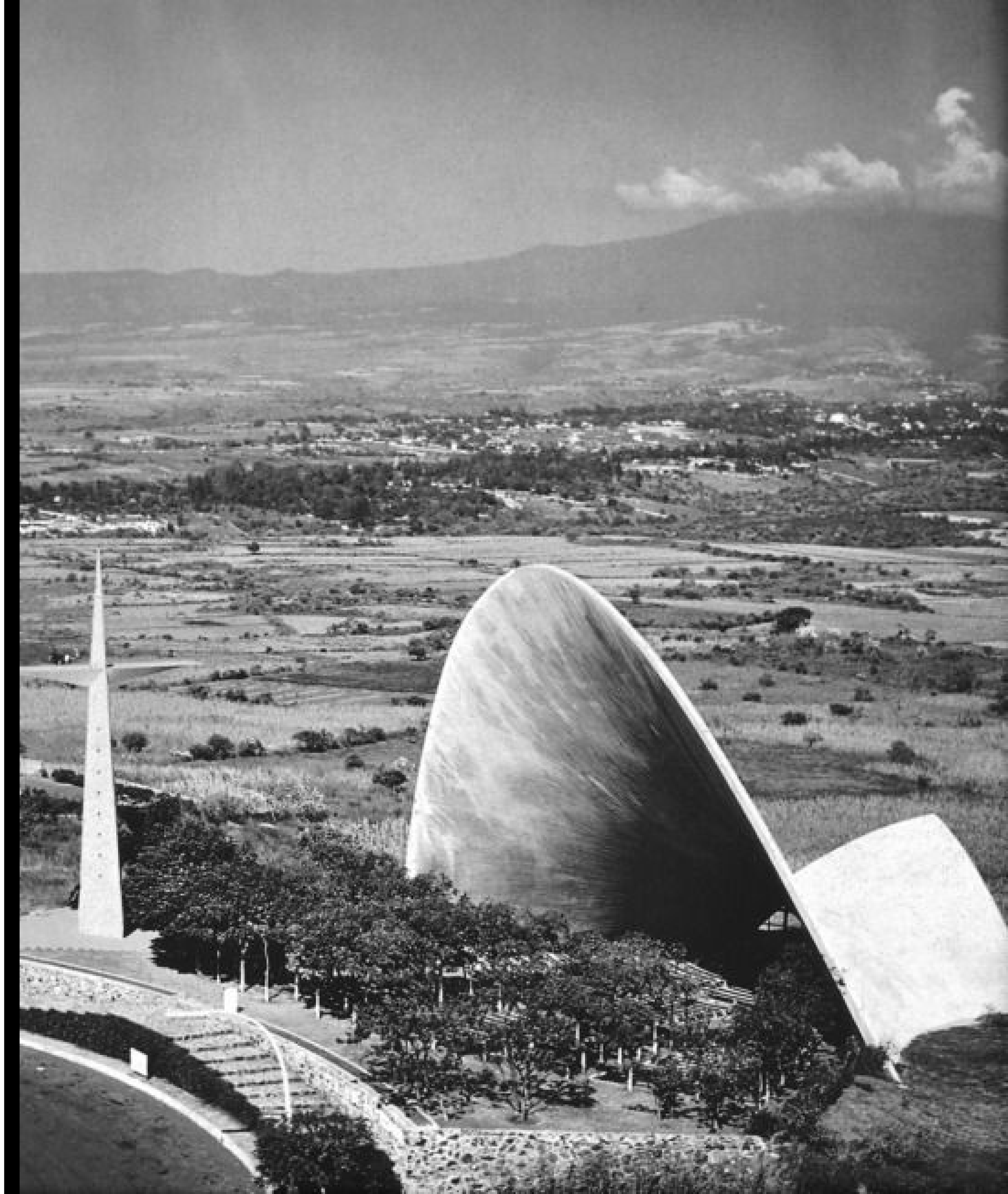
ANSEL MAN

SENIOR PORTFOLIO
ARCE 453
ED SALIKLIS



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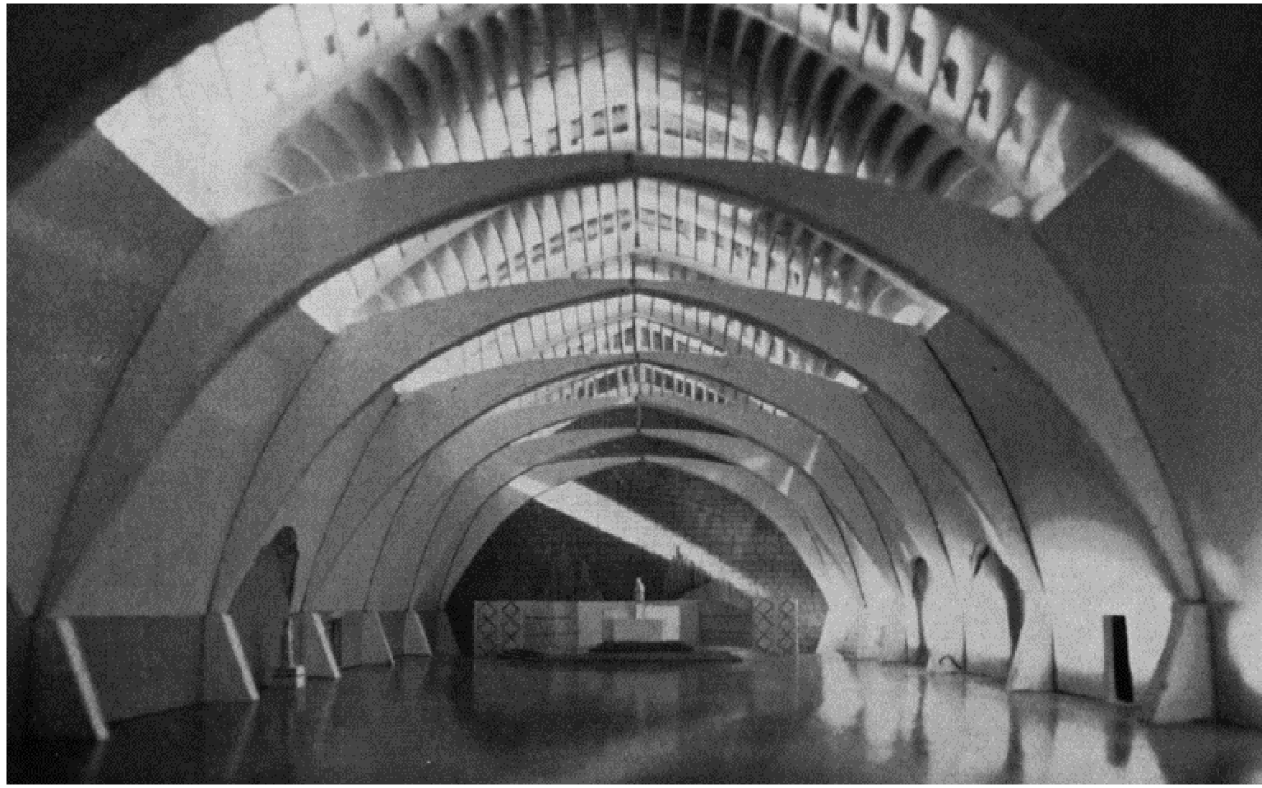
FORM-FINDING EXERCISE
ENRICO CASTIGLIONI'S THREE-HINGED ARCHES



Castiglioni's conceptual design for a church in Montecatini, Italy (Note the "concealed" upper set of arches stacked on top of the lower set)

What is form-finding?

Form-finding is an iterative process through which the form of a structure is optimized.

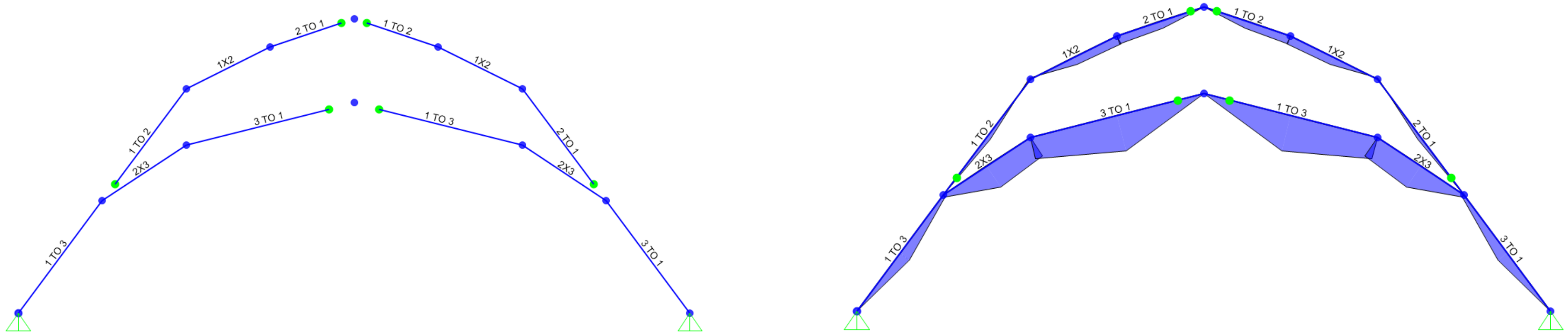
Within each iteration, the existing shape is subjected to various loads; the resulting *moment envelope* is used as the basis for the next iteration.

The next iteration does not need to match the shape of the moment envelope; it simply needs to *encompass* it.

Undeformed Shape | BMD

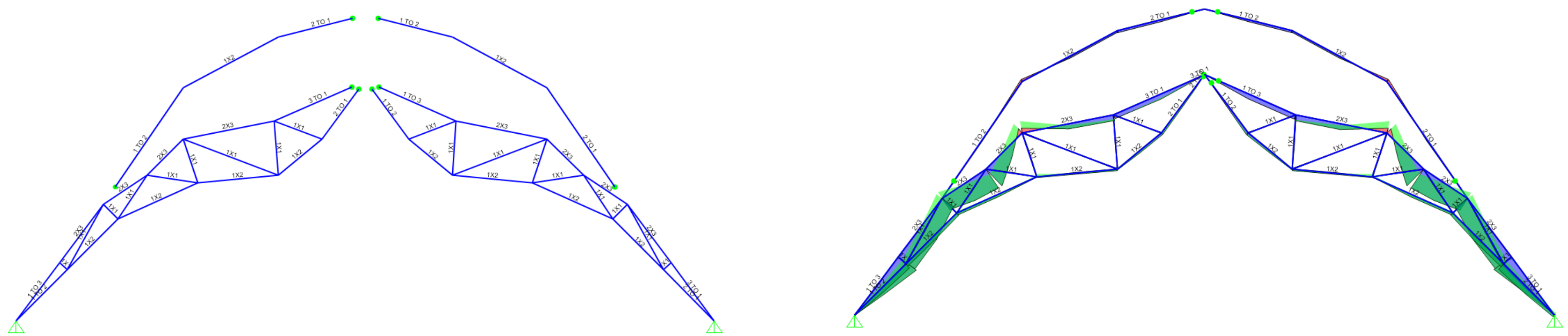
1ST ITERATION

Upper arch 'resting' on the shoulders of the lower arch



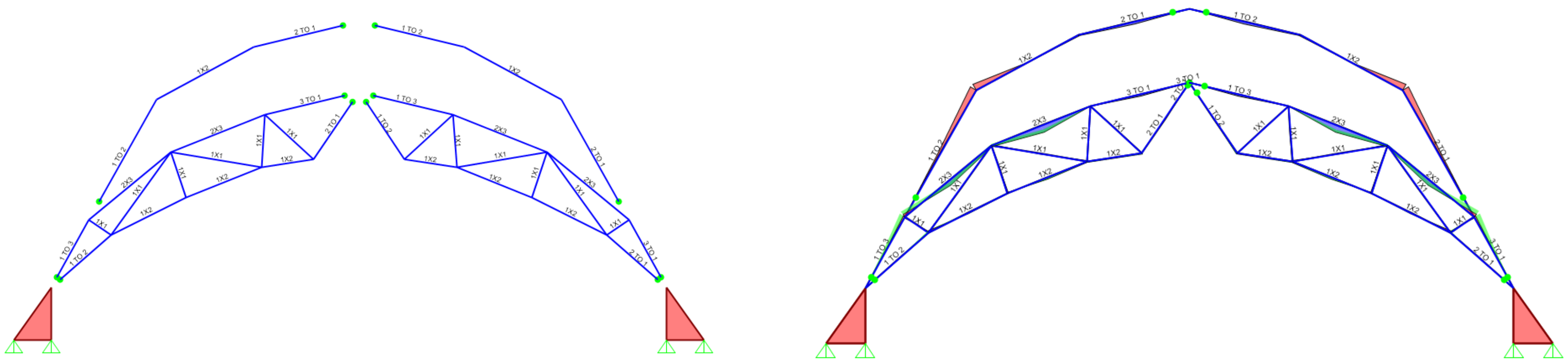
2ND ITERATION

Trusses developed via form finding to resist flexure due to gravity/lateral forces

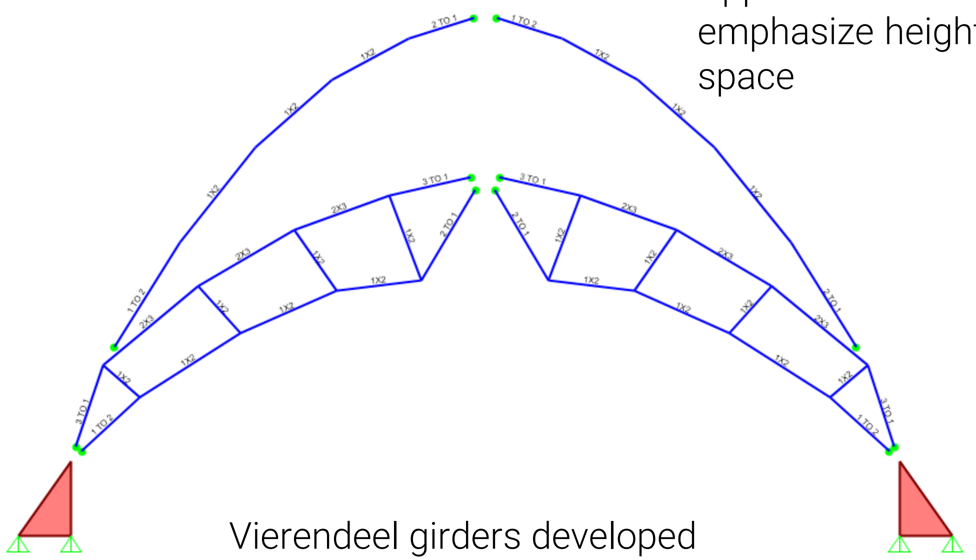


3RD ITERATION

Refinement of truss and connection to ground

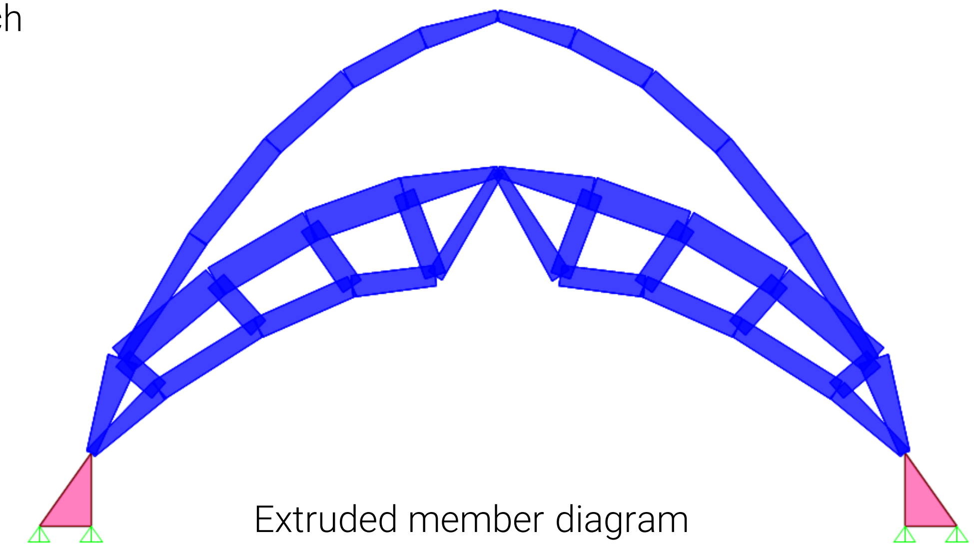


FINAL [*OPTIMIZED*] ITERATION

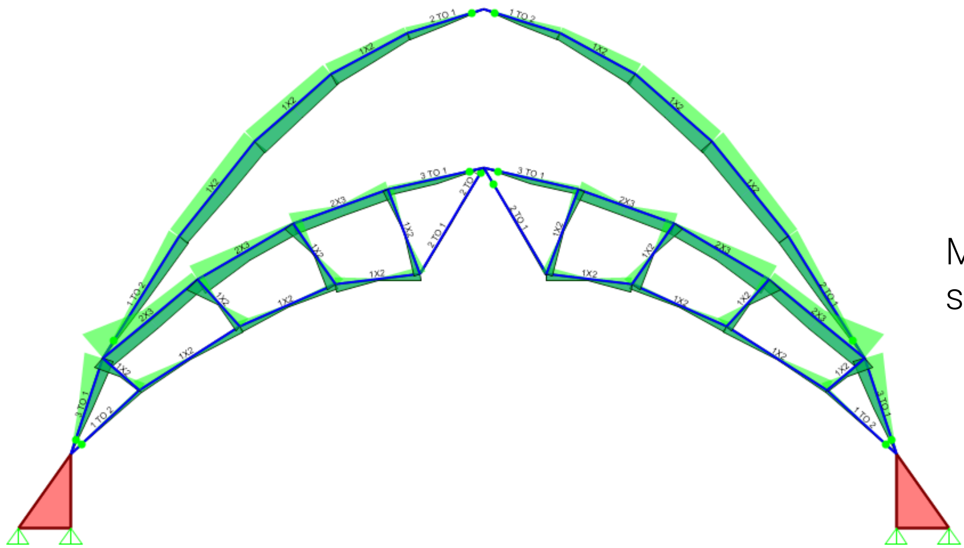


Upper arch modified to emphasize height of church space

Vierendeel girders developed to preserve openness of space



Extruded member diagram highlighting tapered concrete members



Moment envelope from self-weight and seismic inertial forces in both directions

MÜLLER-BRESLAU EXERCISE

Heinrich Müller-Breslau, the German civil engineer who conceived the Müller-Breslau method

THE POWER OF THE MÜLLER-BRESLAU METHOD

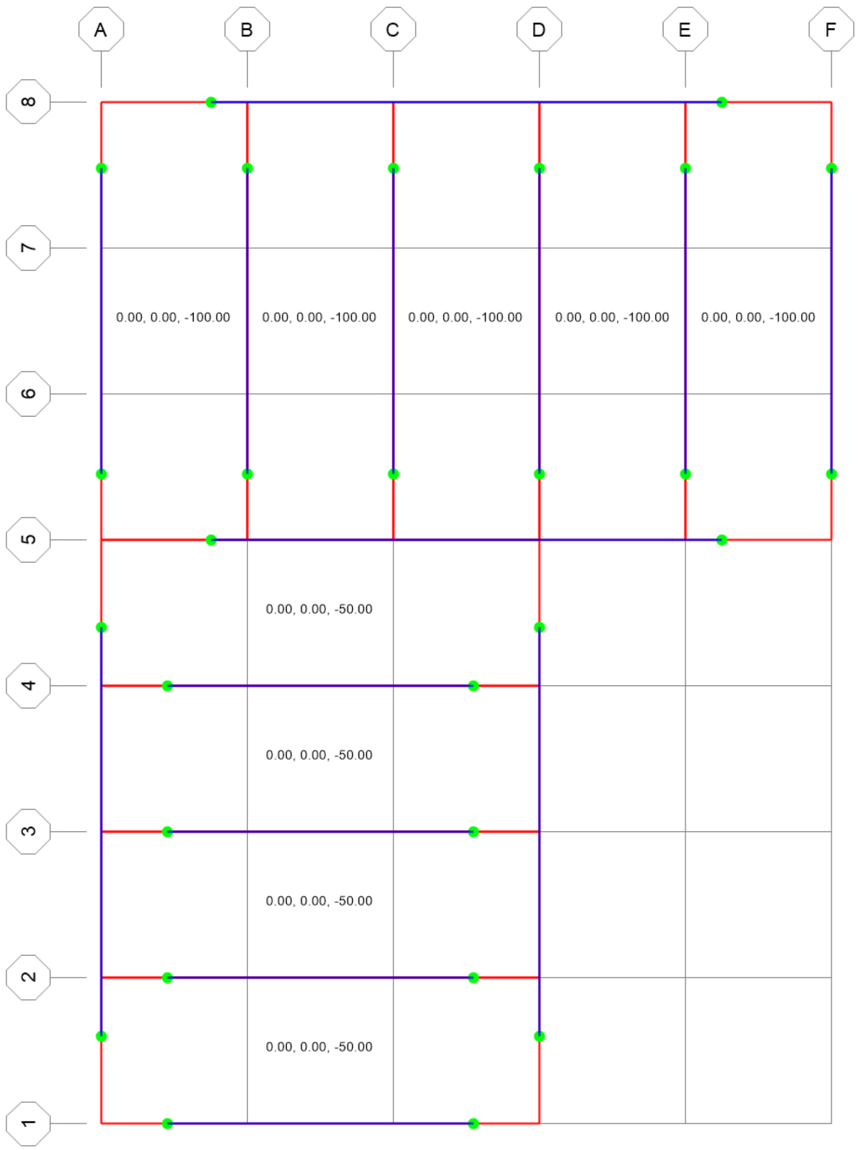
Using influence lines and pure geometry, this method can be used to solve for ANY reaction or internal shear/moment in ANY system of beams and columns

FUNDAMENTALS:

1. Remove constraints of the unknown at the point of interest
2. Rest of beam shall be infinitely rigid, behaving like a straight line rotating about its support
3. Loft or rotate by a unit amount
4. Enforce all other boundary conditions

MÜLLER-BRESLAU METHOD

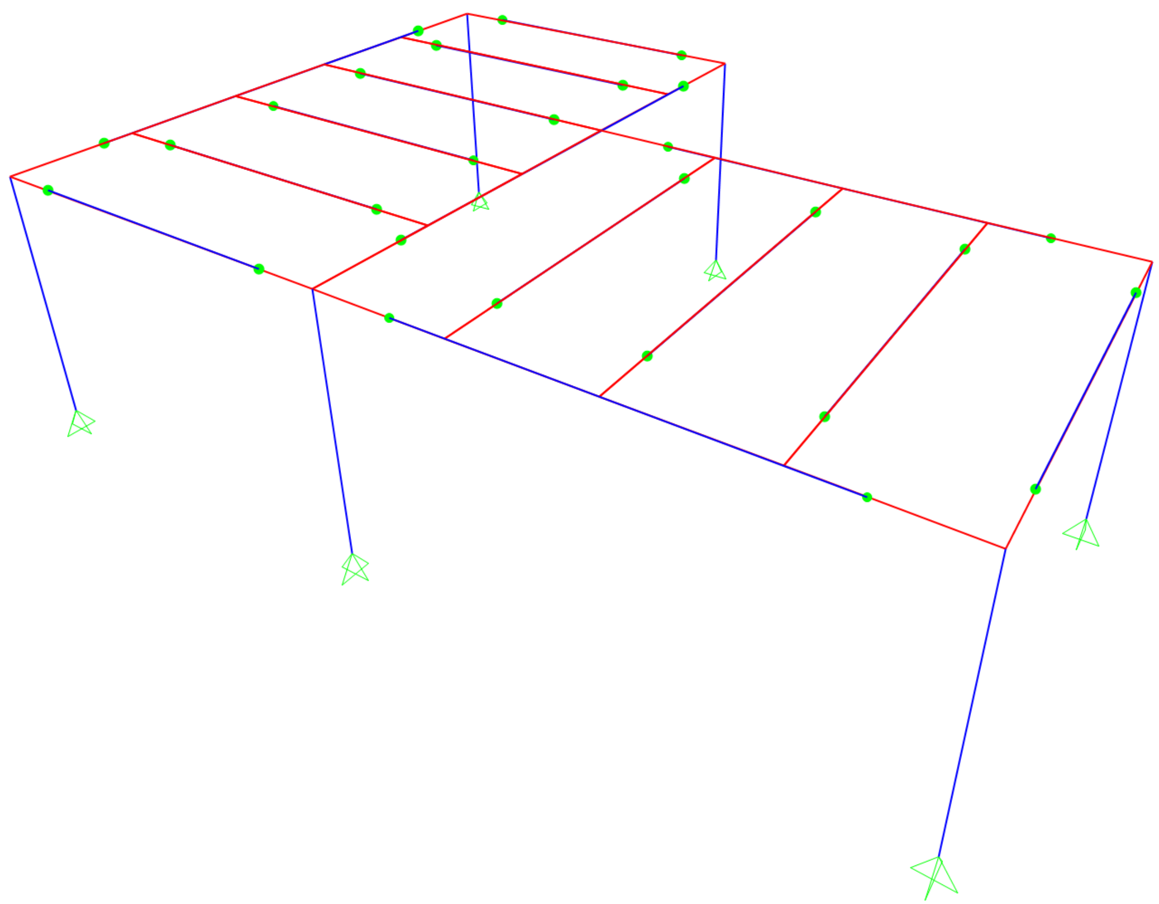
ANALYSIS OF DETERMINATE BEAM SYSTEM



Grid lines = 5' typ.

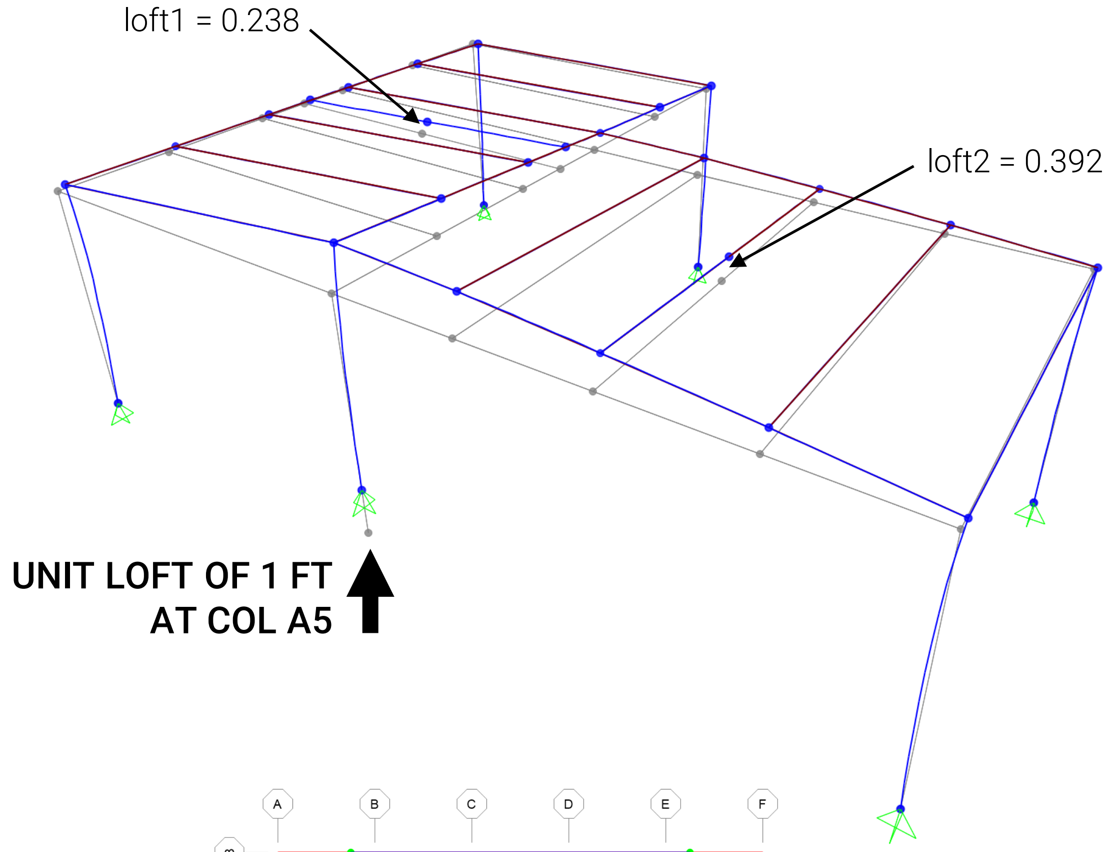
Upper Area Load = 100 psf

Lower Area Load = 50 psf



MÜLLER-BRESLAU METHOD

ANALYSIS OF DETERMINATE BEAM SYSTEM

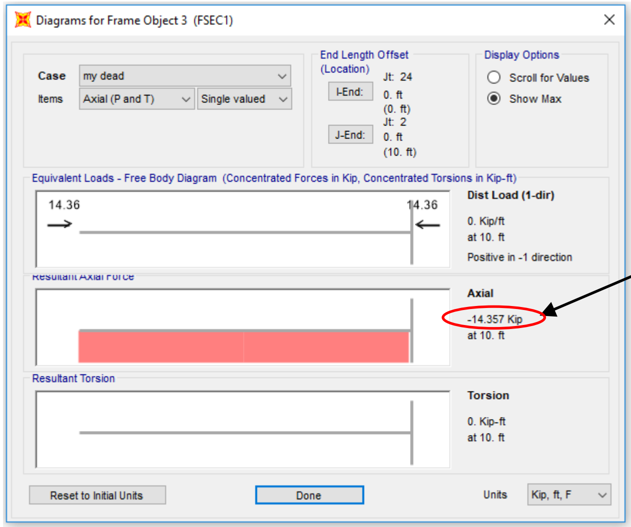


COLUMN REACTION AT A5

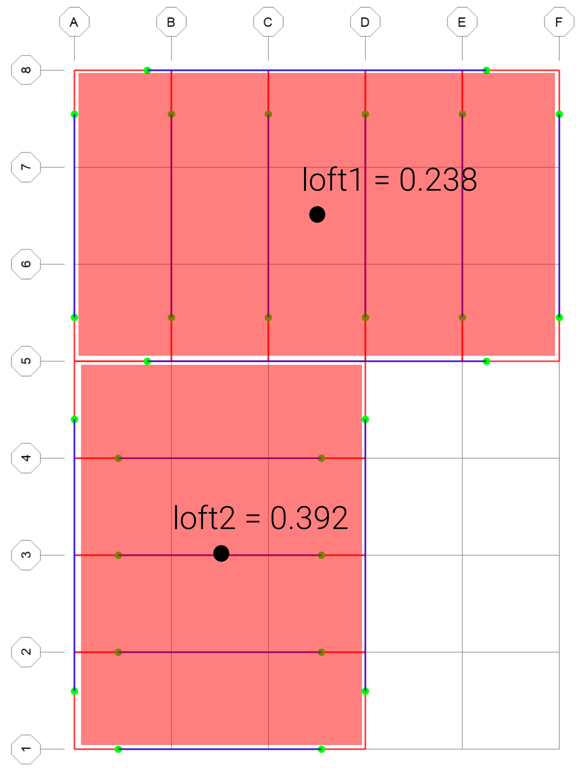
$$Rxn = \Sigma(area\ load * area * loft)$$

```
>>
areaLoad1 = 100; %psf
area1 = 25*15; %sq ft
loft1 = 0.238;

areaLoad2 = 50; %psf
area2 = 15*20; %sq ft
loft2 = 0.392;

Rxn = (areaLoad1*area1*loft1+areaLoad2*area2*loft2)/1000 %kips

Rxn =

   14.8050
```

"Müller-Breslau" Rxn = 14.81 kips



"Actual" Rxn = 14.36 kips



MÜLLER-BRESLAU METHOD

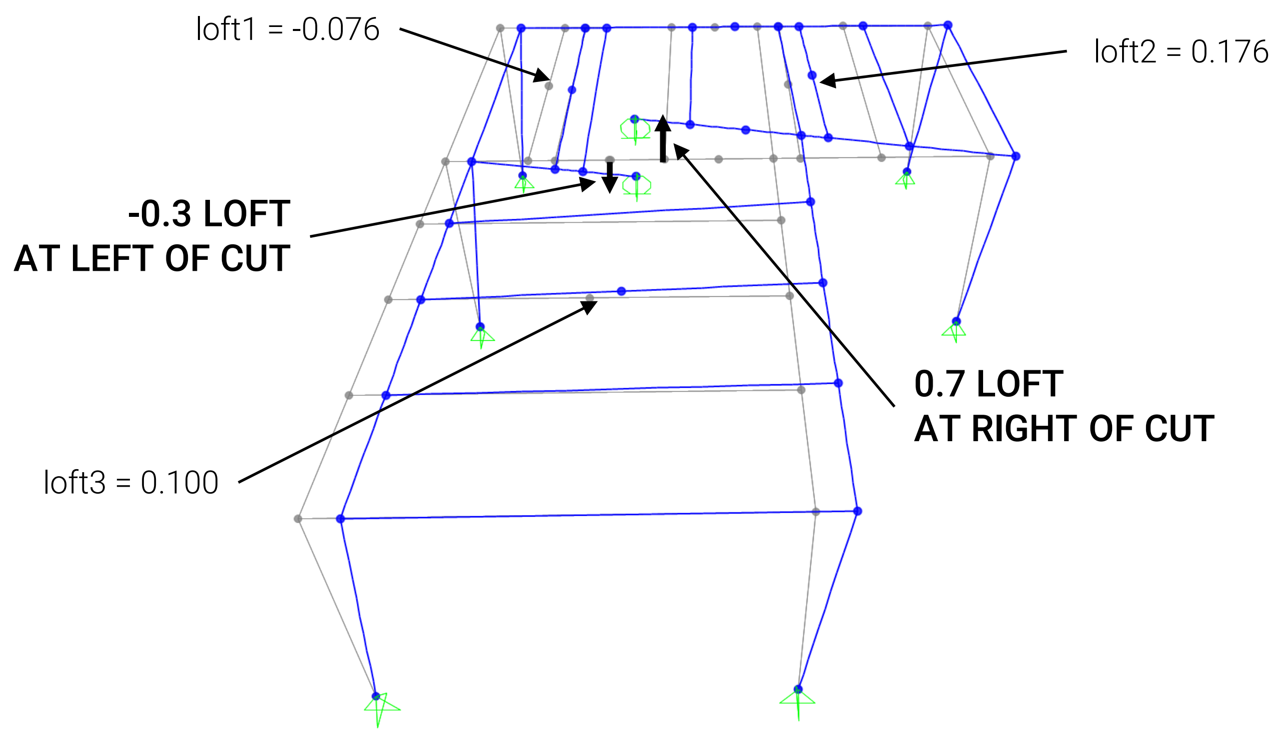
ANALYSIS OF DETERMINATE BEAM SYSTEM

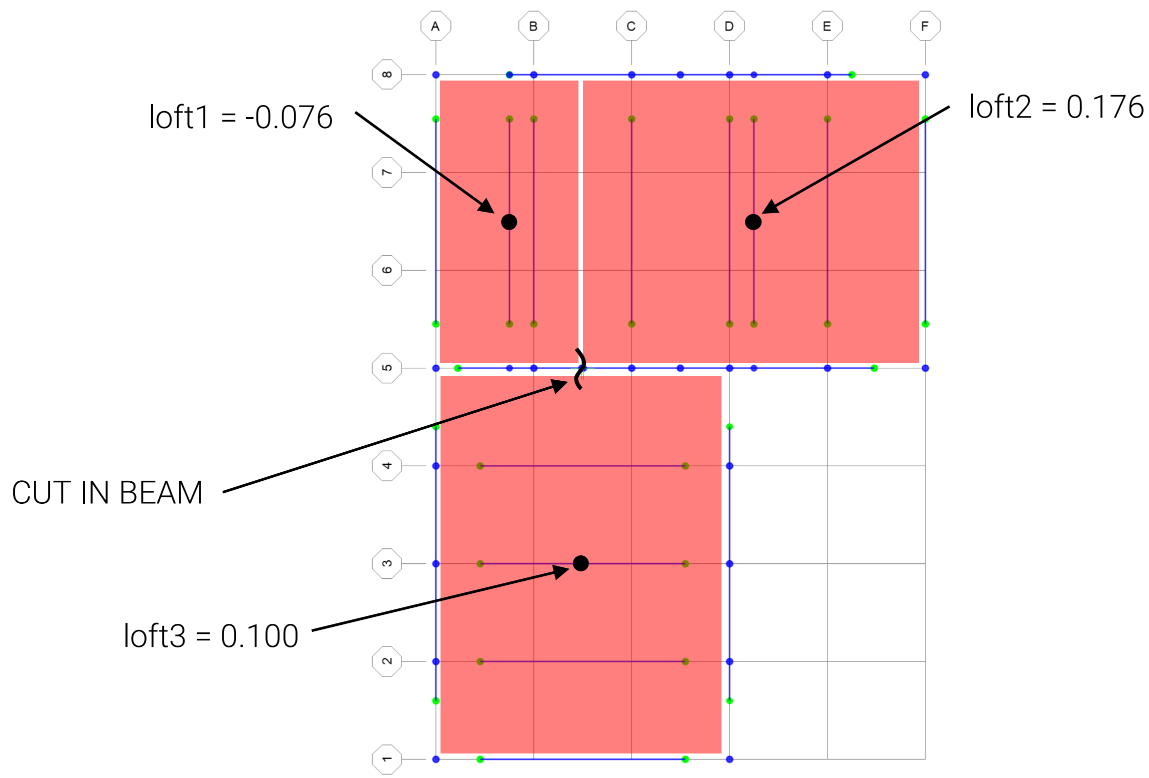
INTERNAL SHEAR AT CUT IN BEAM

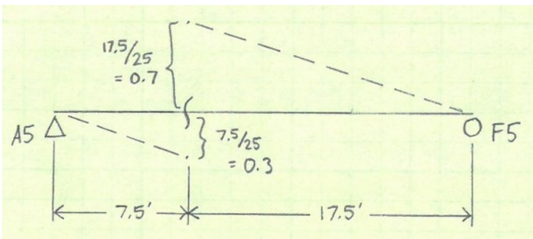
$V = \Sigma(area\ load * area * loft)$

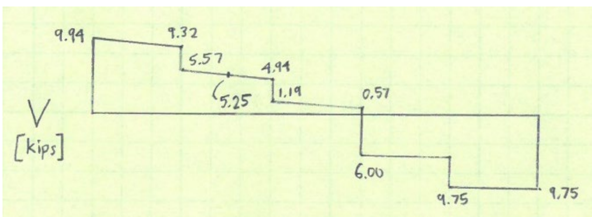
```
>>
areaLoad1 = 100; %psf
area1 = 7.5*15; %sq ft
loft1 = -0.0755;

areaLoad2 = 100; %psf
area2 = 17.5*15; %sq ft
loft2 = 0.1755;

areaLoad3 = 50; %psf
area3 = 15*20; %sq ft
loft3 = 0.1003;

V = (areaLoad1*area1*loft1+areaLoad2*area2*loft2+areaLoad3*area3*loft3)/1000 %kips

V =

    5.2620
```

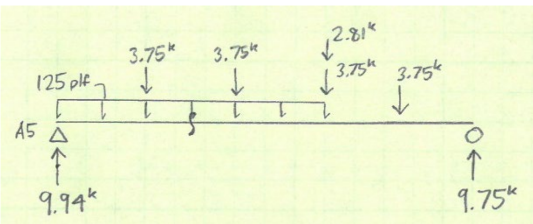
"Müller-Breslau" Shear = 5.26 kips

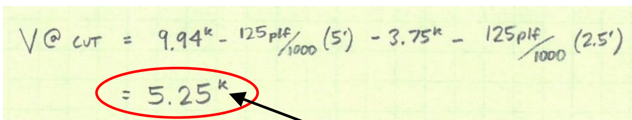








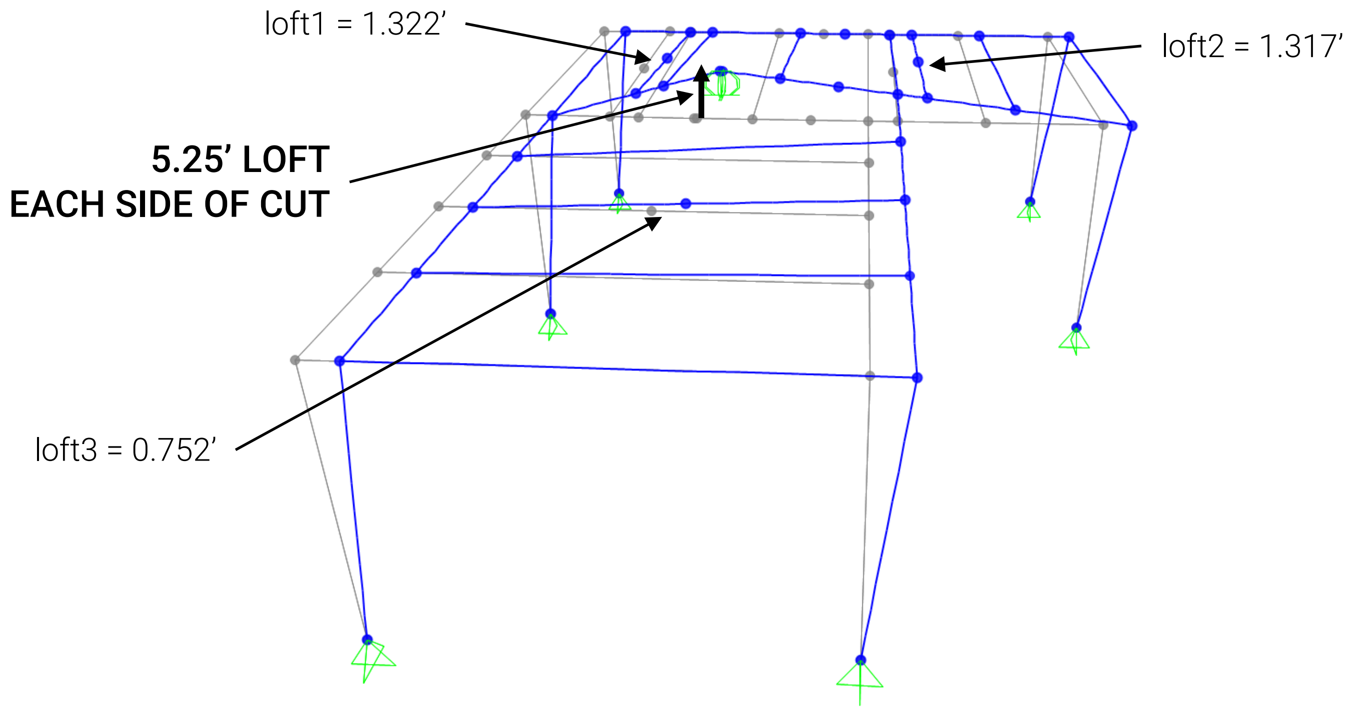




"Actual" Shear = 5.25 kips

MÜLLER-BRESLAU METHOD

ANALYSIS OF DETERMINATE BEAM SYSTEM

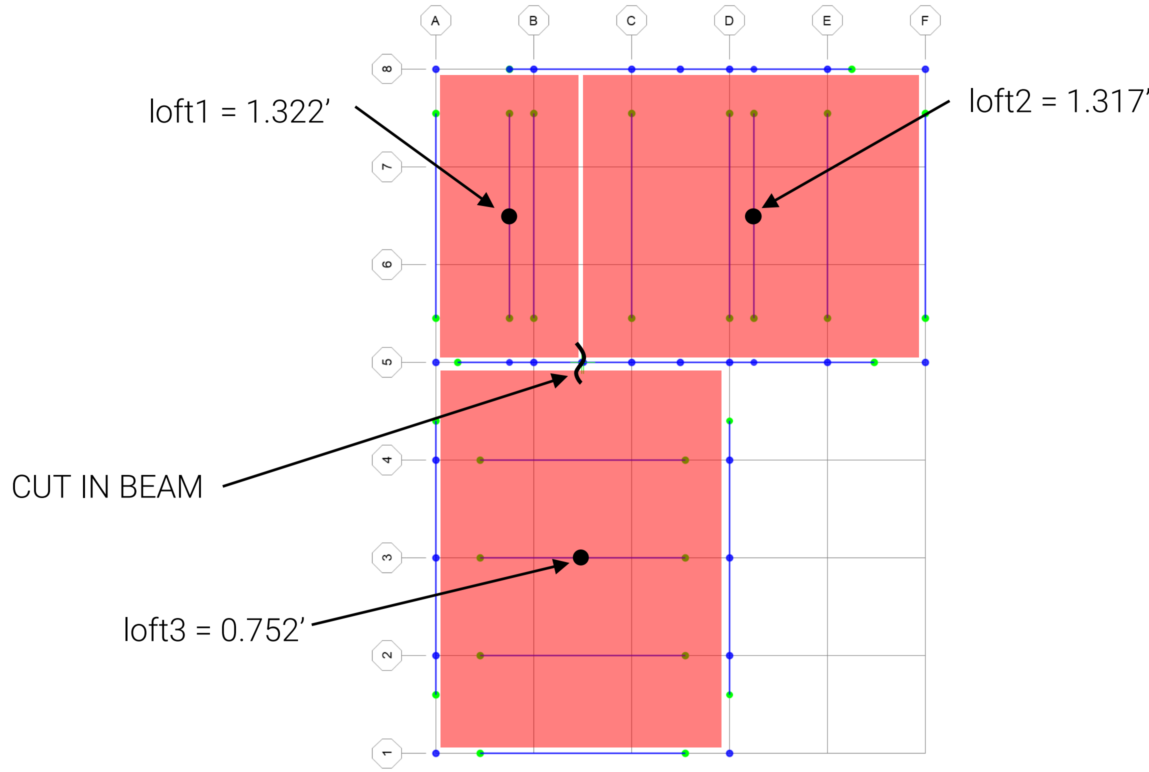


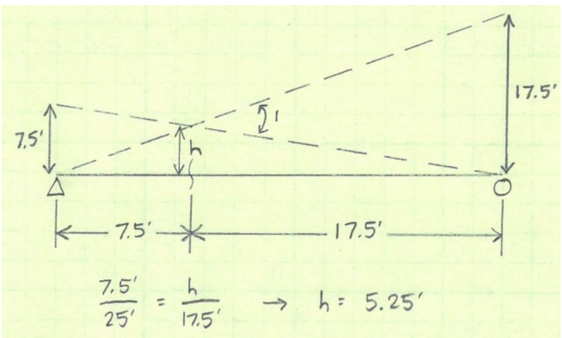
INTERNAL MOMENT AT CUT IN BEAM

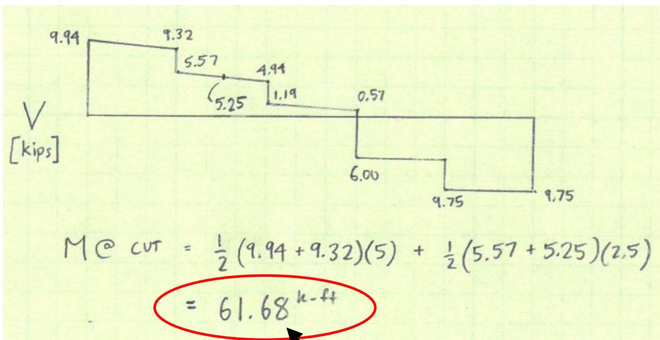
$$M = \Sigma(area\ load * area * loft)$$

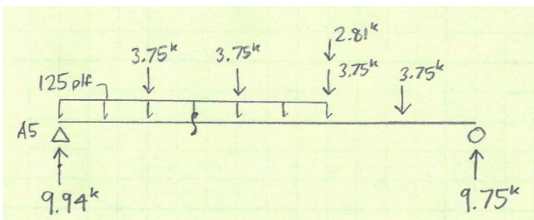
```
>>
areaLoad1 = 100; %psf
area1 = 7.5*15; %sq ft
loft1 = 1.3219; %ft

areaLoad2 = 100; %psf
area2 = 17.5*15; %sq ft
loft2 = 1.3172; %ft

areaLoad3 = 50; %psf
area3 = 15*20; %sq ft
loft3 = 0.7522; %ft

M = (areaLoad1*area1*loft1+areaLoad2*area2*loft2+areaLoad3*area3*loft3)/1000 %k-ft

M =

   60.7309
```

"Müller-Breslau" Moment = 60.73 k-ft









"Actual" Moment = 61.68 k-ft

UNSEEN:

A COLLABORATION BETWEEN ARCHITECT + ENGINEER

Image courtesy of Chelzea Furtado

A MENTAL ILLNESS DESTIGMATIZATION MUSEUM

UNSEEN is the title of Chelzea Furtado's senior architecture thesis.

Meant to serve as the support structure for the roof of the museum, this assembly of members resembles the forest-like network of neurons within the brain.

In collaboration with her project, I performed a structural analysis of her model in SAP2000. The purpose was to determine which material, concrete or steel, would be most efficient for the given form of the structure.

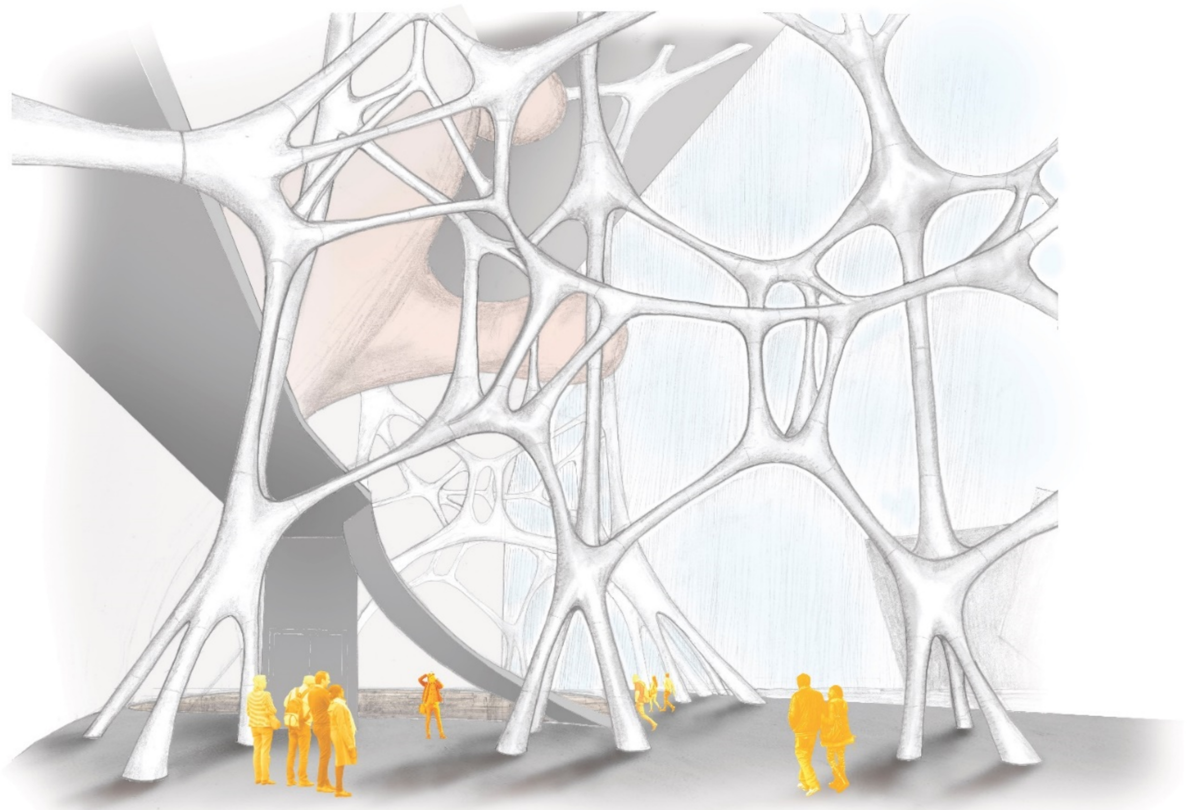


Image courtesy of Chelzea Furtado

This study consists of:

- Axial Diagrams (Self-Weight)
- Axial Diagrams (0.3g Lateral)
- Deflected Shapes (Self-Weight)
- Buckling Analysis

MATERIAL STUDY

Concrete Model

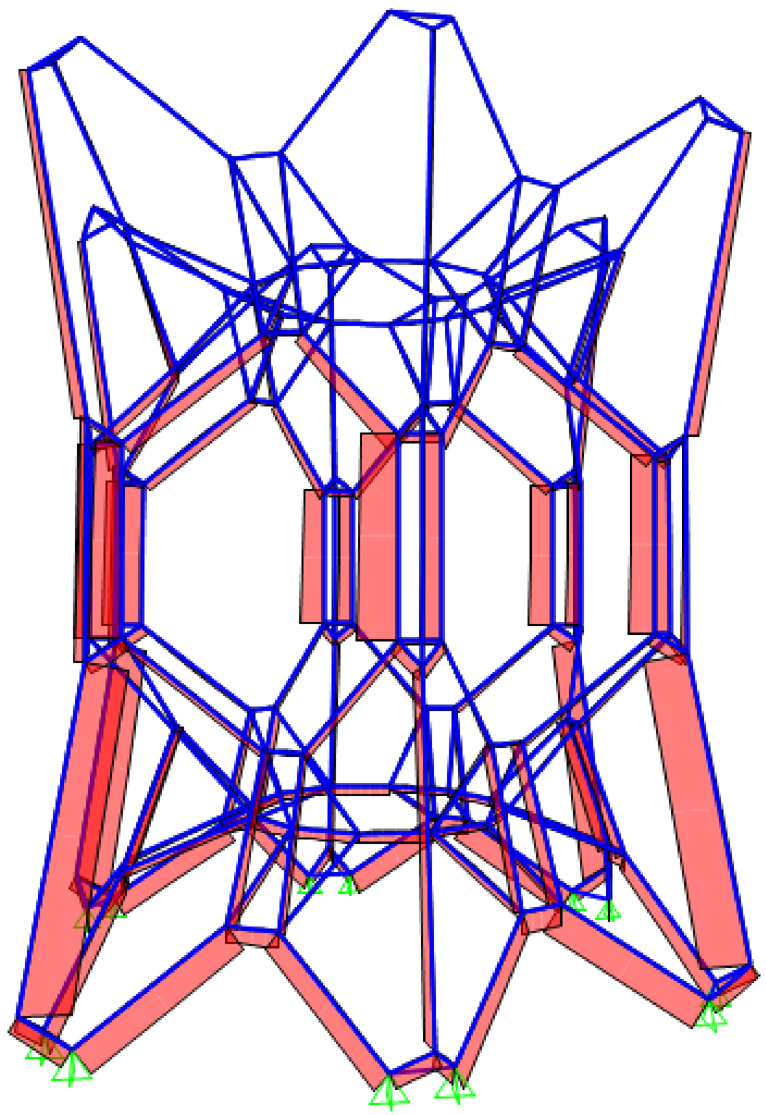
- Circular concrete section
- 12" diameter
- 4000 psi concrete
- Reinforcement:
  - (8)#8 longitudinal bars
  - #3 ties @ 6" o.c.

Steel Model

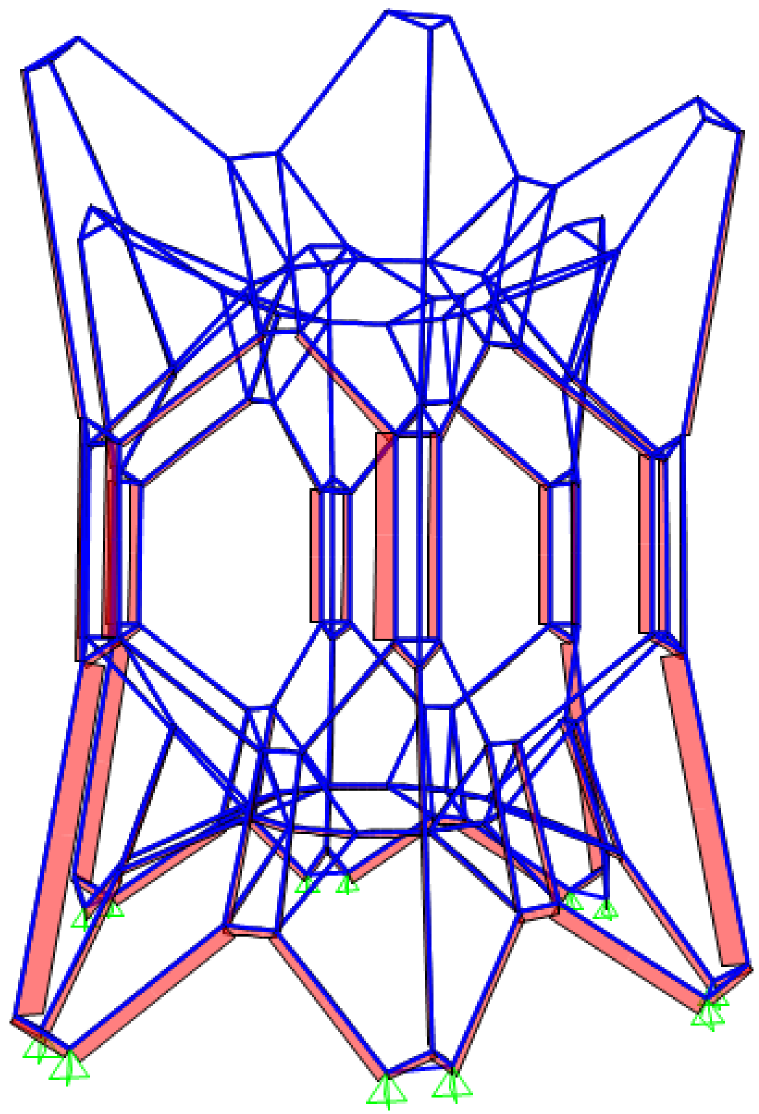
- Steel pipe section
- 12" outside diameter
- 0.5" wall thickness
- A53 Gr. B steel

RED = COMPRESSION

Axial Diagrams (Self-Weight)



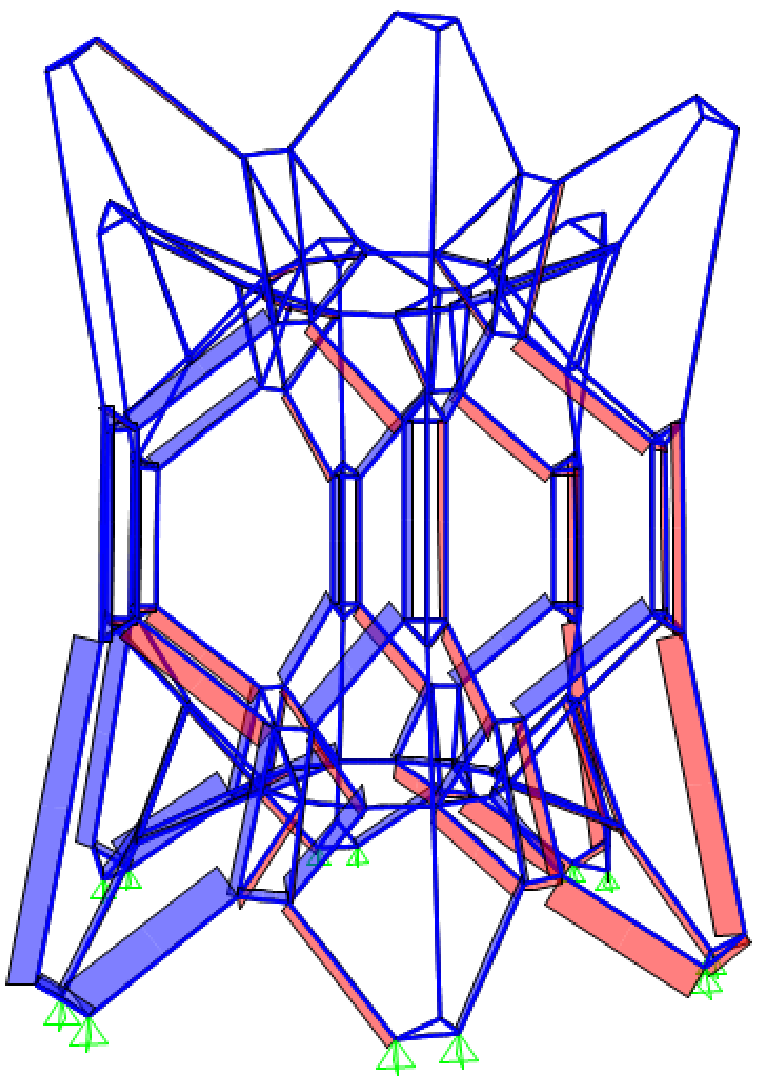
Concrete Model



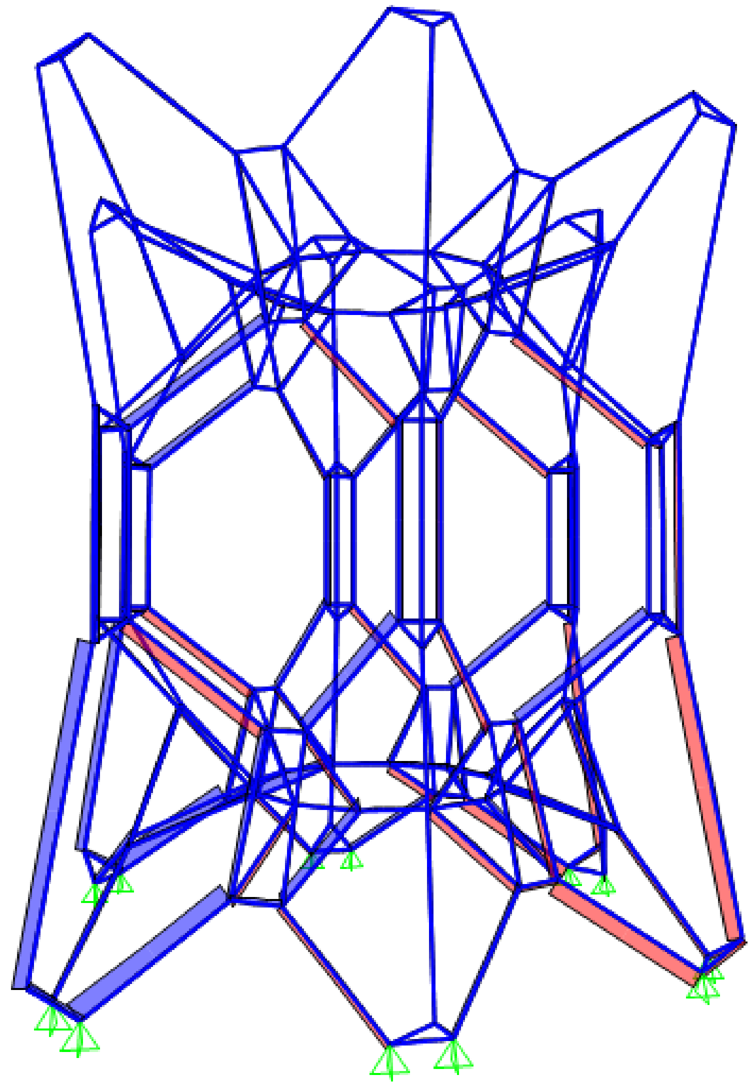
Steel Model

Axial Diagrams (0.3g Lateral)

RED = COMPRESSION
BLUE = TENSION

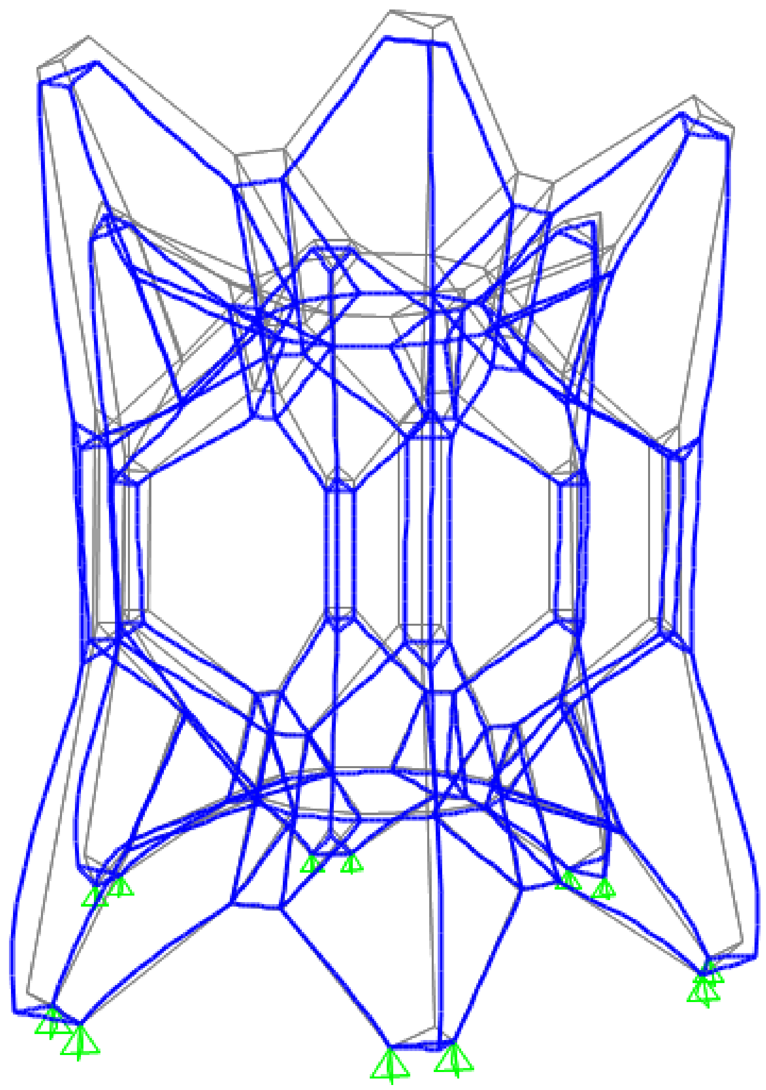


Concrete Model

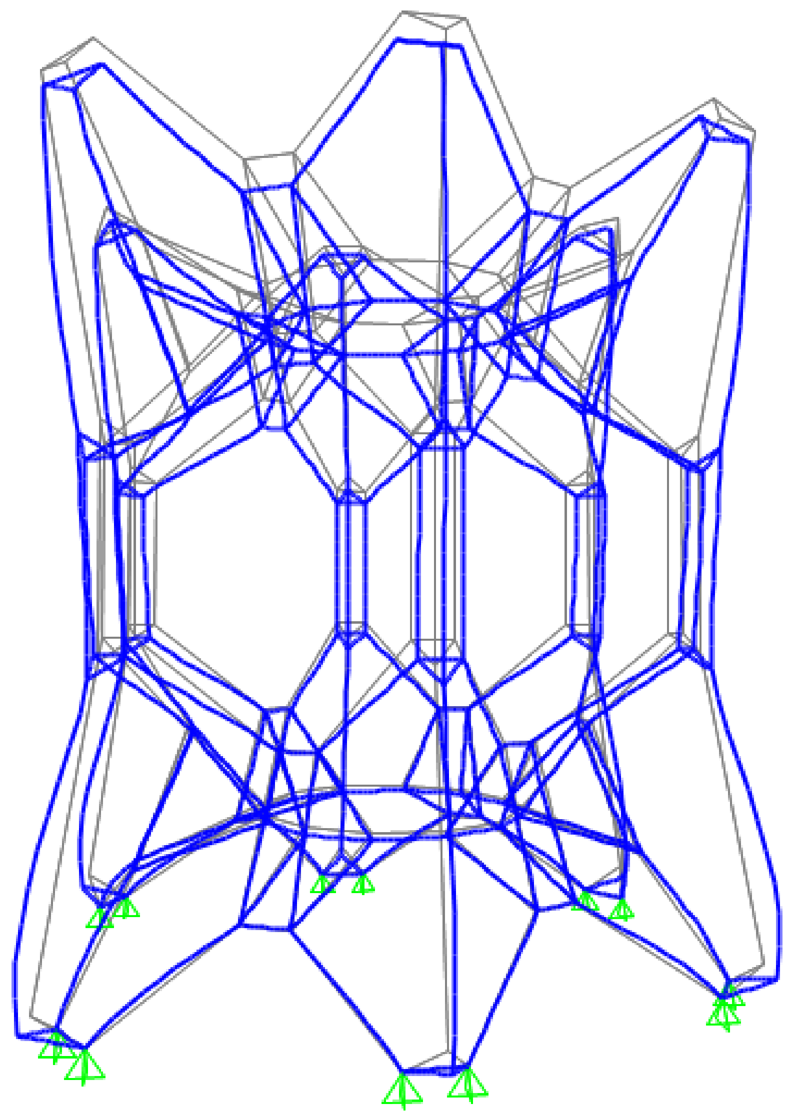


Steel Model

Deflected Shapes (Self-Weight)

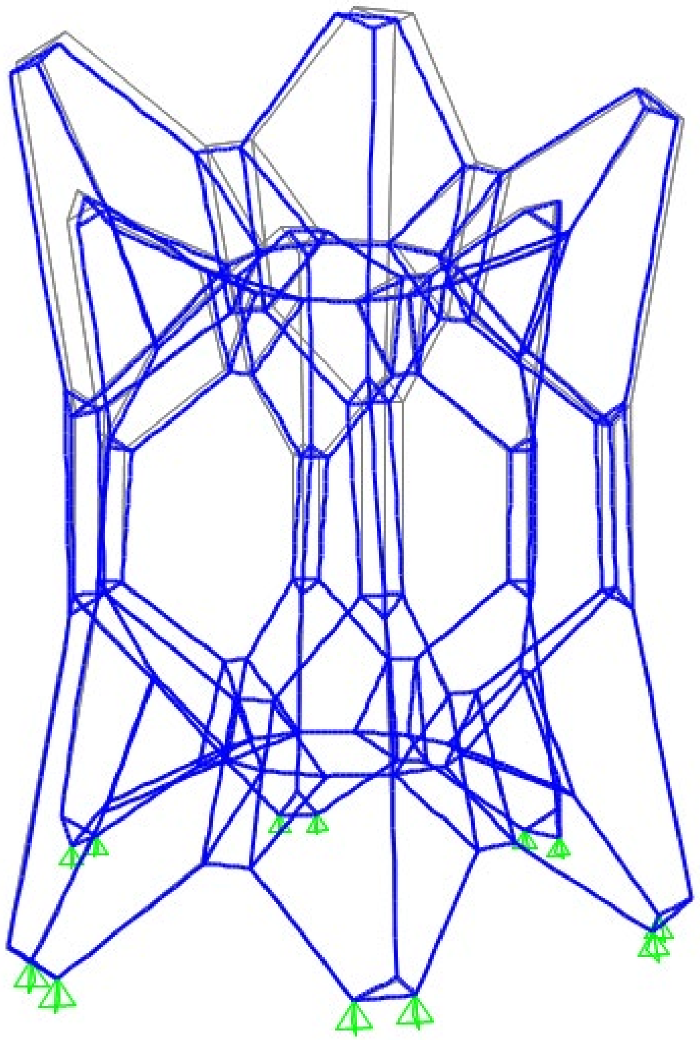


Concrete Model

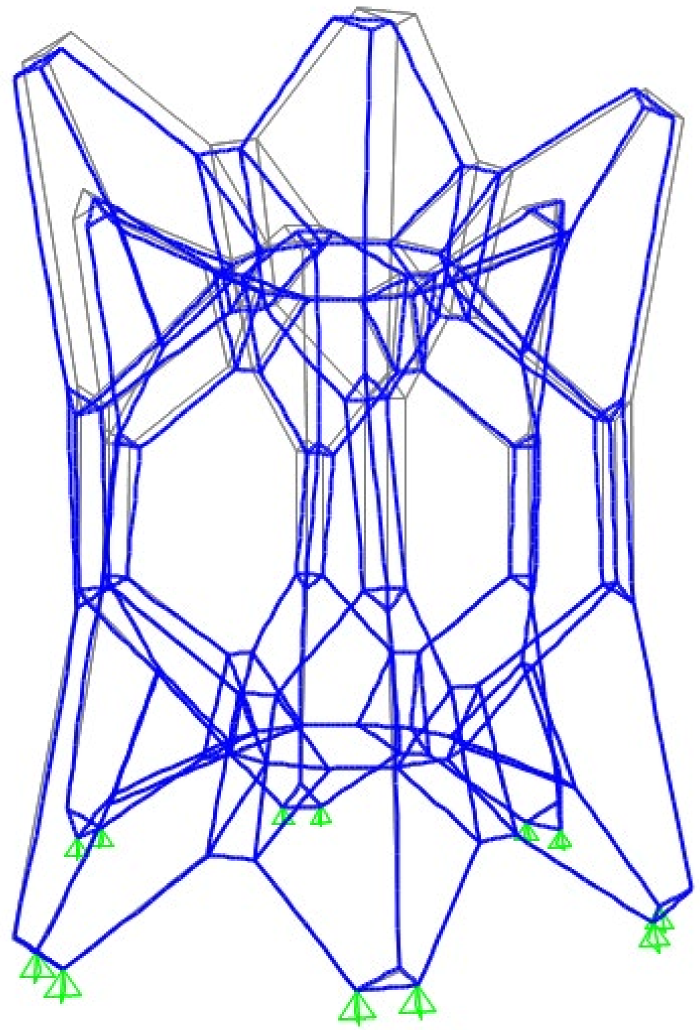


Steel Model

Buckling Analysis



Concrete Model
F.S. = 7.7



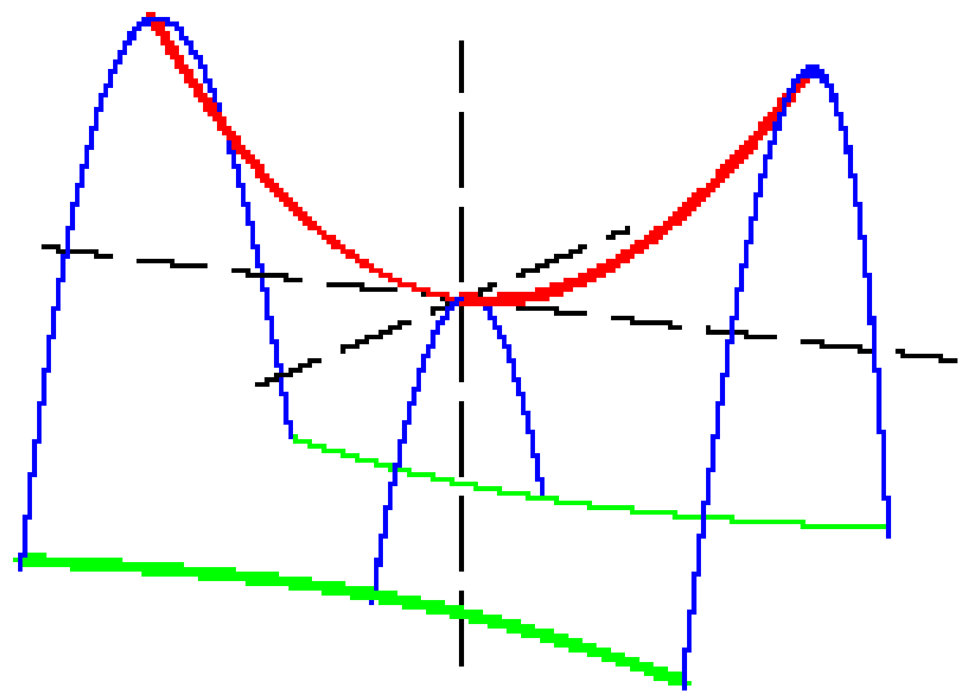
Steel Model
F.S. = 34.1

CONCLUSION OF STUDY

- Due to its significantly higher self-weight, the concrete model experienced higher axial loads and was over four times as susceptible to buckling
- Solutions for concrete model:
  - More lightweight concrete
  - More efficient geometry of structure

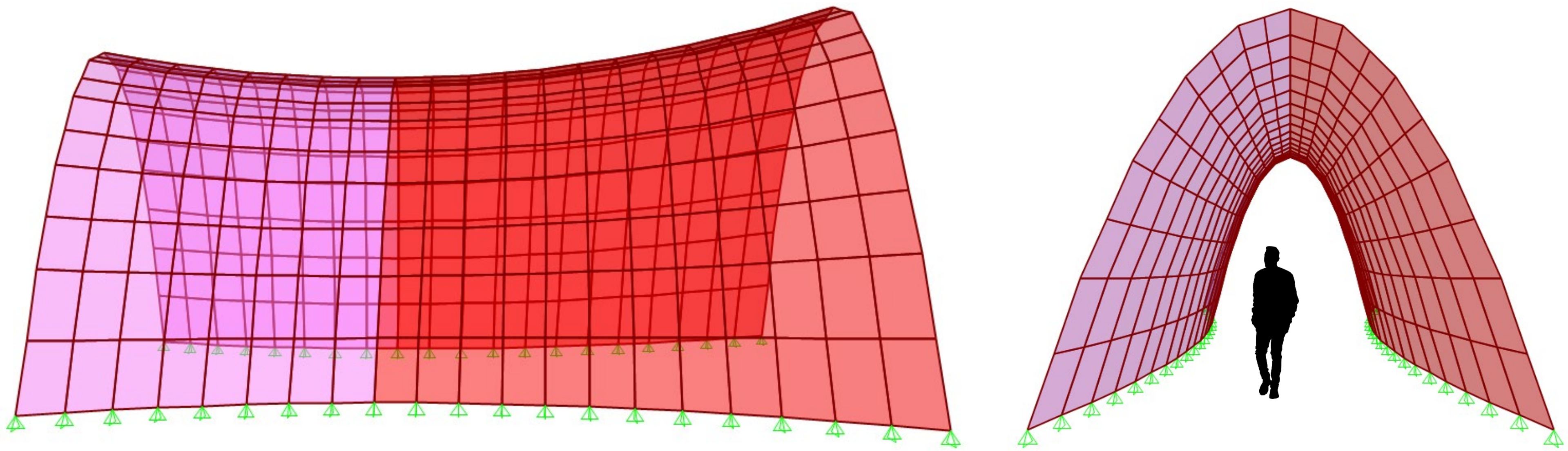
PRELIMINARY SHELL EXPLORATION #1

HYPERBOLIC PARABOLOID



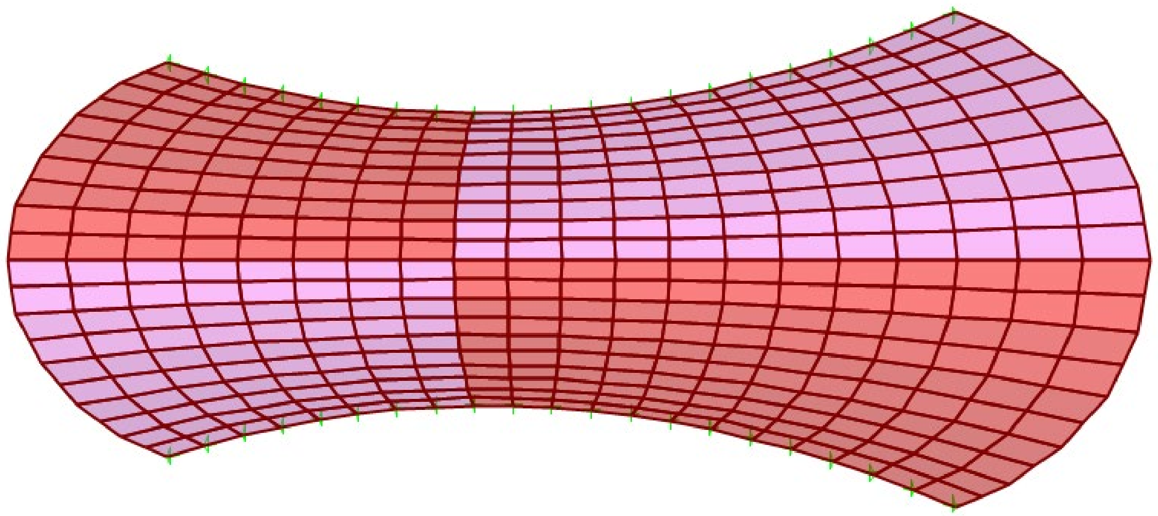
1ST ITERATION

ELEVATIONS



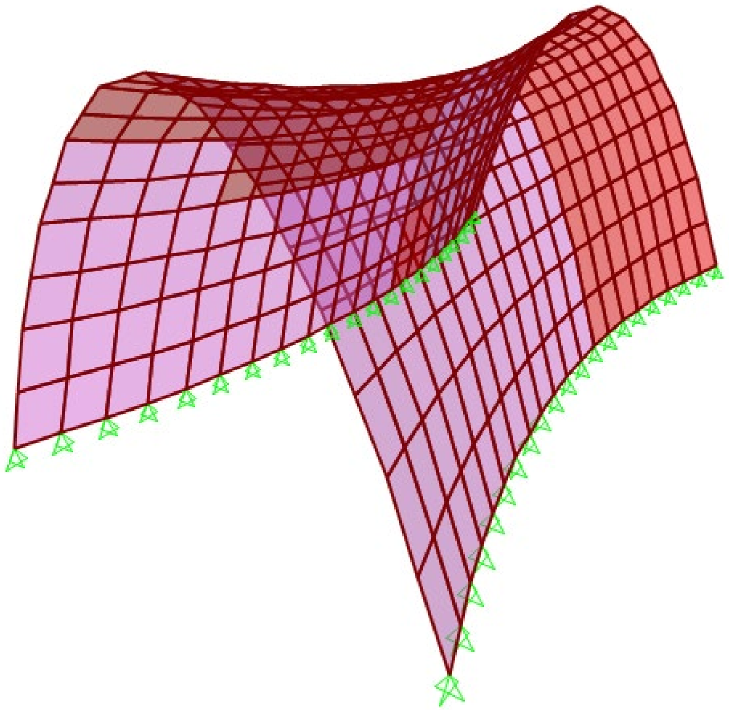
1” 3000psi concrete

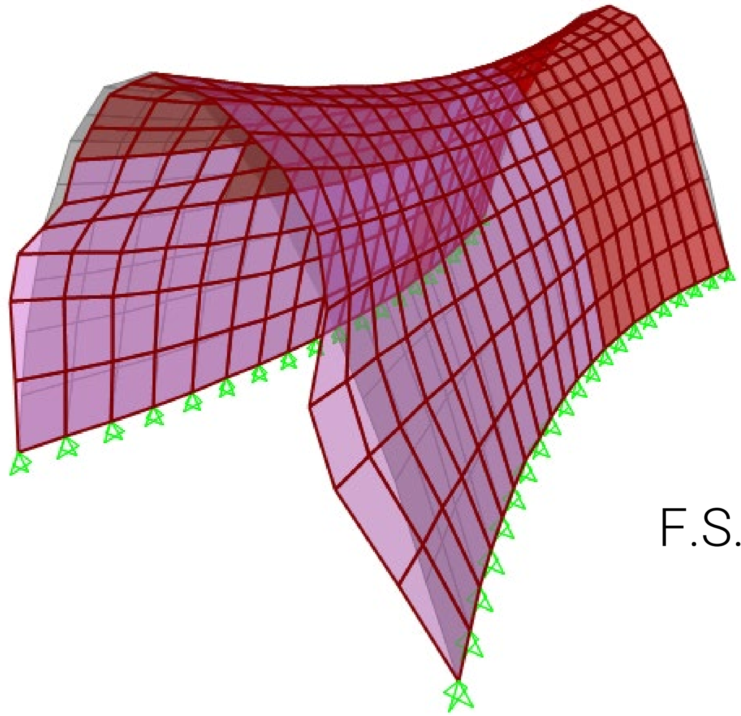
PLAN



1ST ITERATION

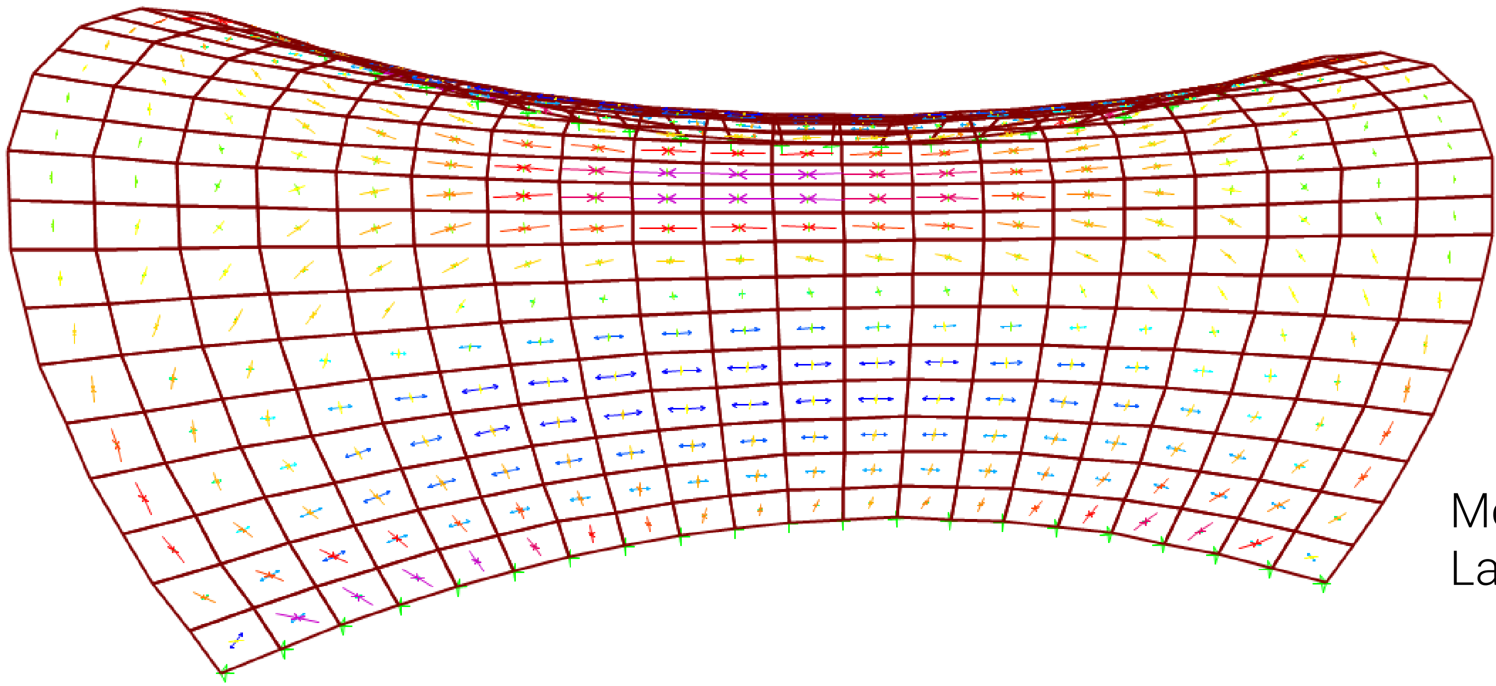
BUCKLING ANALYSIS





F.S. = 486

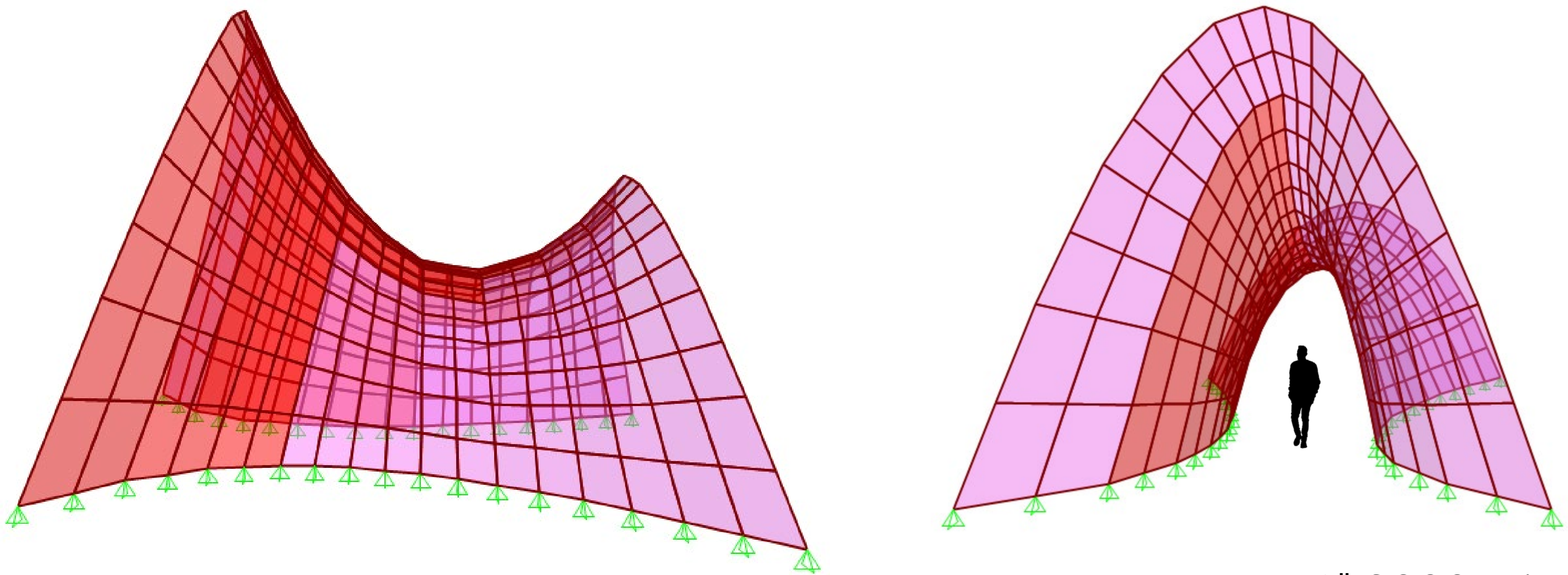
LOAD FLOW



Mostly in compression
Large area of tension in middle
(Blue arrows) → NOT funicular

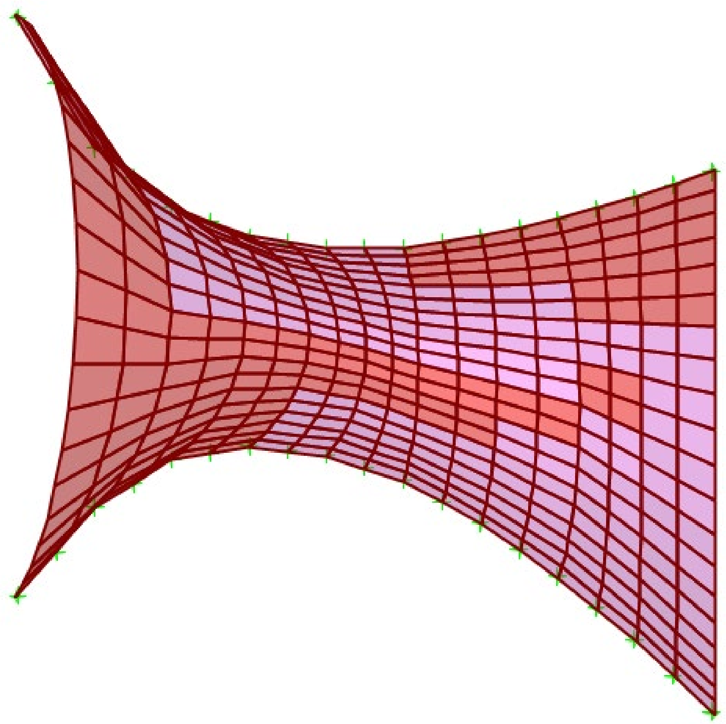
2ND ITERATION

ELEVATIONS



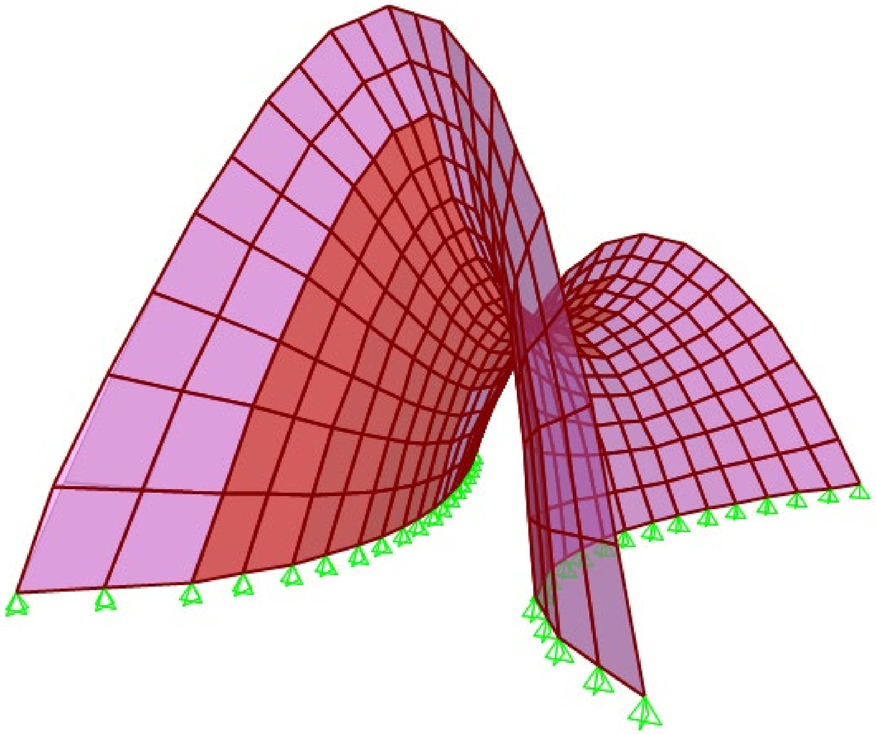
1” 3000psi concrete

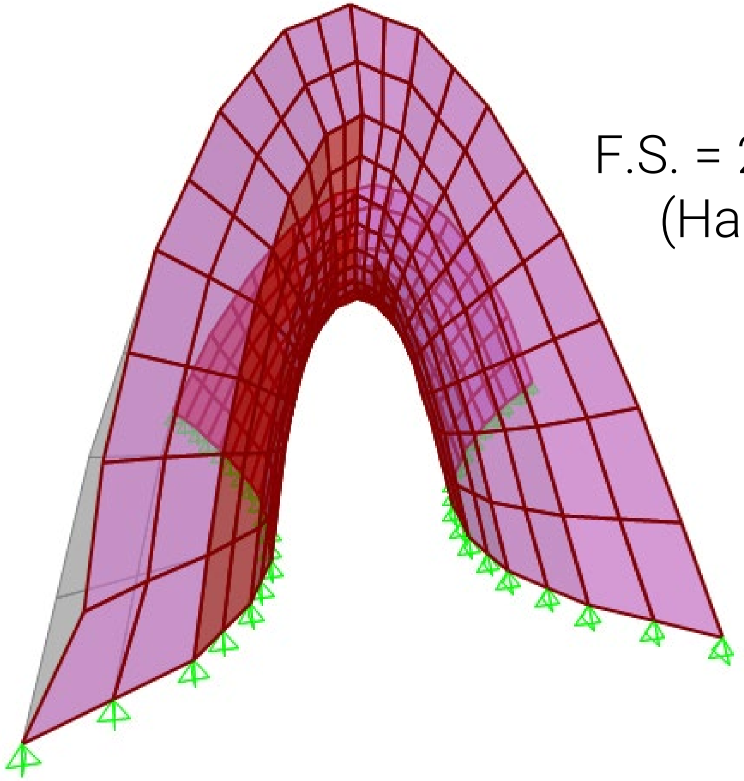
PLAN



2ND ITERATION

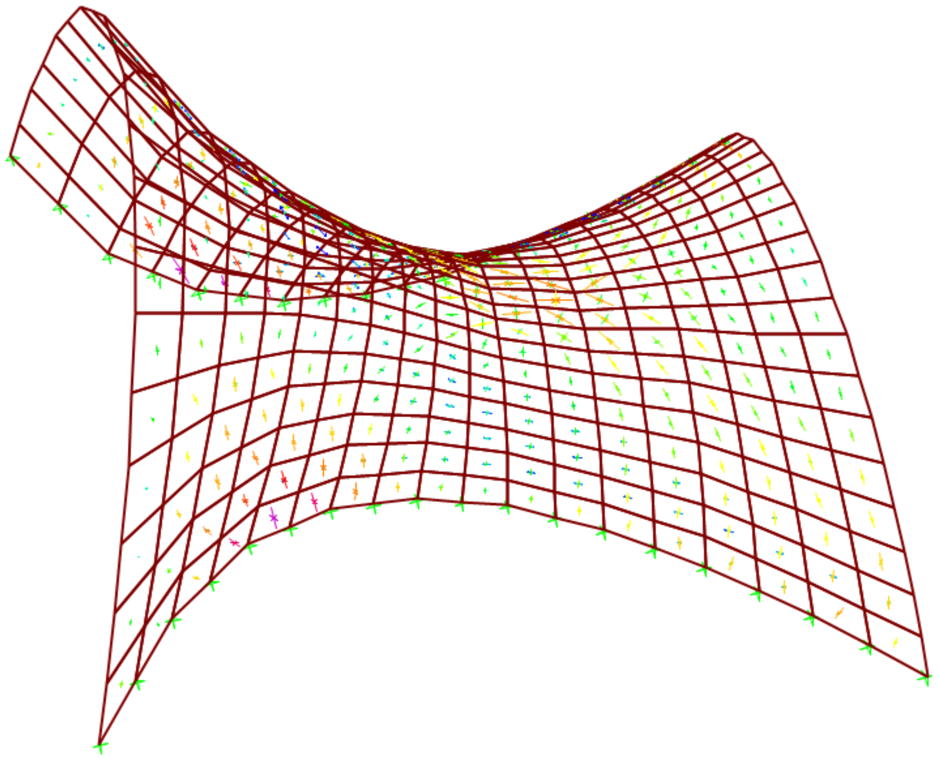
BUCKLING ANALYSIS





F.S. = 229
(Halved from 1ST iteration)

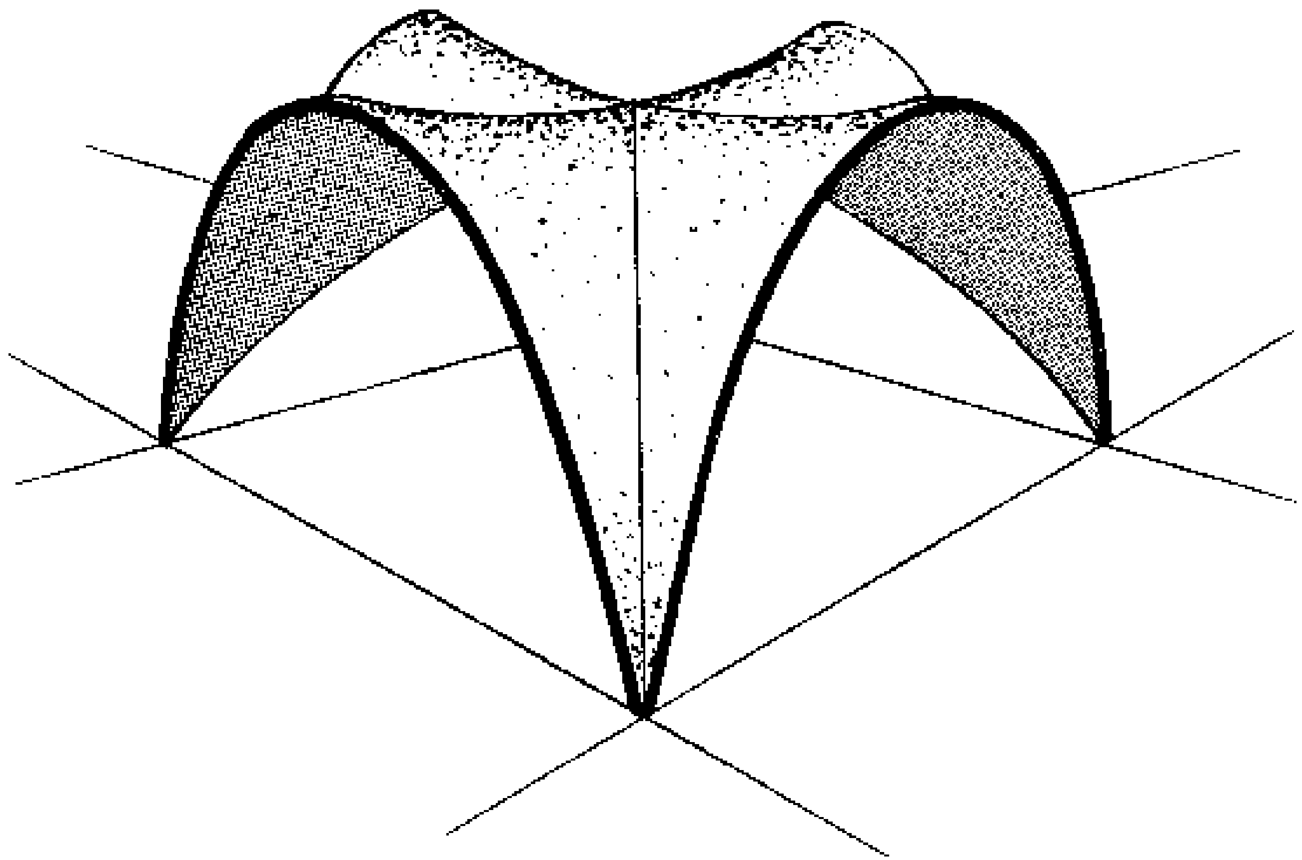
LOAD FLOW



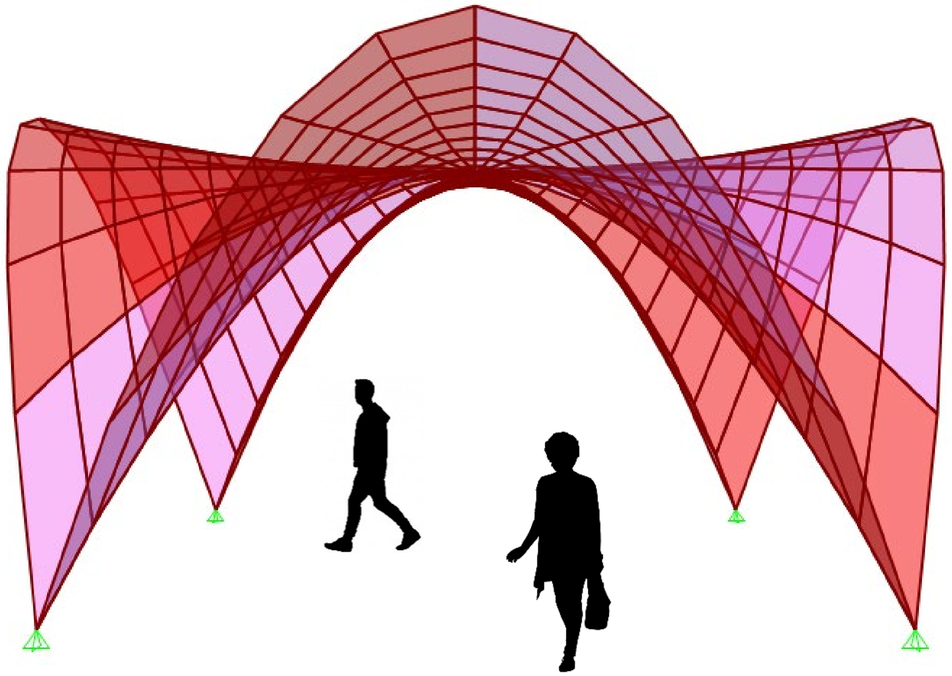
Higher compression forces on top
Decreased tension forces → NOT funicular

PRELIMINARY SHELL EXPLORATION #2

GROIN VAULT

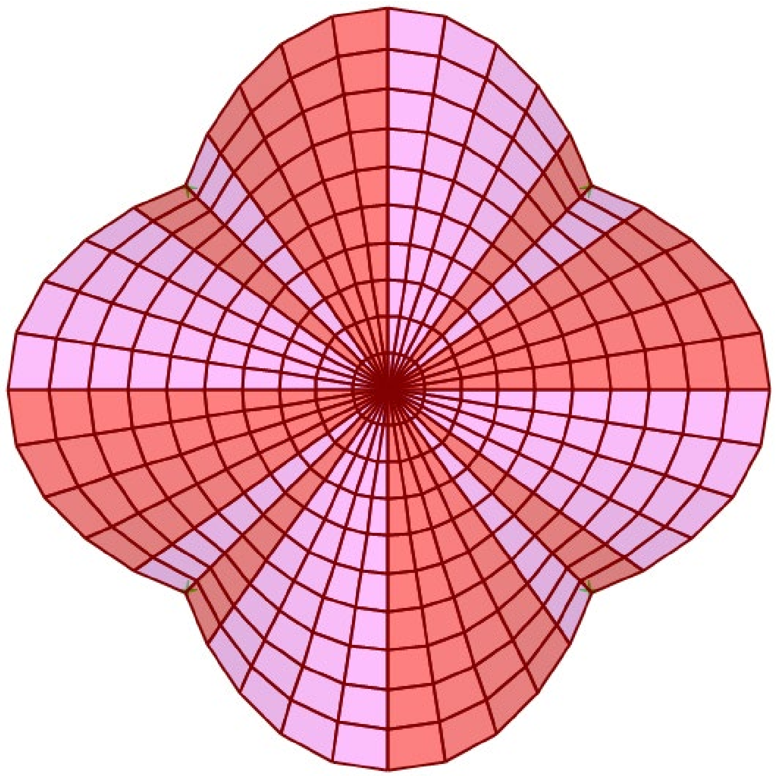


ELEVATIONS

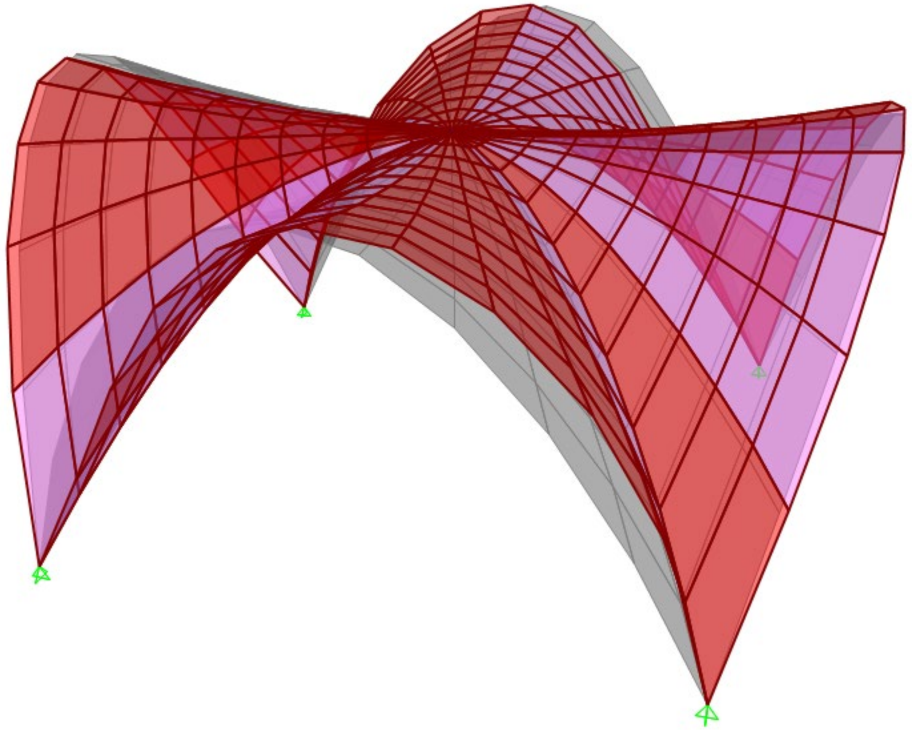


1” 3000psi concrete

PLAN

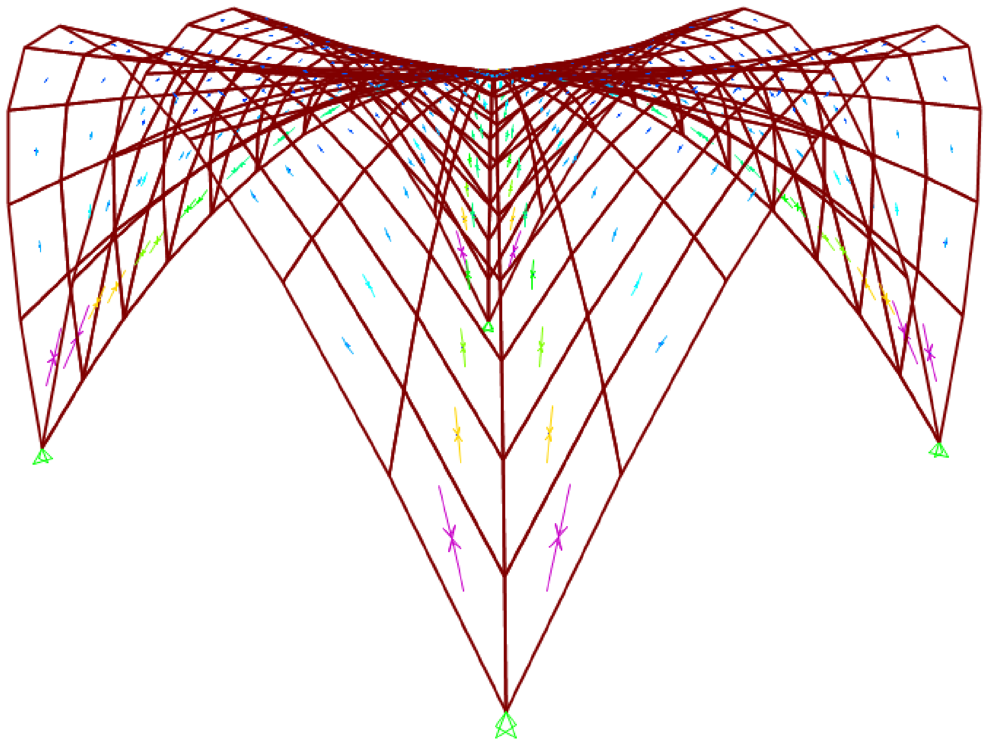


BUCKLING ANALYSIS



F.S. = 39

LOAD FLOW



All in compression → Funicular!

DEEP DIVE INTO SHELL FORMS

PART 0. Precedent Study

PART 1. Material Property Study

PART 2. Geometric Form Study

Main Objectives of Study:

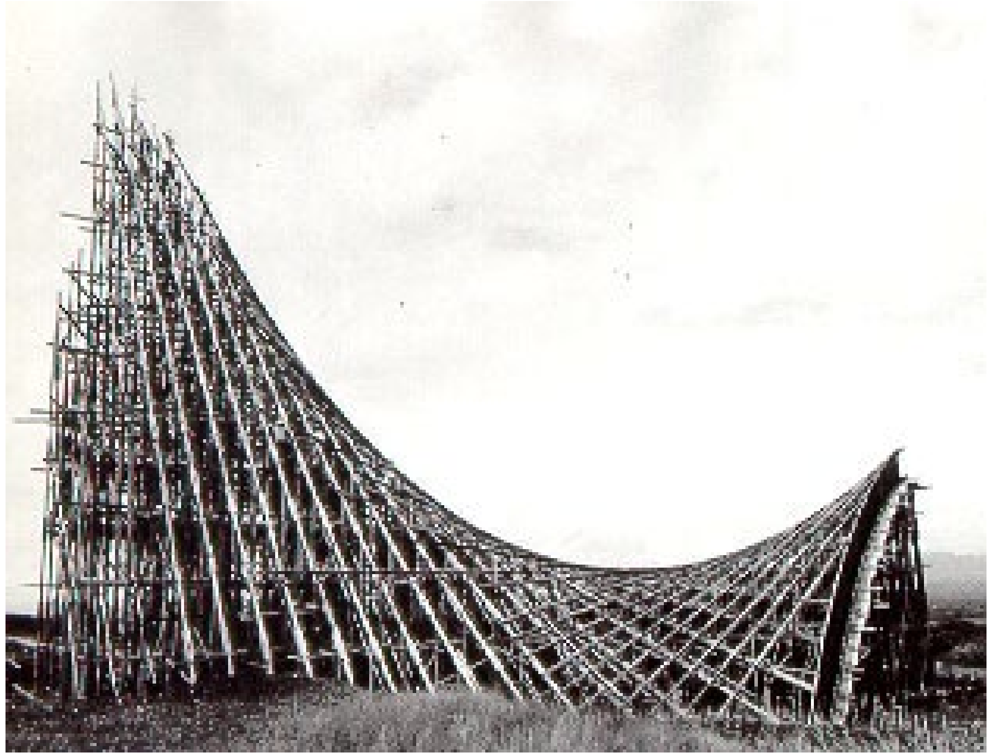
LOAD FLOW – Identify areas of tension

BUCKLING ANALYSIS – Most prominent mode of failure in thin concrete shells

PRECEDENT STUDY

Chapel Lomas de Cuernavaca

Félix Candela
Cuernavaca, Mexico
Completed in 1958



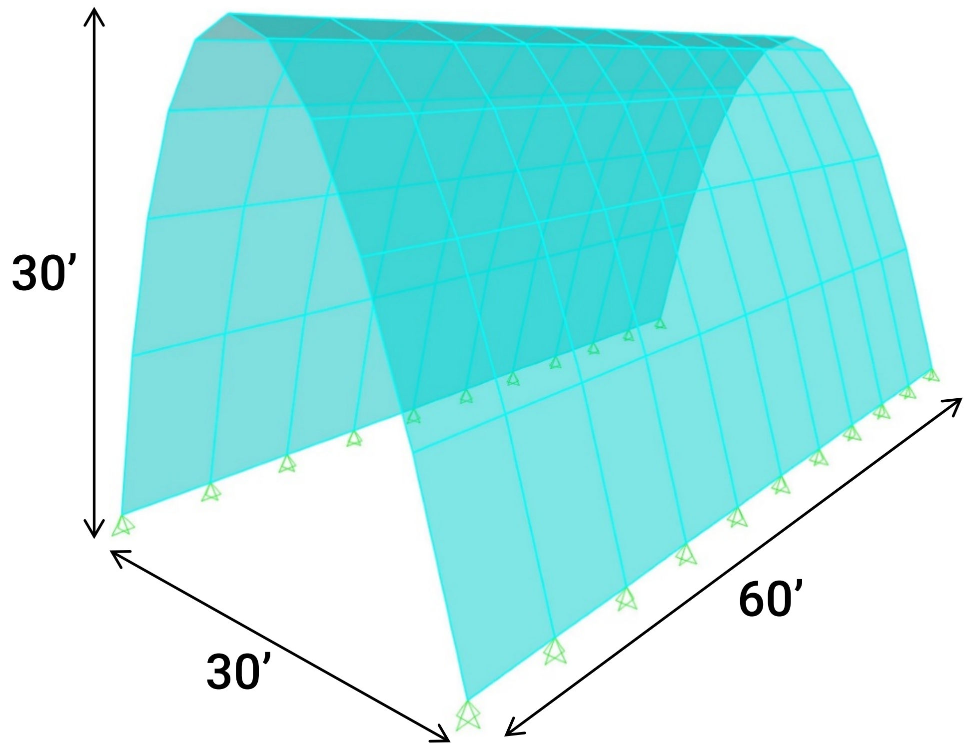
Most of structure is only 4 cm (1.5 in) thick

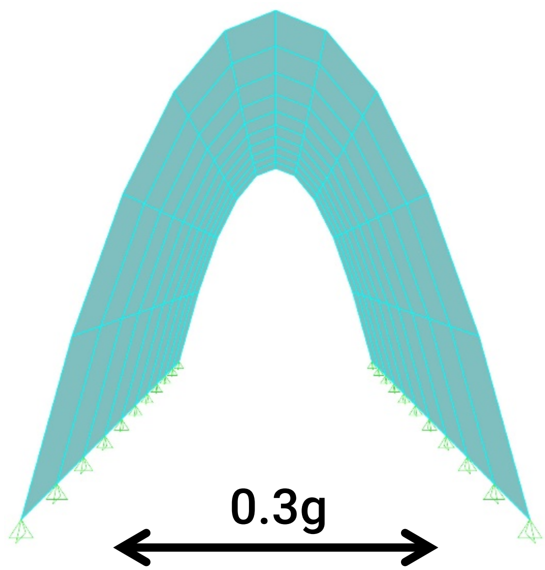
Open end rises up to 21 meters (70 feet)

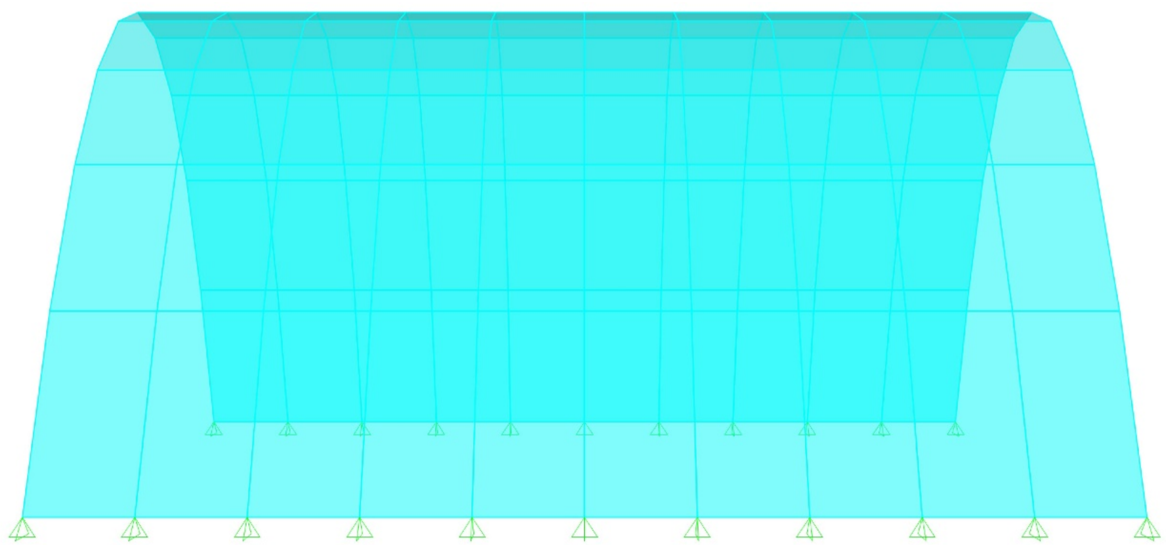
MATERIAL STUDY

BASE MODEL:

- Simple form → Single Curvature Vault
- Loading: self-weight and 0.3g lateral acceleration
- Variables: thickness, f'c (E), unit weight





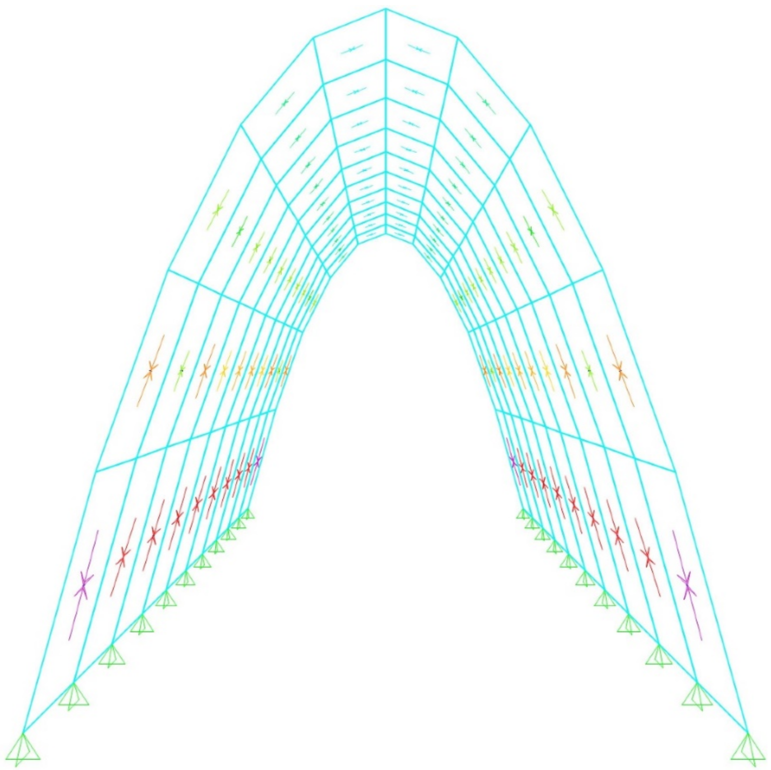


ITERATION 1: base model

1” thick shell

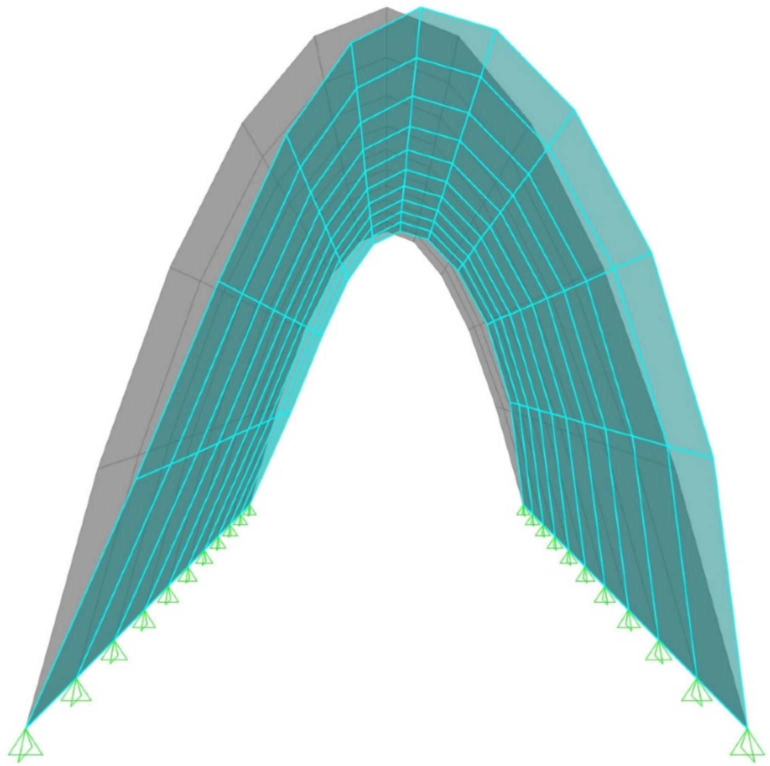
1000 psi LW concrete (E = 1204 ksi)

Load Flow



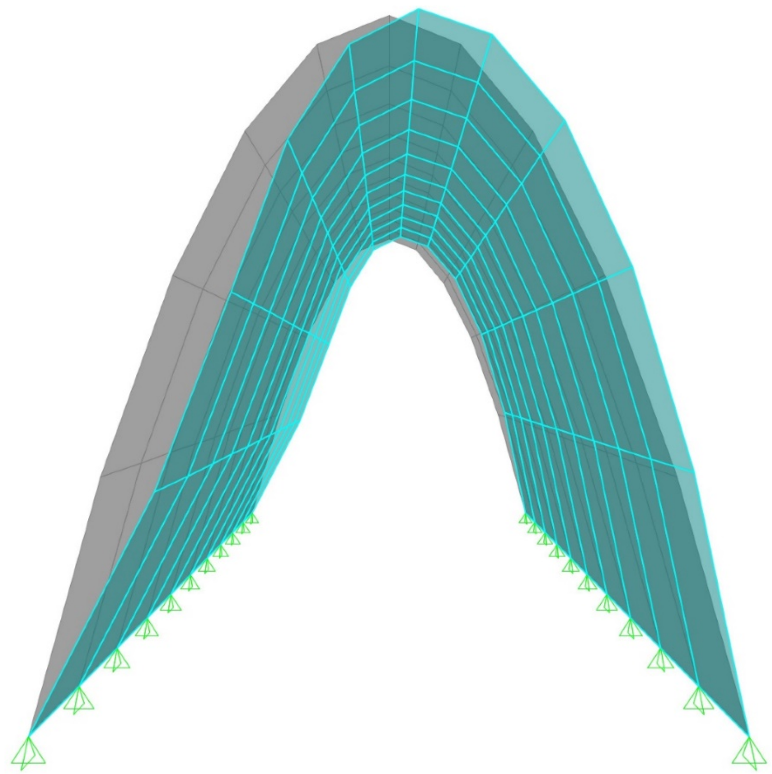
All in compression

Buckling (Self-Wt)



F.S. = 0.279

Buckling (0.3g Lateral)



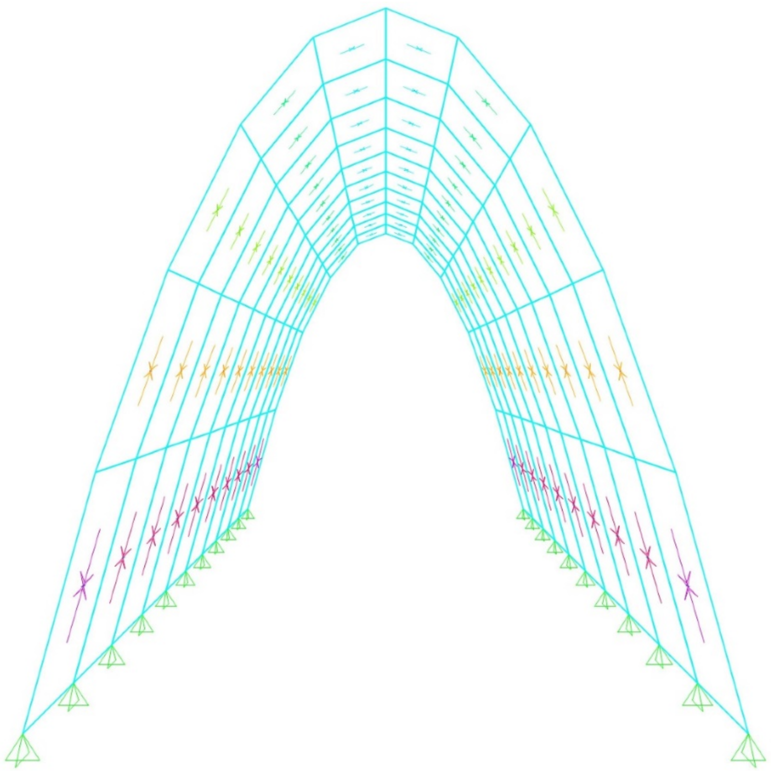
F.S. = 1.116

ITERATION 2: 12” thickness

12” thick shell

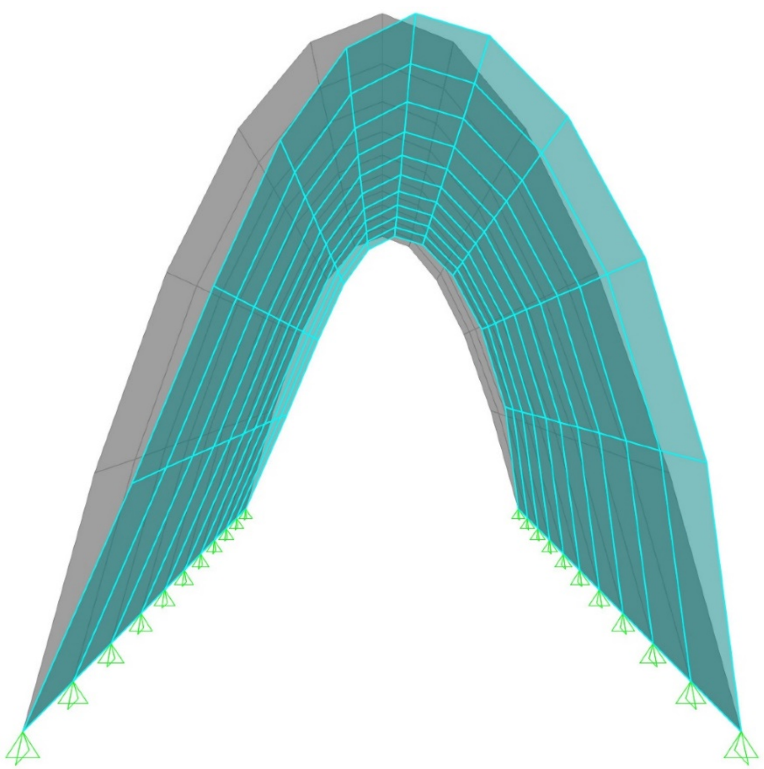
1000 psi LW concrete (E = 1204 ksi)

Load Flow



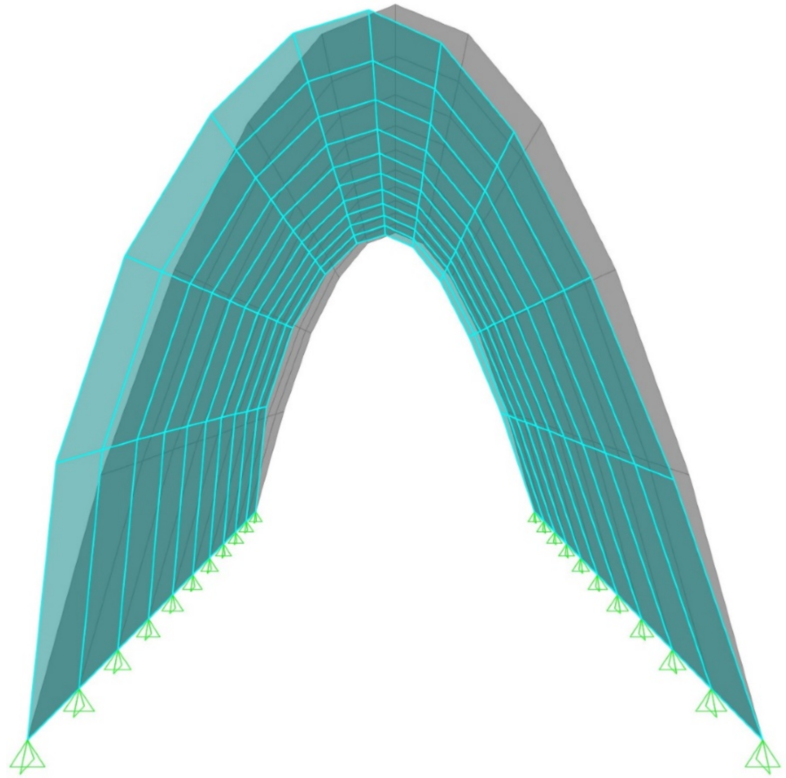
All in compression

Buckling (Self-Wt)



F.S. = 39.874

Buckling (0.3g Lateral)



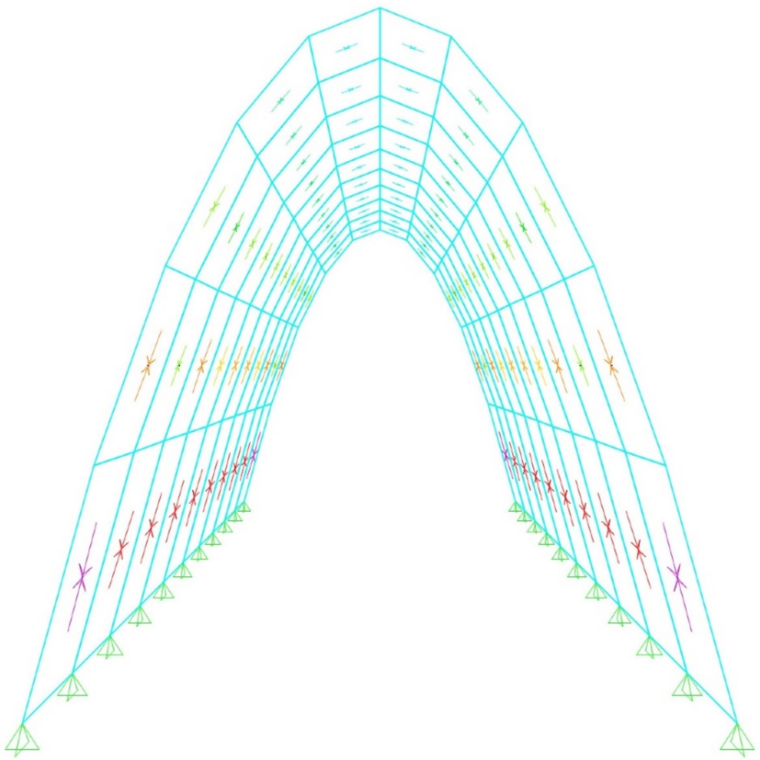
F.S. = 159.675

ITERATION 3: 10,000 psi

1” thick shell

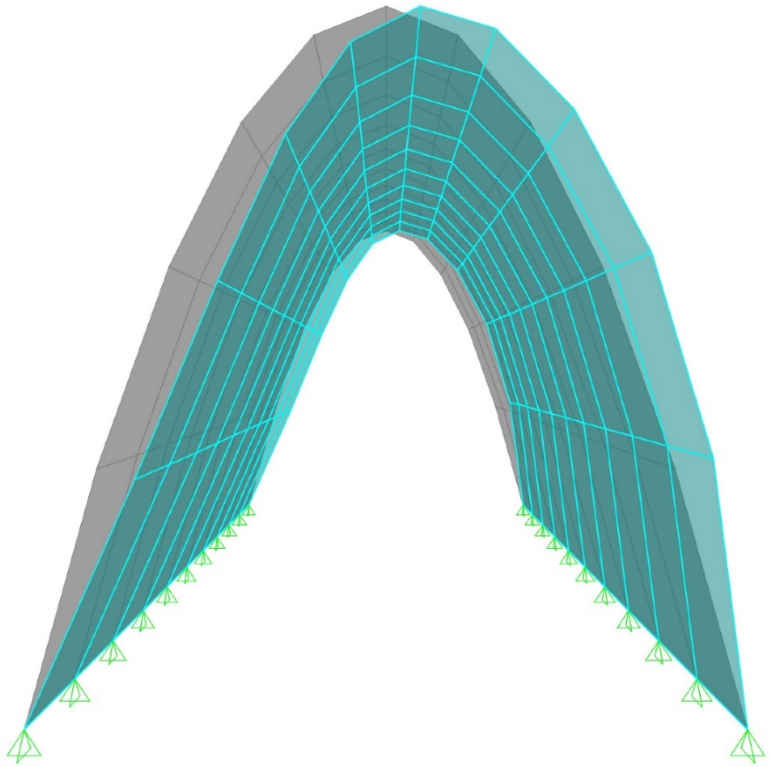
10,000 psi LW concrete (E = 3807 ksi)

Load Flow



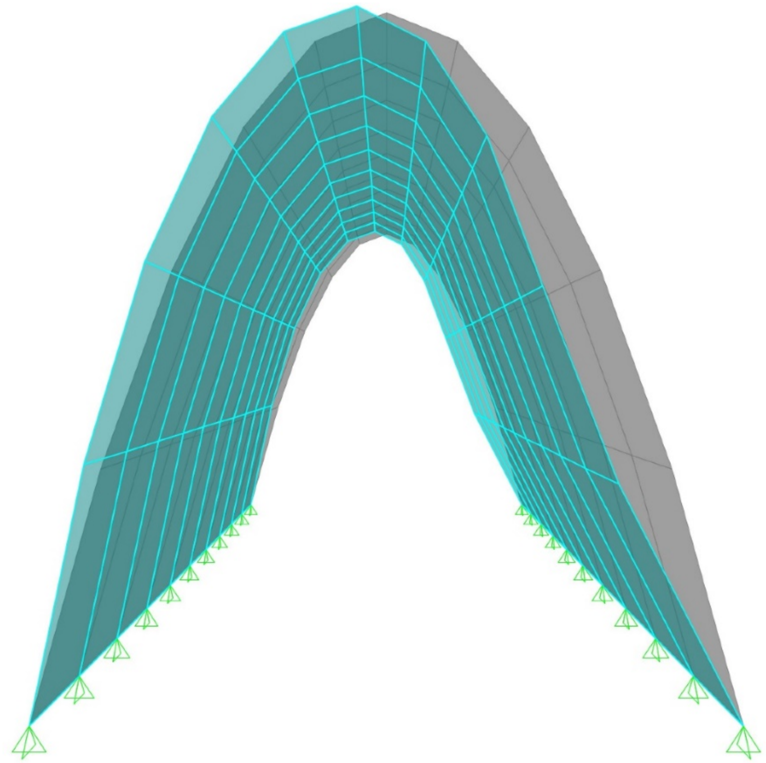
All in compression

Buckling (Self-Wt)



F.S. = 0.881

Buckling (0.3g Lateral)



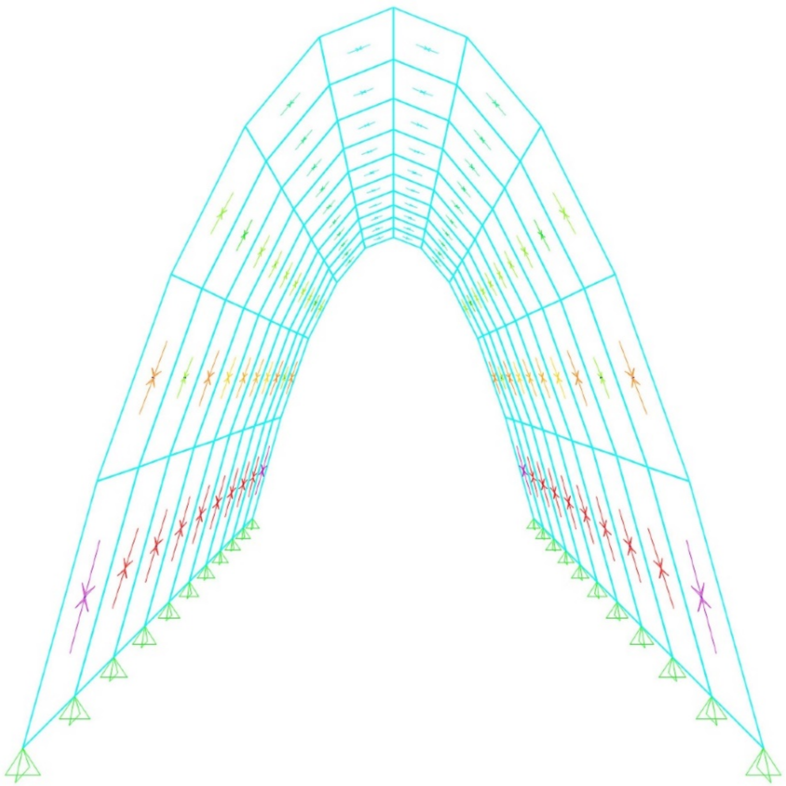
F.S. = 3.528

ITERATION 4: NW concrete

1" thick shell

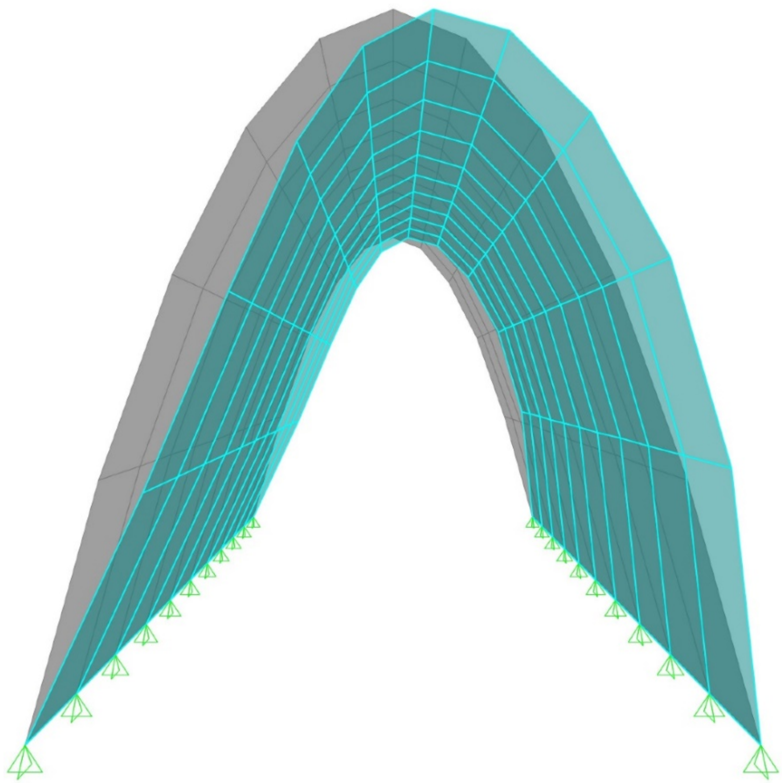
1000 psi NW concrete (E = 1802 ksi)

Load Flow



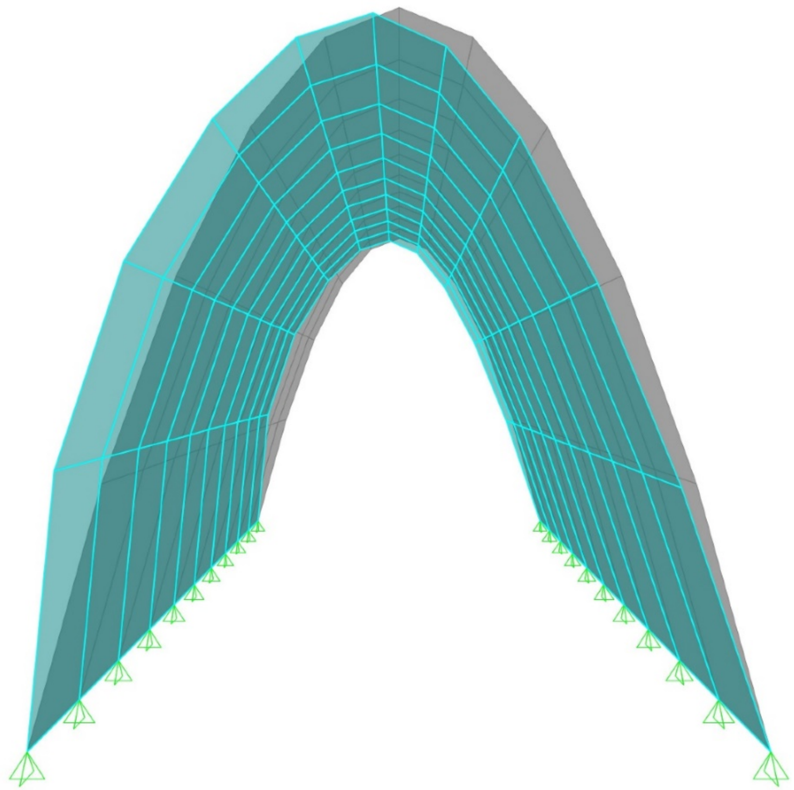
All in compression

Buckling (Self-Wt)



F.S. = 0.306

Buckling (0.3g Lateral)



F.S. = 1.225

SUMMARY OF ANALYSIS

LOADING	MODE 1 BUCKLING FACTORS			
	1” 1000psi LW (E = 1204ksi)	12” thick (E = 1204ksi)	10000psi (E = 3807ksi)	NW conc (E = 1802ksi)
Self-Wt	0.279	39.874	0.881	0.306
0.3g Lateral	1.116	159.675	3.528	1.225

Load Flow: All models nearly identical (in complete compression)

Shells more susceptible to buckling from self-weight than lateral

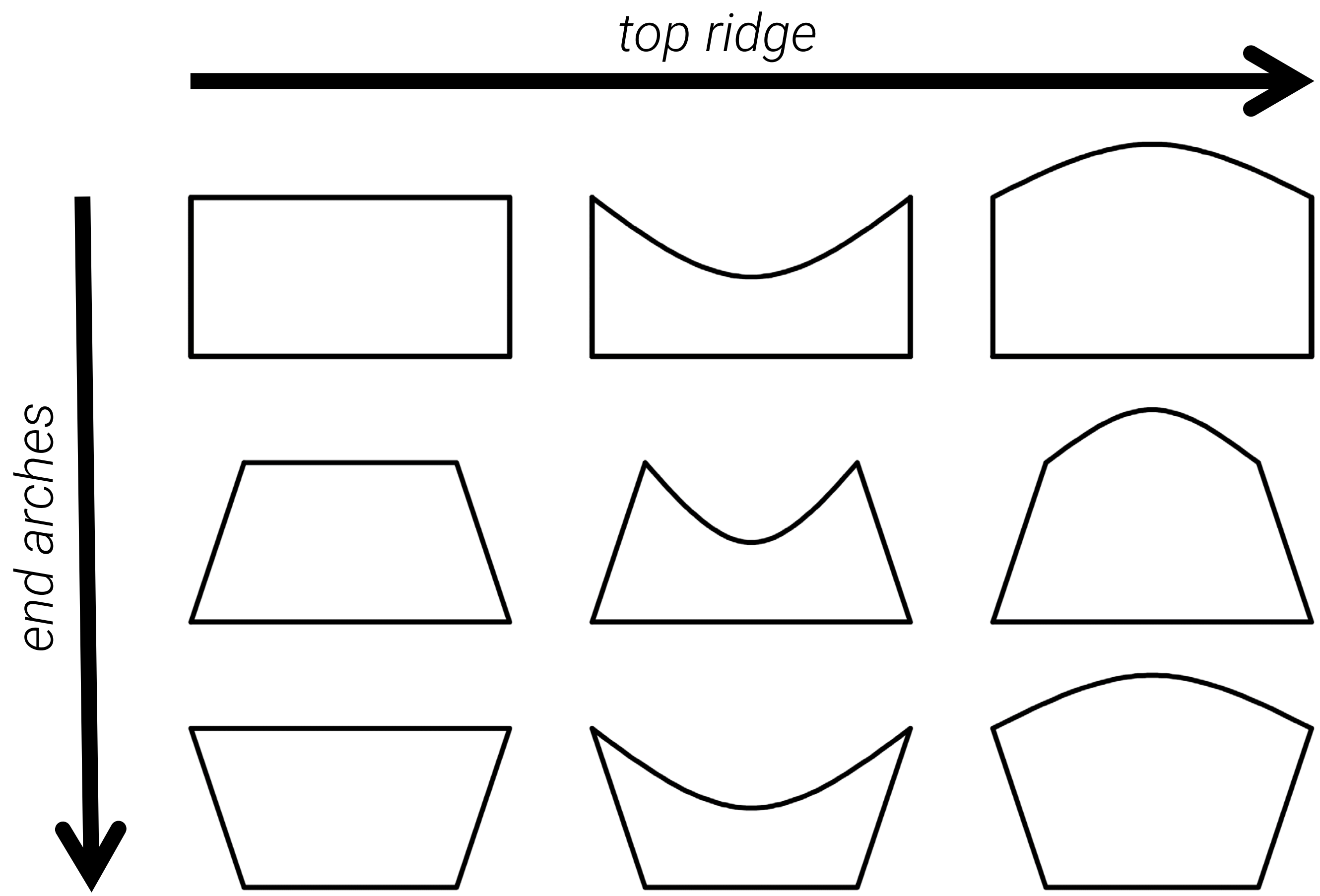
12” thick model: most buckling-resistant by a HUGE margin

Geometry → More important factor than material properties?

GEOMETRIC FORM STUDY

Variables:

- Curving of top ridge
- Leaning of end arches
- Overall dimensions of shell

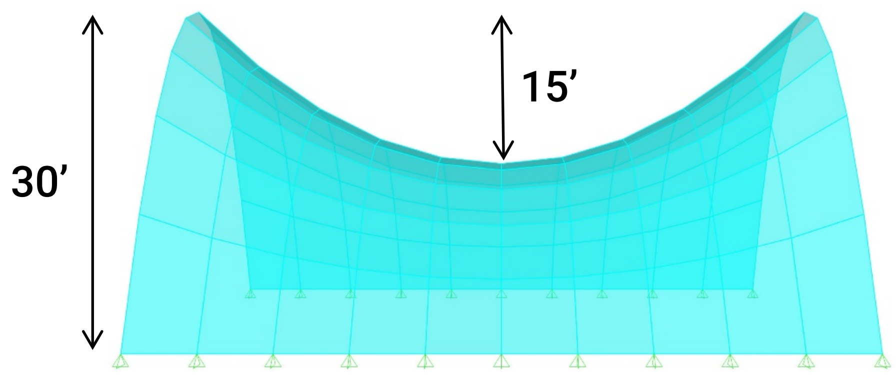


profiles of shell forms

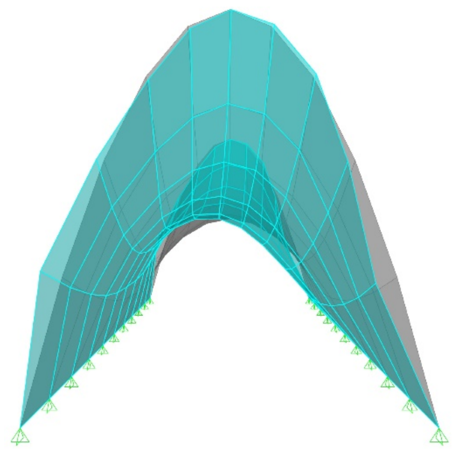
ITERATION 5: top ridge curves down

1" thick shell

1000 psi LW concrete (E = 1204 ksi)

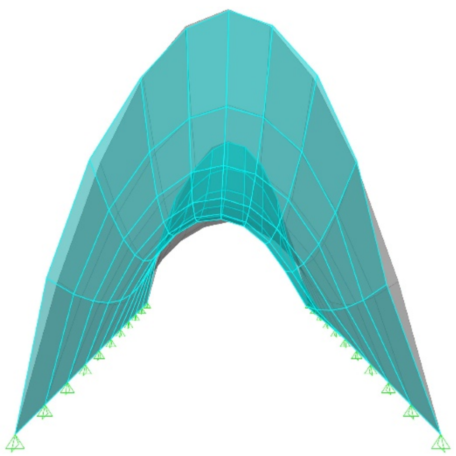


Buckling (Self-Wt)

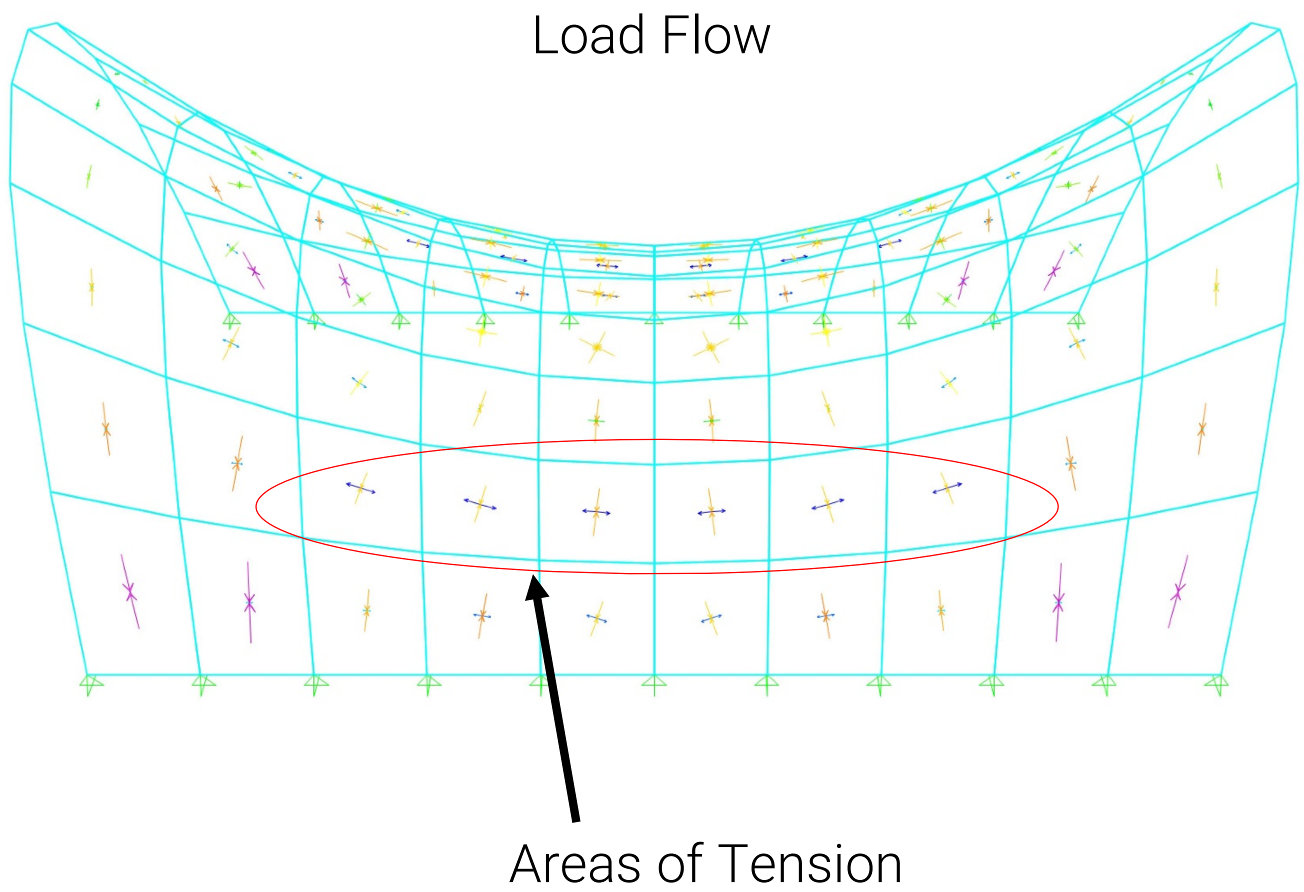


F.S. = 1.811

Buckling (0.3g Lateral)



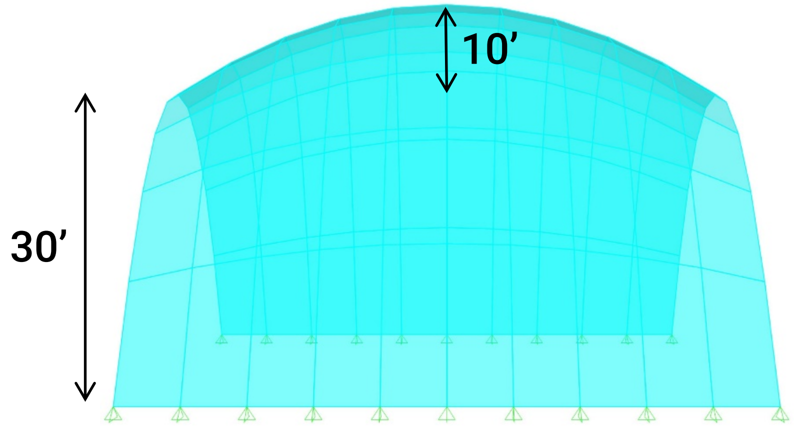
F.S. = 2.447



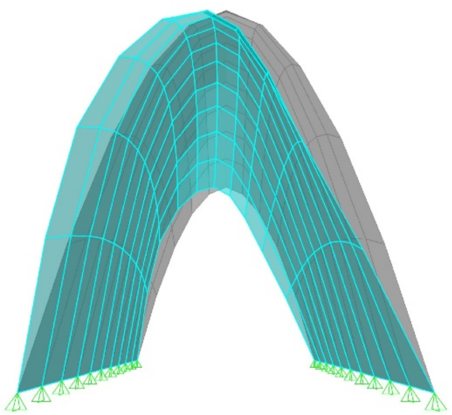
ITERATION 6: top ridge curves up

1” thick shell

1000 psi LW concrete (E = 1204 ksi)

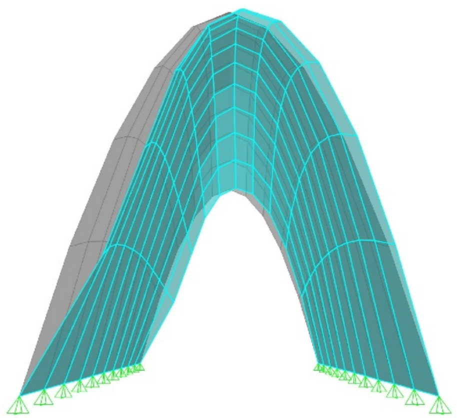


Buckling (Self-Wt)



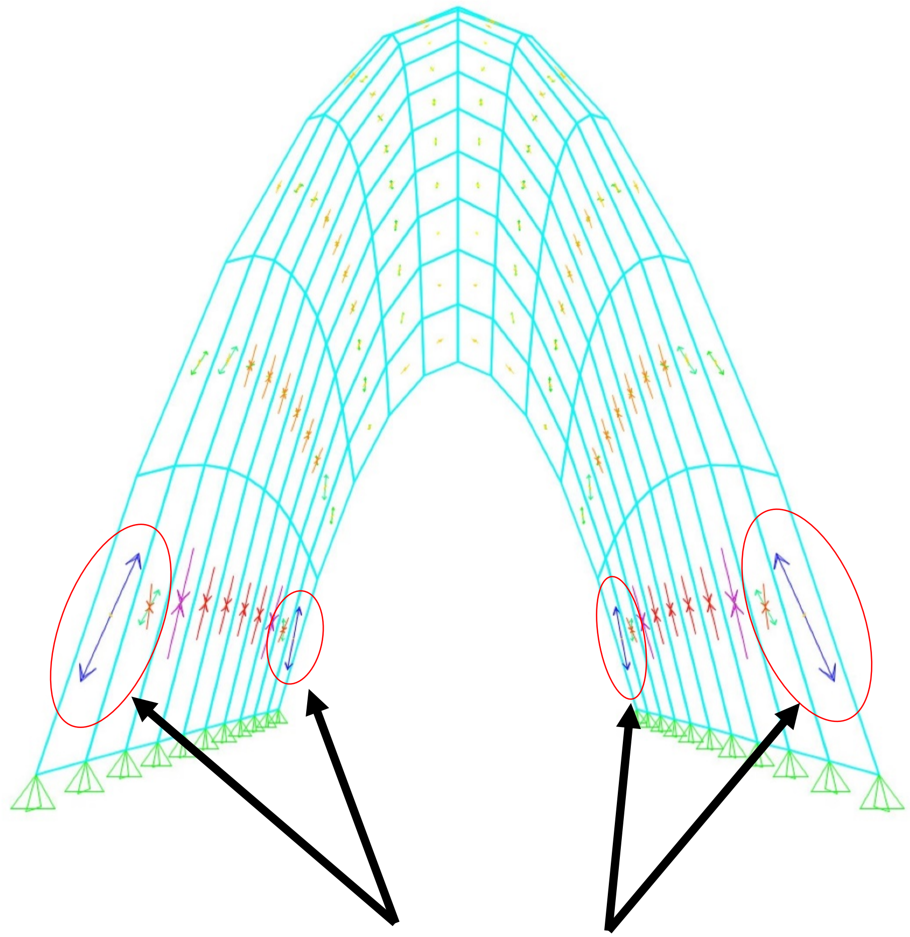
F.S. = 1.048

Buckling (0.3g Lateral)



F.S. = 0.219

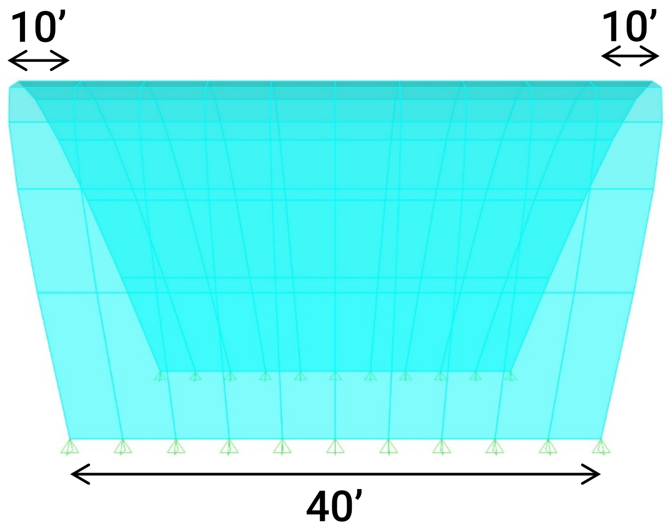
Load Flow



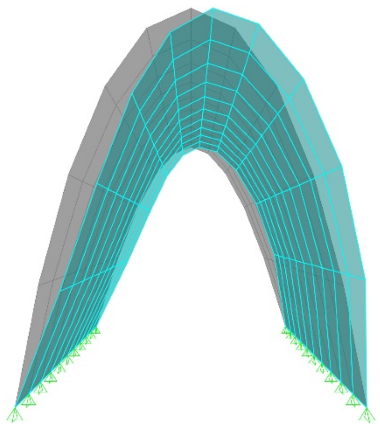
ITERATION 7: arches lean outward

1" thick shell

1000 psi LW concrete (E = 1204 ksi)

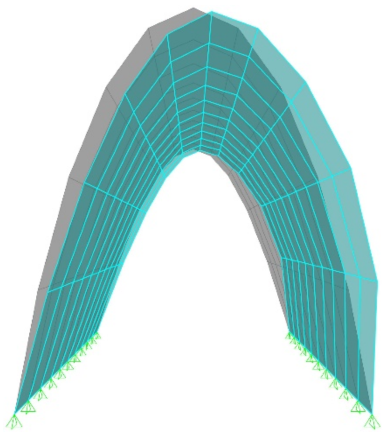


Buckling (Self-Wt)



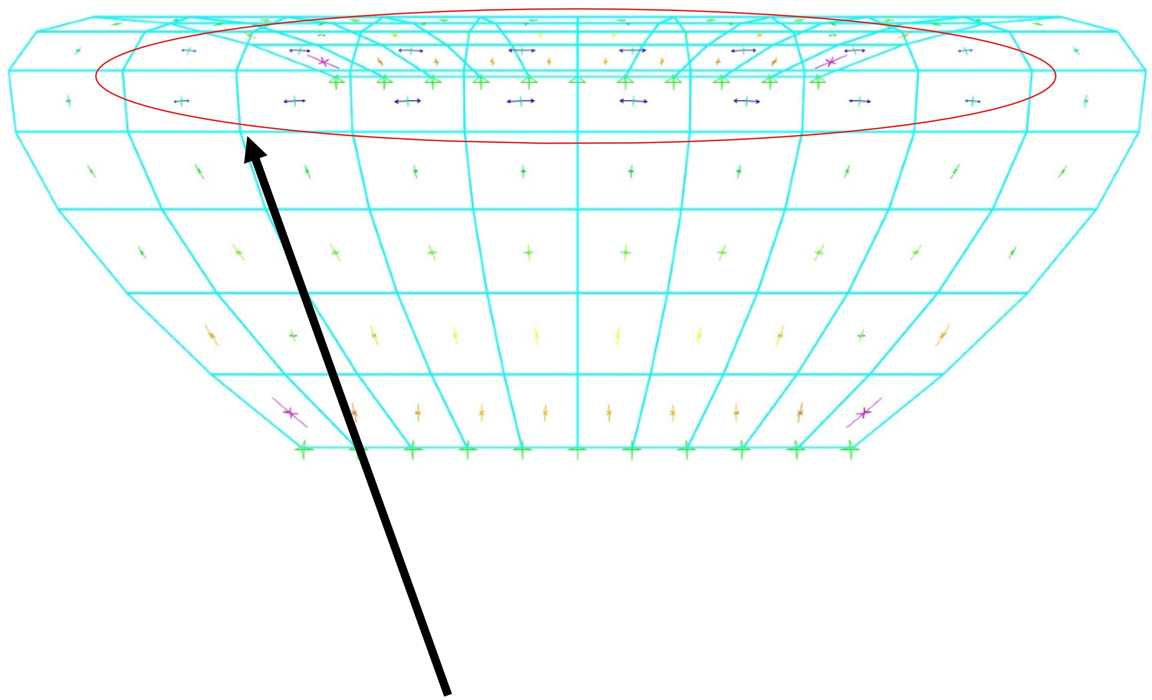
F.S. = 0.263

Buckling (0.3g Lateral)



F.S. = 0.998

Load Flow

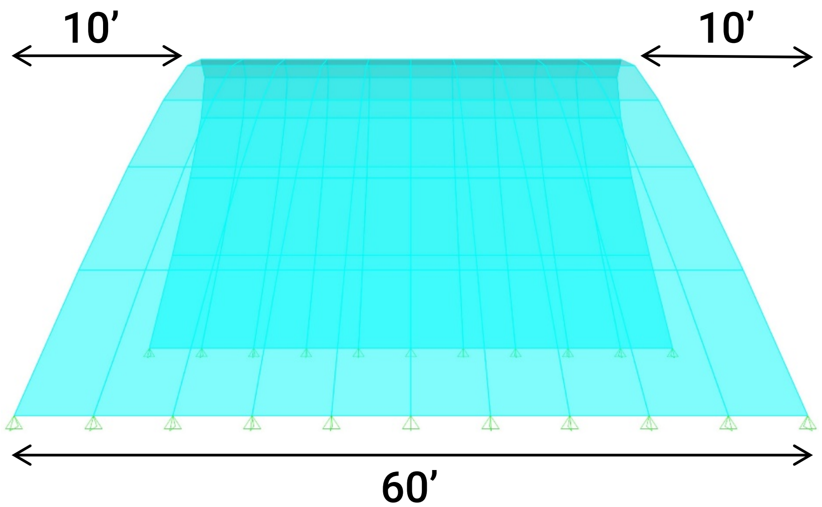


Areas of Tension

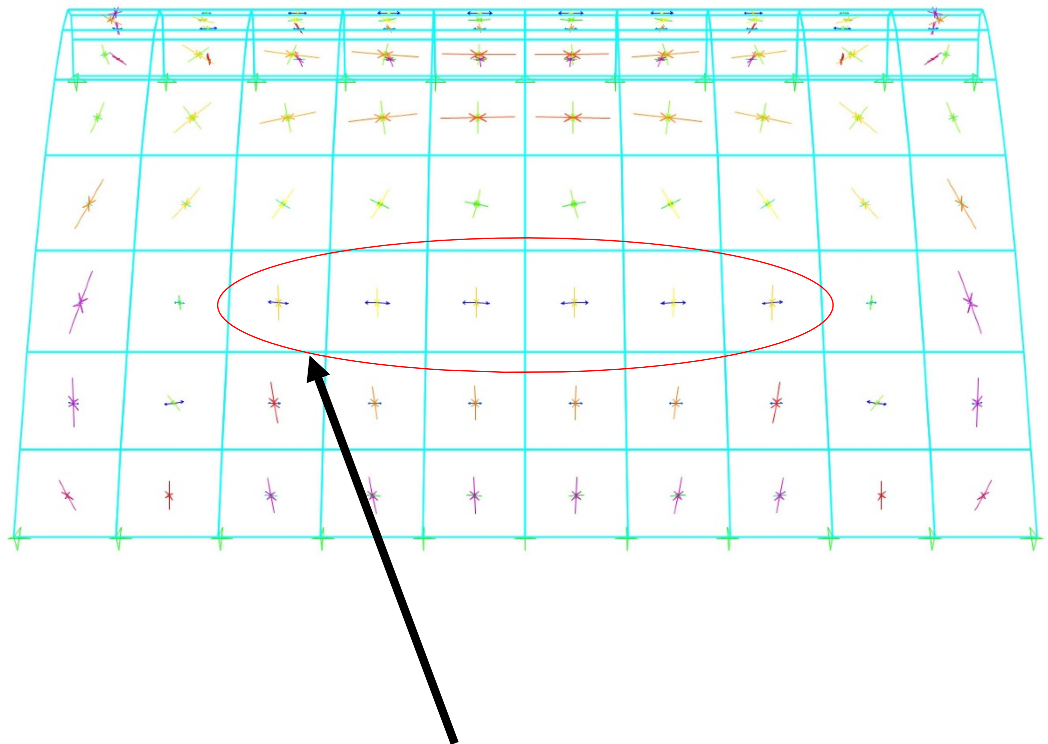
ITERATION 8: arches lean inward

1" thick shell

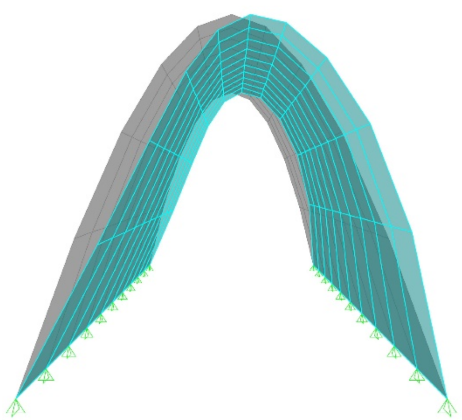
1000 psi LW concrete (E = 1204 ksi)



Load Flow

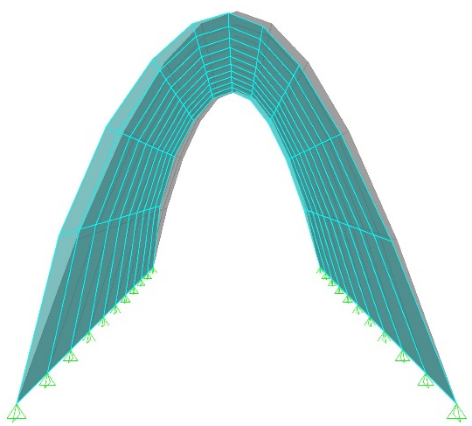


Buckling (Self-Wt)



F.S. = 0.289

Buckling (0.3g Lateral)

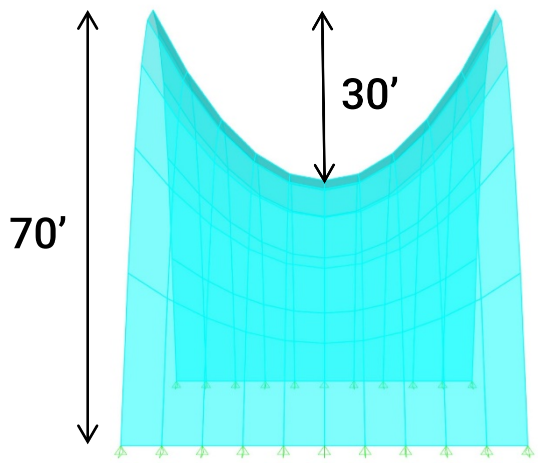


F.S. = 1.183

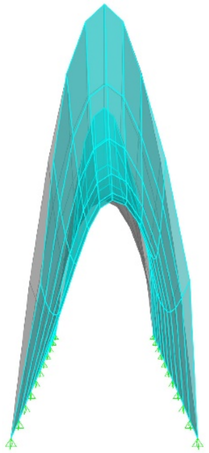
ITERATION 9: exaggerated height

1" thick shell

1000 psi LW concrete (E = 1204 ksi)

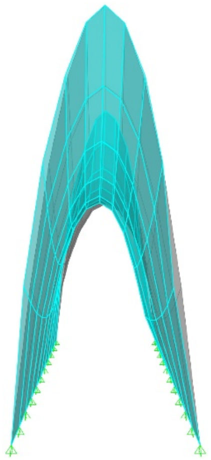


Buckling (Self-Wt)



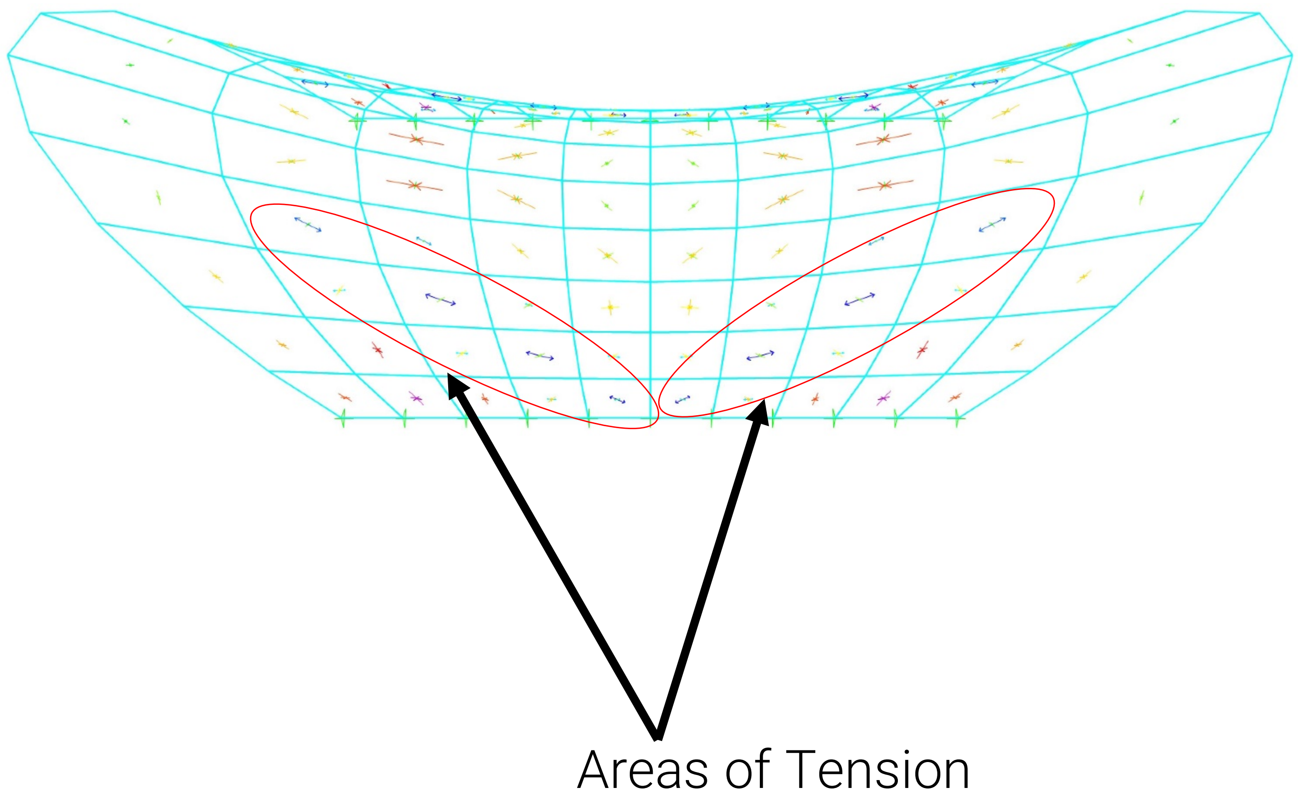
F.S. = 0.387

Buckling (0.3g Lateral)



F.S. = 0.110

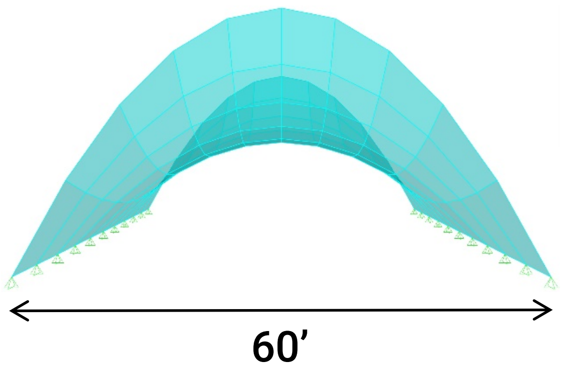
Load Flow

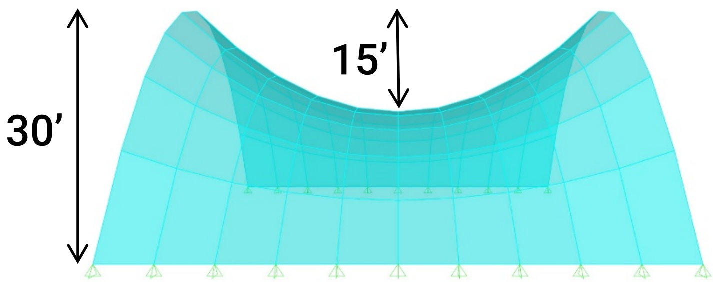


ITERATION 10: exaggerated width

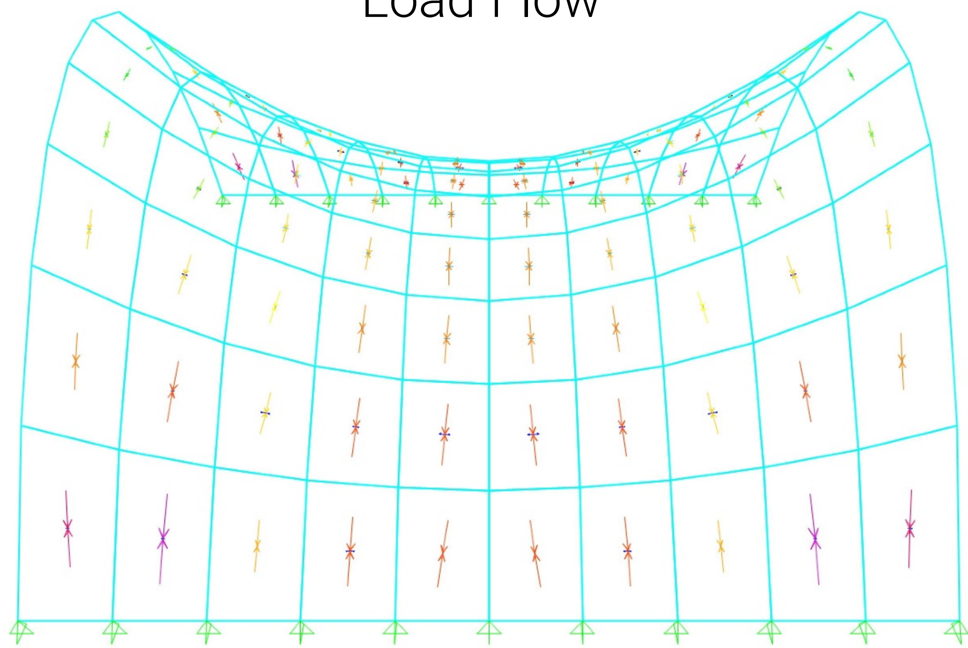
1” thick shell

1000 psi LW concrete (E = 1204 ksi)



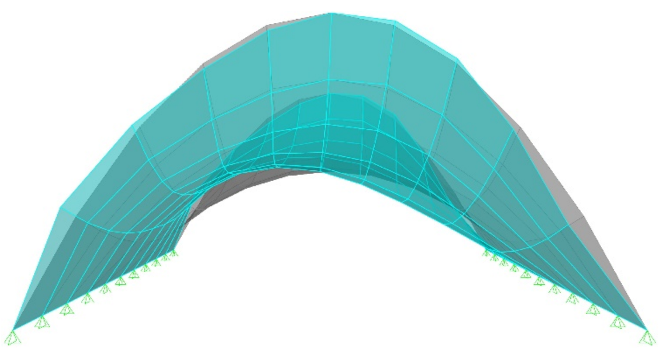


Load Flow



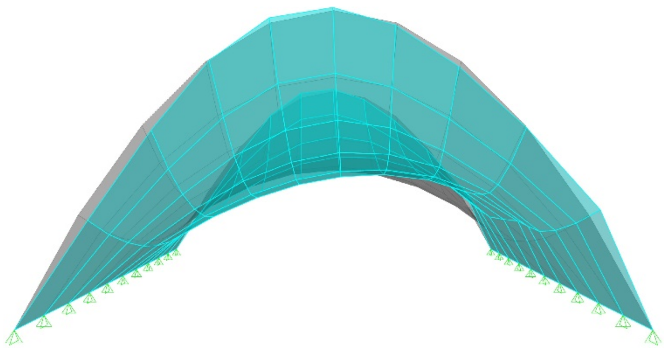
All in compression → Funicular!

Buckling (Self-Wt)



F.S. = 0.635

Buckling (0.3g Lateral)



F.S. = 1.675

SUMMARY OF ANALYSIS

LOADING	MODE 1 BUCKLING FACTOR						
	Single Curvature	Downward Curve	Upward Curve	Outward Arches	Inward Arches	Tall	Wide
Self-Wt	0.279	1.811	1.048	0.263	0.289	0.387	0.635
0.3g Lateral	1.116	2.447	0.219	0.998	1.183	0.110	1.675

*All shells: 1” 1000PSI LW conc

Downward curve → most resistant to buckling

Outward arches & Tall model → least resistant to buckling

Upward curve → buckles from lateral loading but not self-weight

Single Curvature & Wide model → Only ones with no tension (funicular!)