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.
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 DETERMINE BEAM SYSTEM**

**COLUMN REACTION AT A5**

\[ R_{xn} = \Sigma (\text{area load} \cdot \text{area} \cdot \text{loft}) \]

\[
\text{loft1} = 0.238 \\
\text{loft2} = 0.392
\]

**"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

\[ V = \Sigma (\text{area load} \times \text{area} \times \text{loft}) \]

\[
\begin{align*}
\text{areaLoad1} &= 100; \ \text{psf} \\
\text{area1} &= 7.5 \times 15; \ \text{sq ft} \\
\text{loft1} &= -0.0765; \\
\text{areaLoad2} &= 100; \ \text{psf} \\
\text{area2} &= 17.5 \times 15; \ \text{sq ft} \\
\text{loft2} &= 0.1765; \\
\text{areaLoad3} &= 50; \ \text{psf} \\
\text{area3} &= 15 \times 20; \ \text{sq ft} \\
\text{loft3} &= 0.1005; \\

V &= (\text{areaLoad1} \times \text{area1} \times \text{loft1} + \text{areaLoad2} \times \text{area2} \times \text{loft2} + \text{areaLoad3} \times \text{area3} \times \text{loft3}) / 1000 \ \text{kips} \\
V &= 5.2620 \text{kips}
\end{align*}
\]

"Müller-Breslau" Shear = 5.26 kips

"Actual" Shear = 5.25 kips

loft1 = -0.076
loft2 = 0.176
loft3 = 0.100

-0.3 LOFT AT LEFT OF CUT

0.7 LOFT AT RIGHT OF CUT

CUT IN BEAM
**MÜLLER-BRESLAU METHOD**
**ANALYSIS OF DETERMINATE BEAM SYSTEM**

**INTERNAL MOMENT AT CUT IN BEAM**

\[ M = \sum (\text{area load} \times \text{area} \times \text{loft}) \]

\[
\begin{align*}
\text{areaLoad1} &= 100; \text{psf} \\
\text{area1} &= 7.5 \times 15; \text{sq ft} \\
\text{loft1} &= 1.322'; \text{ft} \\
\text{areaLoad2} &= 100; \text{psf} \\
\text{area2} &= 17.5 \times 15; \text{sq ft} \\
\text{loft2} &= 1.317'; \text{ft} \\
\text{areaLoad3} &= 50; \text{psf} \\
\text{area3} &= 15 \times 20; \text{sq ft} \\
\text{loft3} &= 0.752'; \text{ft}
\end{align*}
\]

\[ M = \frac{(\text{areaLoad1} \times \text{area1} \times \text{loft1}) + (\text{areaLoad2} \times \text{area2} \times \text{loft2}) + (\text{areaLoad3} \times \text{area3} \times \text{loft3})}{1000} \text{ k-ft} \]

\[ M = 60.73 \text{ k-ft} \]

"Müller-Breslau" Moment = 60.73 k-ft

"Actual" Moment = 61.68 k-ft
UNSEEN:
A COLLABORATION BETWEEN ARCHITECT + ENGINEER

Image courtesy of Cheleza Furtado
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.

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
Axial Diagrams (Self-Weight)

Concrete Model

Steel Model

RED = COMPRESSION
Axial Diagrams (0.3g Lateral)

Concrete Model

Steel Model

RED = COMPRESSION
BLUE = TENSION
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
BUCKLING ANALYSIS

1ST ITERATION

LOAD FLOW

F.S. = 486

Mostly in compression
Large area of tension in middle
(Blue arrows) → NOT funicular
2ND ITERATION

ELEVATIONS

PLAN

1” 3000psi concrete
Higher compression forces on top
Decreased tension forces → NOT funicular

F.S. = 229
(Halved from 1ST iteration)
PRELIMINARY SHELL EXPLORATION #2
GROIN VAULT
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
PRECEDE NT 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

Buckling (Self-Wt)
F.S. = 0.881

Buckling (0.3g Lateral)
F.S. = 3.528

All in compression
ITERATION 4: NW concrete

1" thick shell
1000 psi NW concrete (E = 1802 ksi)

Load Flow
Buckling (Self-Wt)
Buckling (0.3g Lateral)

All in compression
F.S. = 0.306
F.S. = 1.225
## SUMMARY OF ANALYSIS

<table>
<thead>
<tr>
<th>LOADING</th>
<th>MODE 1 BUCKLING FACTORS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1” 1000psi LW (E = 1204ksi)</td>
<td>12” thick (E = 1204ksi)</td>
</tr>
<tr>
<td>Self-Wt</td>
<td>0.279</td>
</tr>
<tr>
<td>0.3g Lateral</td>
<td>1.116</td>
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</tbody>
</table>

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
ITERATION 5: top ridge curves down

30’

15’

1” thick shell
1000 psi LW concrete ($E = 1204$ ksi)

Areas of Tension

Load Flow

Buckling (Self-Wt) Buckling (0.3g Lateral)

F.S. = 1.811 F.S. = 2.447
ITERATION 6: top ridge curves up

1" thick shell
1000 psi LW concrete (E = 1204 ksi)

Areas of Tension

Load Flow

Buckling (Self-Wt)
Buckling (0.3g Lateral)

F.S. = 1.048
F.S. = 0.219
ITERATION 7: arches lean outward

1” thick shell
1000 psi LW concrete (E = 1204 ksi)

Load Flow

Areas of Tension

Buckling (Self-Wt) Buckling (0.3g Lateral)

F.S. = 0.263 F.S. = 0.998
ITERATION 8: arches lean inward

1" thick shell
1000 psi LW concrete (E = 1204 ksi)

F.S. = 0.289
F.S. = 1.183

Areas of Tension

Load Flow
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

Areas of Tension
ITERATION 10: exaggerated width

1" thick shell
1000 psi LW concrete (E = 1204 ksi)

F.S. = 0.635
F.S. = 1.675

All in compression → Funicular!
## SUMMARY OF ANALYSIS

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<tr>
<td></td>
<td>Single Curvature</td>
</tr>
<tr>
<td>Self-Wt</td>
<td>0.279</td>
</tr>
<tr>
<td>0.3g Lateral</td>
<td>1.116</td>
</tr>
</tbody>
</table>

Downward curve $\rightarrow$ most resistant to buckling

Outward arches & Tall model $\rightarrow$ least resistant to buckling

Upward curve $\rightarrow$ buckles from lateral loading but not self-weight

Single Curvature & Wide model $\rightarrow$ Only ones with no tension (funicular!)