Structural Analysis and Testing of a Subscale Sunshield Membrane Layer

John Johnston – NASA Goddard Space Flight Center

Joseph Blandino – James Madison University

Jonathan Black – George Washington University

Richard Pappa – NASA Langley Research Center

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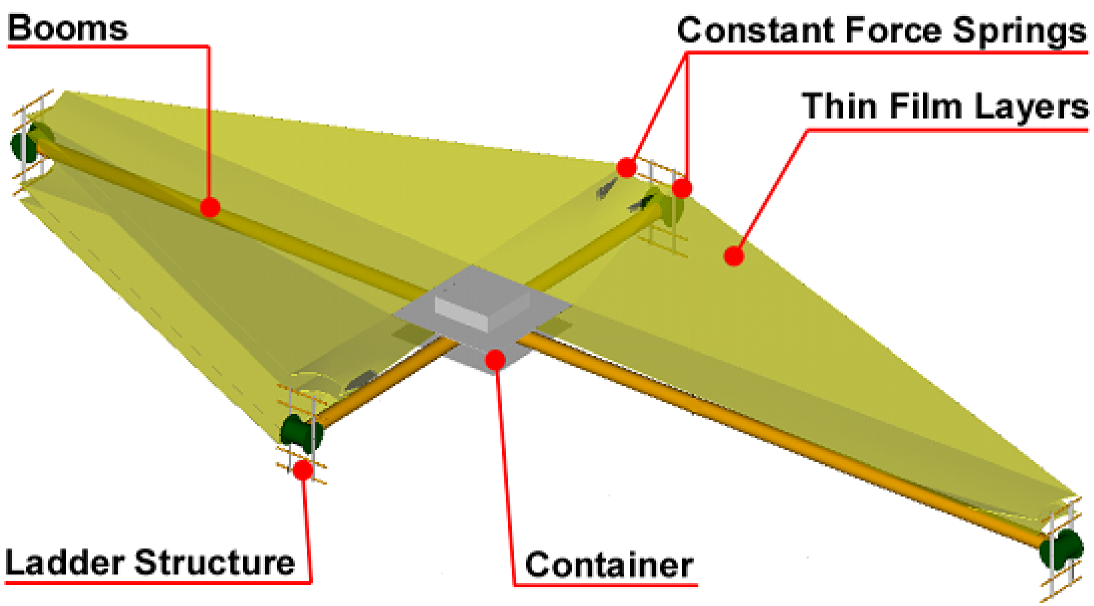
Sunshield Structures

- Post-deployment structural performance of the sunshield is a concern since it may impact observatory performance in areas ranging from dynamics and control to thermal performance.

- The sunshield structure must meet requirements relating to both spacing and flatness of the film layers while accommodating complicating factors such as thermal strains and wrinkling since the geometry of the layers directly impacts thermal performance.



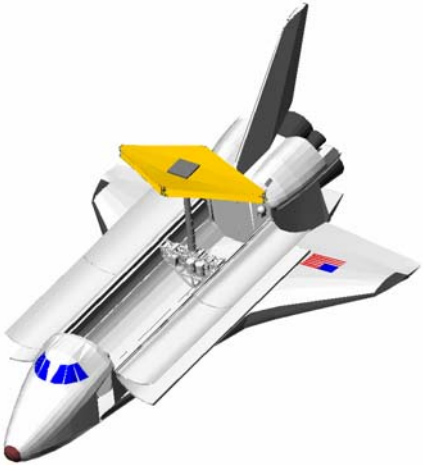
NASA Reference Concept:
- Overall size = 30 m x 15 m
- Total Mass = 200 kg
- "V-Groove" Geometry

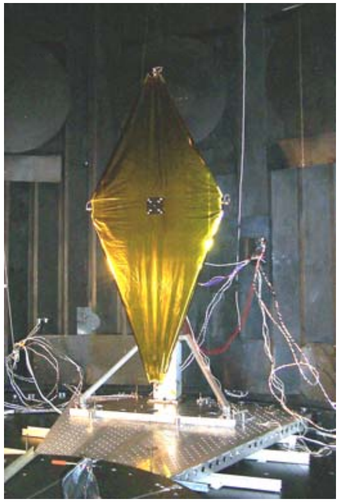
Thin film layers:
-Material: Kapton
-Thickness = 0.001-0.0005 in
-Global stresses ~ 10 psi
-Local stresses ~ 100 psi

Sunshield Technology Development

- The JWST project has supported the development of subscale sunshields based on the NASA reference concept to reduce risks associated with packaging, deployment, film management, structural dynamics, wrinkling, and structural analysis and testing.
  - ½ scale engineering model sunshield for deployment demonstration
  - 1/3rd scale sunshield/ISIS flight experiment concept
  - 1/10th scale model sunshield for ground dynamic testing

- Recent efforts have focused on the development of improved capabilities for analysis and ground testing of sunshield structures that will enable the accurate prediction of post-deployment structural performance.



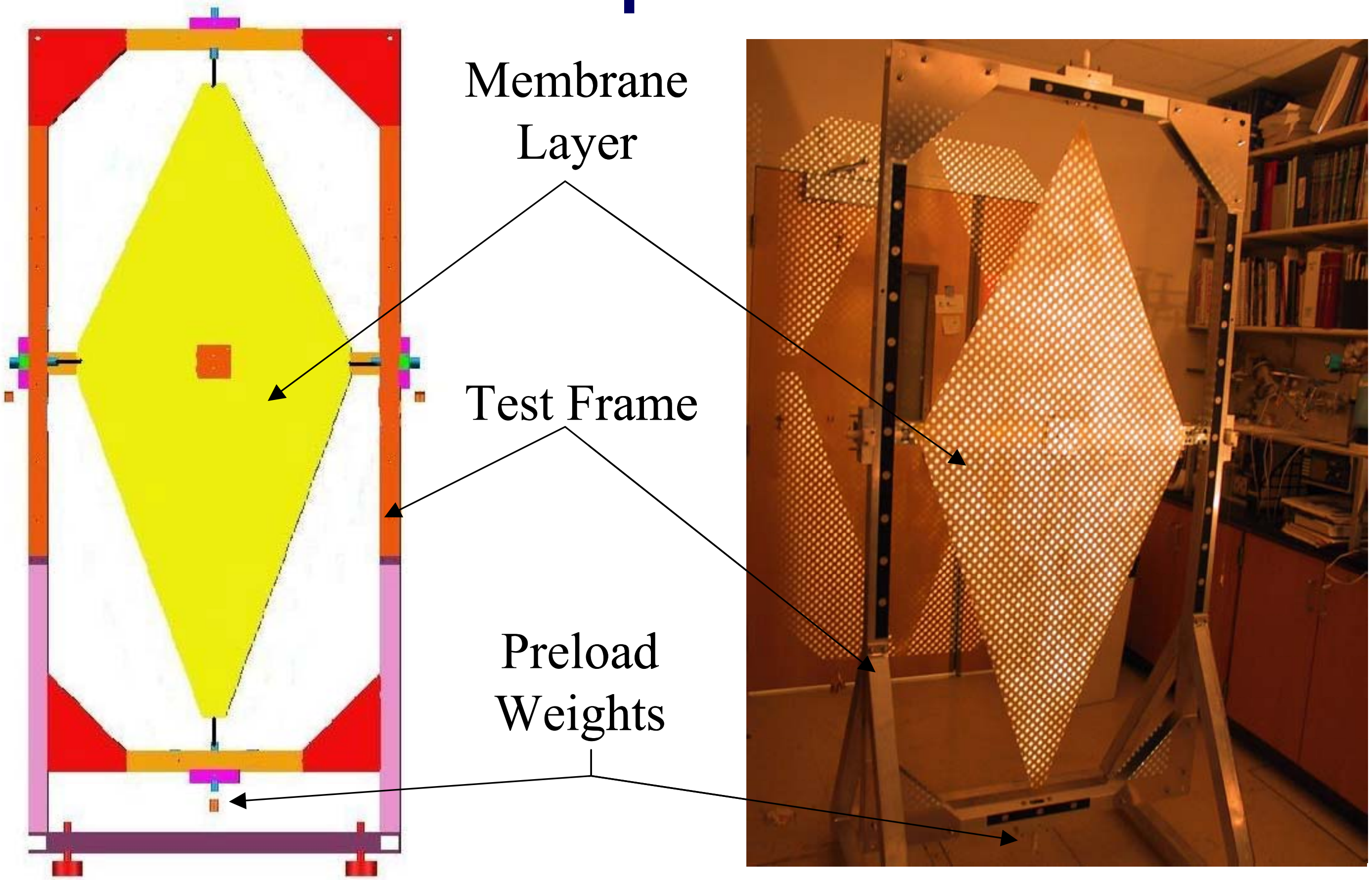


Subscale Sunshield Membrane Layer Study

- Analysis and ground testing of a subscale sunshield membrane layer based on the NASA reference concept for the JWST observatory is being carried out to develop and validate capabilities to predict and verify post-deployment static performance.

- The objective of the study is to characterize the preloaded geometry of a single membrane layer on both the global (shape) and local (wrinkling) scale:
  - Predict structural behavior using nonlinear FEA
  - Measure surface profiles using photogrammetry
  - Validate analysis through comparison with test results

Test Setup - Overview

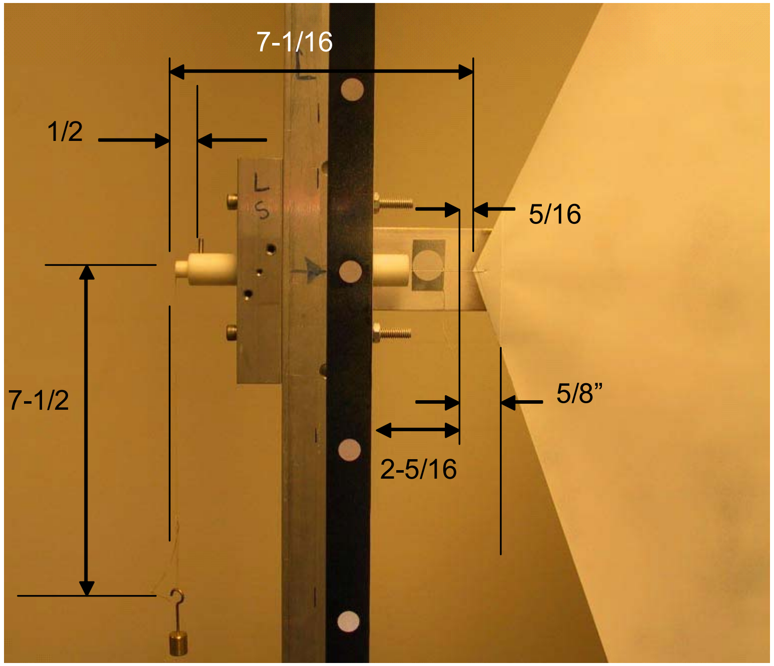


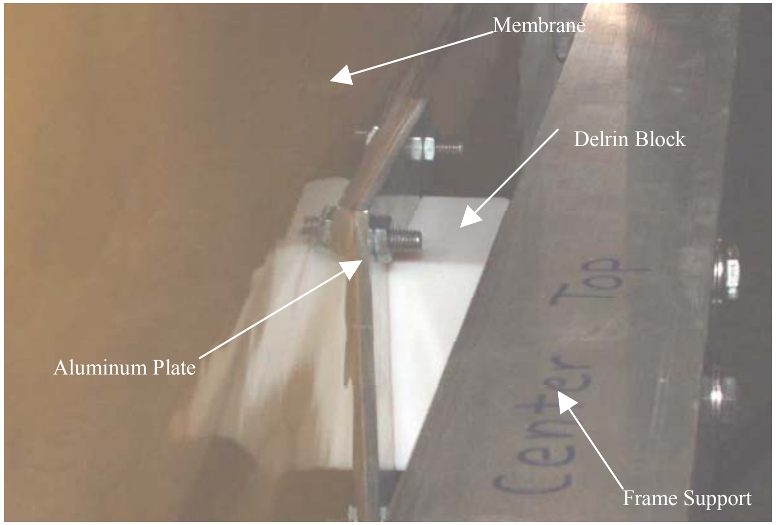
Test Article Characteristics

- Overall dimensions = 1.7 m x 0.7 m (1/20th scale)
- Thickness = 2.54E-5 m (1 mil)
- Material = Kapton (Aluminized on one side)
- Constant Force Preload = 4.3 N (440 g) per corner

Test Setup – Supports

- Membrane is attached to test frame at center and corners
- Membrane corners reinforced with UHMW polyethelene tape
- Kevlar threads apply loads at the corners of membrane and connect membrane to test frame
- Membrane is 'sandwiched' between two aluminum plates at its center:
  - Plates are connected to test frame support by Delrin block
  - Different thickness blocks are used to offset the center of membrane relative to corners

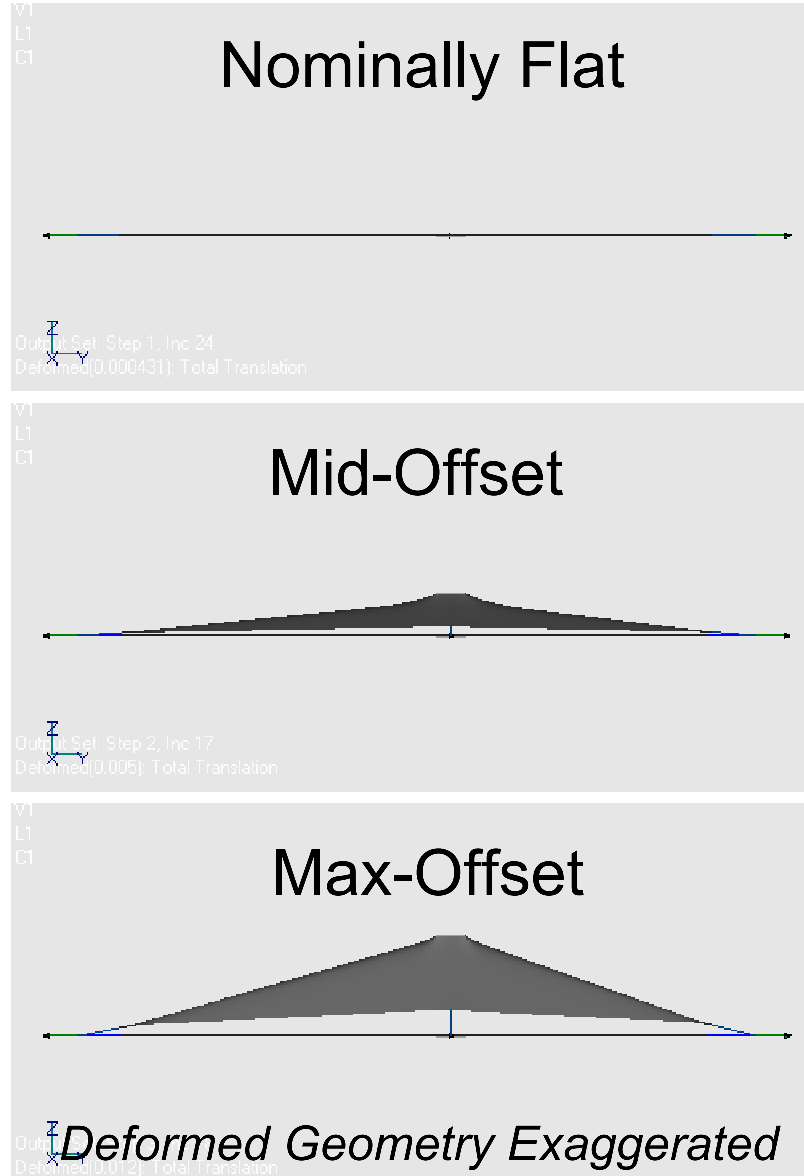




Test Setup – Membrane Configurations

- Three different membrane configurations were studied, each representing a different global geometry:
  - Nominally flat
  - Center offset by 0.005 m (mid-offset)
  - Center offset by 0.012 m (max-offset)

- The angle between the central support and the corners due to the offsets is representative of the "v-groove" angles considered for the full-scale sunshield.



Analytical Study

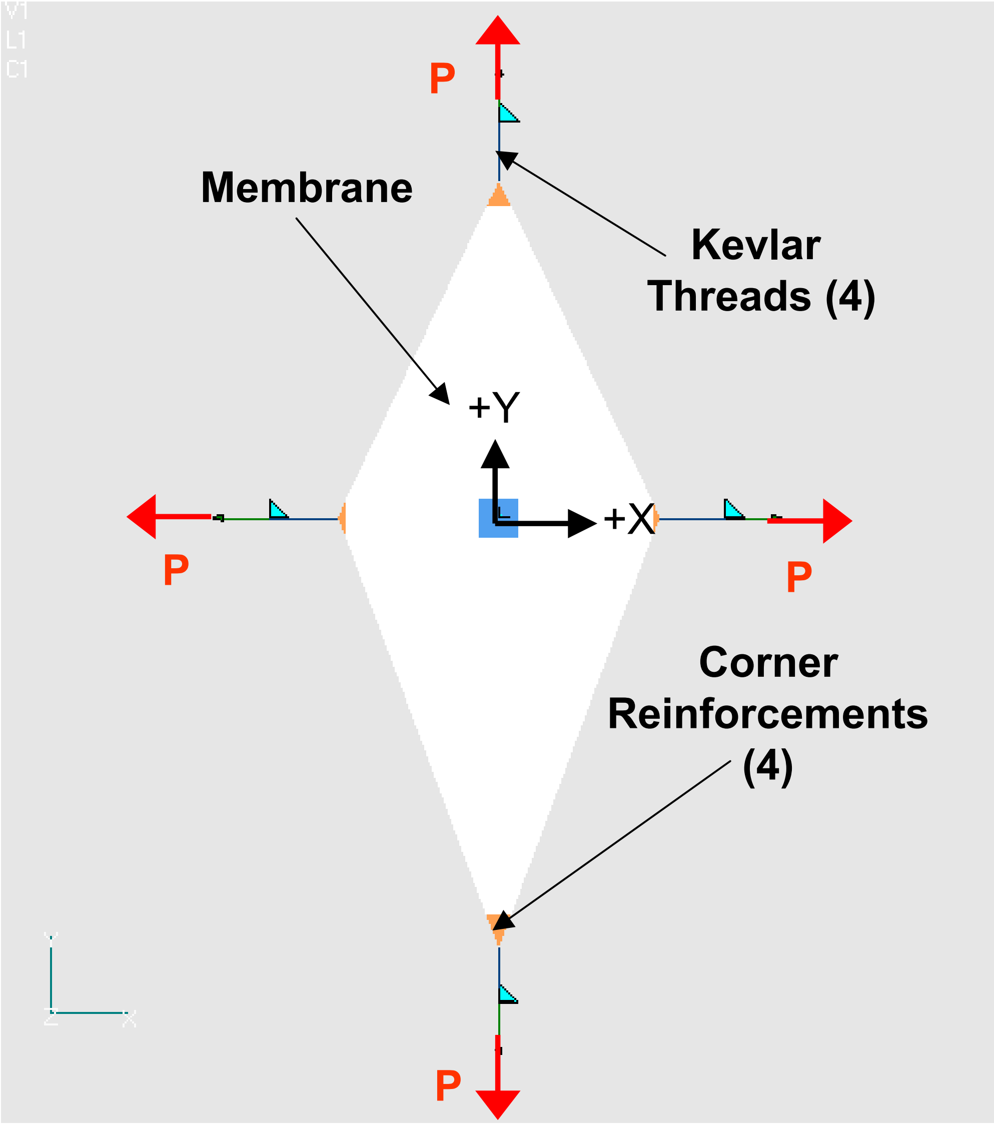
- A challenging aspect of sunshield analysis is modeling the nonlinear behavior of partially wrinkled, thin-film membranes.

- The objective of the analysis is to predict the deformed geometry of a single sunshield membrane layer:
  - Membrane (2-D) analysis predicts global shape
  - Shell (3-D) analysis predicts both global shape and wrinkling details.

- Nonlinear static finite element analysis performed using ABAQUS

Finite Element Model

- Mesh:
  - 48545 Nodes
  - 47462 Elements
- Components:
  - Film
  - Corner reinforcements
  - Threads
  - Center support
- Support conditions:
  - Constrained at the center
  - Threads free to move in loading direction only



Membrane (2-D) Model

- Membrane layer modeled using membrane elements (M3D3/M3D4) in conjunction with a wrinkling material model.
  - Material model is a finite element implementation of Stein-Hedgepeth membrane wrinkling theory.
  - Approach developed by Miller-Hedgepeth (1982) and Adler-Mikulas (2000).

- Membrane element stiffness iteratively modified to account for the effects of wrinkling.
  - Element state determined using a mixed stress-strain criteria:
  - Stiffness matrix formulation based on the element state

- Nonlinear static analysis uses ABAQUS STABILIZE parameter to provide numerical stabilization.

- Approach predicts stress distributions corrected for wrinkling and slackness as well as wrinkled/slack regions, but not wrinkling details (amplitude, wavelength, number, etc.)

Shell (3-D) Model

- Membrane layer modeled using thin shell elements (S4R5/STRI3)
- Mesh is "seeded" with an initial out-of-plane geometric imperfection to induce wrinkling:
  - Based on a superposition of buckling modes
  - Imperfection scaled to an amplitude of 10% of the membrane layer thickness
  - Approach outlined by Wong and Pellegrino (2002)
- Analysis uses ABAQUS STABILIZE feature to provide numerical stabilization
- Approach predicts wrinkling details

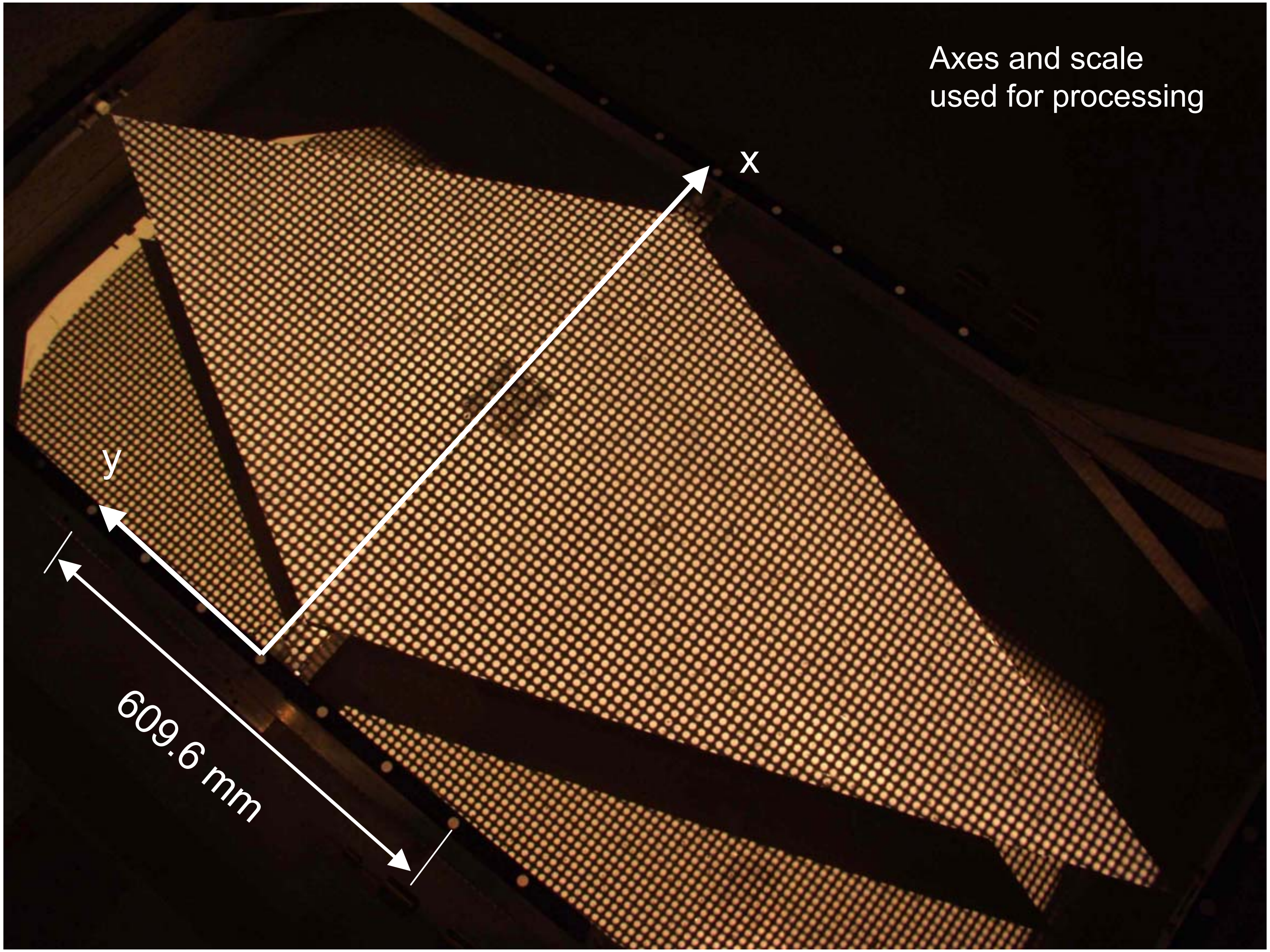
Experimental Study

- Photogrammetry was used to determine the surface profile of the membrane:
  - Approximately 4000 targets were projected onto the surface of the membrane using a high intensity projector.
  - Fixed retro-reflective targets were attached to the two vertical supports of the test frame to set the scale and coordinate axes during processing.
  - Membrane was coated with a thin layer of a talc-based developer to accommodate target projection. The white developer provided uniform illumination of the targets over the entire membrane.

- Photographs were taken simultaneously at four positions using identical 5.0 megapixel digital cameras.

- Images were processed using PhotoModeler®, a commercially available photogrammetry software package.

Image From Photogrammetry Data Processing



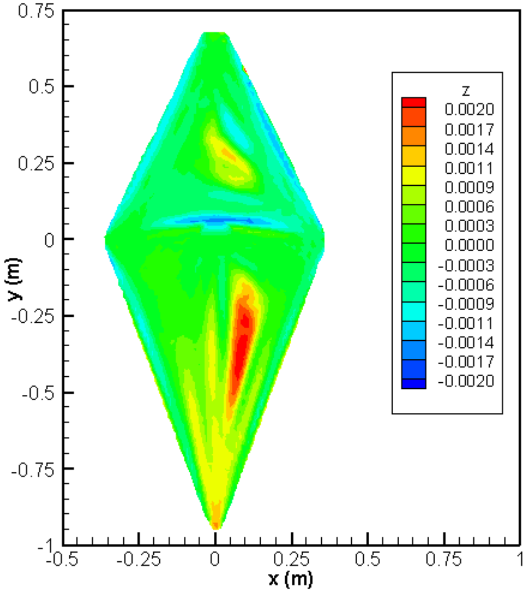
Comparison of Analysis and Experiment

- Analytical predictions from the membrane and shell models were compared with test results via the following:

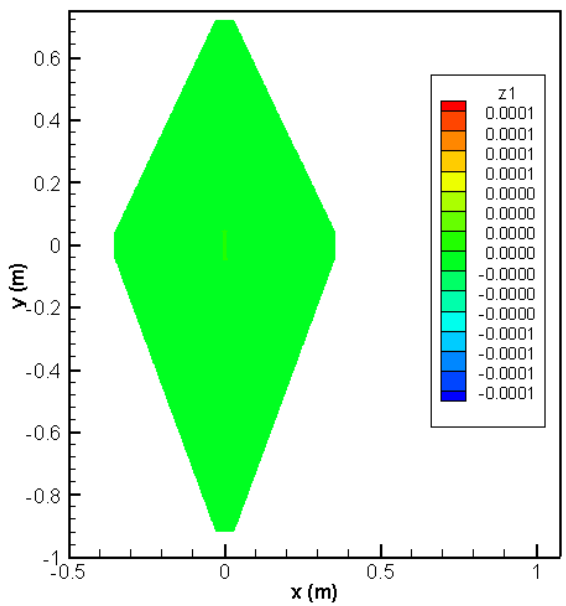
1. Contour plots of displacements in out-of-plane (z) direction
2. X-Y plots of out-of-plane displacement as a function of x along lines of constant y-coordinate:
   – Y = +0.4 m (top half of membrane)
   – Y = 0.0 m (center of membrane)
   – Y = -0.5 m (bottom half of membrane)

Preload = 4.3 N, Offset = 0.000 m

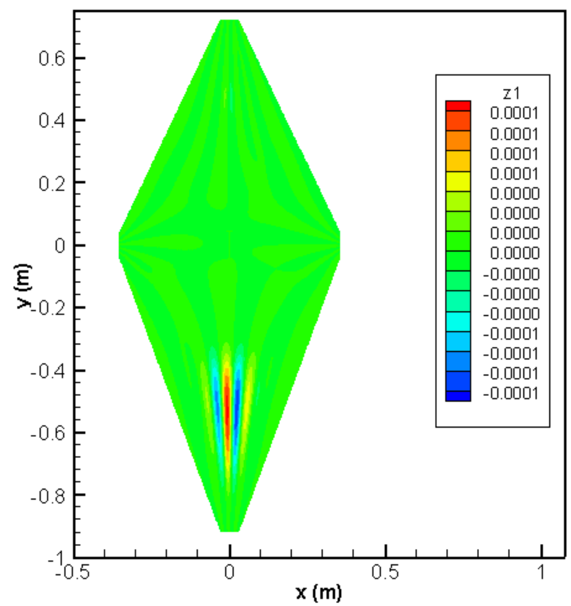
Experiment



Membrane FEM

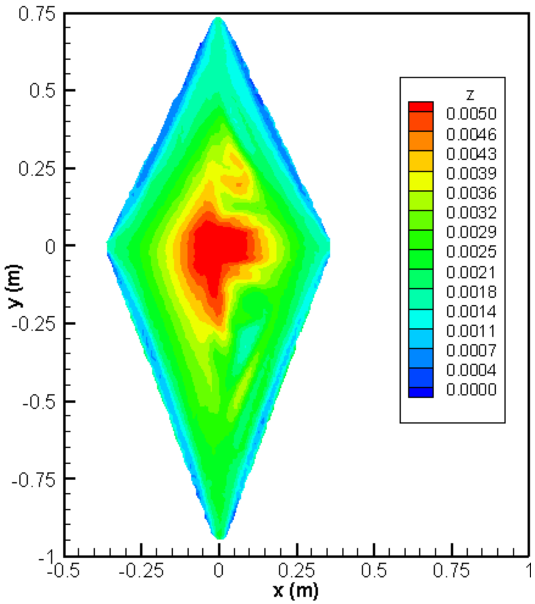


Shell FEM

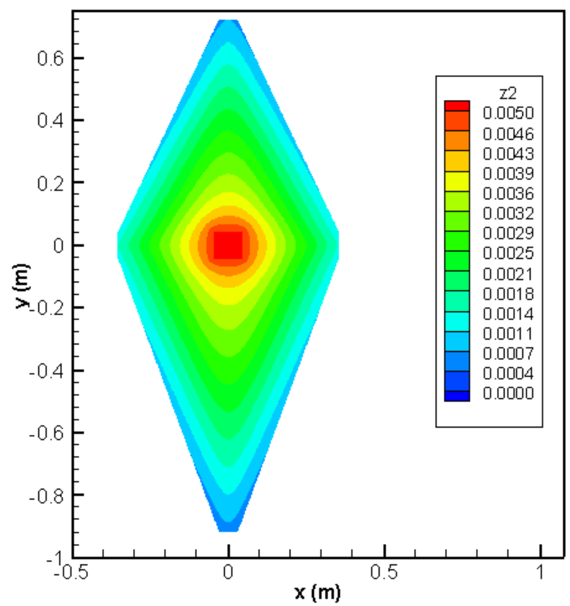


Preload = 4.3 N, Offset = 0.005 m

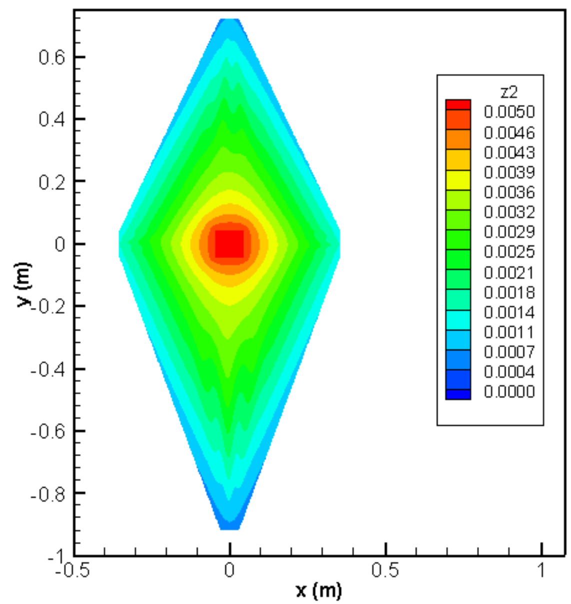
Experiment



Membrane FEM

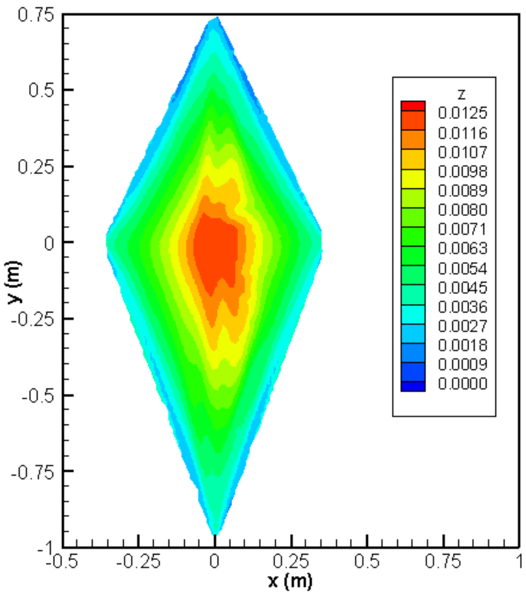


Shell FEM

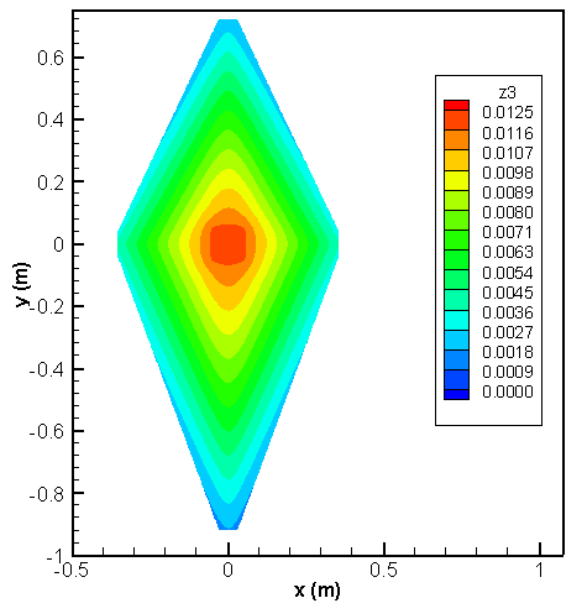


Preload = 4.3 N, Offset = 0.012 m

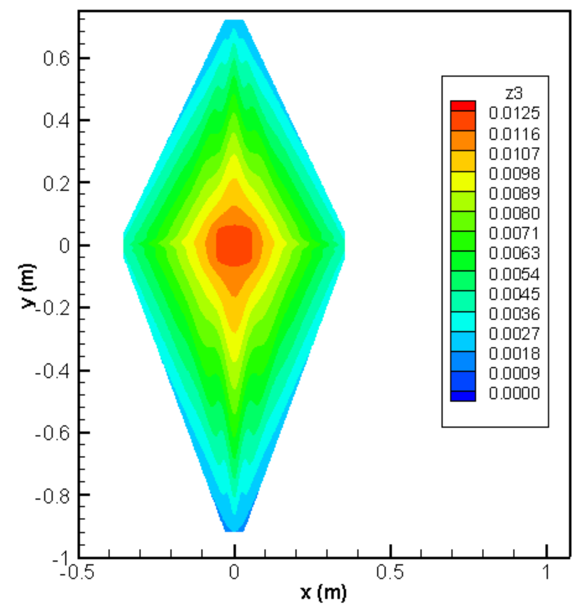
Experiment



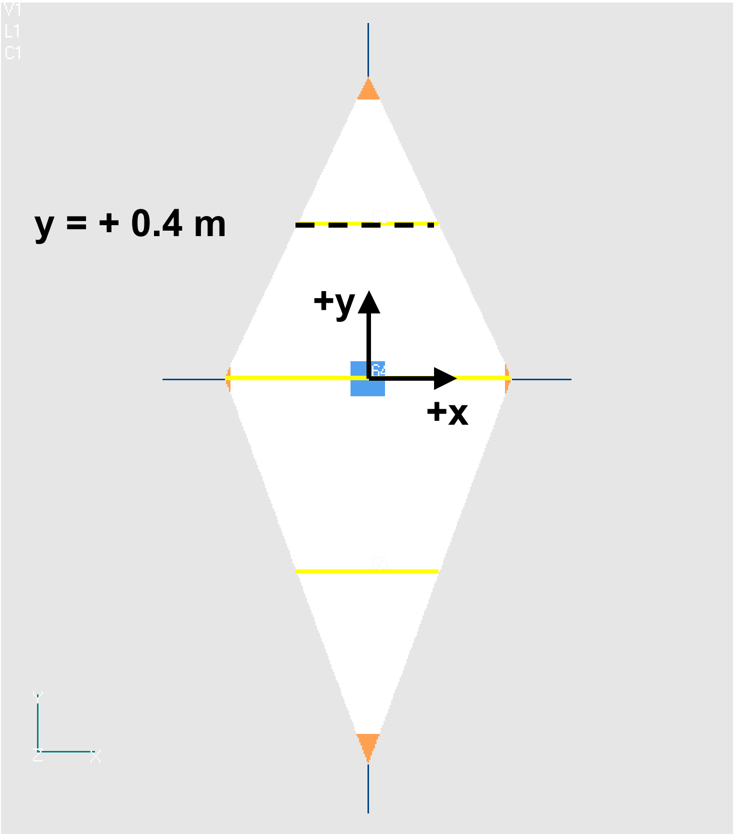
Membrane FEM

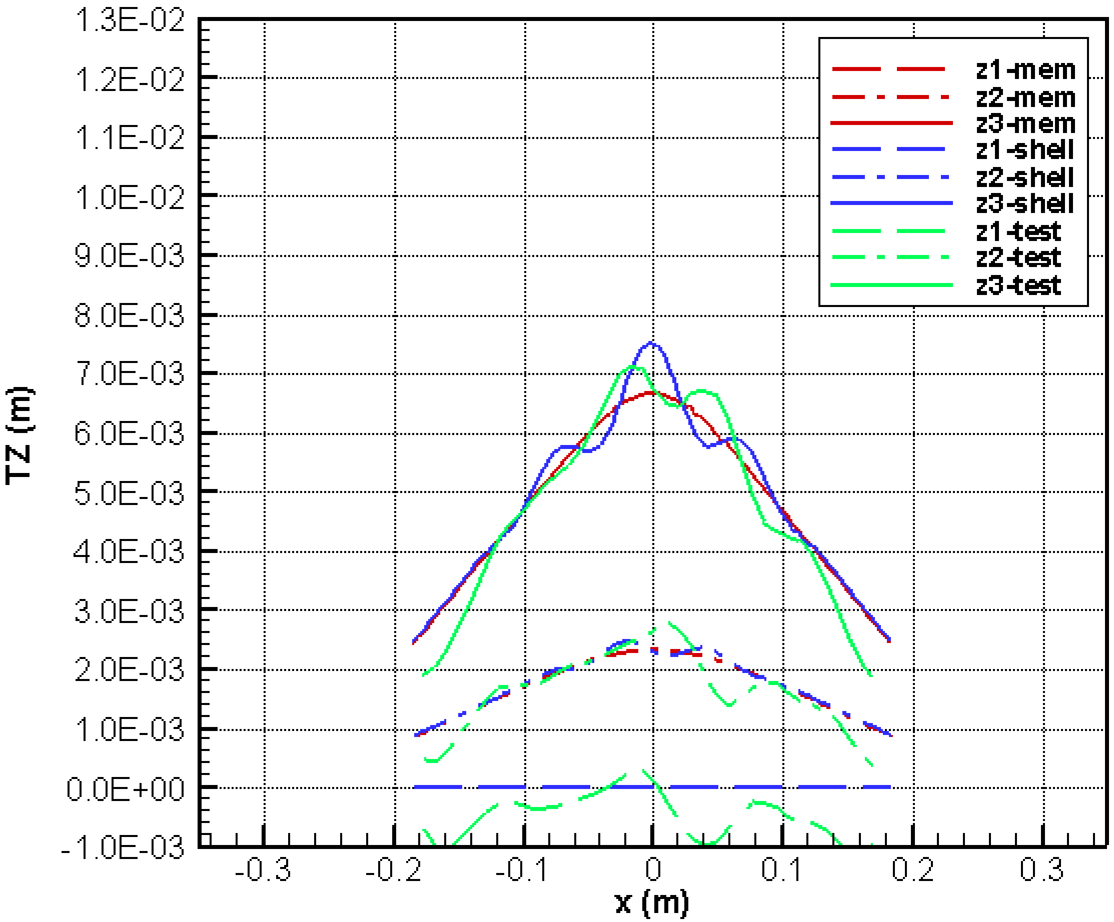


Shell FEM

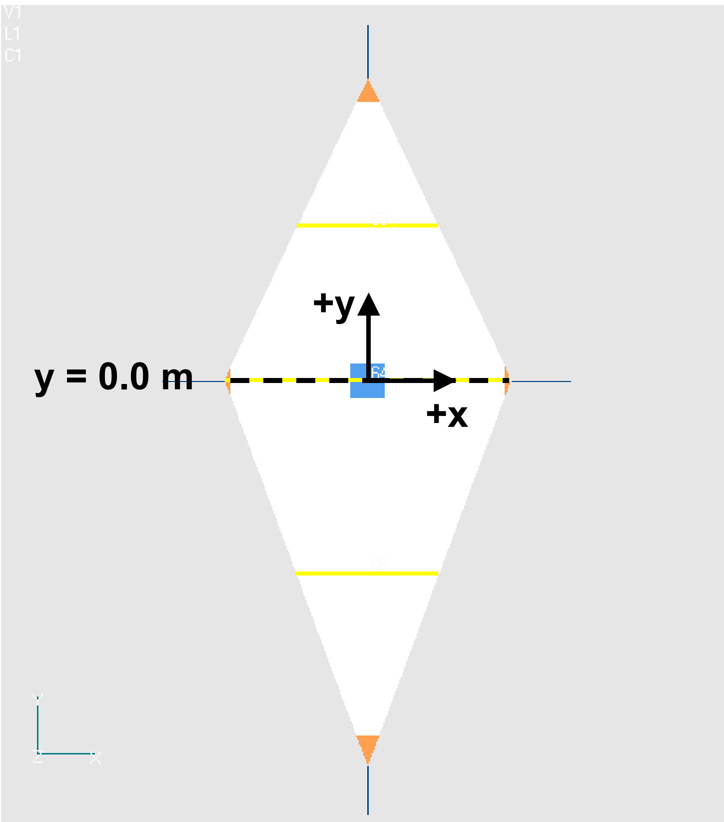


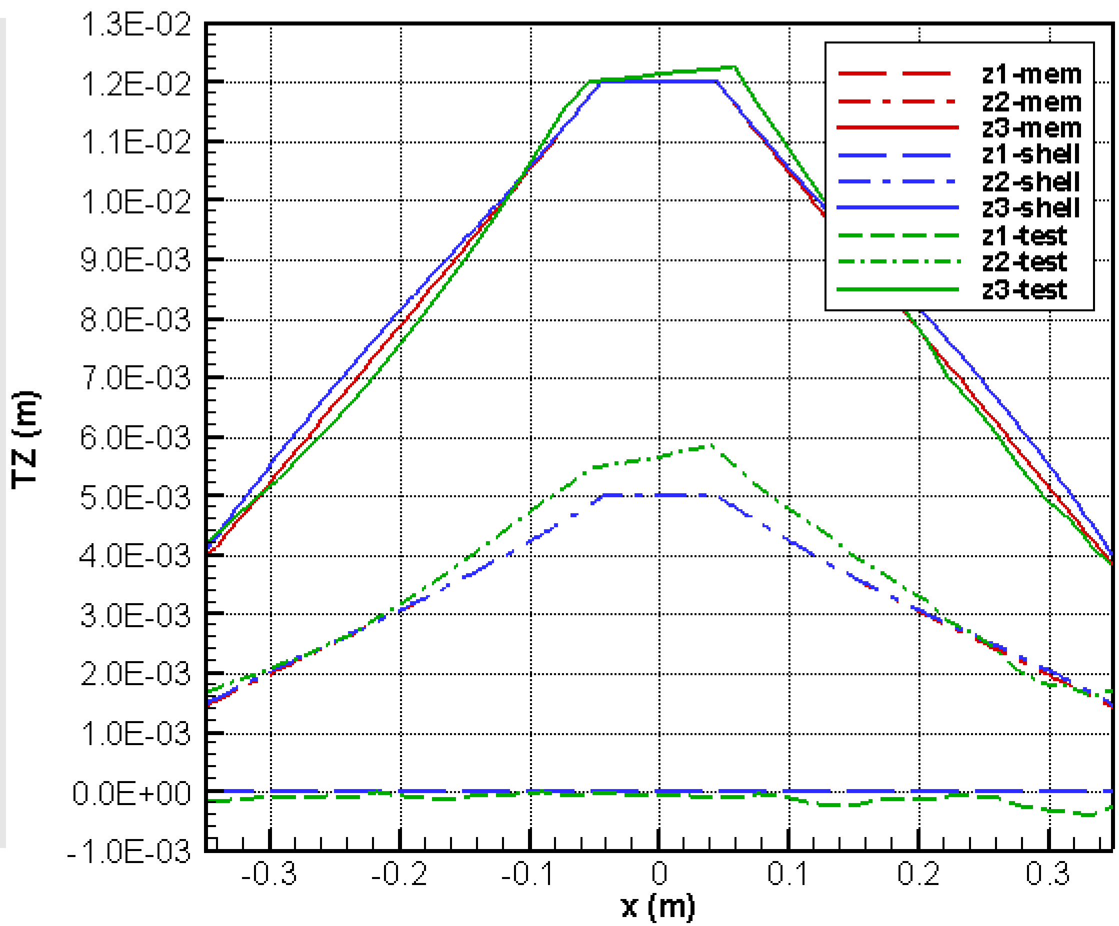
Out-of-plane displacements along y = +0.4 m as a function of x
Preload = 4.3 N, Offsets = 0.000, 0.005, and 0.012 m



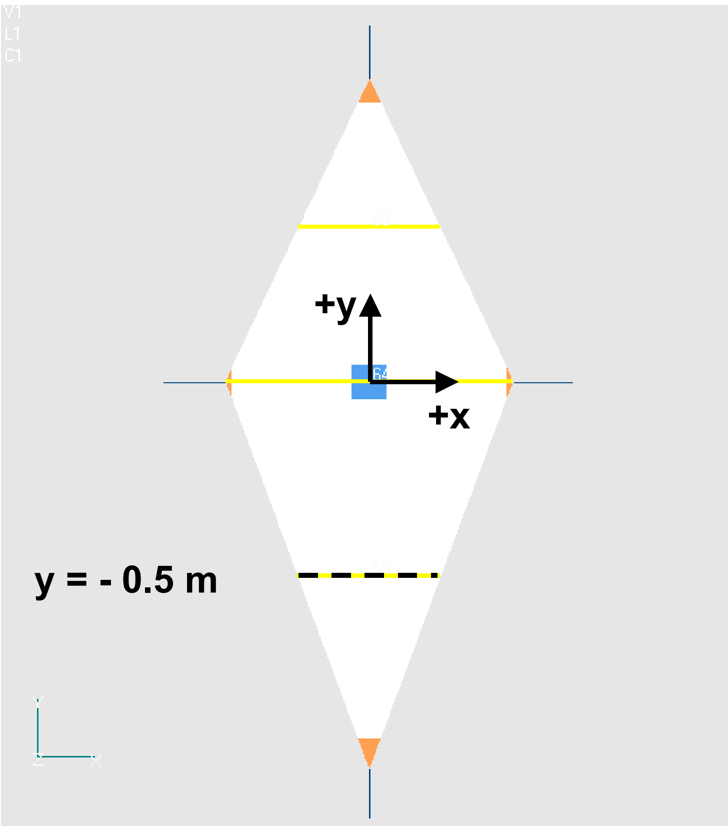


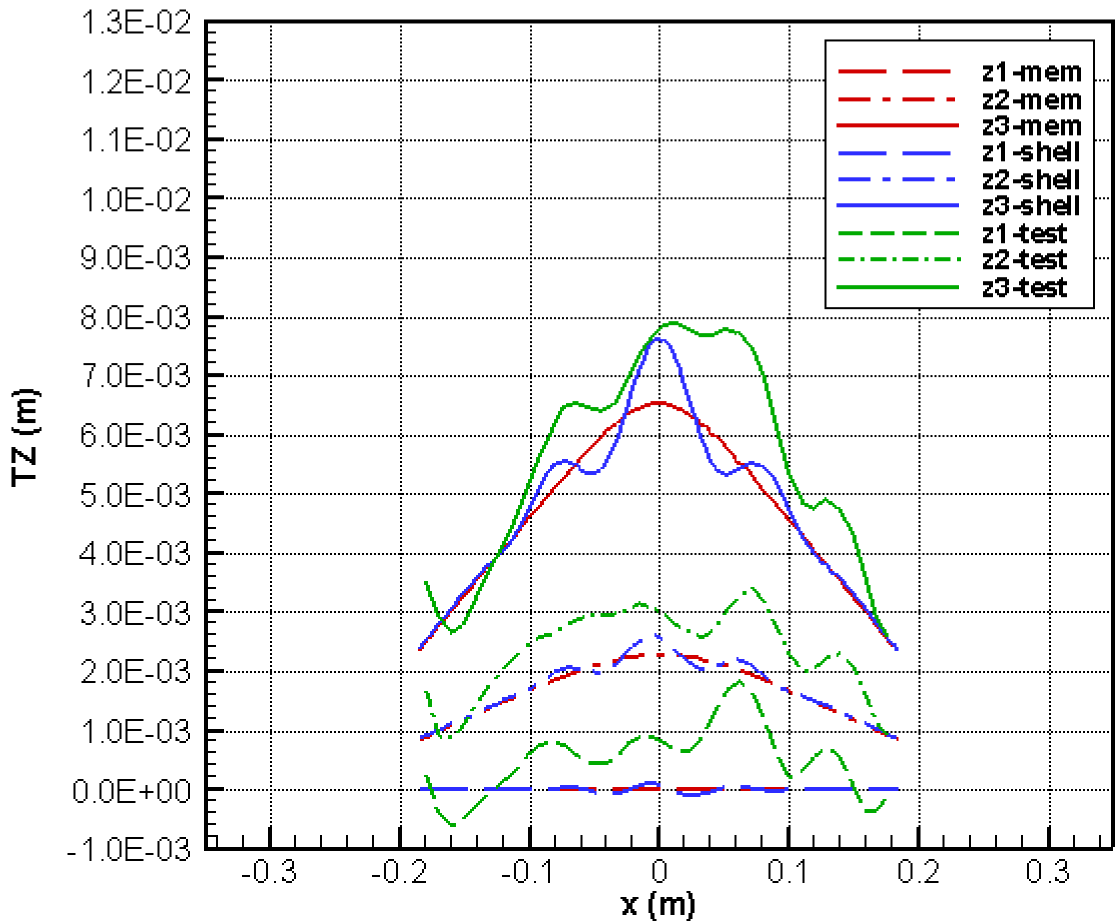
Out-of-plane displacements along y = 0.0 m as a function of x
Preload = 4.3 N, Offsets = 0.000, 0.005, and 0.012 m





Out-of-plane displacements along y = -0.5 m as a function of x
Preload = 4.3 N, Offsets = 0.000, 0.005, and 0.012 m





Summary

- Completed a study to characterize the preloaded geometry of a single sunshield membrane layer on both global (shape) and local (wrinkling) scales.

- Compared predictions from nonlinear finite element analysis with test results:
  - Membrane model shows good agreement with test results in terms of the global shape, but cannot predict wrinkling details.
  - Shell model shows good agreement with test results in terms of global shape and fair agreement for local wrinkling details