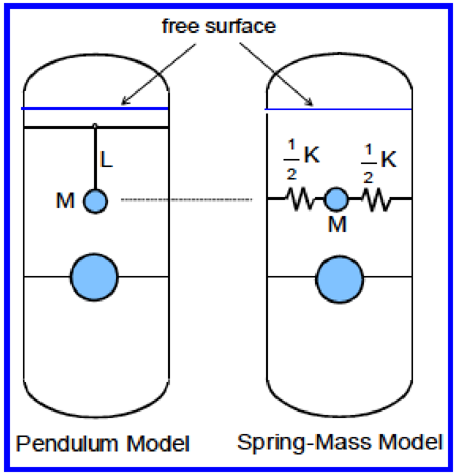
- The structure shall be verified against the effects of the interaction with fluids (e.g. sloshing, POGO, cavitation effects and pressure fields).

Fluid Structure Interaction (FSI) In fluid dynamics, **slosh** refers to the movement of liquid inside another object (which is, typically, also undergoing motion). Strictly speaking, the liquid must have a free surface to constitute a **slosh dynamics** problem, where the dynamics of the liquid can interact with the container to alter the system dynamics significantly. Important examples include propellant slosh in spacecraft tanks and rockets (especially upper stages), and cargo slosh in ships and trucks transporting liquids (for example oil and gasoline). However, it has become common to refer to liquid motion in a completely filled tank, i.e. without a free surface, as "fuel slosh"

Bibliography

- H.N. Abramson, The Dynamic Behavior of Liquids in Moving Containers, with applications to Space Vehicle Technology, NASA SP-106 (1967)





Pendulum model concept

Finite Element Analysis
Boundary Element Analysis

snap.lbl.gov/pub/bscw.cgi/S48bd154b/.../SwRI_SLOSH_Update.pdf

THE NEW "DYNAMIC BEHAVIOR OF LIQUIDS IN MOVING CONTAINERS"

Overview of Sub-Course E-32 Structures

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

Space engineering

ECSS-E-HB-32-26
TBD Issue Date

Spacecraft loads analysis

Chapter 12

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.

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.

Damage Tolerant

- 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

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

Overview of Sub-Course E-32 Structures

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

Verification by Test

Space engineering

Testing

ECSS-E-ST-10-03C Draft 12.5
4 March 2011

- Qualification and Acceptance Testing

- Static test
  - Thermal-Stress test (Difficult to perform)
  - Pressure test
- Dynamic test
  - Modal survey test
  - Sine and Random tests on shaker
    - Notching (Primary & Secondary) to prevent over-testing
  - Acoustic in reverberant chamber
  - Shock test
  - Micro-vibration test

Qualification & Acceptance Test

- Qualification
  - Qualification tests shall be performed to verify that the structure design and manufacturing technique fulfill specification requirements.
  - Qualification test shall account for the worst hardware characteristics which can be present in a flight unit but are not present in the test unit (e.g. by means of dedicated correction factors).
- Acceptance
  - Acceptance tests shall be performed on the flight hardware.

Test Factors, Rate and Duration (e.g. Soyuz)

S/C tests	Qualification*		Protoflight		Acceptance	
	Factors	Duration/Rate	Factors	Duration/Rate	Factors	Duration/Rate
Static (QSL)	1,25	N/A	1,25	N/A	N/A	N/A
Sine vibrations	1,25	2 oct/min	1,25	4 oct/min	1.0	4 oct/min
Acoustics	+3 dB (or 2)	120 s	+3 dB (or 2)	60 s	1.0	60 s
Shock	+3 dB (or 1.41)	N/A	+3 dB (or 1.41)	N/A	N/A	N/A

- Spacecraft qualification and Acceptance test levels are determined by increasing the flight limit loads. The spacecraft must have positive margins of safety for yield and ultimate loads

- Qualification by analysis factor of safety of 2.0 and MoS>1

Modal Survey (Modal Analysis) Test

- General objectives and requirements
- Modal Survey test procedures
- Pre-test Analysis
- Annex A Excitation signals
- Annex C Estimation methods for modal parameters
- Annex C Modal Test-Mathematical Model verification checklist

Dynamic Tests: Sine, Random, Shock

- Dynamic tests (sine, random, shock) shall be performed to verify:
  - the dynamic behavior, in terms of accelerations and interface forces (including units and appendages)
  - the compliance to the stiffness requirements, and
  - the strength and alignment stability under dynamic loads.

Sine Vibration Test (A5 User's Manual)

Sine	Frequency range (Hz)	Qualification levels (0-peak)	Protoflight levels (0-peak)	Acceptance levels (0-peak)
Longitudinal	2-5* 5-50 50-100	12.4 mm 1.25 g 1 g	12.4 mm 1.25 g 1 g	9.9 mm 1 g 0.8 g
Lateral	2-5 5-25 25-100	9.9 mm 1 g 0.8 g	9.9 mm 1 g 0.8 g	8.0 mm 0.8 g 0.6 g
Sweep rate		2 oct./min	4 oct./min	4 oct./min

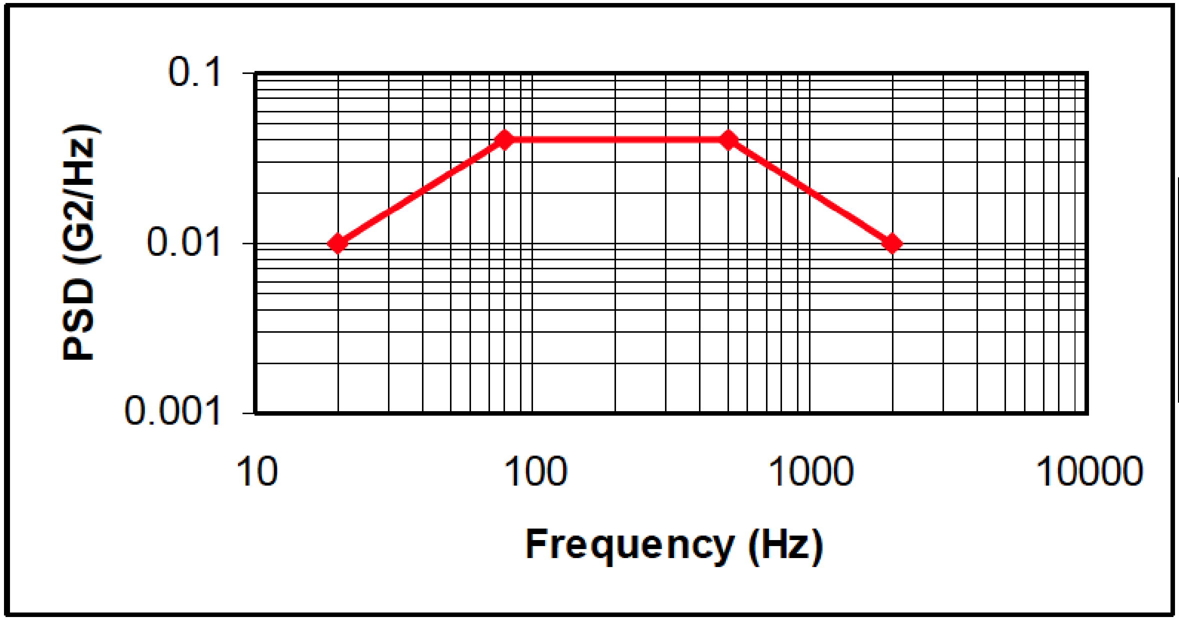
* Pending on the potential limitations of the manufacturer's test bench, the fulfillment of the requirement in that particular frequency range can be subject to negotiation in the field of a request for waiver process, and providing that the S/C does not present internal modes in that range.

Test duration (s)

$$T = \frac{86.6}{n} \ln\left(\frac{f_{max}}{f_{min}}\right)$$

n is sweep rate (Oct/min)
f_{max} maximum frequency (Hz)
f_{min} minimum frequency (Hz)

Random Vibration Test (Example of levels, NASA-ST-7001)



Frequency (Hz)	PSD (G2/Hz)
20	0.01
80	0.04
500	0.04
2000	0.01
Composite	**6.8 Grms**

Slope between 20-80 Hz 3dB/oct
SLope between 500-2000 Hz -3dB/oct
Time duration e.g. Qualification 120 s

Notching

- Modification of sine or random vibration test spectrum

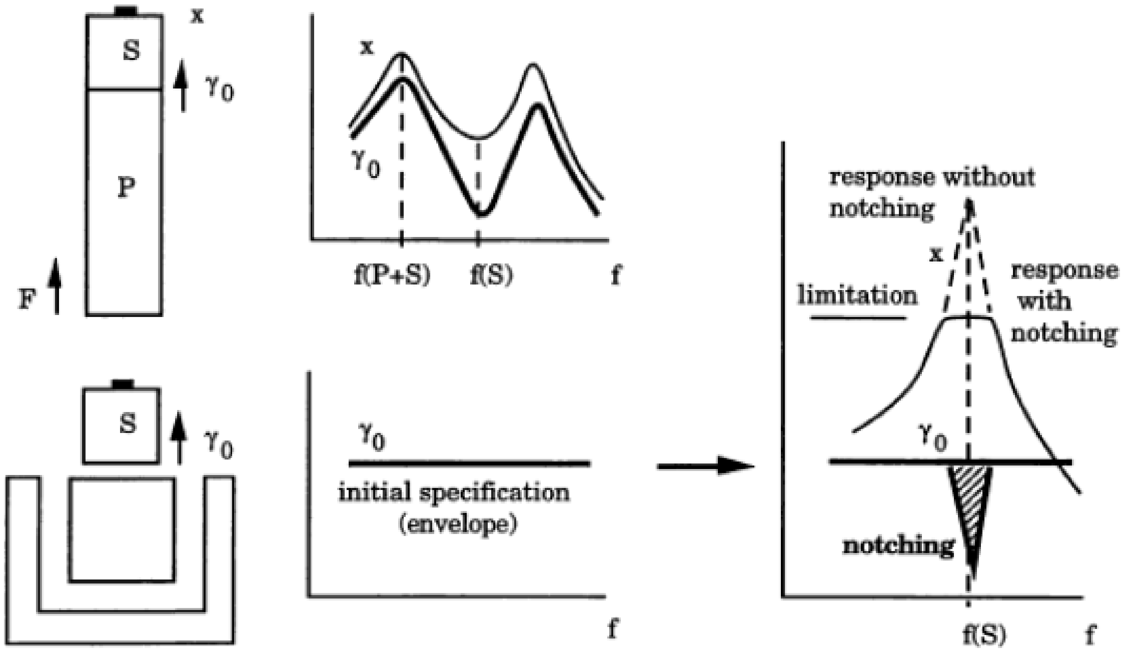
- Notching based on QSL
- Force limiting

Notching

- Based on QSL
  - The primary notching applies to the primary structure compared with the quasi static loads.
  - The secondary notching applies to the equipment when we consider a satellite or structural elements when we perform a test on an instrument or an equipment.
- Force Limited
  - Semi-Empirical

- NASA HDBK-7004B, Force Limited Vibration Testing, 2003
- Scharton, T.D., Force Limited Vibration Testing Monograph, NASA RP-1403, 1997
- NASA TM-1999-209382, Benefits of Force Limited Vibration Testing

Notching



- ❖ Girard, A., Dupuis, P.E., Bugeat, L.P., Notching in Random Vibration Testing, 1999, Proceedings European Conference on Spacecraft Structures, Materials and Mechanical Testing, Braunschweig, Germany, 4-6 November, pages 647-651
- ❖ Girard, A., Newerla, A., Methodology for Notching in Random Vibration, Proceedings 4e International Symposium on Environmental Testing for Space Programmes, Liege, Belgium, 12-14 June, 2001, pages 347--352

FLVT, Semi-Empirical Method (SEM)

$$W_{FF}(f) = C^2 M_o^2 W_{aa}(f) \qquad f \le f_o$$

$$W_{FF}(f) = C^2 M_o^2 W_{aa}(f) \left(\frac{f_o}{f} \right)^2 \qquad f > f_o$$

M_o	Component mass
$C^2, 1 \le C^2 \le 5$	Empirical factor
$W_{aa}(f)$	Enforced acceleration PSD
$W_{FF}(f)$	Interface force PSD
f	Frequency
f_o	Natural frequency (first significant mode)

Acoustic Noise Test

- Acoustic tests shall be performed to verify:
  - The ability of the structure and its equipment to withstand the vibrations induced by the specified acoustic field.
  - The random dynamic design environment for subsystems and equipment.

Acoustic Noise Test

Acoustic vibration test levels (A5 User's manual)

Octave band centre frequency (Hz)	Qualification Level (dB)	Protoflight Level (dB)	Acceptance level (flight) (dB)
	ref: 0 dB = 2 x 10^{-5} Pascal		
31.5	131	131	128
63	134	134	131
125	139	139	136
250	136	136	133
500	132	132	129
1000	126	126	123
2000	119	119	116
Overall level	142.5	142.5	139.5
Test duration	2 minutes	1 minute	1 minute

Fill factor

Special consideration shall be given to spacecraft which fill factor, calculated as the ratio of the maximum horizontal cross area of spacecraft including its appendages solar panels and antennae over the fairing is greater than 60 %.

Fill factor	0 to 60 %	60% to 85%	85%
Fill factor correction	0 %	Linear interpolation	100 %

100 % of fill factor correction corresponds to +4 dB at 31.5 Hz and + 2 dB at 63 Hz.

TOLERANCES

-2, +4 dB for 31.5 Hz band

-1, +3 dB for following bands

Herschel Spacecraft in LEAF

Mechanical Shock Design and Verification Handbook

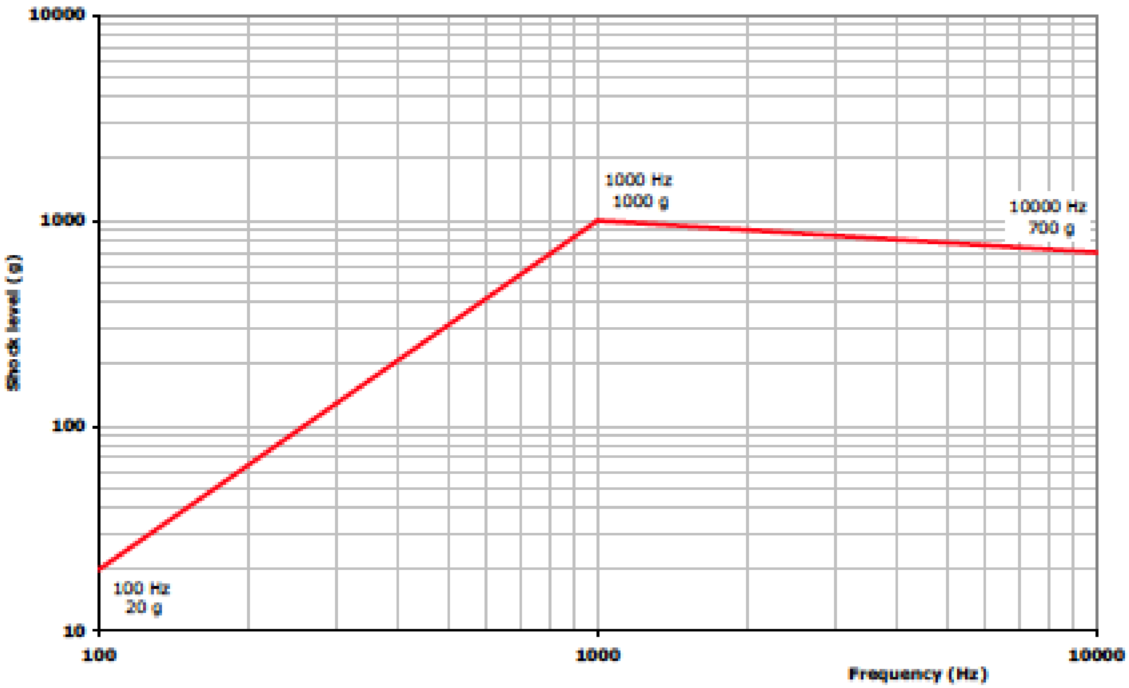
ESA-Contract No 20503/06/NL/SFe

ESA study manager: S. KIRYENKO, ESA/ESTEC, Noordwijk

Shock Test

Verification against shock loads

SRS (A5 User's Manual)



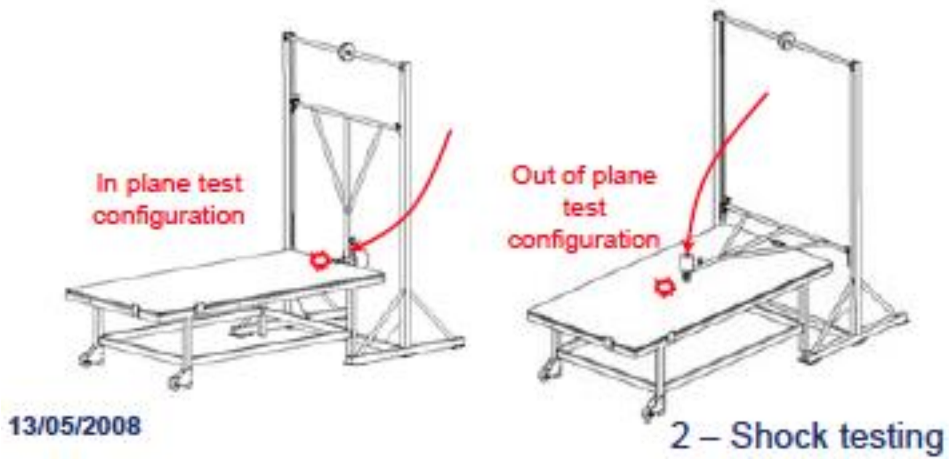
PAS 1194 – Shock spectrum of clamp band release

Shock can be performed using SHOck Generating UNit (SHOGUN)

SRS Ringing Table

Mechanical Shock Design and Verification Handbook

ESA-Contract No 20503/06/NL/SFe
ESA study manager: S. KIRYENKO, ESA/ESTEC, Noordwijk



Overview of Sub-Course E-32 Structures

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

Structural Requirements Flow Down

- Requirements specified in Launch Vehicle Manual on Spacecraft
- Requirements flow down from system to subsystems
  - Stiffness
  - Loads
  - Interfaces
  - …

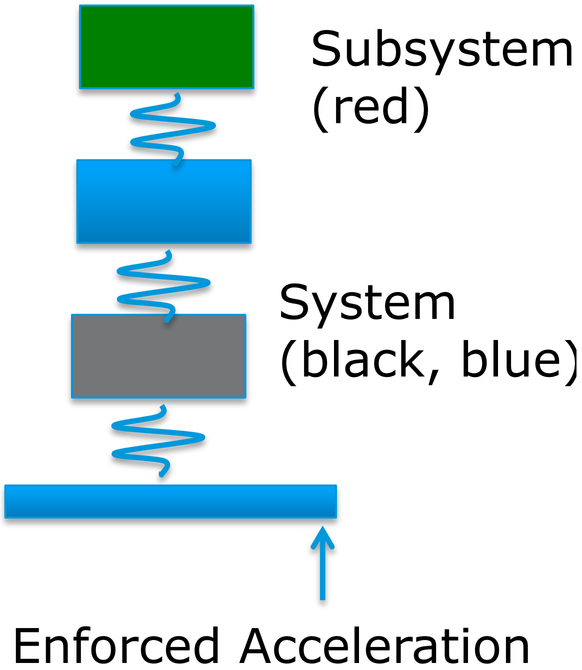
Stiffness

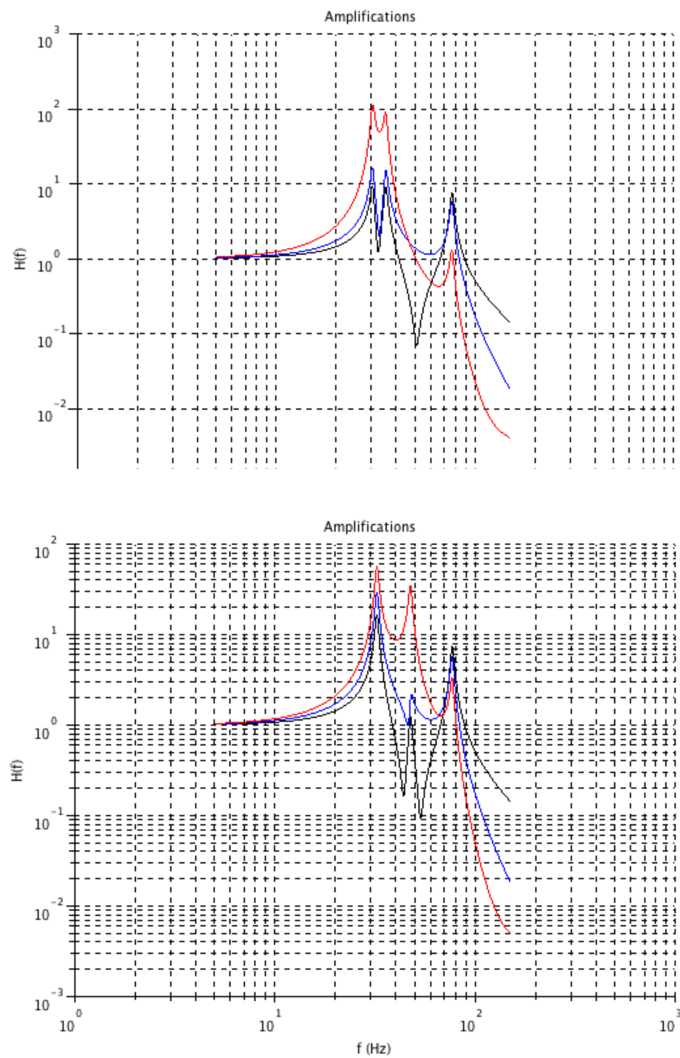
- Subsystem regarding system
  - Fixed interface
  - The lowest natural frequency requirement of the subsystem is $f_{subsystem} \geq f_{system}\sqrt{2}$ with associated significant modal effective mass to prevent vibration absorber effect

Examples

- System is spacecraft, subsystem is solar wing
- System is spacecraft, subsystem is instrument
- System is instrument, subsystem electronics box mounted to instrument
- ….

Stiffness (Cont'd)





$$f_{subsystem} = f_{system}$$

$$f_{subsystem} = f_{system}\sqrt{2}$$

Flow Downs of Loads

- Flow down of mechanical loads fom system to subsystem

- Static Loads
  - Limit loads (e.g. Mass Acceleration curve)
- Dynamic Loads
  - Enveloping sine vibration specification (potential over-testing)
  - Enveloping random vibration specification (potential over-testing)
  - Acoustic environment (System requirements) $\frac{A}{m} \geq 0.215\left(\frac{m^2}{kg}\right)$
  - Shocks (system requirements)
  - ….

Overview of Sub-Course E-32 Structures

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

Mechanical Interfaces (Handbooks)

- Adhesive Bonding Handbook, ECSS-E-HB-32-21A, 20/3/2011
- Insert Design Handbook, ECSS-E-HB-32-22A, 20/3/2011
- Threaded Fasteners Handbook, ECSS-E-HB-32-23A, 10/4/2010

Joining methods for space structures

- Welding (alloys or thermoplastics), Soldering, Grazing
- Mechanical fastening
- Adhesive bonding
- A combination of both bonding and mechanical fastening.

Space engineering

Adhesive bonding handbook

ECSS-E-HB-32-21A
20 March 2011

Adhesive handbook

This handbook is an acceptable way of meeting the requirements of adhesive materials in bonded joints of ECSS- E- ST- 32C.

Adhesive Bonding Aspects

Successful joining by adhesive bonding needs consideration of a large number of factors which influence the:

- design of the whole structure,
- design of the component parts of the structure,
- design of the joints between components of the structure,
- material selection,
- manufacturing, and
- inspection and maintenance.

It is therefore necessary to adopt a fully- integrated design and materials selection process. This point is emphasized throughout this handbook. Nonetheless, adhesive bonding is a tried and proven technique within aerospace industries, resulting from many years of research, development and analytical activities leading to practical implementation

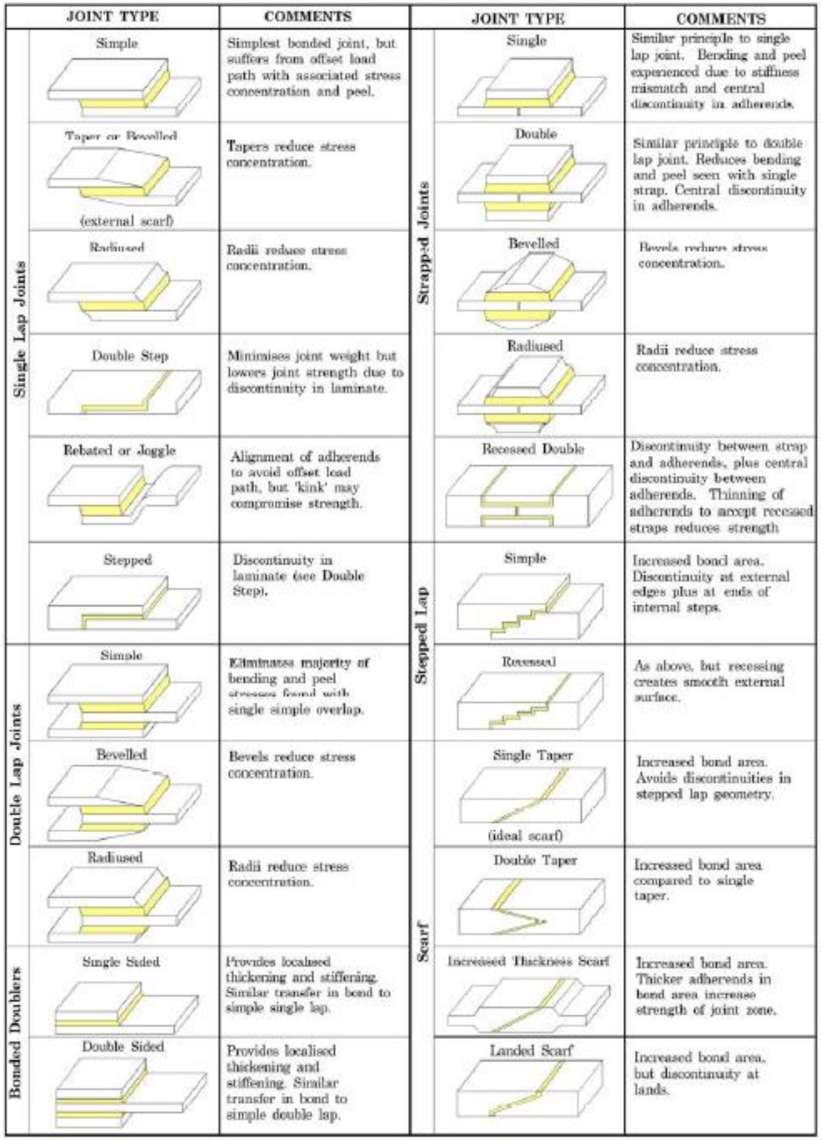
Types and Geometry Adhesive Bonded Joints

Space engineering

Adhesive bonding handbook

ECSS-E-HB-32-21A

20 March 2011



Group	Joint type	Comments
Single Lap Joints	Simple	Simplest bonded joint, but suffers from offset load path with associated stress concentration and peel.
Single Lap Joints	Taper or Bevelled (external scarf)	Tapers reduce stress concentration.
Single Lap Joints	Radiused	Radii reduce stress concentration.
Single Lap Joints	Double Step	Minimises joint weight but lowers joint strength due to discontinuity in laminate.
Single Lap Joints	Rebated or Joggle	Alignment of adherends to avoid offset load path, but 'kink' may compromise strength.
Single Lap Joints	Stepped	Discontinuity in laminate (see Double Step).
Double Lap Joints	Simple	Eliminates majority of bending and peel stresses found with single simple overlap.
Double Lap Joints	Bevelled	Bevels reduce stress concentration.
Double Lap Joints	Radiused	Radii reduce stress concentration.
Bonded Doublers	Single Sided	Provides localised thickening and stiffening. Similar transfer in bond to simple single lap.
Bonded Doublers	Double Sided	Provides localised thickening and stiffening. Similar transfer in bond to simple double lap.

Group	Joint type	Comments
Strapped Joints	Single	Similar principle to single lap joint. Bending and peel experienced due to stiffness mismatch and central discontinuity in adherends.
Strapped Joints	Double	Similar principle to double lap joint. Reduces bending and peel seen with single strap. Central discontinuity in adherends.
Strapped Joints	Bevelled	Bevels reduce stress concentration.
Strapped Joints	Radiused	Radii reduce stress concentration.
Strapped Joints	Recessed Double	Discontinuity between strap and adherends, plus central discontinuity between adherends. Thinning of adherends to accept recessed straps reduces strength
Stepped Lap	Simple	Increased bond area. Discontinuity at external edges plus at ends of internal steps.
Stepped Lap	Recessed	As above, but recessing creates smooth external surface.
Scarf	Single Taper (ideal scarf)	Increased bond area. Avoids discontinuities in stepped lap geometry.
Scarf	Double Taper	Increased bond area compared to single taper.
Scarf	Increased Thickness Scarf	Increased bond area. Thicker adherends in bond area increase strength of joint zone.
Scarf	Landed Scarf	Increased bond area, but discontinuity at lands.

Space engineering

Insert design handbook

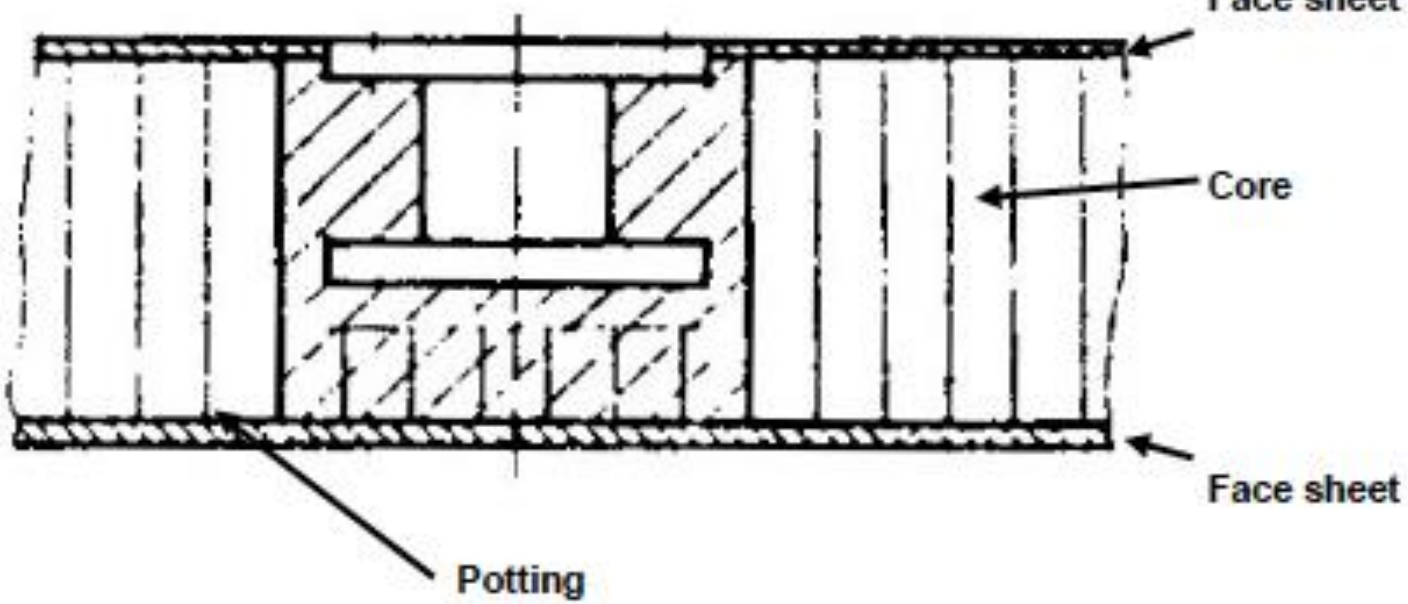
ECSS-E-HB-32-22A
20 March 2011

Insert Design handbook

- Inserts
- Sandwich panels

- Very detailed discussion about design, strength, stiffness and fatigue of inserts and sandwich construction, 488 pages of information

Honeycomb Panels & Insert



Space engineering

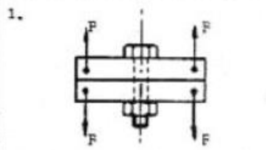
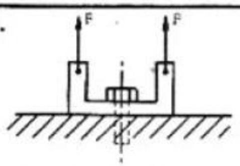
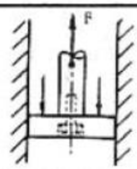
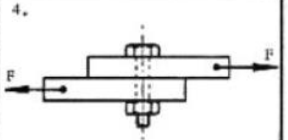
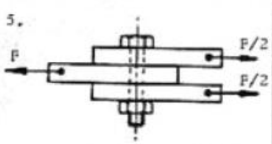
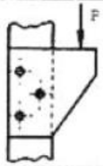
Threaded fasteners handbook

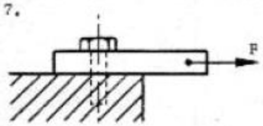
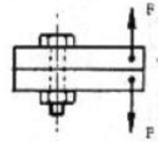
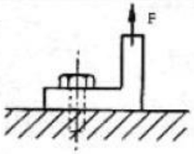
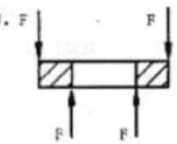
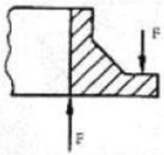
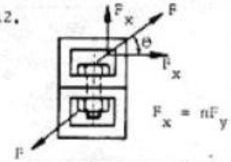
ECSS-E-HB-32-23A
16 April 2010

Threaded Fasteners Handbook

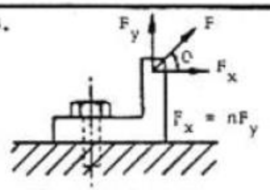
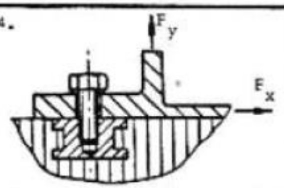
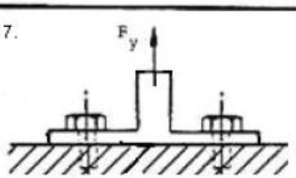
- The aim of the handbook is to assist the structural design engineers by presenting them in a single document with all the information relevant to the use of threaded fasteners in jointed spacecraft components

Main Joint Categories

GEOMETRY	NOTES	JOINT CATEGORY
1. 	1. SINGLE OR MULTIBOLTED	CONCENTRIC AXIAL
2. 	1. SINGLE OR MULTIBOLTED	CONCENTRIC AXIAL
3. 	1. SINGLE OR MULTIBOLTED	CONCENTRIC AXIAL
4. 	1. SINGLE OR MULTIBOLTED 2. BEARING LOAD TRANSFER 3. FRICTION GRIP LOAD TRANSFER	SYMMETRIC SHEAR
5. 	1. SINGLE OR MULTIBOLTED 2. BEARING LOAD TRANSFER 3. FRICTION GRIP LOAD TRANSFER	SYMMETRIC SHEAR
6. 	1. BEARING LOAD TRANSFER 2. FRICTION GRIP LOAD TRANSFER	ECCENTRIC SHEAR

GEOMETRY	NOTES	JOINT CATEGORY
7. 	1. SINGLE OR MULTIBOLTED 2. BEARING LOAD TRANSFER 3. FRICTION GRIP LOAD TRANSFER	SHEAR PLATE
8. 	1. SINGLE OR MULTIBOLTED	ECCENTRIC
9. 	1. SINGLE OR MULTIBOLTED	ECCENTRIC
10. 	1. PLAIN FLANGE	ECCENTRIC
11. 	1. WELDNECK FLANGE	ECCENTRIC
12. 	1. SINGLE OR MULTIBOLTED 2. LOAD RATIOS	a) CONCENTRIC AXIAL b) UNSYMMETRIC SHEAR c) COMBINED LOADING

Main Joint Categories (Cont'd)

GEOMETRY	NOTES	JOINT CATAGORY
13. 	1. SINGLE OR MULTIBOLTED 2. LOAD RATIOS IF:- a) $0 < n < 0.1$ b) $9 < n < \infty$ c) $0.1 < n < 9$	a) ECCENTRIC b) SHEAR PLATE c) COMBINED LOADING MAY BE LOW DUTY
14. 	1. SINGLE OR MULTIBOLTED 2. MOUNT TO SANDWICH PANEL WITH POTTED INSERT 3. MAY BE PART OF HEAT CONDUCTION PATH	LOW DUTY
15. 	1. NORMALLY SINGLE BOLTED	LOW DUTY
16. 	1. NORMALLY MULTIBOLTED	LOW DUTY
17. 	1. THIN FLANGES CAN DEFORM INDEPENDENTLY 2. PRYING MUST BE CONSIDERED	ANALYSE AS INDEPENDENT ECCENTRIC JOINTS