[team

torroja]

lindsey brophy | brandon watrin | justine teoh

arce 415 | winter 2022 | ed saliklis
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[lindsey brophy]

My name is Lindsey, a Cal Poly student studying at the Architectural Engineering program. I am always finding the next outdoor challenge to attempt while I am in the beautiful city of San Luis Obispo.

[Brandon Watrin]

Hi! My name is Brandon and I am a senior Architectural Engineering major at Cal Poly SLO. I am a transfer student from the San Fernando Valley enjoying my last year in SLO. Also, I enjoy sports, and am a musician, producer, and videomaker.

[Justine Teoh]

Hello! My name is Justine and I am a fourth year Architectural Engineering major with a Music minor. I am originally from Seattle but I love the Central Coast. Some hobbies of mine include dancing, hiking, and reading as well as just anything arts and crafts!
[nathan lundberg]
We would like to recognize Nathan Lundberg for his significant contributions in developing the Grasshopper and G-Code for the various double shell and nesting codes. We also would like to acknowledge him for the design of our first shell.

[vince pauschek]
We would like to recognize Vince Pauschek for his significant contributions in developing and setting up the H-Connector testing and confinement. We also would like to acknowledge him for all his overall assistance and cooperation throughout the entire construction process of our shells.

[ed saliklis]
We would like to recognize Ed Saliklis for keeping the wild ideas (and coffee) flowing and for his help with supplying and advising the project.

[adria burton]
We would like to recognize Adria Burton for her contributions in testing the H-connections, the Hydrocal/ cladding.

[ethan mach]
We would like to recognize Ethan Mach for his contributions towards H-Connector testing.

[jay skaff]
We would like to recognize Jay Skaff for the design of the second shell.

[the winter 2022 ARCE 415 class]
We would like to recognize all members of our ARCE 415 class for their work on the group shells: from cutting, to assembly, to photos, to testing.
[acknowledgements]
For this project, we were tasked with designing a sun shelter by SLO Botanical Gardens for their Children's Garden. It was requested that the form be derived from structural shells. The structure is to serve as a multi-purpose space to host a variety of activities on the 30 foot by 60 foot site.
[project overview]
[digital discovery]
Opposite Page: Learning about shells and the fundamental principles through exploration of graphic statics and creating funicular diagrams in Geogebra (a graphical math-based engine). Then utilizing Rhino (computer-aided design program), Grasshopper (coding plug-in for Rhino), and Kangaroo 2 and Karamba (physics based engines within Grasshopper). Created and studied various methods of creating load-derived forms. In Grasshopper used catenaries (the curves a hanging chain assumes under self-weight; in pure tension/compression according to direction) (middle). In Kangaroo 2 and Karamba used spring-based "solvers" (bottom).

[SEE FORM FINDING FOR MORE]

Below: Utilized Karamba to perform analysis of simple beams to explore the analytical power and limits of the program.
[first shell]
[paper model]
Utilizing Nathan Lundberg's design for the "double shell" , featuring five footings and an oculus (Latin for "eye"; the inner hole giving the form its ring-like shape) we began with a laser-cut study model to learn about the forms behavior in real life and also to begin learning the labeling and organization system Nathan had thoroughly developed. This specific model used a quadrilateral mesh for its design.
All panels were connected to each other by a h-shaped connector that slotted into holes in the respective panels. So, each panel and H-connector had unique labels that identified the connecting pieces to allow for easy assembly.

Some of the major issues and observations we applied to the full scale were the slots in the panels for the H-connectors being too small and the footings not being adequate alone for thrust containment.
Assembly of the large-scale model began with cutting out the panels with the CNC machine (above) and jigsaws (upper right). Panels and H-connectors were then sorted out and assembled by sections according to their numbering (bottom right).
The shell was loaded until failure in order to test its capacity. A uniform load was emulated by using several 94 pound cement bags across the surface of the shell. Failure occurred at 1100-1200 pounds, due to thrust containment at the footing failing (the horizontal force the structure was placing on the footing exceeded the capacity of the containment system. See Footings and Thrust Containment for more).
[second shell]
[inspiration]
One of the main inspirations for the second shell was Felix Candela’s *Chapel Lomas de Cuernavaca* and its overhanging-type design
Taking what we learned from the first shell, we made some major changes for the second shell. First, we switched from small quadrilateral panels to larger triangular panels which allowed for larger engraving. Together the reduction in number of pieces and the larger labels helped reduce assembly time from 6 weeks to cut and assemble (first shell) to 2 weeks to cut and assemble (second shell). The triangular mesh also allowed for more efficient material usage since more panels could be fit onto one sheet.
Another major change was the material. We had used OSB for its availability and relatively low cost initially, but we switched to plywood for the second shell as it is stronger, more sustainable, and more uniform than OSB. Thus we gain both strength and aesthetic beauty.

The H-connectors were improved by rounding the corners of the tabs (for easier installation) as well as making them more unique shapes, and adding a carat in the engraving to indicated the down direction (so pieces could not be installed in the incorrect orientation).

[out with the old, in with the new]
The distance between the skins was reduced to help make the shell lighter.

The new shell has a more orthogonal footprint which allows for easier confinement and alignment of the forces.

Footings were changed from semi-circles to quadrilaterals to allow for the buttressing concrete blocks to be able to have more contact surface (this way the failure mode would not be thrust containment but rather the structure itself). However, these footings are potentially less sturdy. This is because the triangular shape of the panels meant there was less room for the panels to interlock with the footings since the footings must avoid the H-connectors.
The final major change between the first and the second shell was the footing design and placement. By aligning the footings and placing them parallel to each other, we are able to equally distribute the force and avoid introduction of additional stresses to the shell from the thrust containment.
[Symbolic]
We're reclaiming traditions of finding form by listening to the forces flowing through a structure.

[Social]
Building these load-informed structures allows for material efficiency (reduction of resource usage) and this method of panelized construction does not require particularly specialized labor.

[Global]
These shell-like structures can be assembled and built nearly anywhere once panels are acquired.

[significance of the work]
[Footings and Thrust Containment]
The footings and thrust containment can be further developed in order to more naturally integrate with the form of the shell.

[Form]
In this iteration of the course, we focused on the methods of construction and finding forms. In future iterations of the class can perhaps focus more on addressing the specific needs and environmental influences of the SLO Botanical Gardens and the Children's Garden. Similarly the aesthetics and implementation of elements such as the cladding can also be further developed.

[future improvements]
[Special Report: The Foundation] by brandon watrin
ORIGINAL PLAN FOR THE FOOTINGS:
- 4x perpendicular semi-circle panels interlocked with each skin layer
- There was no initial design for thrust containment.

Lesson learned from *paper model*:
-Friction alone cannot contain outward thrust.

*Thrust containment mechanism must be designed for Test Shell #1

[shell #1: foundation]
However, construction on Test Shell #1 had already started when we realized we needed to add some sort of thrust containment mechanism, so Ed Saliklis and I figured out a way to amend the shell design that already existed.

Several 2x4s were screwed on to each footing so that straps could be attached. Each footing was strapped to 1 of 2 central chain rings to apply tension that holds the footings in place once load is applied.
The footings with the 2x4 affixed to the exterior side proved to be a much better design. Because the strap is pulling in everything from the outside, the entire footing is within compression.

With the 2x4 affixed to the interior side of the footing, the screws are in withdrawal, and the footing connections are in tension, which is much weaker than compression for OSB.

Also, the non-orthogonal orientation of the footings lead to creates a torsion in the footing that is non-ideal. Some straps even laterally push on the perpendicular panels, creating a bearing pressure.

[shell #1: foundation]
Thrust containment was most likely the reason for structure failure.

Due to a constructibility obstacle in the field, the highlighted footing needed to be connected to both tension rings.

Well, this is most likely the cause of failure, because the 2x4 that was holding the straps ended up approximately 10 feet away from the footing it was attached to.

[shell #1: foundation]
When Shell #1 was tested, it failed from a distributed live load of 1125 lbs.

**Lessons learned from testing:**
- Ensure the members are in compression (except the straps)
- All footings should have equal tension
- Developing sturdy base beforehand diminished the constructibility.
- 2x4 strap rigging proved to be too bulky. (see below)

*attach footing platforms before all the footings were attached made it too difficult to connect the sections together, some flexibility in the panels is required.*

[shell #1: foundation]
TEST SHELL #2

To address the faults in the first shell's footings, we must dive in to the Grasshopper code, and open the "Double Shell Generation" cluster

[shell #2: foundation]
I was able to develop a grasshopper code to design the footings to be any size polygon, and adjust the height of footings. Code also needed to be developed so that the footings would lie flat, to be able to place the hole for the rebar in any location.

[shell #2: foundation]
Nathan Lundberg designed the perfect compromise between the square and triangular designs (figure shown furthest right)-

- the sides are at perpendicular angles so that it can be buttressed
- the top has a diagonal angle to accept the diagonal load.
- a hole is placed to run a steel bar through the footing plates to attach the straps to the footings.

= Footings are less sturdy (less room for panels to interlock)

The footing panels needed to be adjusted to account for the triangular shape, so the Grasshopper code needed to be redesigned.

[shell #2 vs shell #1]
- Improved footing design and placement

- More efficient orthogonal footprint

[shell #2 vs shell #1]
Both tension straps and buttressing used to resist thrust.

CONCLUSION-
With the redesigns to the overall shell, and especially the foundation, we are confident that the mode of failure for Test Shell #2 will not be thrust containment, and that we will be able to determine the shell’s crushing capacity to be far beyond it’s self-weight.

[shell #2: foundation]
[form finding] by Justine Teoh
[cats, lofts, meshes, form]
[EXPLORATIONS OF FORM]
(Opposite Page) Our goal was to find forms that would be in pure compression. Initially I started using Grasshopper’s catenary function to create four catenaries anchored at four points along the ground plane. I then use the loft function to create surfaces between the curves. In order to add complexity, I experimented with adding intermediate catenaries (anchored to two primary catenaries) to create different peaks in the lofted form.

(Current Page) Taking these ideas of catenaries and anchoring, I then experimented anchoring all constituent catenaries to a central point, for both four and five points along the ground.

It is noted that this method of form finding is limited by the limitations of the loft function.
Exploring the capacities of Grasshopper and its associated plug-ins of Kangaroo 2 and Karamba (two physics-based solvers), we attempted to emulate previously created forms using the built in Bouncy Solver and Zombie Solver functions. The goal was to find a similar form more rooted in physics as it accounted for the interaction between points rather than arbitrary and independent catenaries as before.

Taking inspiration from the initial catenary studies and from the idea of amphitheaters I experimented with lofting between two intersecting catenaries: one horizontal and one vertical, but tilted along the axis at which the two catenaries intersected. I used a similar idea when revisiting the initial four catenary explorations by turning two of the opposing catenaries on their sides and tilting the remaining two catenaries.
(Opposite Page) The fine-tuning of the horizontal catenary base and the tilted arches resulted in a form similar to that of Felix Candela’s *Chapel Lomas de Cuernavaca*.

(Current Page) Deciding to take one step back, I raised a horizontal catenary to vertical to emulate a more canopy-like form rather than an tunnel-like form. The progress from base curves to shell to double shell can be seen above.
(Current Page) After deciding upon the desired shape I utilized various re-meshing functions to compare different mesh patterns. (These meshes take the desired shapes and approximates the 3-D form in a series of 2-D panels) I settled on the triangular mesh pattern and then experimented with resolution of the re-meshed form by varying the sizes of the constituent triangles.

(Opposite Page) The progression of the three forms can be seen rendered as well as the plan and elevation views of the final designed shell. In aid stability, flat feet were added to the base where the shell meets the ground at two points. Thus contact surface was increased.
To further refine the final design, the footprint of the design was taken and flattened back down to provide the base shape for the physics-based zombie solver. After defining the corresponding anchors and boundaries, and adjusting the input parameters, the resulting form was reached with three entrances leading into the covered space. The corresponding double shell for the refined and the final designs (based on a triangular-mesh) are both shown.
[h-]

testing

by Lindsey Brophy
compression and tension tests were conducted and set up on Tinus Olsen
# Blowout Distance Impacts on Tensile Strength

<table>
<thead>
<tr>
<th>Ratio'd Edge Distance (AS %)</th>
<th>Average Strength (LBF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{.25}{.75} \times 100 = 33.3%)</td>
<td>178</td>
</tr>
<tr>
<td>(\frac{.25}{.875} \times 100 = 28.6%)</td>
<td>158</td>
</tr>
<tr>
<td>(\frac{.25}{1.125} \times 100 = 22.2%)</td>
<td>116</td>
</tr>
</tbody>
</table>

[tensile blowout strength]
[hydrocal testing] by lindsey brophy
YIELD SPECIMENS

SPALDING

FAILURE MODE: TENSILE RUPTURE
monks cloth dipped in hydrocal

consists of two iterations, each placed on broken pieces of shell no. 1
H-Connection Strength Testing
By Lindsey Brophy, Adria Burton, and Ethan Mach

1.0 Compression:
1.1 Test Set-Up:

Loading was applied via the Tinius Olsen testing apparatus. A single point load was applied to the center of the tab (see Figure 1.1.1 below), to test the strength of the H-Connection. The specimen was divided into two equal pieces, and stabilized with the machine’s plates and bolts (see Figure 1.1.1 below). The loading was applied at 0.25 inches/minute until yielding occurred in the OSB.

![Figure 1.1.1: Compression Test Set-Up](image)
1.2 Data Analysis:
The OSB yielded with a range of 140 lbf, and an overall average compressive strength capacity of 342 lbf per tab (see Table 1.2.1 below). The nominal 3/4” OSB varied slightly in thickness, contributing to the range of strength. Overall, there was very little observed displacement (0.16” average), and no cracks in the OSB. While the material yielded, the H tabs did not break off.

Table 1.2.1: Compression Strength Test

<table>
<thead>
<tr>
<th>Trial</th>
<th>Compression Force (lbf)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>321</td>
<td>0.173</td>
</tr>
<tr>
<td>2</td>
<td>268</td>
<td>0.113</td>
</tr>
<tr>
<td>3</td>
<td>409</td>
<td>0.203</td>
</tr>
<tr>
<td>4</td>
<td>346</td>
<td>0.117</td>
</tr>
<tr>
<td>5</td>
<td>365</td>
<td>0.198</td>
</tr>
<tr>
<td>Average</td>
<td>342</td>
<td>0.161</td>
</tr>
</tbody>
</table>

1.3 Method of Failure:
The tab reached yielding point, with visible splitting of the OSB and deformation of the specimen - however the tab remained attached to the rest of the “H-Connector,” (see Figure 1.3.1 below).
1.4 Secondary Compressive Test:
Following the first compressive test, changes were made to the structure of the “H-Connectors” in an attempt to increase their strength. Tab size was increased from the original 3/4” to 1-13/16” for one specimen set, and a third tab was added on another specimen set. Each of these variations was expected to increase the overall strength of the H-Connectors.
<table>
<thead>
<tr>
<th>Trial</th>
<th>Compression Force (lbf)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>321</td>
<td>0.173</td>
</tr>
<tr>
<td>2</td>
<td>268</td>
<td>0.113</td>
</tr>
<tr>
<td>3</td>
<td>409</td>
<td>0.203</td>
</tr>
<tr>
<td>4</td>
<td>346</td>
<td>0.117</td>
</tr>
<tr>
<td>5</td>
<td>365</td>
<td>0.198</td>
</tr>
<tr>
<td>Average</td>
<td>342</td>
<td>0.161</td>
</tr>
</tbody>
</table>

### Table 1.4.2: Compression Strength Test of 1-13/16” Tab

<table>
<thead>
<tr>
<th>Trial</th>
<th>Compression Force (lbf)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>369</td>
<td>0.423</td>
</tr>
<tr>
<td>2</td>
<td>389</td>
<td>0.163</td>
</tr>
<tr>
<td>3</td>
<td>388</td>
<td>0.079</td>
</tr>
<tr>
<td>4</td>
<td>320</td>
<td>0.157</td>
</tr>
<tr>
<td>5</td>
<td>374</td>
<td>0.214</td>
</tr>
<tr>
<td>Average</td>
<td>368</td>
<td>0.207</td>
</tr>
</tbody>
</table>

### Table 1.4.3: Compression Strength Test of ¾” Tab with E-Shape (3-tabs)

<table>
<thead>
<tr>
<th>Trial</th>
<th>Compression Force (lbf)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>204</td>
<td>0.106</td>
</tr>
<tr>
<td>2</td>
<td>167</td>
<td>0.117</td>
</tr>
<tr>
<td>3</td>
<td>105</td>
<td>0.148</td>
</tr>
<tr>
<td>4</td>
<td>253</td>
<td>0.163</td>
</tr>
<tr>
<td>5</td>
<td>202</td>
<td>0.113</td>
</tr>
<tr>
<td>Average</td>
<td>186</td>
<td>0.130</td>
</tr>
</tbody>
</table>
From testing new tab sizes based on thickness of tabs and number of tabs, the thickness allowed for slightly higher compressive strength but not substantially higher. The change in material allows for greater analyses.

1.5 Material Testing:
After completing more OSB plywood compression tests, we created a control on the relative tab size and changed the material to 3/4” thick plywood. The inference of strength related to the material is predicted to be stronger than the OSB plywood.

Table 1.5.1: Compression Strength Test of Plywood Tab

<table>
<thead>
<tr>
<th>Plywood Tab</th>
<th>Compression Force (lbf)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>207</td>
<td>0.819</td>
</tr>
<tr>
<td>2</td>
<td>312</td>
<td>0.291</td>
</tr>
<tr>
<td>3</td>
<td>870</td>
<td>0.456</td>
</tr>
<tr>
<td>4</td>
<td>375</td>
<td>0.093</td>
</tr>
<tr>
<td>5</td>
<td>467</td>
<td>0.210</td>
</tr>
<tr>
<td>Average</td>
<td>446</td>
<td>0.374</td>
</tr>
</tbody>
</table>
Based on data collected from Table 1.5.1, two outliers created an unstable compression force average to be compared to the OSB plywood values. After removing the outliers of 206.824 lbf and 870.011 lbf, the new average is 384.923 lbf. From this new value, we created assumptions of strength related to the material types used.

2.0 Tension:

2.1 Test Set-Up

The Tinius Olsen was utilized again to test the tension capacity of the tabs. Holes were drilled into each tab, and bolts were threaded through each tab in order to be connected to the machine. The testing machine would gradually pull the top bolt upwards at a rate of 0.25 inches per minute until the failure state was reached (see Figure 2.1.1).

![Tinius Olsen Tensile Test Set-Up](image)

*Figure 2.1.1: Tinius Olsen Tensile Test Set-Up*

The initial tension strength test consisted of the 3/4” tabs of OSB plywood, then subsequently the 7/8” tab and the 1-1/8” tab. Each test consisted of five trials with the assumption that the thickest tab would have the greatest tensile strength.


### Table 2.1.1: Tensile Strength Test of 3/4” Tab

<table>
<thead>
<tr>
<th>Trial</th>
<th>Tension Force (lbf)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>186</td>
<td>0.051</td>
</tr>
<tr>
<td>2</td>
<td>166</td>
<td>0.161</td>
</tr>
<tr>
<td>3</td>
<td>175</td>
<td>0.089</td>
</tr>
<tr>
<td>4</td>
<td>208</td>
<td>0.281</td>
</tr>
<tr>
<td>5</td>
<td>155</td>
<td>0.134</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>178</strong></td>
<td><strong>0.143</strong></td>
</tr>
</tbody>
</table>

### Table 2.1.2: Tensile Strength Test of 7/8” Tab

<table>
<thead>
<tr>
<th>Trial</th>
<th>Tension Force (lbf)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>182</td>
<td>0.420</td>
</tr>
<tr>
<td>2</td>
<td>149</td>
<td>0.359</td>
</tr>
<tr>
<td>3</td>
<td>103</td>
<td>0.225</td>
</tr>
<tr>
<td>4</td>
<td>235</td>
<td>0.245</td>
</tr>
<tr>
<td>5</td>
<td>123</td>
<td>0.192</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>158</strong></td>
<td><strong>0.288</strong></td>
</tr>
</tbody>
</table>

### Table 2.1.3: Tensile Strength Test of 1-1/8” Tab

<table>
<thead>
<tr>
<th>Trial</th>
<th>Tension Force (lbf)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>61</td>
<td>0.193</td>
</tr>
<tr>
<td>2</td>
<td>79</td>
<td>0.265</td>
</tr>
<tr>
<td>3</td>
<td>205</td>
<td>0.367</td>
</tr>
<tr>
<td>4</td>
<td>78</td>
<td>0.254</td>
</tr>
<tr>
<td>5</td>
<td>159</td>
<td>0.313</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>116</strong></td>
<td><strong>0.278</strong></td>
</tr>
</tbody>
</table>

From the tensile strength results, the assumption of failure being largest with the smaller tabs was incorrect. Instead, the method of failure is closely related to the location of the hole to the edge of tab distance, or “x” (see Figure 2.1.2 below). The breakout of hole to the edge of the
tab occurs at a higher chance when “x” is small. Based on this knowledge, the test needed to be updated to compare the edge distance to the relative connection strength (Figure 2.1.3).

Figure 2.1.2: Tensile Test Failure Mode with “x” Distance

Figure 2.1.4: Bolt Hole Breakout
3.0 Conclusion:
The tabs on the H-connections are significantly stronger in compression than tension. In fact, the average compression capacity of the connections is nearly twice the value of the average tension capacity. Omitting the holes in the tabs would most likely increase the tension capacity of the connections. However, in our trial specimen the holes were drilled and placed by hand with no regard for accuracy compared to the specified design. If holes are necessary for the overall structure, then the CNC machine’s accuracy and precision is required to create the holes.
HYDROCAL Strength Testing
By Lindsey Brophy and Adria Burton

1.0 Compression:
1.1 Test Set-Up:

Loading is applied using the RIEHLE testing machine by using a constant loading of force (see Figure 1.1.1). From each of the two specimens, the force is recorded and compared with surface area to determine a total strength of the Hydrocal.

![Test Set-Up on RIEHLE Testing Machine](image)

Figure 1.1.1: Test Set-Up on RIEHLE Testing Machine

1.2 Test Results:

The advertised uncured compressive strength of HYDROCAL is 1000 psi. The two (2x4 Cylinder) specimens were tested after 1 week, and left in a water bath. The first specimen had no visual imperfections, and had a strength 23% higher than advertised. The second specimen had a large (visual) air pocket, and still was tested to have a strength equivalent to the advertised strength (see Table 1.2-1).
Table 1.2-1: Hydrocal Compression Test Results

<table>
<thead>
<tr>
<th>Trial</th>
<th>Expected Maximum Strength (psi)</th>
<th>Force (lbs)</th>
<th>Area (in²)</th>
<th>Strength (psi)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>3875</td>
<td>3.14</td>
<td>1233</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>3150</td>
<td>3.14</td>
<td>1003</td>
<td>0</td>
</tr>
<tr>
<td>Average</td>
<td>1000</td>
<td>3513</td>
<td>3.14</td>
<td>1118</td>
<td>12</td>
</tr>
</tbody>
</table>

1.3 Failure Modes:
The failure mode was tensile rupture, and spalding action was observed as the specimens were loaded (see Figure 1.3.1 and 1.3.2).

*Figure 1.3.1: Spalding at Yielding*
Figure 1.3.2: Tensile Rupture