EXPLORING ELEMENTS THAT OBSTRUCT THE SUCCESSFUL DEPLOYMENT OF PUMPKIN BALLOONS

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Finite Element Modeling Continuous Improvement

FEMCI Workshop 2004

NASA Goddard Space Flight Center

Greenbelt, MD

May 6, 2004

*Supported in part by NASA Award NAG5-5353

Consider two self-deploying structures

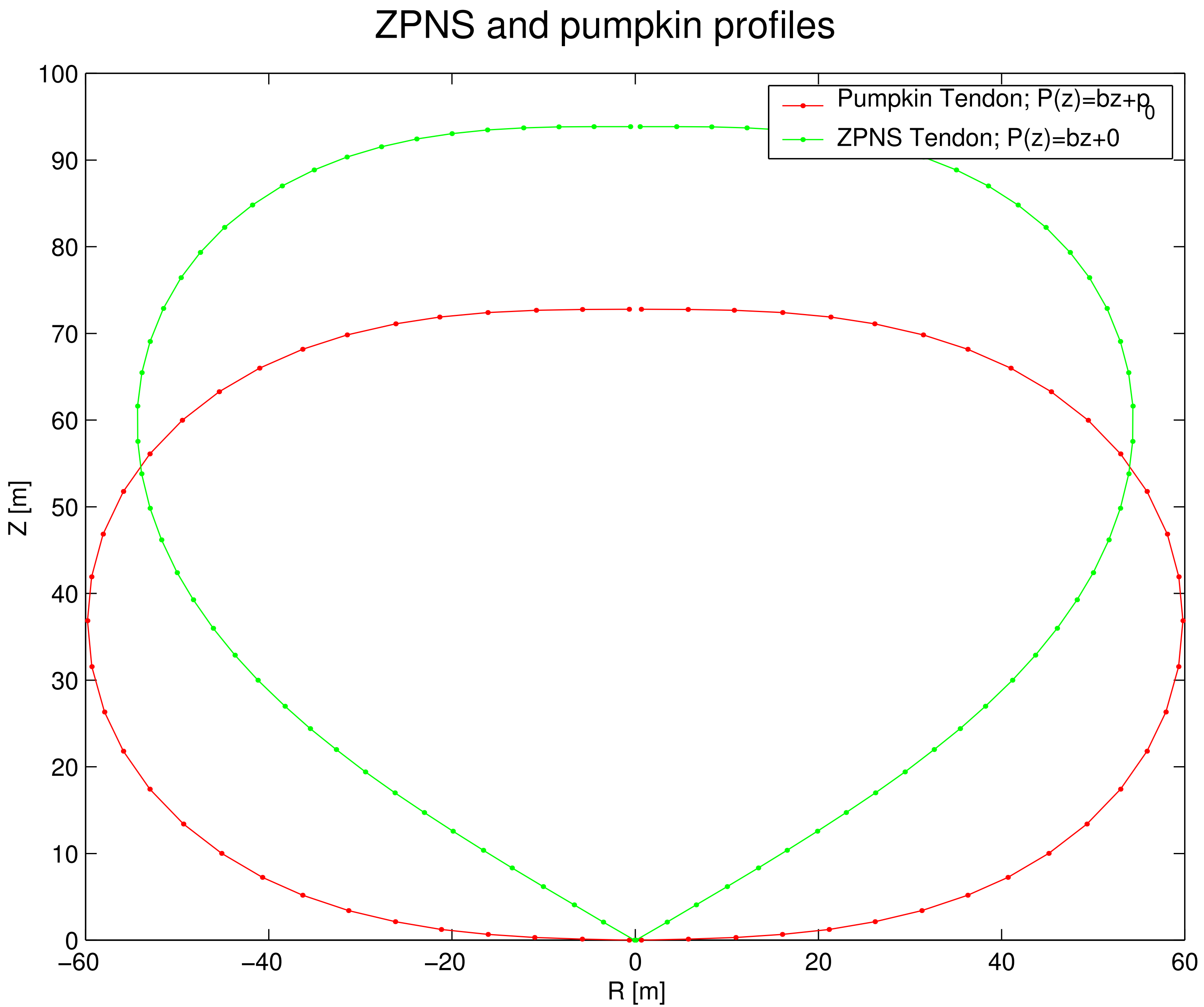
1. The *zero-pressure natural shape balloon* (ZPNS)
   (a) Flown by NASA since the 1970s
   (b) Free of deployment problems
2. The *pumpkin balloon* (still in development)
   (a) New design for NASA's Ultra Long Duration Balloon (ULDB)
   (b) Deployment problems on a number of flights

Problem: Improper deployment - balloon may not achieve the design altitude; film stress resultant levels could be many times greater than expected by the design, and ultimately lead to a failure of the balloon envelope.

Approach: Use a finite element representation of the balloon and an optimization-based solution process to explore conditions that must be present for proper deployment and those that favor flawed deployment.

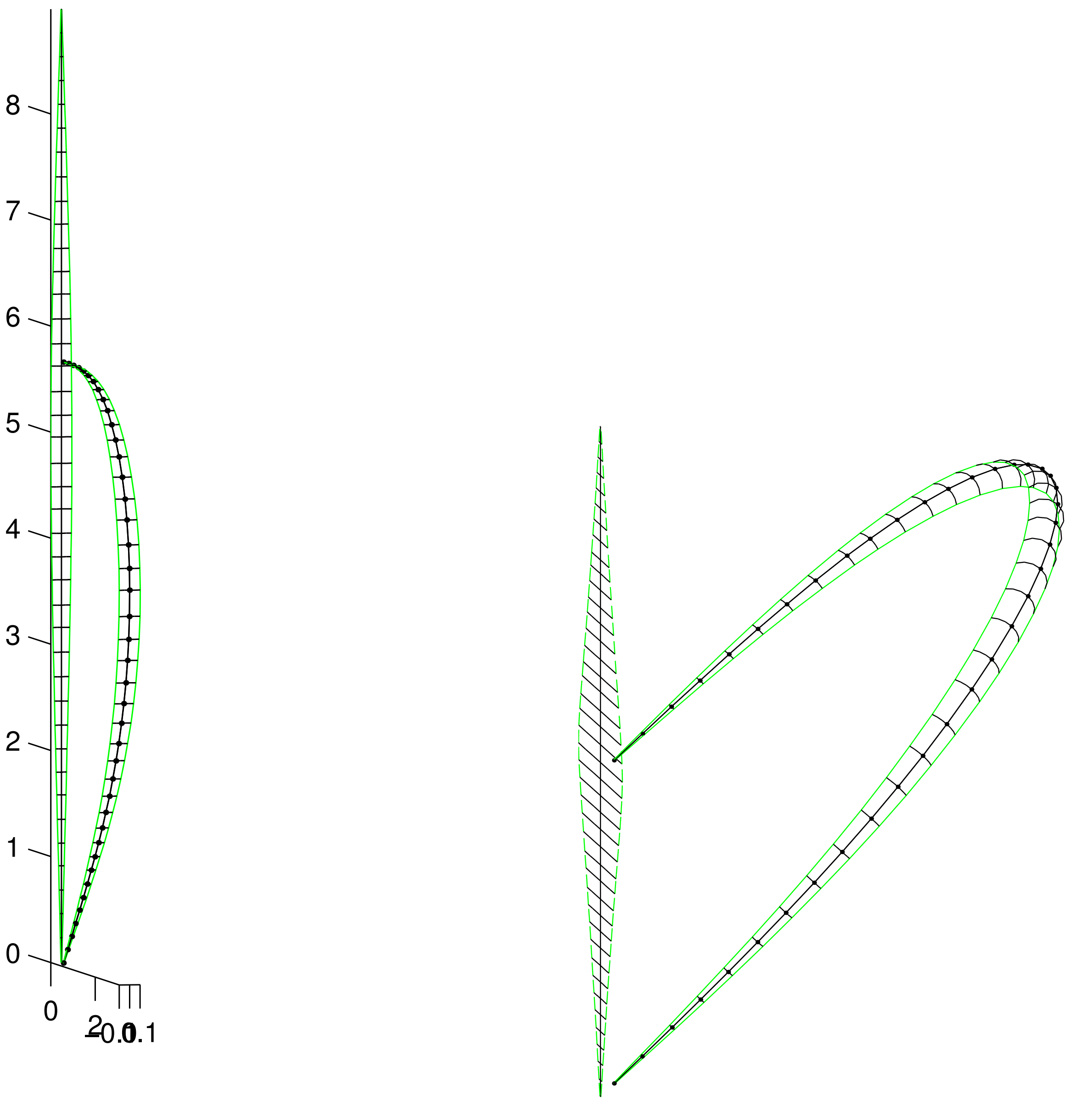
Goal: Provide reliable design guidelines

ZPNS and Pumpkin Balloon Designs


ZPNS and pumpkin profiles
Pumpkin Tendon; P(z)=bz+p0
ZPNS Tendon; P(z)=bz+0
Z [m]
R [m]
100
90
80
70
60
50
40
30
20
10
0
−60
−40
−20
0
20
40
60

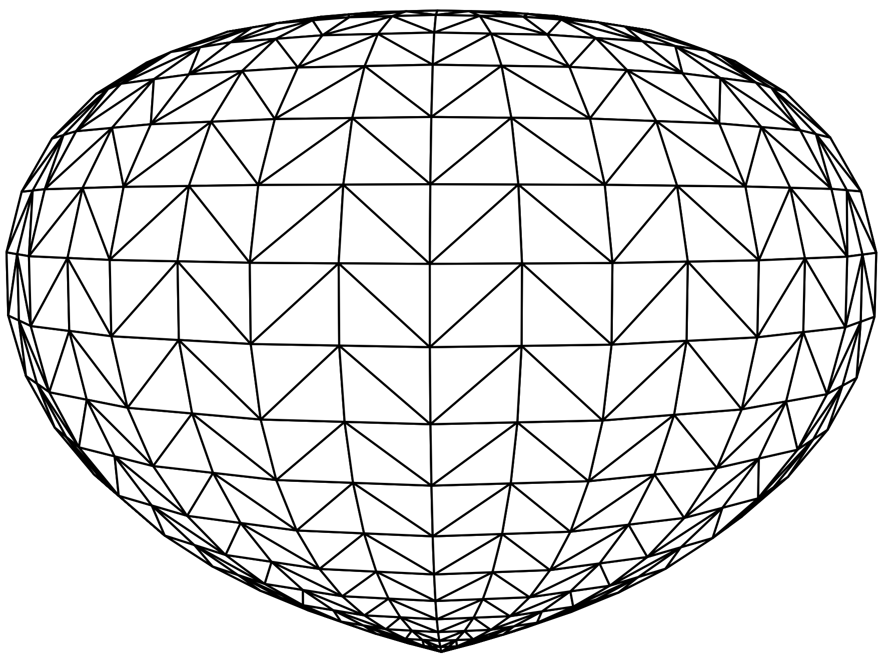
Theoretical gore with lay-flat pattern.

(a) ZPNS (developable surface)   (b) Pumpkin (doubly-curved wrinkled).

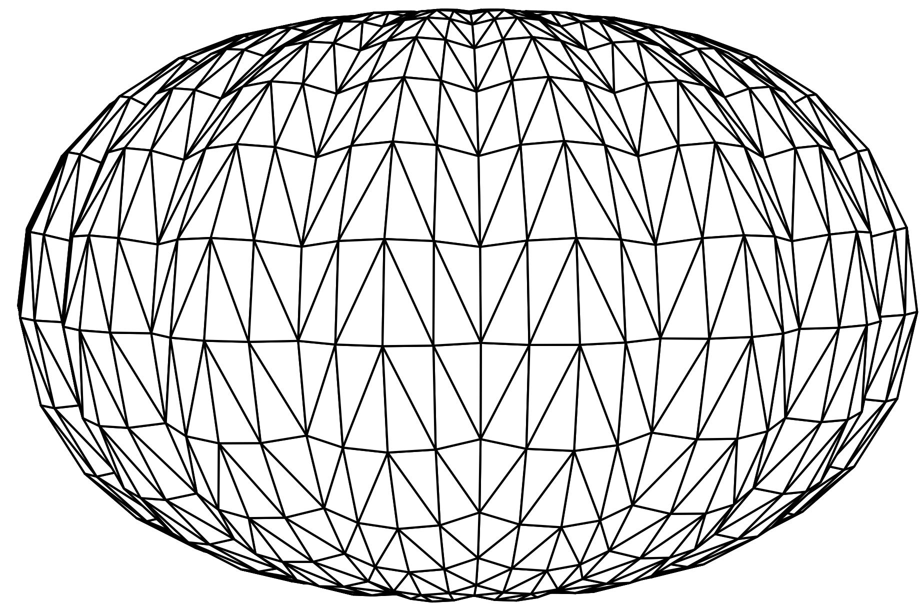


Finite element representations of high altitude balloons

(a) ZPNS



(b) Pumpkin



Finite Element Balloon Model
Optimization-Based Solver

Find the balloon shape $\underline{\mathcal{S}} \in \mathcal{C}$ that solves $\min\limits_{\mathcal{S}\in\mathcal{C}} \mathcal{E}(\mathcal{S})$

$$\mathcal{E}(\mathcal{S}) = E_{gas}(\mathcal{S}) + E_{film}(\mathcal{S}) + E_{tend}(\mathcal{S}) + E_{top} + S^*_{tend}(\mathcal{S}) + S^*_{film}(\mathcal{S})$$

Hydrostatic Pressure: $E_{gas}(\mathcal{S}) = -\int_{\mathcal{S}} (\frac{1}{2}bz^2 + p_0 z)\mathbf{k} \cdot d\vec{S},$

Film Wt: $E_{film}(\mathcal{S}) = \int_{\mathcal{S}} w_f z dA,$

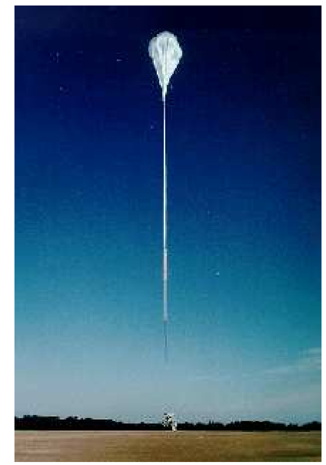
Tendon Wt: $E_t(\mathcal{S}) = \int_{\Gamma\in\mathcal{S}} w_t \tau(s) \cdot \mathbf{k}\ ds,$

Top Wt: $E_{top} = w_{top} z_{top},$

Film Strain: $S^*_{film}(\mathcal{S}) = \int_{\mathcal{S}} W^*_f\, dA,$
(includes wrinkling)

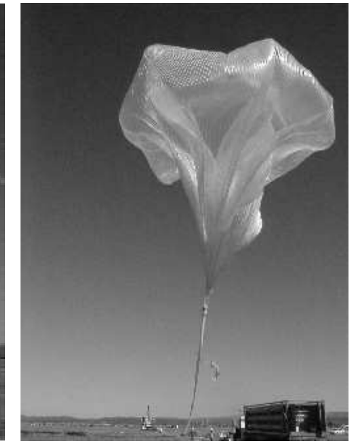
Tendon Strain: $S^*_t(\mathcal{S}) = \int_{\Gamma\in\mathcal{S}} W^*_t(\varepsilon) ds.$
(slack or foreshortened tendons)

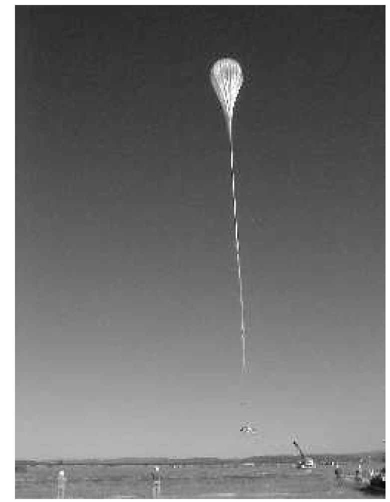
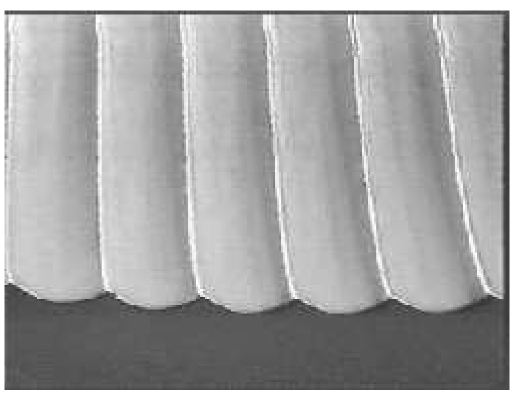
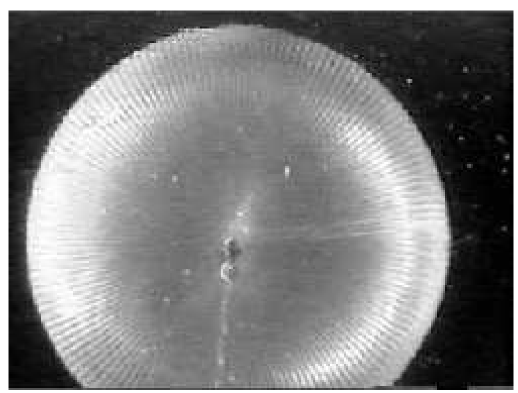
Typical ZPNS Mission



A Pumpkin Mission





See NASA BPO:
http://www.wff.nasa.gov/ code820/

Pumpkin Pictures from a Telescope

Cleft (?)

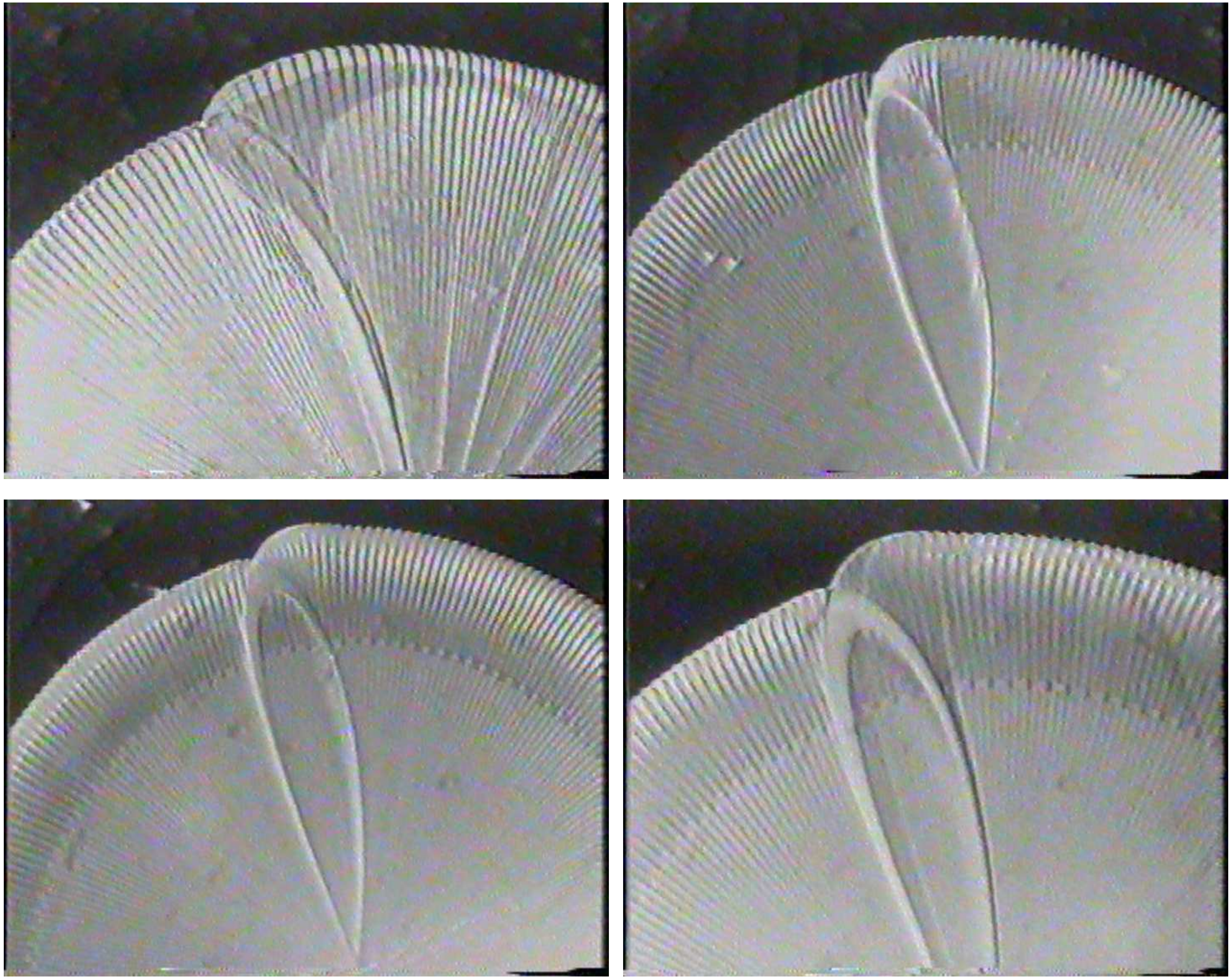
OK (?)

Clefting in Flight 517

Features of Flight 517 Cleft

- Cleft was observed in the launch configuration
- Cleft persisted through ascent phase
- Cleft was maintained once float altitude was achieved and balloon was fully pressurized

Flight 517 Cleft



⋆ - Photographs provided by NASA Balloon Program Office.

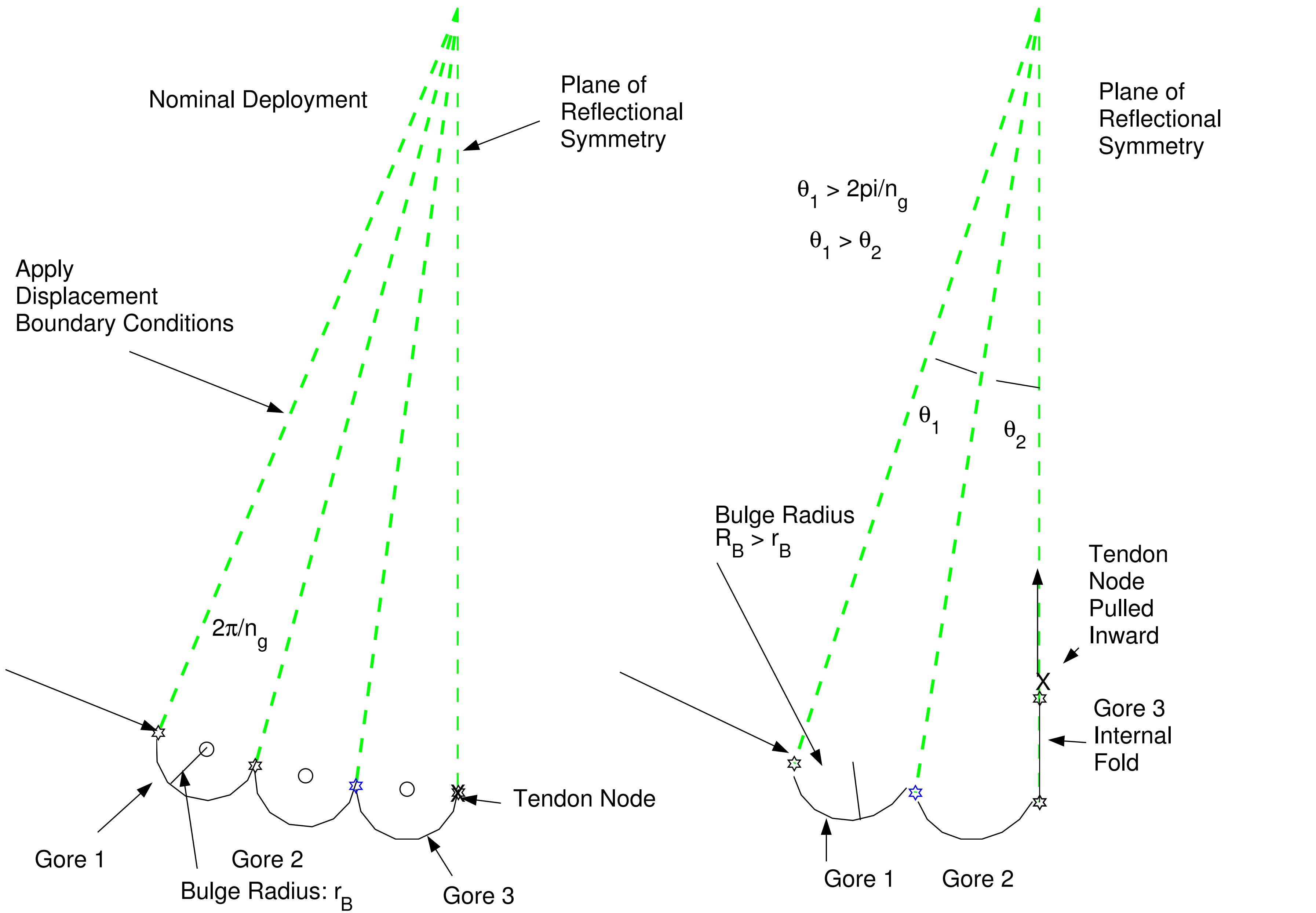
Questions

- Is clefting an inherent problem with large pumpkin balloons?
- Is clefting due to a mechanical locking that prevents proper deployment?
- Given a balloon design, can we predict if an undesirable equilibrium is likely to occur?

Observations

Experiments with small balloons and experience with test flights involving large balloons suggest increasing the number of gores increases the chance of improper deployment

Schematic for inducing a cleft



Sensitivity with respect to variation in N
N-number of gores

ZPNS studies

$p_0 = 0$ Pa, 0% - load tape slackness assumed, no volume constraint

N	$\alpha(N)$ [deg]	$\mathcal{E}_T$ [MJ]	$\max \delta_1$ m/m	$\hat{\delta}_1$ m/m	$\max \mu_1$ [N/m]	V/N [m^3]	$(\max r, \max z)$ [m,m]
294	1.22	-1.651	0.00277	0.00115	50	1939	(55.50, 97.37)
290	1.24	-1.664	0.00321	0.00149	62	1962	(55.51, 97.35)
286	1.26	-1.666	0.00621	0.00192	434	1976	(55.19, 99.25)

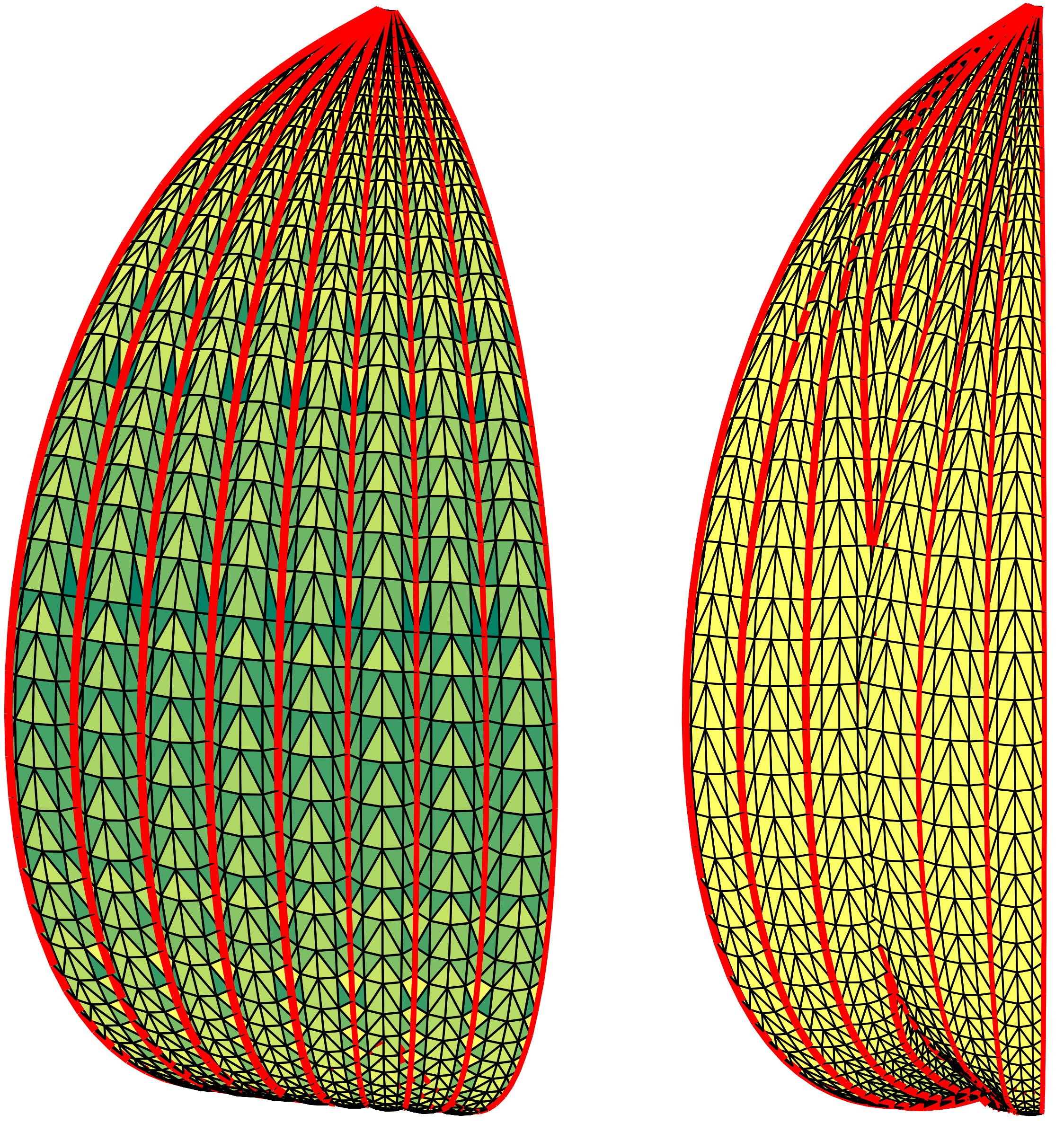
Pumpkin studies

$p_0 = 170$ Pa, $r_B = 0.786$ m, Tendon/film lack-of-fit $+ 0.8\%$ tendon foreshortening

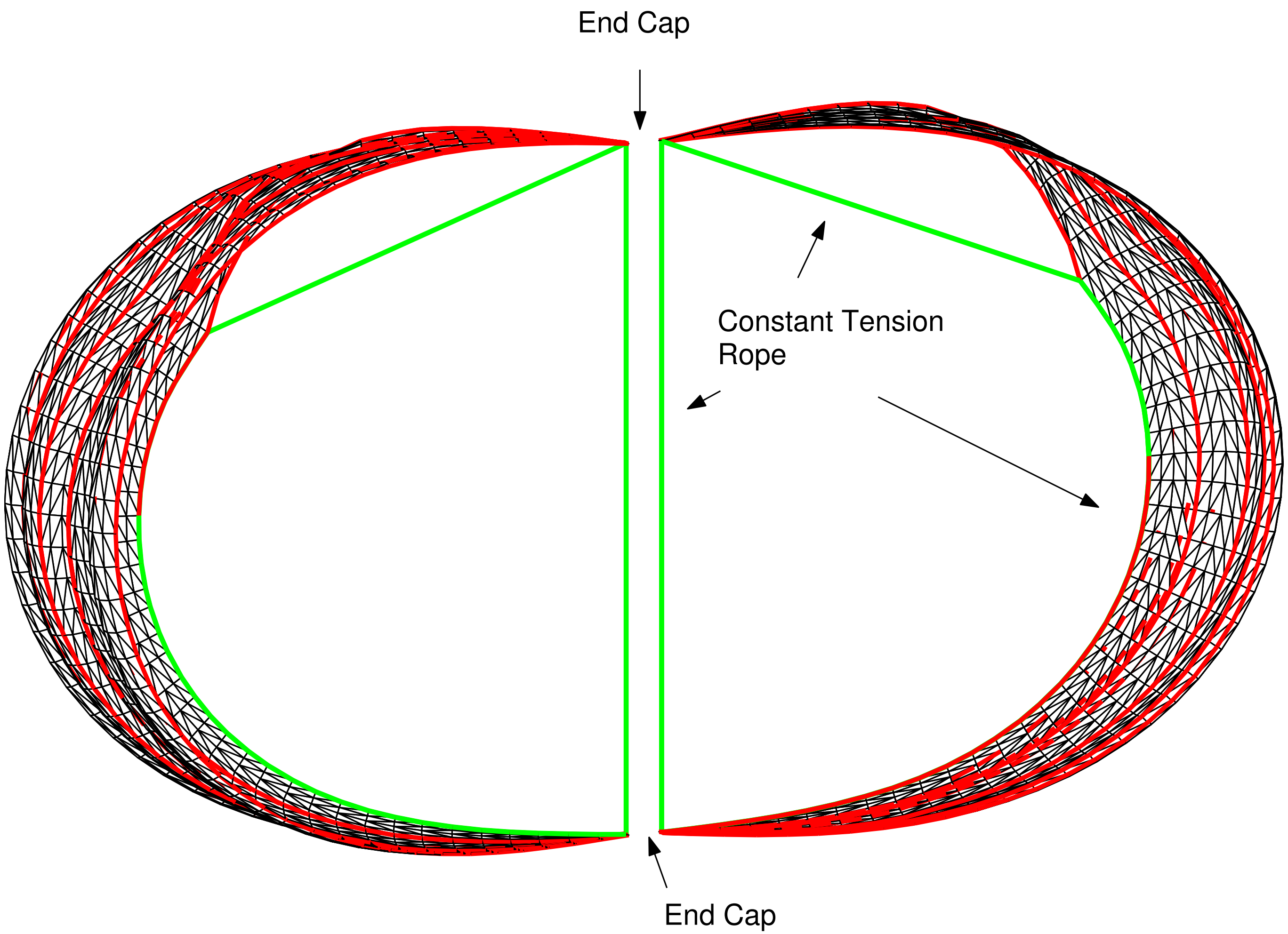
N	$\alpha(N)$ [deg]	$\mathcal{E}_T$ [MJ]	$\max \delta_1$ m/m	$\hat{\delta}_1$ m/m	$\max \mu_1$ [N/m]	$\triangle p_0$ [Pa]	V/N [m^3]	$(\max r, \max z)$ [m, m]
294	1.22	-99.09	0.0110	0.0061	169	0.4433	1993	$(59.81, 72.43)$
290	1.24	-99.07	0.0112	0.0065	173	0.0000	2020	$(59.80, 72.47)$
286	1.26	-99.06	0.0114	0.0071	176	0.6946	2049	$(59.79, 72.52)$
282	1.28	-99.03	0.0117	0.0085	252	1.8416	2078	$(59.78, 72.58)$

Finite element representation

(a) Eight fully deployed gores   (b) Eight gores with cleft



Encouraging the formation of a cleft



Green rope loops through pulleys located inside the balloon

(pulleys along load tendon and end caps).

Rope tension is 30 N (in previous slide $\approx$ 2.0 N).

Stability Analysis

Joint work with Ken Brakke, Susquehanna University

Let $\mathcal{E}(\mathbf{q})$ be the total energy of a balloon configuration $\mathcal{S}(\mathbf{q})$ with DOF: $\mathbf{q} = (q_1, q_2, \ldots, q_N)$.

The gradient of $\mathcal{E}$ evaluated at $\mathbf{q}$ is the $N \times 1$ vector

$$\nabla \mathcal{E}(\mathbf{q}) = \left[\frac{\partial \mathcal{E}}{\partial q_i}(\mathbf{q}) \right], i = 1, 2, \ldots, N,$$

The hessian of $\mathcal{E}$ evaluated at $\mathbf{q}$ is the $N \times N$ matrix,

$$H_{\mathcal{E}}(\mathbf{q}) = \left[\frac{\partial^2 \mathcal{E}}{\partial q_i \partial q_j}(\mathbf{q}) \right], \ \ i = 1, 2, \ldots, N, \ \ j = 1, 2, \ldots, N.$$

Definition

Let $\mathcal{S} = \mathcal{S}(\mathbf{q})$ be an equilibrium configuration.
$\mathcal{S}$ is *stable* if all the eigenvalues of $H_{\mathcal{E}}(\mathbf{q})$ are positive.
$\mathcal{S}$ is *unstable* if at least one eigenvalue of $H_{\mathcal{E}}(\mathbf{q})$ is negative.

Stability Case Studies using *Surface Evolver*

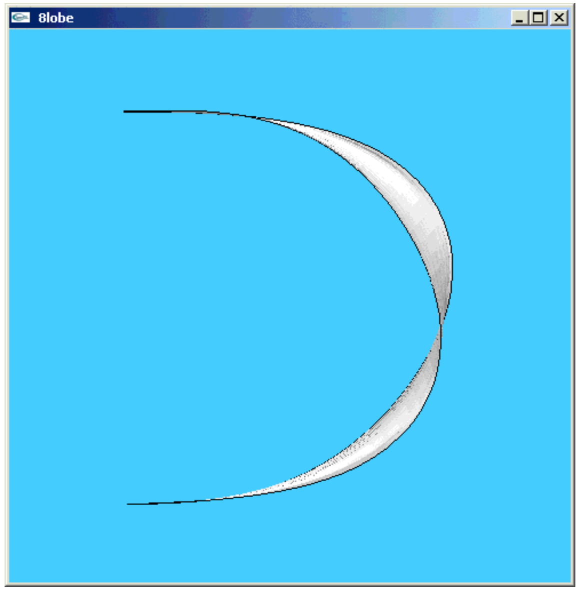
Summary

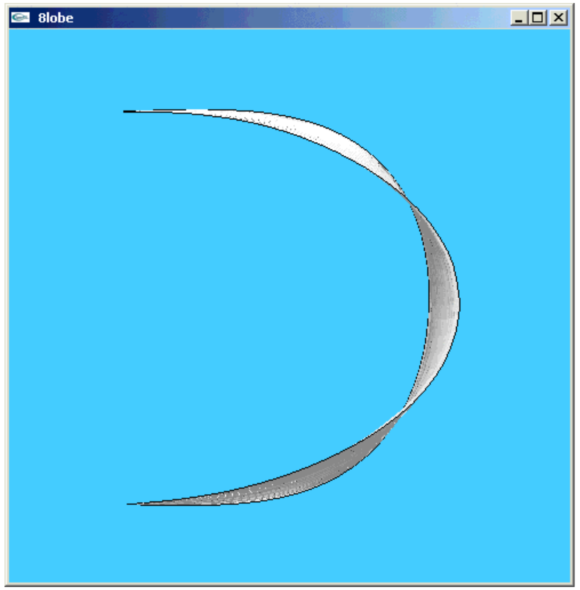
Design	Stability
Flight 517 Baseline	Unstable
Flight 517 Baseline, 9 gores removed	Stable
Flight 517 Baseline, molded gores	Stable
ZPNS comparable to 517 Baseline	Stable
96 gore, 6.6 meter diameter	Stable
96 gore design, 4 gores added	Unstable

What are the unstable modes?

Exaggerated Unstable Modes

(6.6 m diameter pumpkin)



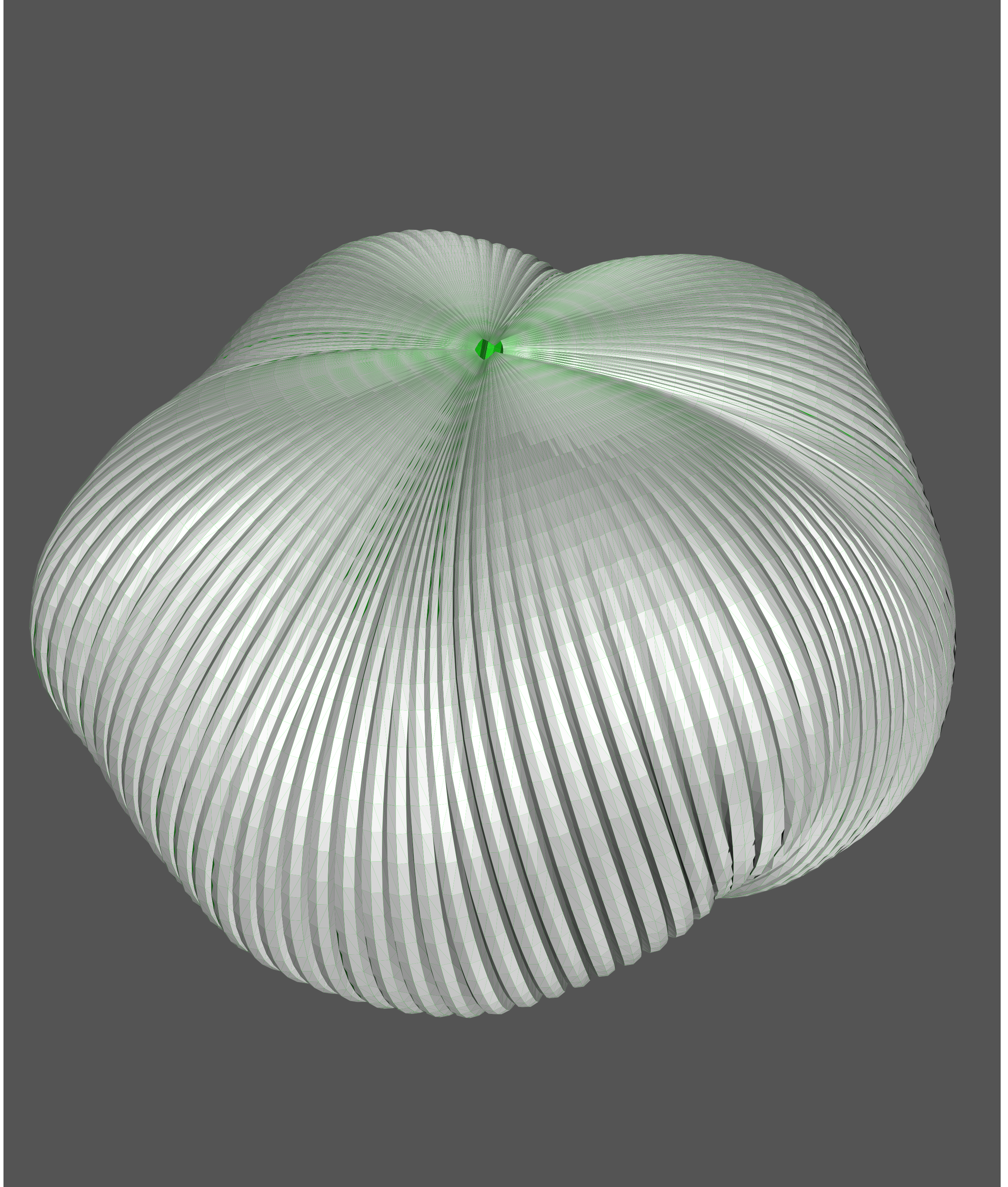


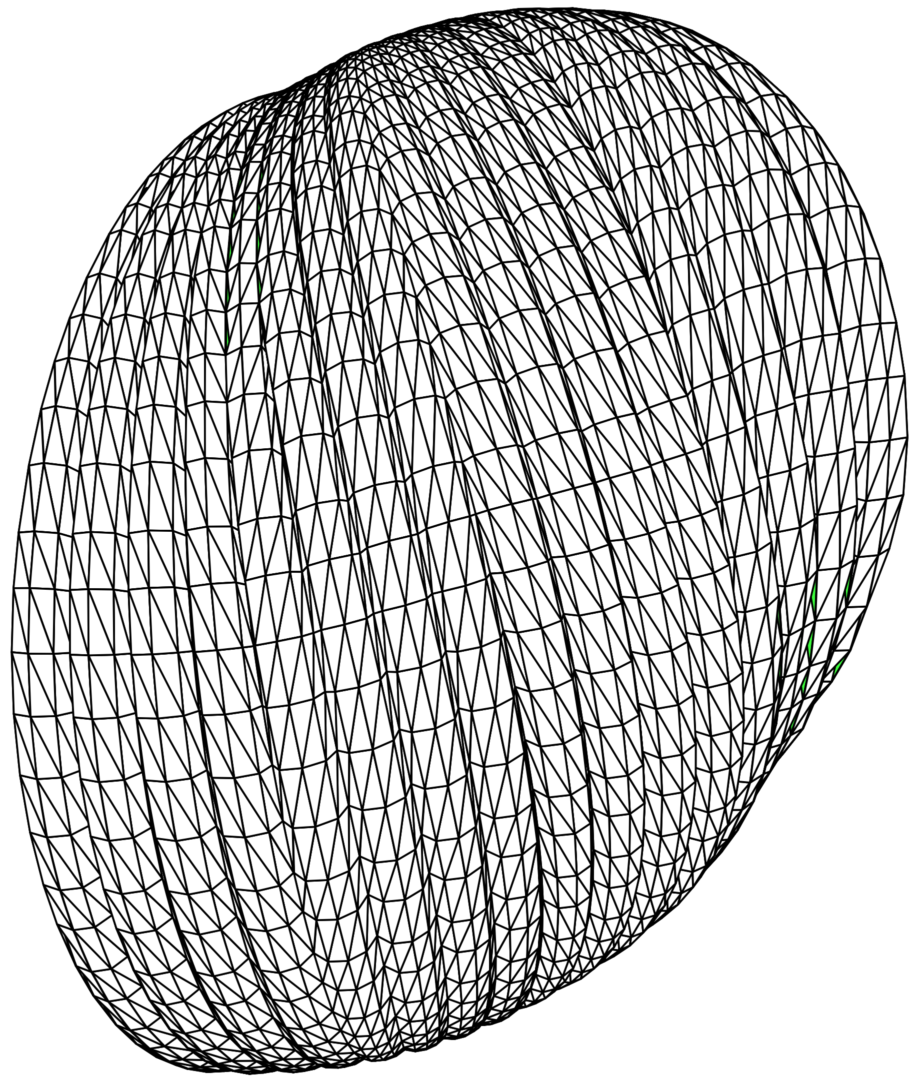
One-eighth of a 96 Gore Pumpkin with 4 Additional Gores

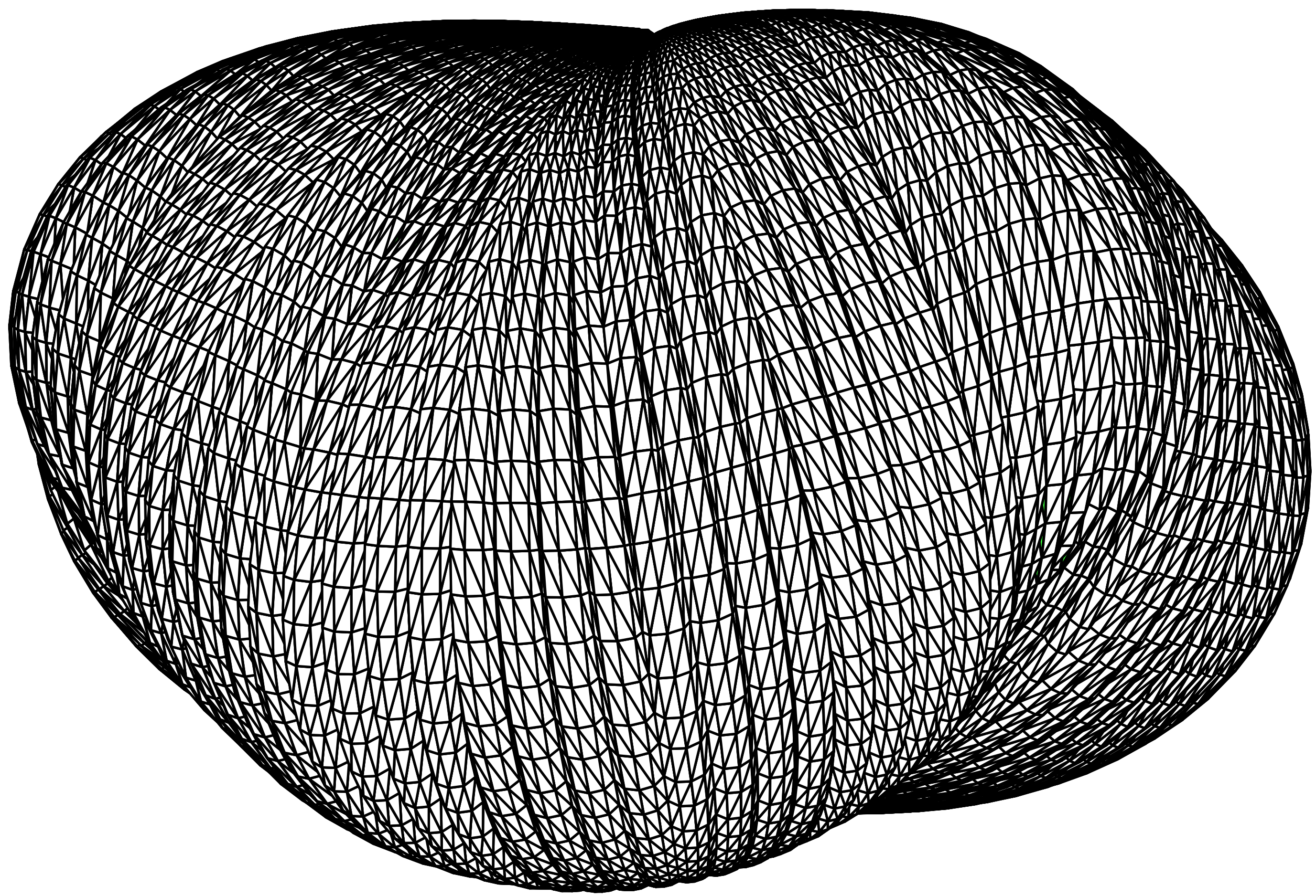
(without rope constraint, cleft pulls itself out)

An Unstable Equilibrium Configuration

Nominal 96 Gore Pumpkin with 32 Additional Gores







Summary

- Preliminary analysis suggests that our FE-balloon representation can model off-nominal shapes, including cleft-modes and other undesirable equilibria
- Variational formulation and optimization-based solution process works well

Future Work

Short Term

- Demonstrate analytical capability to predict/avoid clefting $\Longleftrightarrow$ Corroborate with test results on moderately sized pumpkin balloons
- Investigate the possibility for mechanical locking
- Continue stability analysis

Long Term

- Provide reliable design guidelines