Effective Modeling of Thin-Film Shells Exhibiting Wrinkling Deformations

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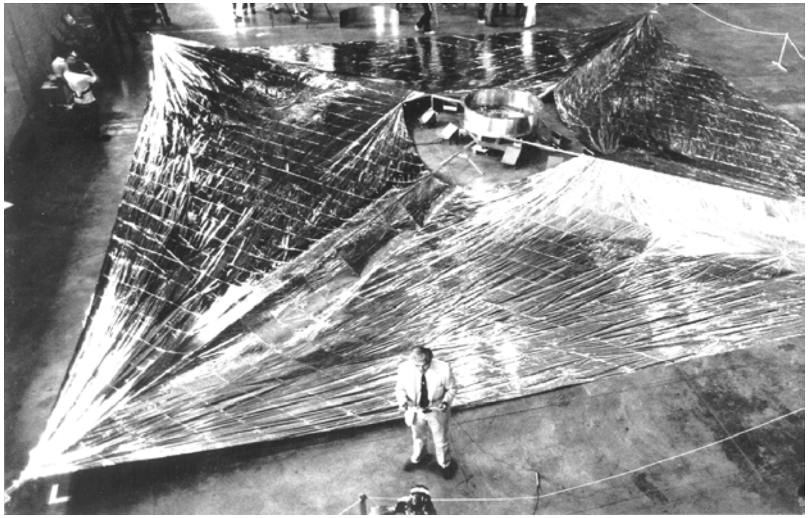
Outline

- 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

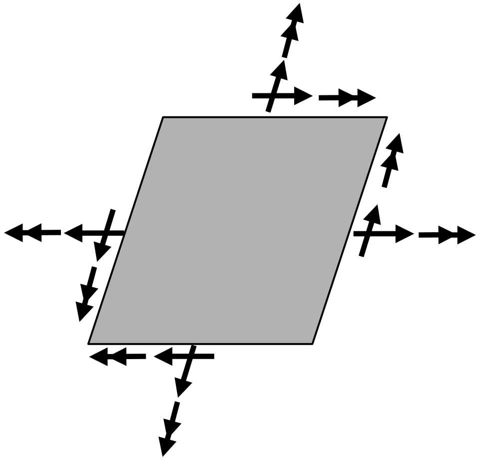


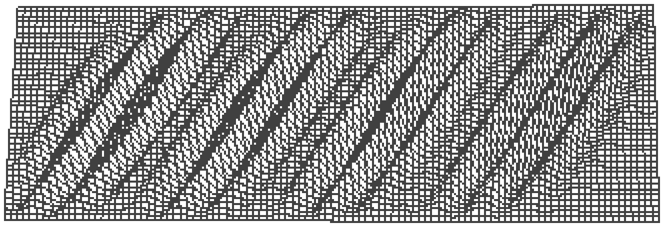
Objectives

- 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)**

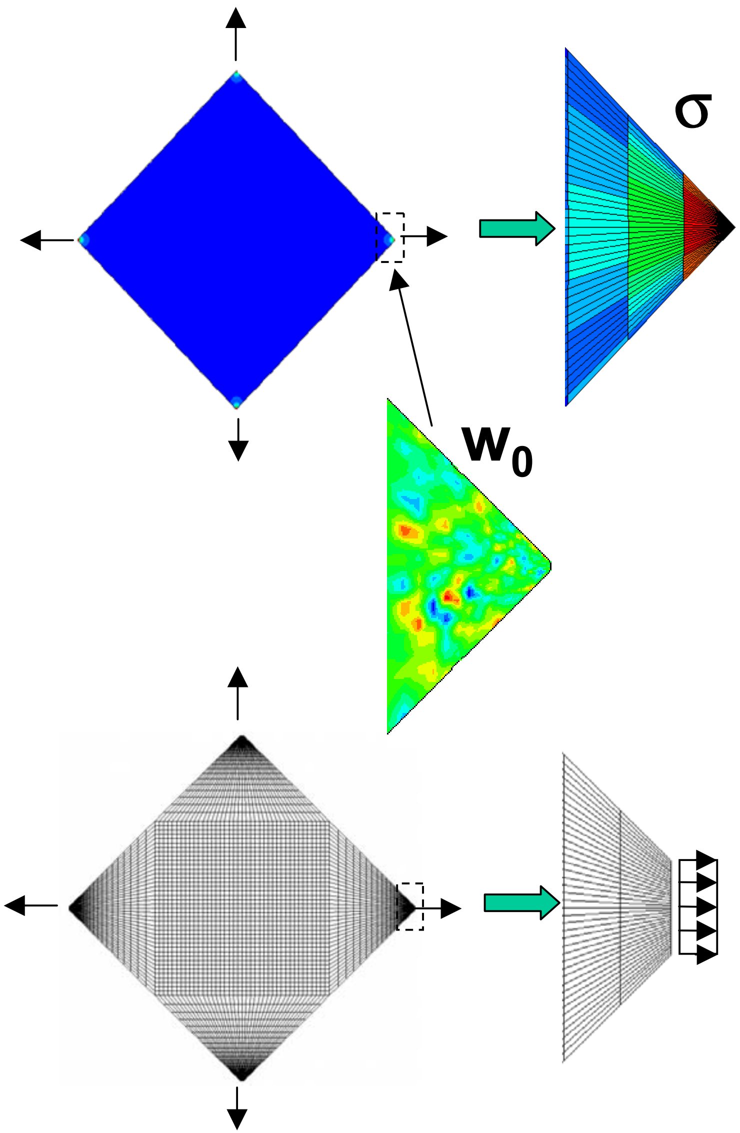




Wong & Pellegrino

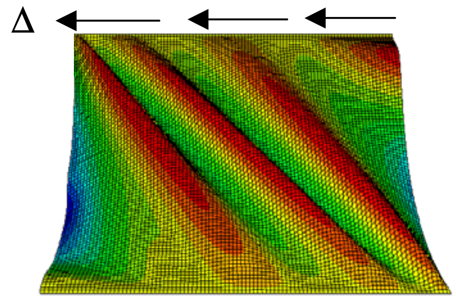
Shell Analysis Issues

- **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

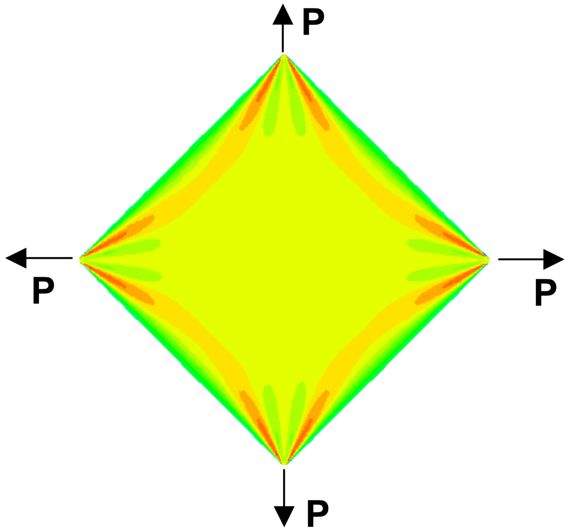


Numerical and Experimental Results

- **Square thin-film membranes**
  - **Shear loaded**

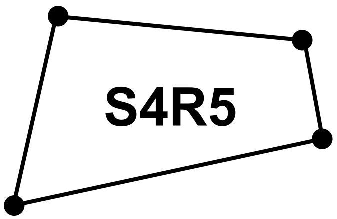


  - **Tension loaded**



ABAQUS Shell Modeling

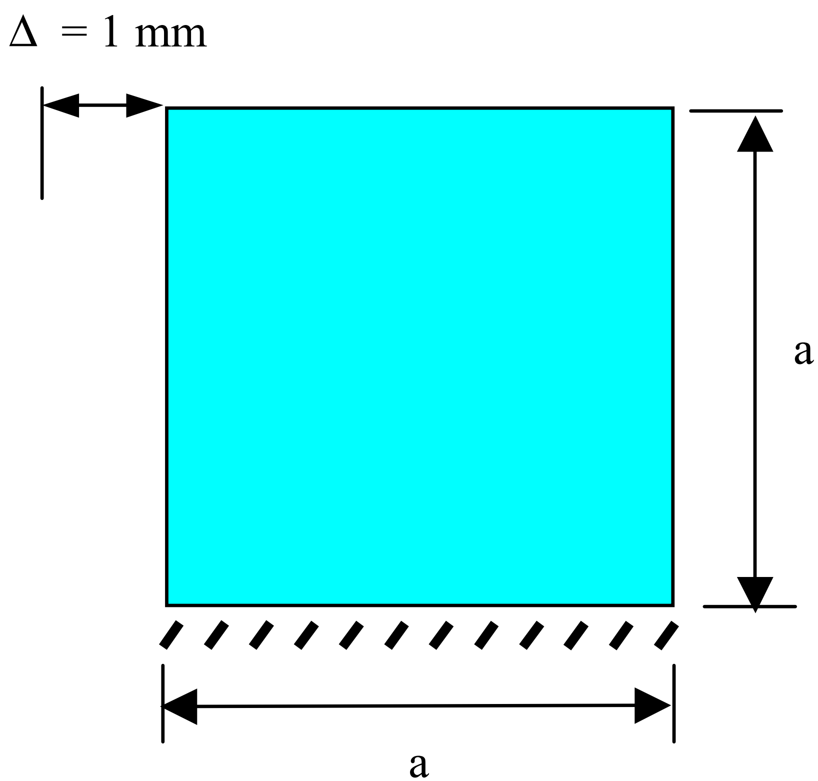
- **Basic modeling strategies**
  - **Use robust, locking-free, shell element**
  - **Add fictitious viscous forces to circumvent numerical ill-conditioning (STABILIZE)**
  - **Introduce small, unbiased, random transverse imperfections to enable membrane-to-bending coupling**



$$F_v = c\,M^A\,v$$
$$P - I - F_v = 0$$

$$w_0 = \alpha \cdot \delta_{random} \cdot h$$
$$\delta_{random} \equiv \delta \in [-1, 1]$$
$$\alpha = 0.10$$

Shear Loaded Thin-Film Membrane

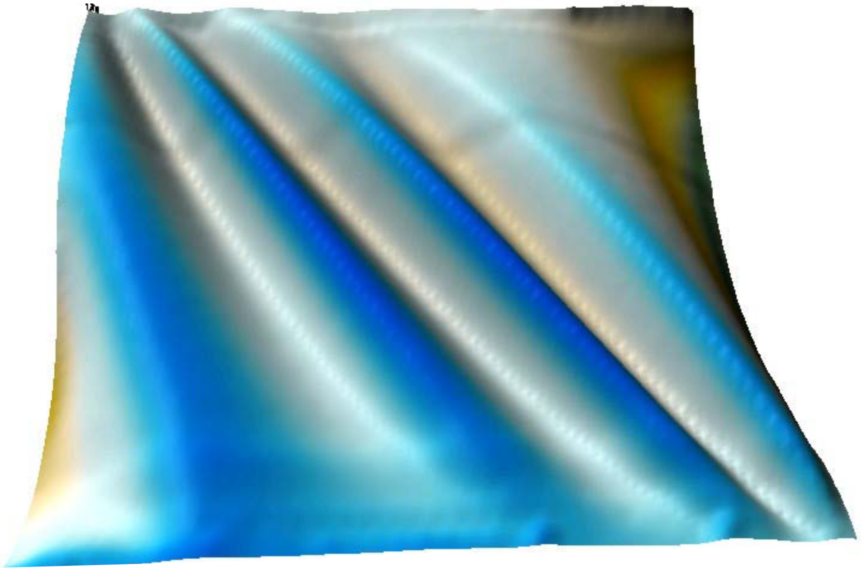


Mylar® Polyester Film Properties	
Edge length, a (mm)	229
Thickness, *h (mm)*	0.0762
Elastic modulus, E (N/mm^2)	3790
Poisson's ratio, ν	0.38

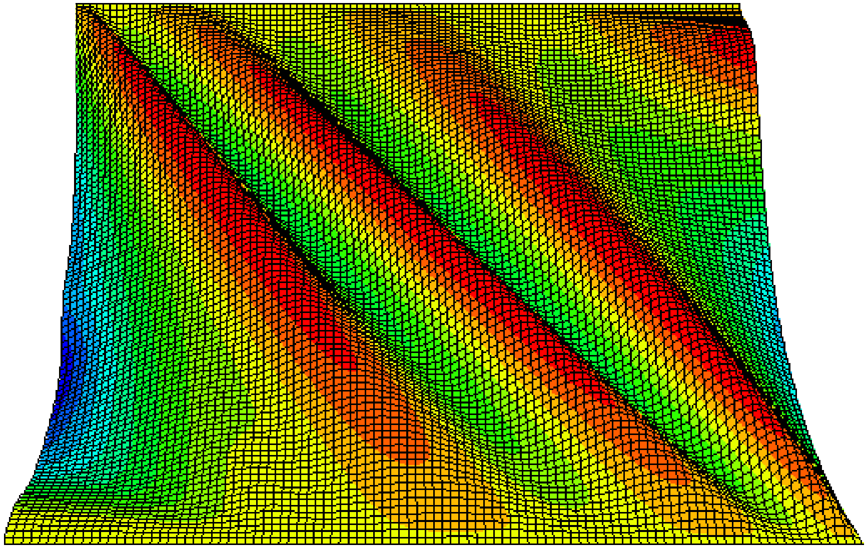
Experiment: J. Leifer (2003)

- Tested at NASA LaRC
- Photogrammetry

Experiment vs. Simulation



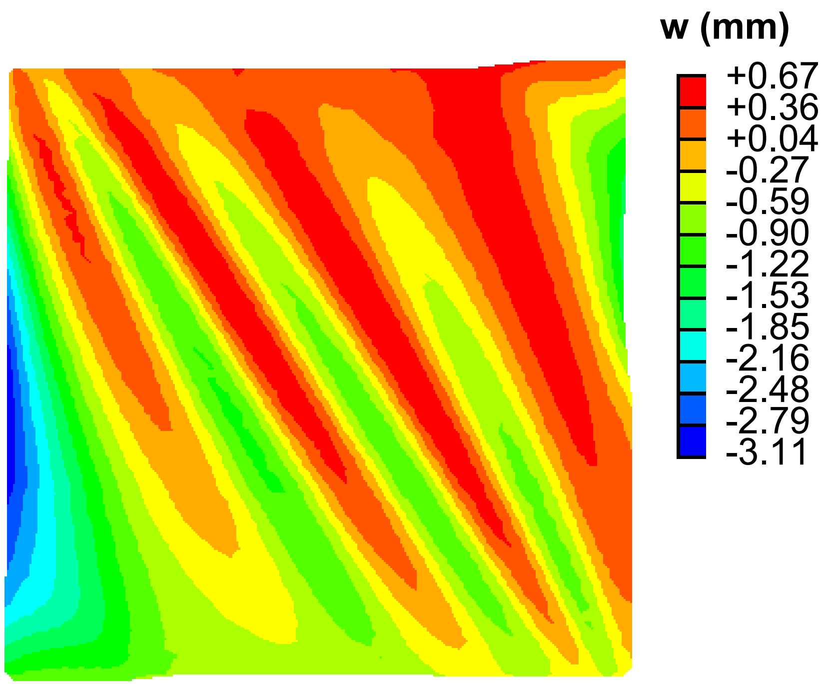
Experimental Observations using Photogrammetry



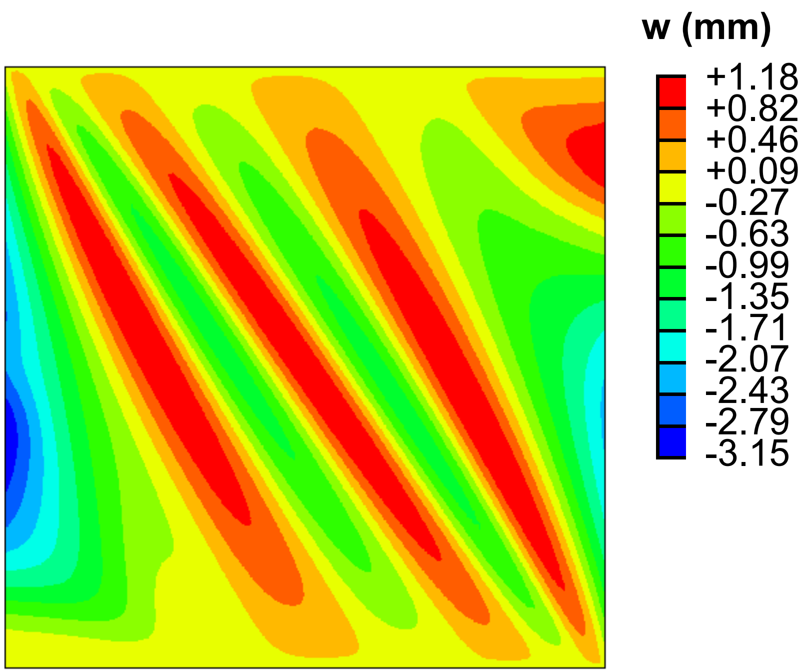
ABAQUS Nonlinear Shell FEA

Experiment vs. Simulation

- **Random imperfections imposed**
- **Actual initial imperfections not used**

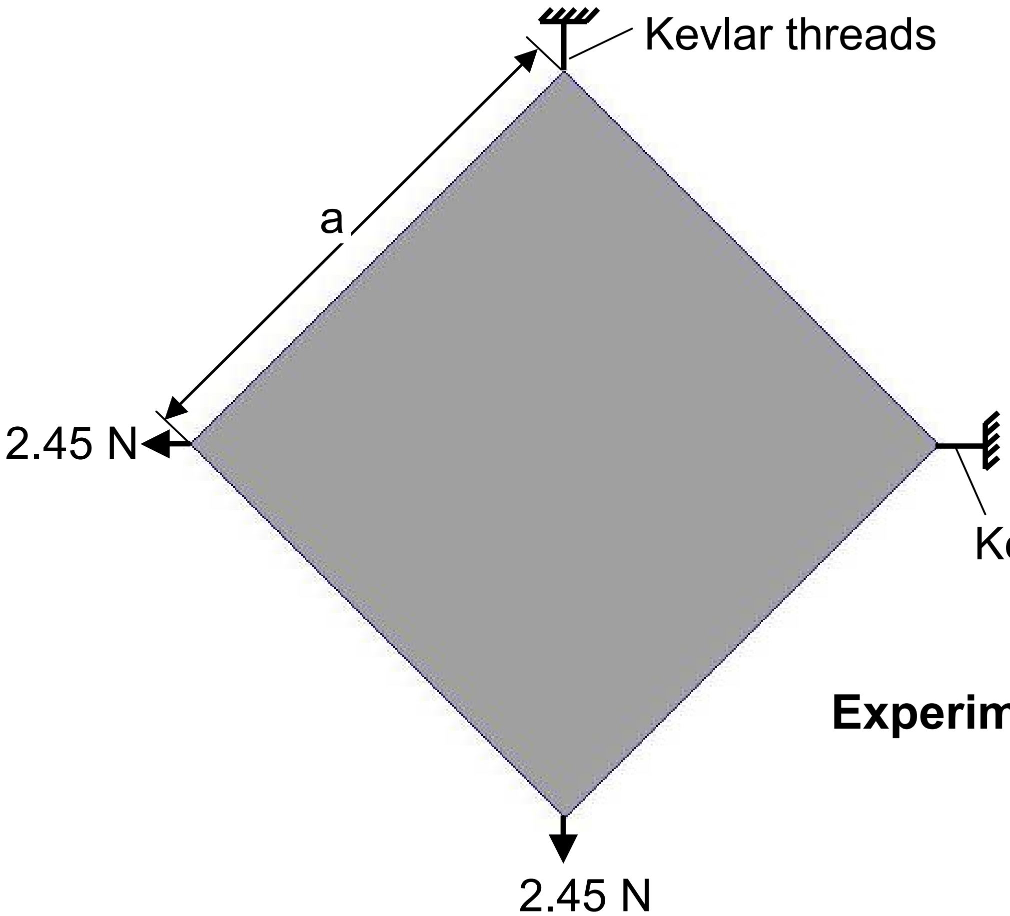


Experimental Observations using Photogrammetry



ABAQUS Nonlinear Shell FEA

Tension Loaded Thin-Film Membrane



KAPTON® Type HN Film Properties	
Edge length, *a* (mm)	500
Thickness, *h* (mm)	0.0254
Young's modulus, *E* (N/mm^2)	2590
Poisson's ratio, ν	0.34

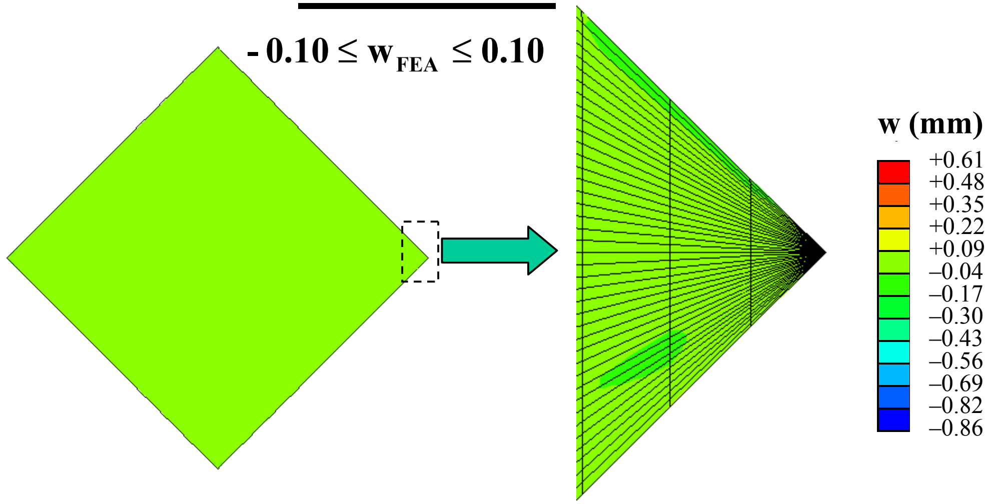
Experiment: J. Blandino & J. Johnston (2002)

Simulation from Corner Point Loads

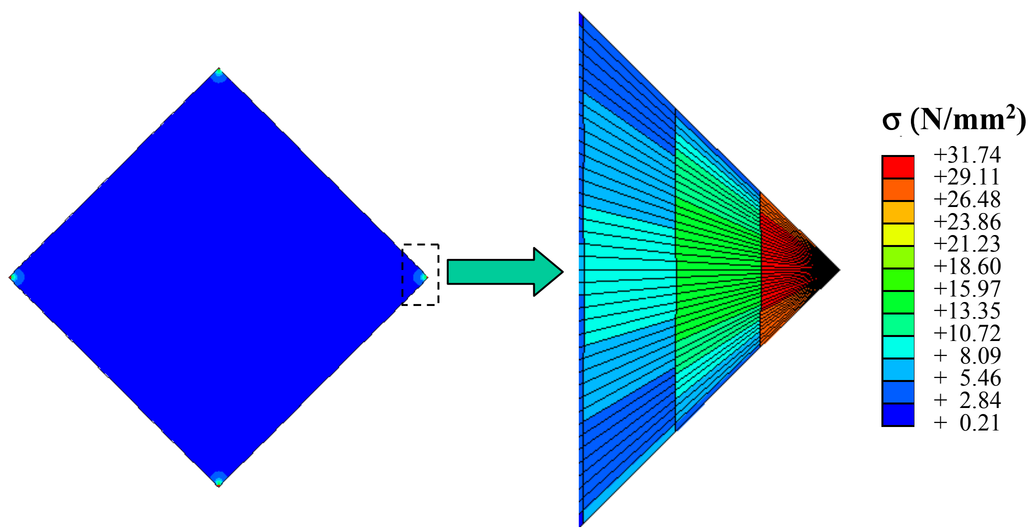
Corner region

- Quad elements collapsed into triangles
- Severe stress concentration

Deflection

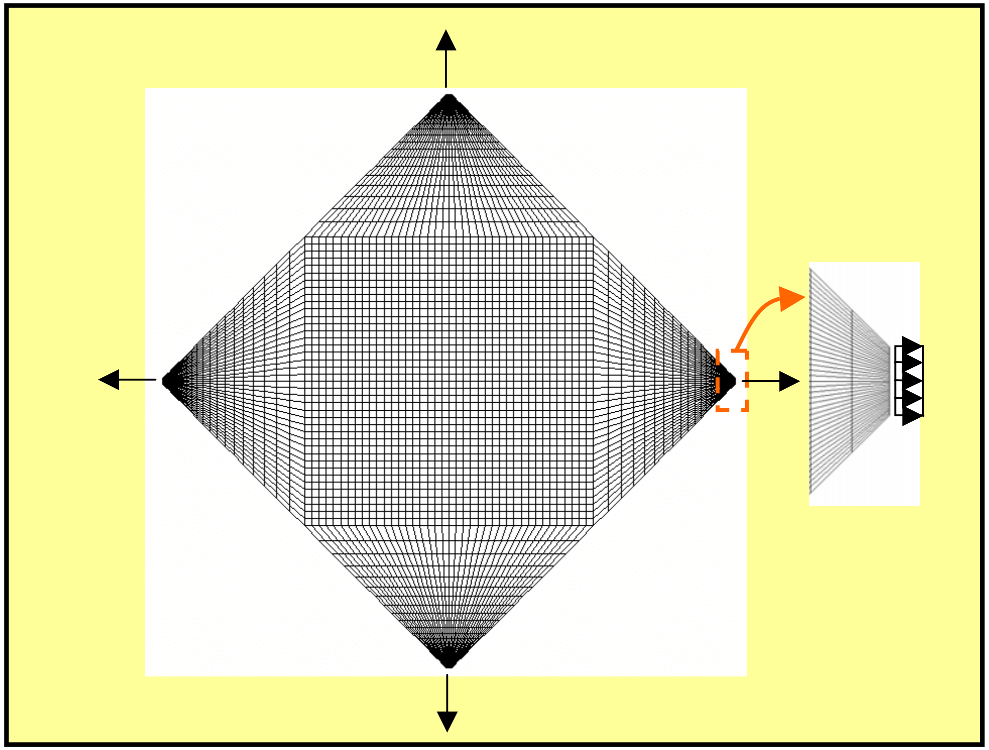


Von Mises Stress



Shell Modeling with Truncated Corners

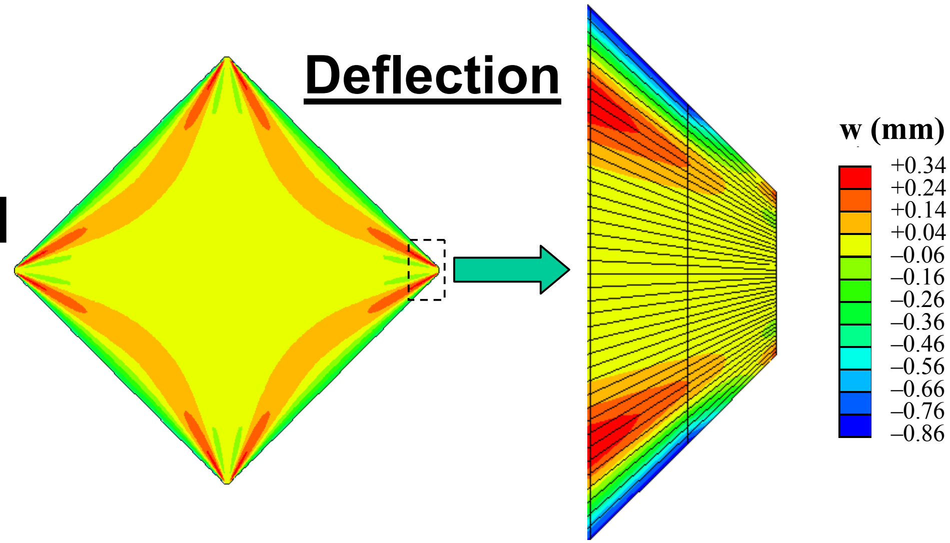
- **Basic modeling strategies**
- **Additional enhancements**
  - **Remove sharp corners where loads applied**
  - **Represent point loads as distributed tractions**



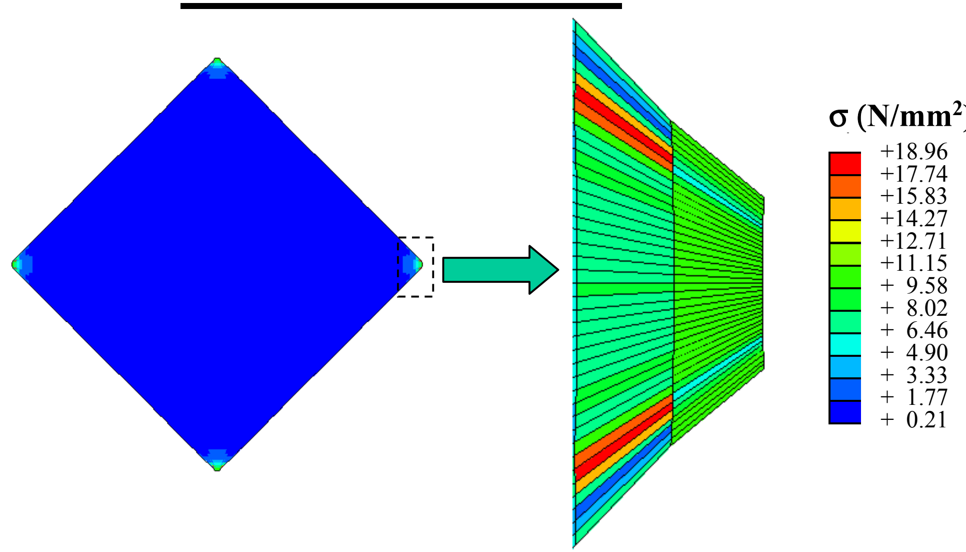
Truncated Corners Model

Corner region

- Sharp corners removed
- Severe concentration reduced
- Wrinkles develop

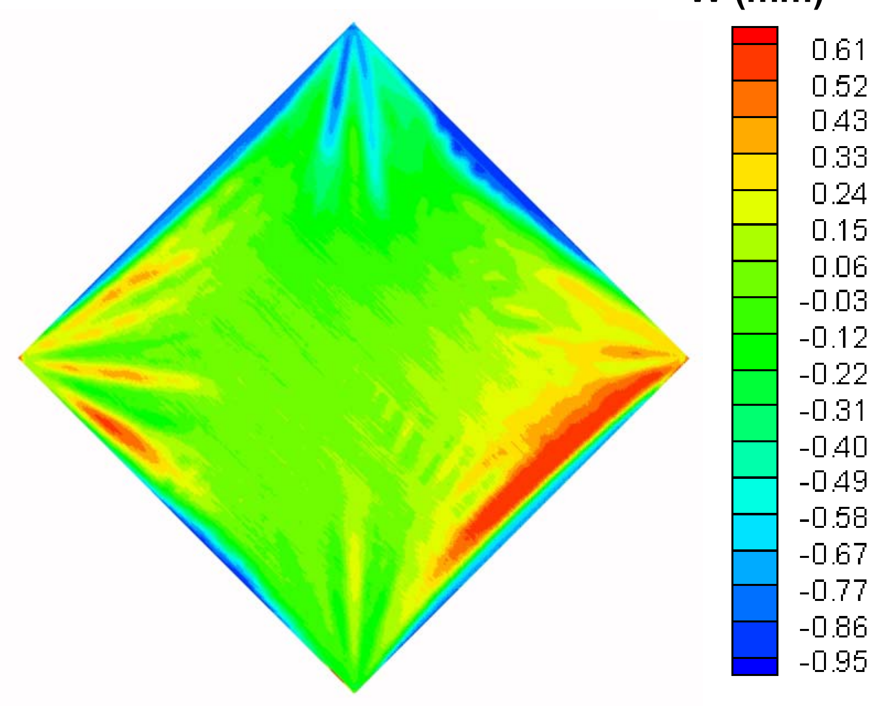


Von Mises Stress

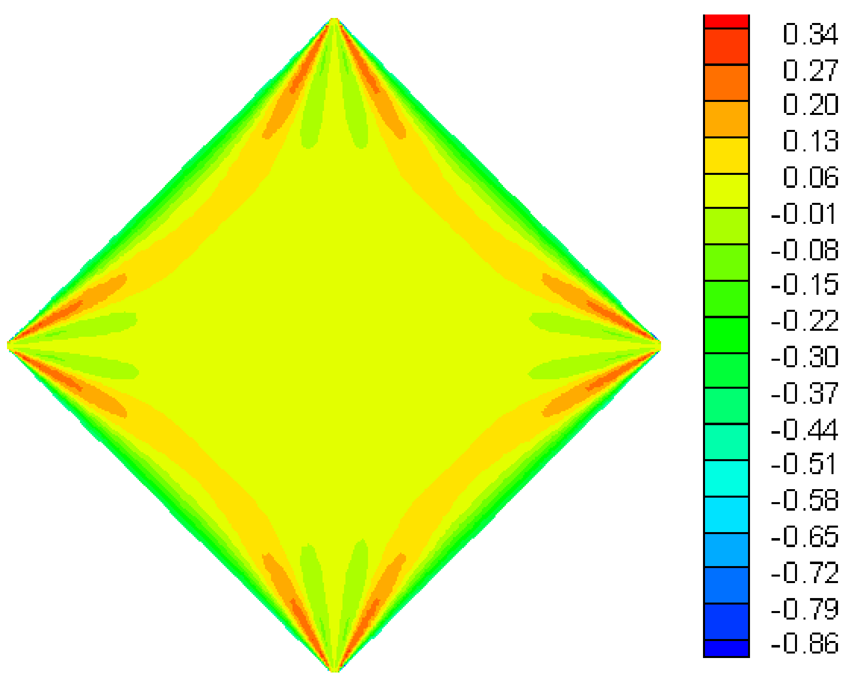


Experiment vs. Simulation

Experimental Results (J. Blandino, 2002)



ABAQUS Nonlinear Shell FEA



- **Initial imperfections present**
- **Non-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