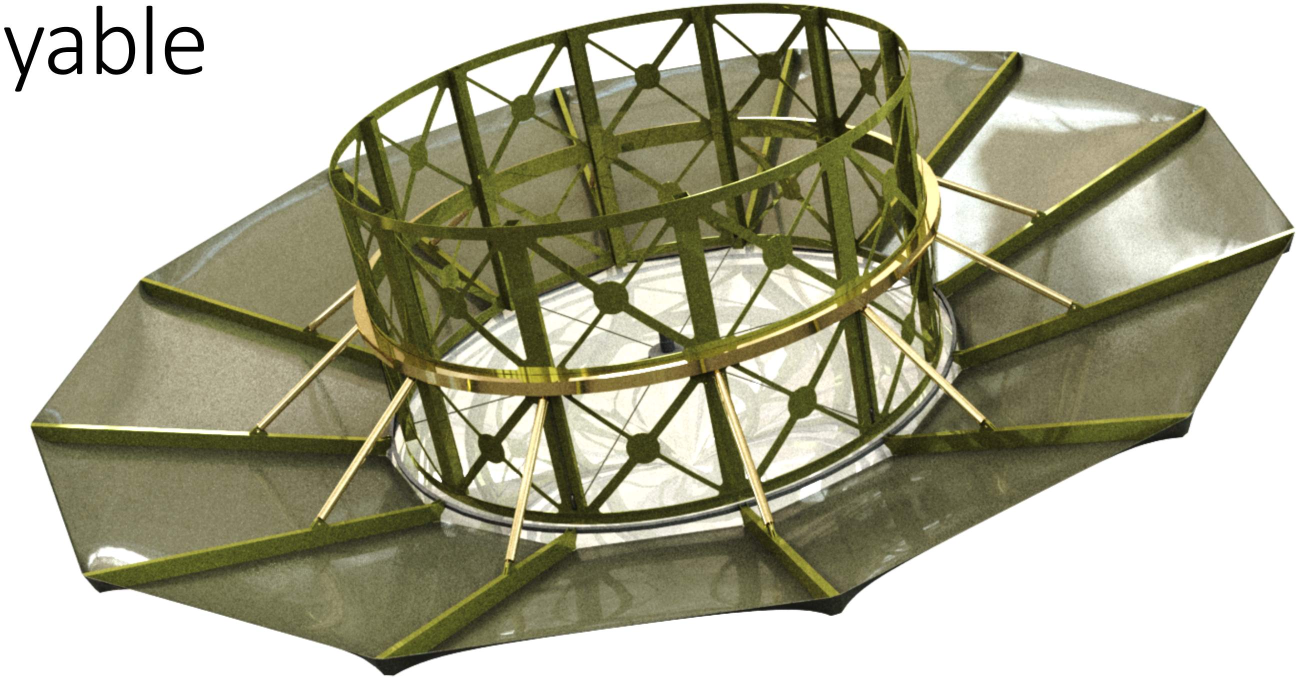
Coupled Aero-Structural Modelling and Optimisation of Deployable Mars Aero-Decelerators



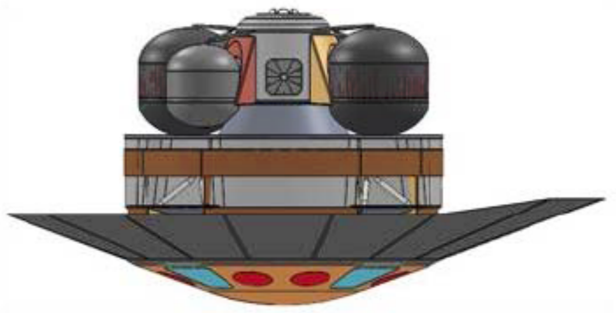
Lisa Peacocke, Paul Bruce
and Matthew Santer

International Planetary Probe Workshop

11-15 June 2018

Boulder, CO, USA

Deployable Aero-Decelerators



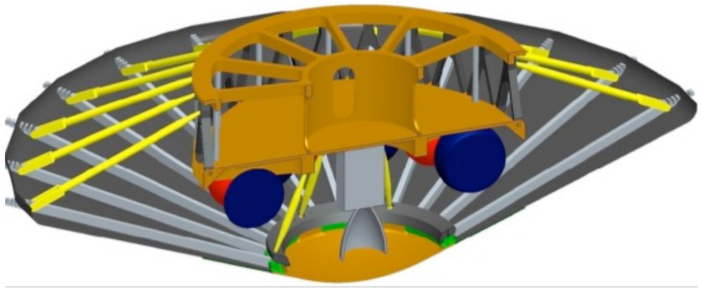
Cassell et al. (2017)

- Enable large masses to be delivered to Mars surface
  - Also enable higher elevation landing sites and more precise landing
- Other advantages
  - Can be deployed and restowed
  - Resilient to micrometeoroid impact
  - Can withstand dual heat pulse
  - Could enable guidance by individual control of ribs
  - Could use ribs as landing gear

Savino et al. (2015)

Wiegand & Konigsmann (1996)

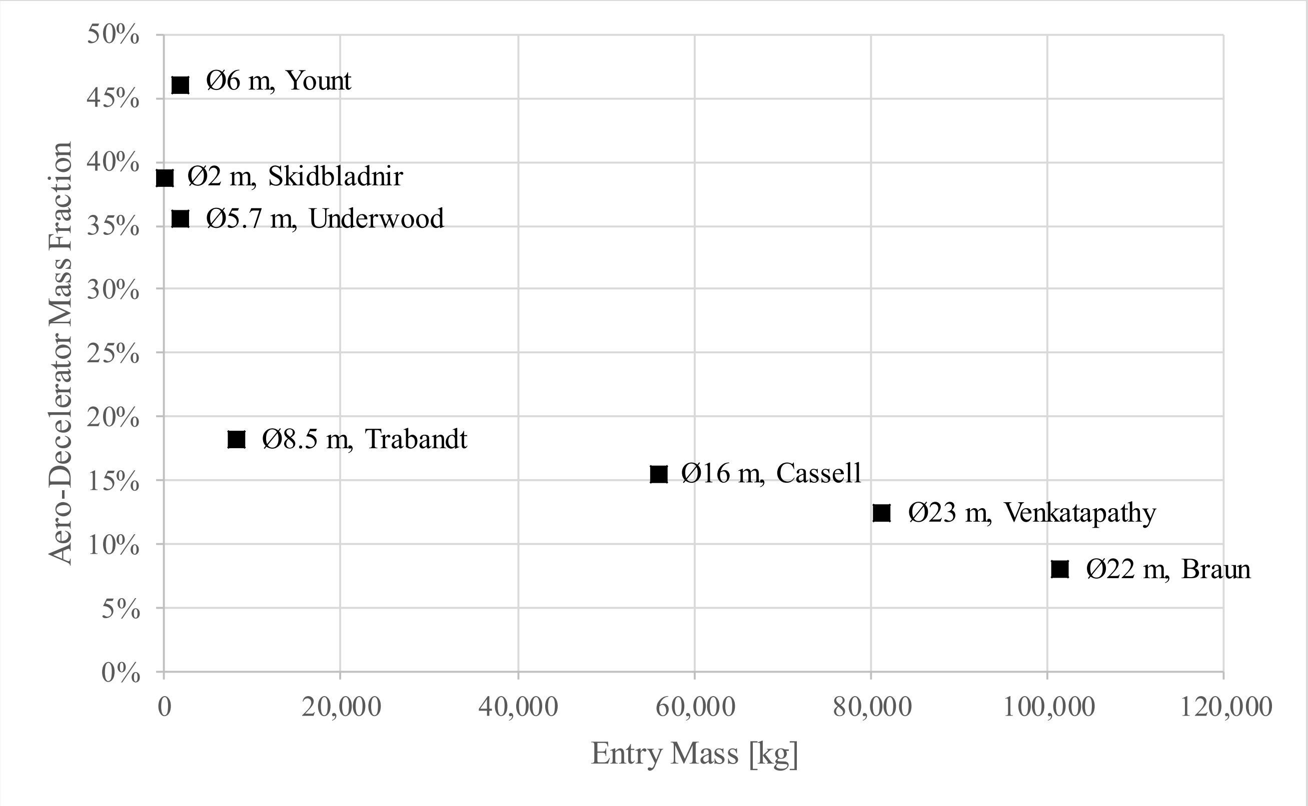
Akin (1990)



Venkatapathy et al. (2011)

Mass Estimation

- Widely varying mass assessments for all concepts
  - 8% - 46% of entry vehicle mass
  - Different margin assumptions
  - Hard to compare against inflatables and rigid bodies
- Robust mass estimates are key for determining performance
  - A coupled aero-structural tool will improve deployable rib mass estimation process
- Enables assessment of different architectures/concepts



Coupled Aero-Structural Model

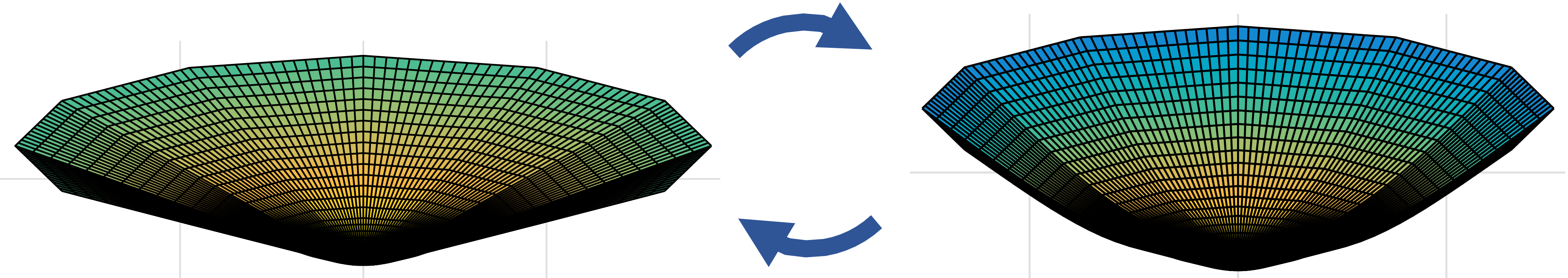
6DOF entry trajectory simulator

- Geometry mesh of any shape/size
- European Mars Climate Database
- Modified Newtonian method
- Equations of motion integrated
- Aerodynamic forces & coefficients updated at each timestep

+

Structural model of deployable ribs

- Aerodynamic forces across TPS summed and applied to rib nodes
- Euler-Bernoulli beam model
- Numerical integration method
- Individual ribs deform separately
- Updated shape passed back

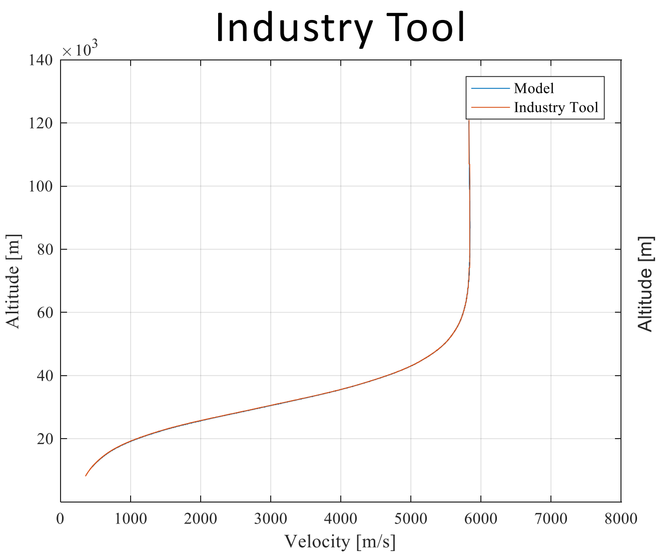


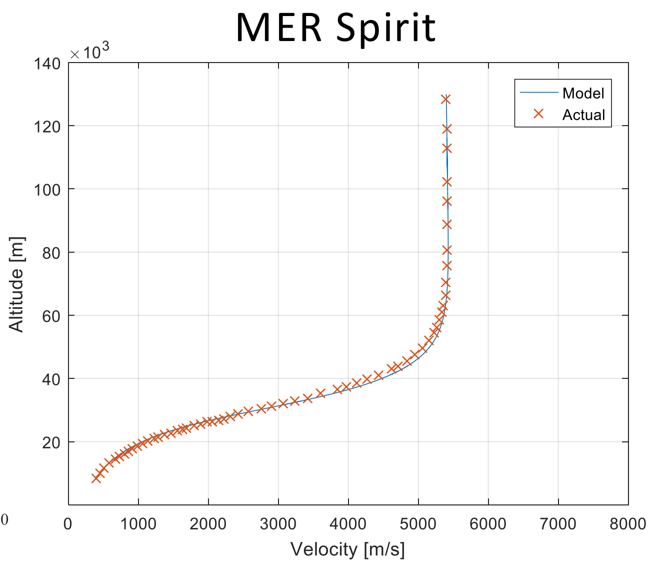
Undeformed Mesh

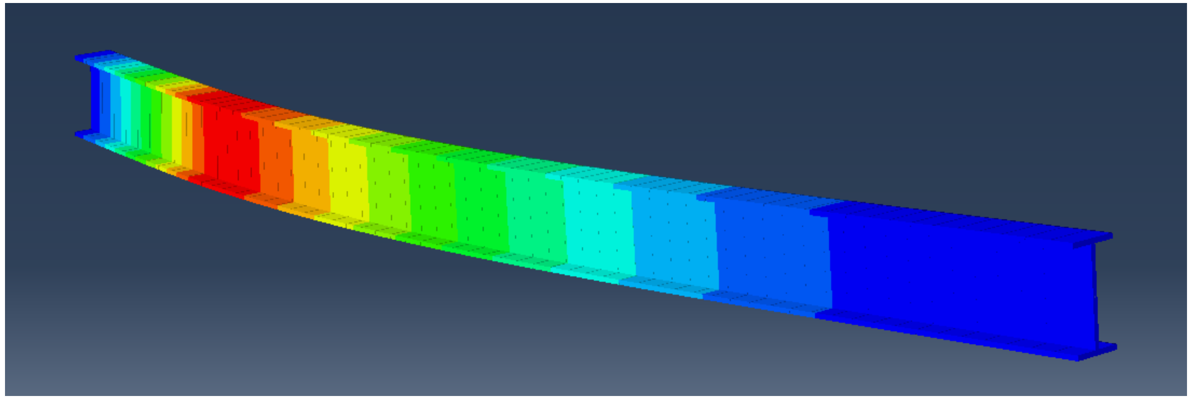
Mesh at Peak Deformation

Correlation and Validation

- Trajectory Simulator
  - Correlated against results from internal Airbus tool BL43
    - Schiaparelli-based rigid entry vehicle
  - Validated against published NASA flight data
- Structural Model
  - Correlated against deflection results from Abaqus FEA model
  - 5% deflection error with mesh points > 15 along rib length

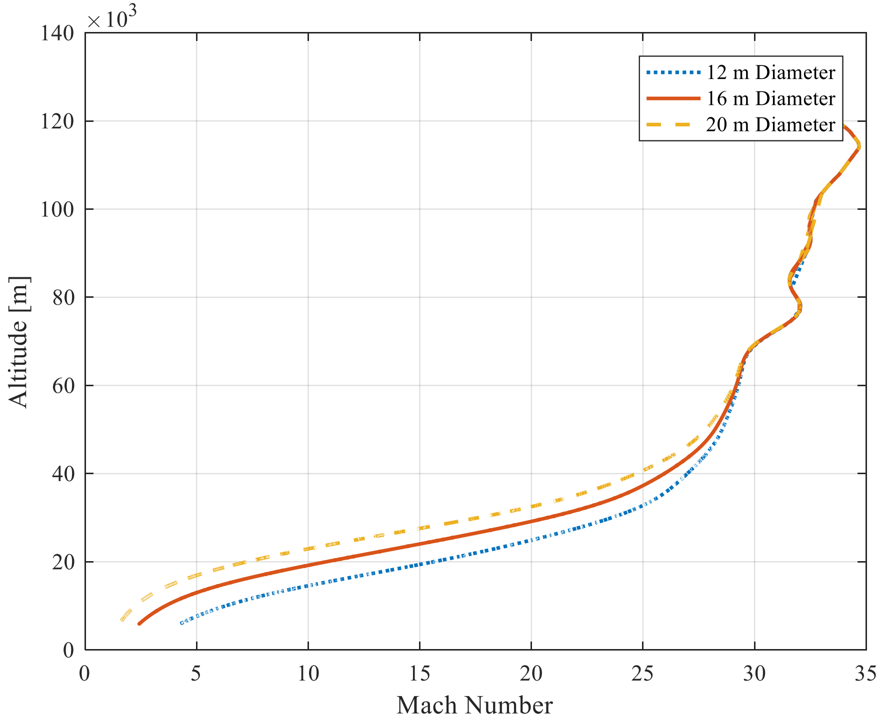


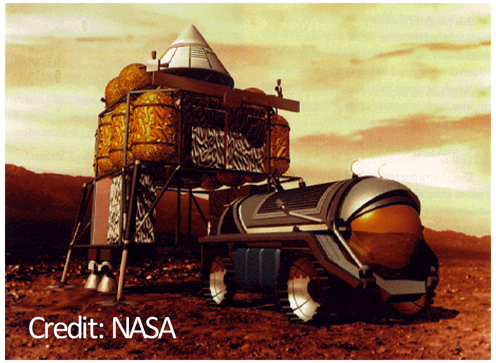


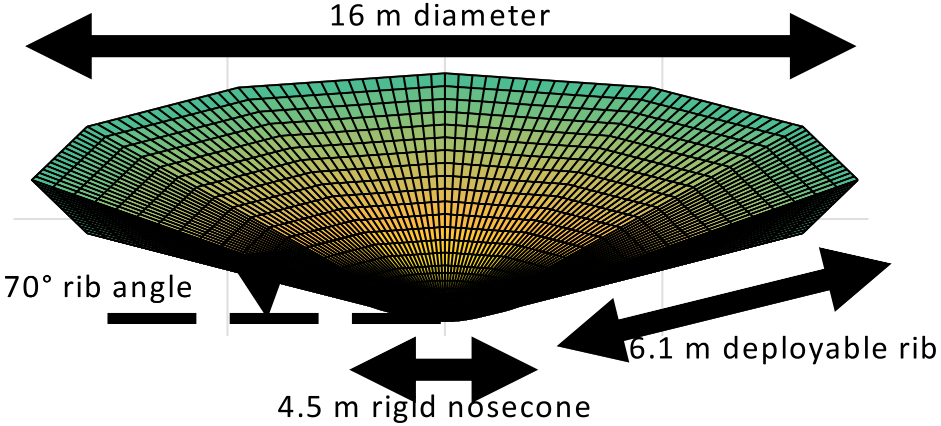


Reference Mission

Mission	Human Cargo
Surface Payload	20 tonnes
Stowed Diameter	4.5 m
Entry Strategy	Direct entry from transfer trajectory
Entry Velocity	6 km/s
Descent Strategy	Supersonic retropropulsion at Mach 3.5 above 3 km altitude
Landing Site Elevation	0 km MOLA

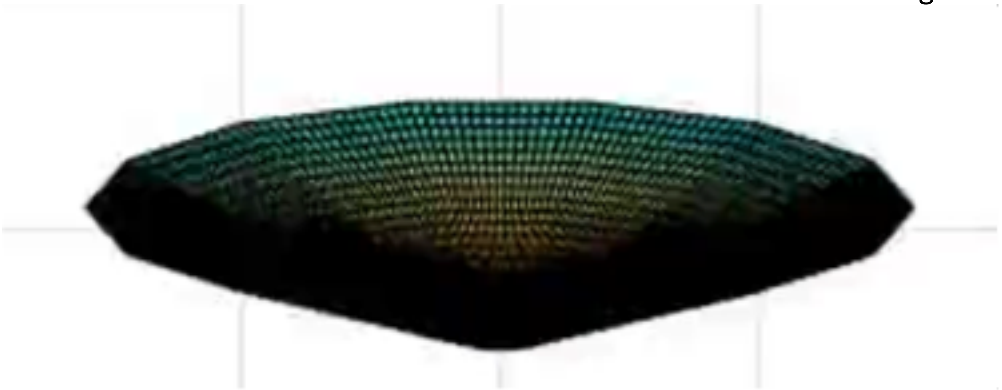




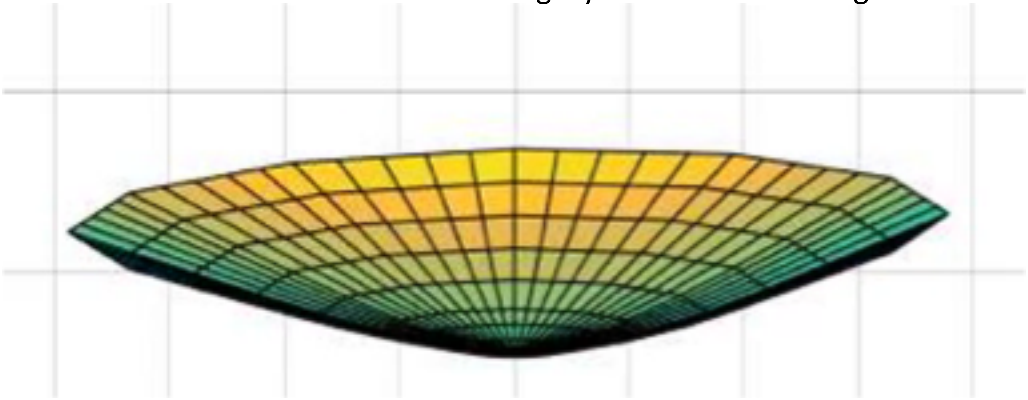


Deformation Animations

Reference Mission 16 m Diameter with Realistic Rib Design



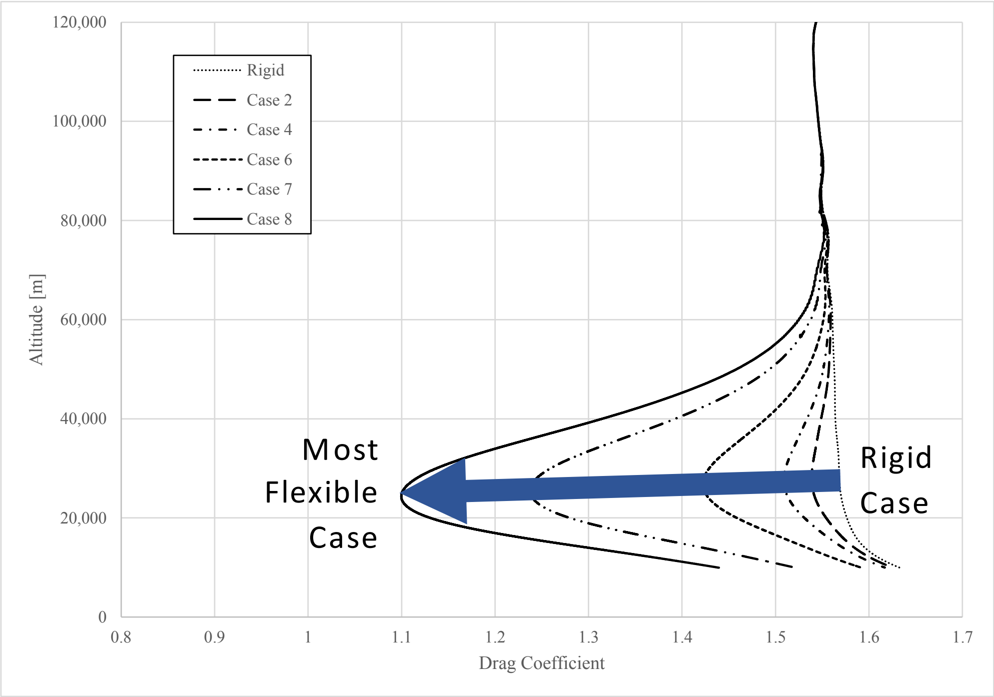
Unbalanced Forces with Highly Flexible Rib Design

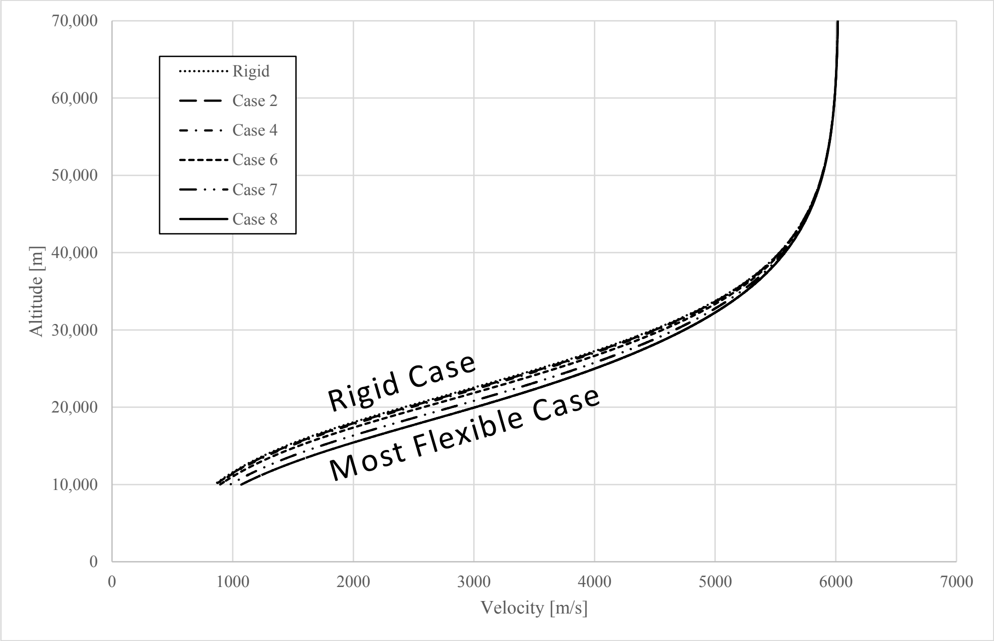


- Variable parameters include:
  - All 6DOF trajectory initial conditions
  - Entry vehicle size and shape
  - Number of ribs
  - Rib cross-section, dimensions and material properties
  - Support strut location
  - Payload centre of gravity

Rib Stiffness Variation

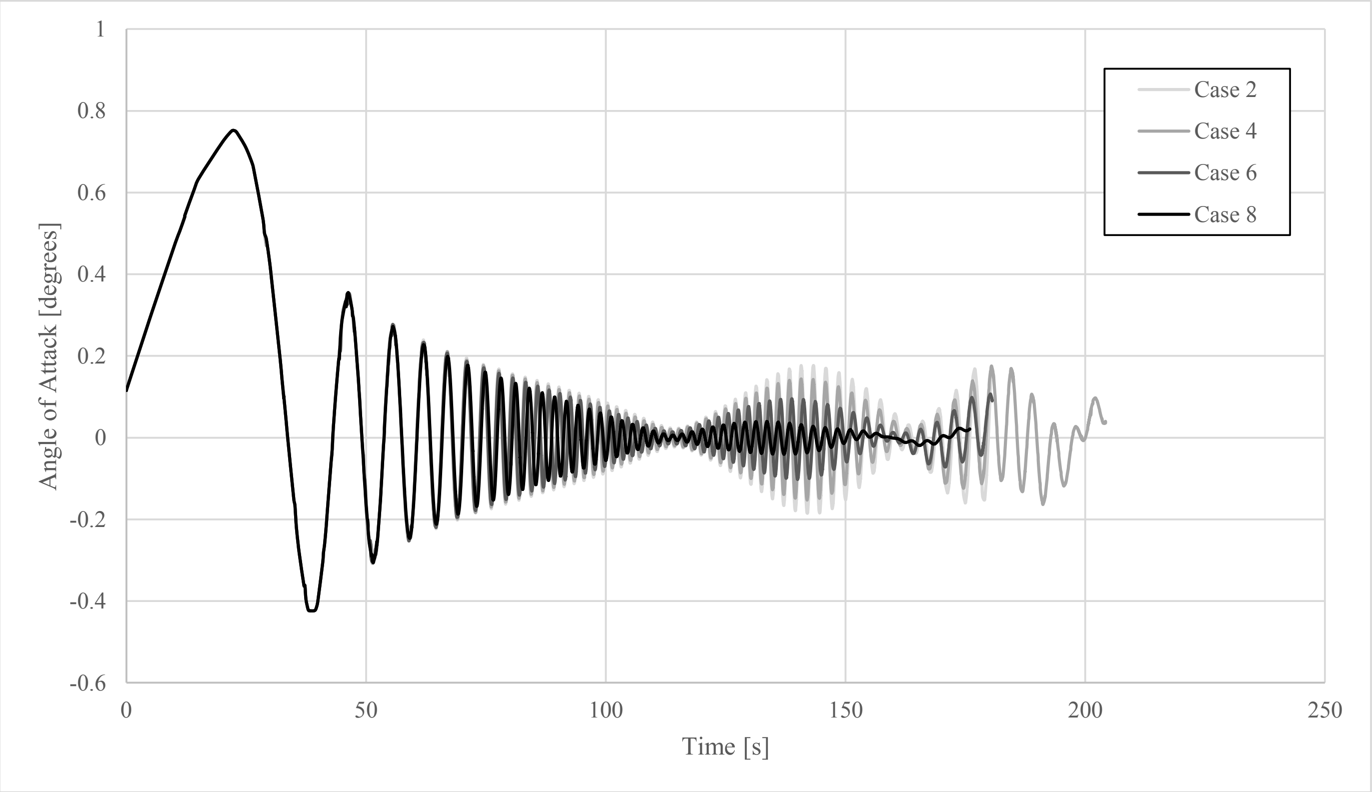
- Varied bending stiffness of ribs
  - EI range: 4-84 $\times 10^6$ Nm^2
  - Reference Human Cargo mission assumed
- Clear effect on drag coefficient
- Only very flexible ribs show significant effect on trajectory
  - $EI \leq 7 \times 10^6$ Nm^2
  - 25% higher velocity at 10 km
  - 7% increase in peak heat flux
  - 13% decrease in peak g-load





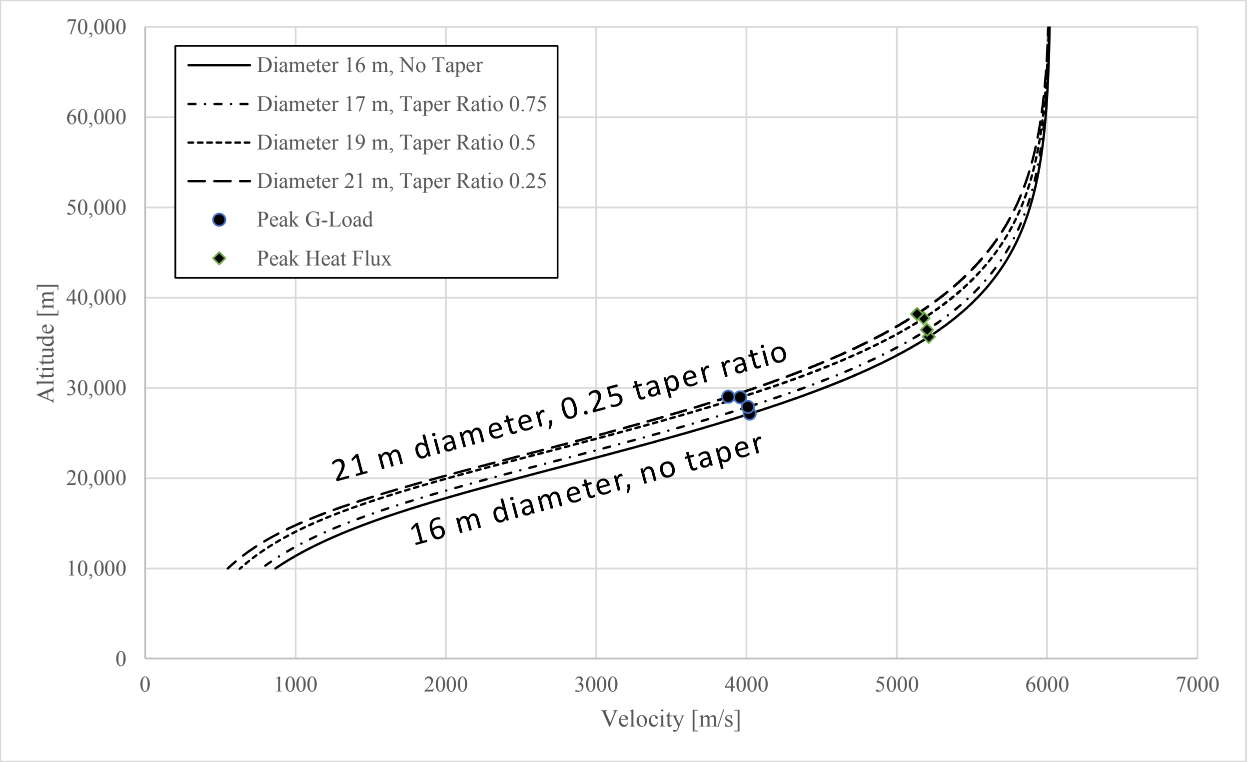
Rib Stiffness Variation

- Increasing rib flexibility damps attitude oscillations more effectively
  - New deformed shape is more stable
  - e.g. similar to 45° sphere-cone having greater stability
- Flexibility alone does not lead to beneficial effects on trajectory



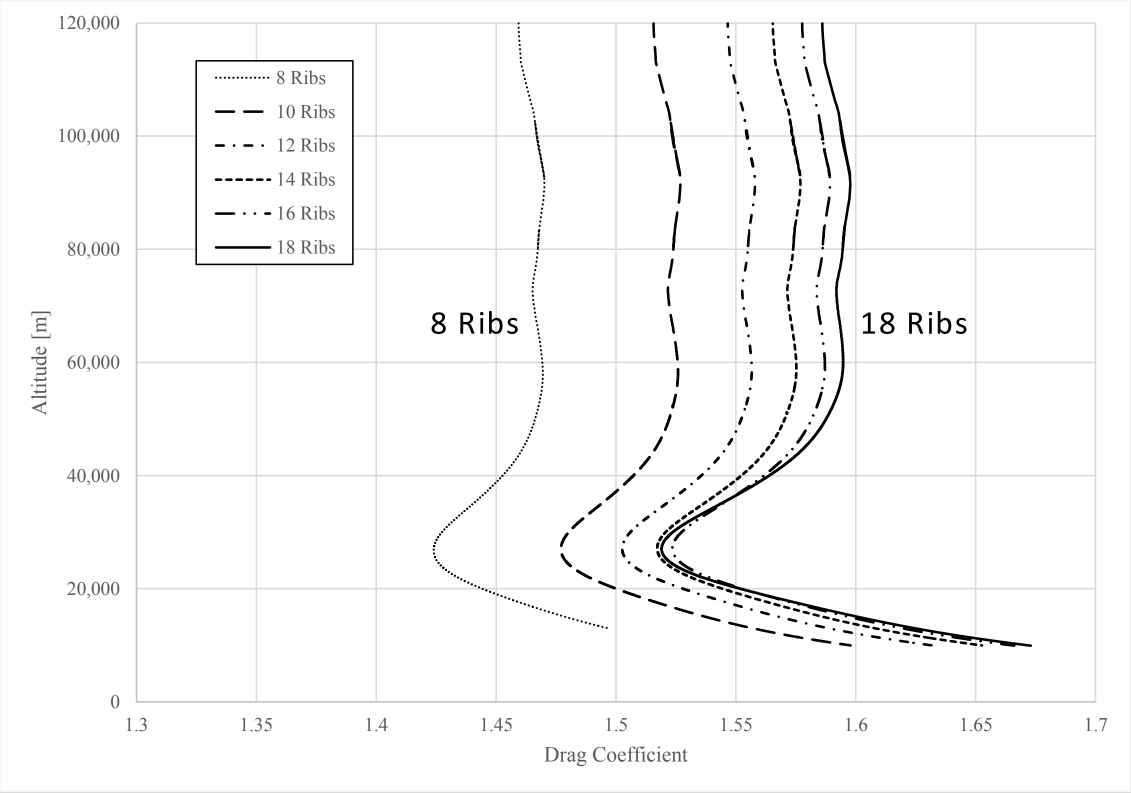
Rib Tapering Effect

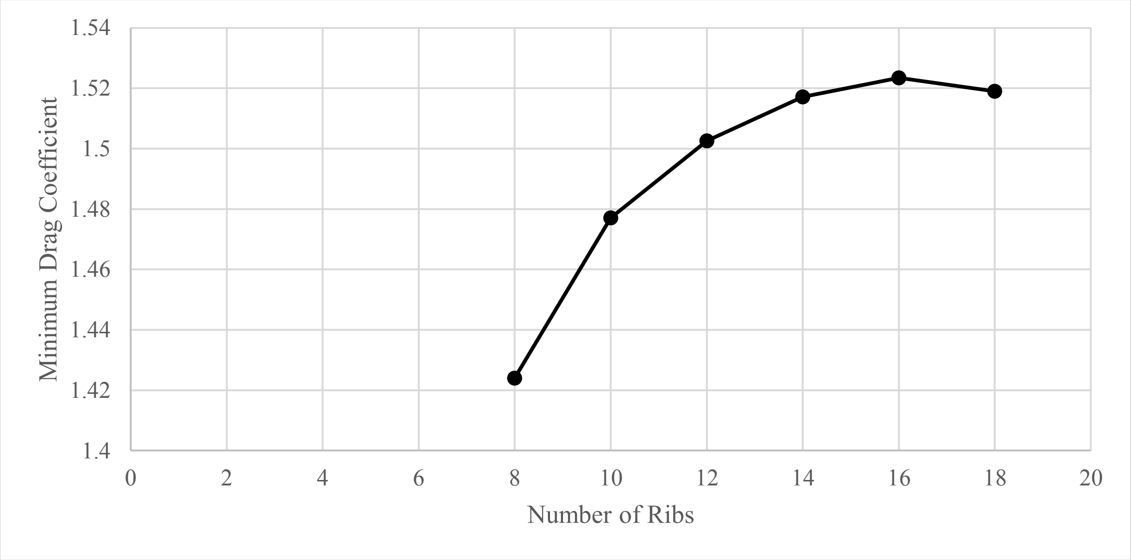
- Mass savings from flexible tapered ribs => increase entry vehicle diameter
  - Maintained entry vehicle mass
  - Balanced decreased rib mass with increased TPS mass
- Beneficial trajectory effect
  - Larger diameters decelerate more effectively at higher altitudes
  - Lowers peak heat flux significantly (42 => 30 W/cm^2)
- Reallocating the mass gained from flexibility is very beneficial



Number of Ribs

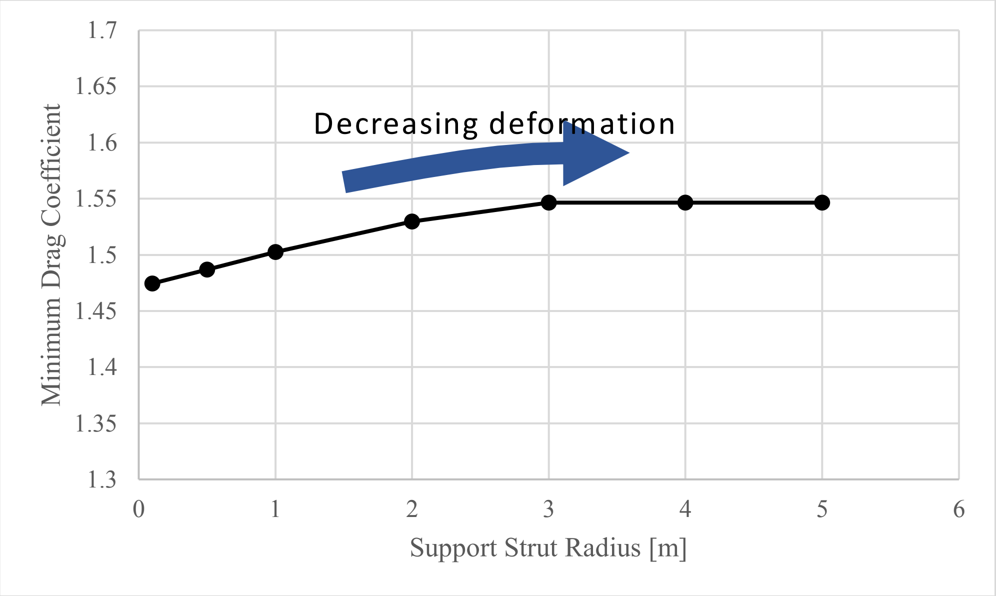
- Maintained total rib mass by balancing rib size/stiffness with number of ribs
- Very large effect on trajectory
  - Drag coefficient varies significantly
  - Fewer stiffer ribs deform less but give lower drag coefficient initially
  - Prefer larger number of more flexible ribs – to a limit
  - e.g. 16 ribs in this case
- Optimise number of ribs for each specific mission – more flexible ribs generally preferred

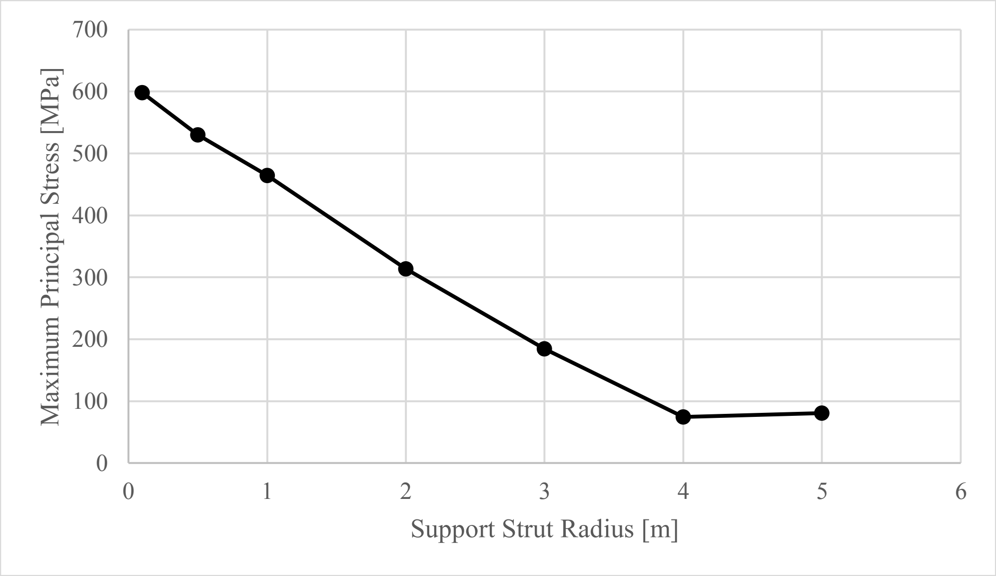




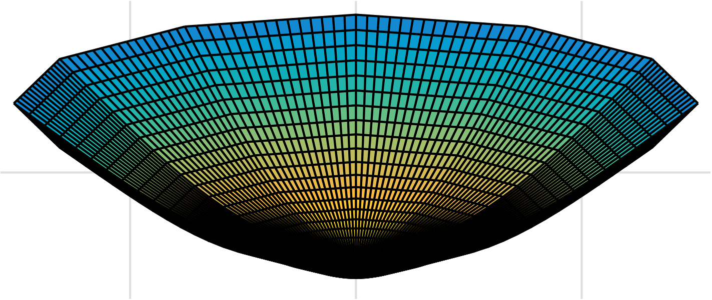
Support Strut Location

- Strut can be located at any point along deployed element
  - Investigated for **one rib design case**
  - Improvement in drag coefficient with strut distance from hinge
  - Minor (< 3%) change in peak heat flux, g-load, velocity at 10 km
- => Strut location should be based on maximum principal stress
  - Ensure material yield strength including safety factor is not exceeded
- Optimise with rib flexibility for lowest mass design





Conclusions and Next Steps



- Aero-structural simulator tool developed to assess deployable aero-decelerator concepts and improve mass estimates
  - Continue using tool to investigate variables and optimise designs
- Flexible deployable ribs are beneficial if resulting mass savings are reallocated to increase vehicle diameter
  - Decreases peak heat flux significantly
  - Attitude damping increases with flexibility
- Number of ribs has a large effect on the drag properties and must be optimised for each mission
- Next steps: validation of aero-structural effects via experiment
  - Lab-scale test to investigate TPS flexure/wrinkling as ribs deform
  - High-speed wind tunnel test to investigate stability

Backup Slides

Mesh Convergence