Effective Modeling of Thin-Film Shells Exhibiting Wrinkling Deformations

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Outline

- Motivation
- Objectives
- Shell modeling strategies
- Numerical and experimental results
- Conclusions
Wrinkling in Solar Sails

- Wrinkling
  - Large displacements
  - Low strain energy
  - Rigid-body motion

- Detrimental effects
  - Performance
  - Stability
  - Maneuverability
  - Local heating

- Testing difficult
  - Large size
  - Gravity
  - Aerodynamics
Objectives

- Explore nonlinear shell modeling of thin-film membranes using ABAQUS
- Achieve high-fidelity wrinkling predictions
- Perform experimental validation
Shell Modeling

- **Characteristics**
  - Bending and membrane coupling effects included
  - Geometrically nonlinear shell deformations

- **Capabilities**
  - Wrinkling amplitude, wave length and shape
  - Membrane-to-bending coupling using imperfections
    - Buckling modes (Wong & Pellegrino, 2002)
    - Trigonometric functions (Lee & Lee, 2002)
Shell Analysis Issues

- **Wrinkling initiation issues**
  - Shear locking for thin shell elements
  - Membrane-to-bending coupling in initially flat membranes
  - Numerical ill-conditioning of tangent stiffness matrix
  - Sensitivity to modeling, loading, and B.C.’s

- **Modeling and computational strategies**
  - Employ robust shell elements
  - Introduce computationally efficient, unbiased random imperfections ($w_0$)
  - Add fictitious viscous forces to circumvent numerical ill-conditioning
  - Remodel sharp corners and concentrated loads
**Numerical and Experimental Results**

- **Square thin-film membranes**
  - Shear loaded
  - Tension loaded
ABAQUS Shell Modeling

- Basic modeling strategies
  - Use robust, locking-free, shell element
  - Add fictitious viscous forces to circumvent numerical ill-conditioning (STABILIZE)
  - Introduce small, unbiased, random transverse imperfections to enable membrane-to-bending coupling

\[
F_v = c M^A v \\
P - I - F_v = 0 \\
w_0 = \alpha \cdot \delta_{\text{random}} \cdot h \\
\delta_{\text{random}} \equiv \delta \in [-1, 1] \\
\alpha = 0.10
\]
Shear Loaded Thin-Film Membrane

\[ \Delta = 1 \text{ mm} \]

Mylar® Polyester Film Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Edge length, ( a ) (mm)</td>
<td>229</td>
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<tr>
<td>Thickness, ( h ) (mm)</td>
<td>0.0762</td>
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<tr>
<td>Elastic modulus, ( E ) (N/mm²)</td>
<td>3790</td>
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<tr>
<td>Poisson’s ratio, ( \nu )</td>
<td>0.38</td>
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</table>

- Tested at NASA LaRC
- Photogrammetry
Experiment vs. Simulation

Experimental Observations using Photogrammetry

ABAQUS Nonlinear Shell FEA
Experiment vs. Simulation

- Random imperfections imposed
- Actual initial imperfections not used

Experimental Observations using Photogrammetry

ABAQUS Nonlinear Shell FEA
Tension Loaded Thin-Film Membrane

KAPTON® Type HN Film Properties

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<tr>
<td>Thickness, $h$ (mm)</td>
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<tr>
<td>Young’s modulus, $E$ (N/mm$^2$)</td>
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<td>Poisson’s ratio, $\nu$</td>
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Simulation from Corner Point Loads

**Corner region**
- Quad elements collapsed into triangles
- Severe stress concentration

- Deflection
  \[-0.10 \leq w_{FEA} \leq 0.10\]

- **Von Mises Stress**

  - \(\sigma (N/mm^2)\)
  - \(+31.74\)
  - \(+29.11\)
  - \(+26.48\)
  - \(+23.86\)
  - \(+21.23\)
  - \(+18.60\)
  - \(+15.97\)
  - \(+13.35\)
  - \(+10.72\)
  - \(+ 8.09\)
  - \(+ 5.46\)
  - \(+ 2.84\)
  - \(+ 0.21\)
Shell Modeling with Truncated Corners

- Basic modeling strategies
- Additional enhancements
  - Remove sharp corners where loads applied
  - Represent point loads as distributed tractions
Truncated Corners Model

Corner region
- Sharp corners removed
- Severe concentration reduced
- Wrinkles develop

Von Mises Stress

Deflection

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<td>+17.74</td>
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<td>+12.71</td>
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<td>+ 9.58</td>
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<td>+ 4.90</td>
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<td>+ 3.33</td>
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<td>+ 1.77</td>
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<td>+ 0.21</td>
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<table>
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<th>w (mm)</th>
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<td>-0.76</td>
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<td>-0.86</td>
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Experiment vs. Simulation

Experimental Results (J. Blandino, 2002)

- Initial imperfections present
- Non-symmetric wrinkle pattern

ABAQUS Nonlinear Shell FEA

- Random imperfections applied
- Symmetric wrinkle pattern

Random imperfections applied
Symmetric wrinkle pattern
Conclusions

- Large displacement shell modeling of thin-film membranes to achieve wrinkling deformations
  - Robust shell elements free of shear locking
  - Fictitious viscous forces to circumvent numerical ill-conditioning
  - Unbiased random transverse imperfections to enable membrane-to-bending coupling
  - Improved modeling of sharp corner regions subjected to tension loads

- Numerical examples and experimental validation
  - Square membranes loaded in shear and tension
  - Numerical results compared favorably with experiments
Conclusions (cont.)

- Remaining Issues
  - Element technology
  - Nonlinear analysis convergence and viscous-force stabilization
  - Adaptive mesh refinement / robust error estimation
  - Sensitivity to boundary conditions and applied loading