Finite Element Analysis of Wrinkled Membrane Structures for Sunshield Applications

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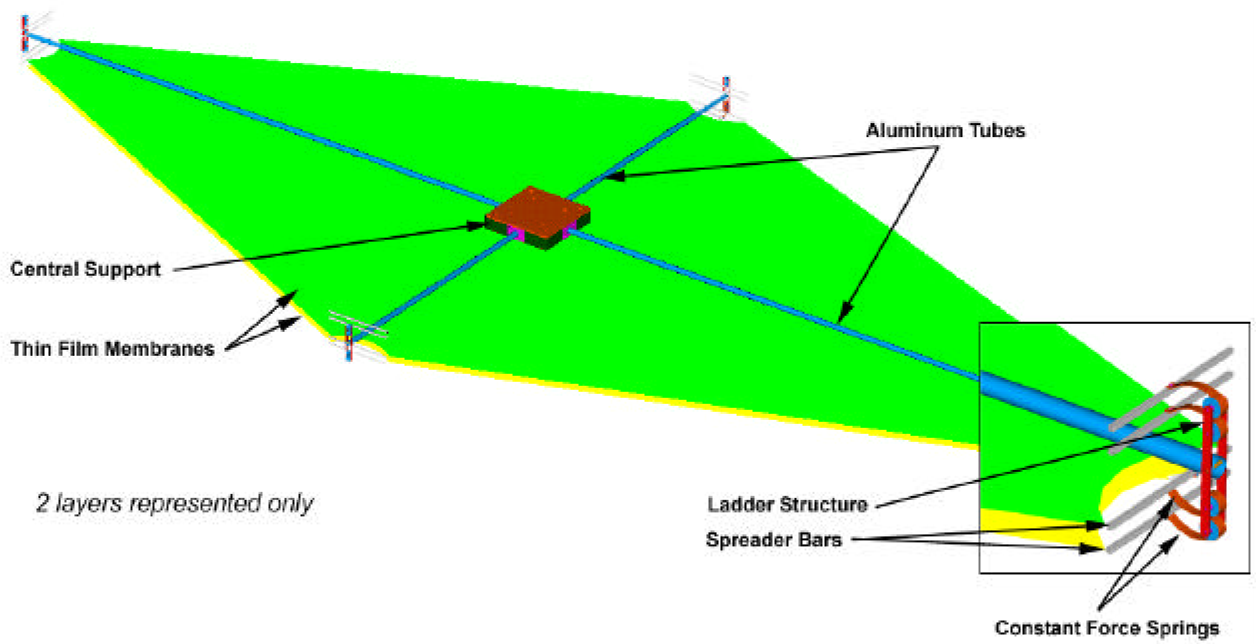
2002 FEMCI Workshop
May 23, 2002

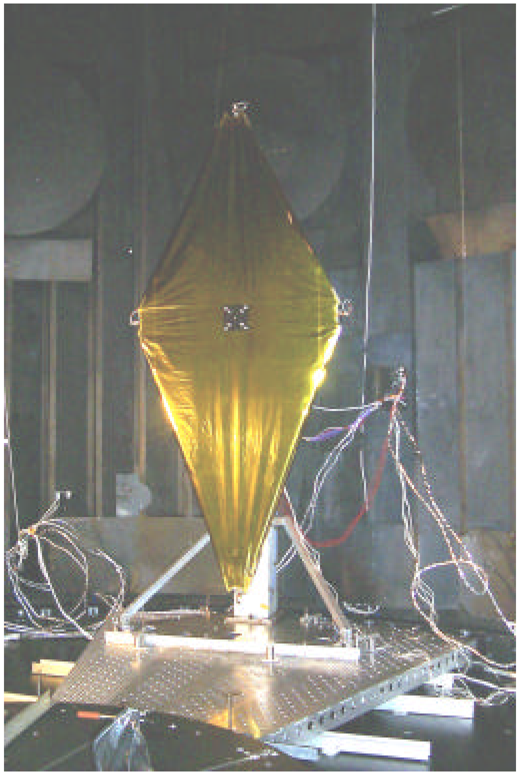
(Based on a presentation at the 2002 AIAA Gossamer Spacecraft Forum)

NGST Sunshield

- The Next Generation Space Telescope (NGST) requires a lightweight, deployable sunshield to provide passive cooling and straylight control.
- NGST ‘yardstick’ concept sunshield characteristics:
  - Central support structure
  - Deployable support booms
  - Pretensioned, thin-film membranes

1/10th Scale Model NGST Sunshield





Analysis and ground testing of a one-tenth scale model of the NGST 'yardstick' concept sunshield is being carried out to develop and validate capabilities to predict and verify sunshield structural characteristics.

Sunshield Membrane Modeling

- A challenging aspect of sunshield analysis is modeling the nonlinear behavior of partially wrinkled, thin-film membranes.

- Modeling techniques previously used to model the NGST sunshield membranes:
  - Standard shell elements
  - Cable network method
  - Membrane elements with a ‘wrinkling’ material model

Sunshield Membrane Modeling – cont.

- Wrinkling material model:
  - Finite element implementation of Stein-Hedgepeth wrinkling theory
  - 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:
    - $?_2 > 0$? taut
    - $?_1$? 0 ? slack
    - $?_1 > 0$ and $?_2$? 0 ? wrinkled
  - Stiffness matrix formulation based on the element state:

$$K_{Taut} \; ? \; \frac{E}{1 ? ?^2} \begin{bmatrix} 1 & ? & 0 \\ ? & 1 & 0 \\ 0 & 0 & \frac{1 ? ?}{2} \end{bmatrix} \qquad K_{Wrinkled} \; ? \; \frac{E}{4} \begin{bmatrix} 2(1 ? P) & 0 & Q \\ 0 & 2(1 ? P) & Q \\ Q & Q & 1 \end{bmatrix} \qquad K_{Slack} \; ? \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$P \; ? \; 2\cos(2?)$$

$$Q \; ? \; 2\sin(2?)$$

? ? principal stress angle

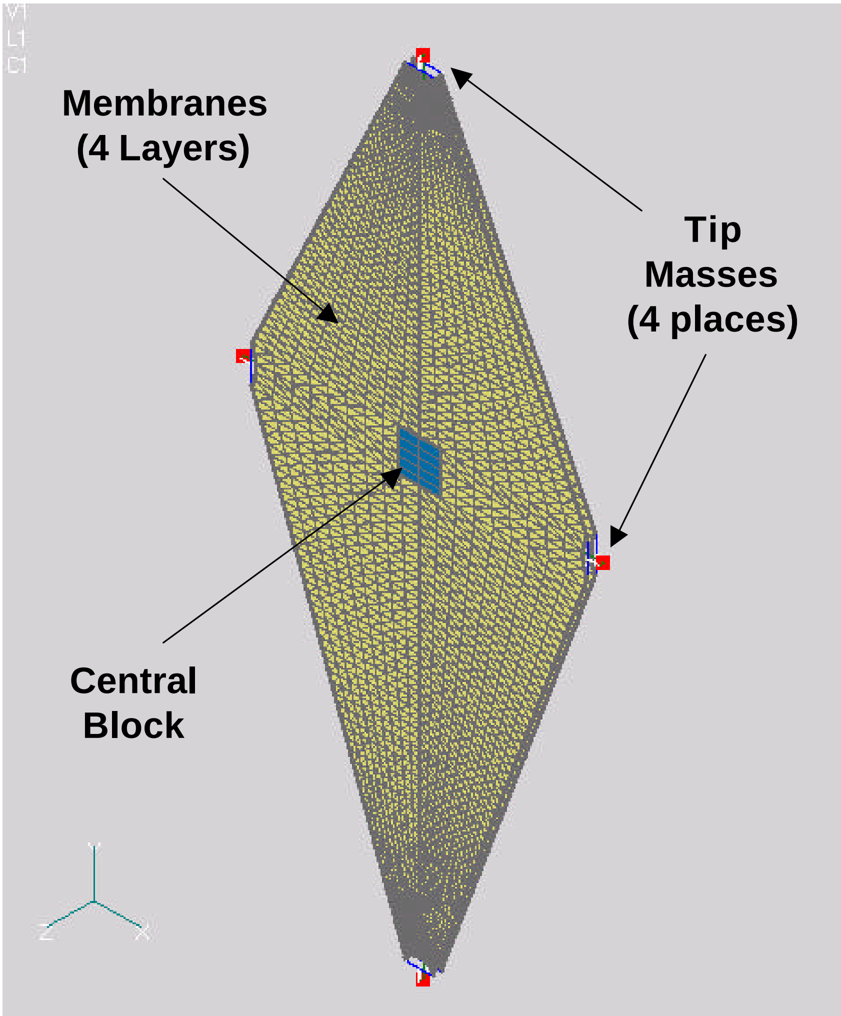
Finite Element Analysis

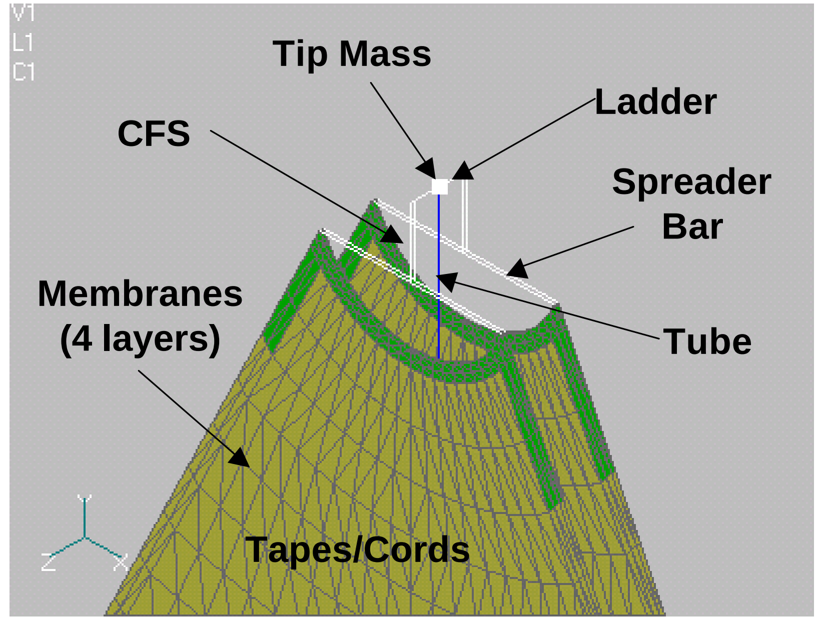
- The commercially available finite element analysis program ABAQUS is used to perform the analysis:
  - ABAQUS has robust nonlinear analysis capabilities.
  - ABAQUS user material (UMAT) subroutine feature allows for the implementation of custom nonlinear constitutive relations.
  - Iterative Membrane Properties (IMP) UMAT subroutine developed by Adler/University of Colorado-Boulder.

- The baseline structural analysis consists of several ABAQUS steps:
  - Step 1: Nonlinear static analysis – Initial preloading
  - Step 2: Nonlinear static analysis – Application of full preloads
  - Step 3: Modal analysis
  - Step 4: Frequency domain dynamic analysis

- Gravity and/or thermal loads may also be included in additional nonlinear static analysis steps.

Finite Element Model



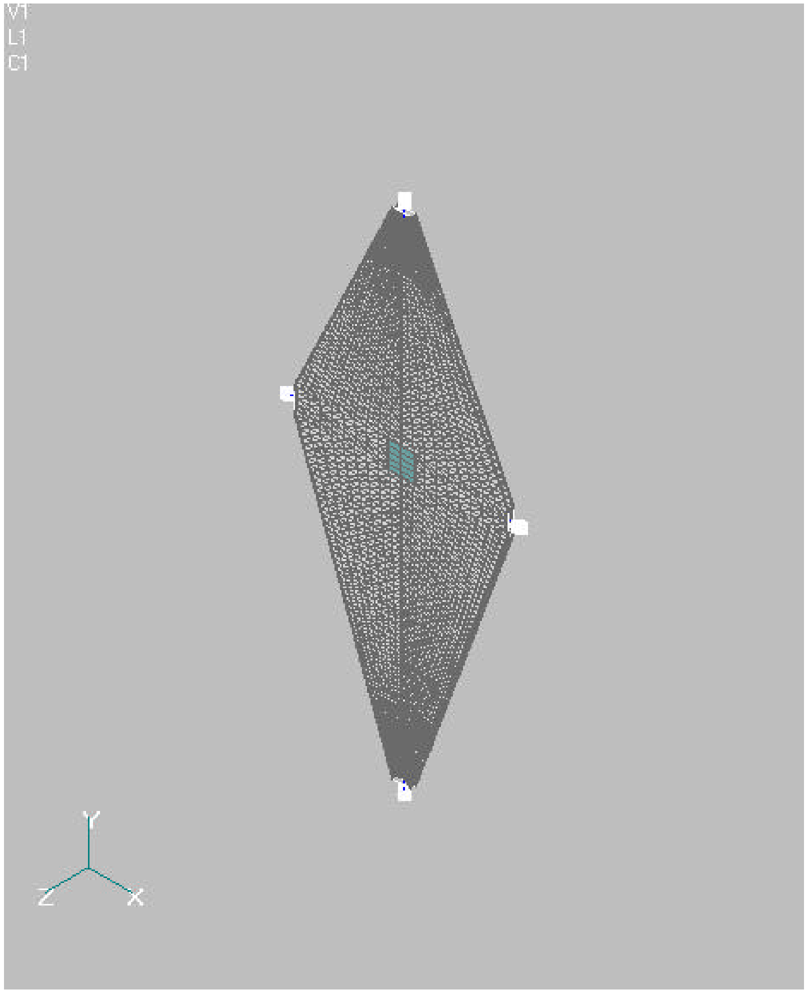


- Finite element mesh:
  - 9505 nodes
  - 18005 elements
- Components:
  - Films = Membranes, Tapes, Cords
  - Support Structure = Central Block, Tubes, Ladders, Spreader Bars
  - CFS (ABAQUS Pretension Sections)

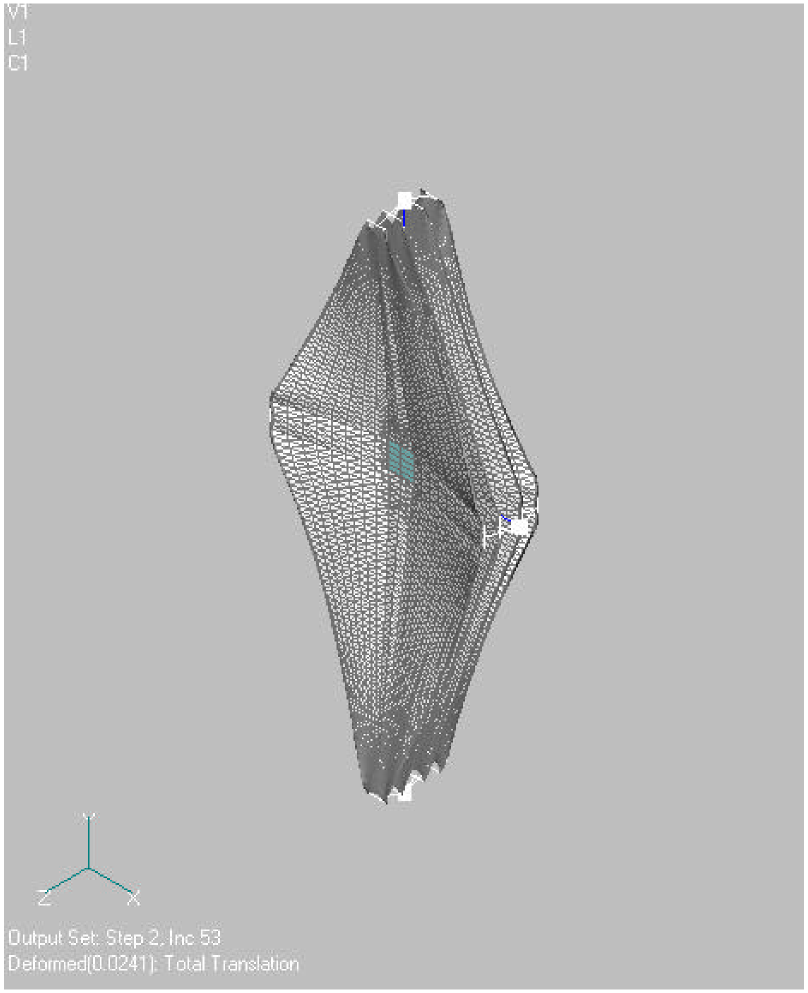
Preloading Analysis Results – CFS1

Deformed Geometry

Undeformed Geometry



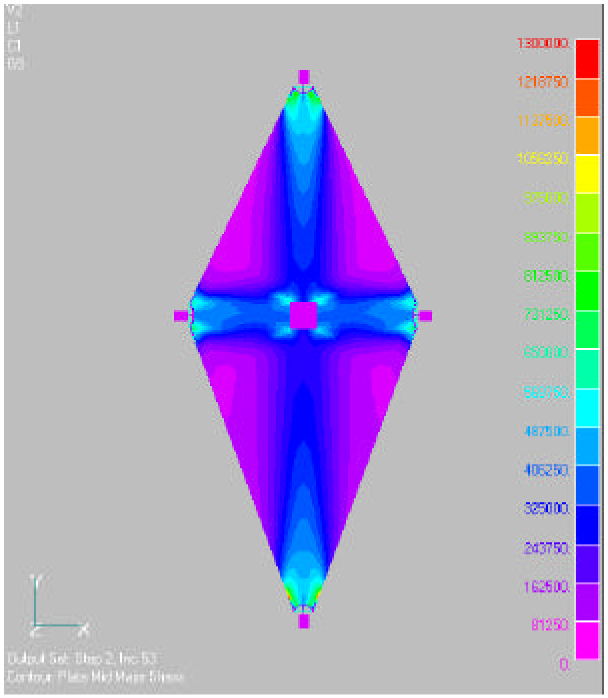
Preloaded Geometry (exaggerated)



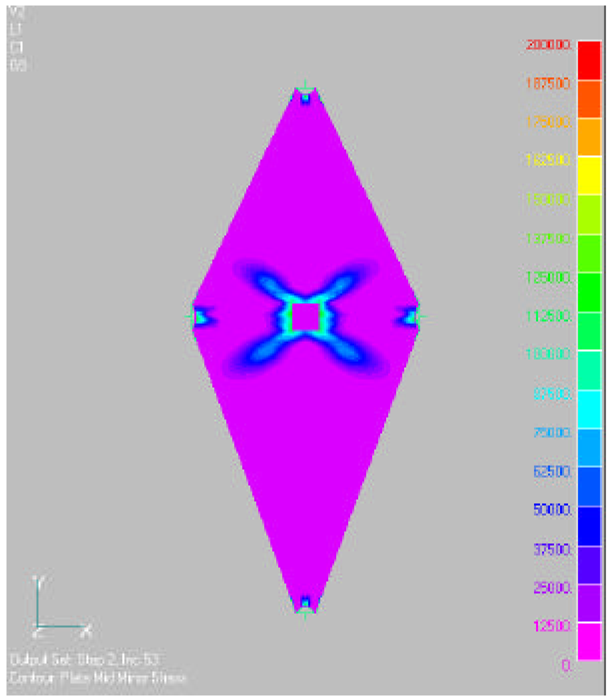
Preloading Analysis Results – CFS1

Principal Stresses and Wrinkle Region

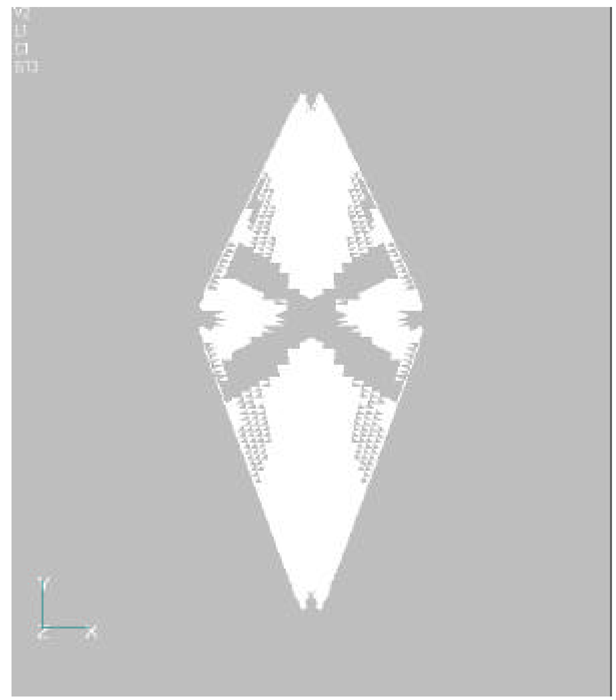
Major Principal Stress
Max = 1.26E+6 Pa (191 psi)
Min = 7.60E+3 Pa (1 psi)



Minor Principal Stress
Max = 2.14E+5 Pa (31 psi)
Min = 0 Pa (0 psi)



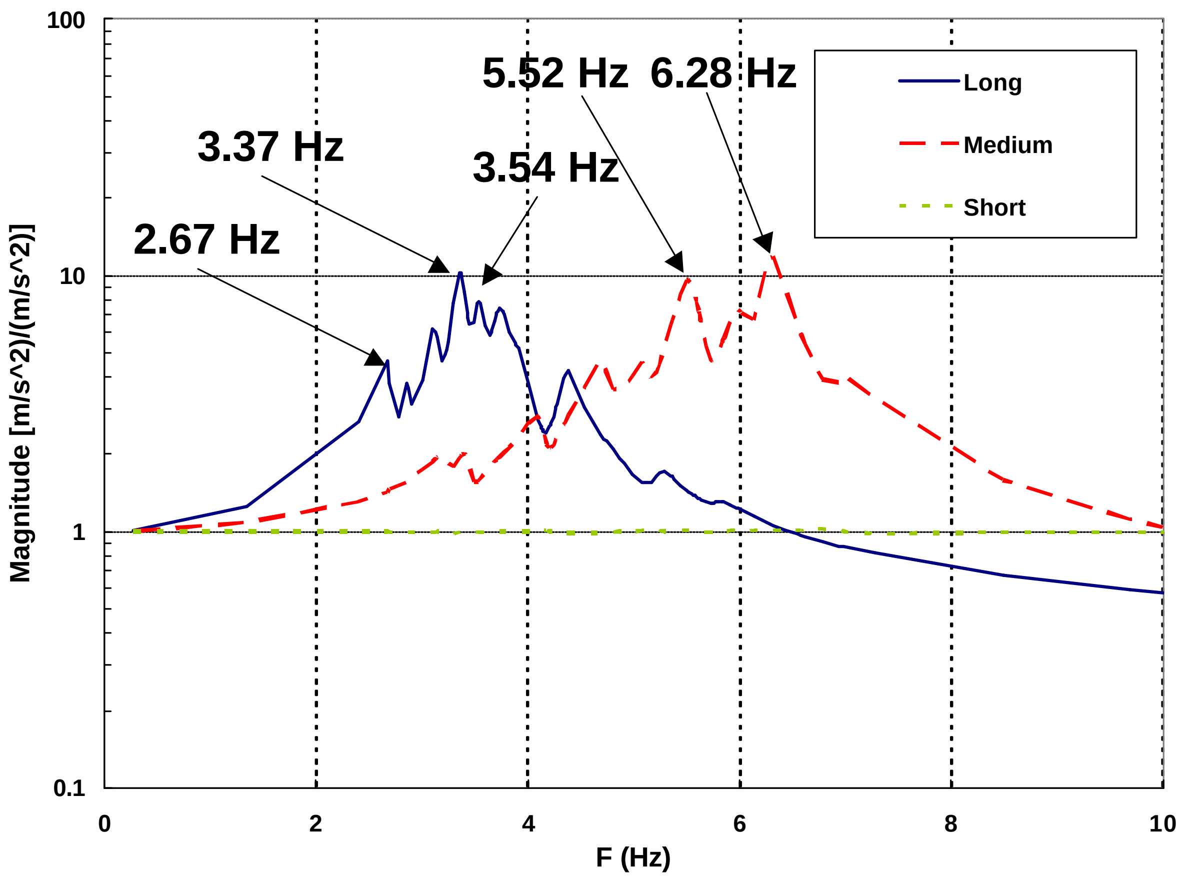
Wrinkle Region
73% of surface area is in wrinkled region



NOTE: Results show are for outer membrane layer.
Stresses and wrinkle region differ slightly for inner membrane layer.

Dynamics Analysis Results – CFS1

- Modal analysis predicts 347 modes in 0 – 10 Hz frequency range
  - Lowest mode = 2.541 Hz ('Twist' mode of long side of membranes)
  - 31 modes have EFFM-RX > 0.1% (account for 94% of the total mass)



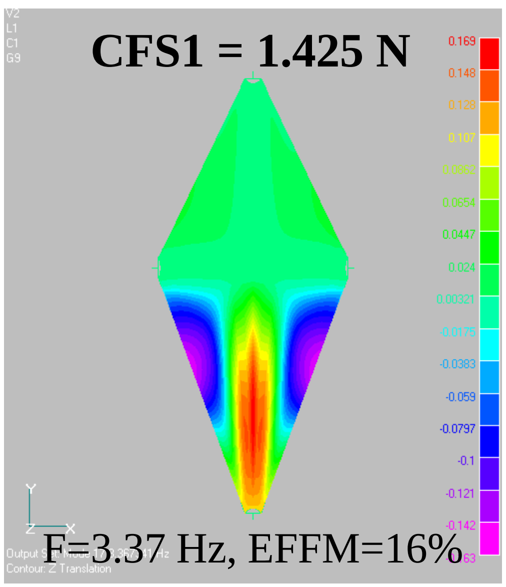
Mode #	F (Hz)	%RX
3	2.6716	8.1
7	2.8706	5.4
10	3.1271	6.8
16	3.2313	0.5
17	3.3673	15.6
20	3.4332	0.9
25	3.5376	10.2
27	3.6553	0.4
33	3.7026	6.6
35	3.764	3.7
45	3.8882	2.9
51	4.1214	0.4
54	4.138	0.6
67	4.214	0.4
73	4.2654	1.0
77	4.3458	3.5
82	4.7201	2.0
90	4.8813	0.8
94	5.0965	1.7
99	5.2261	0.4
102	5.3634	0.6
110	5.5154	5.0
112	5.5705	2.4
114	5.6155	0.4
120	5.7366	0.3
123	5.7771	0.1
126	5.8391	1.4
138	5.9834	3.6
150	6.2801	8.4
162	6.5801	0.2
186	6.9785	0.6

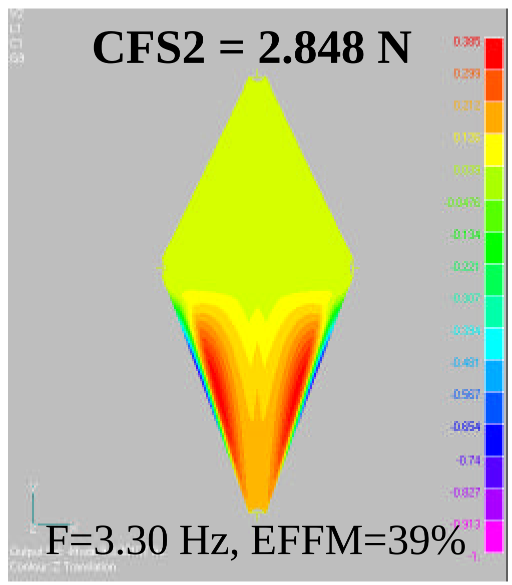
Preload Variation Study

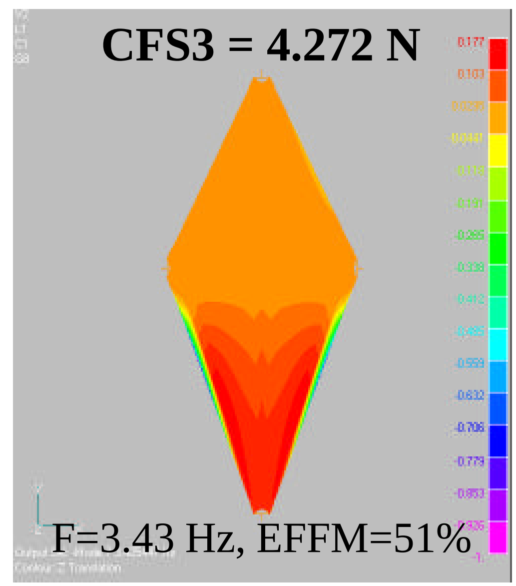
Parameter	CFS1	CFS2	CFS3
# of Modes	347	278	184
Total EFFM (%)	96	93	95
F_0 (Hz)	2.54	2.66	3.10
F_1 (Hz)	2.67	2.68	3.10
F_A (Hz)	2.54	2.66	3.12
F_B (Hz)	3.37	3.30	3.43

Note:
Mode 0: First mode
Mode 1: First significant mode
Mode A: Long side twist mode
Mode B: Mode w/ greatest EFFM

Mode Shapes For Dominant System Mode





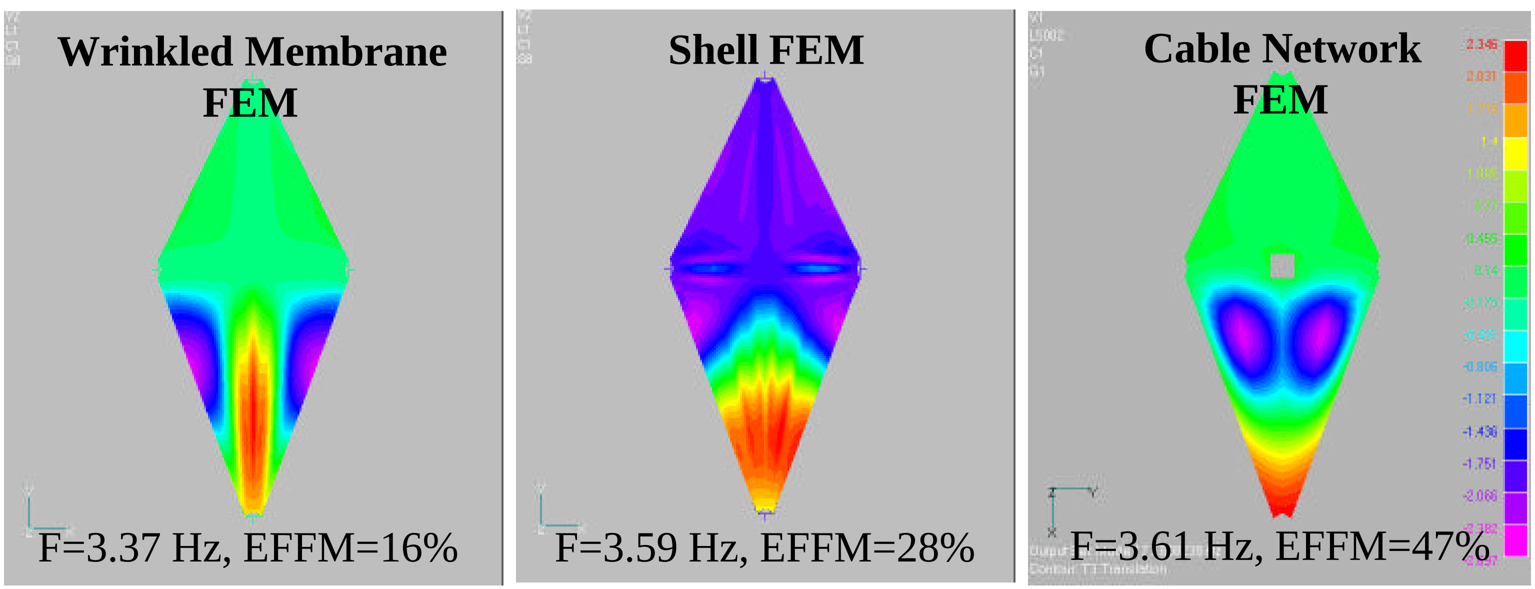


Modeling Technique Study

Parameter	Wrinkled Membrane	Shell	Cable Network
# of Modes	347	156	103
Total EFFM (%)	96	96	95
F_0 (Hz)	2.54	1.41	2.50
F_1 (Hz)	2.67	3.10	2.50
F_A (Hz)	2.54	2.86	2.64
F_B (Hz)	3.37	3.59	3.61

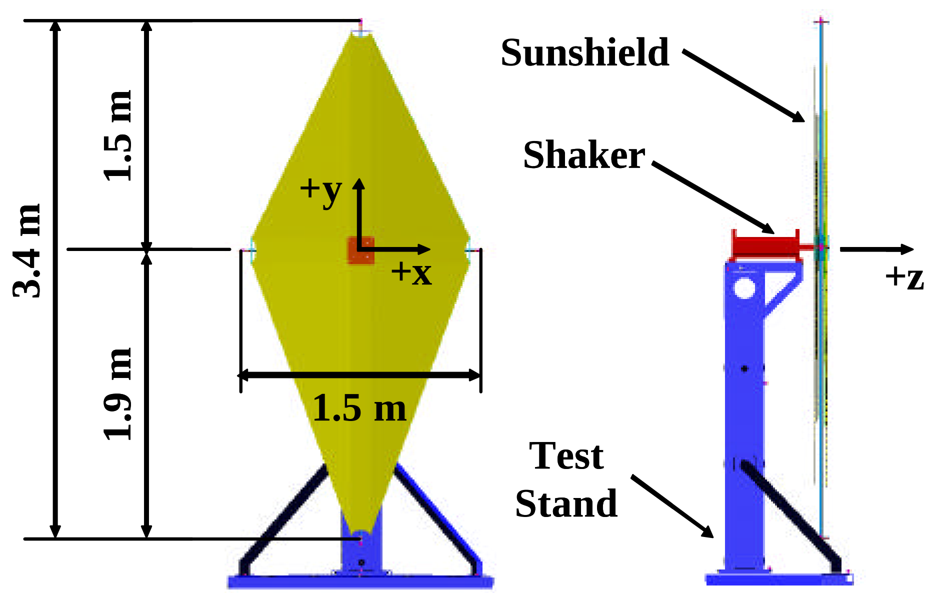
<u>Note:</u>
Mode 0: First mode
Mode 1: First significant mode
Mode A: Long side twist mode
Mode B: Mode w/ greatest EFFM

Mode Shapes For Dominant System Mode



Ground Tests

- Modal survey of sunshield carried out in vacuum.
- Four different configurations tested. Each configuration exhibited ~12 modes in 1-10 Hz range.
  - Fundamental modes of sunshield primarily involve outer edges of membrane.
  - Typically 2 dominant modes involving significant interaction between membranes and support tubes
- Testing details presented later this session : "Parametric Study of the Effect of Membrane Tension on Sunshield Dynamics," AIAA-2002-1459.



Comparison of Analysis and Ground Tests

Frequencies

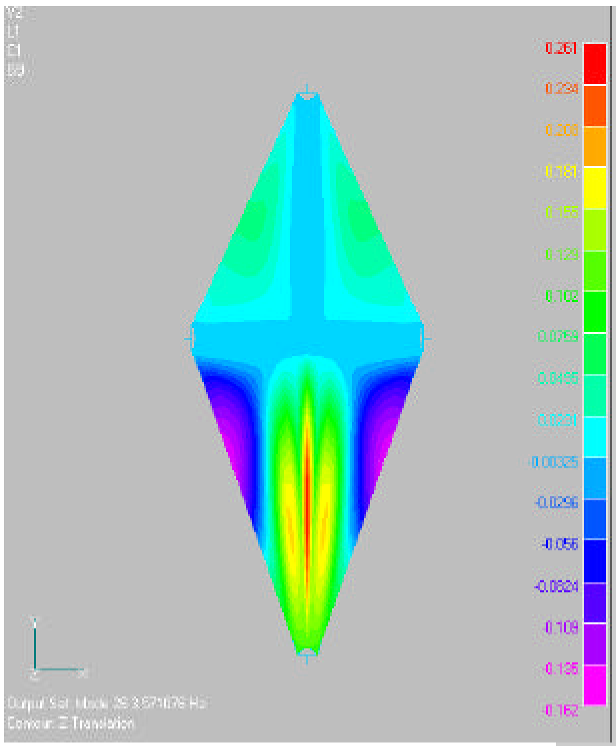
- Ground test analysis includes gravity loads and shaker support condition.
- Analysis / test correlation performed used modal assurance criteria (MAC) calculations from Dynaview software to identify mode pairs.
- In general, dominant system modes correlate better than low-frequency membrane modes.

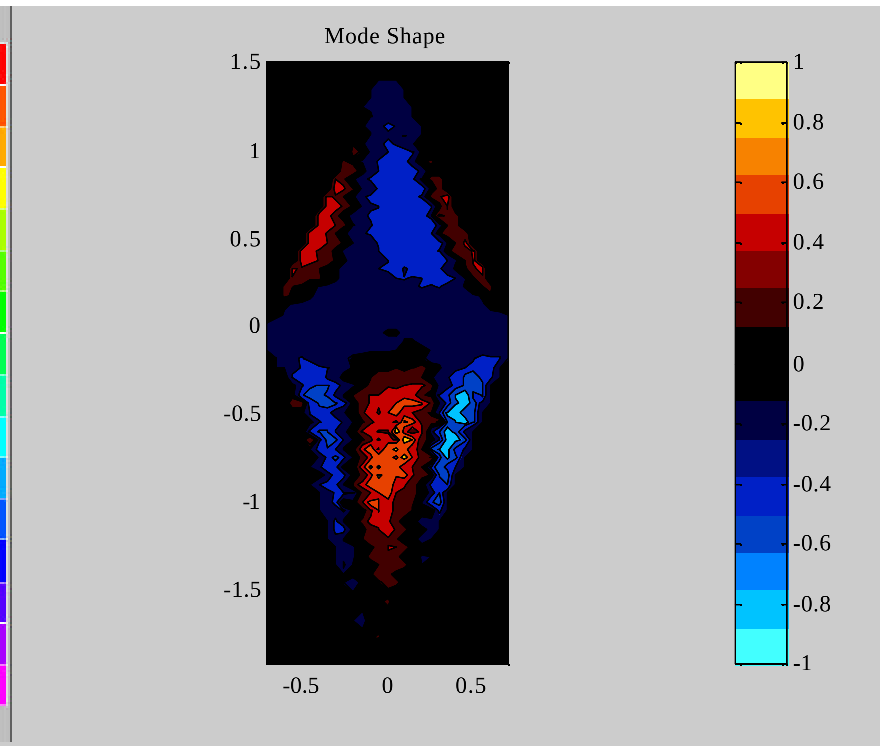
Configuration	Mode	Analysis	Test	% Diff
Tubes-LSD	LT	3.77	3.63	-3.8
	MT	6.06	5.75	-5.4
Tubes-SSD	LT	3.71	3.43	-8.2
	MT	6.10	5.92	-3.1
SS-CFS1-LSD	LT	3.57	3.35	-6.6
	MT	5.51	5.51	0.0
SS-CFS1-SSD	LT	3.54	3.21	-10.3
	MT	6.36	5.83	-9.1
SS-CFS2-LSD	LT	3.22	3.22	0.0
	MT	6.44	5.57	-15.6
SS-CFS3-LSD	LT	3.55	3.21	-10.6
	MT	5.65	5.85	3.4

Comparison of Analysis and Ground Tests

Mode Shapes

Dominant System Mode for CFS1 - Long Side Down Configuration





Analysis = 3.57 Hz

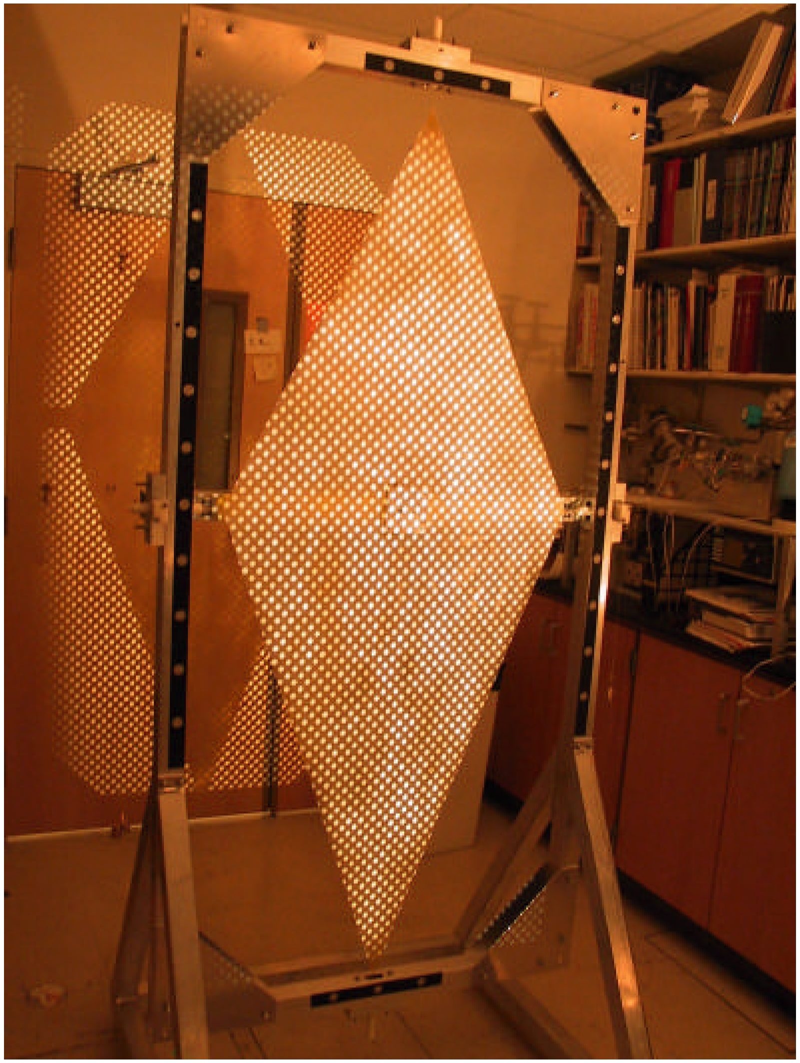
Test = 3.34 Hz

Closing Remarks

- Finite element analysis was used to predict the structural dynamic behavior of a one-tenth scale model of the NGST ‘yardstick’ concept sunshield.
  - Membranes modeled using membrane elements in conjunction with a ‘wrinkling’ material model.
  - Comparison of analytical predictions and test results showed good agreement for dominant system modes, but only fair agreement for fundamental membrane modes.
  - Predictions from the wrinkled membrane model show better agreement with test results than shell element and cable network models.

- Current / Future Work:
  - Model updating study for one-tenth scale model sunshield.
  - Analytical/Experimental Study of Sunshield Membrane Wrinkling
  - Application of wrinkled membrane modeling technique to the study of sunshield concepts developed by the NGST prime contractor.

Sunshield Wrinkling Experiment



1/20th Scale Yardstick Sunshield Membrane Test at James Madison University