My Background
**Spacecraft Mechanism:** *noun*
- A system of kinematic parts that collectively support space-faring systems
  - deployables
  - actuators
  - release devices
  - motors
  - pumps
  - gears
  - robotics
  - pyros
  - springs

**Spacecraft Structure:** *noun*
- An arrangement of load bearing elements that collectively support and protect space-faring systems
  - static g-load
  - shock
  - venting
  - thermal expansion
  - extreme heat
  - extreme cold
  - outgassing
  - atomic $O_2$
  - precision alignment
  - coatings
  - pressure vessels
  - ground support equipment
  - fasteners
  - grounding
  - vibration
  - thermal expansion
  - extreme heat
  - extreme cold
  - outgassing
  - atomic $O_2$
  - precision alignment
  - coatings
  - pressure vessels
  - ground support equipment
  - fasteners
  - grounding
ISS Solar Arrays
Space Structures & Mechanisms

Orion Crew Exploration Vehicle
Space Structures & Mechanisms

Deployable Optical Reflector
Space Structures & Mechanisms

Inflatable Structures
Space Structures & Mechanisms

On-Orbit Assembled Structures
Space Structures & Mechanisms

High Strain (Flexed) Structures
High Strain (Flexed) Structures
Designing a structure
Example: 50kg Payload

• Static G-load
  – Sustained load of ±20g
    • FOS of 2.0 to yield, 2.6 to ultimate, test to 1.2
    • FOS of 2.0 ultimate for mechanisms, test to 1.0
  – Stiffness >100Hz
  – Pass random vibration profile
  – Ground Support Equipment, withstand gravity
    • FOS of 5.0 ultimate failure, test to 2.0

Note the difference between margin of safety and factor of safety

\[ MS = \frac{(\text{Allowable Stress})}{FS \times (\text{Actual Stress})} - 1 \]

Factor of safety is embedded in your requirements, a margin of safety of zero means that you meet your requirements.
Mass Acceleration Curve (MAC)

Random Vibration Profile
• Really think about the structural load path

- Directly connect primary structure to Base Plate

- Eliminate unnecessary structural junctions

- Weak junctions between major components

- Complex truss structure

- Jun '07 (SCR)

- Aug '07 (PDR)

- Mar '08 (CDR)
Good ideas:
• Try to limit part count
• Use traditional materials
  – Al 6061-T6 is great
  – Composites fill a unique niche

Always be thinking of:
• Flight Assembly
  – Wiring harnesses
  – Frequent re-assembly
• Reduce risk by incorporating off-the-shelf hardware
• Ground Support Equipment
• Accommodating the space environment
Designing a Structure & Mech.

– Flight assembly, think about step-by-step assembly
Structural Analysis
• Start the basics
  – Get a hand calc. approximation
  – “Roark’s Tables” handbook is your friend

\[ F = ma \quad \sigma = \frac{F}{A} \quad \varepsilon = \frac{\sigma}{E} \]

• Resort to Finite Element Analysis
  – A powerful tool, can tell you a lot
  – Takes years of experience to properly use
    • (it’s hard to get trustworthy answerers)
<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Equations</th>
<th>Maximum Moments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1d.</td>
<td>Left end fixed, right end fixed</td>
<td>( R_A = \frac{W}{E} (l - a)^2(l + 2a) )</td>
<td>( \text{Max } M = \frac{2W(a^2)}{3} ) at ( x = a ); max possible value = ( \frac{Wl}{8} ) when ( a = \frac{l}{2} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( M_A = \frac{-Wa}{F} (l - a)^2 )</td>
<td>Max ( -M = M_A ) if ( a &lt; \frac{l}{2} ); max possible value = ( -0.148Wl ) when ( a = \frac{l}{3} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \theta_A = 0 ) ( y_A = 0 )</td>
<td>( \text{Max } y = \frac{-2W(l - a)^2a^3}{3EI(l + 2a)^2} ) at ( x = \frac{2al}{l + 2a} ); if ( a &gt; \frac{l}{2} ); max possible value = ( \frac{-W^3}{192EI} ) when ( x = a = \frac{l}{2} )</td>
</tr>
<tr>
<td>1e.</td>
<td>Left end simply supported, right end simply supported</td>
<td>( R_A = \frac{W}{l}(l - a) ) ( M_A = 0 )</td>
<td>( \text{Max } M = R_Aa ) at ( x = a ); max possible value = ( \frac{Wl}{4} ) when ( a = \frac{l}{2} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \theta_A = \frac{-Wa}{6EI}(2l - a)(l - a) ) ( y_A = 0 )</td>
<td>Max ( y = \frac{-Wa}{3EI} \left( \frac{l^2 - a^2}{3} \right)^{3/2} ) ( x = l - \left( \frac{l^2 - a^2}{3} \right)^{1/2} ); if ( a &lt; \frac{l}{2} ); max possible value = ( \frac{-W^3}{48EI} ) at ( x = \frac{l}{2} ) when ( a = \frac{l}{2} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R_B = \frac{Wa}{l} ) ( M_B = 0 )</td>
<td>Max ( \theta = \theta_A ) when ( a &lt; \frac{l}{2} ); max possible value = ( -0.0642 \frac{W^2}{EI} ) when ( a = 0.423l )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \theta_B = \frac{Wa}{6EI}(\hat{y} - a^2) ) ( y_B = 0 )</td>
<td>( \text{Max } y = y_A ); max possible value = ( \frac{-W^3}{3EI} ) when ( a = 0 )</td>
</tr>
<tr>
<td>1f.</td>
<td>Left end guided, right end simply supported</td>
<td>( R_A = 0 ) ( M_A = W(l - a) ) ( \theta_A = 0 )</td>
<td>( \text{Max } M = M_A ) for ( 0 &lt; x &lt; a ); max possible value = ( Wl ) when ( a = 0 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( y_A = \frac{-W(l - a)}{6EI} \left( 2l^2 + 2la - a^2 \right) )</td>
<td>Max ( \theta = \theta_B ); max possible value = ( \frac{W^3}{2EI} ) when ( a = 0 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R_B = W ) ( M_B = 0 )</td>
<td>Max ( y = y_A ); max possible value = ( -\frac{W^3}{3EI} ) when ( a = 0 )</td>
</tr>
</tbody>
</table>
Roccor Analysis on Slit-Tubes

Region 1: Structural Region

Region 2: Low Stiffness due to Global Buckling

Region 3: Further Stiffness Reduction due to Shell Buckling
Spacecraft Structural Testing

Structural Testing
Spacecraft Structural Testing

**Sine Sweep:** 1/4g input at base, sweep all frequencies to understand dynamic response

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**Graph:**
- **Sweep Number:** 1.00
- **Sweep Rate:** 2.0000 rad/min
- **Compression:** 50%
- **Elapsed Time:** 00:03:19
- **Fundamental:** 70.000 Hz
- **DB RMS:** 455, inyo
- **Remaining Time:** 00:00:00
- **Test Range:** 20.000, 2000.000 Hz
- **Points Per Sweep:** 450

**Annotations:**
- **WOW!**
- **Excellent Correlation**

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**Notes:**
- **DANDE EDU,** ten months prior to FCR
- **File Information:**
  - **Date:** Mar 11 2008
  - **File:** CU:25G.122
  - **Data Review File:** B: CU:25G.121
  - **Data Preview File:** C: CU:25G.120
  - **A:** DATA 1V
  - **B:** DATA 1V
  - **C:** DATA 1V
Spacecraft Structural Testing

**Sine Burst:** Simulates a static load. Lasting less than a second, shake at a fixed frequency for a few cycles.  
20gs * 1.2 FS = 24Gs

**Random Vibration:** Simulates elastic and acoustic launch vibrations. Vibrates spectrum of frequencies simultaneously. Usually most significant at natural freq, (drives >100 Hz requirement)
The Future of Spacecraft Structures & Mechanisms
Future of Spacecraft Structures & Mechanisms

• SmallSat Revolution
  – Microsatellite Constellations ($$$)
  – Sophisticated Cubesats (high tech, interplanetary)
  – Bulk of the industry will still be traditional

• Increased use in advanced materials
  – Solid state mechanisms
  – Printed primary structures (metal, plastic, carbon)
Spacecraft Failures

~3.5% of spacecraft on-orbit failures are attributed to the structures system.

100% of spacecraft failures are attributed to systems engineering.
Spacecraft Failures: Structures and Mechanisms

Galileo Spacecraft, Launch 1989
Reached Jupiter in 1995
Spacecraft Failures: Structures and Mechanisms

Glory Spacecraft: Launched 2011
SpaceX: June 28th, 2015
Spacecraft Failures: Structures and Mechanisms

SpaceX: June 28th, 2015
Other examples:

• Contamination, debris
• Material degradation
  – Structural integrity
  – Surface properties
• Ground support equipment
  – Red tag items

Repairs: $135m