Structural Design and Analysis

- Lecture #24 - November 16, 2023
- Loads sources
- Factors and margins of safety
- Structural materials
- Structural analysis example – ISS mast canister
- Sources

Structural Design and Analysis

- Loads and Load Sources
  - Designing or Critical Loads
  - Load Information / Estimation
- Piece Parts Analysis
  - Margin of Safety Definition
  - Factors of Safety to use
  - Summary Table

Structural Design and Analysis

- Important Structural Concepts
  - Primary/Secondary Structure
  - Failsafe & Fracture Critical Structure
  - Aerospace Materials
  - Structural Failure

Loads

- "Designing Load" is the load that determines one or more structural characteristic of the part:
  - shape, thickness, strength, stiffness, material...
- Critical Load (somewhat synonymous) is more exactly the load that gives the minimum margin of safety (MS) for a part
  - MS represents the amount of extra structural capability you have over the applied load (elbow room)

Loads

- Examples of Critical Loads
  - pressurization loads for a rocket casing
  - launch loads for a spacecraft
  - thermal loads for a propulsion subsystem
  - crash loads for a car

Load Sources

- Where do these loads come from?
- For every part (subsystem) in your design, you should review every phase of its life and identify all loads that have the potential to be critical:
  - manufacturing & assembly
  - test (qualification, proof test)
  - transportation (truck or launch)
  - operation
  - contingencies (crash landing)

Load Sources

- Obtain or estimate loads
  - look up loads in reference books
  - ask other groups to determine loads
  - guesstimate for the purposes of starting analysis
- Calculate all margins of safety

Launch Vehicle Loads

- Max q - Aerodynamic Loads
  - $q = 1/2\ \rho v^2$
  - maximum pressure and bending on vehicle
- Max g's
  - usually occurs at stage burnout
  - maximum axial load on vehicle and payload
- Abrupt environmental & vehicle changes
  - internal and external pressure drop
  - dramatic thermal changes

Launch Vehicle Loads

- Staging shock loads
  - high g's, high frequency
- Random vibration and acoustics – equivalent g’s= $\sqrt{\frac{\pi}{2} PSD\, f_n\, Q}$
- Some of these loads apply to payload as well

Launch Vehicle Failures

- LV failures are tied to the following subsystems
  - Propulsion (70%)
  - Avionics (11%)
  - Separation (8%)
  - Electrical (7%)
  - Structural (2%)
- Propulsion or Control System Failure More Common
  - Conestoga, LLV, Ariane V, and Antares
  - Structural Failure Relatively Rare
  - AmRoc, Shuttle, Pegasus, and Falcon 9

Spacecraft On-Orbit Loads

- Accelerations
  - orbital accelerations
  - gravity gradient
  - spinning
  - on-board disturbances
  - thrusting (attitude control, reboost)
- Thermal Loads
  - sun / shadow thermal gradients
  - eclipse effects (thermal snap)
- Other Special Cases
  - EVA loads (corners & edges)
  - rendezvous & docking
- **Generally spacecraft are designed by launch loads!**

Planetary Vehicle Loads

- Vibration loads from traversing rough terrain
- Launch / landing loads
- Maneuvering loads
  - tight turn
  - driving on an incline
  - losing traction / support on one wheel
- Crash loads
  - driving into a big boulder
  - rolling vehicle in unstable soil
  - safety is primary consideration

Piece Parts Analysis

- Structural analysis of a system consists of at least the following three tasks
  - Load Cycle Modeling (system-level) - iterative process
  - Piece-Part Analysis (static) - minimum margins of safety
  - Fracture and Fatigue Analysis (dynamic) - safe life analysis
- Piece Parts Analysis
  - Identify all loads on each part / subsystem
  - Calculate margins of safety
  - Tabulate minimum margins of safety

Factors & Margins of Safety

- Limit Loads: maximum loads expected (applied loads)
- Yield Load and Ultimate Load
- Factors of Safety : fixed, specific numbers imposed by the sponsor (or your own good sense) that reflect
  - how uncertain you are of the load or structure
  - how safe you want to be
  - examples: 10 for bridges, 5 for ground handling equip, 2 for a/c

Required Factors of Safety for Metal Structures

Minimum Factors of Safety for Metallic Flight Structures		Yield	Ultimate
Prototype		1.00	1.40
Qualification Test Factor	1.40		
Protoflight		1.25	1.40
Proof Test Factor	1.20		
Factors for hardware post-separation, not going to orbit, prototype program		1.00	1.25
Qualification Test Factor	1.25		

Source: JSC 65828B, change 1 (7/15/2014)

Factors of Safety for Non-Metallic Structures

Minimum Factors of Safety for Non-metallic Flight Structures		Yield	Ultimate
Prototype			
Uniform areas		N/A	1.40
Discontinuity areas		N/A	2.00
Qualification Test Factor	1.40		
Acceptance/Proof Test Factor	1.05		
Protoflight			
Uniform areas			1.50
Discontinuity areas			2.00
Acceptance/Proof Test Factor	1.20		

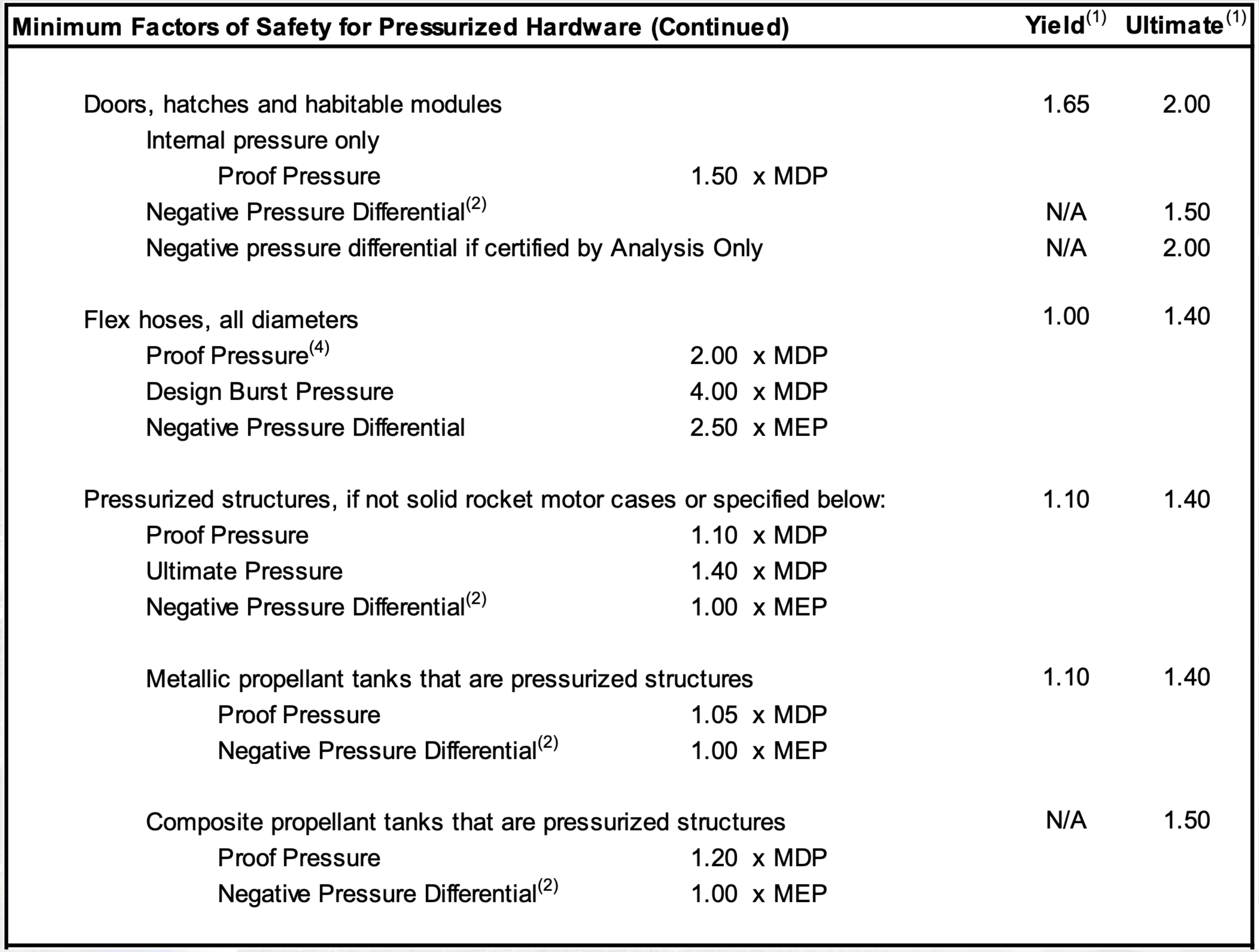
Source: JSC 65828B, change 1 (7/15/2014)

Factors of Safety for Soft Goods (Inflatables)

Minimum Factors of Safety for Structural Soft Goods		Ultimate
Safety critical		4.00
Qualification Test Factor	4.00	
Acceptance/Proof Test Factor	1.20	
Not safety critical		2.00
Qualification Test Factor	2.00	
Acceptance/Proof Test Factor	1.20	

Source: JSC 65828B, change 1
(7/15/2014)

Factors of Safety for Pressurized Hardware (partial)



Minimum Factors of Safety for Pressurized Hardware (Continued)		Yield(1)	Ultimate(1)
Doors, hatches and habitable modules		1.65	2.00
Internal pressure only			
Proof Pressure	1.50 x MDP		
Negative Pressure Differential(2)		N/A	1.50
Negative pressure differential if certified by Analysis Only		N/A	2.00
Flex hoses, all diameters		1.00	1.40
Proof Pressure(4)	2.00 x MDP		
Design Burst Pressure	4.00 x MDP		
Negative Pressure Differential	2.50 x MEP		
Pressurized structures, if not solid rocket motor cases or specified below:		1.10	1.40
Proof Pressure	1.10 x MDP		
Ultimate Pressure	1.40 x MDP		
Negative Pressure Differential(2)	1.00 x MEP		
Metallic propellant tanks that are pressurized structures		1.10	1.40
Proof Pressure	1.05 x MDP		
Negative Pressure Differential(2)	1.00 x MEP		
Composite propellant tanks that are pressurized structures		N/A	1.50
Proof Pressure	1.20 x MDP		
Negative Pressure Differential(2)	1.00 x MEP		

MDP=maximum design pressure

MEP=maximum external pressure

Source: JSC 65828B, change 1 (7/15/2014)

Factors & Margins of Safety

- Margins of Safety are calculated as follows:

$$MoS = \frac{\text{allowable stress (yield or ultimate)}}{FoS\ \text{(yield or ultimate)} \times \text{limit applied stress}} - 1$$

- Requirement is to ensure that all margins of safety are non-negative (i.e., 0 is okay, <0 is unacceptable)
- Beware: There are other definitions of these terms in engineering, but the above approach is the most common in aerospace and is mandated by NASA (and *is* what we will use in ENAE 484)

Primary, Secondary, and Tertiary Structure

- Primary structure is the system's backbone (carries all of the major loads imposed on vehicle)
- Secondary structure includes all essential appendages and support structures (such as solar arrays, antennas, & fuel tanks)
- Tertiary structures are less-essential mounting hardware (brackets, component housings, connector panels)

Example of Primary Structure

- Thin-walled cylindrical launch vehicle
- Challenge is to figure out how to react shear & torsion stresses
- Buckling of skin is most common failure mode
- Buckling of a cylindrical section:

$$\sigma_{crit} = \frac{Et}{R\sqrt{3(1-\nu^2)}}$$

Failsafe and Fracture Critical Structure

- Catastrophic failure is generally defined by customer
- Failsafe structure can take redistributed loads after failure (i.e., not single point failures); shall release no hazardous mass; shall not change dynamics significantly; shall have no fatigue problems
- Low-risk structure is not primary structure; has only a remote possibility of failure; will not propagate a crack in 4 lifetimes
- Fracture critical parts must be labeled and analyzed as such, then inspected, treated, and tracked more carefully than conventional parts

Critical Structure

- Requirement for low fracture criticality $\sigma_{max} < \dfrac{\sigma_{tu}}{4(1-0.5R)K_t}$
- Critical Items List (CIL) contains all parts that
  - are deemed criticality 1 by FMEA (ie, single point failures)
  - are fracture critical (ie, stressed to the point where a flaw will grow to critical size)
- Crack Growth Analysis (FLAGRO)
  - All FC parts must be shown good for four lifetimes of load cycles with an initial flaw (determined by Non Destructive Investigation (NDI))

Aerospace Materials

- Comparison of specific stiffness, specific strength, and buckling parameter for a variety of aerospace metals and composites
- Definition of Structural Failure
  - Detrimental Yield vs Textbook Yield
    - deformation that detrimentally affects functionality of system
    - 0.2% Tresca yield condition (assumes system linear in first place)
  - Ultimate Failure
    - any material rupture or loss of functionality

Material Strength & Stiffness

- Typical yield & ultimate strengths

low strength steel	yield: 36 ksi	ult: 58 ksi
high strength steel	yield: 102 ksi	ult: 116 ksi
titanium	yield: 134 ksi	ult: 145 ksi
aluminum	yield: 37 ksi	ult: 42 ksi

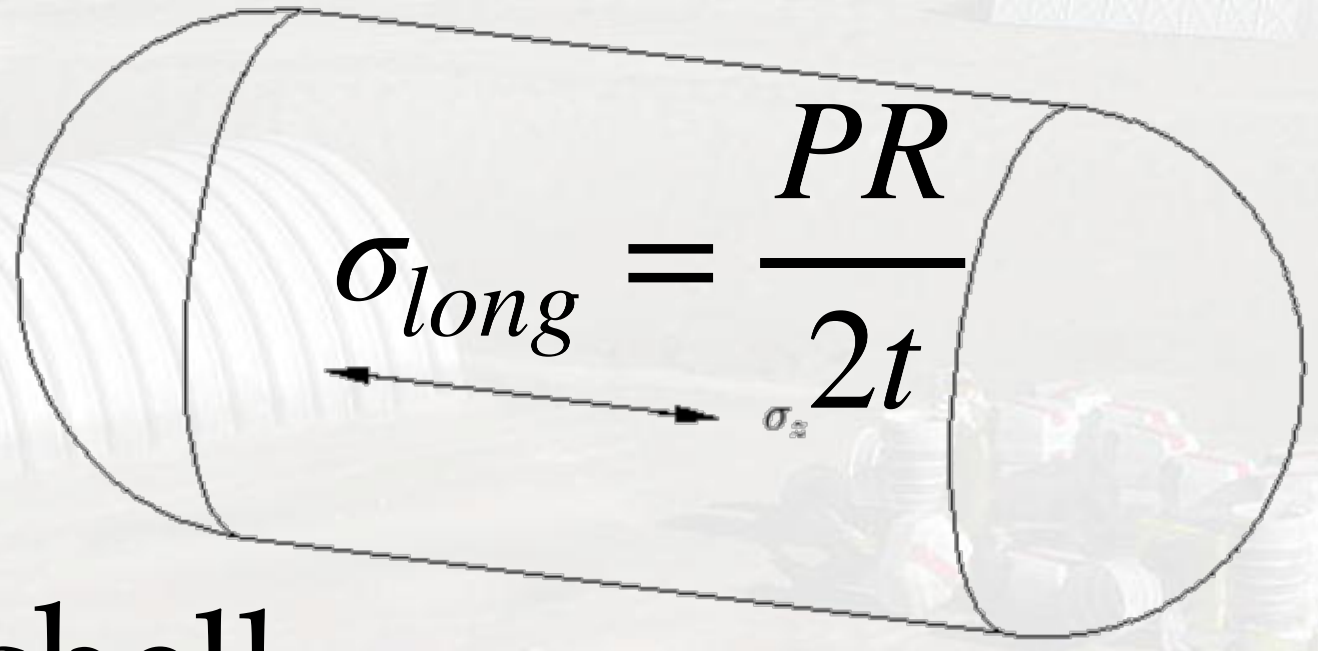
- Stiffness versus strength designs

aluminum	$\rho : 0.10 \text{ lb/in}^3$	$E/\rho : 100$	$\sigma_u/\rho : 420$
low σ_u steel	$\rho : 0.28 \text{ lb/in}^3$	$E/\rho : 102$	$\sigma_u/\rho : 204$
high σ_u steel	$\rho : 0.29 \text{ lb/in}^3$	$E/\rho : 98$	$\sigma_u/\rho : 390$
titanium	$\rho : 0.16 \text{ lb/in}^3$	$E/\rho : 109$	$\sigma_u/\rho : 906$

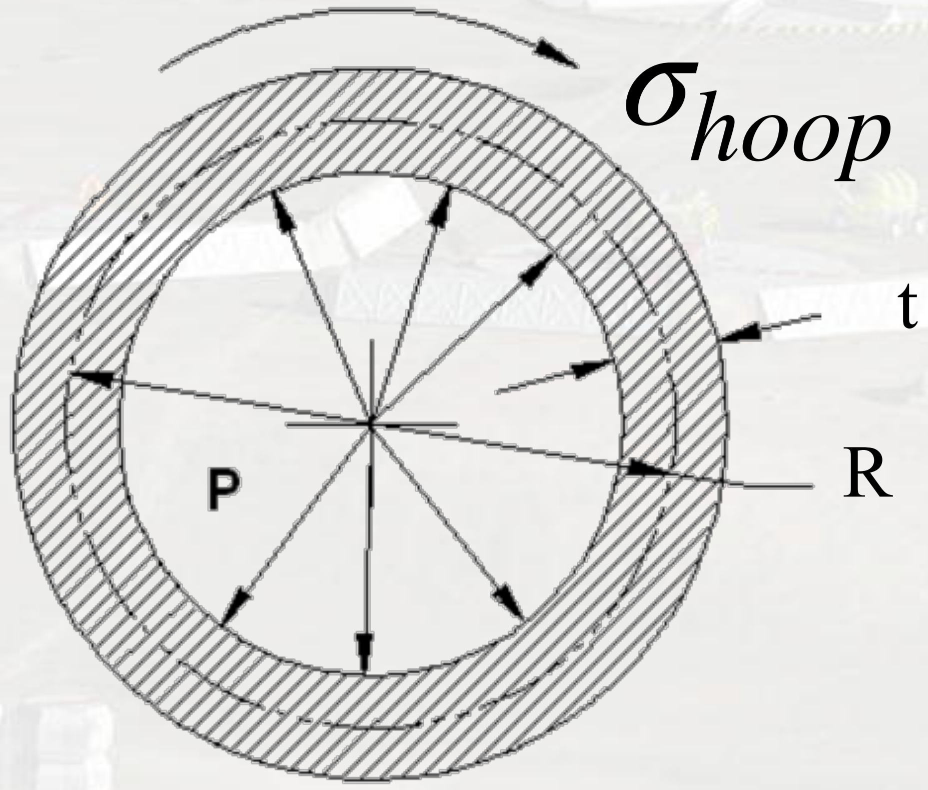
- Conclusion: for aerospace structures - start with aluminum

Structural Analysis

- Some key structural formulas that are handy to have for early (back-of-the-envelope) design analyses:
  - Spring & beam stiffnesses
  - Beam natural frequencies
  - Euler buckling loads
  - Stresses in simple pressurized shell
  - Random vibe and acoustic equivalent g's
- Get a copy of Roark and Young, *Formulas for Stress and Strain*
  - available in the library or as Excel spreadsheets from www.roarksformulas.com



$$\sigma_{long} = \frac{PR}{2t}$$

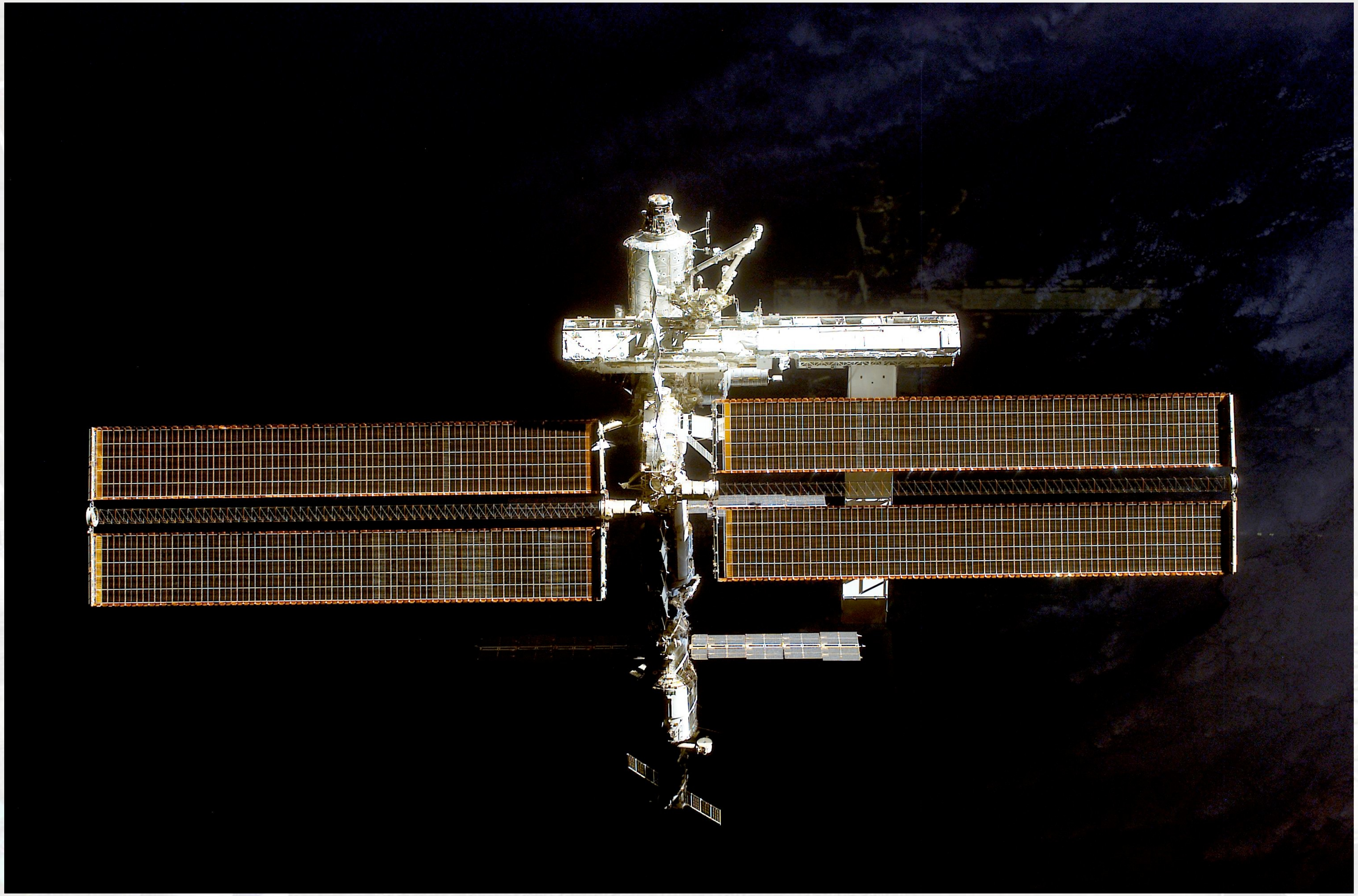


$$\sigma_{hoop} = \frac{PR}{t}$$

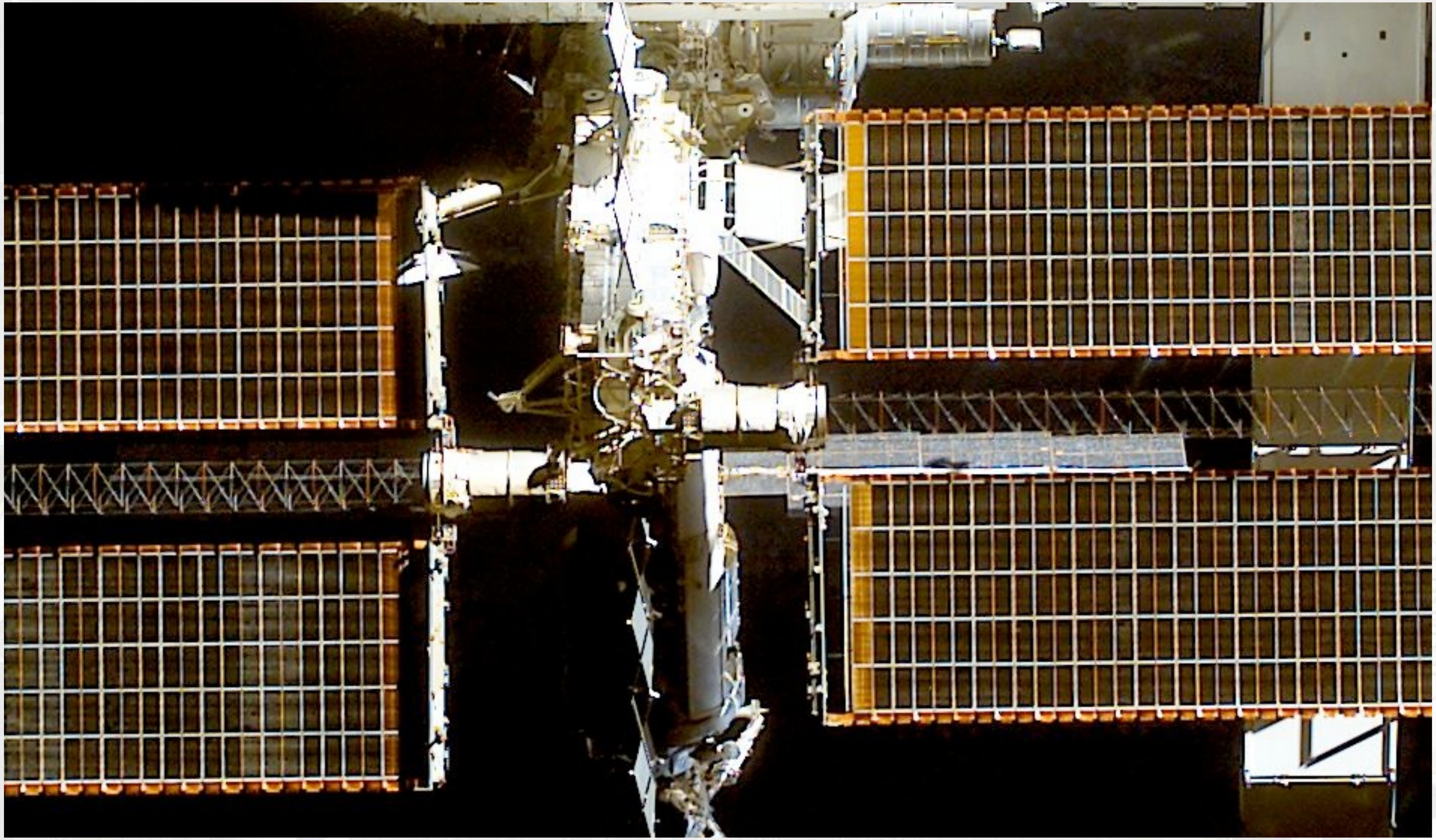
Structural Analysis

- Definition of Example Problem
- Definition of Load Cases
- Analysis of Stresses
- Tabulation of Margins of Safety
- Identification of Critical Load Case

International Space Station

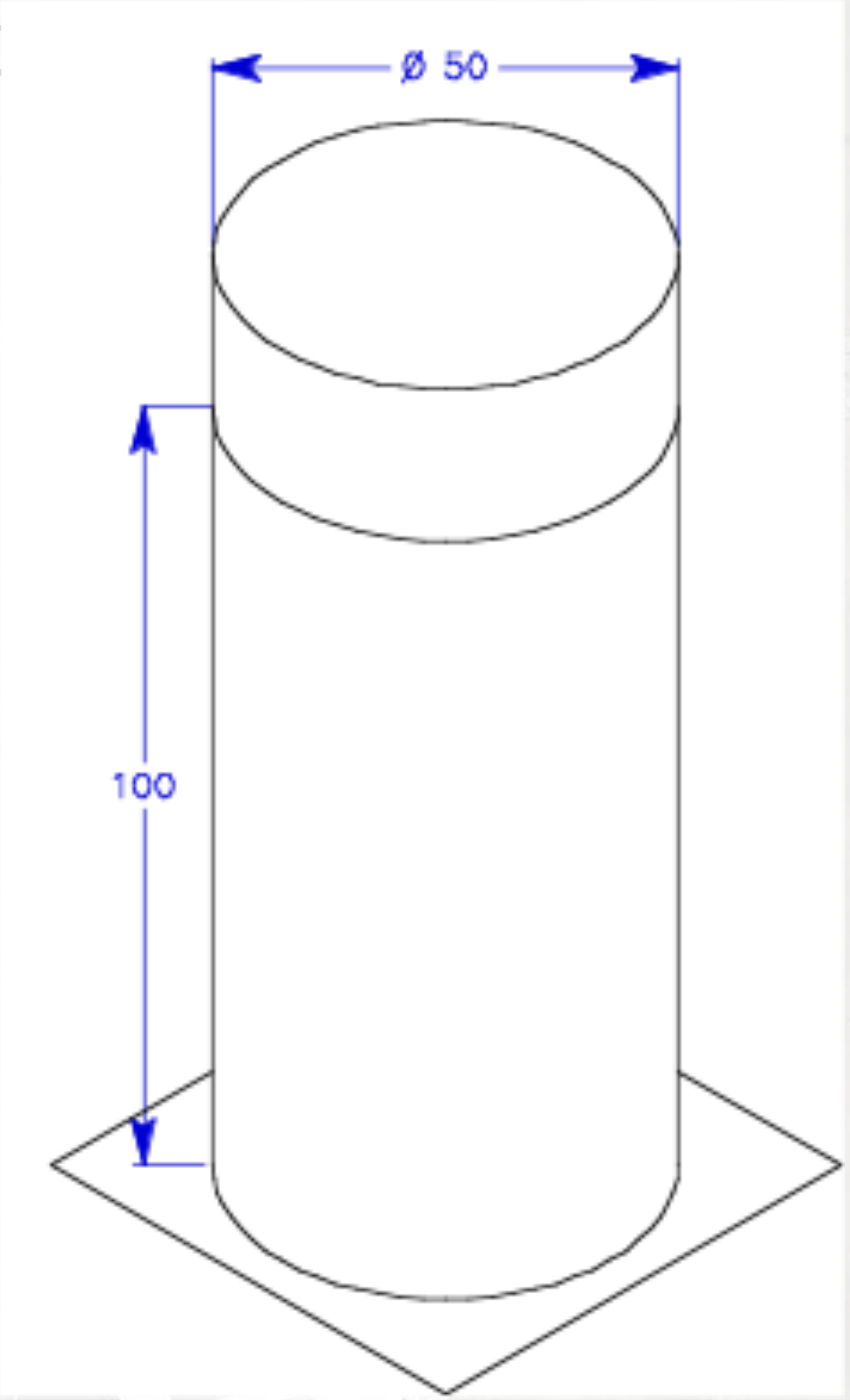


Close-up of Z1 Truss



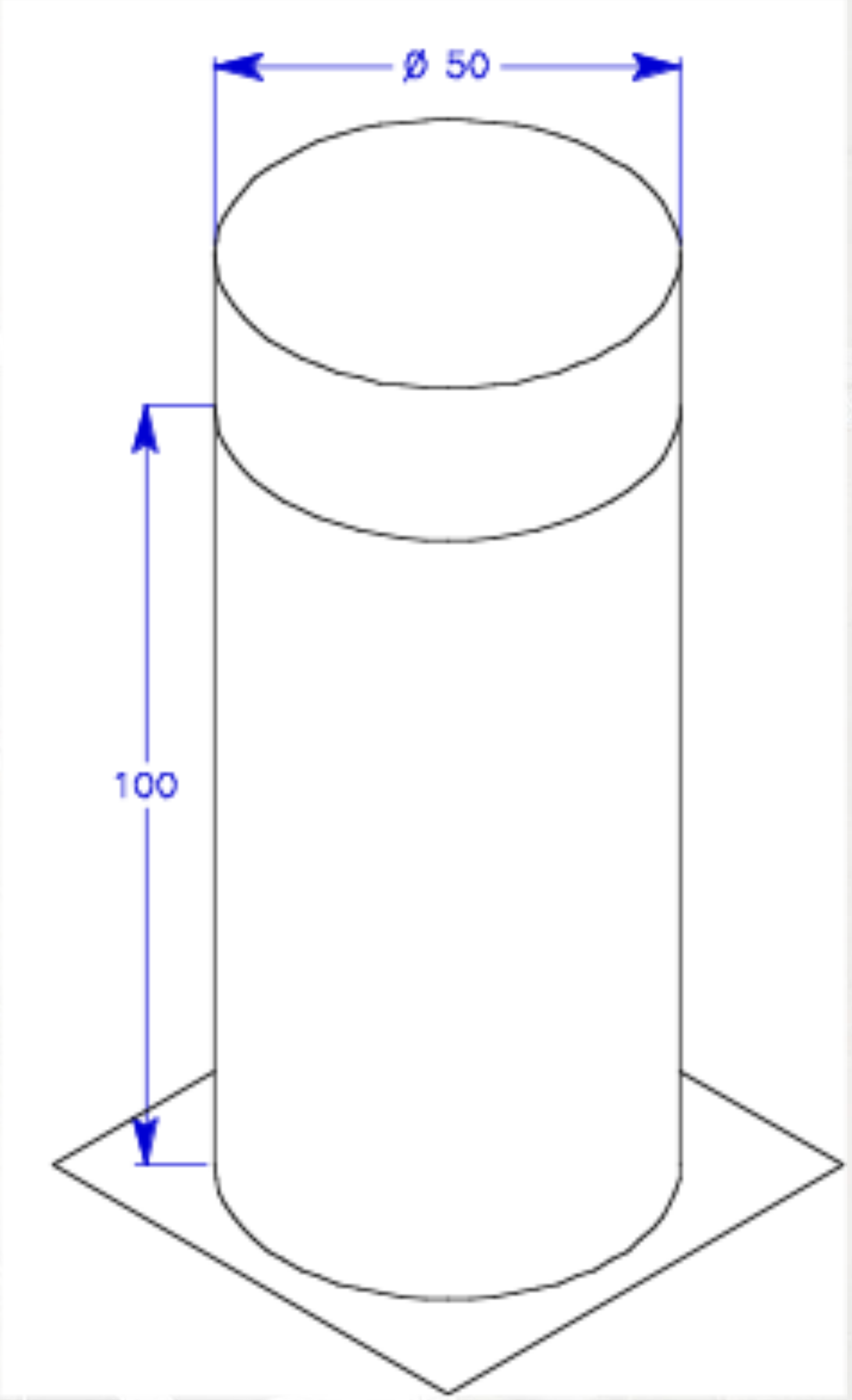
Structural Example

- Storage canister for ISS solar array deployment
- 200 lb tip mass
- Cantilever launch configuration
- Thin-wall aluminum shell structure



Loads Sources

- Launch
  - Accelerations
  - Pressurization
  - Acoustics
  - Random Vibration
  - Thermal
- Crash Landing
- On-Orbit



Structural Parameters

$R = 25\ in$ $\quad \ell = 100\ in$ $\quad t = 0.10\ in$ $\quad \rho = 0.10\ \dfrac{lbs}{in^3}$

$$I = \frac{\pi}{4}\left(R_o^4 - R_i^4\right) \cong \pi R^3 t = 4800\ in^4$$

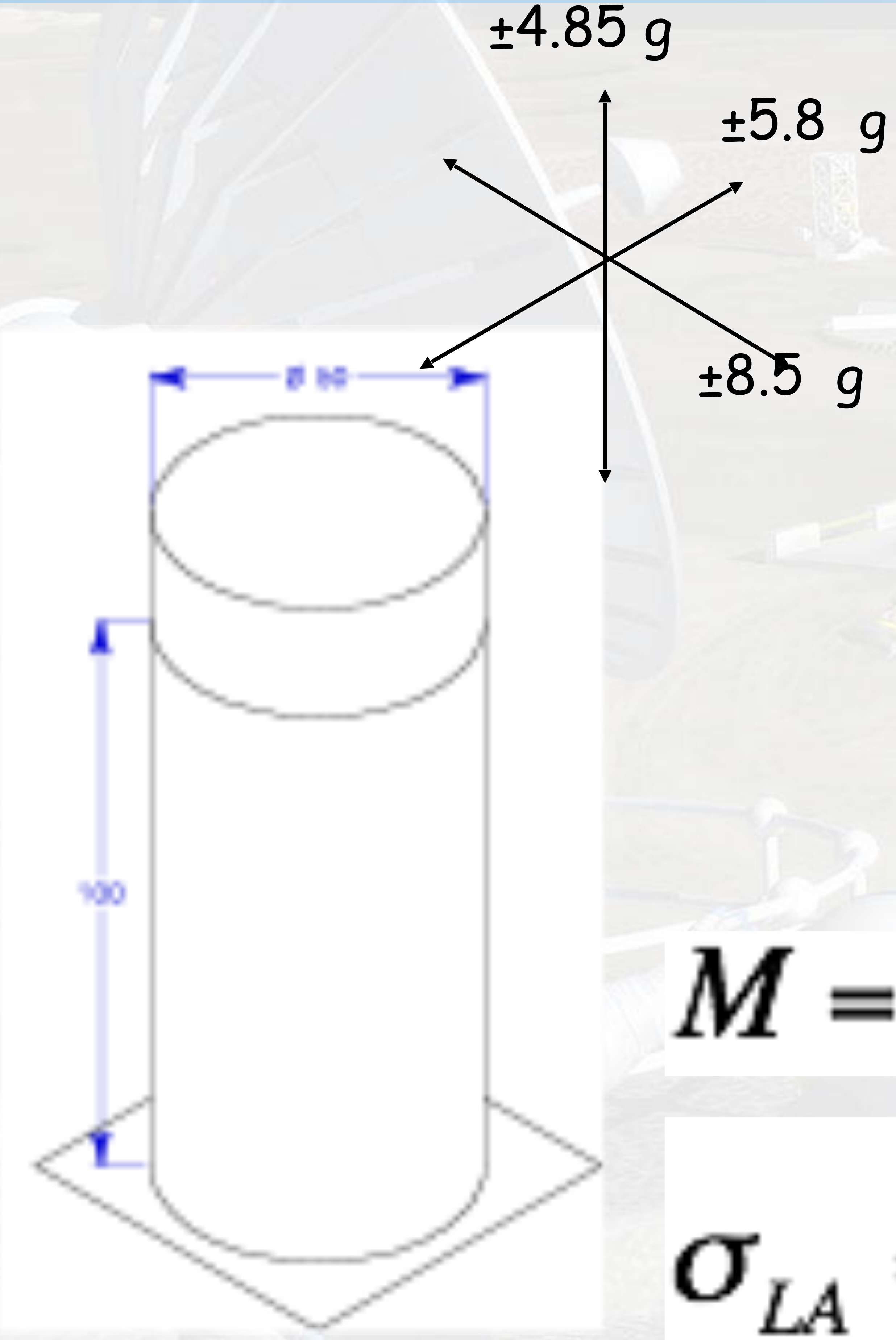
$E = 1 \times 10^7\ psi$ $\quad \alpha = 13 \times 10^{-6}\ \dfrac{in}{in \cdot {}^\circ F}$

$W_{canister} = 2\pi\rho t R\ell = 157\ lbs$ $\quad W_{tip} = 200\ lbs$

$\sigma_{Ty} = 37\ ksi$ $\quad \sigma_{Tu} = 42\ ksi$

$g = 386.4\ \dfrac{in}{\sec^2}$ $\quad A = 2\pi R t = 15.71\ in^2$

Launch Accelerations



$$FOS = 1.4$$

$$\sigma_{LA} = \frac{MR}{I} + \frac{W_{tip}}{A} g_x$$

$$M = g_{transverse}\left(W_{canister} h_{CG} + W_{tip} h_{tip}\right)$$

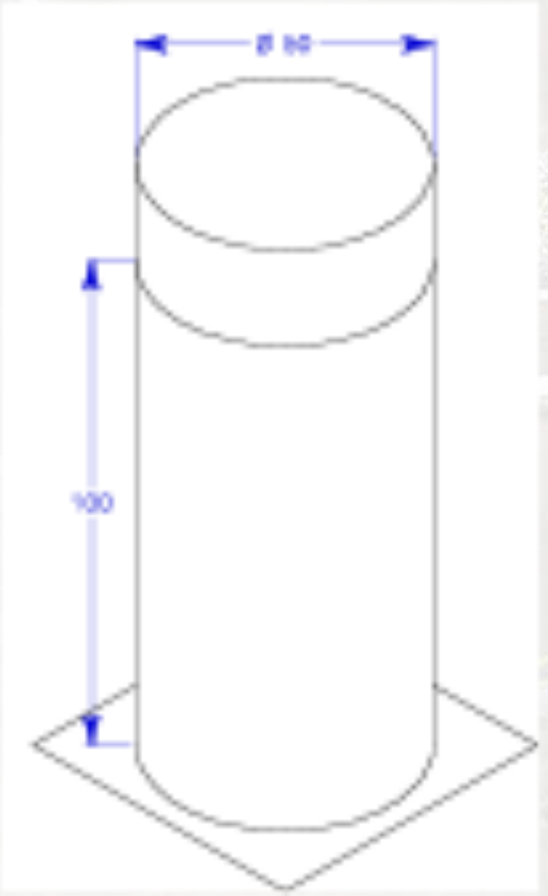
$$g_{transverse} = \sqrt{5.8^2 + 8.5^2} = 10.3\ g$$

$$M = 10.3(157 \cdot 50 + 200 \cdot 100) = 286{,}900\ in \cdot lb$$

$$\sigma_{LA} = \frac{(286900 inlb)(25in)}{4800in^4} + \frac{200lb}{15.71in^2} 4.85$$

$$\sigma_{LA} = 1494 + 61.75 = 1556\ psi$$

Pressurization Loads



$$FOS = 3.0$$

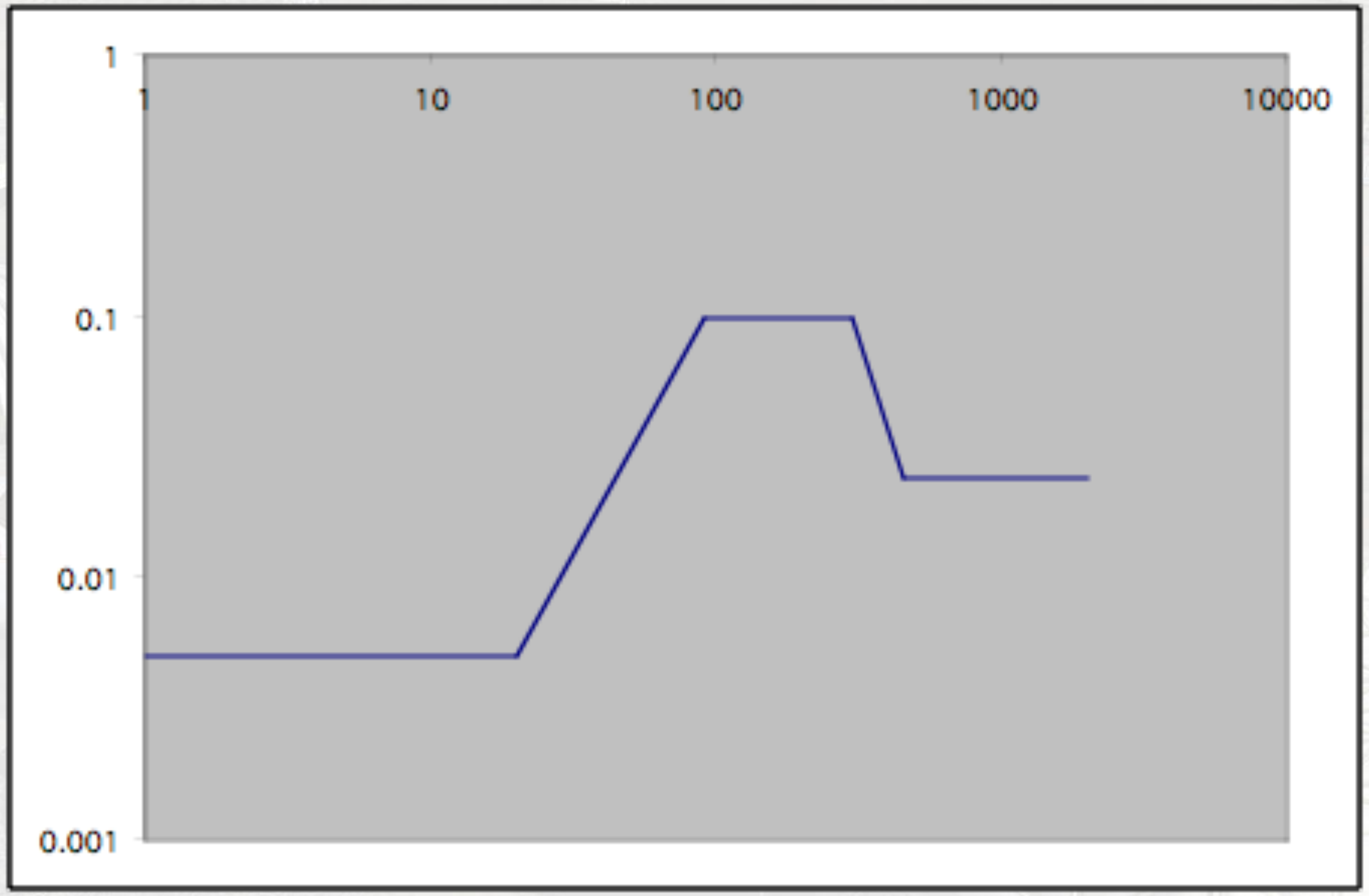
$$\sigma_{Hoop} = \frac{PR}{t} = \frac{(14.7\,psi)(25in)}{0.1in} = 3675\ psi$$

$$\sigma_{Longitudinal} = \frac{PR}{2t} = 1838\ psi$$

Launch Vehicle Vibration Environment

Frequency (Hz)

Power Spectral Density
(g^2/Hz)



Random Vibration Loads

Miles' Equation

$$RLF_n = \sqrt{\frac{\pi}{4\zeta} f_n (PSD@f_n)}$$

$$FOS = 3.0$$

Fundamental Bending Frequency for Cantilevered Beam w/ Tip Mass

$$f_1 = \frac{1.732}{2\pi}\sqrt{\frac{EIg}{W_{tip}\ell^3 + 0.236W_{canister}\ell^3}} = 80\ Hz$$

f_n	ζ
<150 Hz	.045
150-300 Hz	.020
>300 Hz	.005

ζ = critical damping ratio

$$RLF = 7.93\ g$$

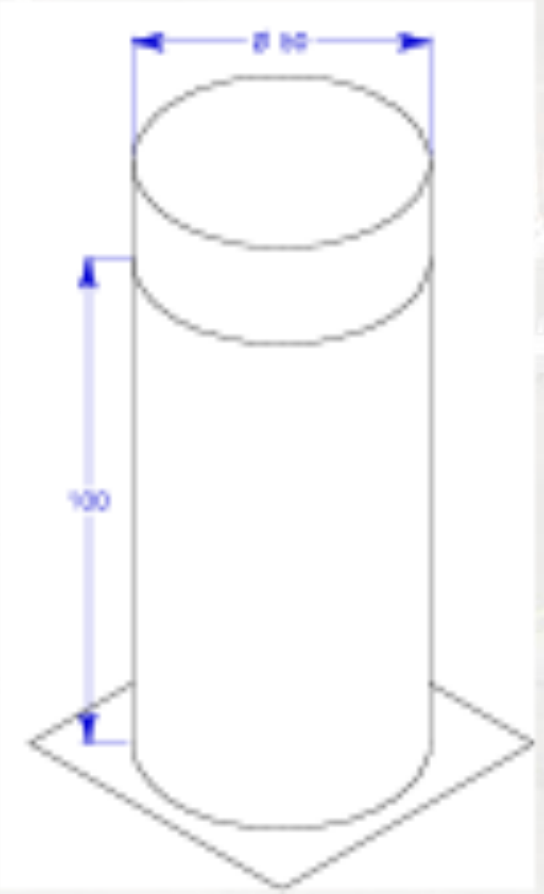
$$M = 220,700\ in \cdot lbs$$

$$\sigma_{RV} = \frac{MR}{I} = 1150\ psi$$

(repeat for each axis)

vibrationdata.com

Thermal Loads



$$FOS = 1.4$$

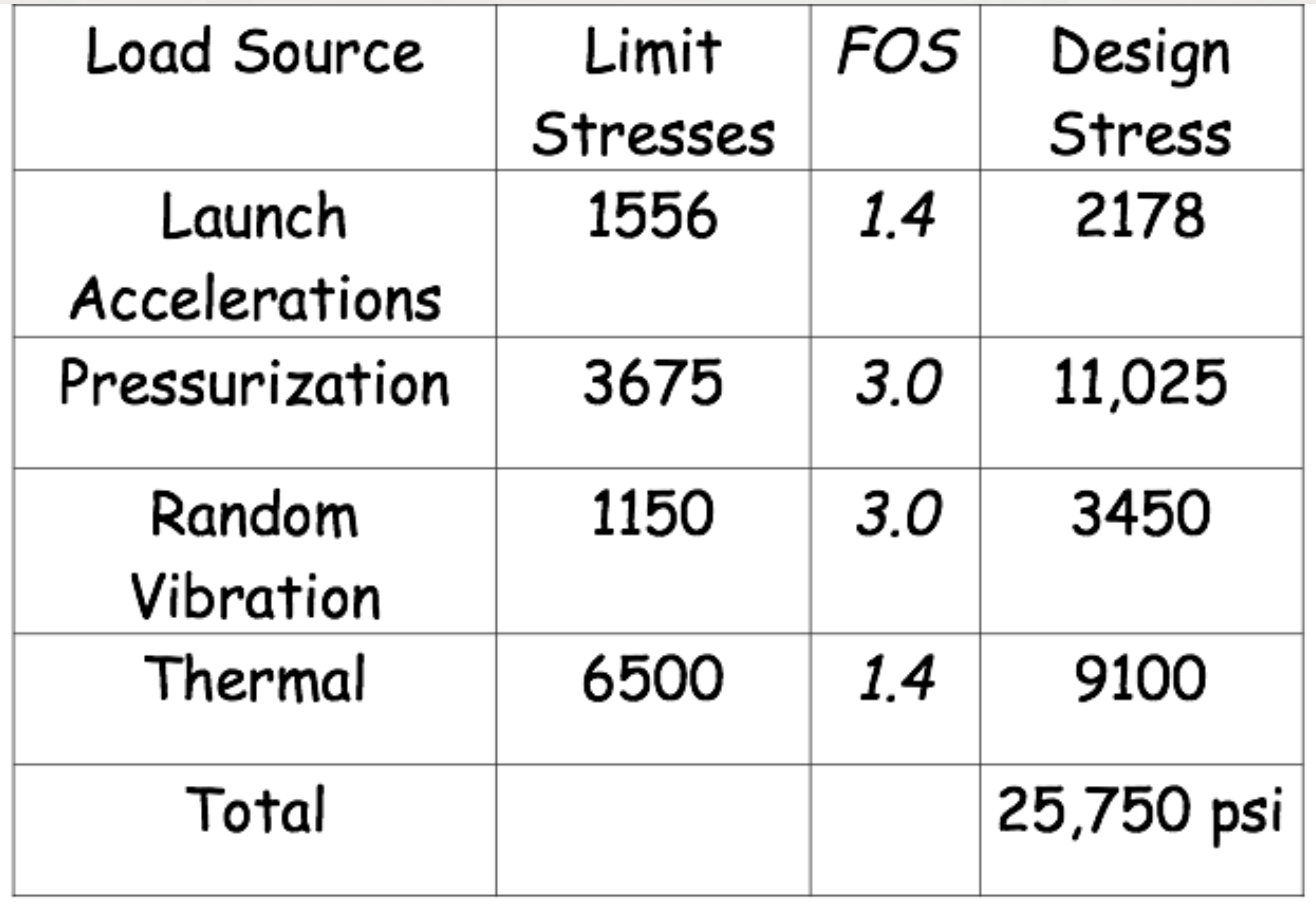
$$\Delta\ell = \alpha \cdot \Delta T \cdot \ell$$

$$\Delta\ell = 13 \times 10^{-6} \cdot -100^\circ F \cdot 100 = .13\ in$$

Assume support structure shrinks only half as much as canister

$$\sigma_{Thermal} = E\varepsilon = 10^7 \cdot \frac{.5 \times .13}{100} = 6500\ psi$$

Launch Loads Summary



Load Source	Limit Stresses	FOS	Design Stress
Launch Accelerations	1556	*1.4*	2178
Pressurization	3675	*3.0*	11,025
Random Vibration	1150	*3.0*	3450
Thermal	6500	*1.4*	9100
Total			25,750 psi

$$MS = \frac{Allowable\ Load}{Design\ Load} - 1 = \frac{37{,}000}{25{,}750} - 1 = 43.7\%$$

Observations about Launch Loads

- Individual loads could be applied to same position on canister at same times - conservative approach is to use superposition to define worst case
- 43% margin indicates that canister is substantially overbuilt - if launch loads turn out to be critical load case, redesign to lighten structure and reduce mass.

Sources (Downloadable Online)

- JSC 65828, rev. B, change 1, *Structural Design Requirements and Factors of Safety for Spaceflight Hardware*
- JSC 65829, rev. A, *Loads and Structural Dynamics Requirements for Spaceflight Hardware*
- NASA-STD-5002A, *Load Analyses of Spacecraft and Payloads*
- NASA-HDBK-7005, *Dynamic Environmental Criteria*
- NASA CR-124075, rev. A, *Isogrid Design Handbook*
- NASA TM-X-73305/6/7, *Astronautic Structures Manual* (3 volumes, 2610 pgs.)
- https://femci.gsfc.nasa.gov/femcibook.html