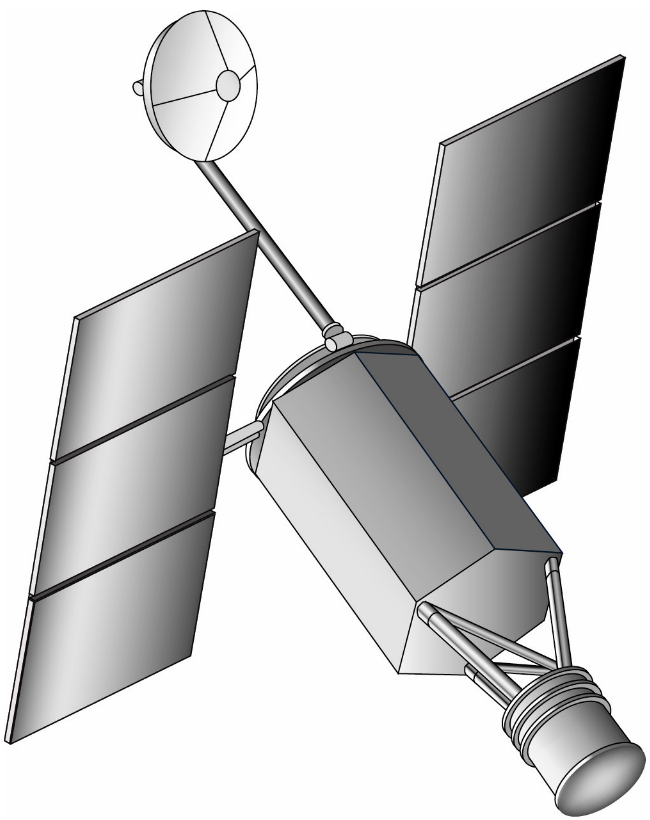
Spacecraft Structures

Tom Sarafin
Instar Engineering and Consulting, Inc.
6901 S. Pierce St., Suite 384, Littleton, CO 80128
303-973-2316 • tom.sarafin@instarengineering.com

Outline

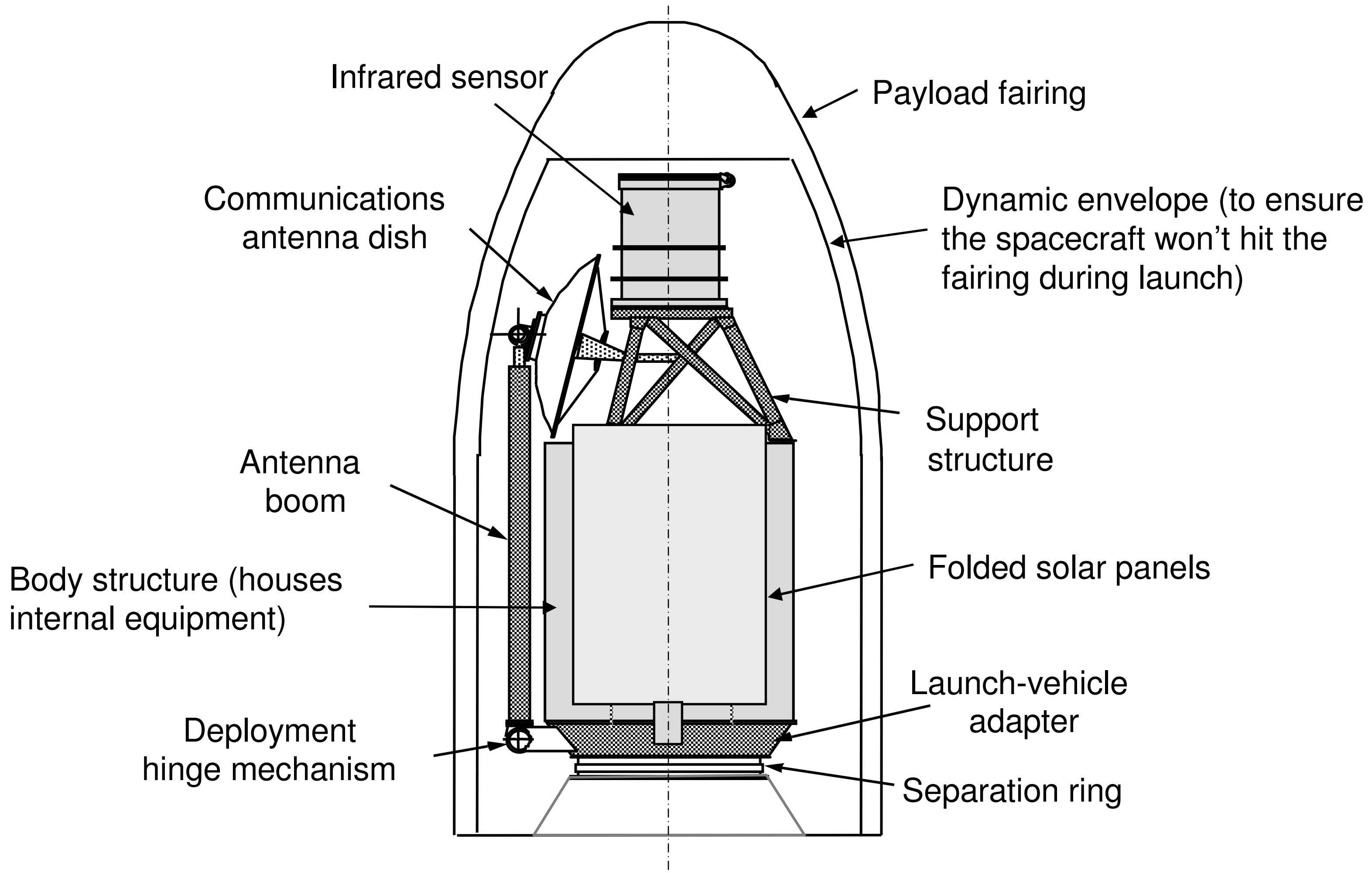
- Functions
- Being Compatible with the Launch Vehicle
- How Launch Affects Things Structurally
- Modes of Vibration
- Selecting Materials
- Other Considerations
- Fields of Expertise Needed to Develop a Spacecraft Structure
- Summary

What Are the Functions of the Spacecraft Structure?



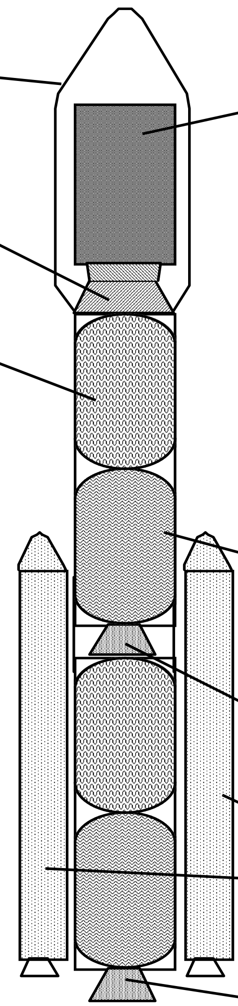
- Physically support spacecraft equipment
- Maintain alignment of sensors and antennas during the mission …
  - – without excessive permanent change (e.g., from launch)
  - – without excessive temporary change (from temperature changes in orbit)
  - – without excessive on-orbit vibration (***jitter***), which could prevent us from controlling the vehicle or operating instruments such as telescopes
- Protect sensitive components or people from vibration during launch, radiation in space, or other hazards

We Have to Design the Spacecraft to Fit Within the Launch Vehicle*



*or plan to assemble it in space

The Spacecraft Is a Small Percentage of the Total Mass of the Launch Vehicle



We must keep the spacecraft structure lightweight to get to the desired orbital altitude.

Mass is not the same as weight. Remember Newton's second law of motion:

$$F = ma$$

Force, Mass, Acceleration

$$w = mg$$

Weight (force), Mass, Acceleration of gravity

How Launch Affects Things Structurally

- Steady-state loads (e.g., steady thrust and constant winds) cause uniform acceleration, with a resisting inertia load that stresses* the materials.
- Time-varying loads (e.g., ignition, pressure, turbulence) not only cause acceleration but also cause structures to vibrate, which in turn stresses the materials.
- A material can take only so much stress before failure occurs:
  - Rupture
  - Collapse
  - Yielding

Structural engineers must quantify or predict …

- Launch environments
- How structures will respond
- The stresses caused by that response

And then use this knowledge to design a lightweight structure that won't fail.

*Stress = force divided by cross-sectional area of the material

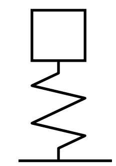
Modes of Vibration

- Every structure has an infinite number of ***modes of vibration***, each of which is characterized by
  - ***Natural frequency***, f_n (cycles per second, or Hz)
  - ***Mode shape*** (deformed shape of the structure)
  - ***Damping*** (how much energy is lost in vibration)
- The ***fundamental frequency*** is the lowest natural frequency, corresponding to the first mode of vibration, which usually has the most energy (most mass moving)
- Natural frequencies and mode shapes depend on mass and stiffness (lb/in or in-lb/rad)

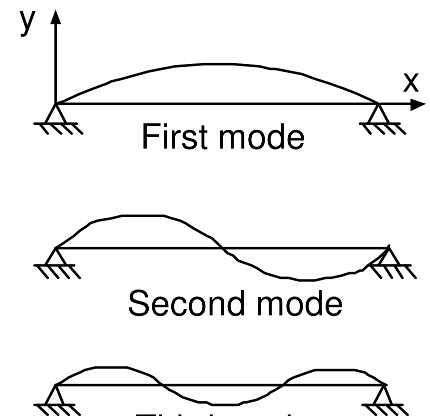
For a spring-mass system,

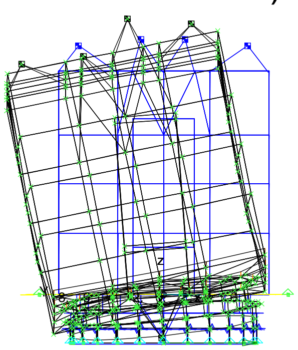
$$f_n = \frac{1}{2\pi}\sqrt{k/m}$$

k = stiffness
m = mass

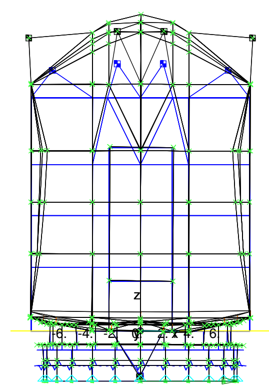


Beam:





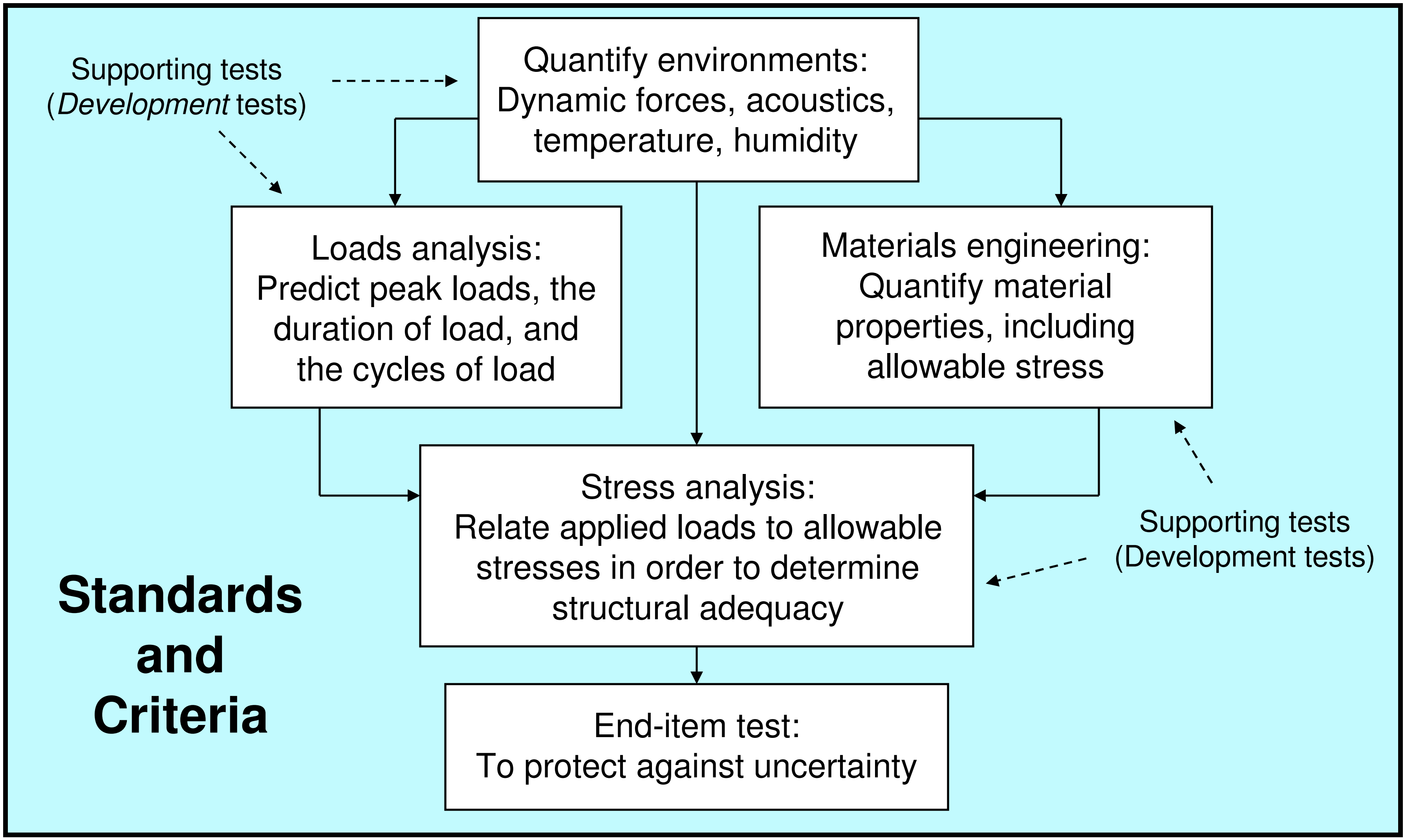
Fundamental lateral (rocking) mode



Fundamental axial mode

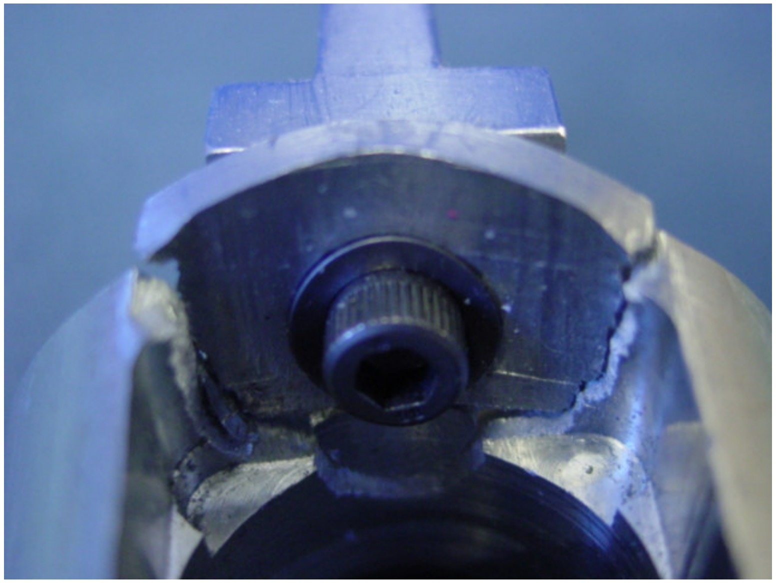
The modes of vibration for a structure affect how it will respond to time-varying forces.

The Process for Verifying Structural Integrity



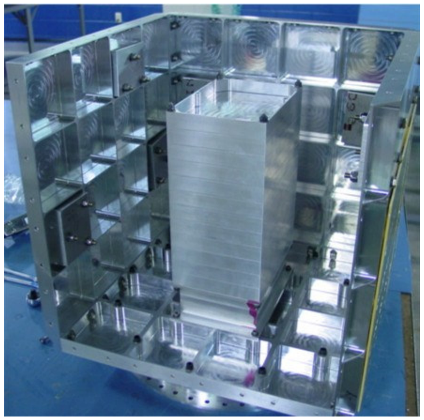
Key Considerations in Selecting Materials

Key Considerations in Selecting Materials



- ***Strength*** (how much stress it can tolerate before it fails)
- Stiffness (as indicated by the material's modulus of elasticity)
- ***Elongation***—a measure of ***ductility*** (amount of plastic deformation or yielding before rupture), which allows energy to be absorbed without rupture
- ***Fatigue resistance*** (ability to tolerate cyclic loading without failure)
- ***Density*** (mass per volume)
- ***Thermal conductivity*** (how easily heat moves through the material)
- How much it deforms under temperature change (***coefficient of thermal expansion***)
- ***Outgassing*** (a solid changing phase to a gas in vacuum)
- Corrosion resistance (for the period on Earth before launch)
- Cost (of raw material, of machining, of processing, etc.)

Material Selection



Partial assembly of the FalconSAT-3 structural engineering model at the U.S. Air Force Academy

Composite-overwrapped tank built by Pressure Systems, Inc.

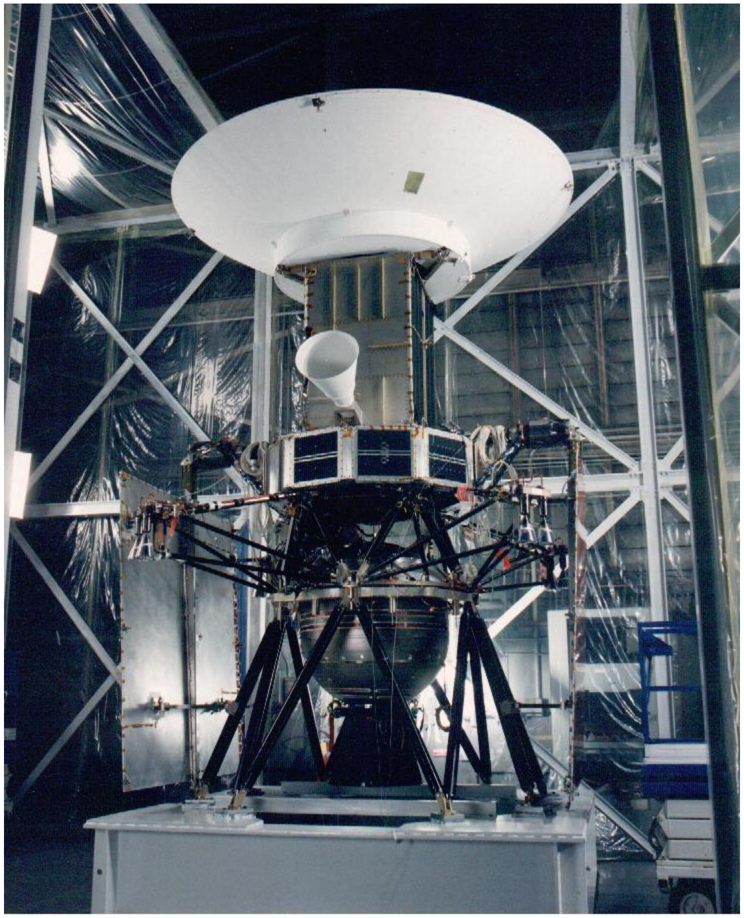
- What are the most common materials for spacecraft structures?
  - Aluminum alloy
  - Graphite/epoxy composite
- Why?
  - Aluminum:
    - Relatively low density
    - Ductile
    - Low in cost
    - Easy to machine
  - Composite:
    - High strength-to-weight ratio
    - Allows properties to be tailored for the design
    - Can provide near-zero coefficient of thermal expansion
    - Brittle (not ductile)

Aluminum is usually the best choice if it will meet requirements because it often leads to lower cost.

Composites are often selected to reduce weight or maintain alignment under temperature changes in orbit.

Other Considerations in Spacecraft Structural Design

- Construction
  – Will we be able to build it affordably?
- Assembling parts and installing equipment
  – How can we make sure the parts will fit together?
  – Will we have access for wrenches and cable bundles?
  – Will there be the possibility that we have to disassemble the structure or remove equipment?
- Test
  – How will we test the structure?
  – Will the test environments be more severe than the mission environments?
- Handling
  – How will we lift the spacecraft?
  – How will we transport it to the launch site?
  – How will we install it in the launch vehicle?
- And we can't lose sight of the mission itself!



Magellan ready for structural testing

Fields of Expertise Needed to Develop a Spacecraft Structure

Building blocks of education

- Mathematics
- Physics
- Chemistry
- Statics
- Dynamics
- Material science
- Mechanics of materials
- Structural analysis
- Mechanical design
- Manufacturing
- Probability and statistics
- Aerospace systems
- Communication (writing, speaking, and listening)

Training and tools

- Computer-aided design and manufacturing (CAD/CAM) and solid modeling
- Finite element modeling and analysis
- Spreadsheets (e.g., Microsoft Excel)
- Fracture mechanics analysis (e.g., FLAGRO)
- Other analysis software (Mathcad, Matlab, etc.)

Fields of specialty

- Structural and mechanical design
- Structural dynamics
- Stress analysis
- Thermal analysis
- Materials
- Manufacturing
- Test
- Quality assurance
- Systems engineering

No one individual can learn all this stuff to the extent required.

Teamwork is necessary!

Summary

Designing a spacecraft structure is challenging because it must …

- function as needed for a successful space mission
- fit within the launch vehicle
- be able to withstand a launch environment that is highly variable and difficult to predict
- be lightweight in order to reach orbit
- be affordable
- include the contributions of a team of specialists that often are in different parts of the country (or world)