• What is a structure, what is a mechanism?
  – Supports loads, enables motion
• Different types of spacecraft structures
• Stories: the successful and less successful examples
• How does one design a structure
  – Predict and build to loads
  – Good design practices
• Structural analysis
• Structural testing
• The future of structures
  – The ‘smallsat’ revolution
  – Next generation materials
My Background
**Spacecraft Structure**: *noun*
- An arrangement of load bearing elements that collectively support and protect space-faring systems

**Spacecraft Mechanism**: *noun*
- A system of kinematic parts that collectively support space-faring systems
ISS Solar Arrays
Space Structures & Mechanisms

SMAP (2015)
Space Structures & Mechanisms

Curiosity Rover (2014)
Dream Chaser (2009?)
Space Structures & Mechanisms

Inflatable Structures
Space Structures & Mechanisms

On-Orbit Assembled Structures
Space Structures & Mechanisms

High Strain (Flexed) Structures
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

Other examples:

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

Repairs: $135m
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
Designing a Structure & Mech.

• Really think about the structural load path

Weak junctions between major components

Jun ‘07 (SCR)

Directly connect primary structure to SIP Plate

Complex truss structure

Aug ‘07 (PDR)

Eliminate unnecessary structural junctions

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
    • (nobody ever gets the analysis right)
### For a beam supported at two ends

<table>
<thead>
<tr>
<th>Condition</th>
<th>Reaction Forces</th>
<th>Equations</th>
<th>Max Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1d. Left end fixed, right end fixed</td>
<td>$R_A = \frac{W}{L}(l-a)\frac{a}{2}(l+2a)$</td>
<td>$M_A = \frac{-Wa}{L}(l-a)^2$</td>
<td>$y_A = 0$</td>
</tr>
<tr>
<td></td>
<td>$\theta_A = 0$</td>
<td>$y_A = 0$</td>
<td>$x = a$; max possible value $\frac{Wl}{8}$ when $a = \frac{l}{2}$</td>
</tr>
<tr>
<td></td>
<td>$R_B = \frac{-W}{L}(3l-2a)$</td>
<td>$M_B = \frac{-Wa}{L}(l-a)$</td>
<td>$x = a$; max possible value $-0.1481Wl$ when $a = \frac{l}{3}$</td>
</tr>
<tr>
<td></td>
<td>$\theta_B = 0$</td>
<td>$y_B = 0$</td>
<td></td>
</tr>
<tr>
<td>1e. Left end simply supported, right end simply supported</td>
<td>$R_A = \frac{W}{l}(l-a)$</td>
<td>$M_A = 0$</td>
<td>$y_A = 0$</td>
</tr>
<tr>
<td></td>
<td>$\theta_A = \frac{-W}{6EI}(2l-a)(l-a)$</td>
<td>$y_A = 0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_B = \frac{W}{l}$</td>
<td>$M_B = 0$</td>
<td>$y_B = 0$</td>
</tr>
<tr>
<td></td>
<td>$\theta_B = \frac{W}{6EI}(l^2-a^2)$</td>
<td>$y_B = 0$</td>
<td>$x = 2al$; if $a &gt; \frac{l}{3}$; max possible value $\frac{-Wl^3}{192EI}$ when $x = a = \frac{l}{2}$</td>
</tr>
<tr>
<td>1f. Left end guided, right end simply supported</td>
<td>$R_A = 0$</td>
<td>$M_A = W(l-a)$</td>
<td>$\theta_A = 0$</td>
</tr>
<tr>
<td></td>
<td>$y_A = \frac{-W(l-a)(2l+2a)}{6EI}$</td>
<td>$\theta_A = 0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_B = \frac{W}{2EI}$</td>
<td>$M_B = 0$</td>
<td>$y_B = 0$</td>
</tr>
<tr>
<td></td>
<td>$\theta_B = \frac{W}{2EI}(l^2-a^2)$</td>
<td>$y_B = 0$</td>
<td>$x = 2al$; if $a &gt; \frac{l}{3}$; max possible value $\frac{-Wl^3}{48EI}$ at $x = \frac{l}{2}$ when $a = \frac{l}{2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$0 = \theta_A$ when $a &lt; \frac{l}{2}$; max possible value $-0.0642\frac{Wl^2}{EI}$ when $a = 0.423l$</td>
</tr>
</tbody>
</table>

Max $M = M_A$ for $0 < x < a$; max possible value $Wl$ when $a = 0$

Max $\theta = \theta_B$; max possible value $\frac{Wl^2}{2EI}$ when $a = 0$

Max $y = y_A$; max possible value $\frac{-Wl^3}{3EI}$ when $a = 0$
Structural Testing
Spacecraft Structural Testing

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

DANDE EDU, ten months prior to FCR
Spacecraft Structural Testing

**Sine Burst:** Simulates a static load. Lasting less than a second, shake at a fixed frequency for a few cycles. 

\[ 20\text{gs} \times 1.2 \text{ FS} = 24\text{Gs} \]

**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)