Agenda

- Hypersonic Inflatable Aerodynamic Decelerator Status
  - HIAD Project focus
  - IRVE-3 development flight test
  - 6m diameter inflatable structure
- Structural Modeling
  - Methodology
  - Process
  - Test data
    - Acceptance tests
    - Wind tunnel testing
  - Verification & Validation status

HIAD Motivation

- How can we advance Entry, Descent, and Landing technologies to provide enhanced access to space?
  - Greater landed mass
  - Access to higher elevations
  - Longer EDL timelines
  - Improved accuracy
- Increasing drag area provides or facilitates improvements in all areas
- Aeroshell size is limited by launch vehicle fairing size
  - Unlikely to drastically change in near-term (>20 years)
- Deployable decelerators provide increased drag area and maintain compatibility with existing launch vehicles
- Inflatable deployable decelerators can provide a minimal mass and volume solution, and enhance mission flexibility

NASA HIAD Project

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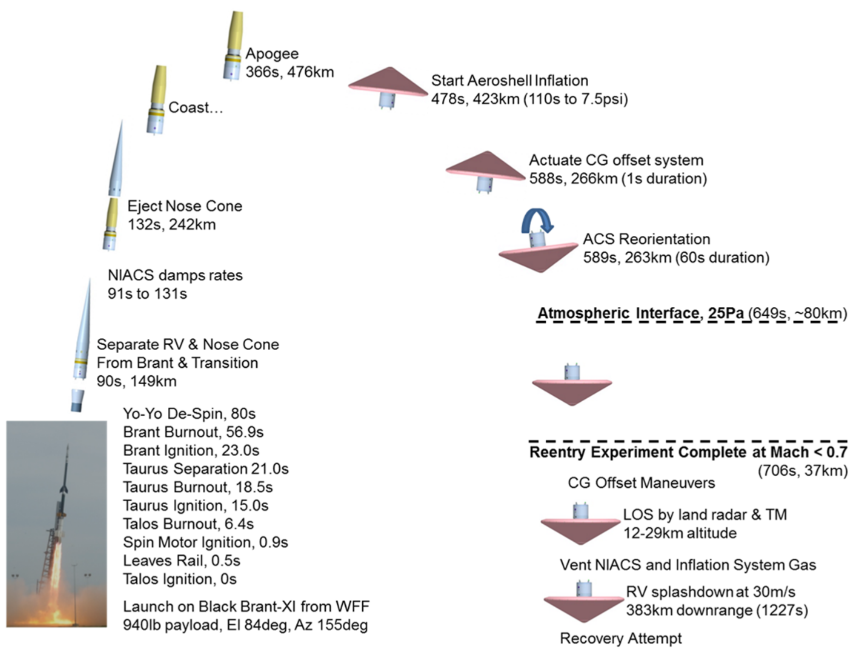
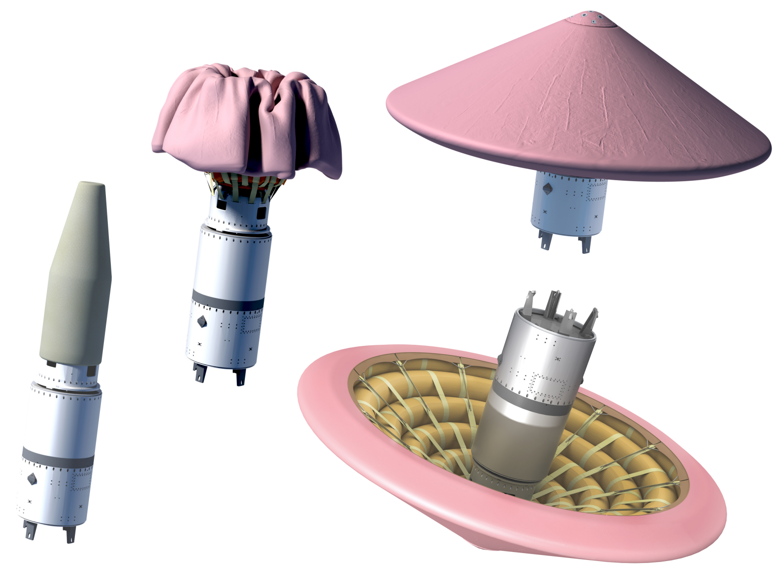
- "The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) project will focus on the development and demonstration of hypersonic inflatable aeroshell technologies suitable for an ISS down-mass capability."
- IRVE-3 development flight test
  - Builds on successful IRVE-II project
  - Expands heat rate from 1.8 W/cm^2 to 18 W/cm^2
  - Doubles reentry vehicle mass
  - Demonstrates CG offset for L/D
- Thermal Protection System (TPS) ground tests
- Inflatable Structure ground tests
  - NFAC Wind Tunnel test campaign 3 m and 6 m
  - Large Scale manufacture 6 m and 8 m designs

IRVE-3

- Objective of the Inflatable Reentry Vehicle Experiment 3 (IRVE-3) is to demonstrate HIAD technology in a relevant environment
  - Flight relevant thermal protection system (TPS)
  - Peak reentry heat rate > 15 W/cm^2
  - Demonstrate the effectiveness of an CG offset for L/D

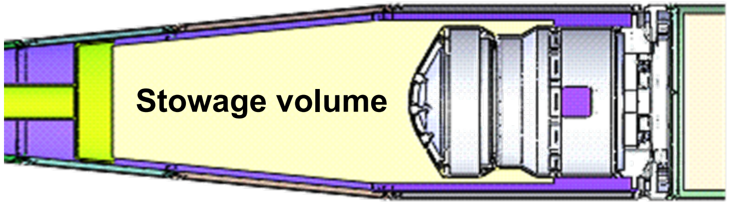




IRVE-3 Inflatable Structure

- The inflatable structure comprises
  - 7 inflatable tori stacked together to create a 60 degree cone
  - Each tori is a fiber reinforced braided tube with a gas barrier liner
  - The stacked assembly is bonded together and supported with pairing straps
  - Radial straps are integrated to provide drag load transfer to the centerbody

- The inflatable structure is covered with a flexible TPS blanket, and in the volume shown below

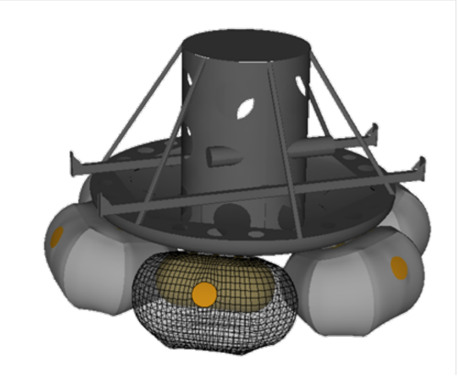


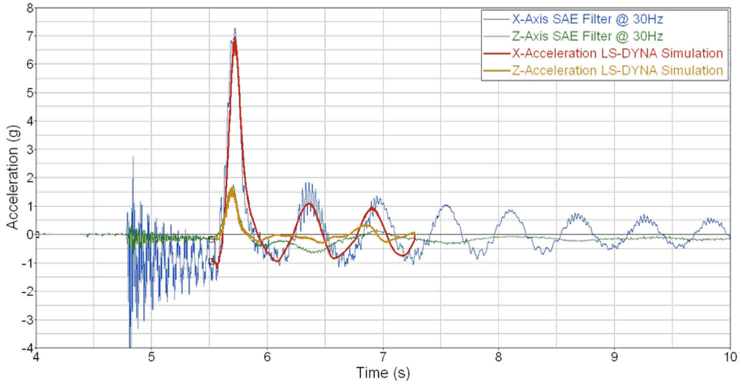
LS-DYNA Model

- LS-DYNA is a commercially available transient dynamic finite element code
  - Ideal for fabric structures, and pressurized volumes
  - Utilized fabric material model and airbag definitions developed for automotive crashworthiness airbags
  - Flexible contact definitions that enable accurate description of different contact interfaces
- Model used to evaluate aerodynamic drag load management in the inflatable structure, by replicating structural ground tests
  - Model used to investigate the influence of manufacturing variability
  - Also used to assess impact of pressure leaks, strap failures, gas supply variability, tori leaks or ruptures

LS-DYNA Model Heritage

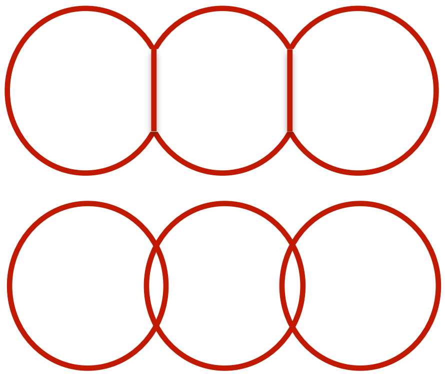
- Similar models developed for airbag landing systems for Orion capsule, as well as other manned spacecraft, and military aircraft
- Tori modeling approaches developed for shelters utilizing airbeam technology



Key Modeling Challenges

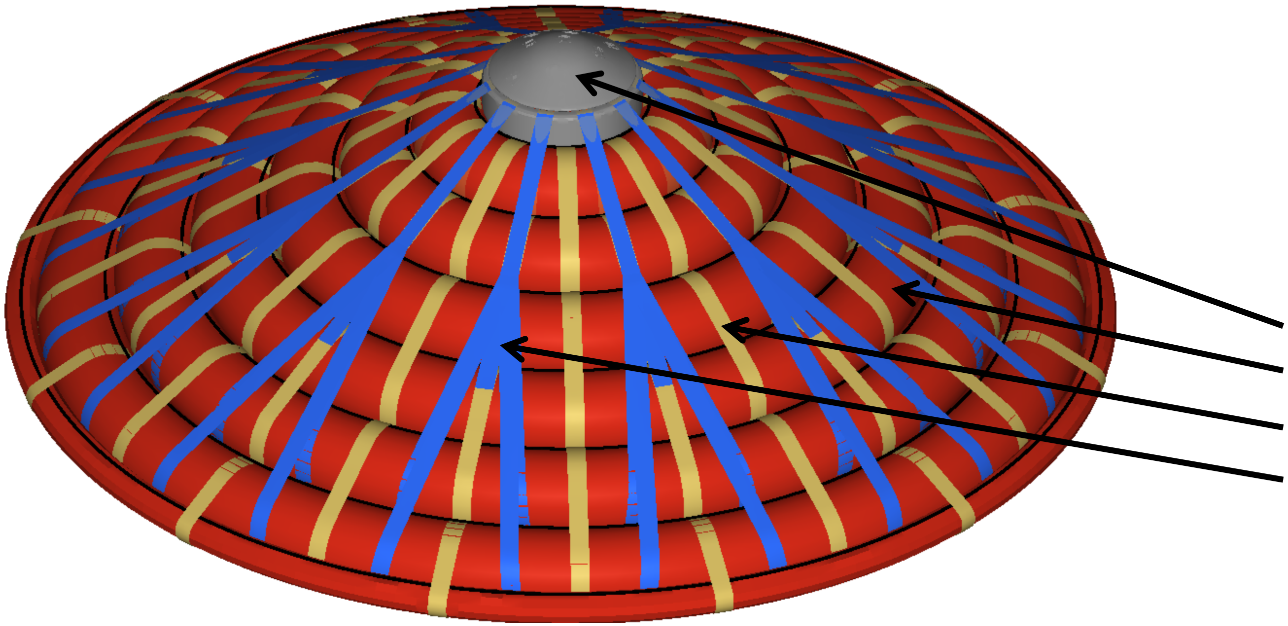
- Replicating nested tori configuration
  - When tori are assembled, adjacent tori create flat sections.
  - Model must generate configuration shown on right but include the tori geometry shown on left. Jumping straight to configuration on right assumes that you know the extent of the interface area for a very complex assembly
  - Modifying tori geometry to have flat sections incorrectly replicates tori geometry by reducing surface area



- Multiple contact interfaces
- Definition of braided tori
  - Non-orthogonal material fiber directions
- Accurate description of system geometry
  - Material behavior and dimensioning

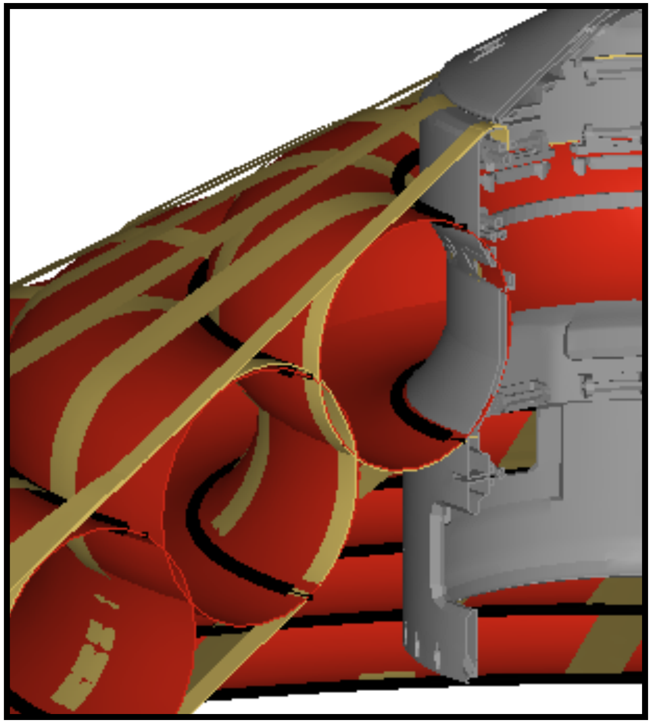
Model Components

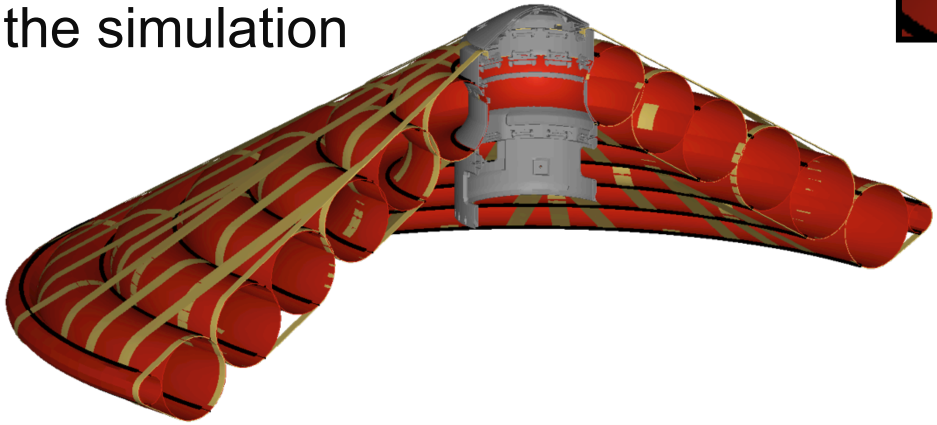
- Centerbody- rigid body definition, fully constrained
- Tori- Kevlar material definition, membrane shell elements with non-orthogonal material angles, 7 separate airbag volumes defined with Wang Nefske control volumes and venting capability
- Load straps- combination of 1¾ and 2 inch wide Kevlar webbing



Initial Geometry

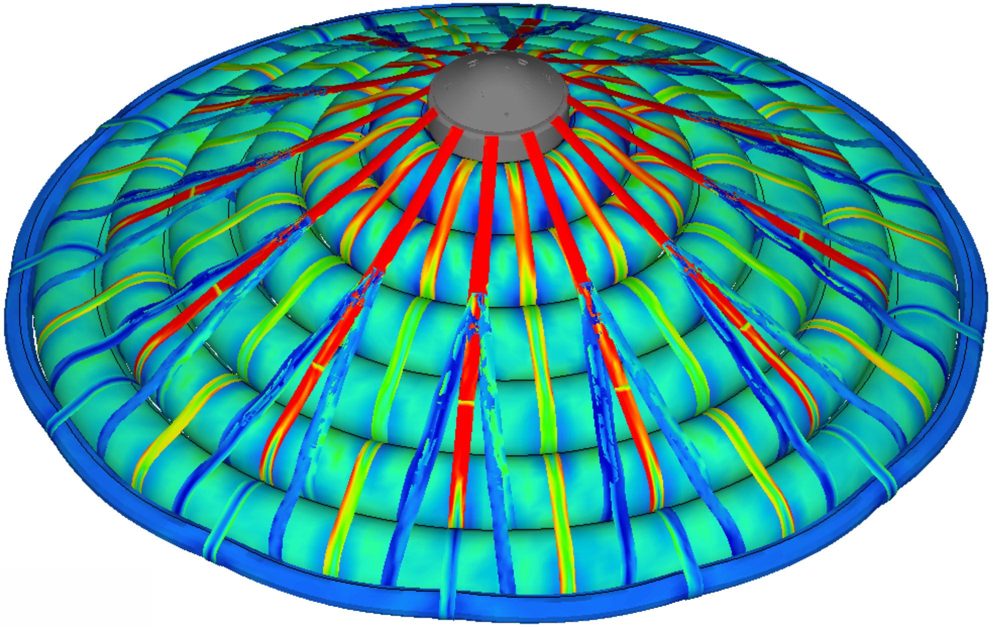
- Using fabrication drawings there are many interfaces that are in conflict
  - Between adjacent tori
  - Between torus #1 and the centerbody
  - Between straps and tori
- These conflicts are what give the structure the required strength and stiffness
- Need to resolve conflicts prior to load application, this is achieved in the first stages of the simulation

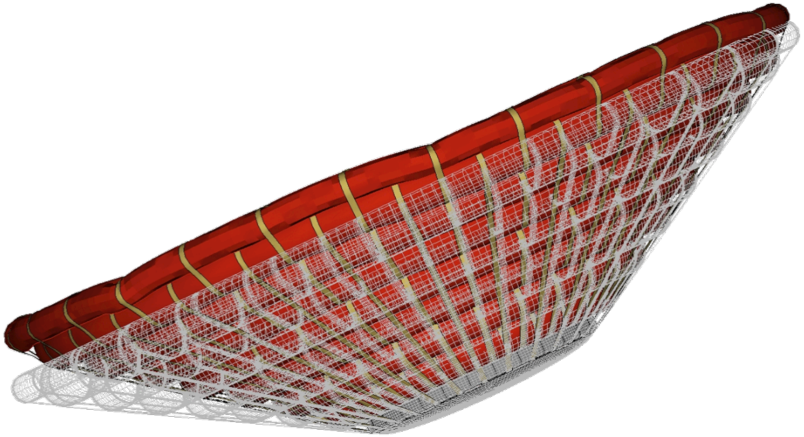




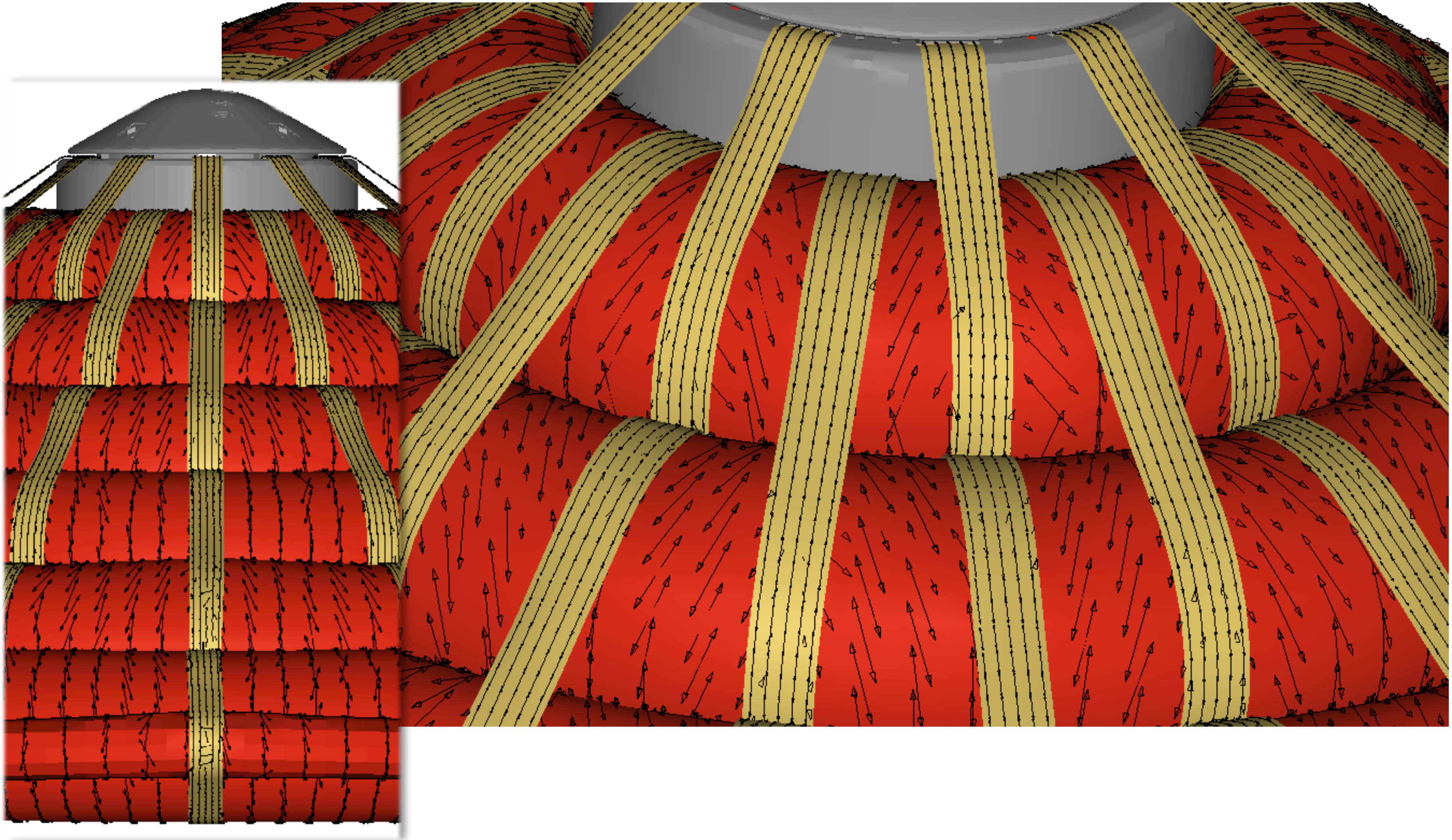
Model Output

- Stress contours
- Webbing loads
- Tori deflection
- Tori indentation
- Attachment load
- Performance at AoA



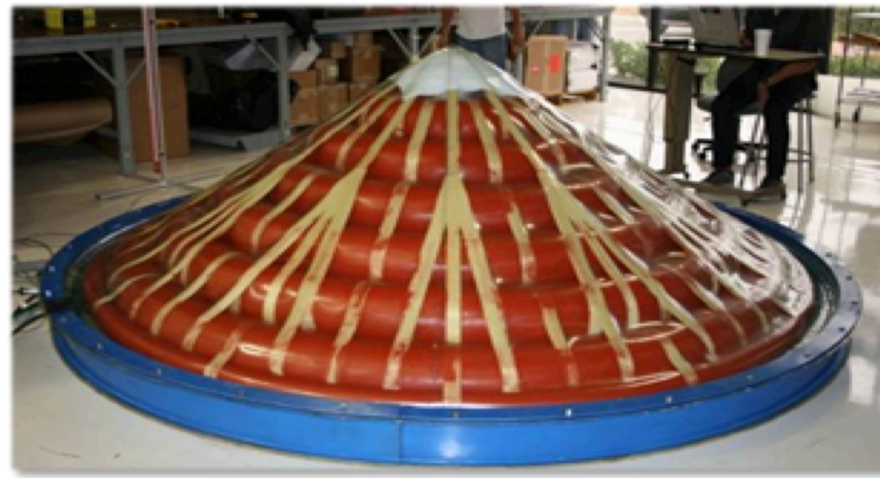


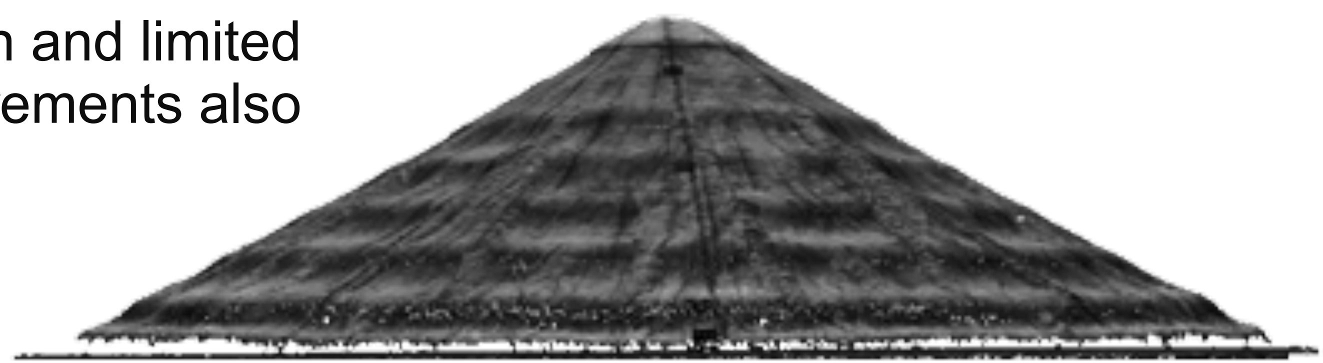
Stress Tensors



Acceptance Ground Test

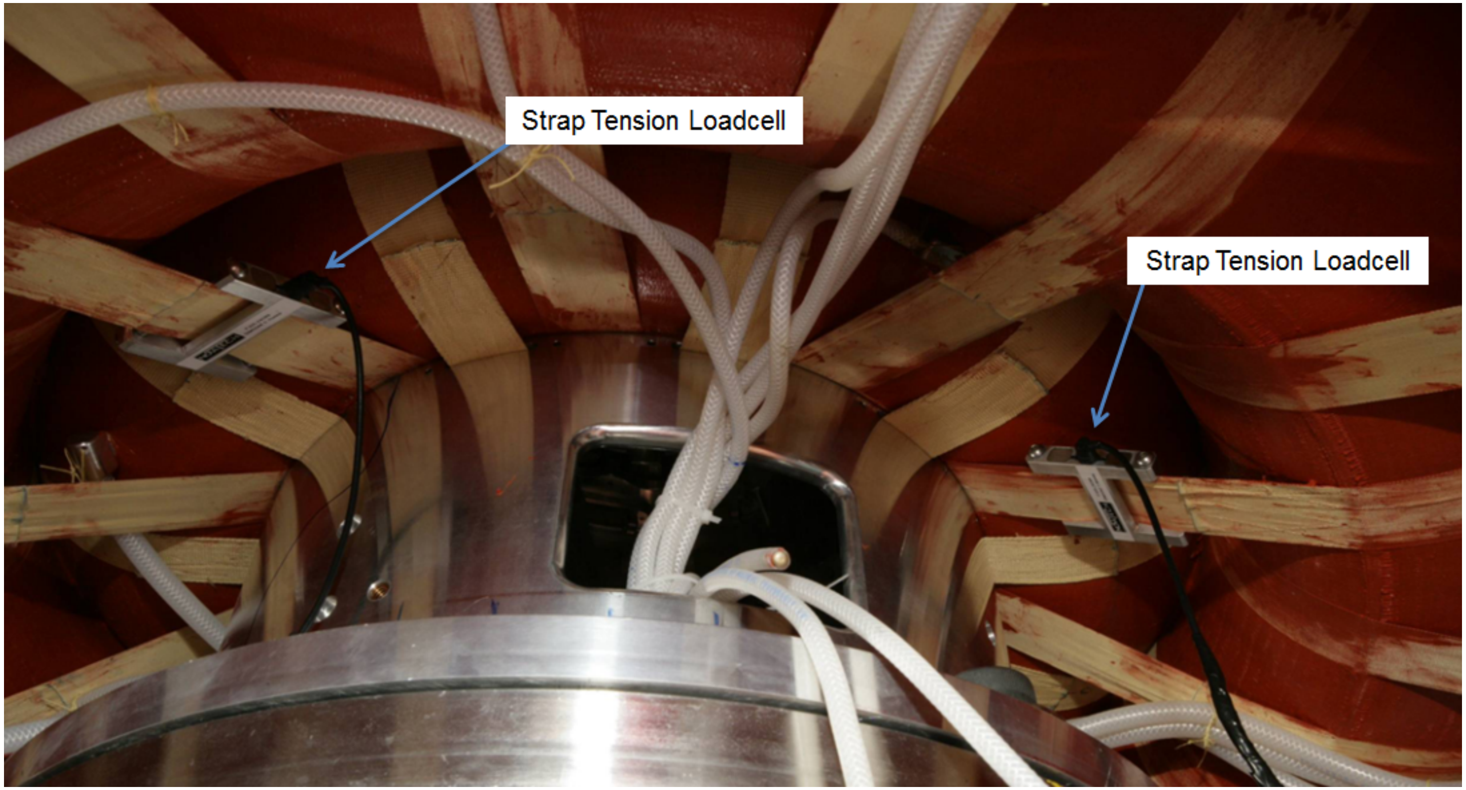
- Pressure application fixture was designed to apply a uniform pressure differential of 1.16 psi (8,000 Pa) across the drag surface
- Generated force of 12,600 lbf (55,600 N), 20g deceleration load
- Laser scan measurements used to create 3D deformed surface geometry
- Structure deflection and limited strap force measurements also recorded





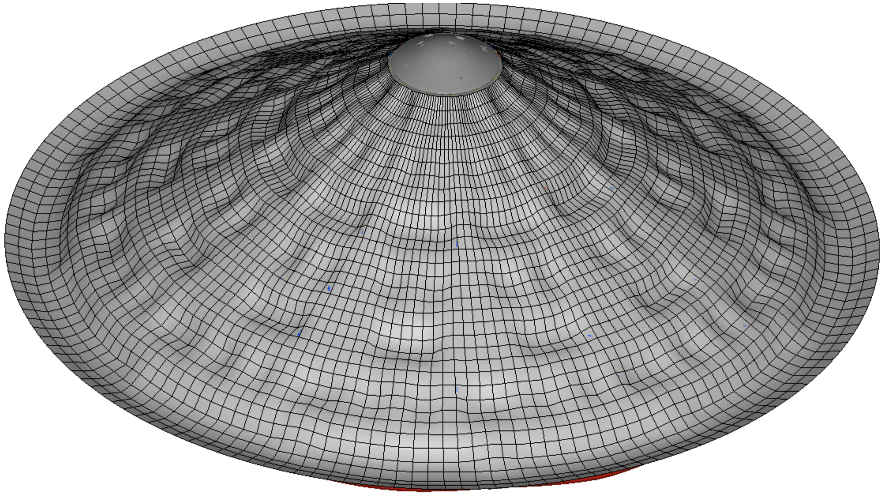
Test Data

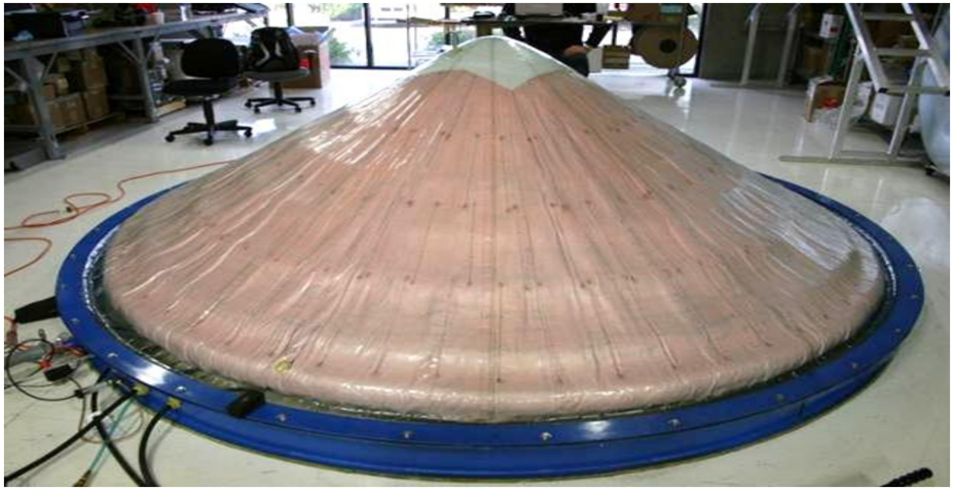
- Strap tension load cells were located on the pairing loop strap between torus #1 and torus #2

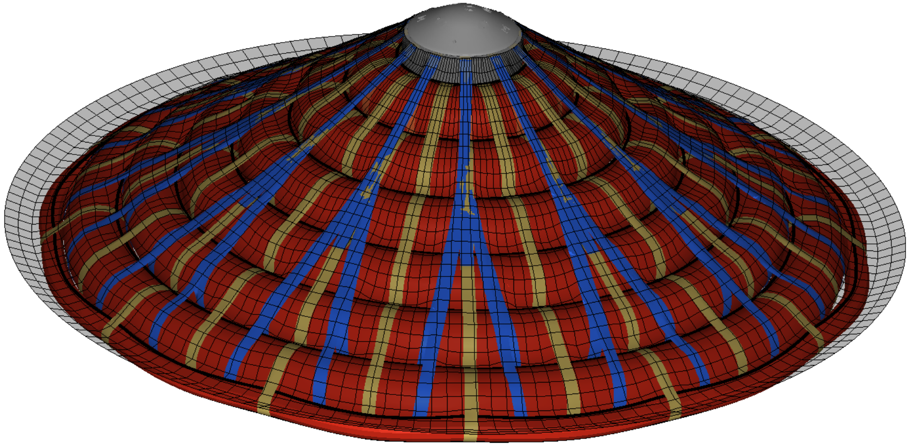


Structural Test Simulation

- Pressure load is applied to the model in similar way as structural test
- Model is explicit, so initial phase is used to resolve interface conflicts, then pressure load is applied over time- producing a time based solution

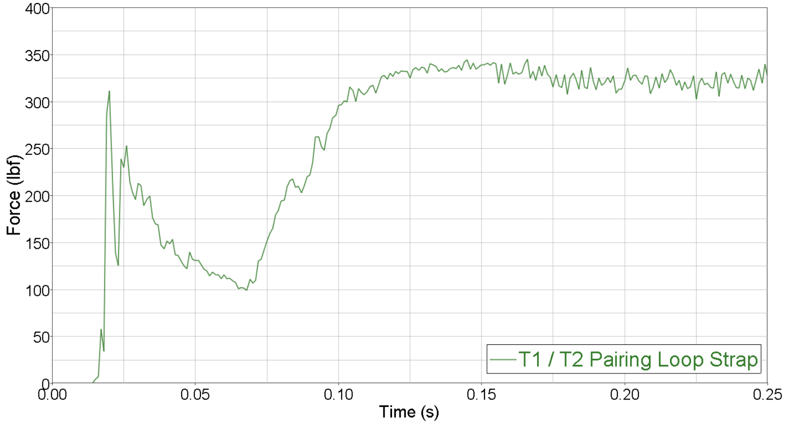


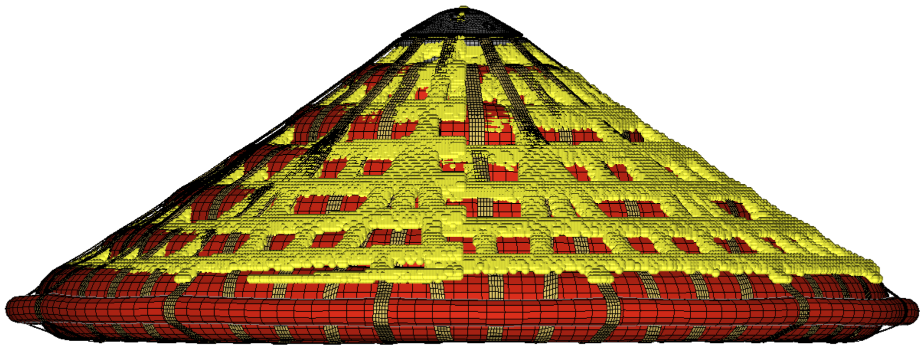


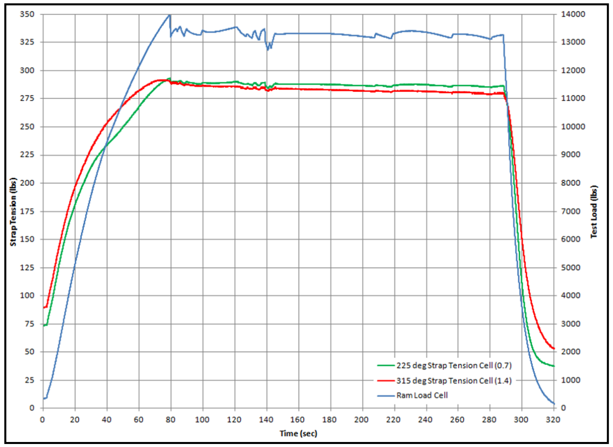


Test Data Comparison

- Total load applied to inflatable structure was 12,600 lbf
- Load in pairing loop strap between torus #1 and torus #2 was measured at 285 lbf
- Model predicted a strap load of 315 lbf
  - ~10% over prediction
- Comparison of laser scan node cloud has been challenging, but model also over predicts deflection by ~10%

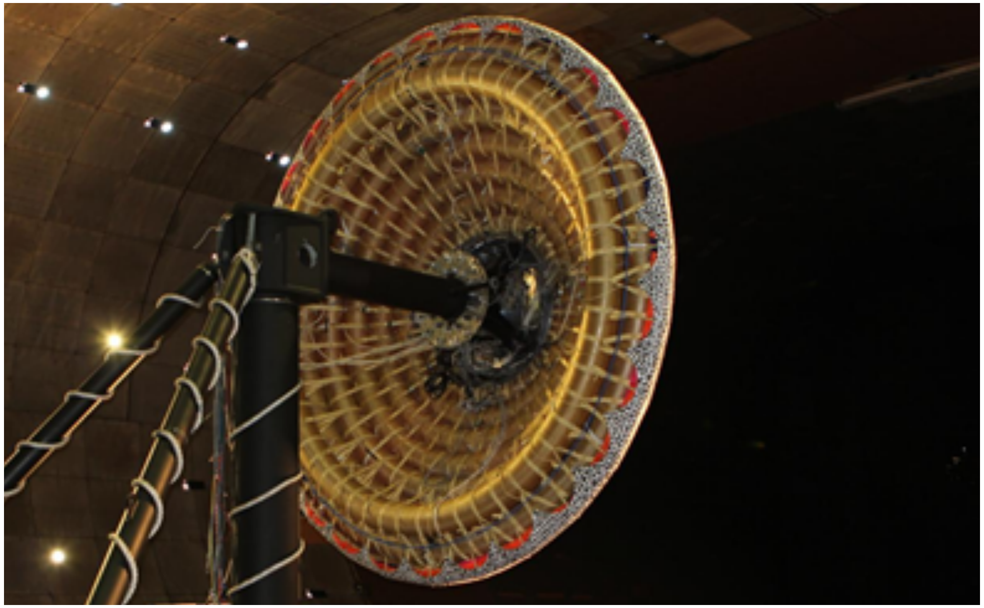


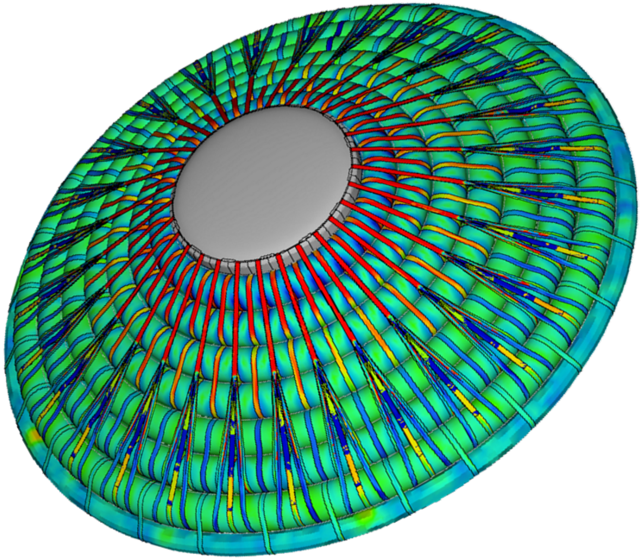




Scaled Designs

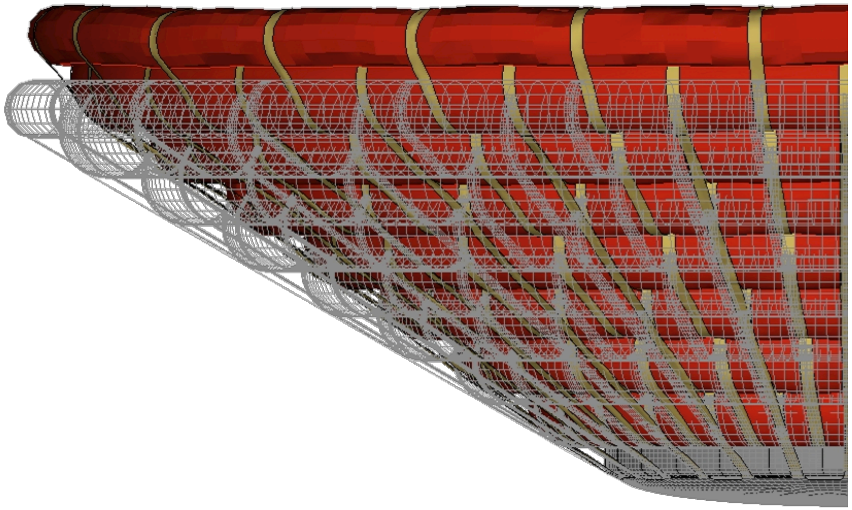
- A 6 meter design is currently undergoing wind tunnel testing at NASA Ames
  - Evaluating drag and stability performance at different angles of attack and providing controlled test data for model validation, and to provide insight into hardware / software interface performance

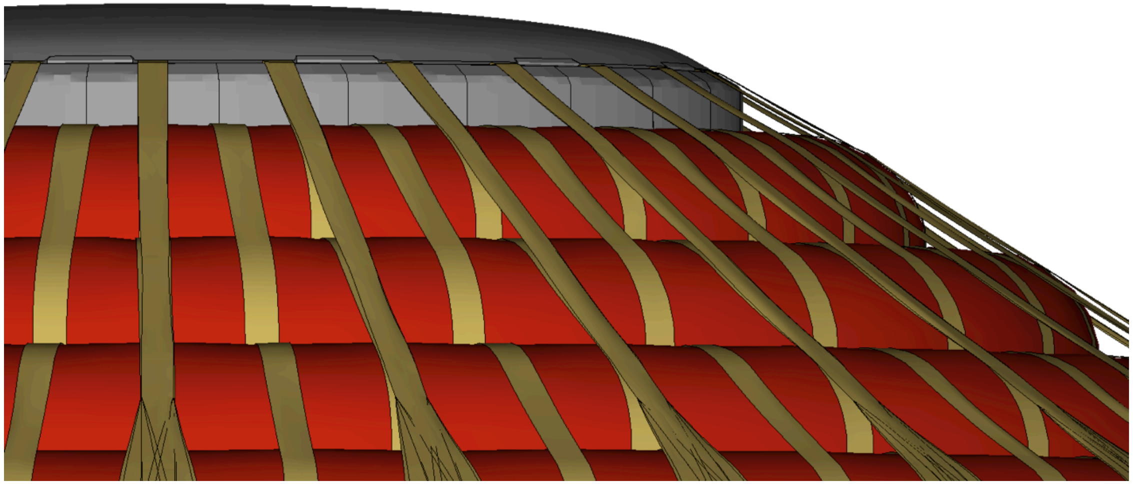




Structural Load Model

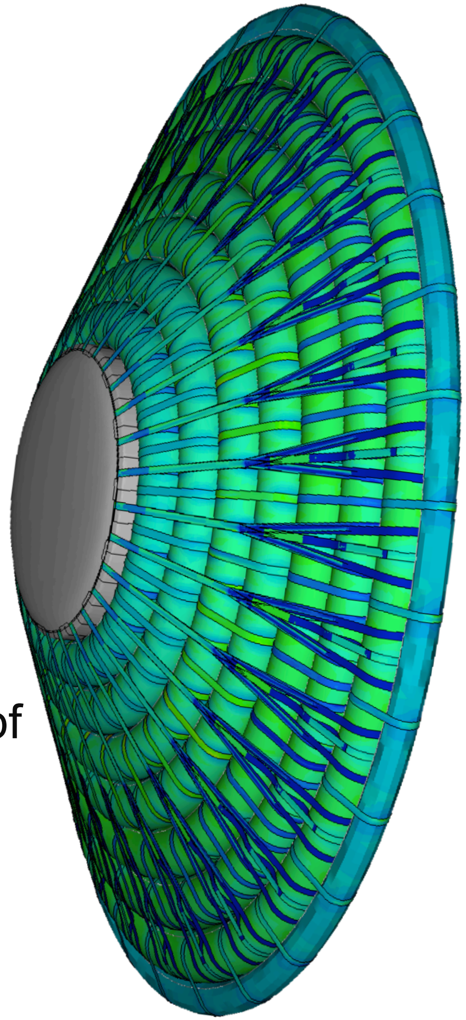
- Structural load was applied as a normal force on a component replicating the aerocover
- Load was ramped in over time (60 ms)
- Internal pressure of 20 and 10 psig models were run, along with failure cases- tori venting and strap release





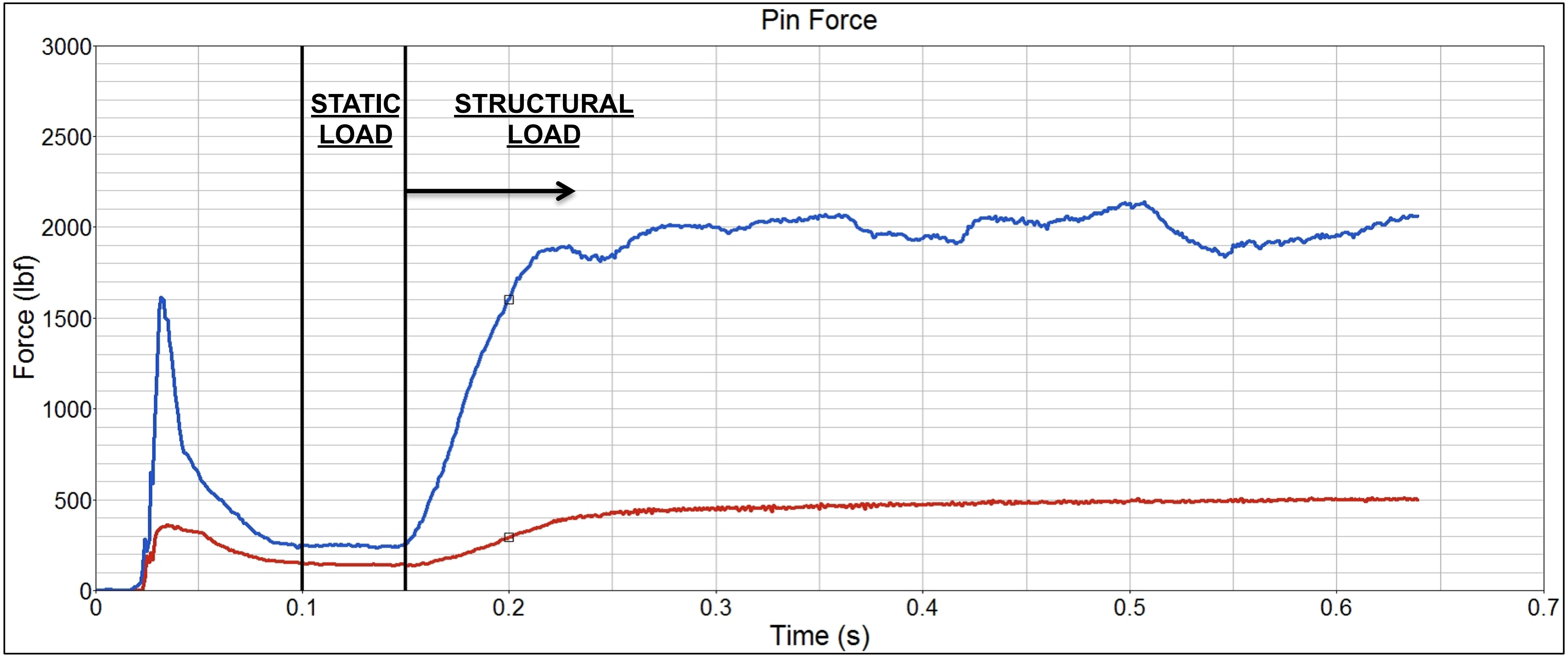
Static Test (pre- load balance)

- Loads measured at 10, 15, and 20 psig
  - Pairing loops, centerbody attachment pins, radials
- Pin forces ranged from 136-291 lbf at 20 psig and dropped to 94-261 lbf at 10 psig
  - Integration and movement of instrumentation impacted the individual results but the overall trend was indicative of test article behavior
- Webbing measurements were low and therefore impacted by equipment
  - T3 / T4 pairing loop was consistently taught, ~50-80 lbf
  - T7 /T8 pairing loop was also consistently taught, ~70-140 lbf
    - Not susceptible to system variables like other pairing loops
- Radial strap load was more reliable
  - Dropped from ~210 lbf at 20 psig to ~95 lbf at 10 psig



Pin Force at 20 PSIG

- Static Load-   AFT= 150 lbf, FWD= 240 lbf
  - Test instrumentation recorded between 136-291 lbf on FWD pins
- Structural Load-   AFT= 500 lbf,   FWD= 2000 lbf



Pairing Loop Force (front only)

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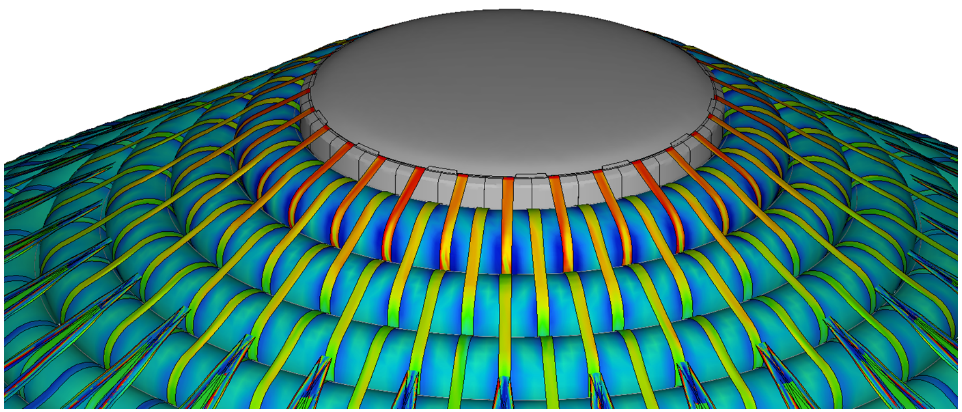
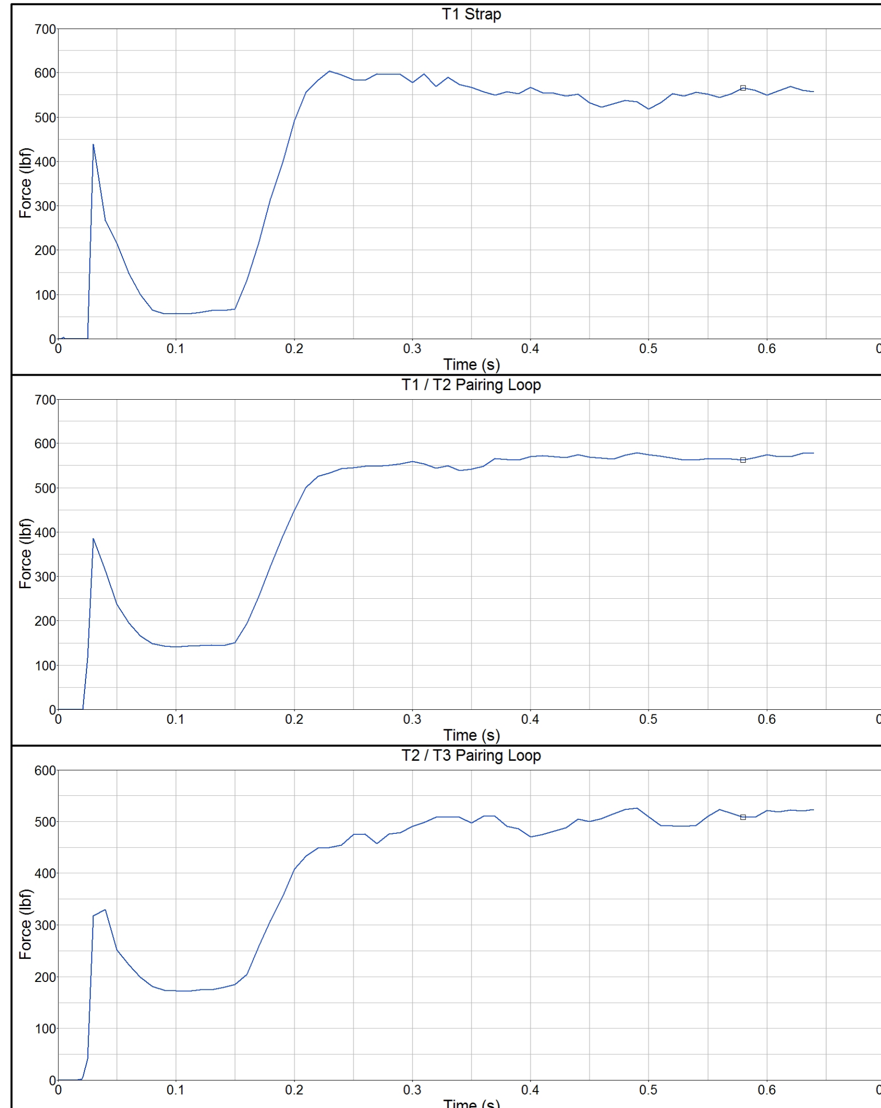
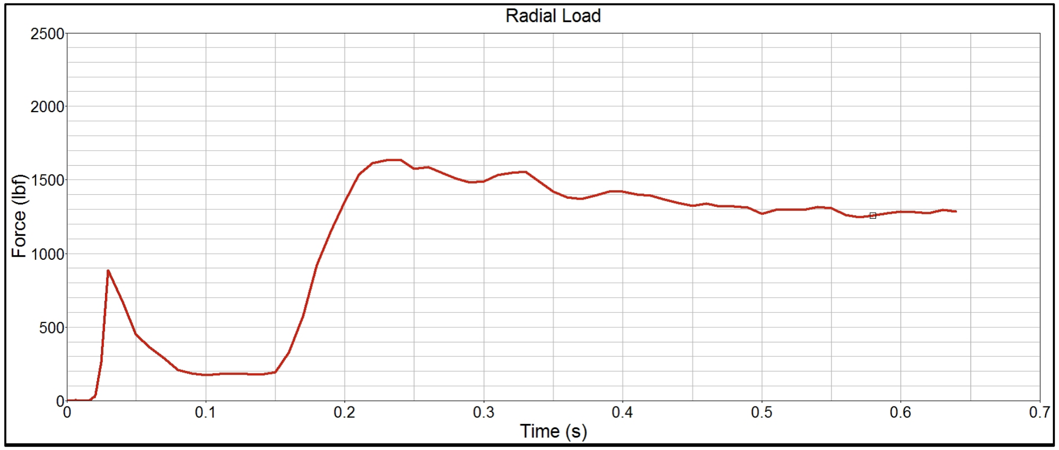
- Model indicates that the pairing loop load appears to self distribute during structural load test
- Static load varies between pairs, but structural load generates approximately 550 lbf across key pairing loops, T1/T2, T2/T3, T3/T4
- Highest static load was 250 lbf between T3/T4 (500 lbf Structural)

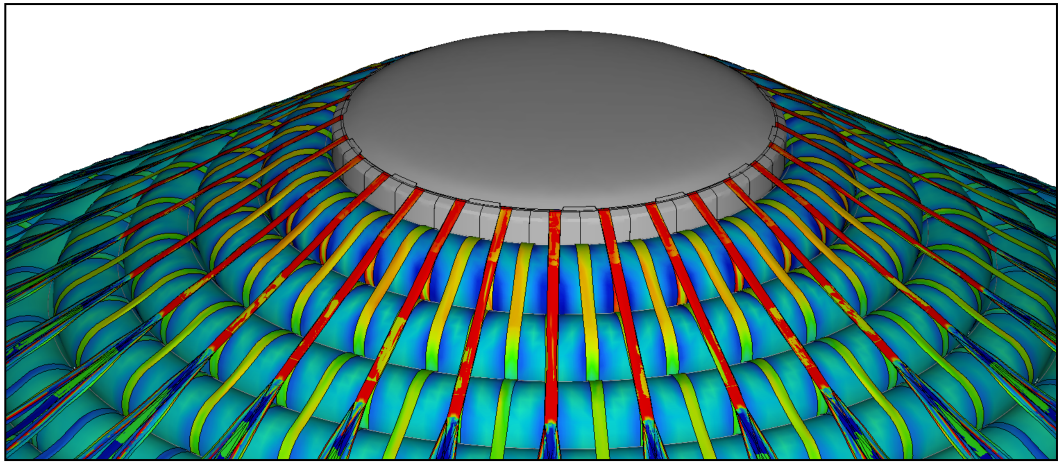




Radial Loading at 20 psig

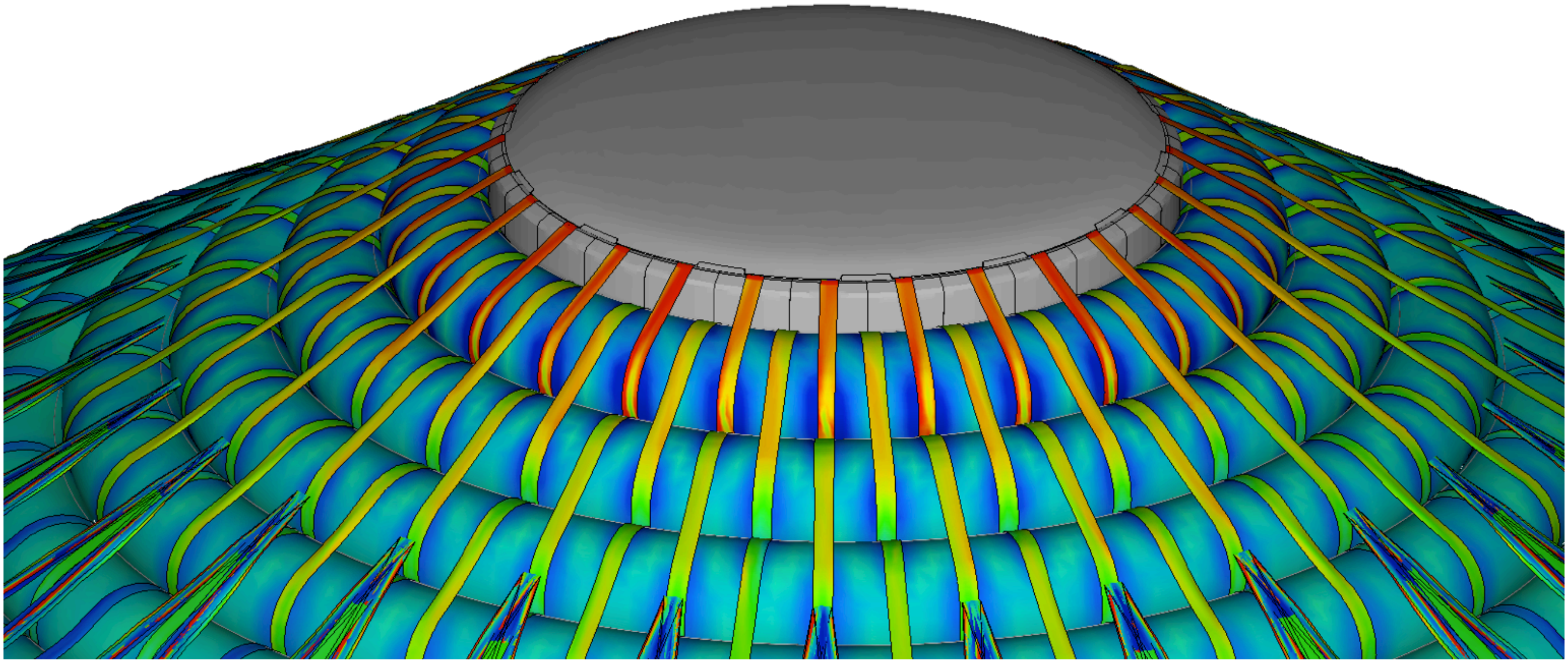
- Static test load = 190 lbf
- Structural test = 1350 lbf





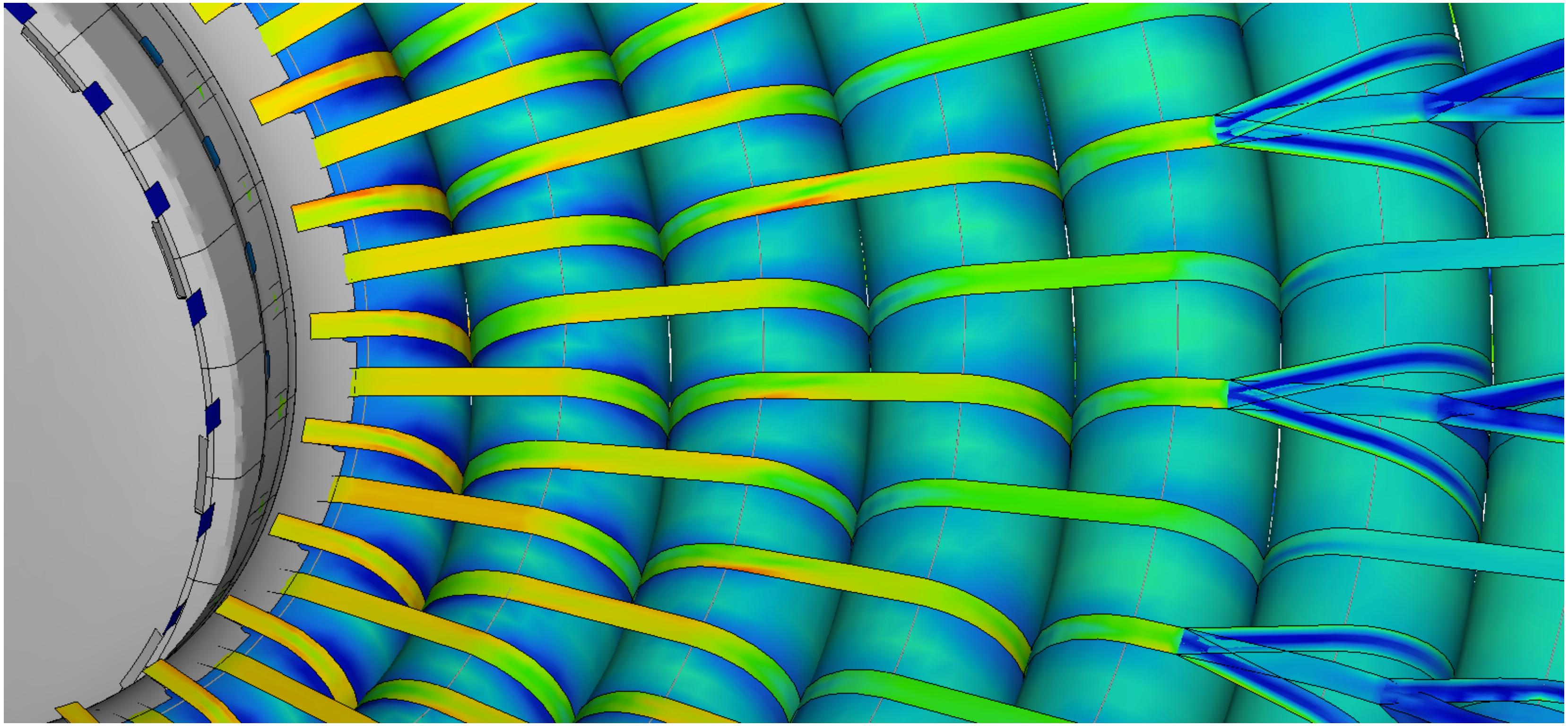
Structural Load at 20 psig

- Front side without main radial, illustrating pairing loop load distribution
  - Note: T1 strap narrower
- Total axial displacement ~3.5 inches



Structural Load at 20 psig

- Rear side of structure



Conclusions

- IADs are complex assemblies of fabric materials whose material properties are not well defined for this rate of loading and environment
- Kevlar, Technora, Vectran are all materials that typically have low elongation properties; this makes understanding both the initial length and initial elongation performance critical, as it can produce uneven load sharing
  - Some materials exhibit elongation at low force due to fiber and weave alignment, this performance can vary based on prior loading events (hysterisis)
  - Component material properties are different than raw fiber material properties
- Recent test data is enabling model validation and further system understanding