Thermal-Structural Analysis of Sunshield Membranes

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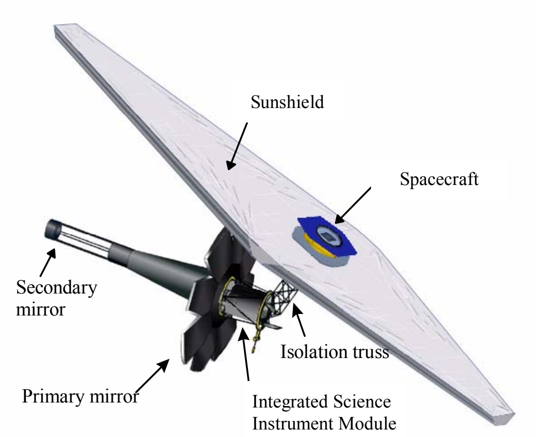
Future IR Space Telescopes

- There are several large infrared (IR) space telescopes planned for the coming decades…
  - James Webb Space Telescope (JWST)
  - Single Aperture Far Infrared (SAFIR)

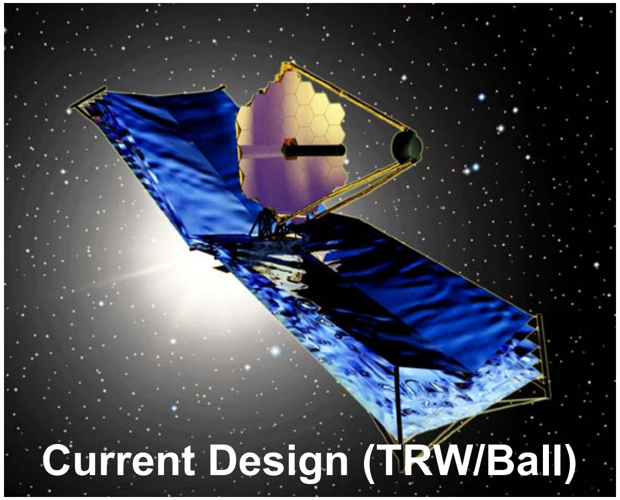
- The JWST consists of a cryogenic telescope and instruments, a room temperature spacecraft, and a deployable sunshield.

- The sunshield provides passive radiative cooling to cryogenic operating temperatures, stability at operating temperature, and stray light control.

JWST Observatory



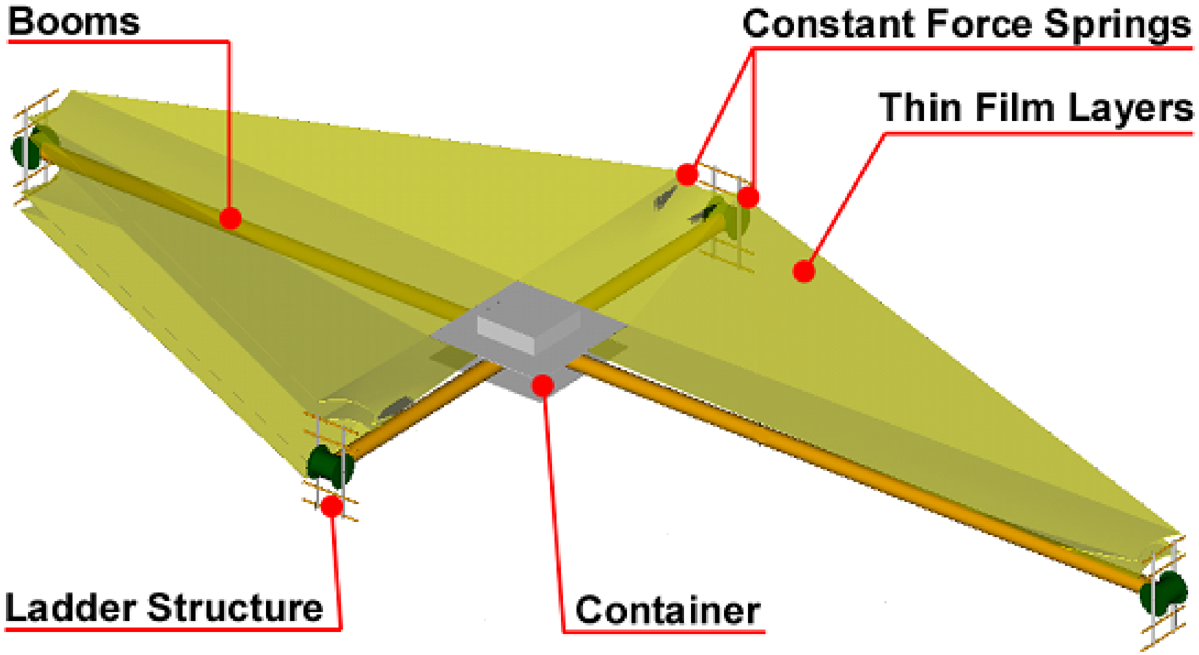
Reference Concept (NASA)



Current Design (TRW/Ball)

Sunshields for Large Space Telescopes

- Typical deployable sunshield concepts consists of:
  - Multiple layers of thin-film membranes
  - Deployable booms to support the film layers
  - Membrane management hardware to position and tension the films:
    - Ladder structures
    - Constant force springs
  - Container for the stowed structure



NASA Reference Concept:
Overall size = 30 m x 15 m
Total Mass = 200 kg

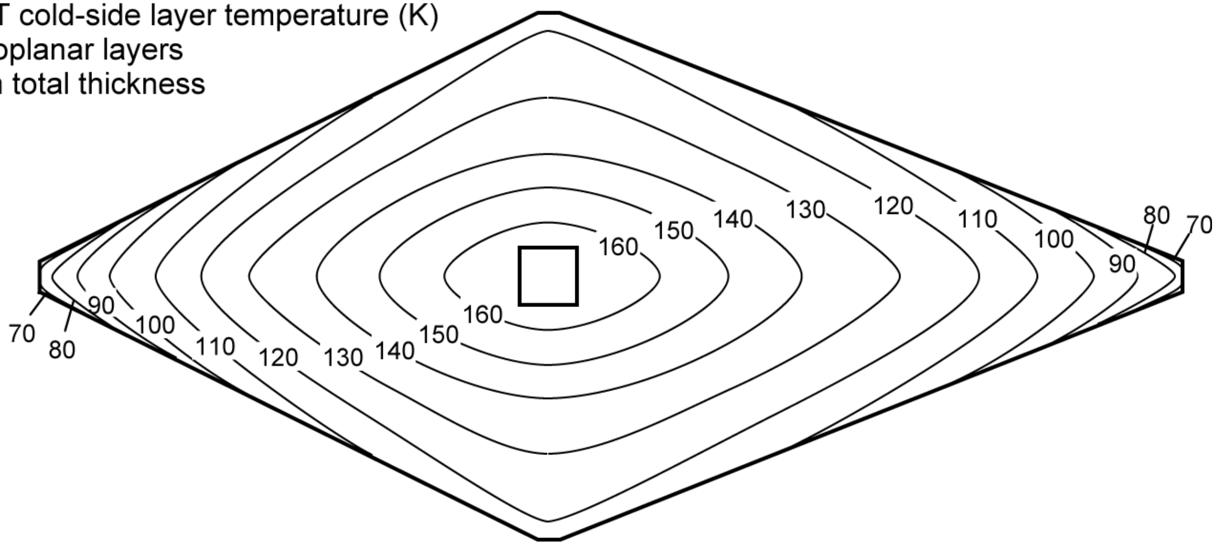
Thin film layers:
Material: Kapton
Thickness = 0.0005-0.001 in
Global stresses ~ 10 psi
Local stresses ~ 100 psi

Sunshield Temperatures

- Mean temperatures will vary widely from layer-to-layer:
  - Sun-side film layer ~ 400 K
  - Cold-side film layer ~ 100 K.

- In-plane temperature variations within the film layers are predicted to be large (up to 100 K) due to:
  - Greater view to deep space at the edges than at the center
  - Presence of the room temperature spacecraft at the center

- Membrane layers must be maintained in their nominal geometry (both spacing and flatness) when subject to thermal strain effects due to both layer-to-layer temperature differences and in-plane temperature gradients.



NGST cold-side layer temperature (K)
Six coplanar layers
0.7-m total thickness

Accommodating Thermal Strains

- Post-deployment structural performance of the sunshield is a concern since it may impact observatory thermal performance.

- A constant-force preloading scheme is typically implemented to accommodate thermal expansion/contraction of the membrane layers and is effective in compensating for uniform temperature changes and layer-to-layer bulk temperature differences.

- Even with constant-force preloading, large radial temperature gradients could lead to a loss of tensile preload within the film layers:
  - Results from over-contraction of the cold film perimeter relative to the warmer center of the film.
  - The formation of a slack region would result if the tensile preload drops to zero.

- Reduced preload or slackness in the films is a concern since any resulting sagging of the films could lead to “thermal shortcuting” if adjacent membrane layers come into contact.

Objective

- The objective was to study the effects of temperature on the structural behavior of preloaded sunshield film layers utilizing recent developments in finite element modeling of partially wrinkled thin-film membranes.

- The problem of a single film layer from the NASA reference concept JWST sunshield is used to demonstrate the analysis process and study sensitivities to:
  - In-plane temperature variations
  - Film preload level

Thermal-Structural Analytical Process

- Multi-step, sequentially coupled thermal-structural analysis:

1. Thermal analysis predicts temperatures

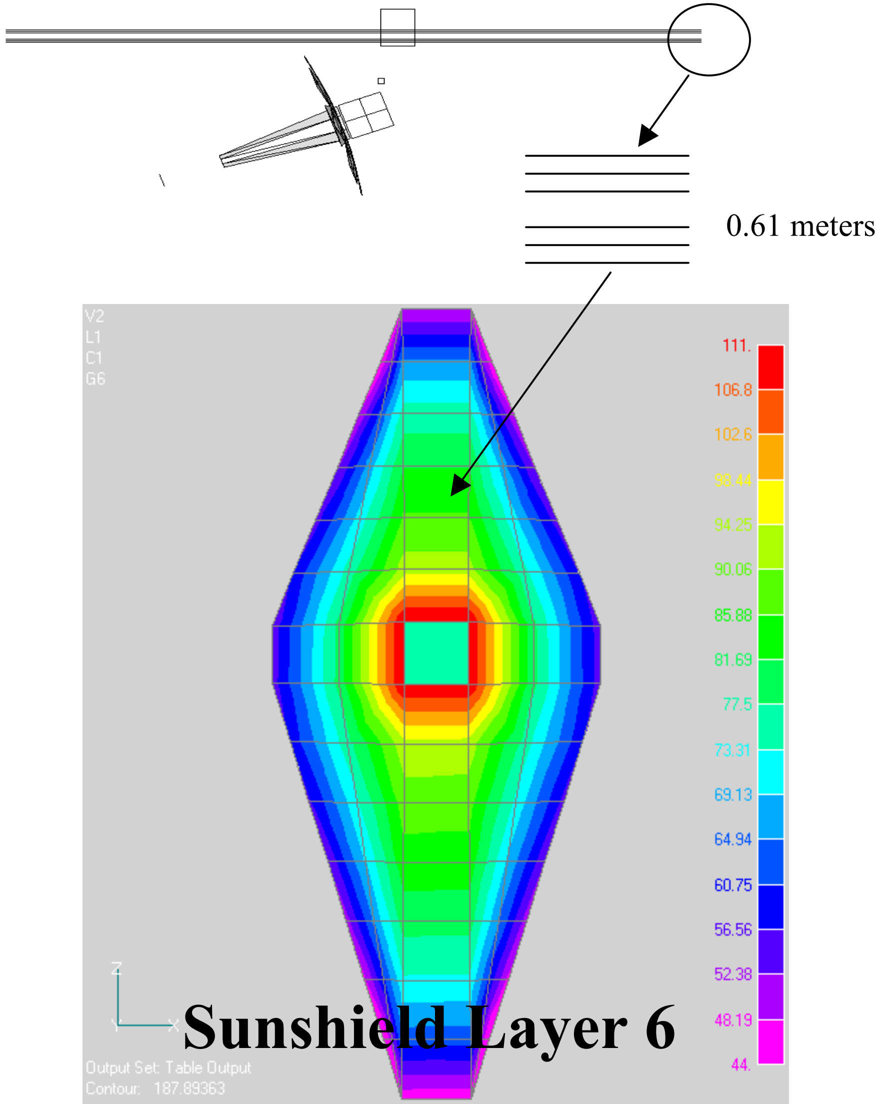
2. Temperature mapping used to interface thermal and structural models

3. Structural analysis predicts displacements/stresses/etc. due to combination of mechanical preloads and prescribed temperatures

Thermal Analysis

- Thermal analysis performed using:
  - Thermal Synthesis System (TSS) to calculate radiation interchange factors
  - SINDA85 to solve for model nodal temperatures

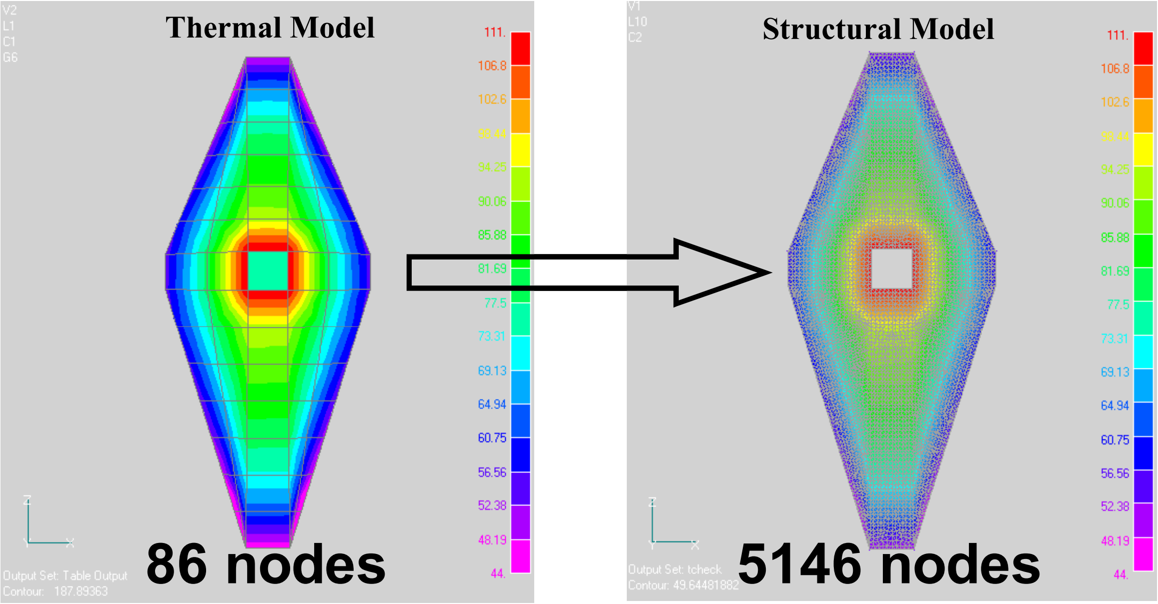
- Sunshield cold-side (layer 6) temperatures:
  - Tmean = 73.9 K
  - Tmax = 111.7 K
  - Tmin = 44.3 K
  - In-plane gradient = 67.4 K



Temperature Mapping

- Since thermal and structural models typically have dissimilar meshes, it is necessary to perform a “mapping” of the temperatures from the thermal model mesh to the structural model mesh.

- Temperature mapping approaches:
  - Pair corresponding thermal and structural model nodes, then prescribe these temperatures in a steady-state heat transfer analysis performed using the FEM.
  - Fit a function to the thermal results, then map this function to the structural model mesh (i.e. MATLAB “griddata” function)



Structural Analysis

- The structural analysis was performed using ABAQUS.

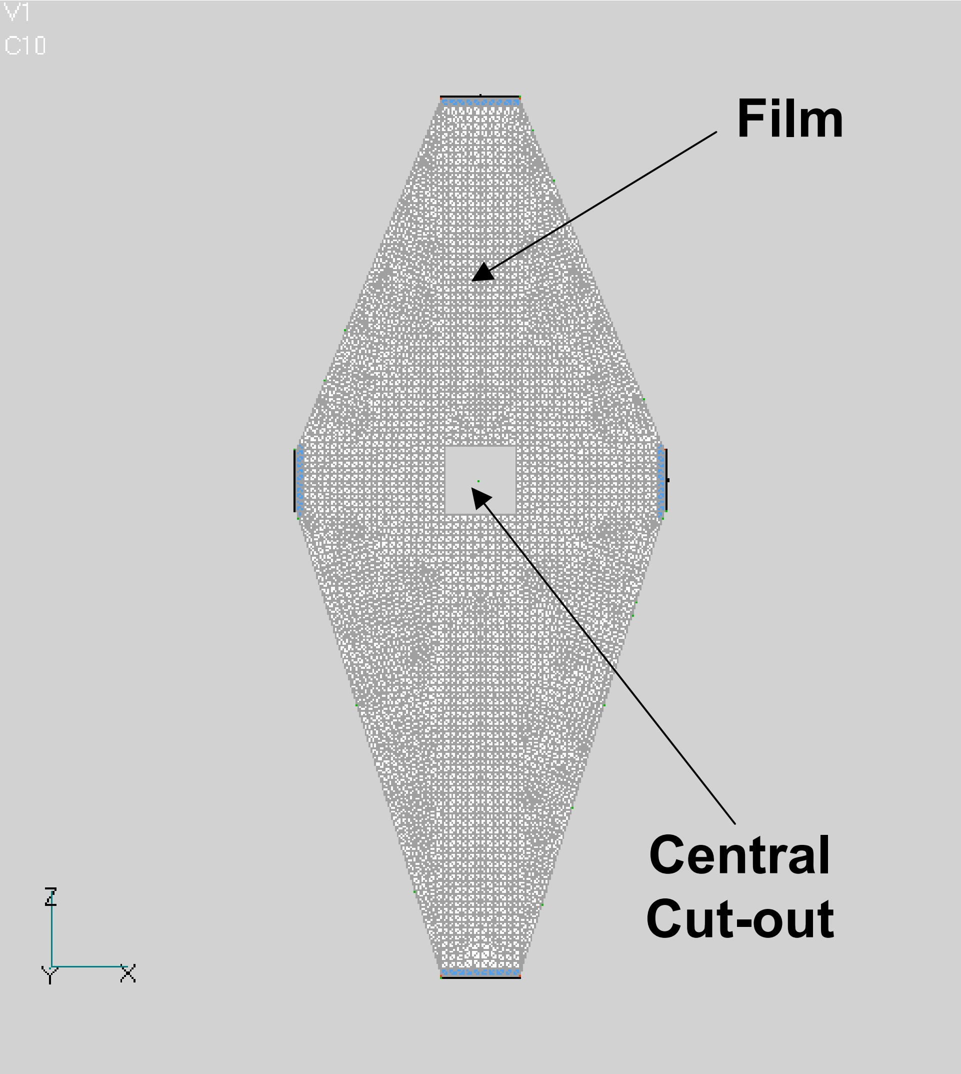
- The baseline analysis consisted of three nonlinear static analysis steps:
  1. Apply constant force spring preloads, Specify uniform temperature = 294 K (room temperature)
  2. Specify uniform temperature = 74 K (mean cold-side temperature)
  3. Specify mapped temperature distribution (mean temperature + gradient)

Thin-Film Modeling

- Thin-film membrane layer modeled using membrane elements (M3D3) 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
  - Approach predicts stress distributions corrected for wrinkling and slackness as well as wrinkled/slack regions, but not wrinkling details.
- Shell element overlay provides small artificial stiffness:
  - Allows slack regions to become taut when preload is increased despite zero in-plane stiffness in slack membrane elements
  - Studies showed minimal effect on the membrane stresses
- Additional numerical stabilization provided by ABAQUS *STABILIZE

Finite Element Model

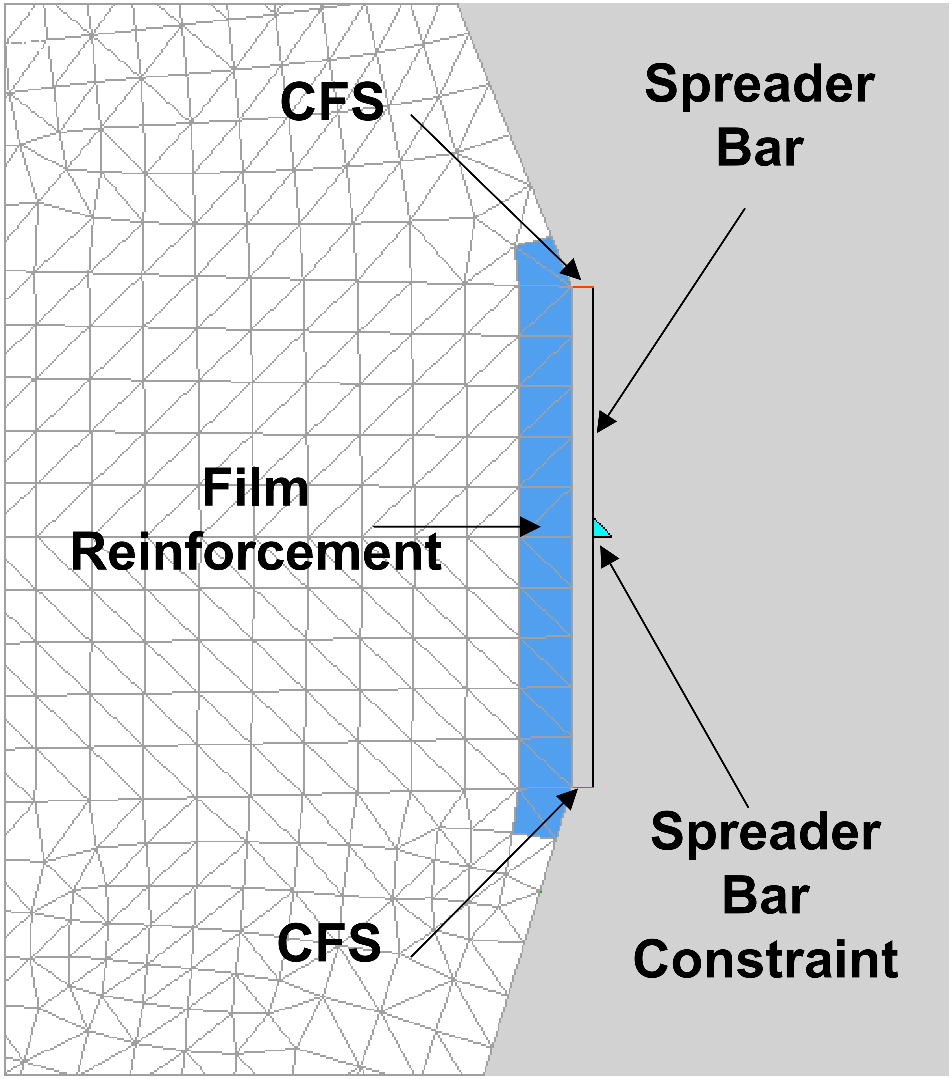
- Mesh:
  - 5146 Nodes
  - 19800 Elements
- Components:
  - Film (M3D3 membrane elements)
  - Corner reinforcements (STRI3 shell elements)
  - Spreader Bars (B31 beam elements)
  - Constant Force Springs (B31 beam elements)
- Central cut-out in film representative of attachment to spacecraft
- Assumed uniform, temperature independent CTE for all materials (2.0E-5 /K)



FEM – Load & Constraints

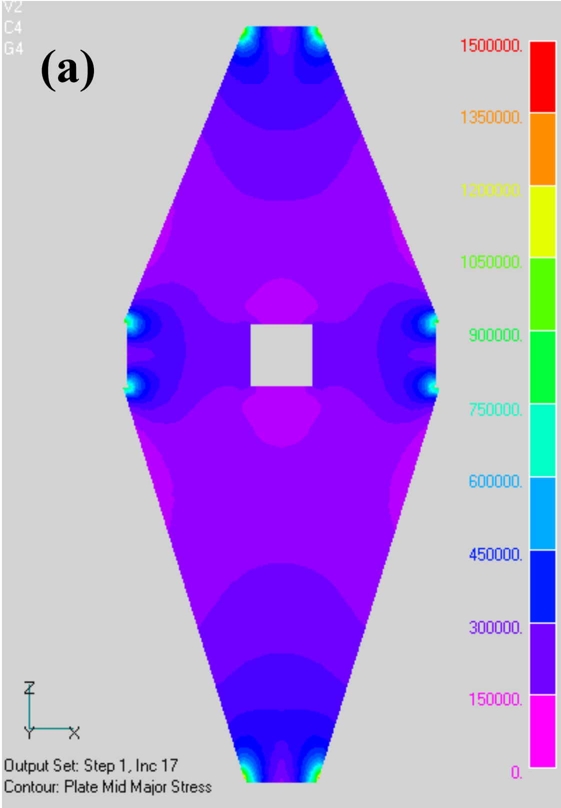
- Loads:
  - 2 CFS per corner
  - 14.25 N total per corner
  - Applied constant force preload using ABAQUS *PRE-TENSION SECTION

- Constraints:
  - Fixed at spreader bars (interface with deployment booms)
  - Pinned around the perimeter of central cut-out

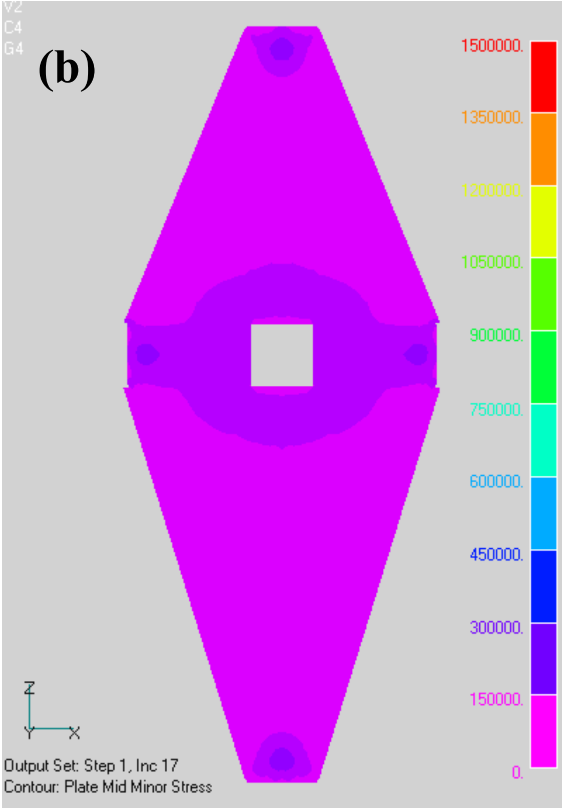


Uniform Temperature = 294 K

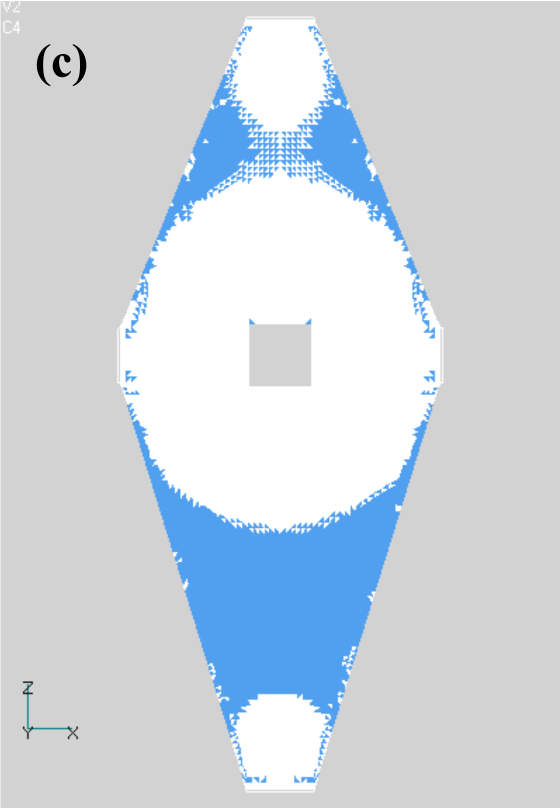
Major Principal Stresses



Minor Principal Stresses

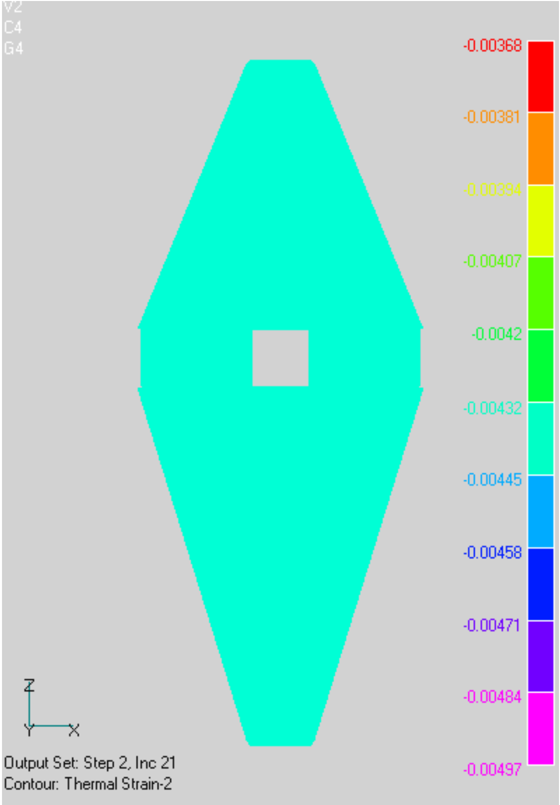


Wrinkle/Slack Regions

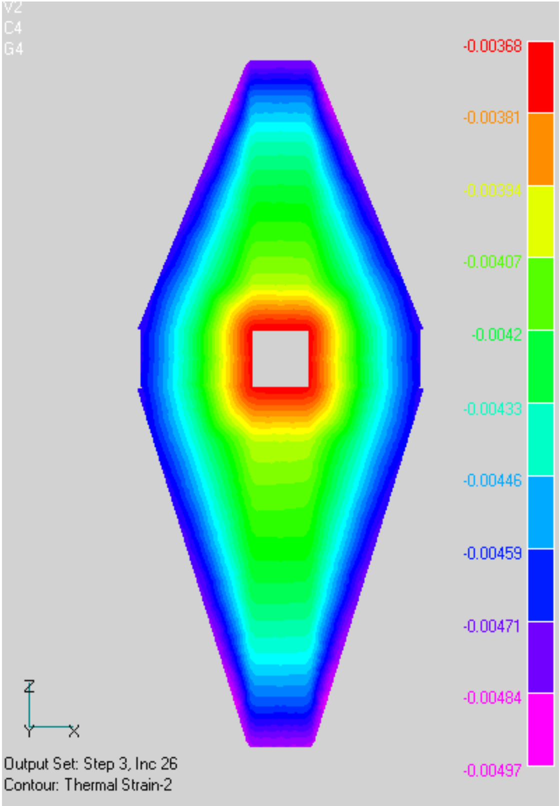


Preload (N)	Temperature (K)		Stresses (Pa)				Area (%)		
	Tmean	Tmax-Tmin	Major - Max	Major - Min	Minor - Max	Minor - Min	Slack	Wrinkled	Taut
14.25	294	0	1.30E+06	7.07E+04	1.27E+05	0.00E+00	0.00	0.33	0.67
14.25	74	0	1.20E+07	7.59E+04	3.51E+05	0.00E+00	0.00	0.40	0.60
14.25	74	67	9.90E+06	0.00E+00	5.44E+05	0.00E+00	0.15	0.63	0.22

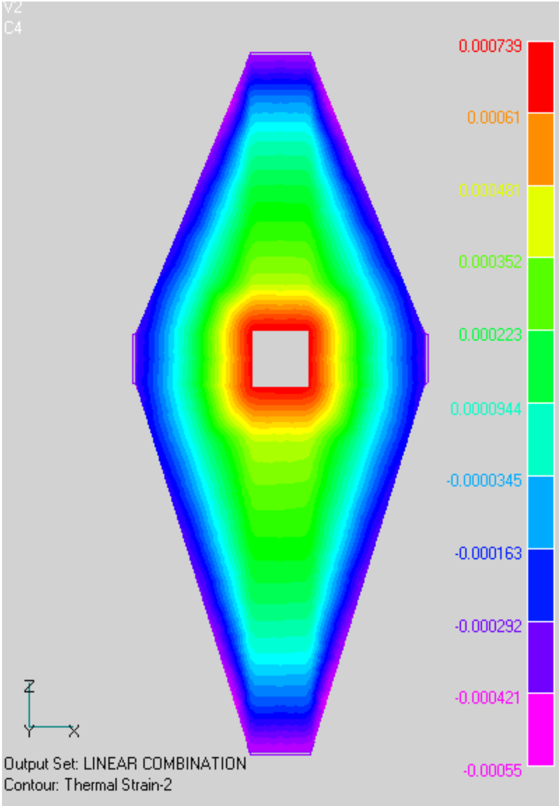
Thermal Strains



Uniform Temperature = 74 K



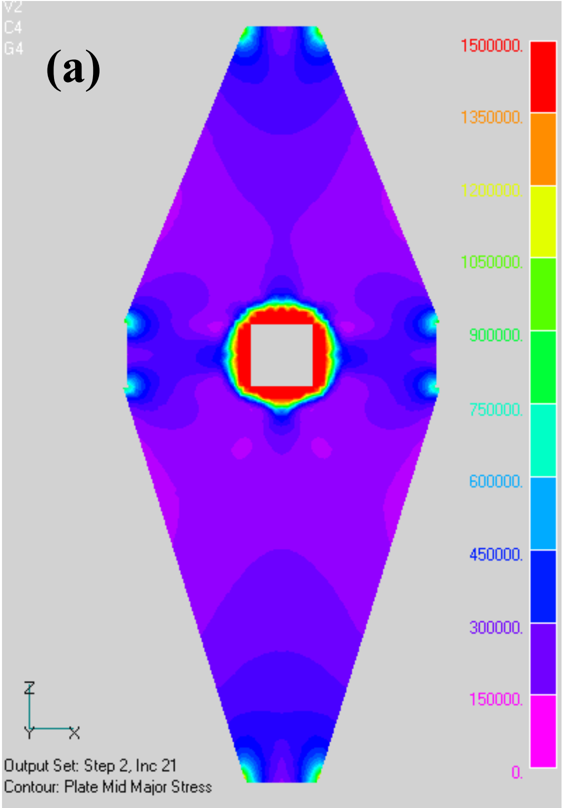
Mapped Temperature Distribution
(Tmean = 74 K, Tmax-Tmin= 67 K)



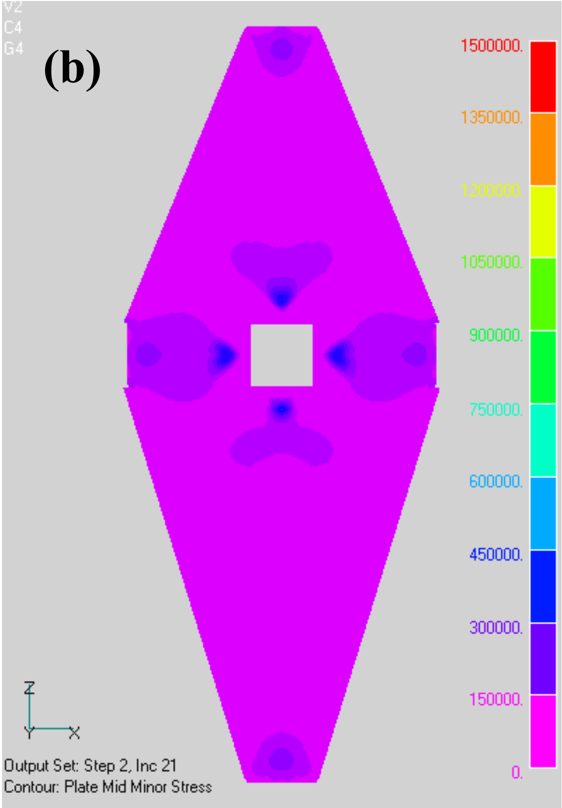
Difference
(i.e. thermal strain due to radial gradient)

Uniform Temperature = 74 K

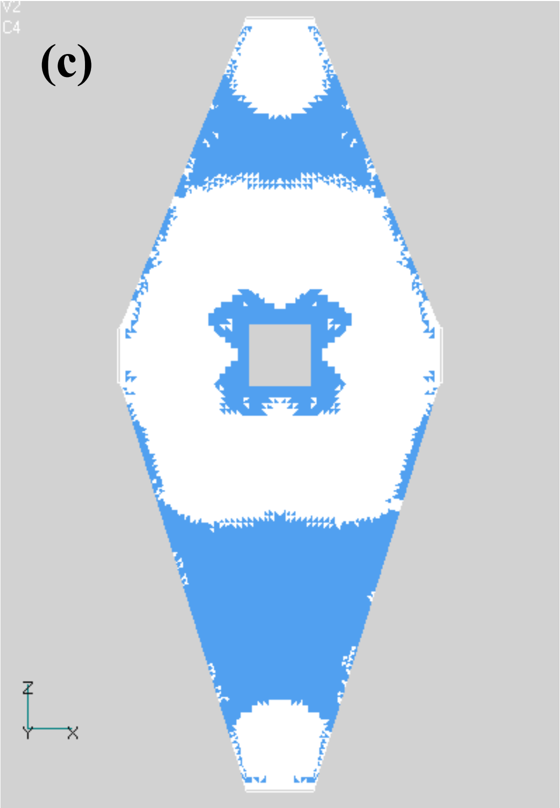
Major Principal Stresses



Minor Principal Stresses



Wrinkle/Slack Regions



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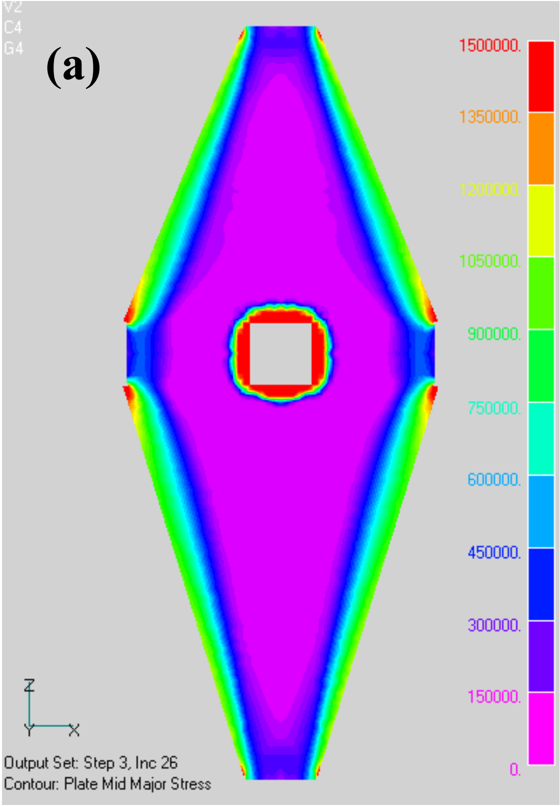
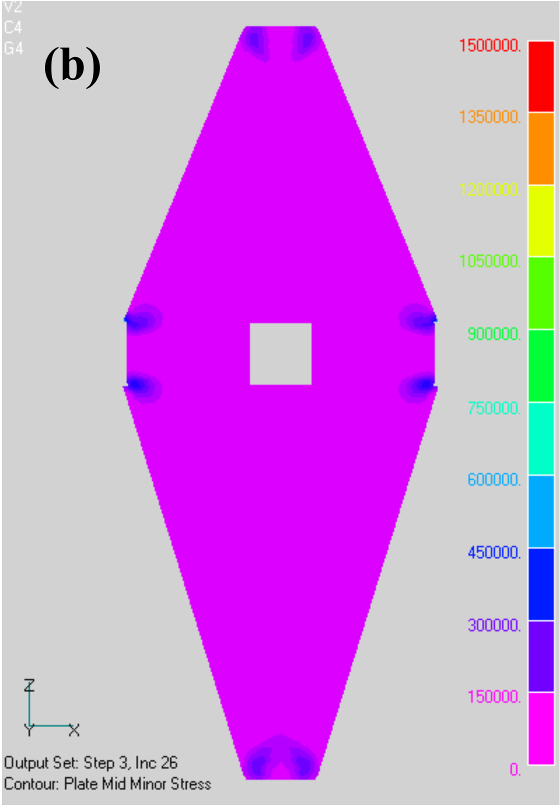
Major Principal Stresses



Minor Principal Stresses



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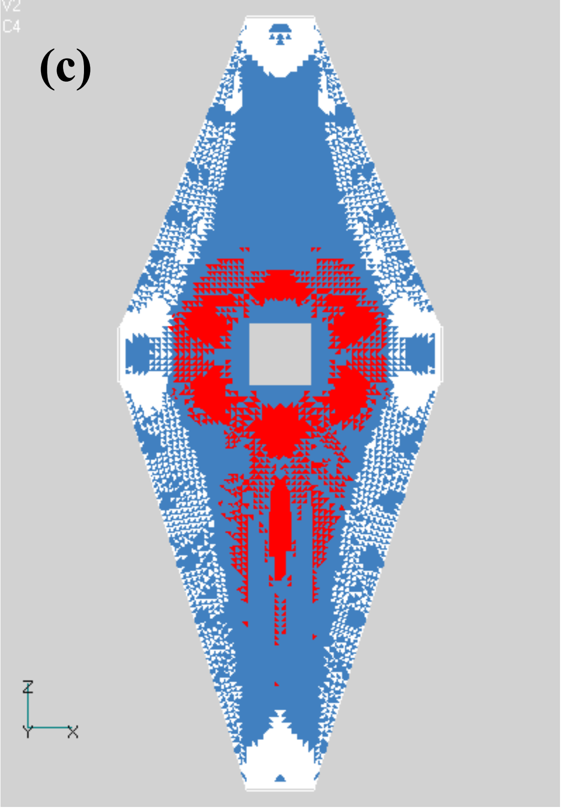

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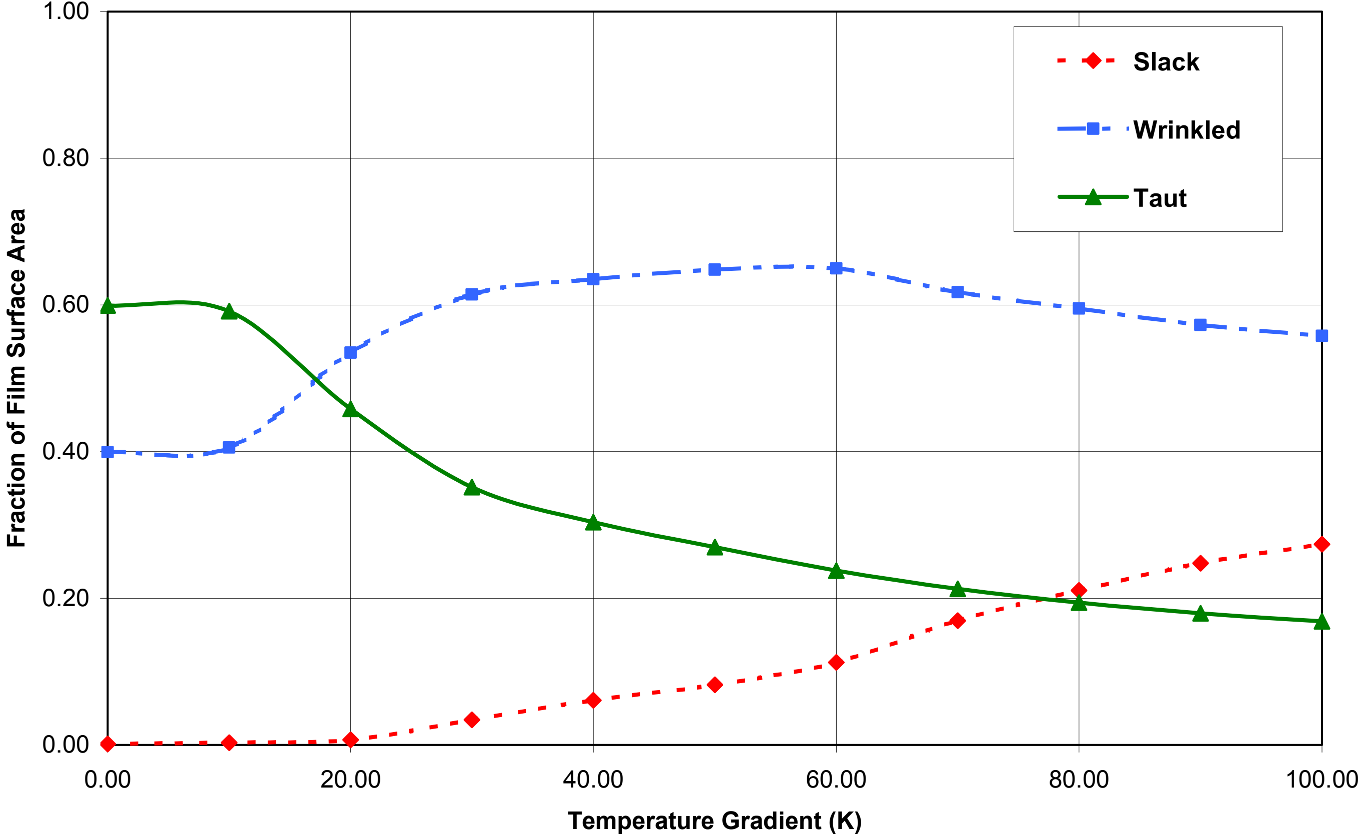
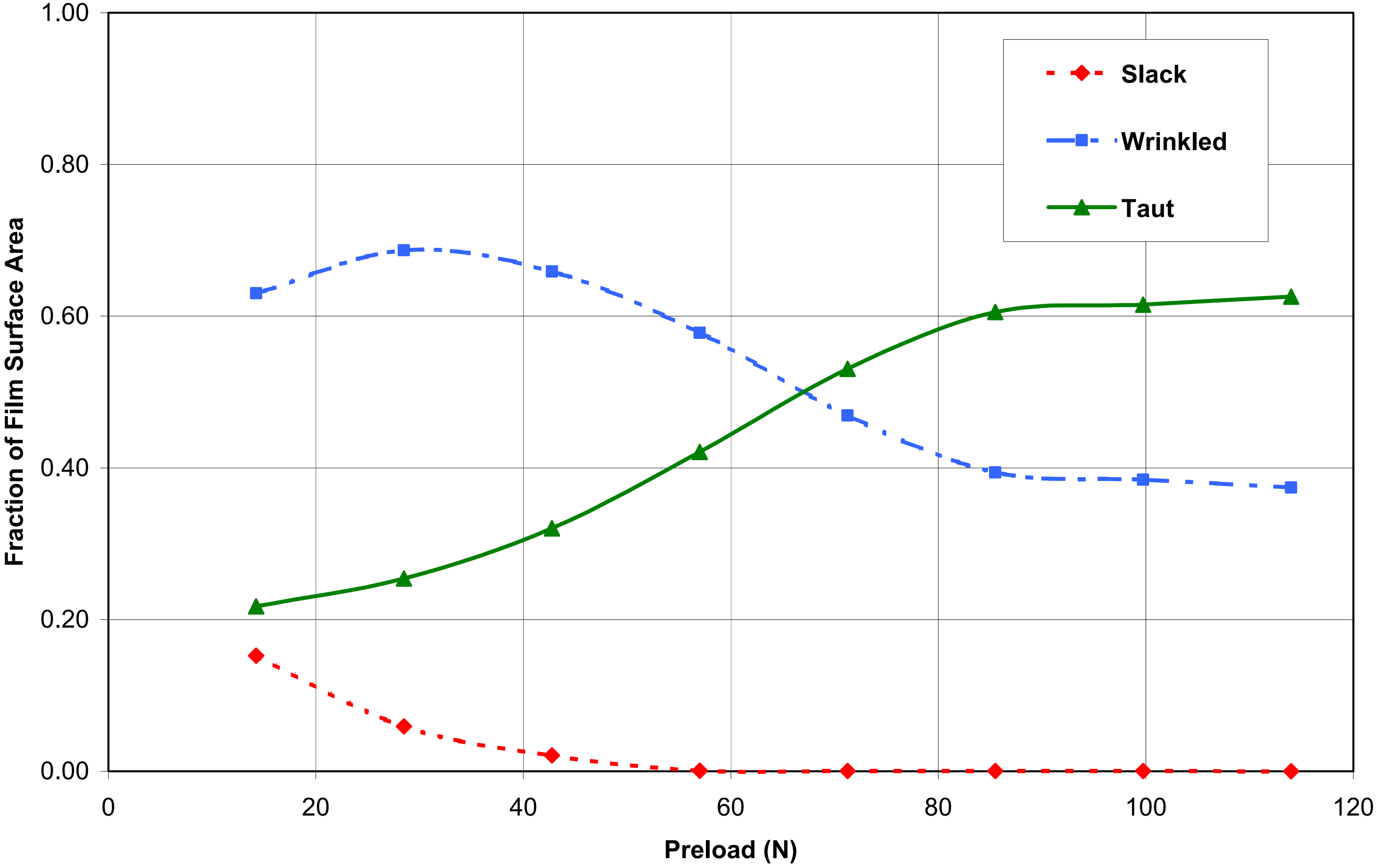
Effects of Varying Temperature Gradient



Support Case	Preload (N)	Temperature (K)		Stresses (Pa)				Area (%)		
		Tmean	Tmax-Tmin	Major - Max	Major - Min	Minor - Max	Minor - Min	Slack	Wrinkled	Taut
B	14.25	294	0	1.30E+06	7.07E+04	1.27E+05	0.00E+00	0.00	0.33	0.67
B	14.25	74	0	1.20E+07	7.59E+04	3.51E+05	0.00E+00	0.00	0.40	0.60
B	14.25	74	10	1.17E+07	1.05E+04	2.23E+05	0.00E+00	0.00	0.41	0.59
B	14.25	74	20	1.14E+07	3.34E+01	2.58E+05	0.00E+00	0.01	0.53	0.46
B	14.25	74	30	1.11E+07	0.00E+00	3.28E+05	0.00E+00	0.03	0.61	0.35
B	14.25	74	40	1.04E+07	0.00E+00	4.51E+05	0.00E+00	0.06	0.64	0.30
B	14.25	74	50	1.01E+07	0.00E+00	5.06E+05	0.00E+00	0.08	0.65	0.27
B	14.25	74	60	9.82E+06	0.00E+00	5.57E+05	0.00E+00	0.11	0.65	0.24
B	14.25	74	67	9.90E+06	0.00E+00	5.44E+05	0.00E+00	0.15	0.63	0.22
B	14.25	74	70	9.53E+06	0.00E+00	6.04E+05	0.00E+00	0.17	0.62	0.21
B	14.25	74	80	9.23E+06	0.00E+00	6.45E+05	0.00E+00	0.21	0.60	0.19
B	14.25	74	90	9.23E+06	0.00E+00	6.45E+05	0.00E+00	0.25	0.57	0.18
B	14.25	74	100	8.94E+06	0.00E+00	6.87E+05	0.00E+00	0.27	0.56	0.17

Effects of Varying Preload



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B	14.25	74	67	9.90E+06	0.00E+00	5.44E+05	0.00E+00	0.15	0.63	0.22
B	28.5	74	67	1.01E+07	0.00E+00	6.90E+05	0.00E+00	0.06	0.69	0.25
B	42.75	74	67	1.02E+07	0.00E+00	8.50E+05	0.00E+00	0.02	0.66	0.32
B	57	74	67	1.03E+07	2.93E+04	9.96E+05	0.00E+00	0.00	0.58	0.42
B	71.25	74	67	1.04E+07	1.05E+05	1.13E+06	0.00E+00	0.00	0.47	0.53
B	85.5	74	67	1.05E+07	1.86E+05	1.24E+06	0.00E+00	0.00	0.39	0.61
B	99.75	74	67	1.05E+07	2.06E+05	1.30E+06	0.00E+00	0.00	0.38	0.62
B	114	74	67	1.13E+07	2.52E+05	1.39E+06	0.00E+00	0.00	0.37	0.63

Summary

- Results from an analysis of the cold-side film layer of the NASA reference concept JWST sunshield were used to demonstrate a thermal-structural analysis approach and provide insight into the response of the membrane to thermo-mechanical loading.

- For the problem considered, the film was shown to develop slack regions when subject to a large in-plane temperature gradient. Subsequent analyses showed that the slack region could be eliminated by increasing the magnitude of the mechanical preload by a factor of four.

- These studies demonstrate the importance of including thermal effects in thin-film membrane structural analyses when significant temperature variations are expected within the structure.

- Topics for future study include: thermal model refinement, temperature-dependent material properties, mismatches in coefficient of thermal expansion, and additional approaches to film tensioning.