STRUCTURAL WRINKLING PREDICTIONS FOR MEMBRANE SPACE STRUCTURES

David W. Sleight, Alexander Tessler, and John T. Wang
Analytical and Computational Methods Branch
NASA Langley Research Center
Hampton, VA

d.w.sleight@larc.nasa.gov

FEMCI Workshop 2002
Innovative FEM Solutions to Challenging Problems
May 22-23, 2002
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
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

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

NGST Test

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: $\theta_2 > 0$ (isotropic material)
  - Wrinkled: $\theta_1 > 0$ & $\theta_2 = 0$ (orthotropic material)
  - Slack: $\theta_1 < 0$ (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: $2.54 \times 10^{-2} \text{ mm thick}$

Applied Loads: 2.45 N (Isothermal)
Wrinkling Results

Experimental Results (Blandino, Johnston, et al)  

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