STRUCTURAL WRINKLING PREDICTIONS FOR MEMBRANE SPACE STRUCTURES

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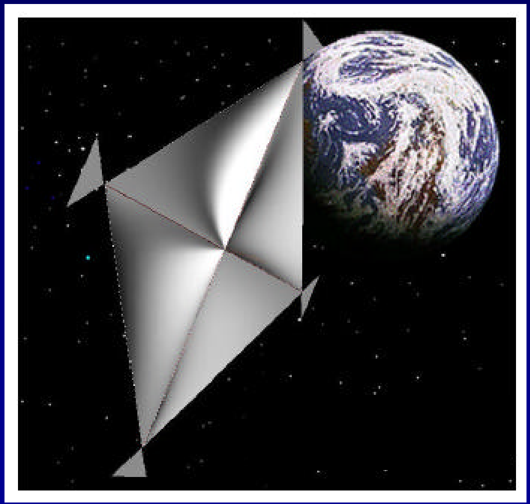
Outline

- Motivation
- Objectives
- Tension Field Theory for Predicting Wrinkling
- Thin-Shell Theory for Predicting Wrinkling
- Wrinkling Analyses
- Summary

Motivation

- **Future space missions enabled by large Gossamer systems**
- **Understanding and predicting the behavior of membrane structures is essential for design and assessment of their performance**



Solar Sail

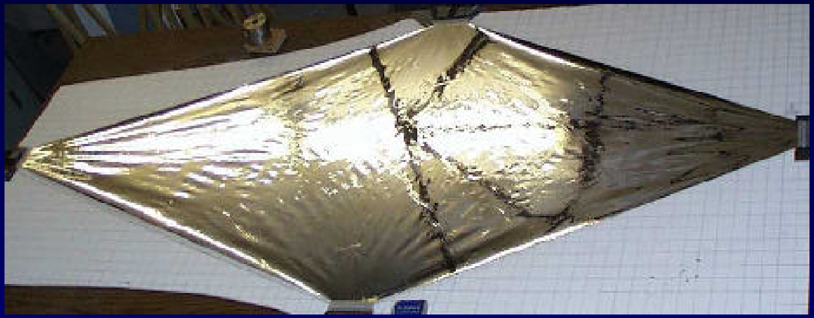
Sunshield

Membrane Optics

Types of Wrinkles

Material Wrinkles

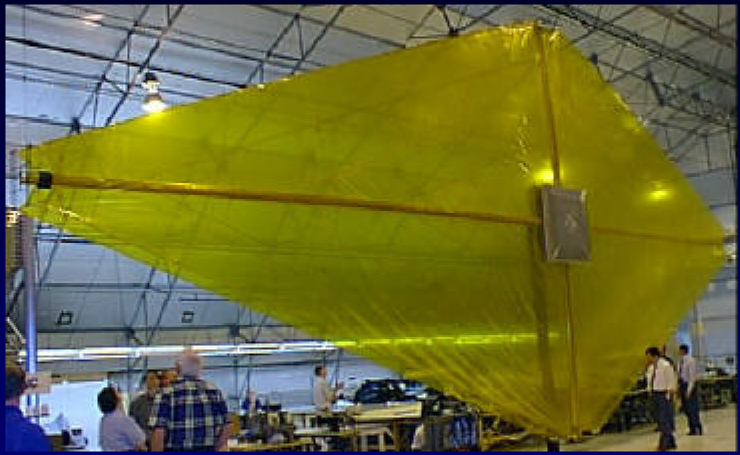
- Permanent deformations
- Creases
- Result from manufacturing or packaging



Structural Wrinkles

- Temporary deformations
- Localized buckling
- Result from loading or boundary conditions
- Change load paths within a membrane structure

Problems Due to Structural Wrinkling



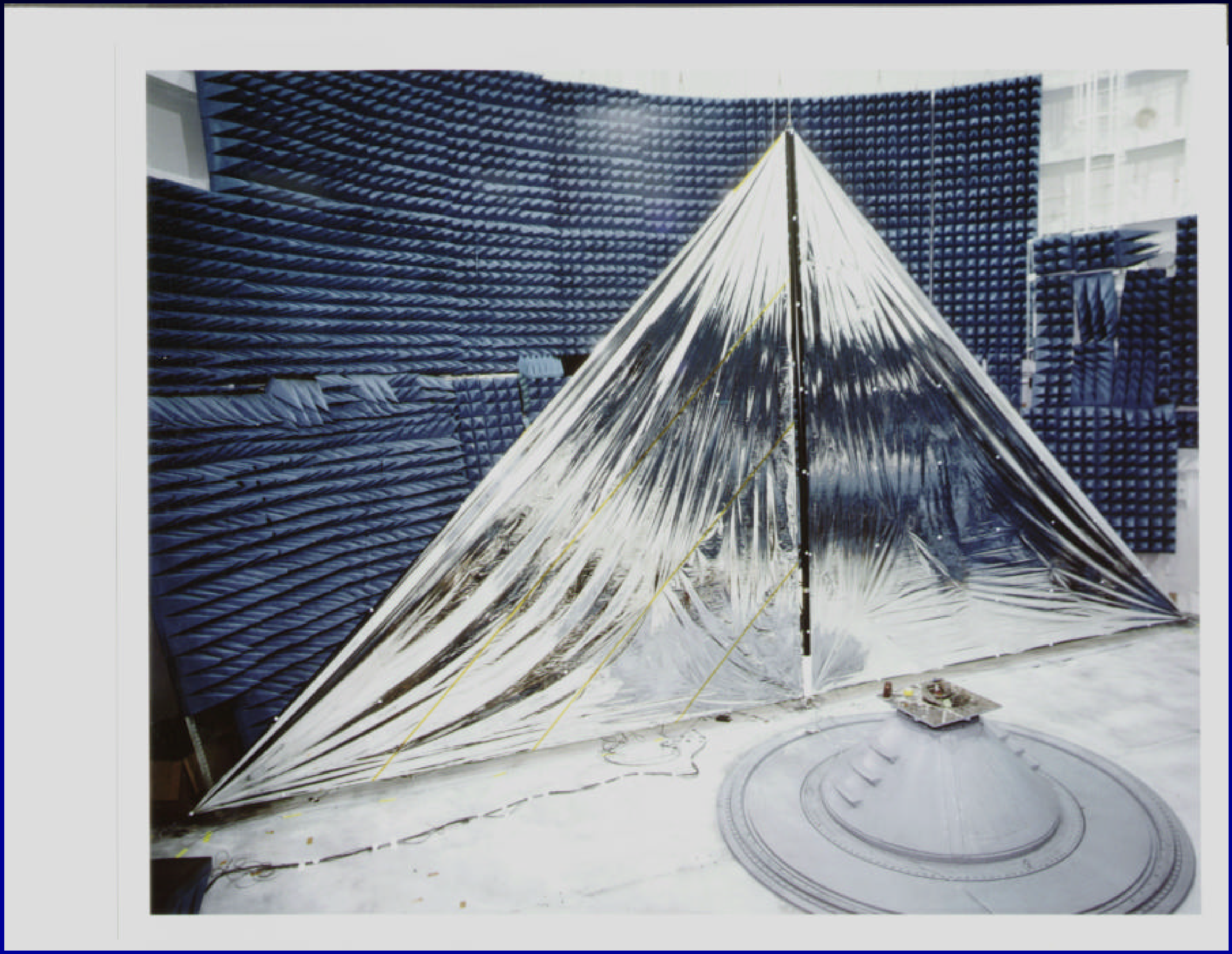
NGST Test

- Degraded performance
- Affect maneuverability and stability
- Poor surface accuracy

Inflatable Antenna

Solar Sail

10 m, 2 Quadrant Solar Sail in LaRC 16m Vacuum Chamber



Objectives

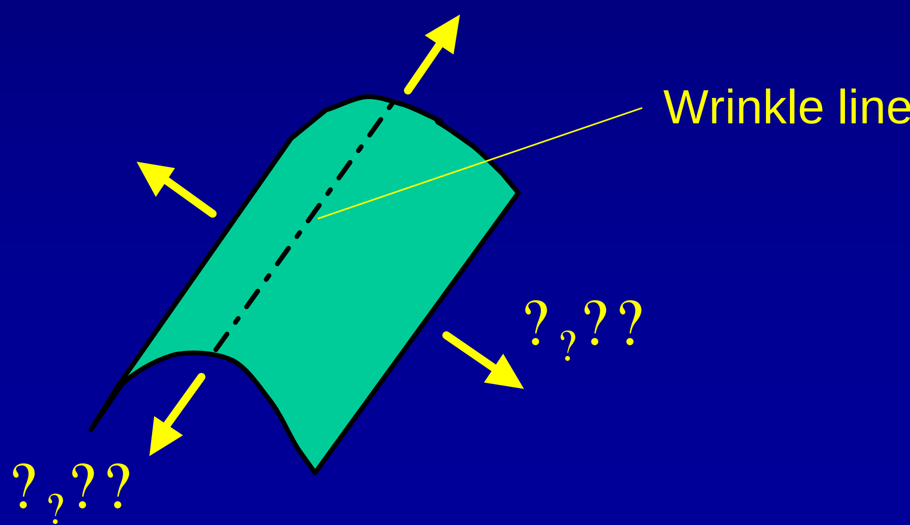
- Develop effective and robust FEA capabilities to predict structural wrinkles in membrane space structures
- Predict surface distribution of structural wrinkles using:
  - Membrane analysis
  - Shell analysis (with out-of-plane deformations)

Tension Field Theory for Predicting Wrinkling

- Originated by Wagner (1929) and Reissner (1938)
- Membranes have negligible bending stiffness and cannot sustain compressive stresses
- Wrinkles are treated as infinitesimally close to one another
- Out-of-plane deformations of wrinkles cannot be determined
- Tension field Theory (TFT) has been implemented by
  - varying linear elastic material properties
  - introducing a wrinkle strain
  - formulating a ‘relaxed’ strain energy density

Stein-Hedgepeth Theory
(SHT) - 1961

- Membrane cannot carry compressive stress
- Two types of regions:
  - Taut
  - Wrinkled
- Effects of wrinkling are accounted for using a variable Poisson's ratio that permits "over-contraction" in the direction of minor principal stresses
- Wrinkles are aligned with the major principal stress axis



Iterative Membrane Property (IMP) Method

(Miller and Hedgepeth, 1982)

- FE implementation of the SHT
- Geometrically nonlinear analysis
- Wrinkle criteria based on element stress/strain states
  - Taut: $?_2 > 0$ (isotropic material)
  - Wrinkled: $?_1 > 0$ & $?_2 = 0$ (orthotropic material)
  - Slack: $?_1 < 0$ (zero stiffness material)
- Finite element implementation into ABAQUS
  - Adler-Mikulas (2000)

Thin-Shell Theory for Predicting Wrinkling

- Membrane theory cannot predict the amplitude and shape of wrinkles
- Shell theory includes both membrane and bending flexibilities
  - enables post-buckling response
  - can predict amplitude and shape of wrinkles
- Geometrically nonlinear analysis is necessary to predict the structural behavior

Thin-Shell Wrinkling Analyses Using ABAQUS

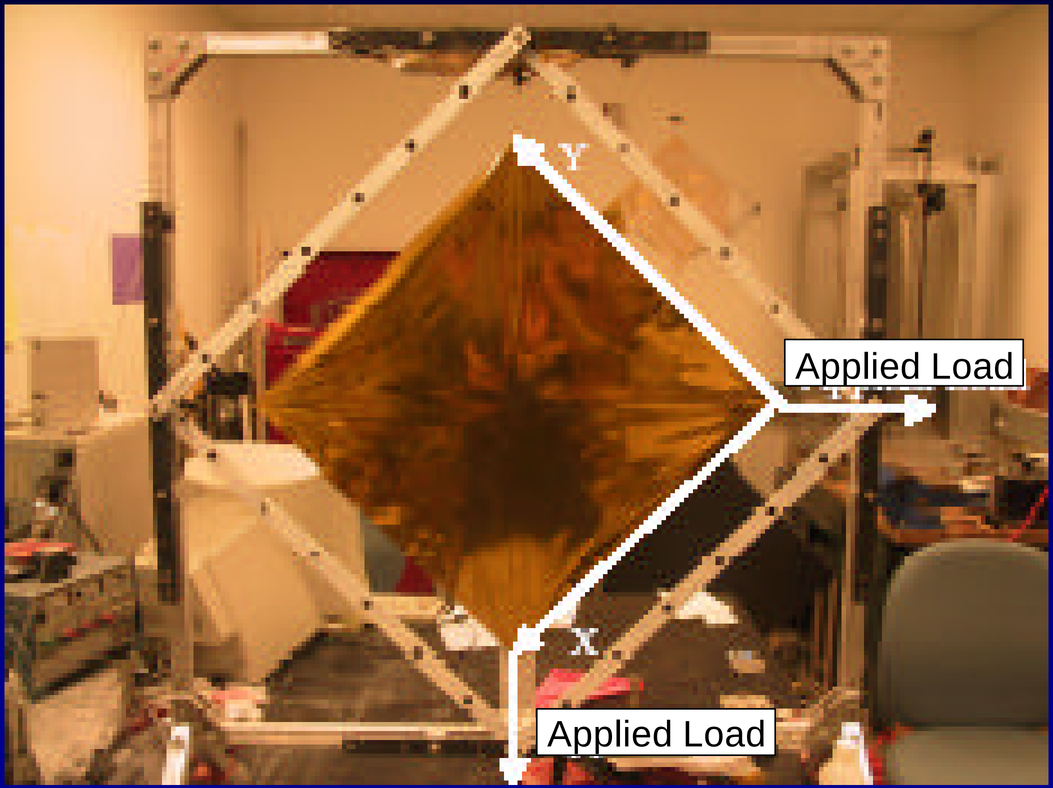
- Geometrically nonlinear FE analysis
- Using reduced integration thin-shell element (S4R5)
- Imperfections are added to initial geometry
  - mode shapes from buckling analysis
  - random imperfections
- Employ ABAQUS with STABILIZE parameter to automatically add damping for preventing unstable and singular solutions
  - for accuracy, use lowest possible value for which convergence can be achieved

Wrinkling Analyses

- Square Membrane Loaded in Tension
- Rectangular Membrane Loaded in Shear

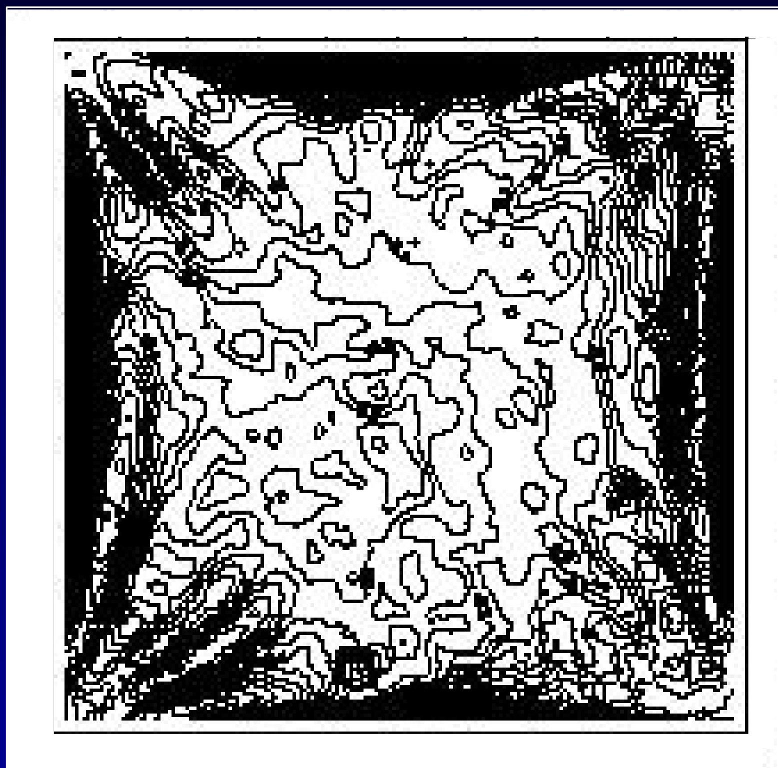
Square Membrane Loaded in Tension

(Blandino, Johnston, et al, 2002)



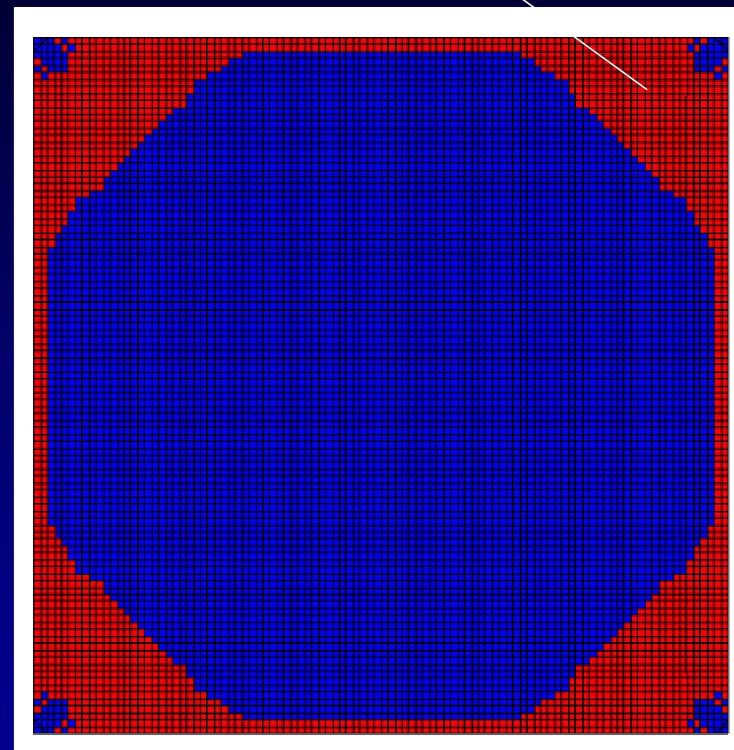
Kapton membrane: 2.54 x 10^{-2} mm thick
Applied Loads: 2.45 N (Isothermal)

Wrinkling Results



Experimental Results
(Blandino, Johnston, et al)

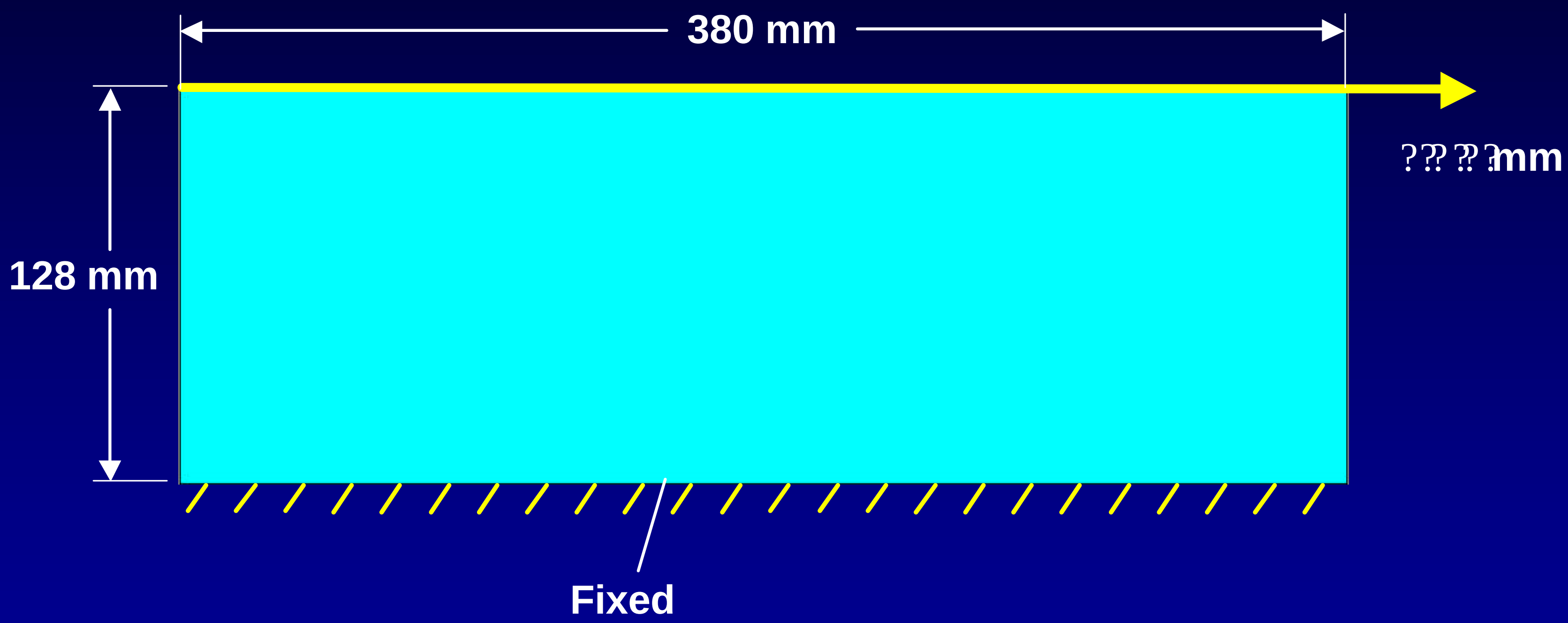
Wrinkled Region



ABAQUS IMP Results
10,000 elements
M3D3/M3D4 Membrane Elements

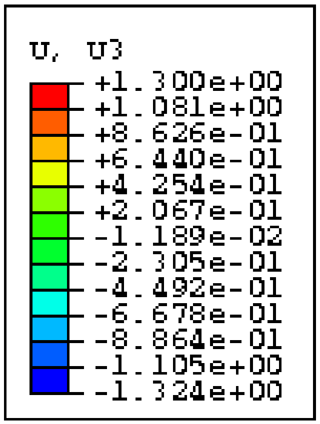
Rectangular Membrane Loaded in Shear

(Wong and Pellegrino, 2002)

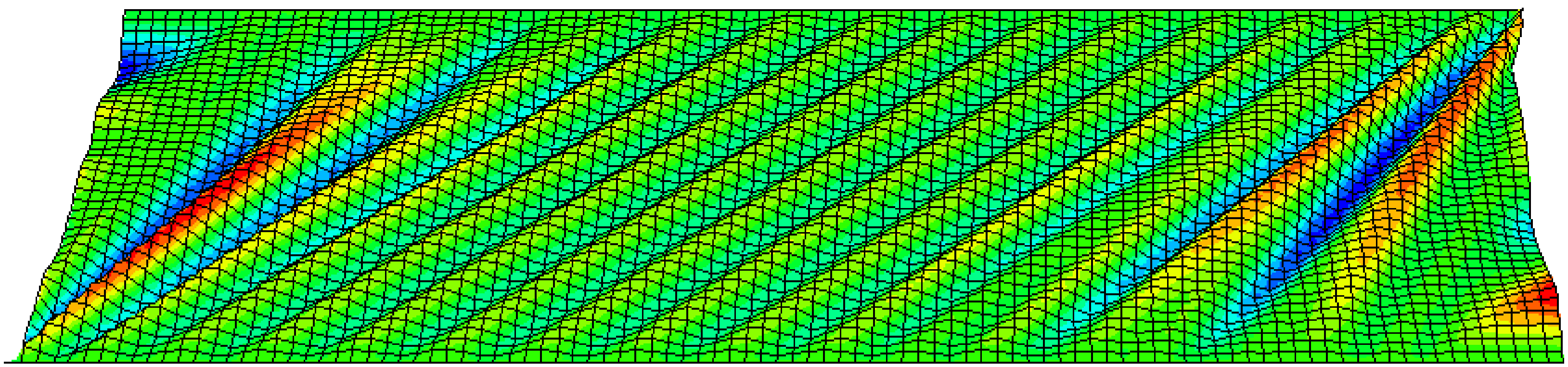


Kapton foil: 25 ?m thick

Wrinkling Results



3960 elements
5% initial random imperfections



Out-of-plane Deflection

Summary

- Future space missions enabled by Gossamer structures
  - Effective and robust analysis tools required
- Structural wrinkles constitute a major concern
  - Affect surface topology and behavior/performance
- FEA analyses using ABAQUS to predict structural wrinkling
  - Membrane analyses with IMP method
  - Thin-shell geometrically nonlinear analyses