Structural Design

• 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

• 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)

• 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)
• Obtain or estimate loads
  - look up loads in reference books
  - ask other groups to determine loads
  - guestimate for the purposes of starting analysis
• Calculate all margins of safety
Launch Vehicle Loads

- **Max Q - Aerodynamic Loads**
  - $Q = \frac{\rho V^2}{2}$
  - 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

- **Staging shock loads**
  - high g's, high frequency

- **Random vibration and acoustics**
  - equiv. g's = $\sqrt{\pi \text{ PSD } f_n Q / 2}$

- 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%)

- Structural Failure Relatively Rare
  - AmRoc, Shuttle, Pegasus

- Propulsion or Control System Failure More Common
  - Conestoga, LLV, Ariane V
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
  - loosing 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

• Example: OTD Boom Piece Parts Analysis
Factors & Margins of Safety

- Limit Loads: maximum loads expected (applied loads)
- Yield Load and Ultimate Load
- **Factors of Safety**: numbers imposed by the Customer (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
- **Margins of Safety** are calculated as follows:

\[
MS = \frac{\text{Allowable Load}}{\text{Applied Load} \times FS} - 1.0
\]

- **Beware**: There are other definitions of these terms in engineering, but the above approach is the most common in Aerospace
Primary Structure

- Primary, Secondary, & 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:
    \[
    \sigma_{\text{crit}} = \frac{E \, t}{R \, \sqrt{3(1-\nu^2)}}
    \]
Critical Structure

- 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)

- Failsafe & Fracture Critical Structure
  - Catastrophic failure is generally defined by customer
  - Failsafe structure can take redistributed loads after failure (ie, 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
    \[ \sigma_{\text{max}} < F_{tu} / [4 (1-0.5 R) K_t] \]
  - Fracture critical parts must be labeled and analyzed as such, then inspected, treated, and tracked more carefully than conventional parts

- Crack Growth Analysis (FLAGRO)
  - All FC parts must be shown good for four lifetimes of load cycles with an initial flaw (determined by 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
  - aluminum yld: 37 ksi  ult: 42 ksi
  - low strength steel yld: 36 ksi  ult: 58 ksi
  - high strength steel yld:102 ksi  ult:116 ksi
  - titanium yld:134 ksi  ult:145 ksi

- Stiffness versus Strength Designs
  - aluminum $w$: 0.10  $E/w$: 100  $\sigma_u/w$: 420
  - Low $\sigma_u$ steel $w$: 0.28  $E/w$: 102  $\sigma_u/w$: 204
  - high $\sigma_u$ steel $w$: 0.29  $E/w$: 98  $\sigma_u/w$: 390
  - titanium $w$: 0.16  $E/w$: 109  $\sigma_u/w$: 906

Conclusion: for aerospace structures - titanium and 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
    \[ \sigma_{\text{hoop}} = \frac{p R}{t}; \quad \sigma_{\text{long}} = \frac{p R}{2 t} \]
  - Random Vibe and Acoustic Equivalent g's