POR TFO LIO

CANDELA

AN INTERDISCIPLINARY CAPSTONE
SENIOR PROJECT - WINTER 2022

INTRODUCTION

Analysis and evaluation of interdisciplinary challenges associated with integrating the design and construction processes to deliver innovative thin shell structures

CONTENT

TEAM MEMBERS

PARTICIPATING CLASS INTERDISCIPLINARY CAPSTONE PROJECT:
USING NATHAN LUNDBERG'S GRASSHOPPER CODE IN RHINO
TO CONSTRUCT DOUBLE-SKINNED SHELL STRUCTURES

Alexis Truong

Designer/Engineer/Fabricator

Choma Shell Case study
RV2 Funicular form-finding
Finite Analysis

Adria Buton

Designer/Engineer/Fabricator

H-connectors testing
Cladding exploration
Hydrocal Testing

Ethan Mach

Designer/Engineer/Fabricator

Xomichilco Case Study
H-connectors testing
Cladding exploration

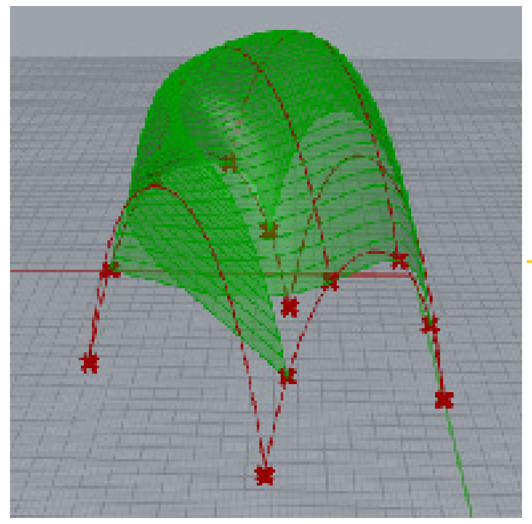
COURSE TIMELINE

A brief timeline of the 10 week senior project course

01/2022

WEEK 1

Software exploration including Geogebra, Rhino 3D, and Grasshopper



WEEKS 2 - 3

Utilized the CNC machine, jigsaws, and routers to carve out OSB panels for the first class shell

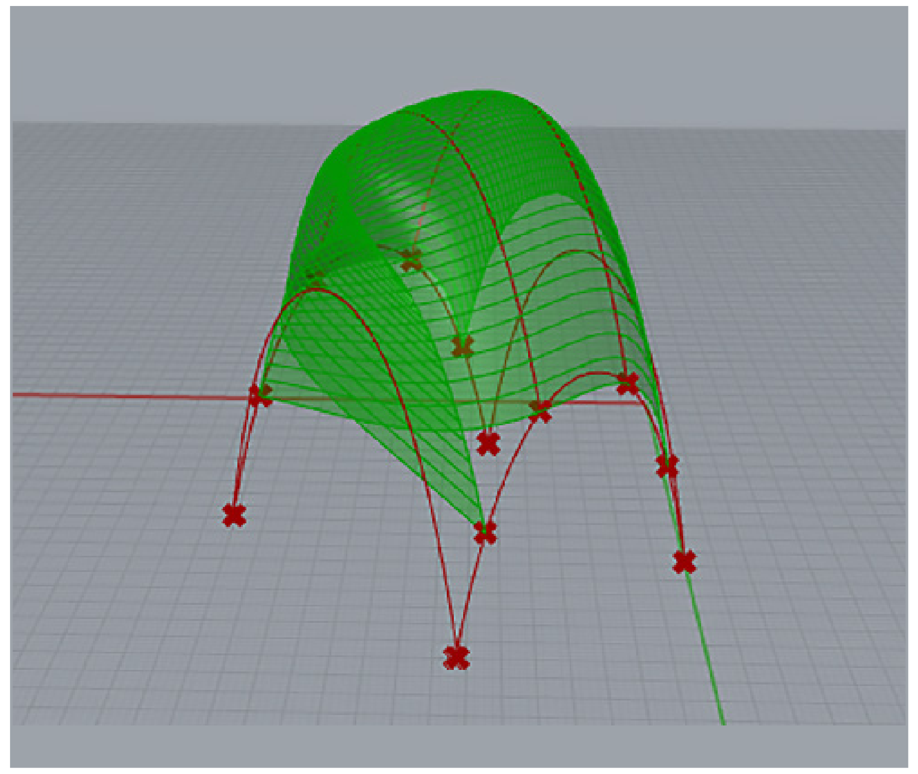
WEEKS 4 - 6

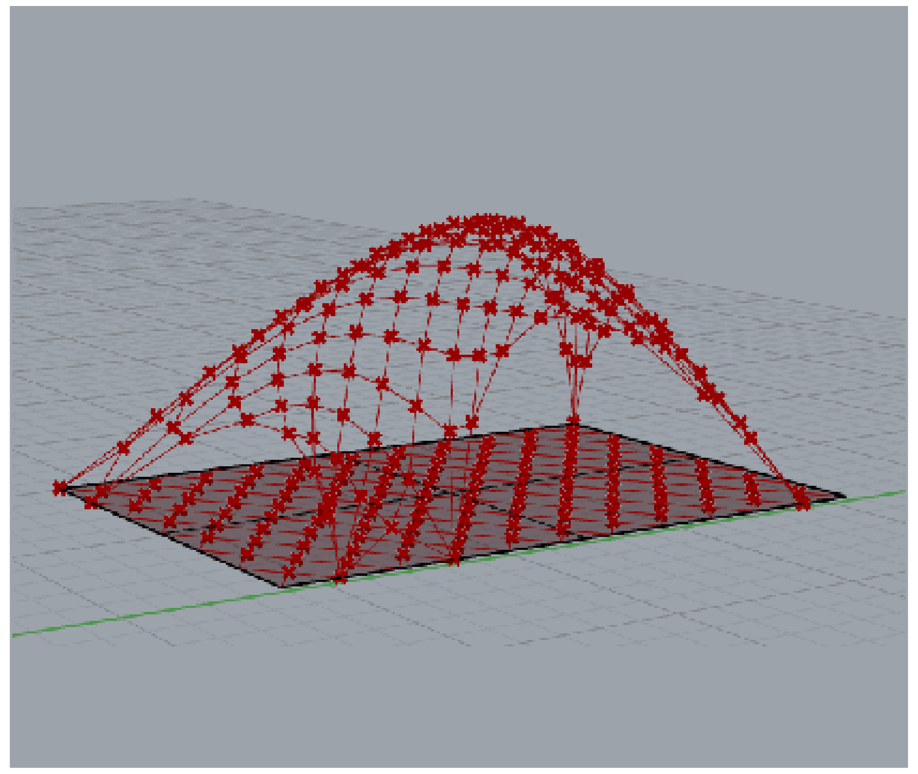
Construction of the first class shell by hand followed by load testing

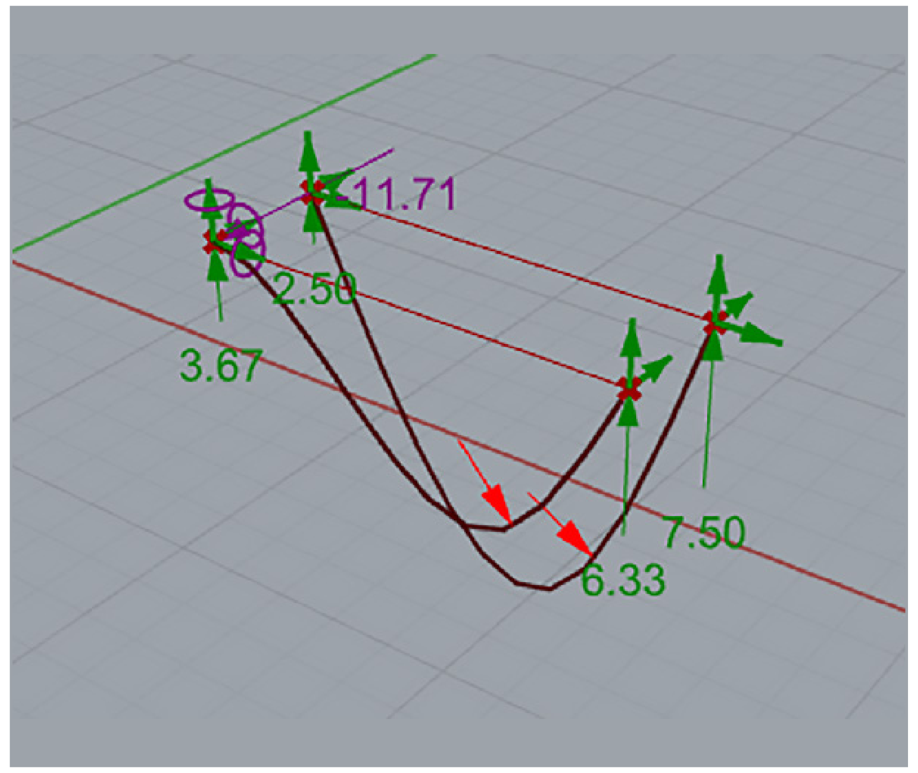
WEEKS 7 - 9

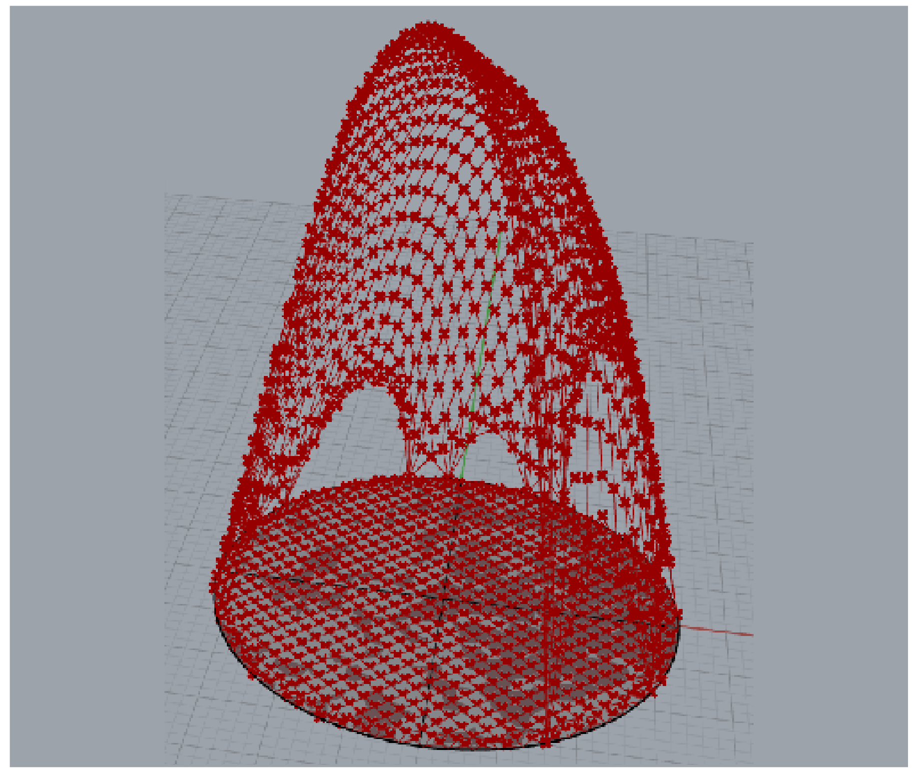
Carved out plywood panels for the second class shell and constructed the model by hand

03/2022









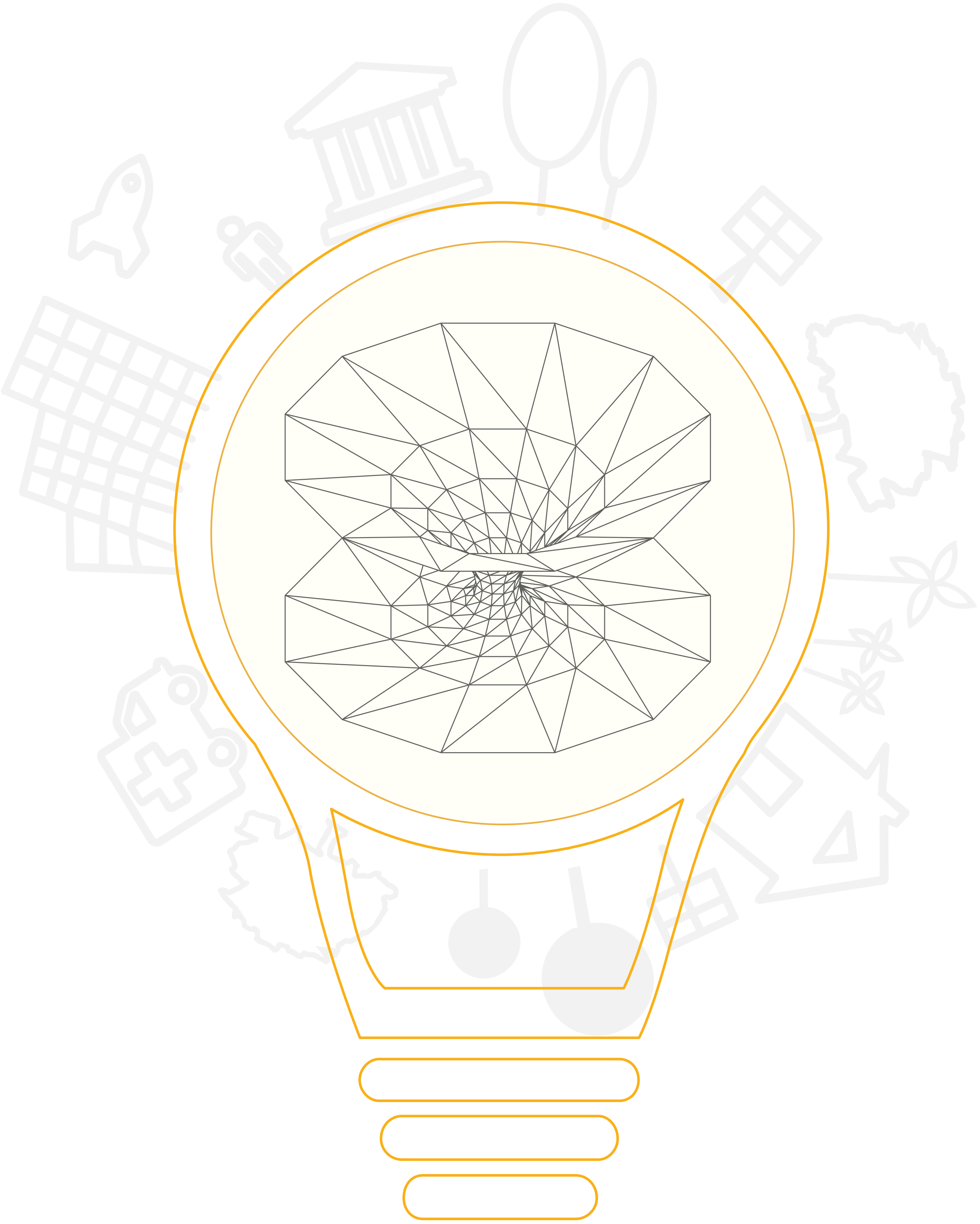
A DIGITAL INTRODUCTION

During the first week of this senior project course, the class was introduced to a few unique applications, including Geogebra, Rhino 3D, Grasshoper, and Karamba3D.

These programs allowed the class to experiment with a variety of tools, from lofted shell forms using the Kangaroo Bouncy Solver to the deflection of a cantilever beam in Karamba3D.

PROJECT SCOPE

Analysis and evaluation of interdisciplinary challenges associated with integrating the design and construction processes to deliver innovative thin shell structures



1 **CASE STUDY**

From mathematical shells to hypar and funicular shells

2 **FORM FINDING**

Introducing Rhino, Grasshopper, Rhino Vault 2

3 **FINITE ELEMENT ANALYSIS**

Karamba and SAP2000. Forces and stresses due to self-weight

4 **CONSTRUCTION**

Assembling CNC cut OSB/Ply-wood panels, H test, and cladding exploration.

CASE STUDY

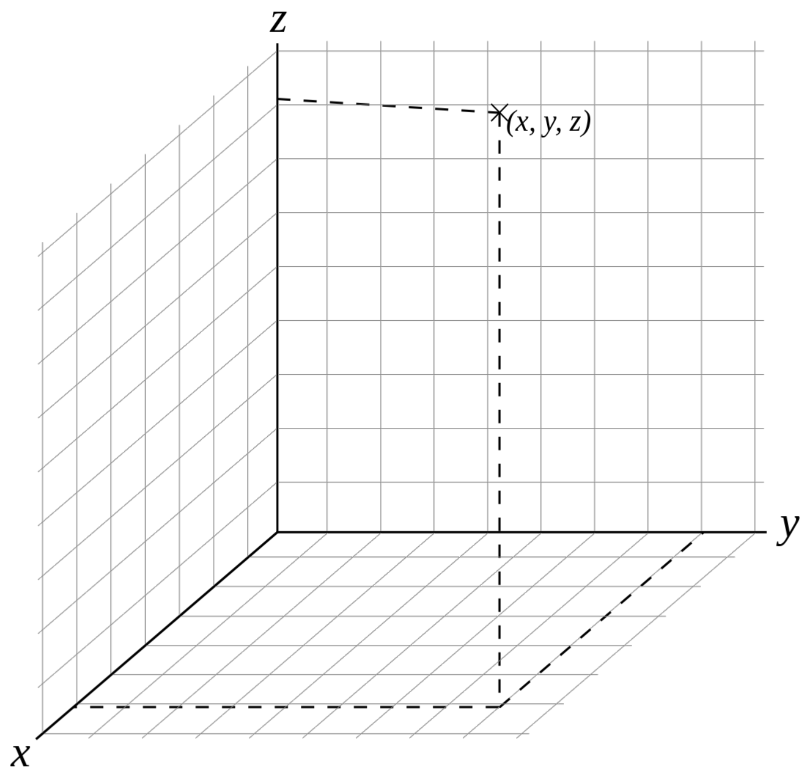
CHOMA

MORPHING GUIDELINE

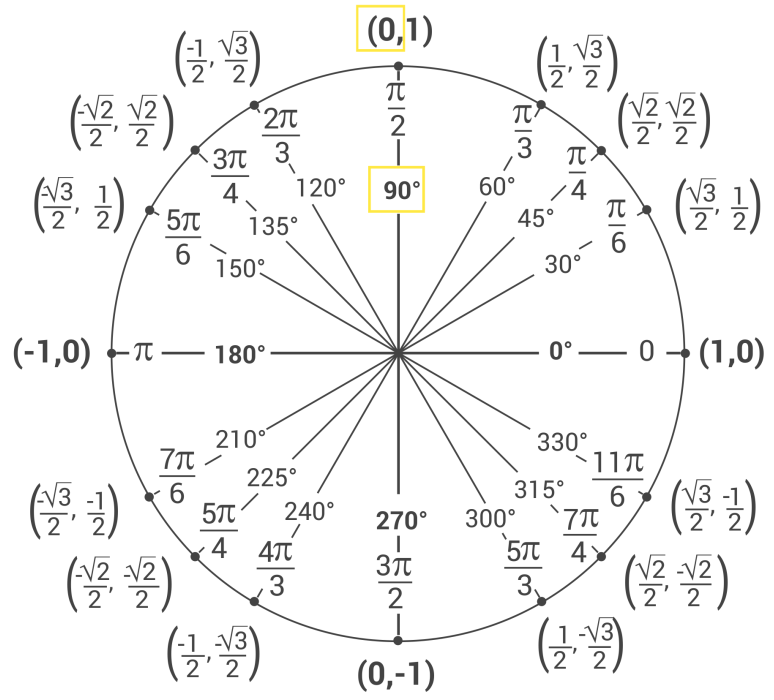
Joseph Choma states that a shape can be mathematically defined with a geometric boundary using a parametric equation in 3-dimensions. As long as a shape maintains its topological continuity, it can be defined by a single equation.

A parametric equation is one way of defining values of coordinates (x,y,z) for shapes with parameters (u,v). And in Cartesian coordinate, xyz is a three-dimensional grid; and uv are domain/range of values or parameters from 0 to (n)pi. The equation then maps the points within the range in three dimensions.

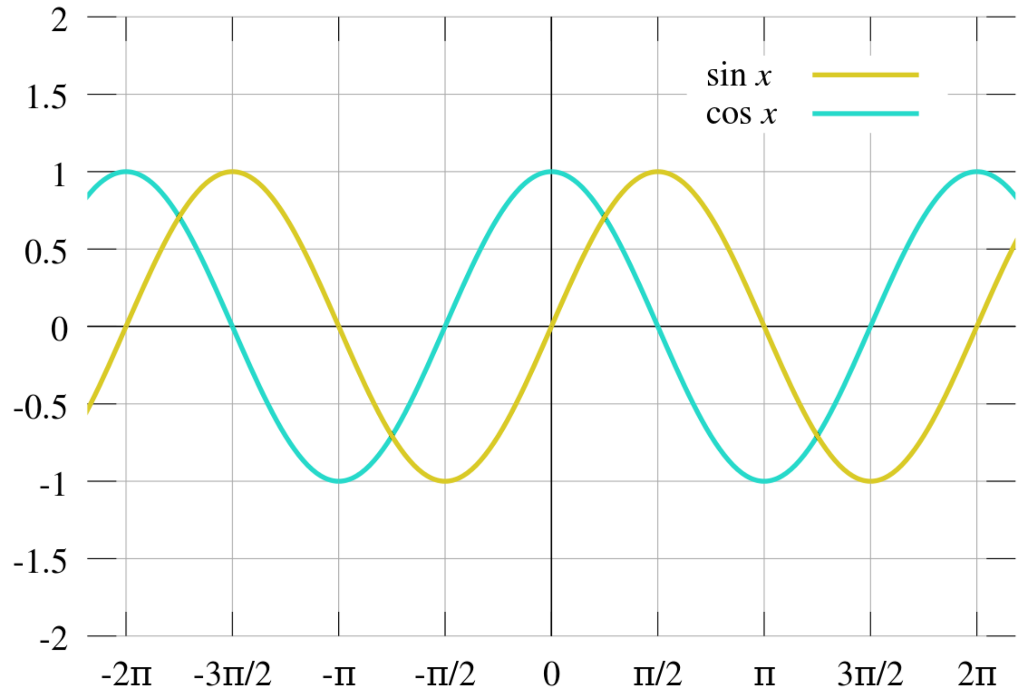
In his guideline, only the functions of sine and cosine are examined to describe shapes. Trigonometry is used to manipulate shapes and understand how each function influences a particular transformation. As the coordinates xyz are altered the shape's two-dimensional projections will change. And mathematical transformations refer to the categorized rules for manipulating shapes with mathematical operations.



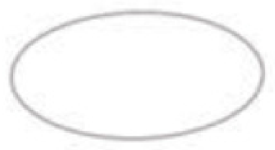
(x,y,z) Cartesian coordinates



(u,v) parameters



sin(u), cos(u) functions



$\{ u \mid 0 \leq u \geq 2\pi \}$

$x = \cos(u)$
$y = \sin(u)$

$\{ (u,v) \mid 0 \leq u \geq 2\pi, 0 \leq v \geq \pi/3 \}$

$x = \cos(u)$
$y = \sin(u)$
$z = v$

MATHEMATICAL
TRANSFORMATION

Collection of six mathematical transformations out of thirteen from the morphing guideline was used for this exercise to explore the possibility of the mathematical implementation in form-finding

y = 1 + sin(u)

Shape moves 1 dis tance in y-direction

Translating

Once adding intergers to a particular coordinate, the shape moves in that direction

y = sin(pi/2)cos(u) - cos(pi/2)sin(u)

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Ref ecting

Multiplying function with -cos(pi/2) then add sin(pi/2)cos(u) results the re - ection at 45 degree

y = 2sin(u)

Shape scale 2 times its size in y-direction

Scaling

Multiplying a shape by an integer will scale that shape accordingly

Modulating

Integers that are embeded inside a trigonometric function control the fre - quency of the curve de ned

y = sin(4u)

Shape repeats its pattern 4 times

Ascending

Adding a u-parameter shifts the shape and produce a diagonal trajectory

y = u + sin(4u)

Shape follows u diagonal line in y direction

Spiralling

Once multiplying function with a u-parameter, the radius of the curve increases incrementally

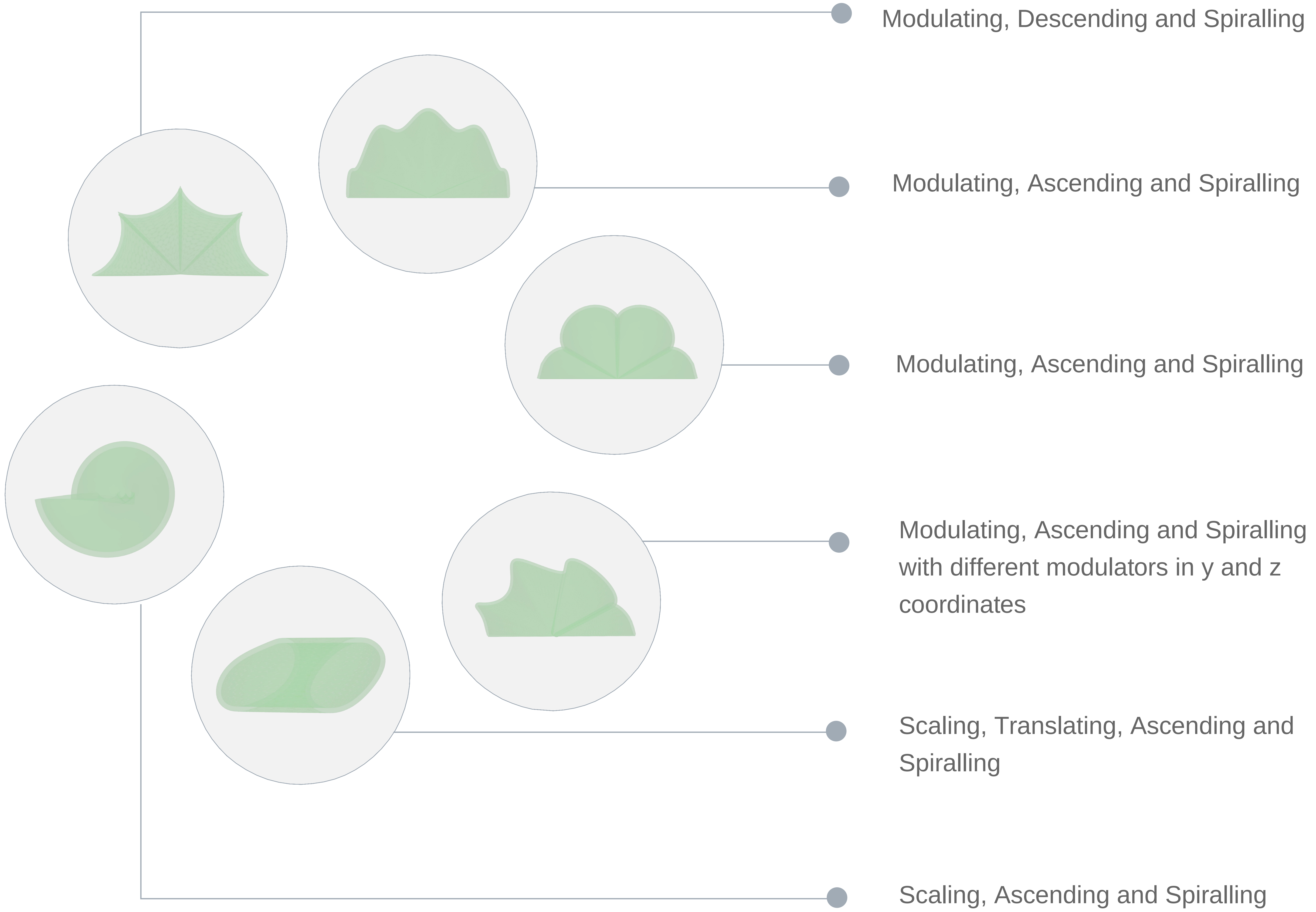
y = u sin(u)

Shape stretches iteratively outward

The goal of the exploration is to study shell shapes in the history of form-finding by introducing mathematical constraints as an innovative step from free-form-finding. Then, there will be a discussion structural design process for the funicular shell.

Mathematics was invented to understand the universe. Through the shell design lens, it is the logical way to explain nature. Shells in nature such as a seashell, the earth sphere, or frog feet membranes are structures or mechanism that was perfected through the infinite of time.

'Mathematic is a formalist discipline'. This study examines what Choma found in his guideline to understand the relationship between shapes and mathematical transformations. Hence the success of creating variations from the practice of manipulating the trigonometric equations. And technical skills are enhanced through learning and practicing Rhino, Grasshopper, Weaverbird plugin, and 3D Printing to bring the models to life.



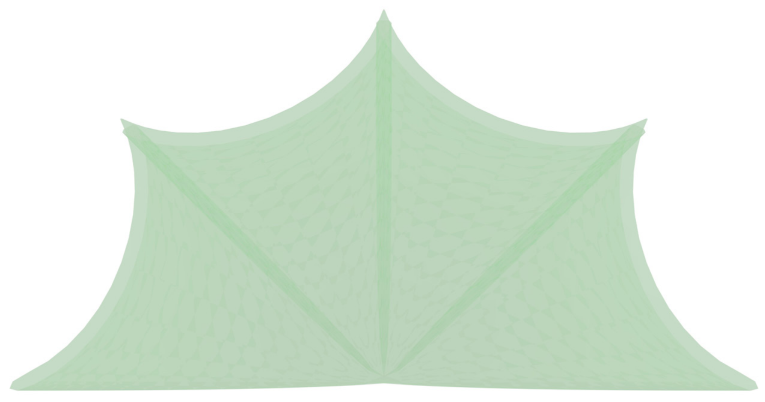
SHELL EXPLORATION

GEOMETRIC SHELLS DESIGNED FROM PARAMETRIC EQUATIONS

- defining values of coordinates (x, y, z) for shapes with parameters (u, v)

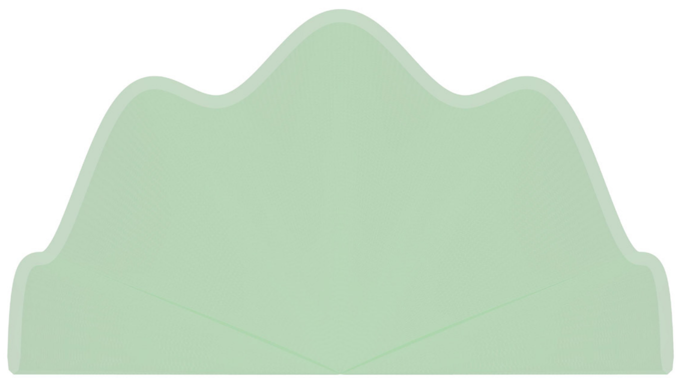
$x = \sin(v)(\cos(v)+\cos(7a)/7)$
$y = \cos(u)$
$z = \sin(u)*(\sin(v)-\sin(7v)/7)$

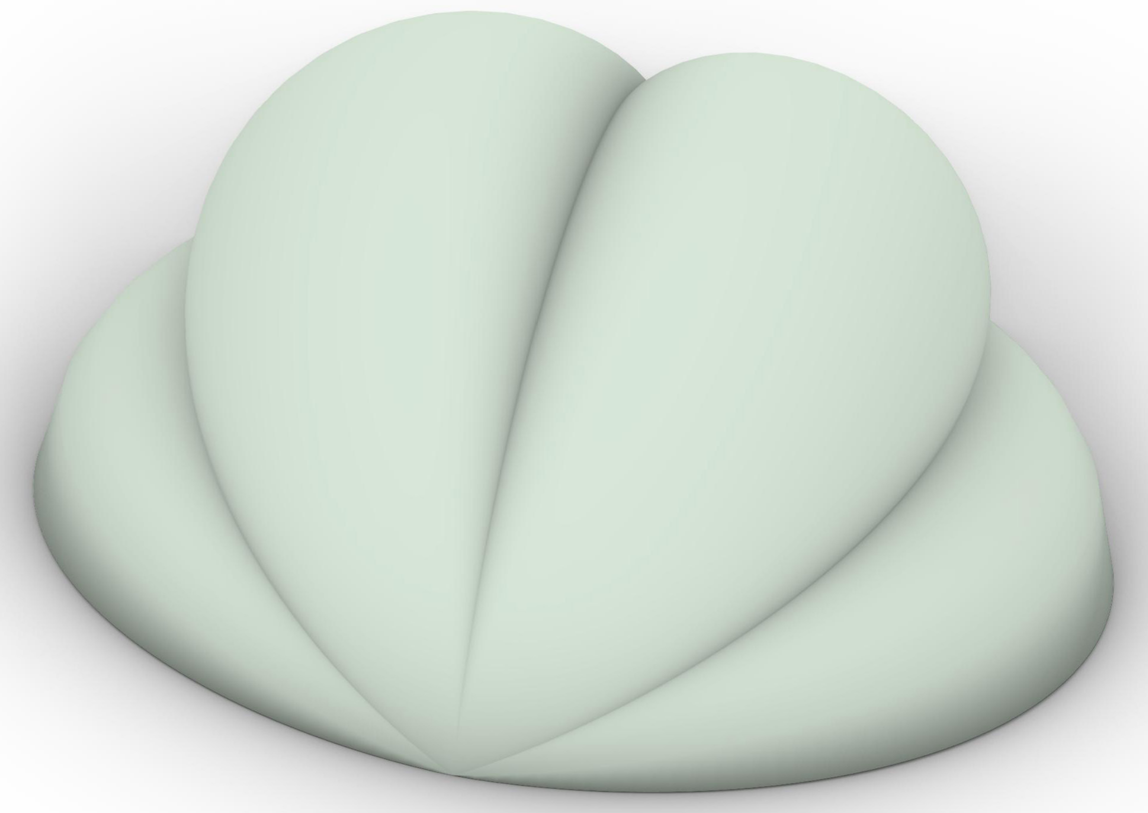
$\{ (u,v) \mid 0 \leq u \geq \pi, 0 \leq v \geq \pi \}$



$x = \cos(u)$
$y = \sin(u)\cos(v)$
$z = \sin(u)(\sin(v)+\sin(9v)/9)$

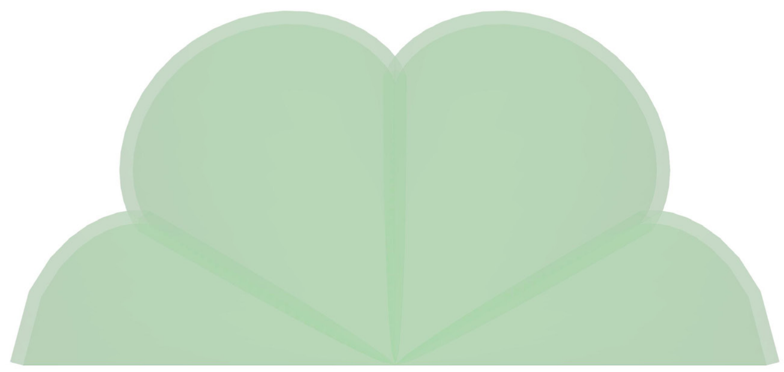
$\{ (u,v) \mid 0 \leq u \geq \pi, 0 \leq v \geq \pi \}$





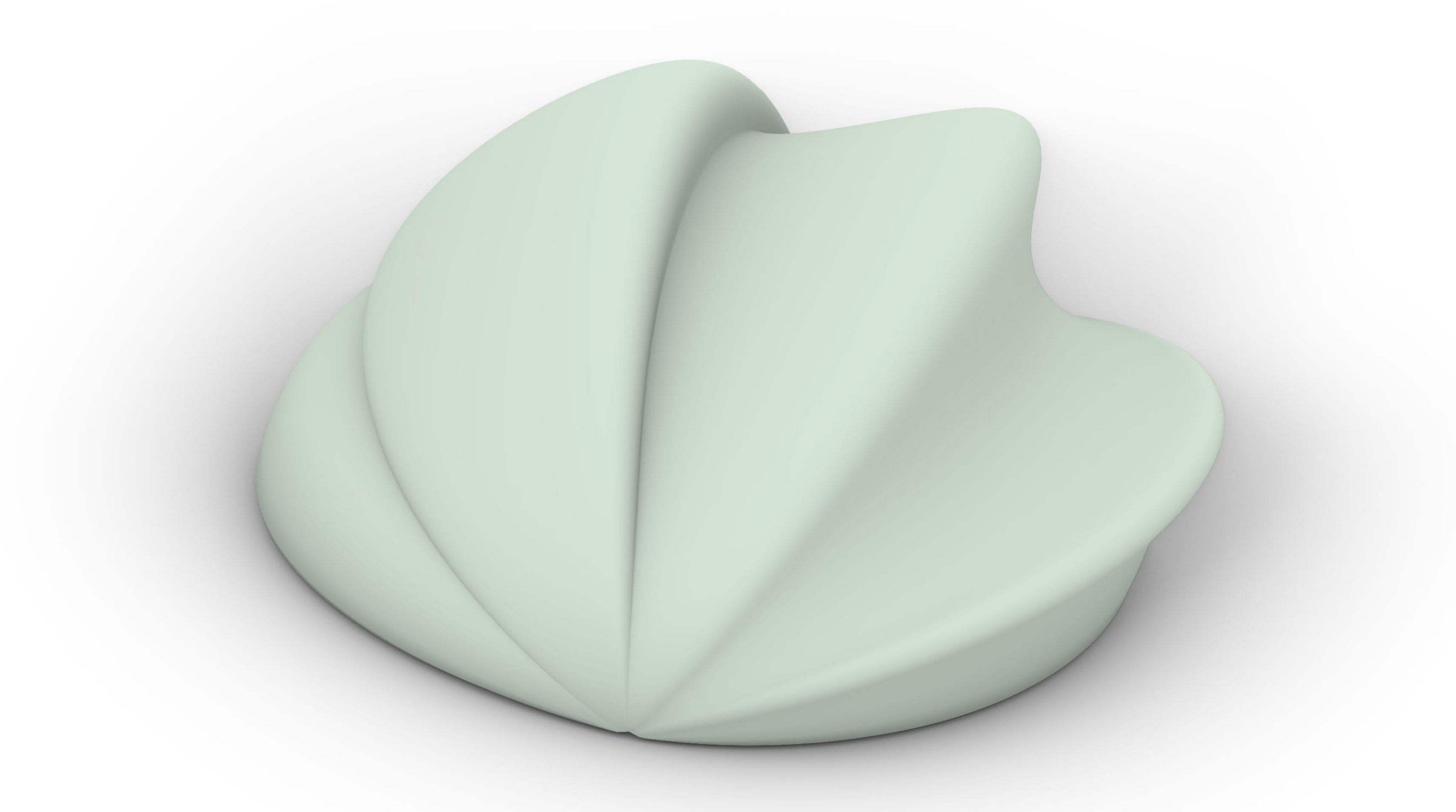
$x = \cos(u)$
$y = \sin(u)(\cos(v)+\cos(7v)/7)$
$z = \sin(u)(\sin(v)+\sin(7v)/7)$

$\{ (u,v) \mid 0 \leq u \geq \pi, 0 \leq v \geq \pi \}$



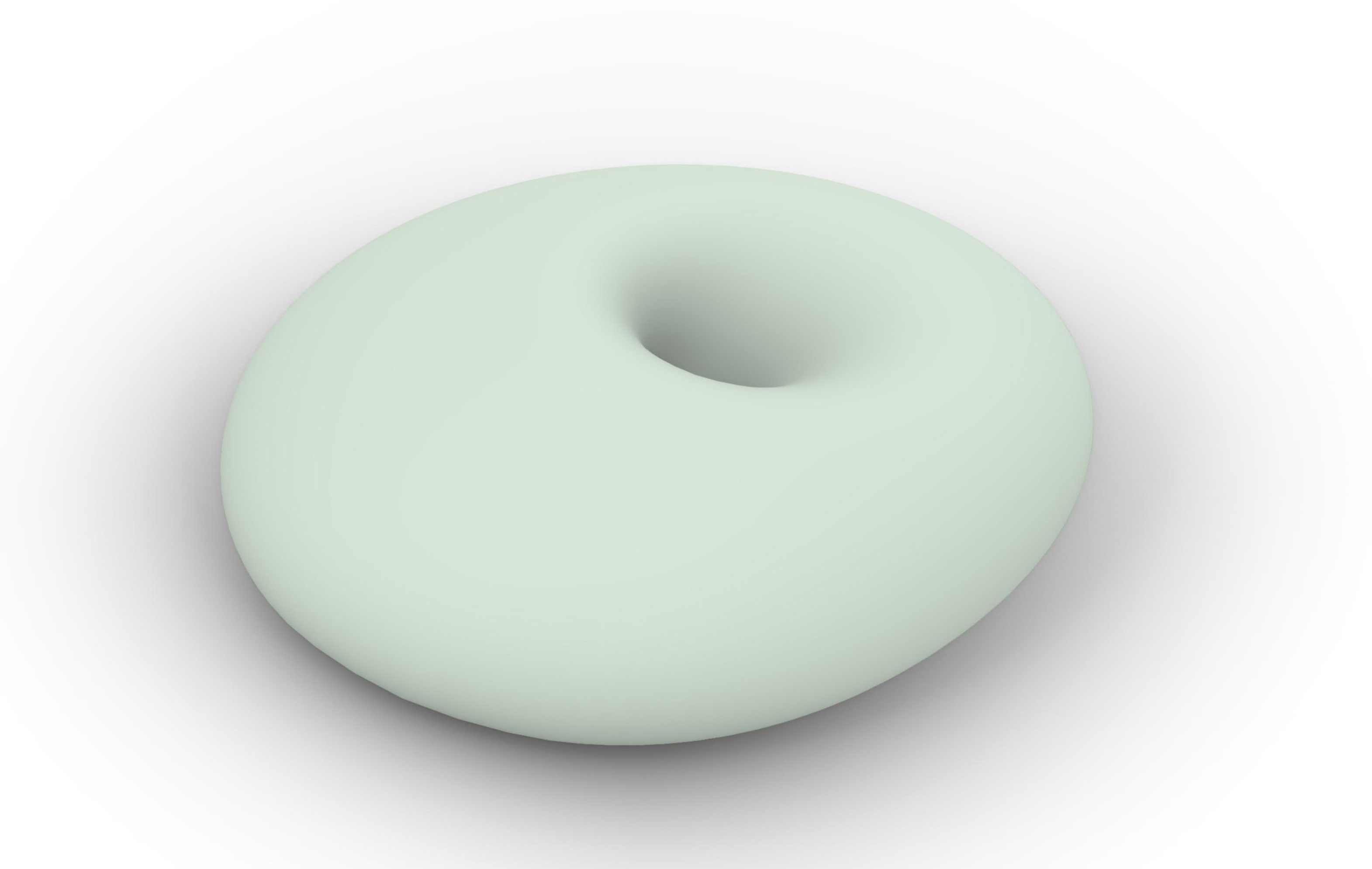
SHELL EXPLORATION

GEOMETRIC SHELLS DESIGNED FROM PARAMETRIC EQUATIONS
- defining values of coordinates (x, y, z) for shapes with parameters (u, v)



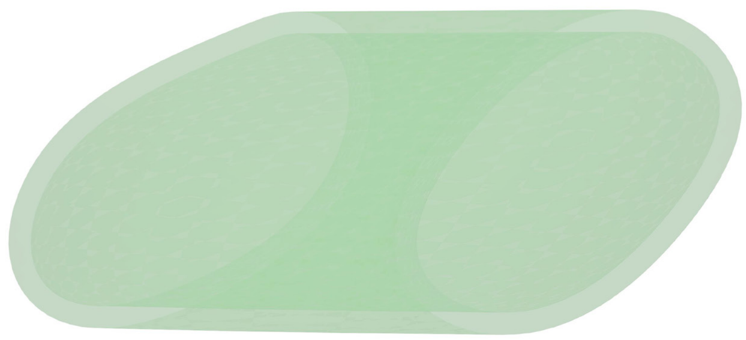
$x = \cos(u)$
$y = \sin(u)(\cos(v)+\cos(8v)/8)$
$z = \sin(u)*(\sin(v)+\sin(7v)/7)$

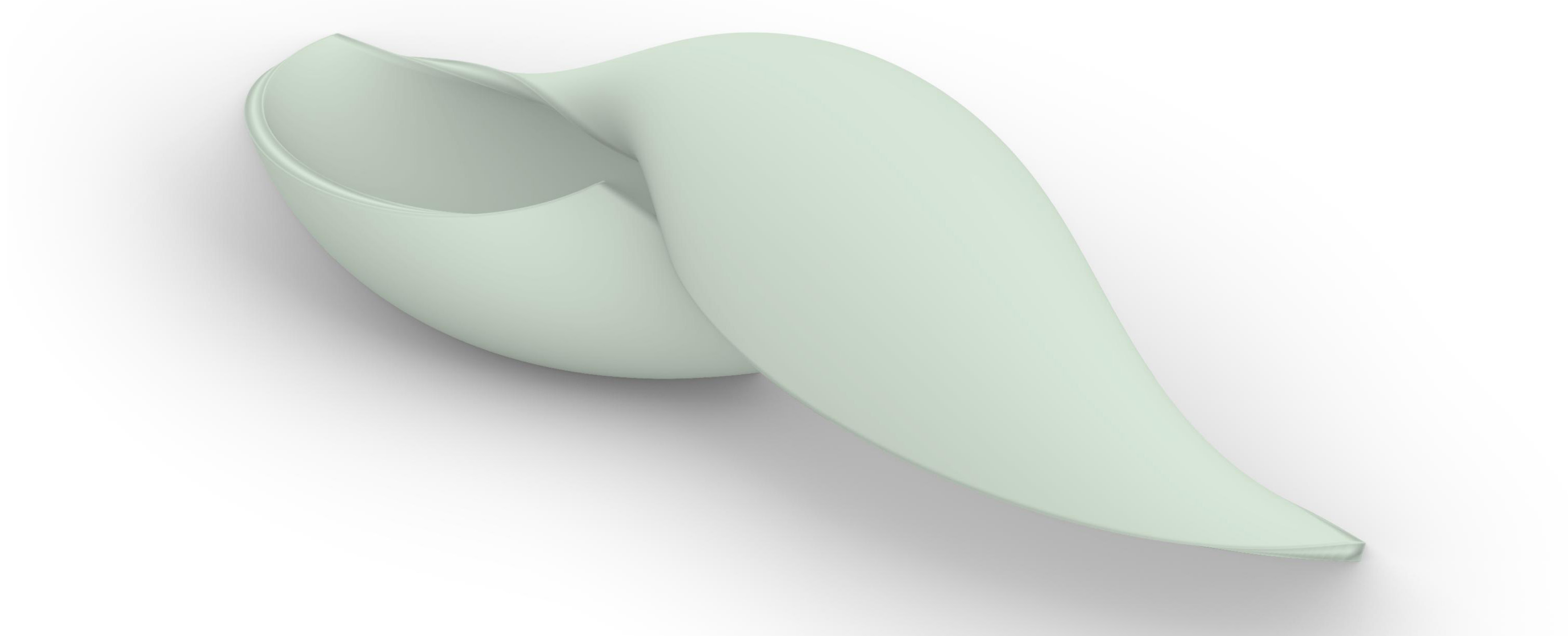
$\{ (u,v) \mid 0 \leq u \geq \pi,\ 0 \leq v \geq \pi \}$



$x = (13/10+\sin(u))\cos(v)$
$y = 2/3\cos(u)+(13/10+\sin(u))\sin(v)$
$z = \sin(100v)/100-(\sin(3u)/10+\cos(u))$

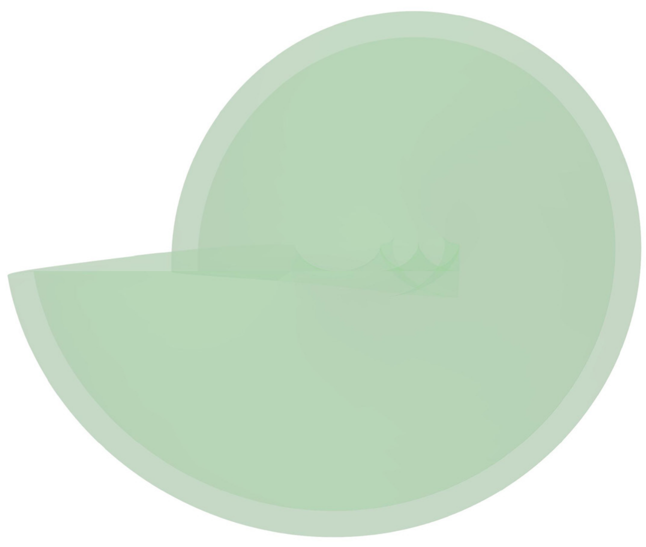
$\{ (u,v) \mid 0 \leq u \geq 2\pi,\ 0 \leq v \geq 2\pi \}$



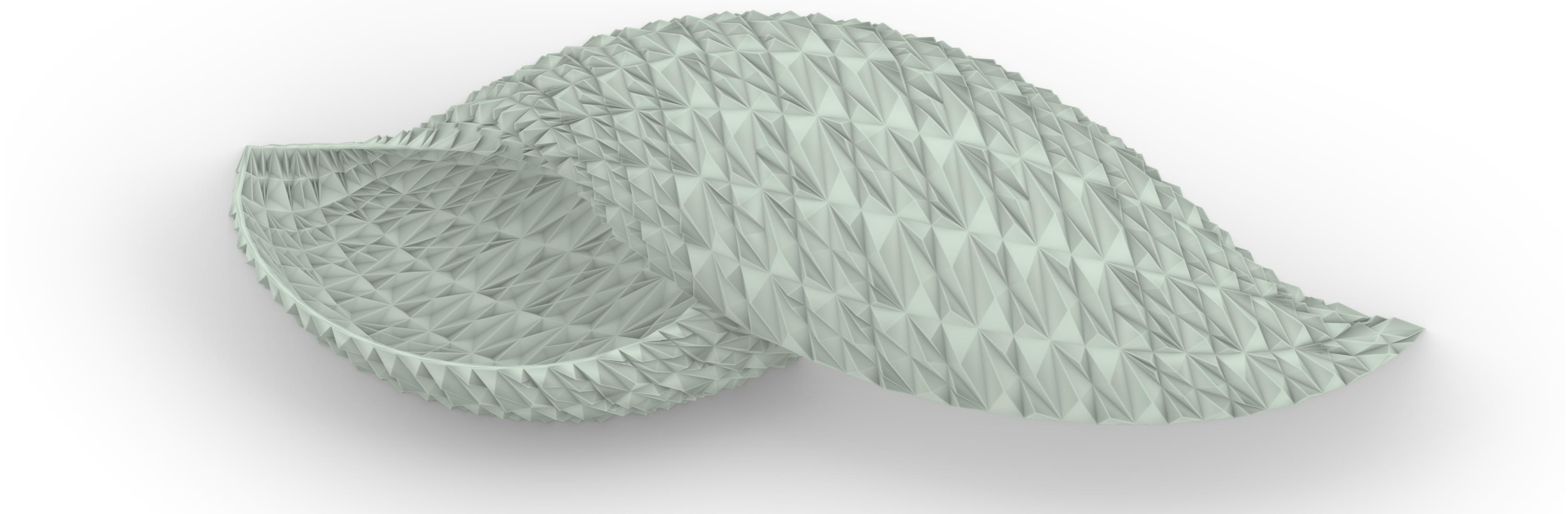


$x = u(v)+10\cos(u)$
$y = u+10\sin(v)\cos(u)$
$z = 10\sin(v)\sin(u)$

$\{ (u,v) \mid 0 \leq u \geq 2\pi,\ 0 \leq v \geq 2\pi \}$



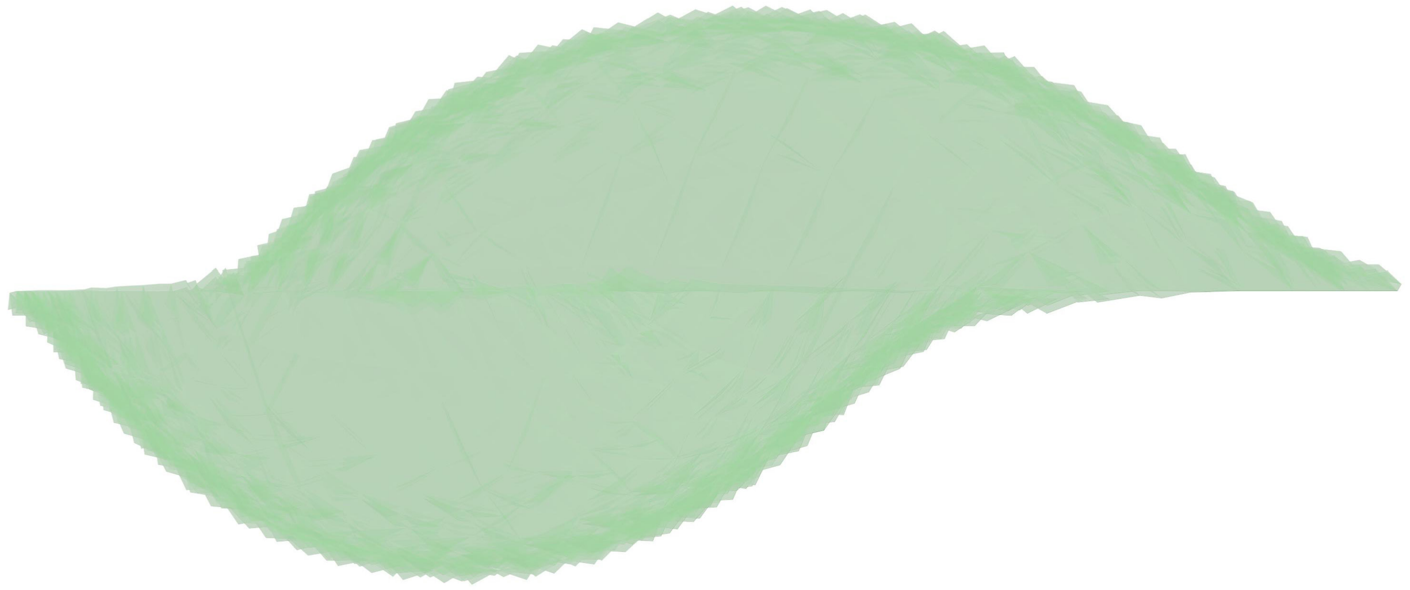
SHELL EXPLORATION



Rhino and Grasshopper was used to map the curves using epression function then lofted the surfaces between the curves and meshed to create a homogenous object. Then Weavebird plugin was used to add thickness and texture to the model.

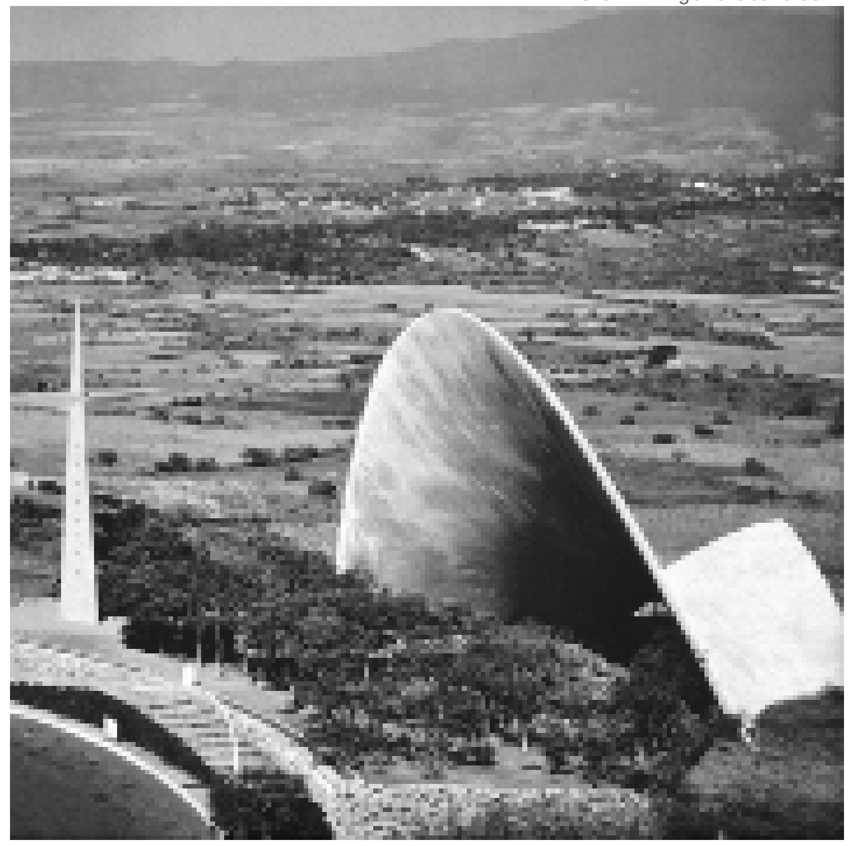
$x = u(v)+15\cos(u)$
$y = u+15\sin(v)\cos(u)$
$z = 15\sin(v)\sin(u)$

$\{ (u,v) \mid 0 \leq u \geq 2\pi, 0 \leq v \geq 2\pi \}$



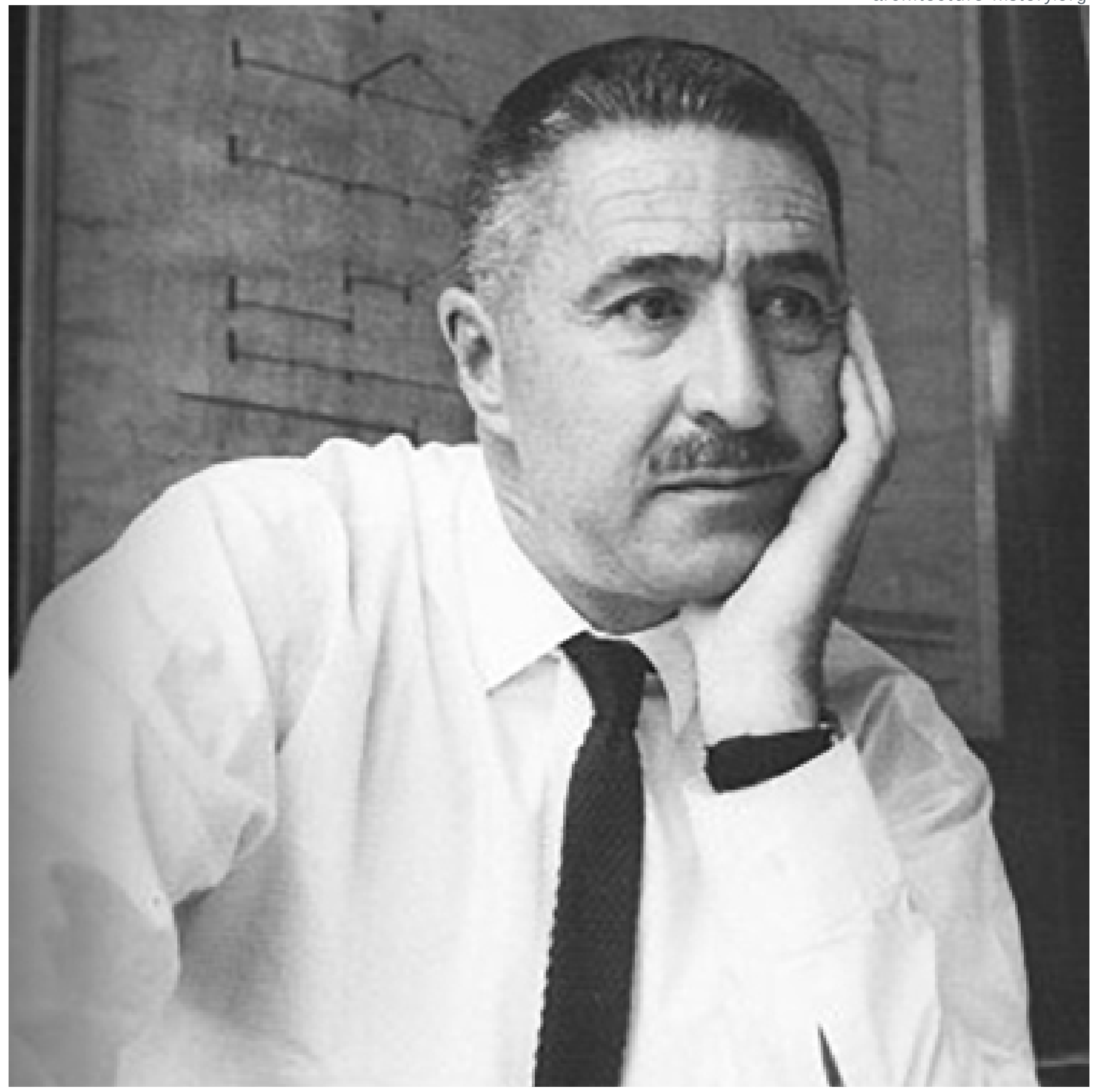
XOCHIMILCO

re-thinkingthefuture.com



THE WIZARD OF CONCRETE SHELLS

architecture-history.org



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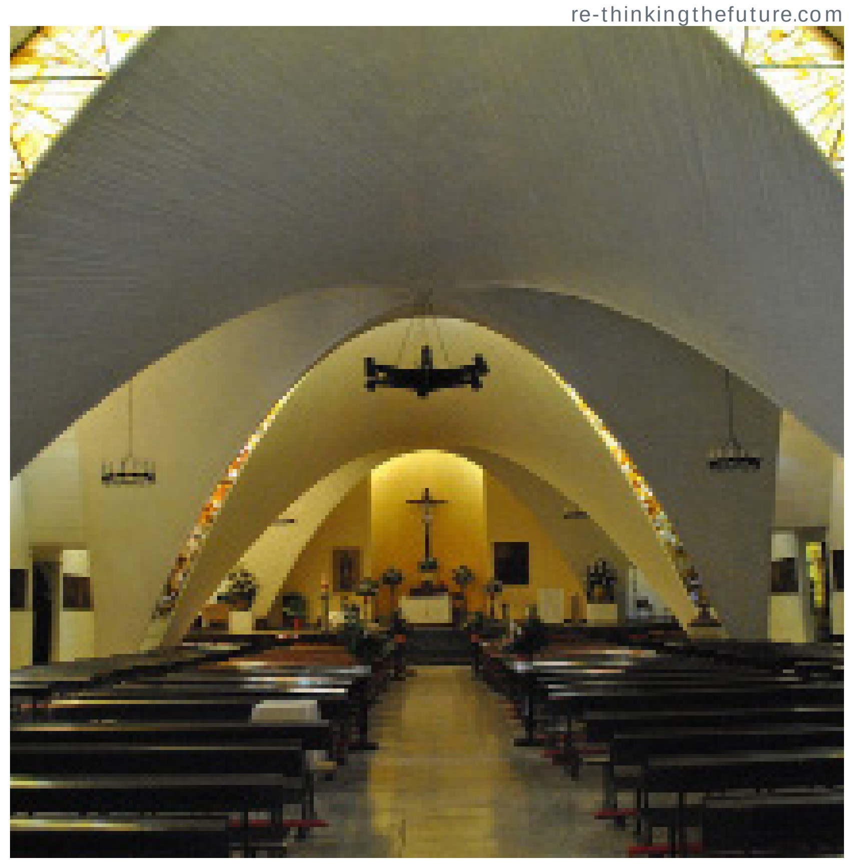


Félix Candela was born on January 27th, 1910, in Madrid, Spain. After earning an architectural degree in 1935, he began his adventure exploring thin concrete shell structures.

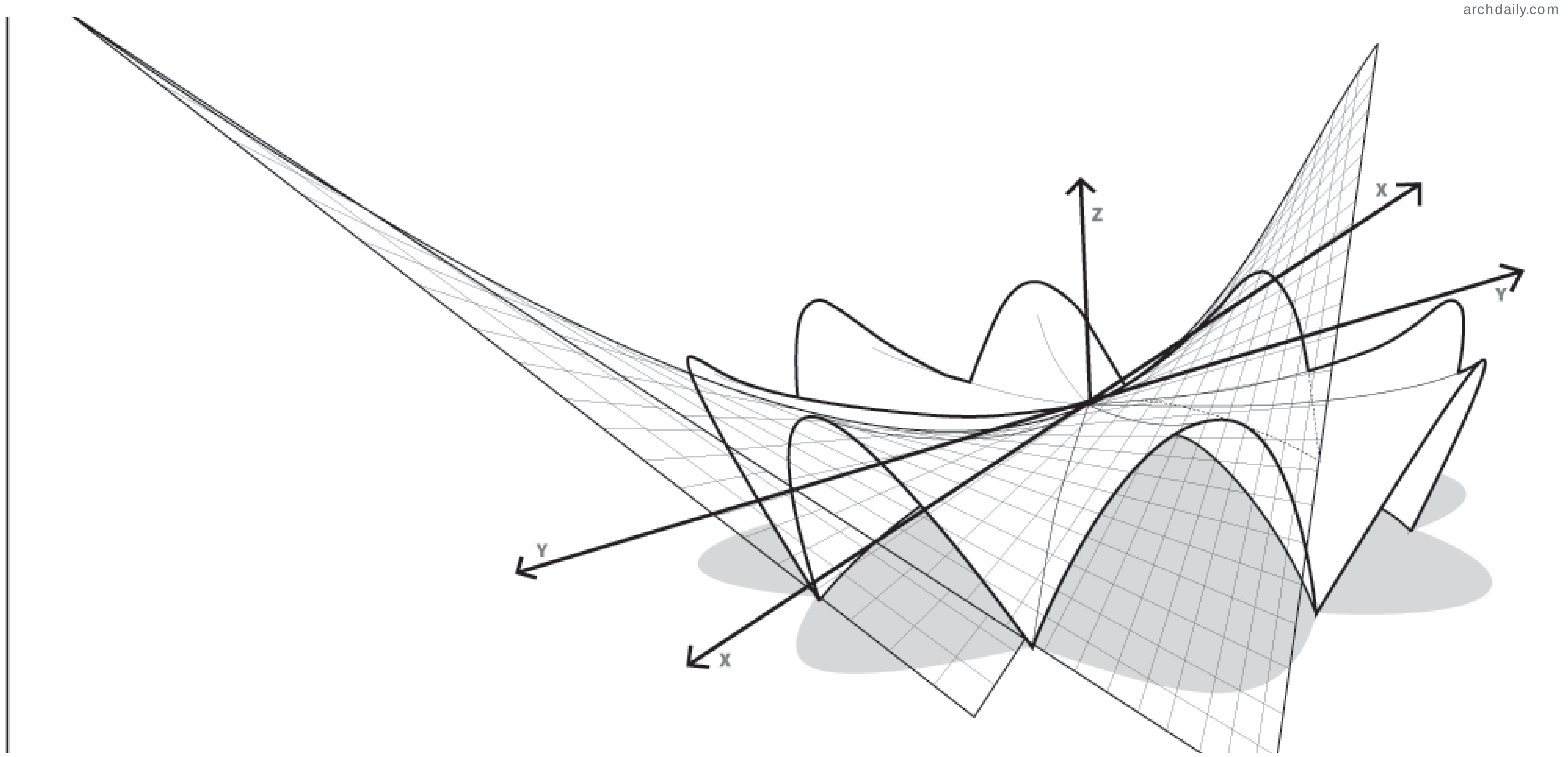
Candela's design philosophies included utility, strength, and beauty. In order to achieve these qualities in his designs, he implemented the use of geometric equations and functions to model his structures.

Over time, the geometric form he was fascinated by was the hyperbolic paraboloid. Candela became known for incorporating this mathematical curve into many of his designs, as seen in the pictures on this spread.

Information obtained from https://informesdelaconstruccion.revistas.csic.es/index.php/informesdelaconstruccion/article/download/1033/1119/1573

FORM FINDING INSPIRED BY LOS MANANTIALES

A deeper analysis of Candela's iconic structure in order to produce shell form iterations

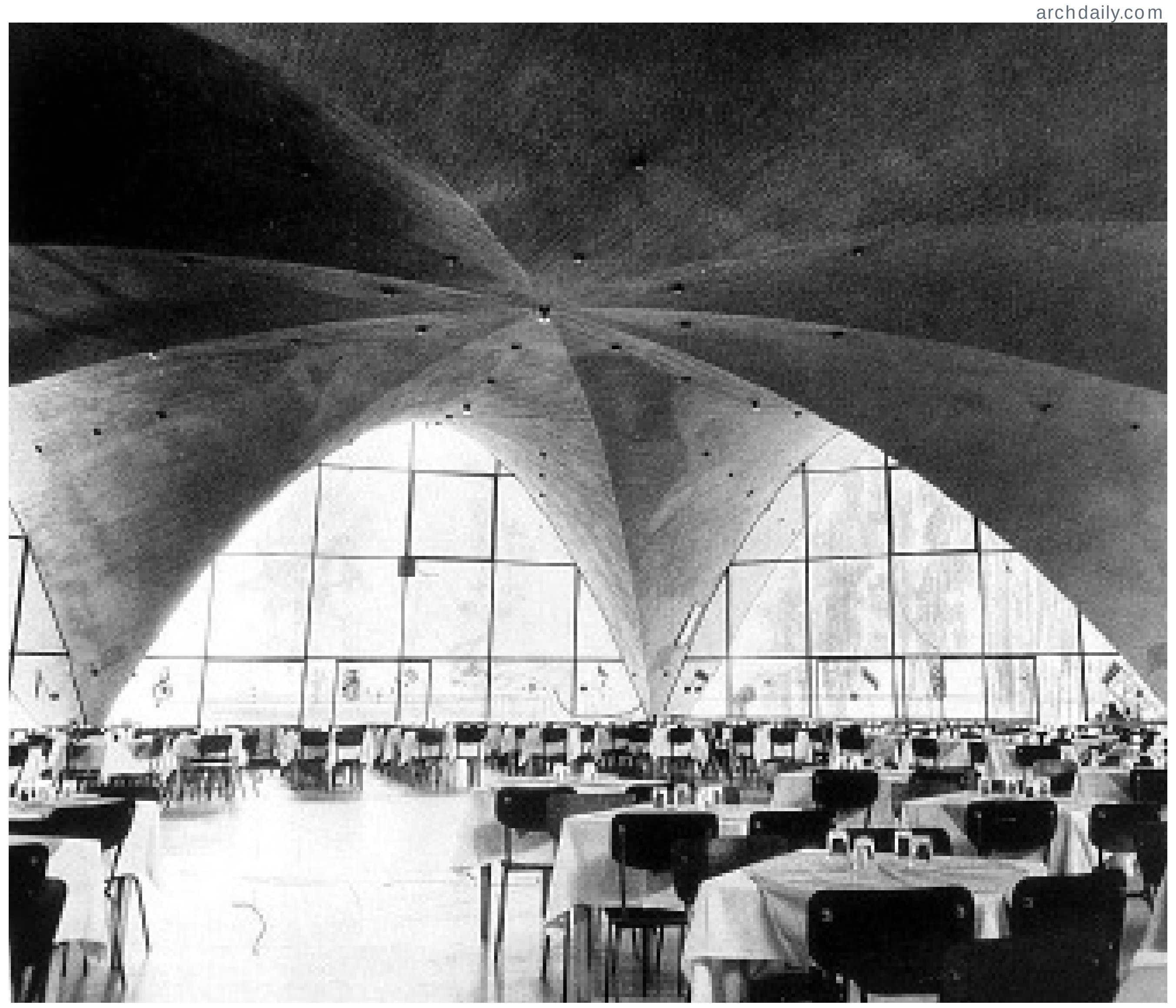


HYPARS IN XOMICHILCO

As mentioned in his brief biography, Candela began implementing the use of a specific geometric configuration in his later designs: the hyperbolic paraboloid. One of the projects that utilized these curves, also known as hypars, in a unique manner was Los Manantiales, which is located in Xomichilco, Mexico City.

When observing the structure as a whole, it may seem a bit unclear how hypars were included in the design. Rather than a single hypar curve, the shell consists of multiple, intersecting hypars cut by vertical planes to create the arches around the perimeter.

archdaily.com



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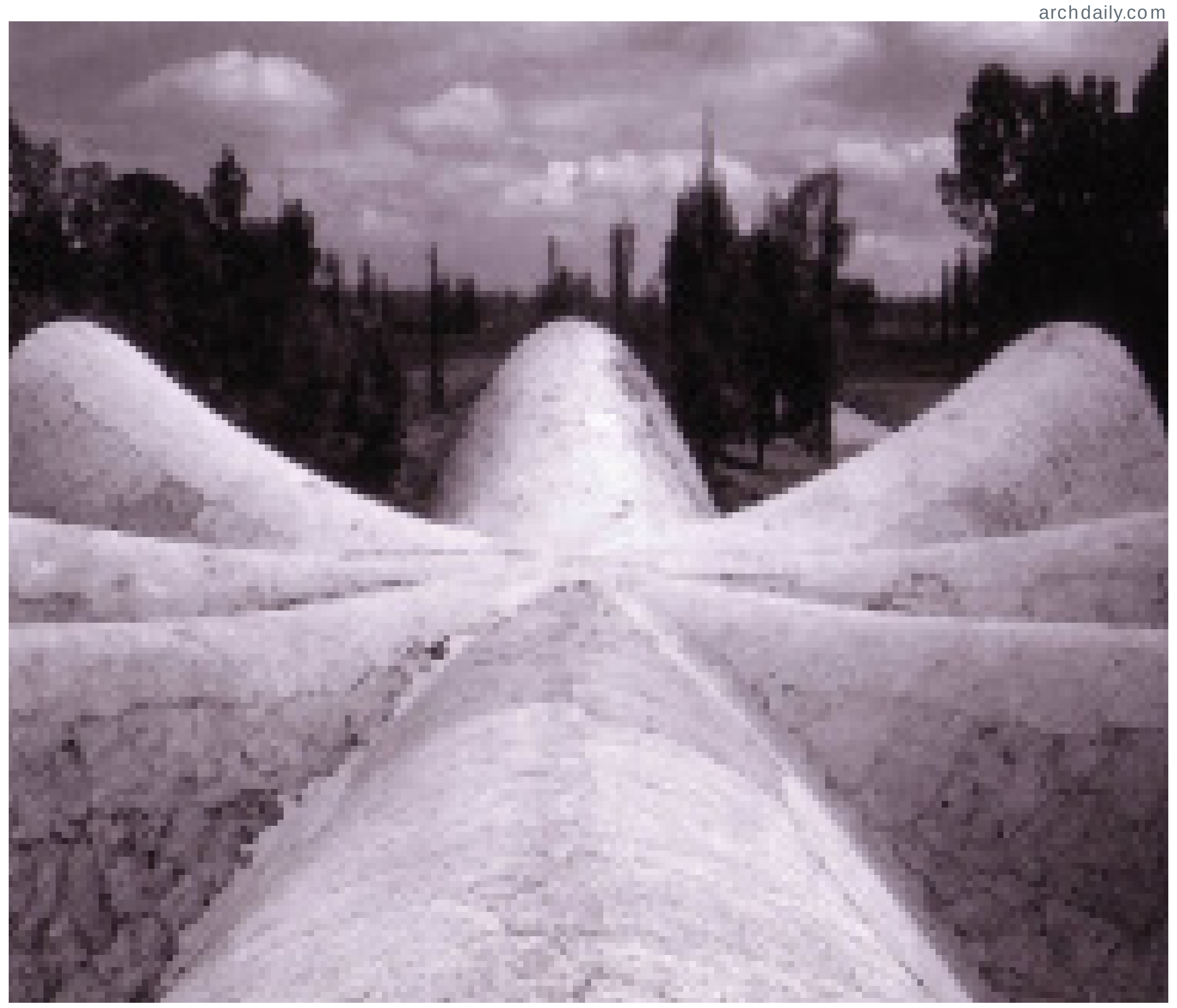
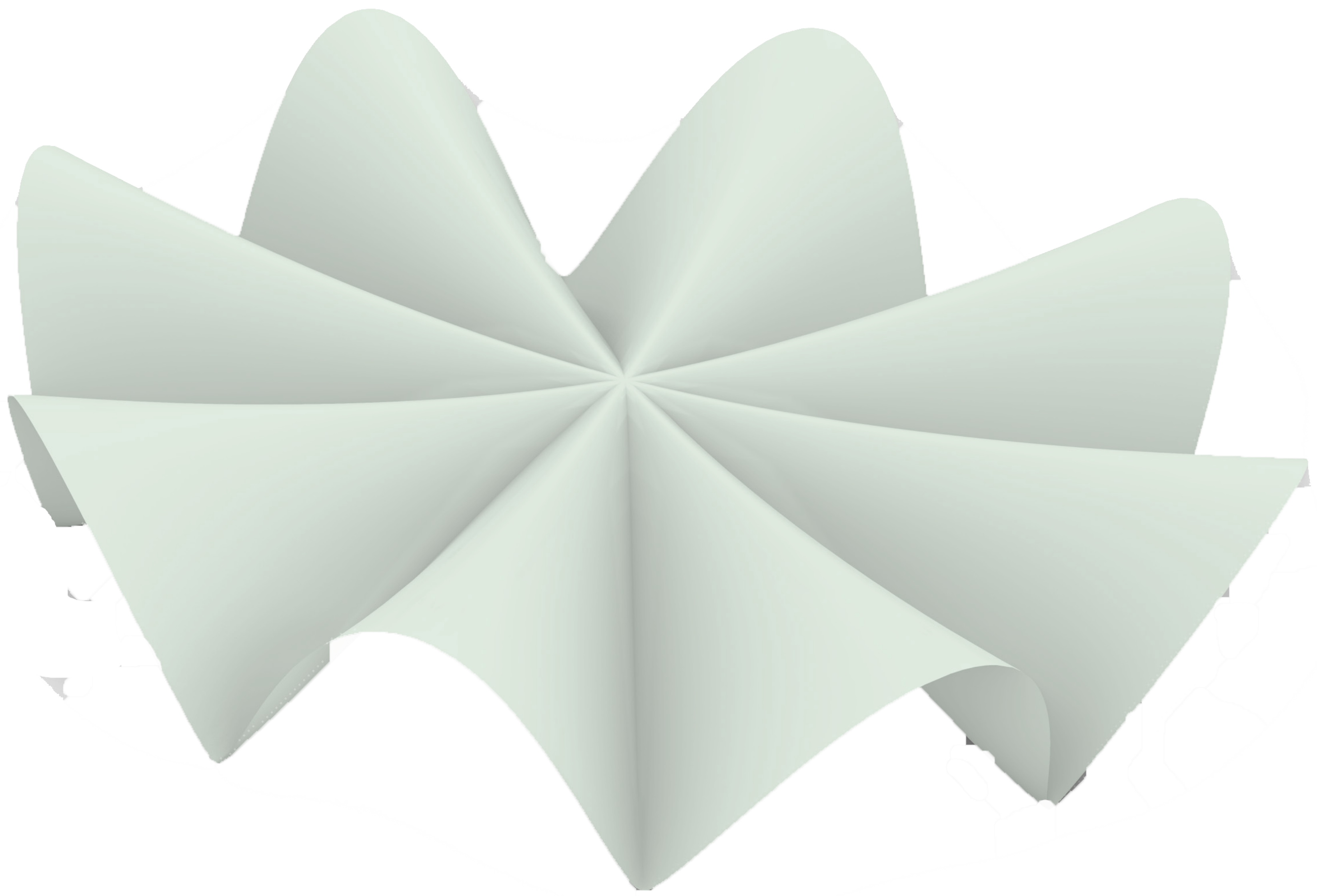


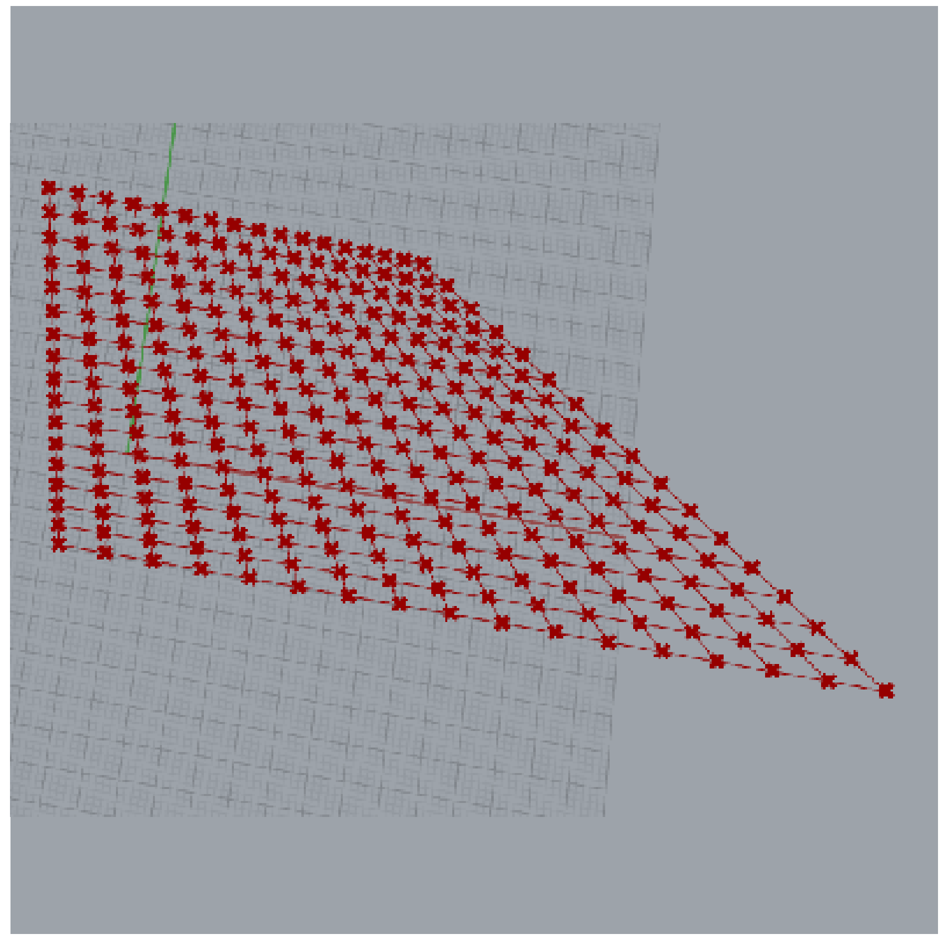
CASE STUDY XOMICHILCO

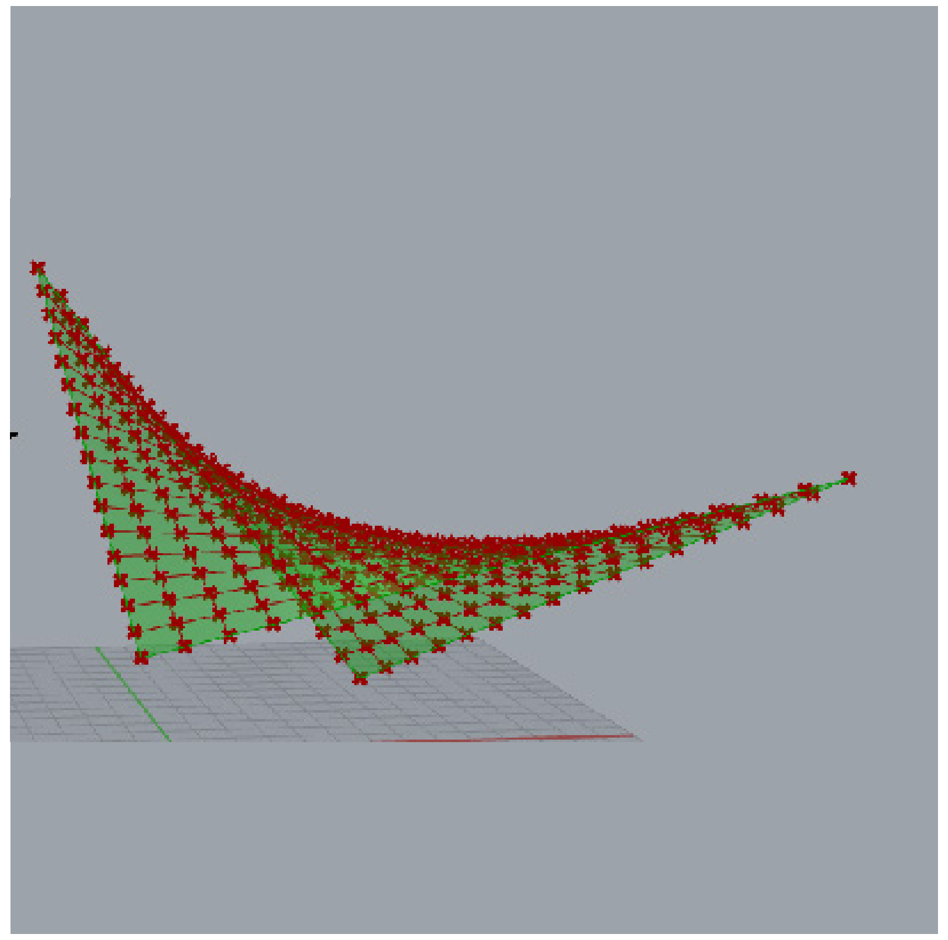
In order to have a closer look at the Los Manantiales structure and perform a deeper investigation on its use of hypars, the model was recreated in Grass-hopper for a 3D view of the shell that could be examined from all corners.

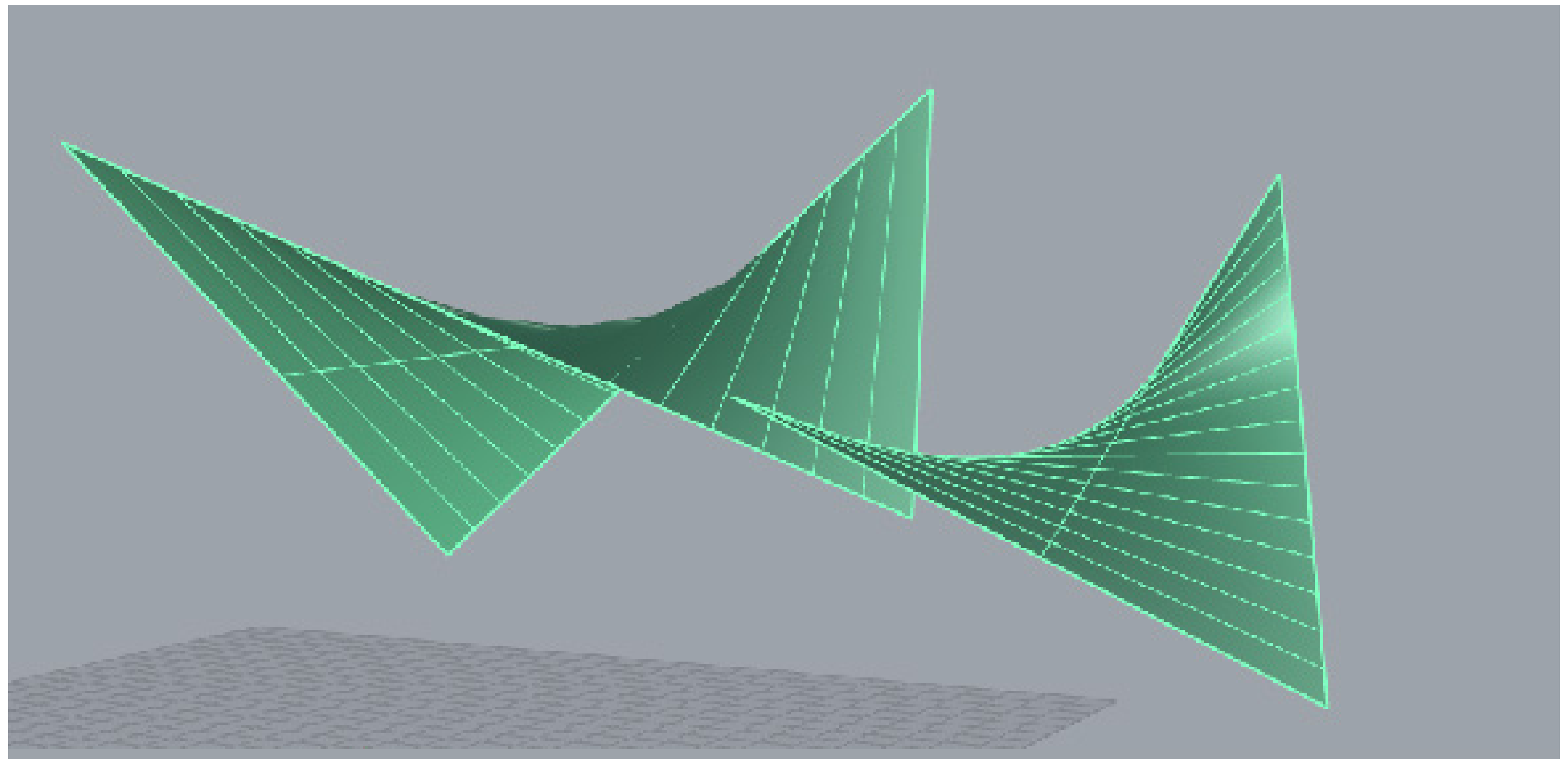
The recreation was achieved using Grasshopper's handy features, including the fabrication of Bezier curves and the mirror function.

In addition to the formation of the digital model, finite element analysis was performed. Only considering the self weight of the structure, SAP2000 allowed for a detailed illustration of the stress patterns.







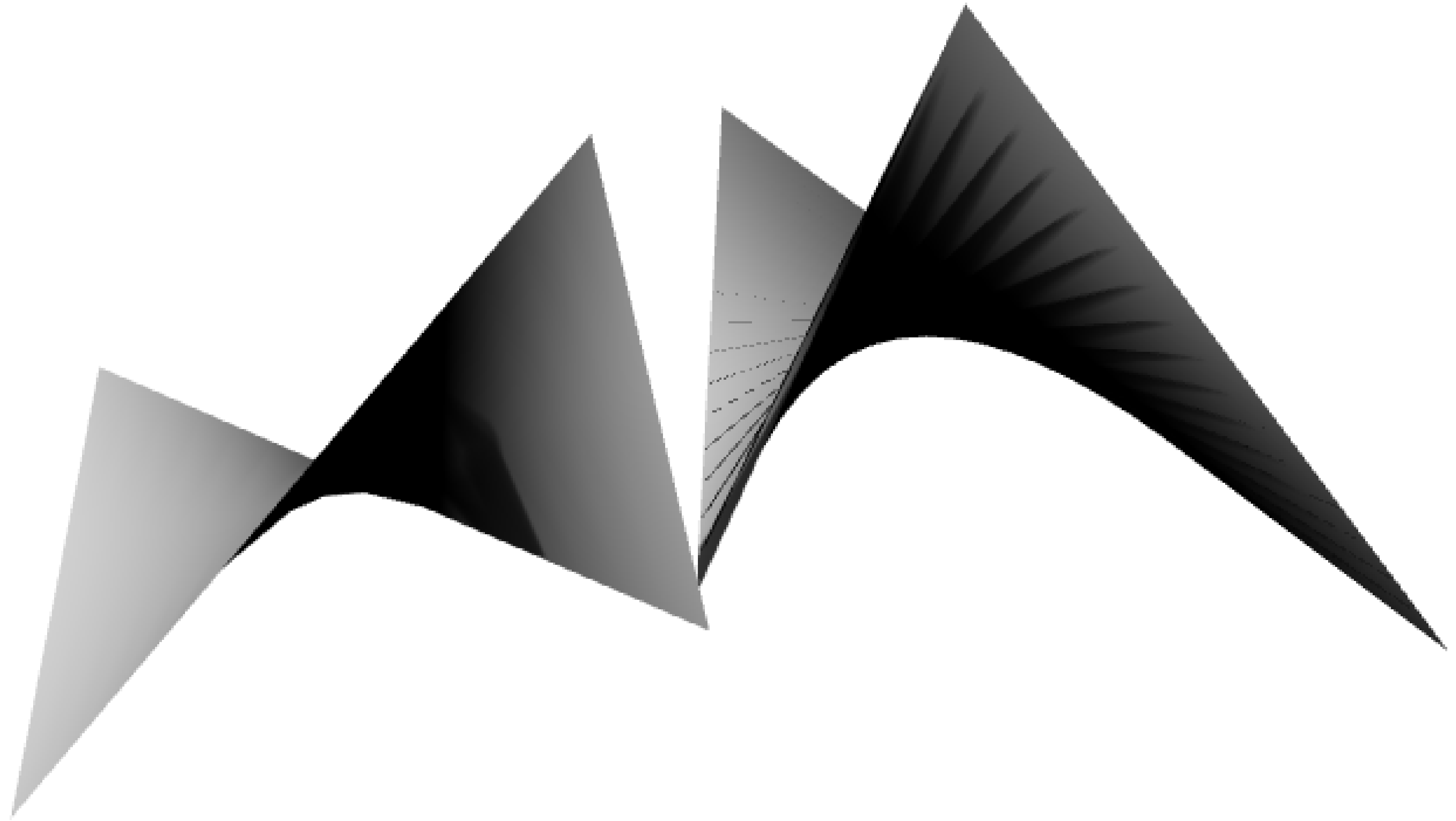


CURVES FROM STRAIGHT LINES

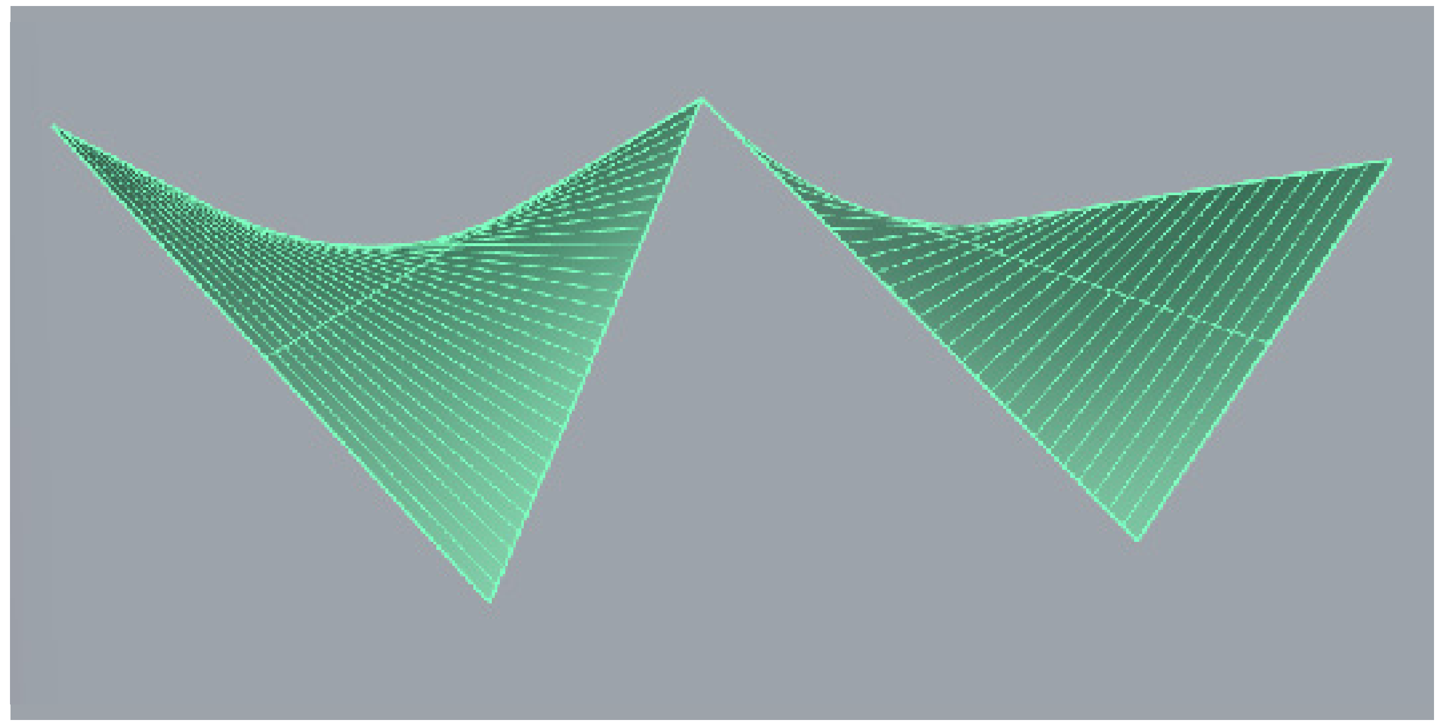
The first step of incorporating the hyperbolic paraboloid into unique forms was to understand what a hypar is comprised of.

Although the geometric configuration is curved and represents a saddle as a whole, theentire function consists of a series of straight lines. A group of evenly spaced parallel lines with differing slopes span in one direction, intersecting with another group of evenly spaced parallel lines with differing slopes spanning perpendicular to the first group of lines.

The hypar was achieved in Grasshopper using the line and divide curve functions.

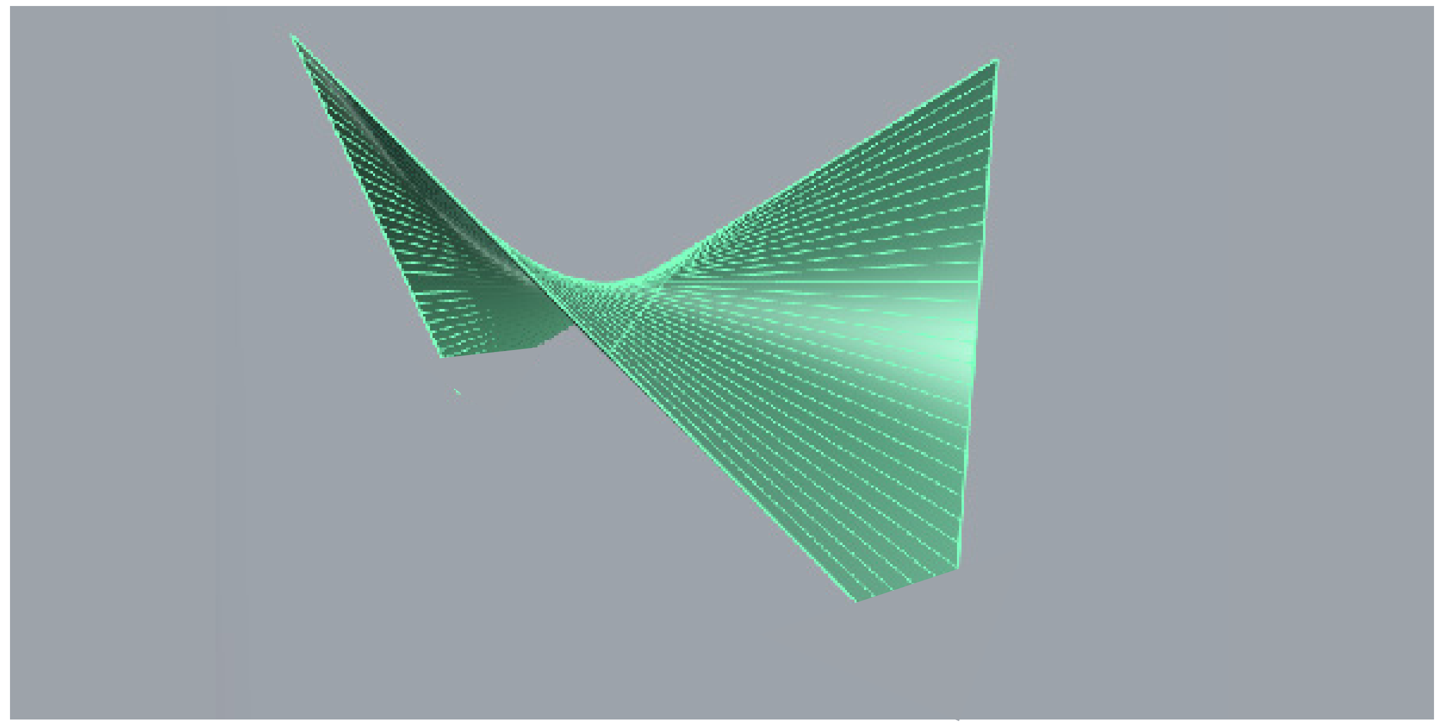


ITERATIONS AND INSPIRATIONS

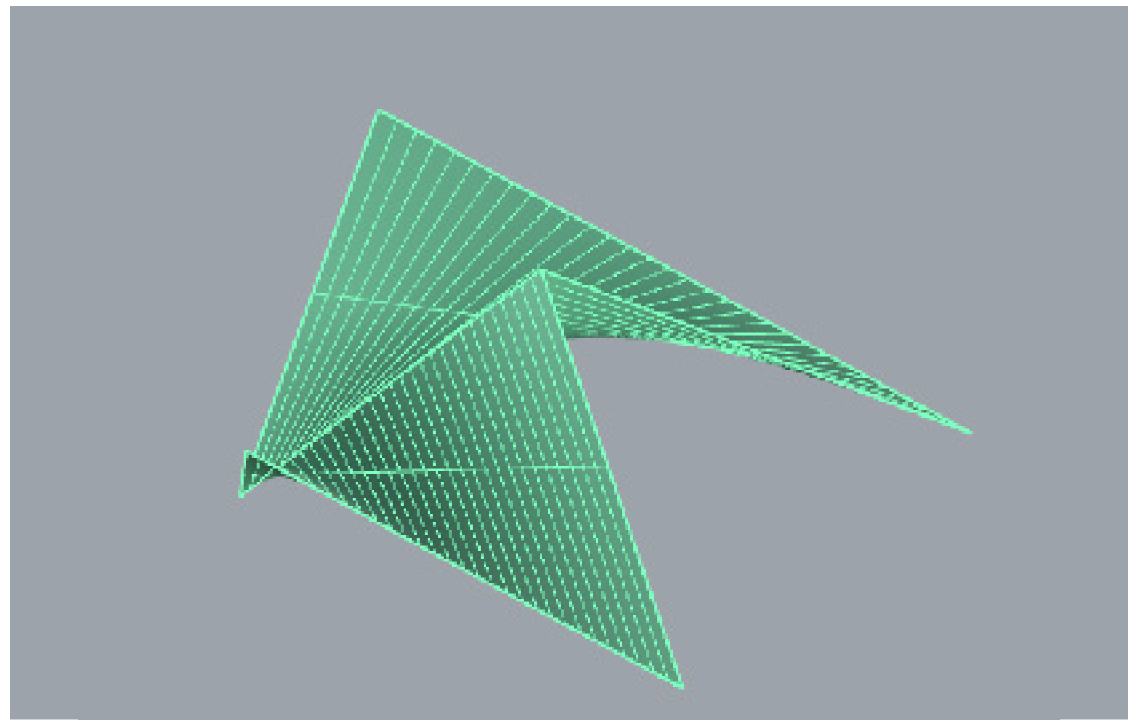


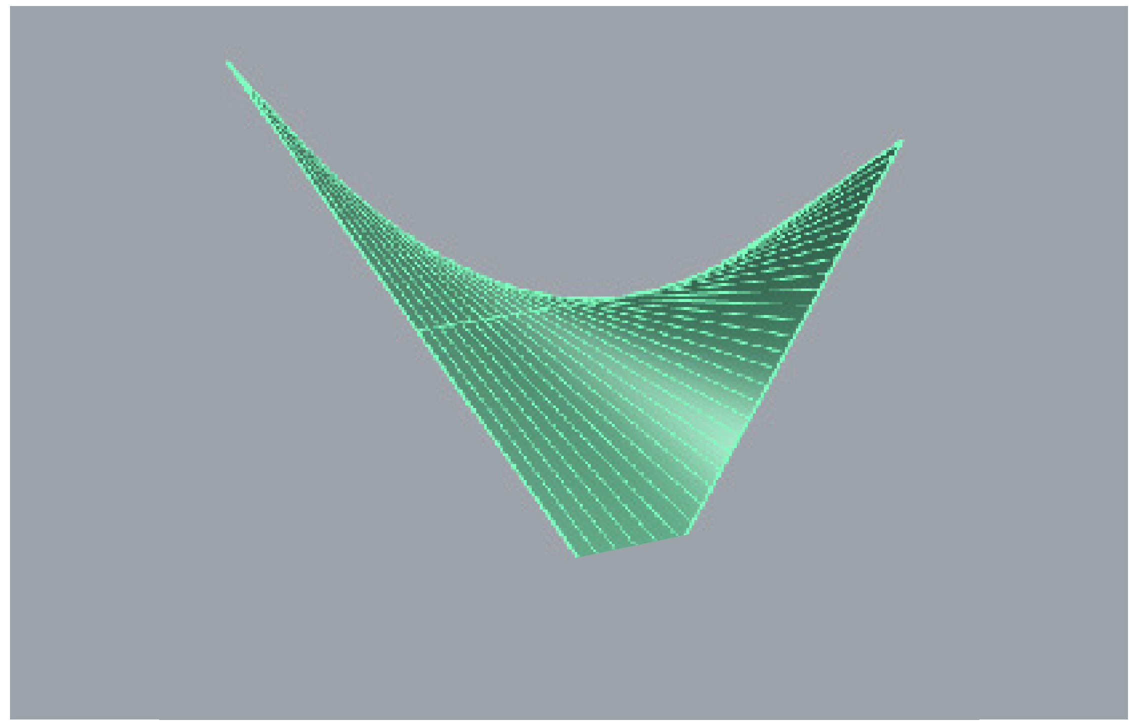
Using the hyperbolic paraboloid form as the basis of various forms along with Candela's concept of intersecting the curves, an elementary exploration of Grasshopper began and a few designs were developed.

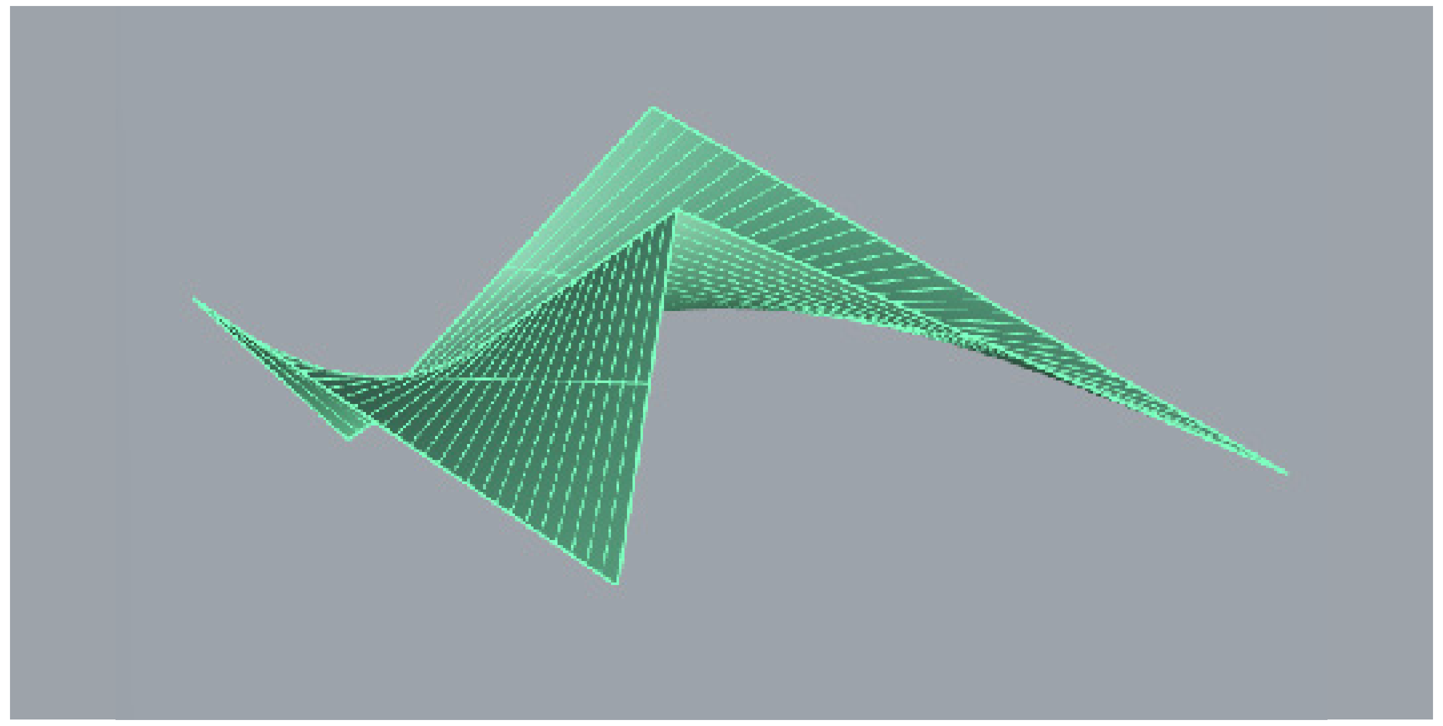
One design included two hypars joined at a shared point. Although not a practical structure, manipulating the Grasshopper code to create the form allowed for a deeper understanding of how to make the curves intersect. Progressing further with the idea of shared points, an iteration where two hypars shared a common edge was developed, a much more practical design.

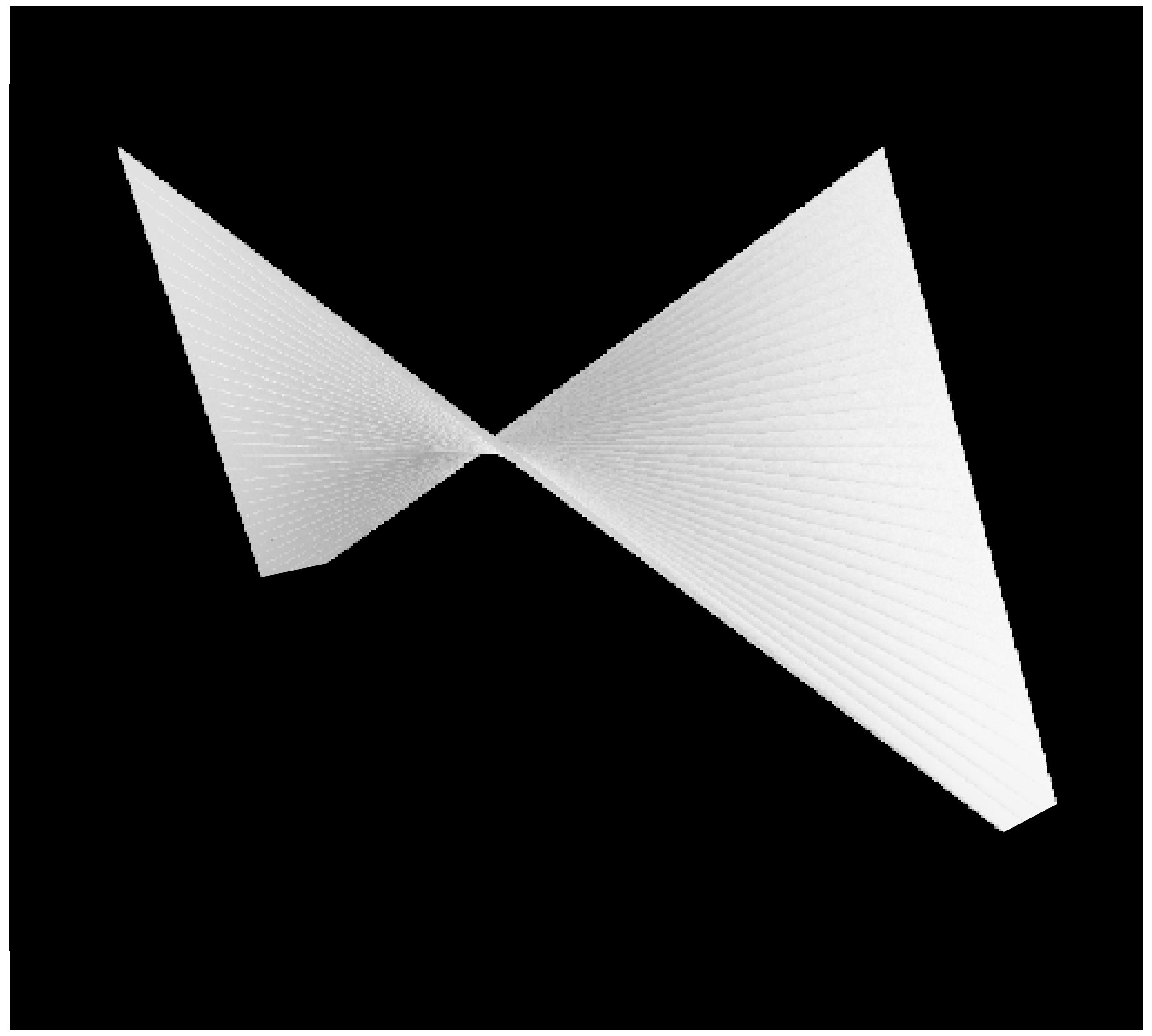


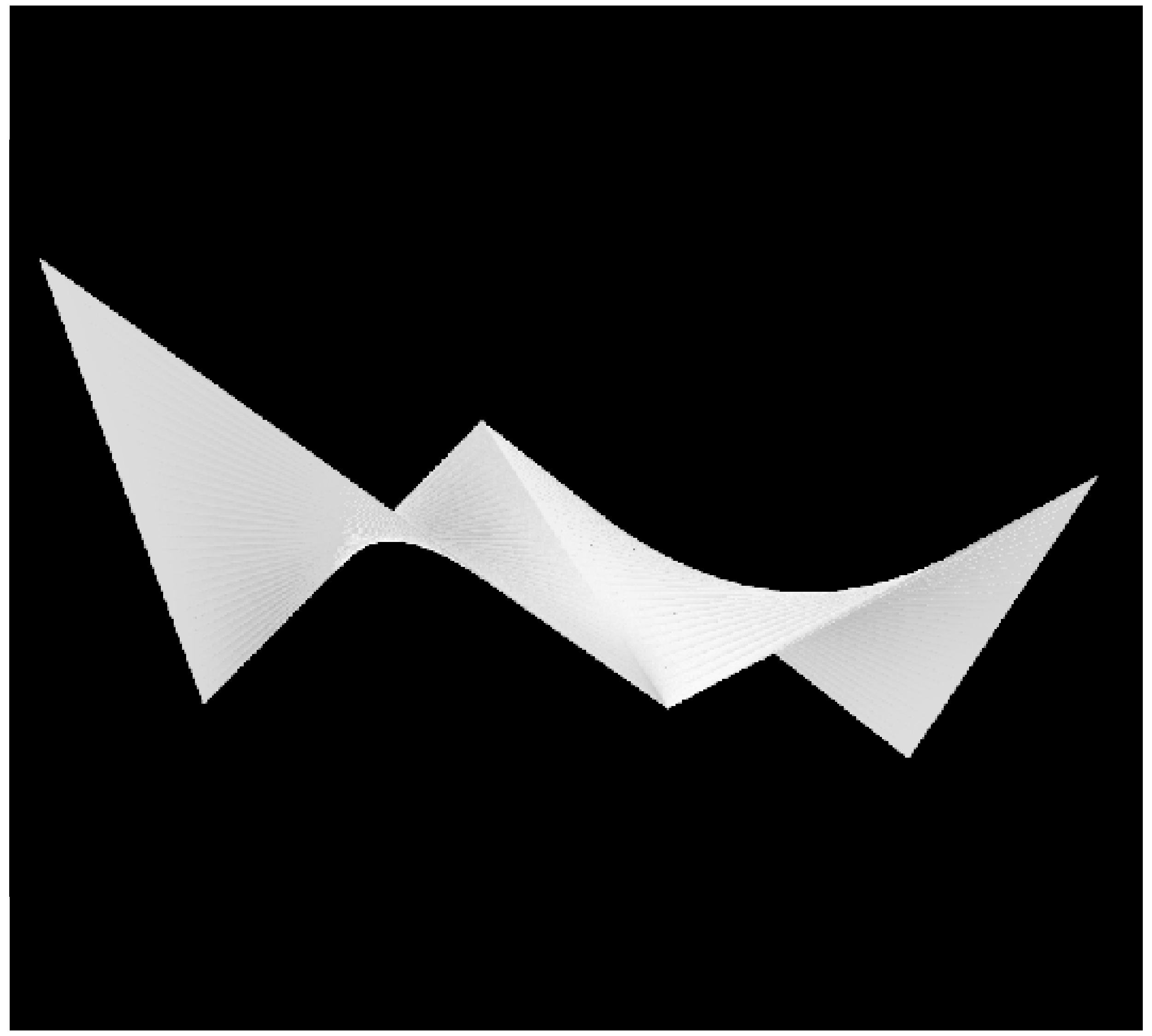
In addition to these two iterations, slicing two corners of a hypar with a perpendicular plane resulted in a form much like the Lomas de Cuernavaca shell.

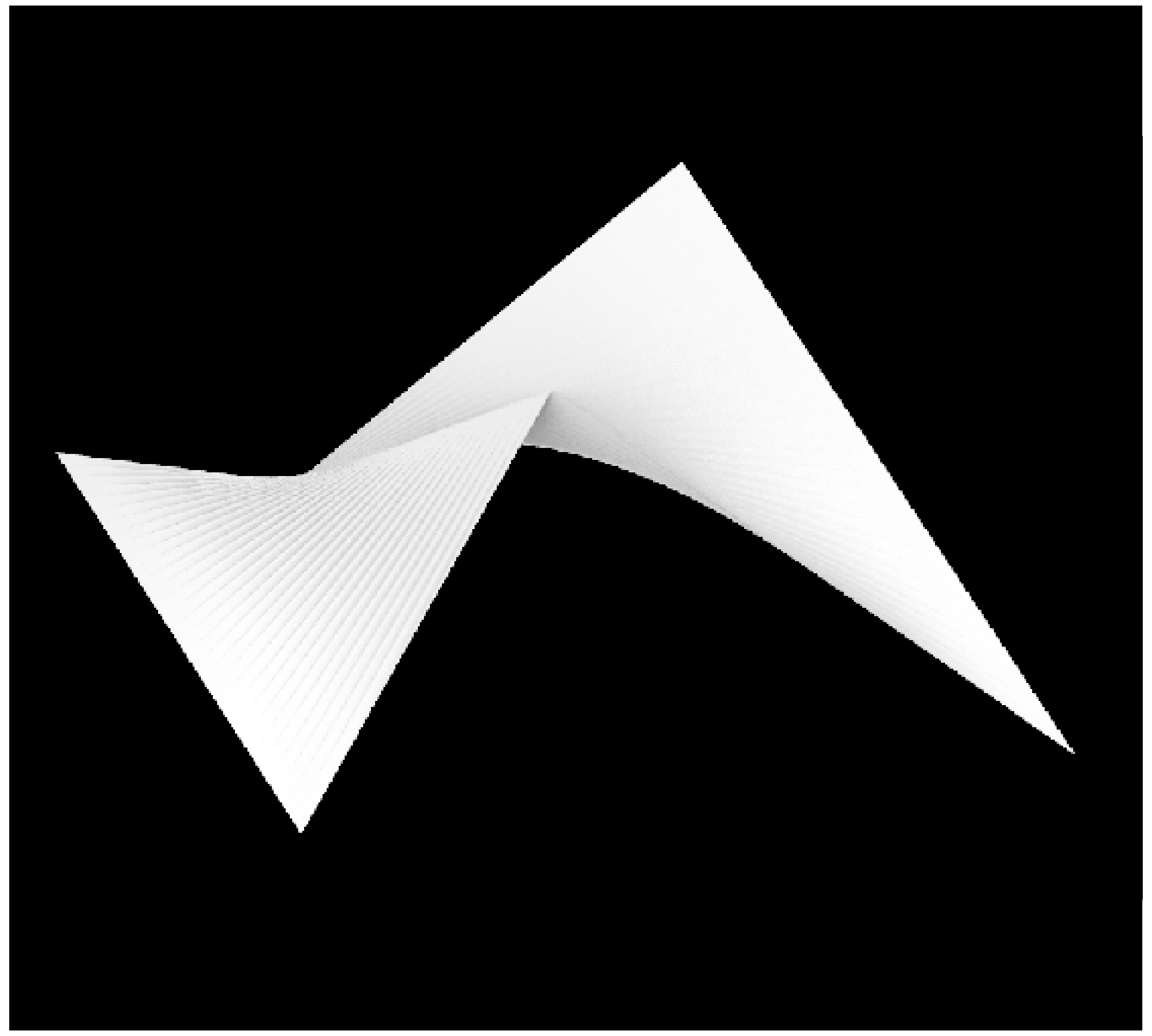


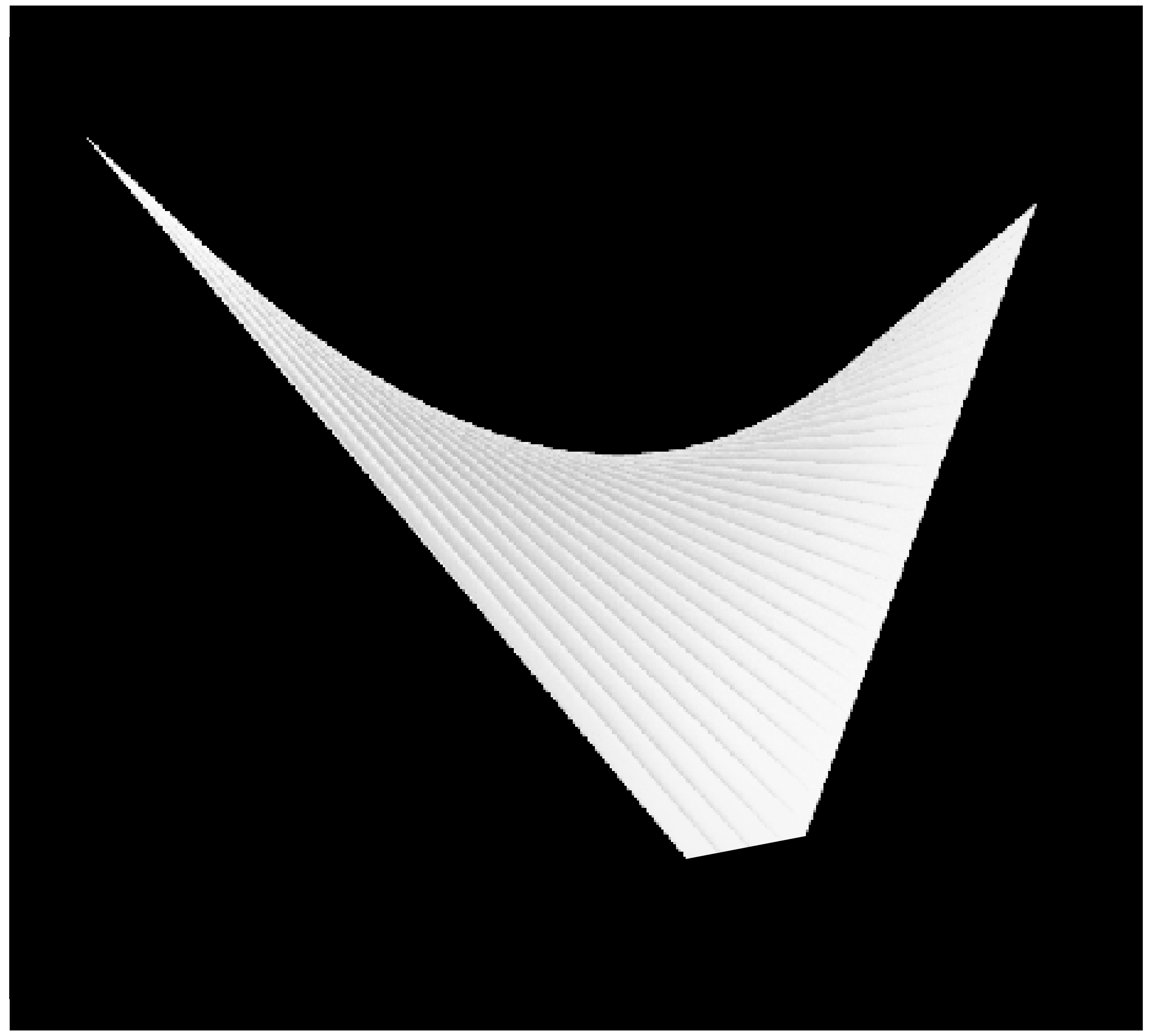












FINAL FORMS

The two iterations that were polished and rendered were the two hypars with a shared edge and the Lomas de Cuernavaca inspired hypar.

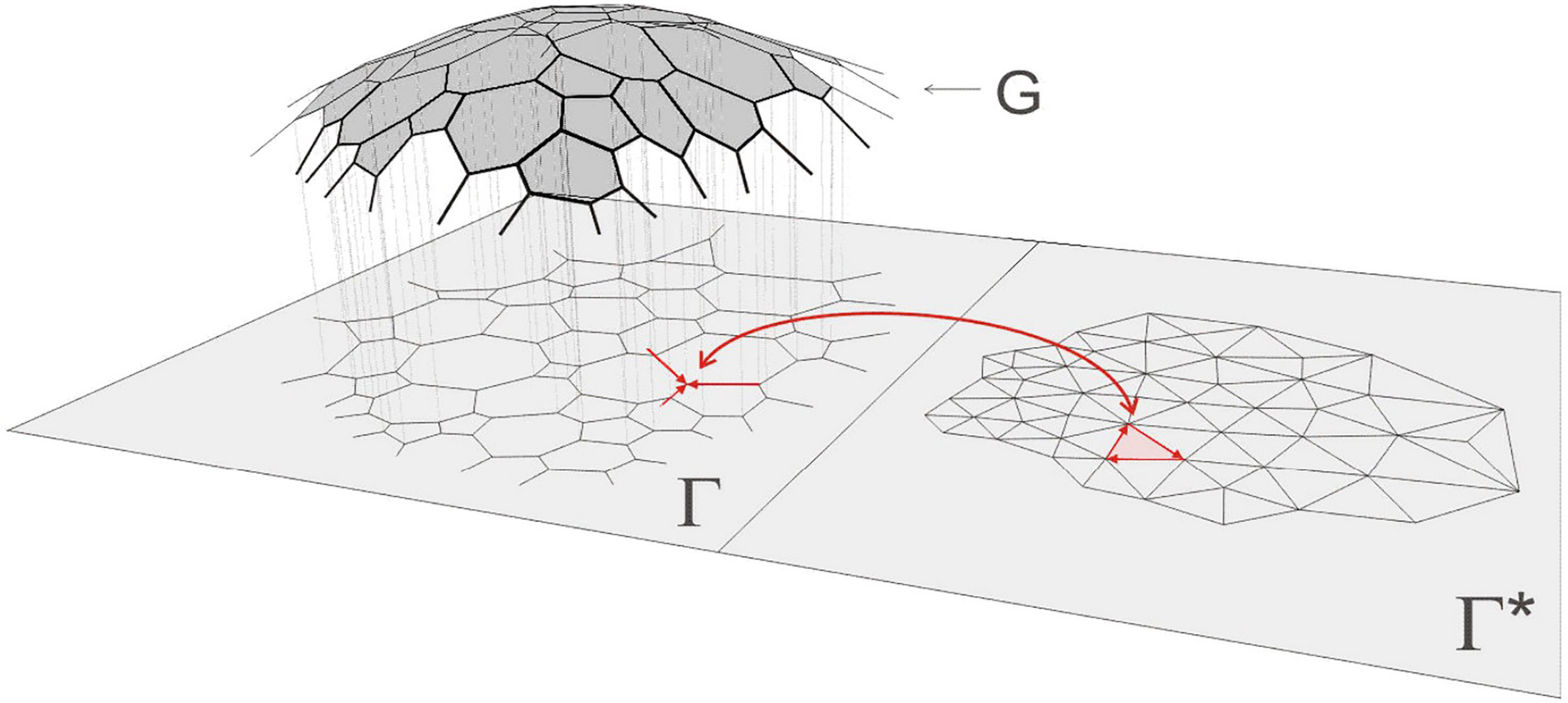
The hypars joined at a common edge was modified to exaggerate the curvature at the midspans of both hypars.

Although the two forms were rendered, they are no where near a complete and cohesive shell structure. Footings have not been accounted for, as this elementary exploration of Grasshopper merely allowed for creative expression and form finding. The next steps for these iterations would be to consider footings and to model them in finite element analysis software.

FORM FINDING

FUNICULAR SHELL

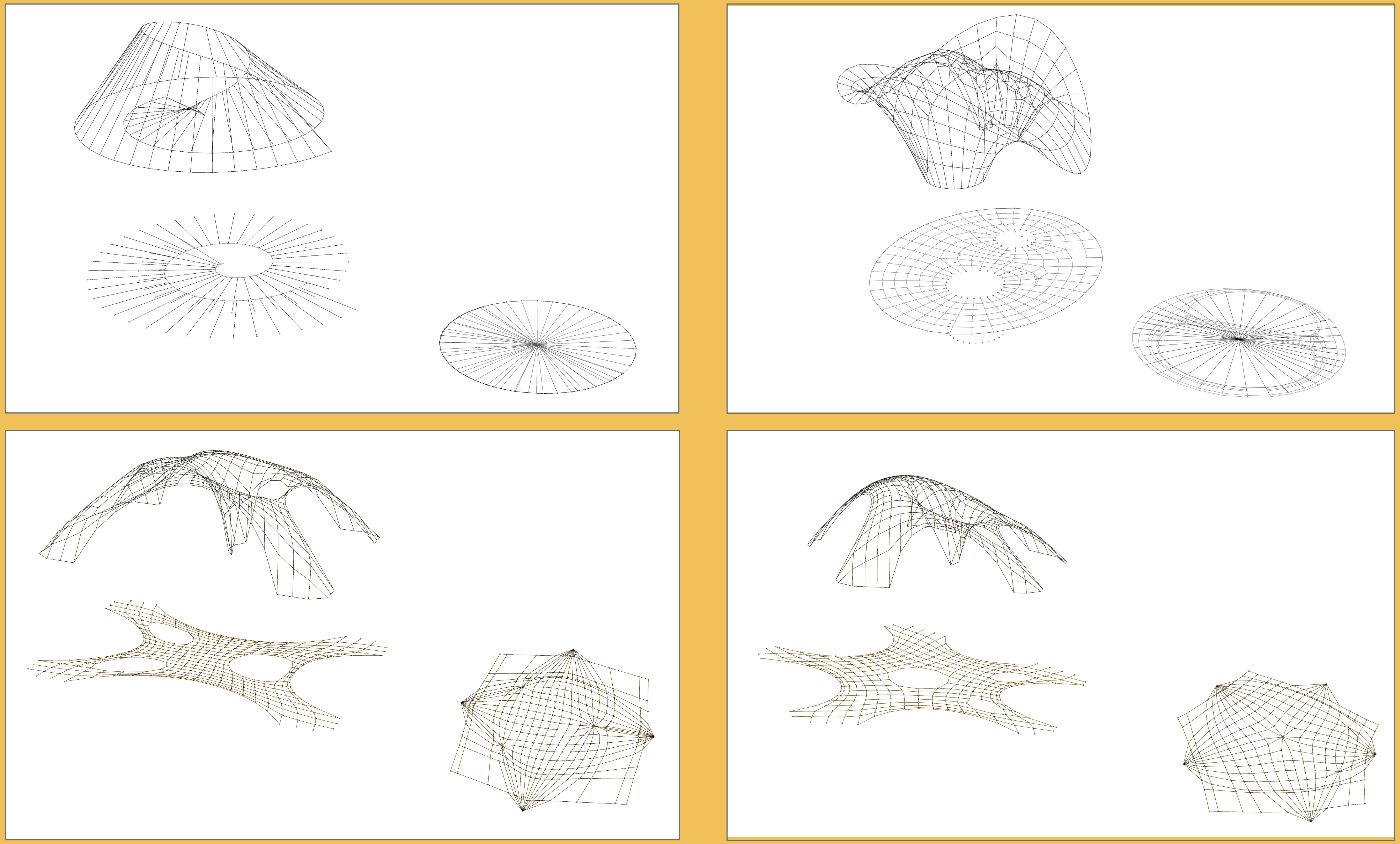
Freeform and mathematical shell design processes do not promise the desired stress state as the funicular shells design process does otherwise. It demands the static equilibrium using the form-finding method that guarantees the in-plane compression under self-weight. In that scenario, bending moments are absent. Therefore, in designing a funicular shell, it is necessary to understand the relationship between form and force to guarantee stability.



Relationship between compression shell (G), its planar projection (primal grid Γ) and the reciprocal diagram (dual grid Γ*) to determine equilibrium. (Block, 2009)

THRUST NETWORK ANALYSIS

Thrust network analysis is an extension of graphic static and trust line analysis in three-dimensional problems. The form diagram Γ represents the plan geometry of the structures, and the reciprocal force diagram Γ* represents the distribution of horizontal thrusts - spatial representations of compressive force resultants in equilibrium.

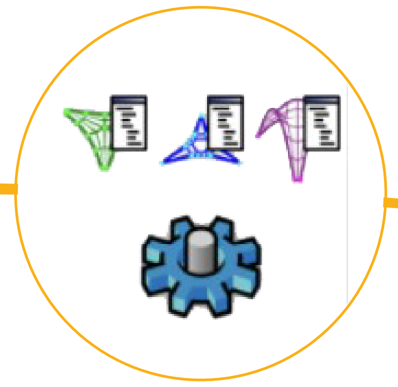


A series of examples were created during this senior project using Rhino Vault 2 to show the relationship between the form and force diagram and the corresponding solution with the applied loads. Horizontal and vertical equilibrium are satisfied.

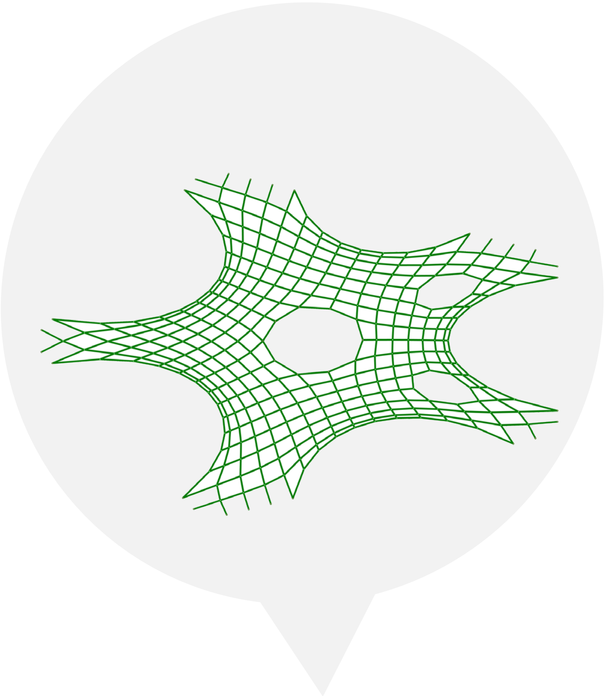
RV2 DESIGN PROCESS

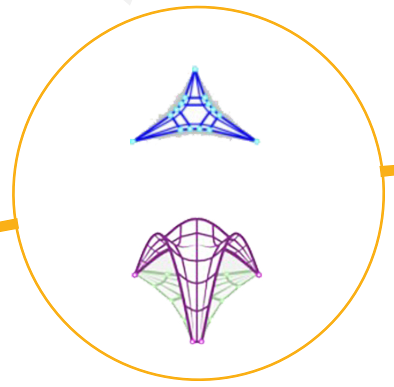
Based on the theory of Thrust Network Analysis (TNA) approach to intuitively create and explore compression-only structures.

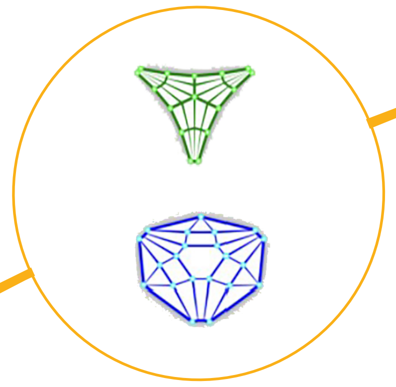
04 Modify Diagrams and Thrust Network

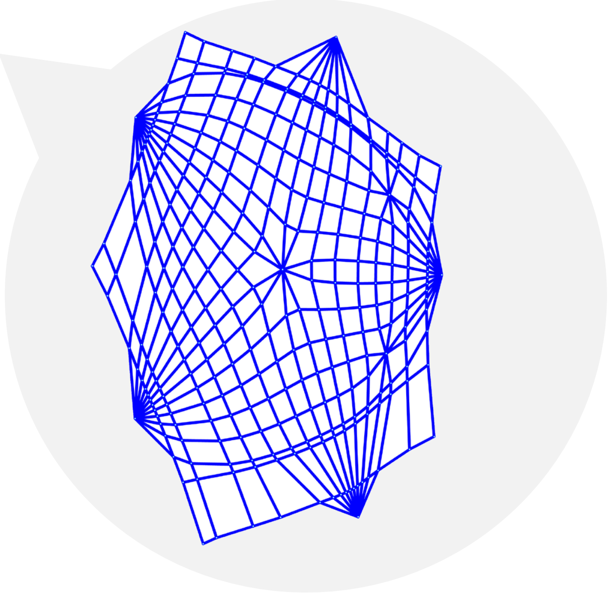


02 Form Diagram and Force Diagram

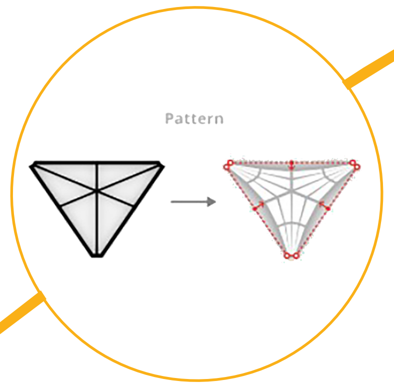


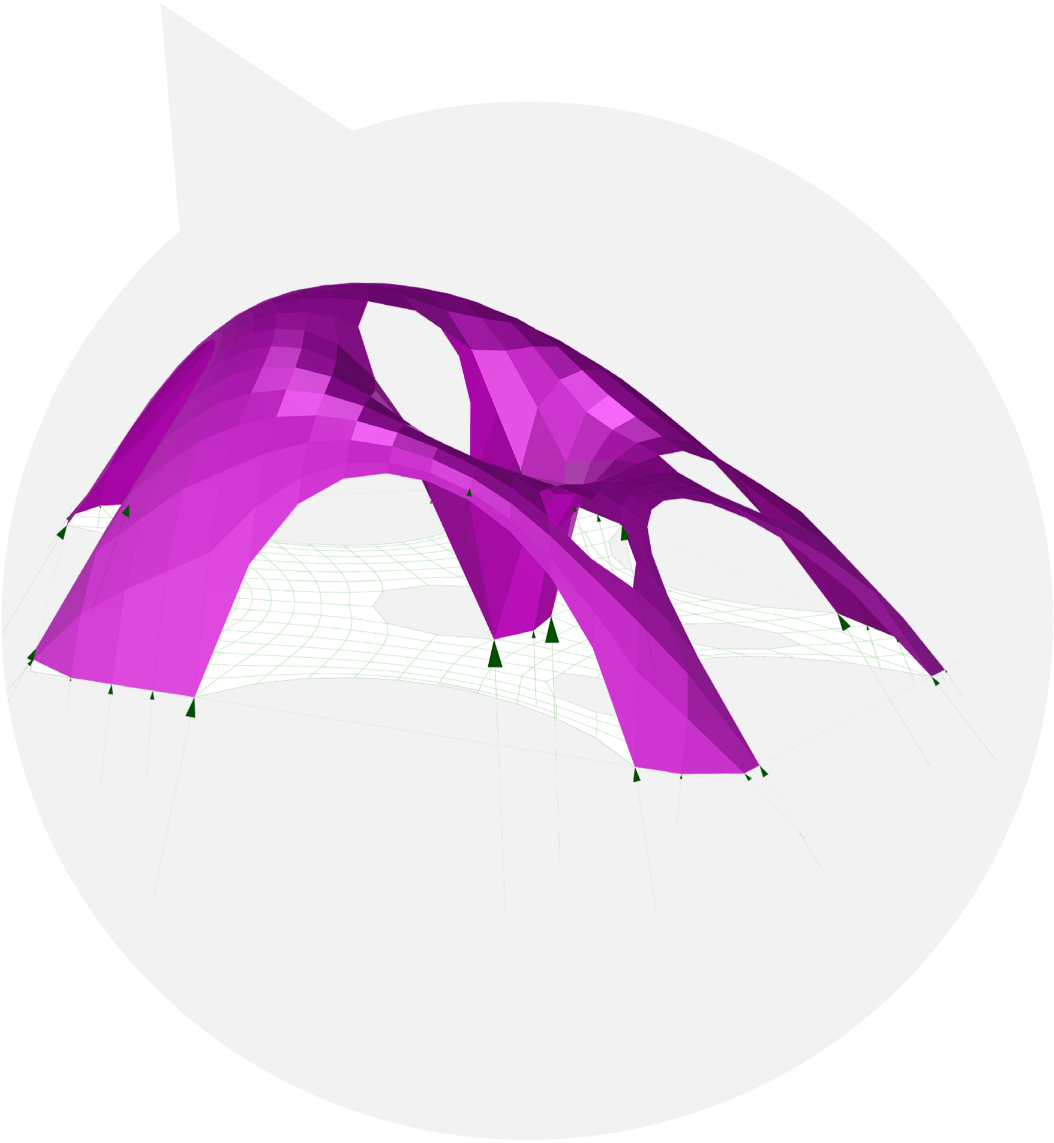




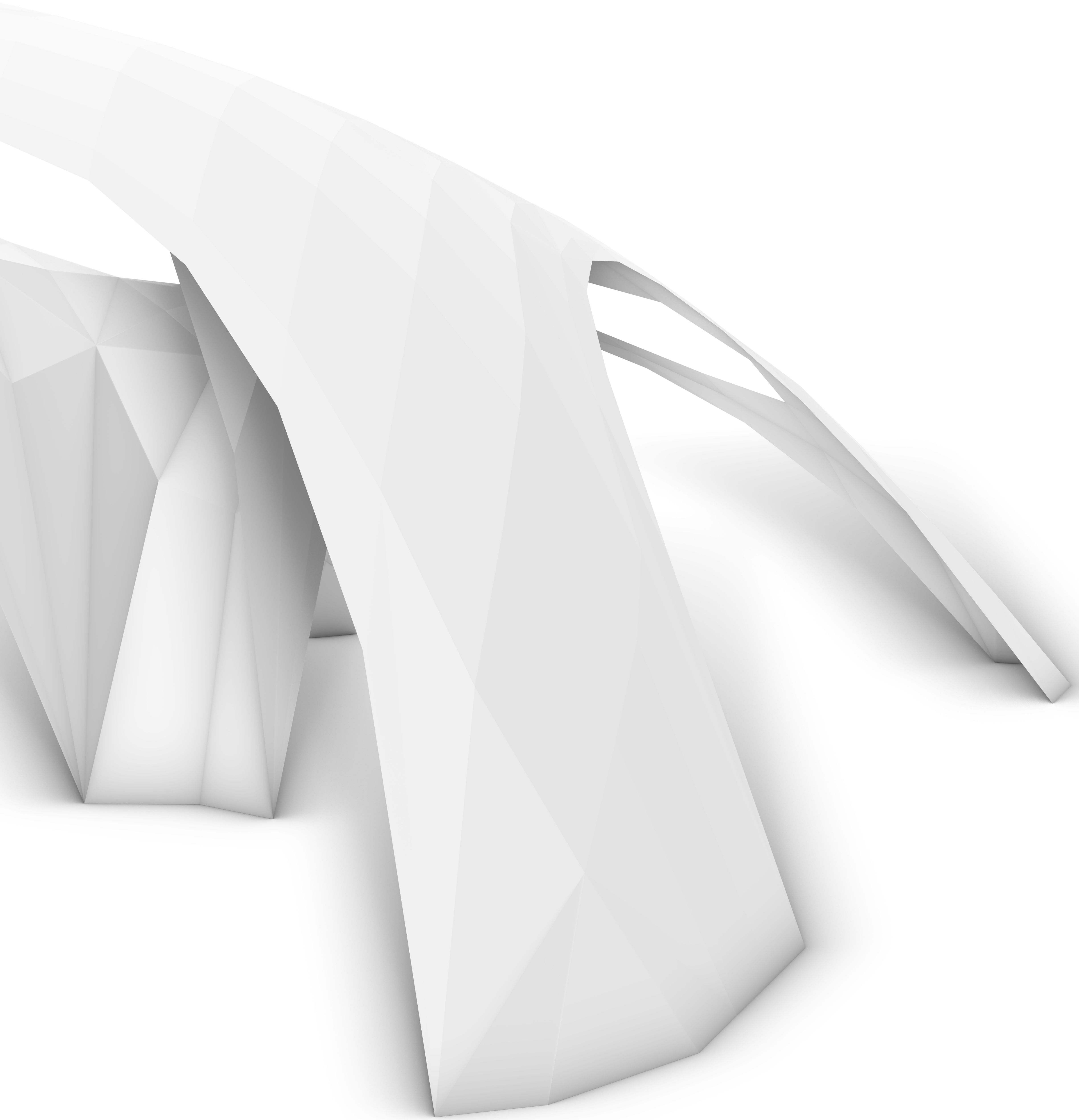


03 Horizontal Equilibrium and Vertical Equilibrium

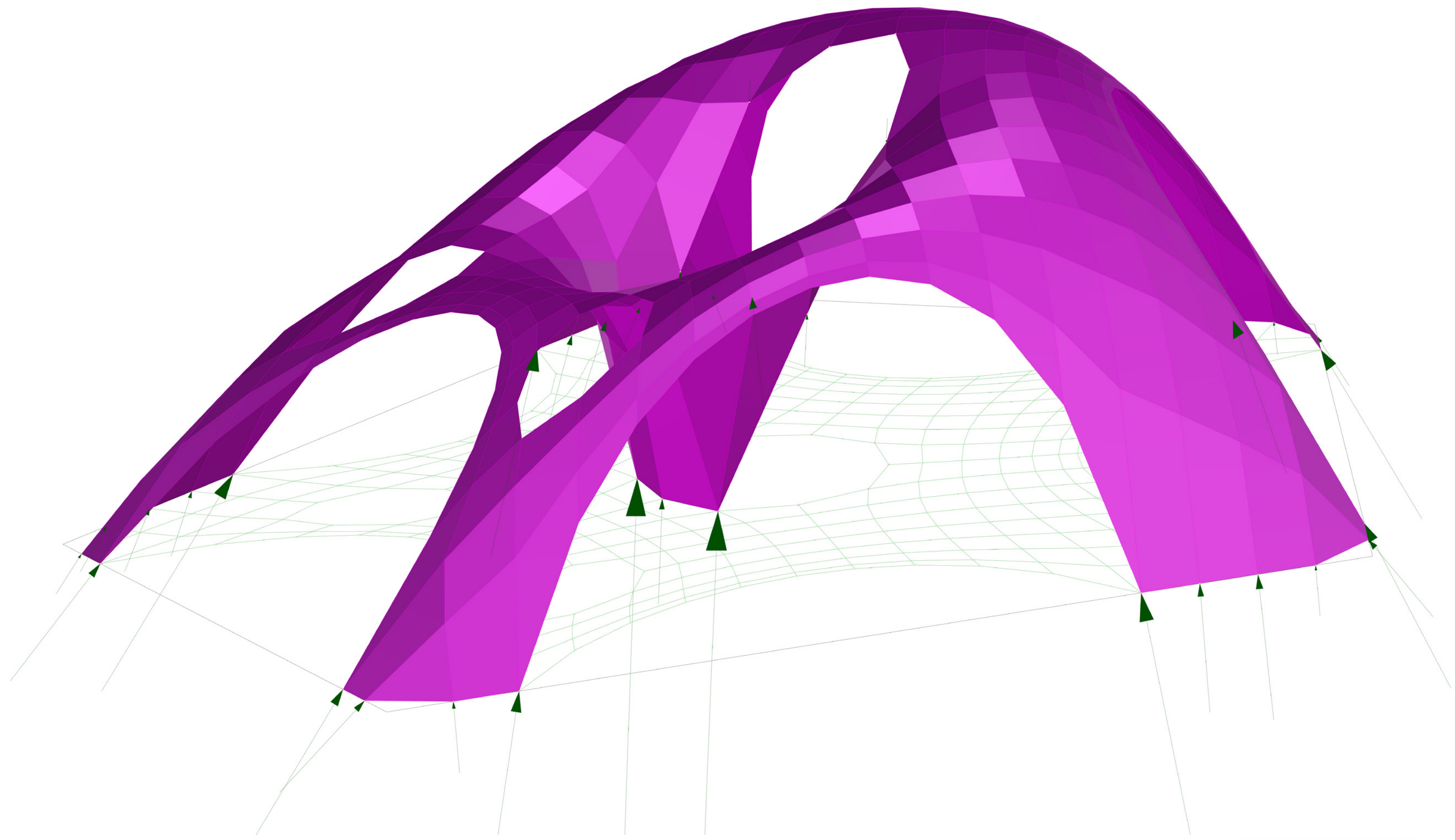


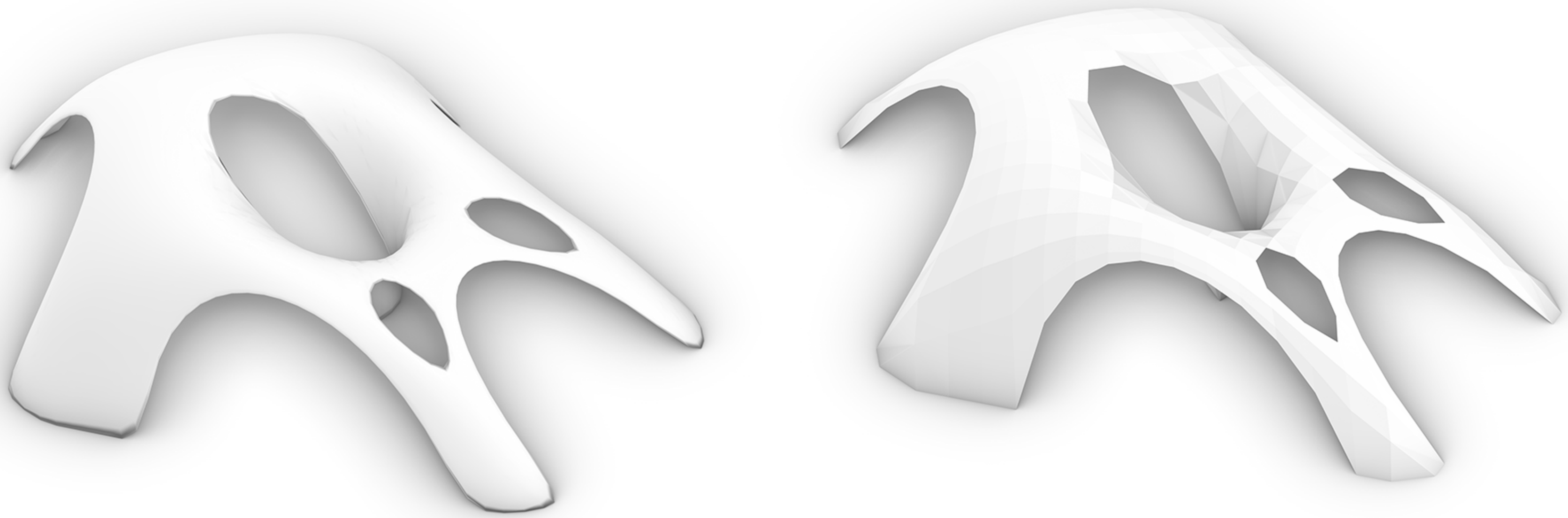


01 Create Pattern and Define Boundary condition



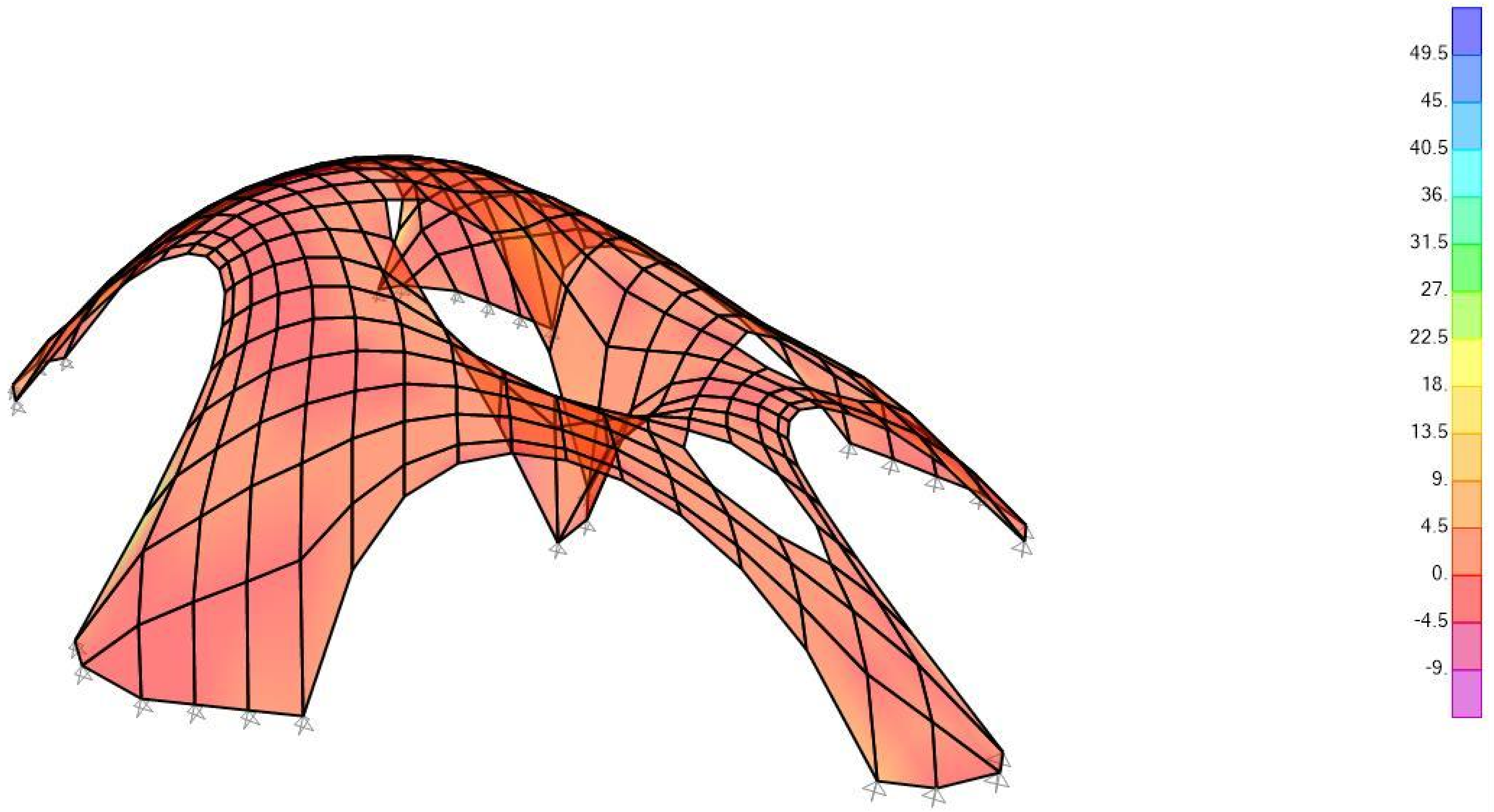
FORM FINDING RV2





Final design from rectangular surface pattern, fixed supports at corners, relaxed pattern, and anchors defined in Thrust Diagram. Grasshopper and weaverbird Plugin meshed the thrust network and create thickness that available for 3D Priting. Different framing systems were generated to achieve the desired final product.

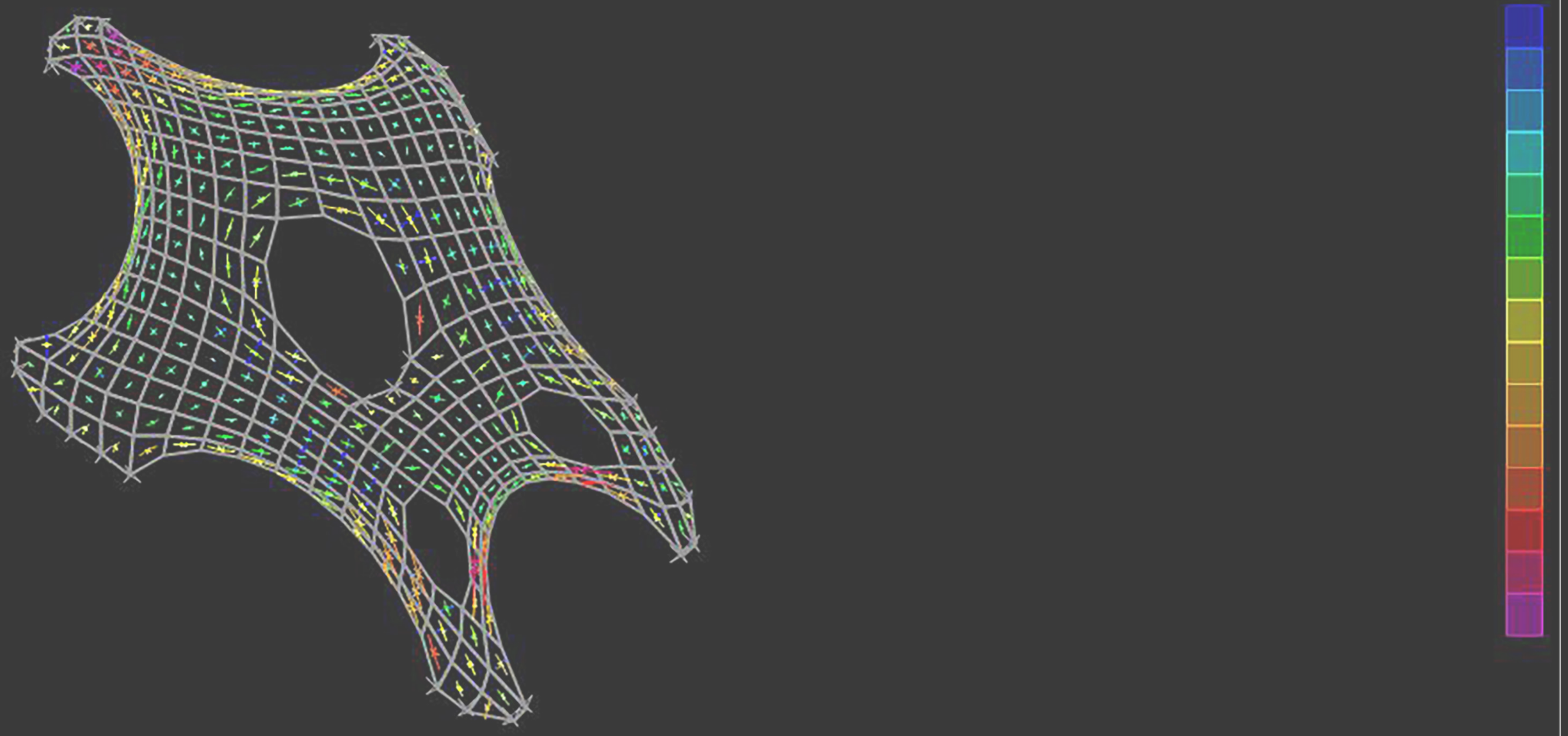
Finite element analysis using SAP2000 computes states of stress and force flow to examine the success of RV2 through the form-finding design process. The model satisfies a compression-only structure under self-weight. The initial assumption includes pinned supports where the model contacts the ground, its material was normal-weight concrete (fc = 4ksi), and the thickness of the shell is 3 inches.



FINITE ELEMENT ANALYSIS

Practice SAP2000 Analysis

As the course moves forward, the modal analysis with distributed live load and asymmetrical loading will be testified to achieve an optimized design. The force flow in the uniformed shell could help analyze the triangular panel H-connections. Testing of such connections will be discussed later on.



SHELL CONSTRUCTION

BACKGROUND 10 WEEKS

ARCE 415 Senior project 10 weeks is a small part of a larger story

IN THE PAST

Professor Ed Saliklis, PhD, PE and his research partner Nathan Lundberg have worked for years bringing a vision to life. Nathan Lundberg developed a code in Grasshopper (G-Code) for a double-skinned shell. The shell is made of a quadrilateral mesh and is flattened onto sheets which can be cut by a CNC machine.

10 WEEK SENIOR PROJECT

Cal Poly's Winter Quarter ARCE 415 helps build the G-Code Shell for the first time. Next, the class (with Ed Saliklis and Nathan Lundberg's expertise) improve and develop a second shell.

IN THE FUTURE

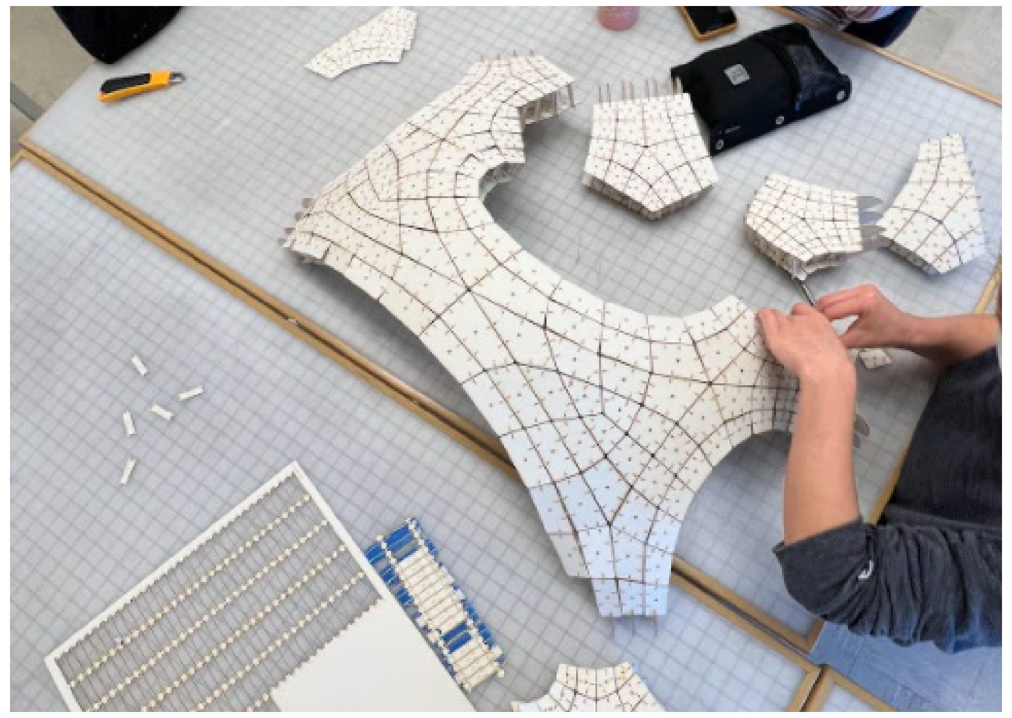
Senior projects of the future will continue to build, design, improve and finalize the shell. It will become an outdoor learning pavilion for the San Luis Obispo Botanical Garden.

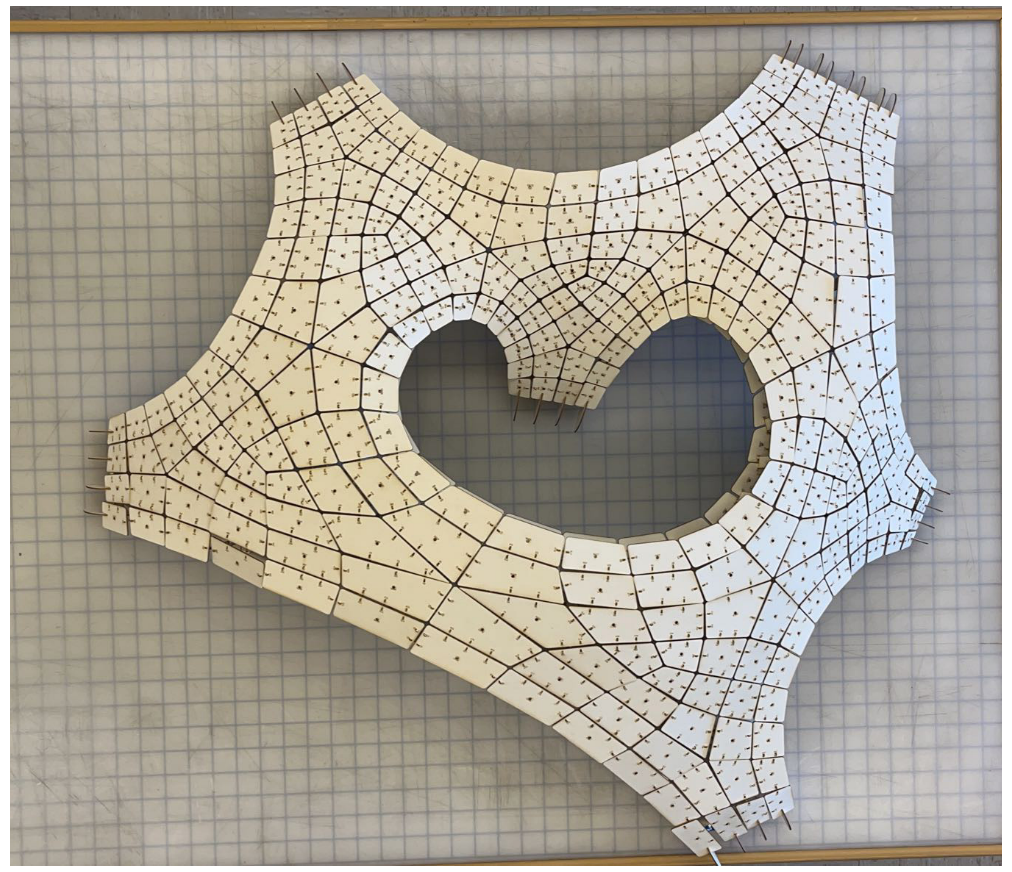
STUDY MODEL

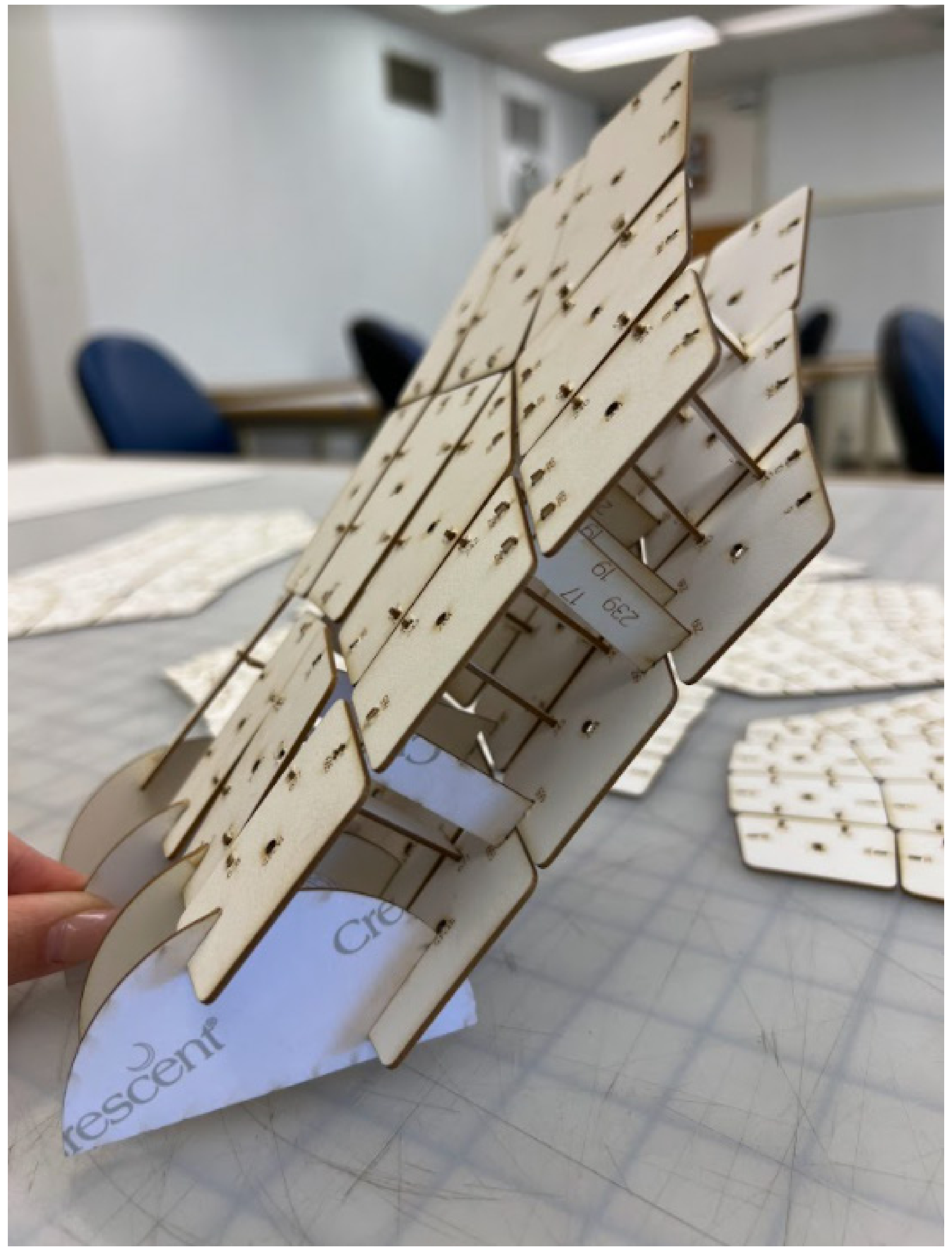
Laser-cutting a down-scaled model of the initial design to practice assembling the full-scale size

SHELL ONE STUDY MODEL

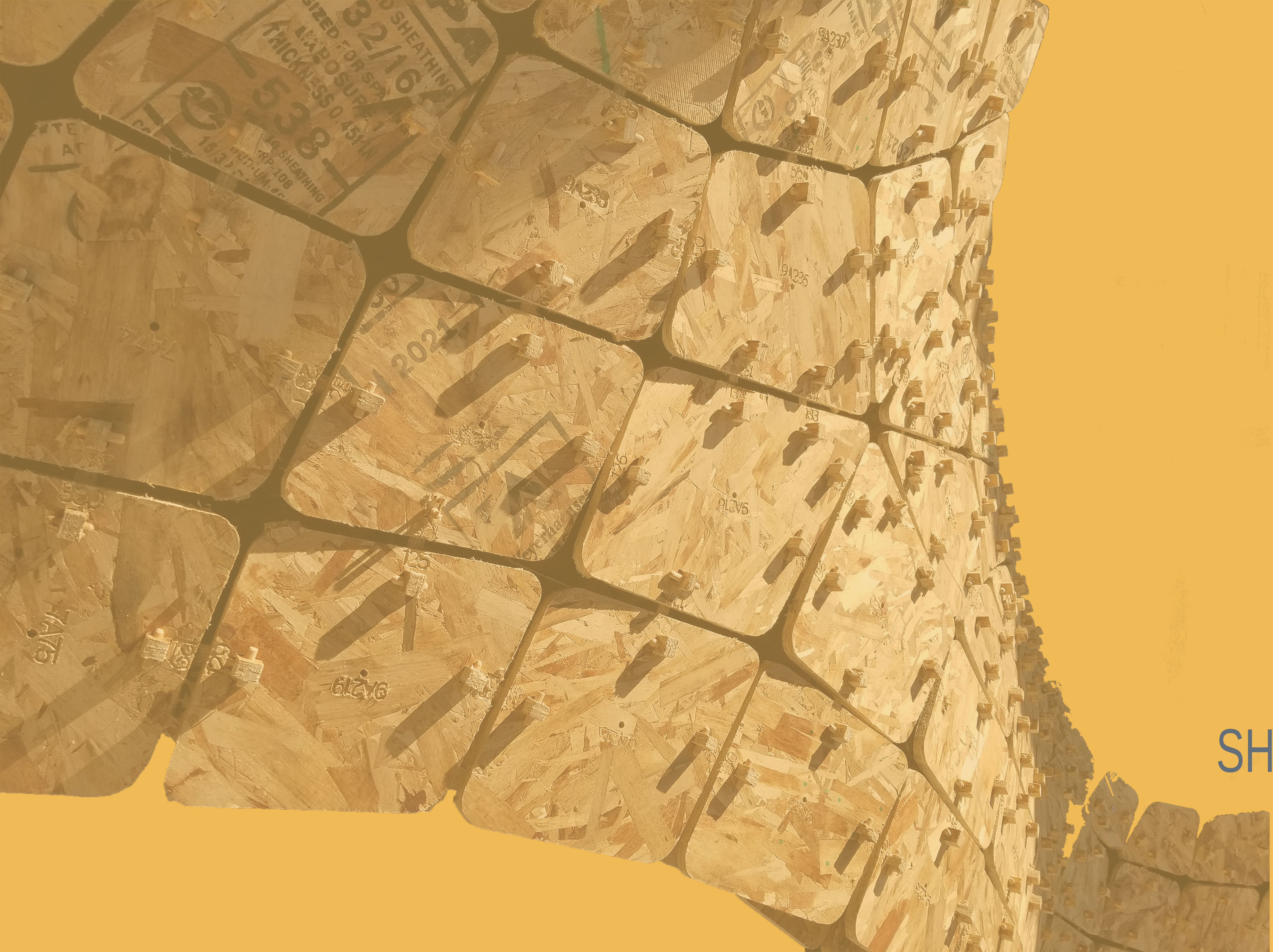
Study model erected by other classmates, and used by everyone to understand the full-scale project







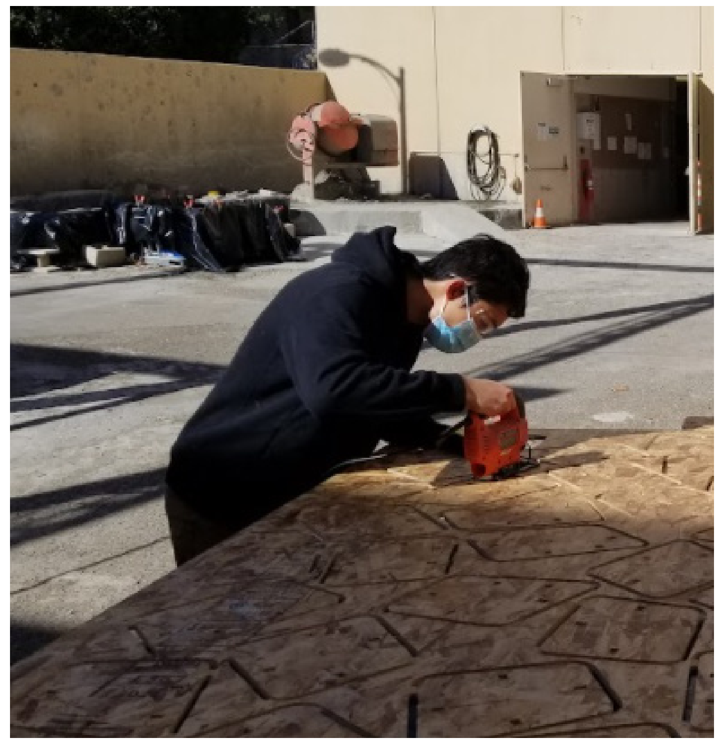
Using Nathan Lundberg's G-Code, the full-scale shell was scaled down to a table-top size, printed on paper crescent board, and assembled.
The model features the double-skin layered structure, the H-Connectors between top and bottom panel layers, and the numbering system used for assembly.
Panel numbers were directly carved (CNC) into the panels, so that matching could be used for easy assembly -- like a puzzle.
An assembly method was established for the larger model. It was decided which sections of the model to assemble first.



SHELL ONE

QUADRILATERAL MESH

The entire ARCE 415 class assmbled this inital full-scale model



SHELL ONE BUILDING

The class cut and prepared the pieces for assembly

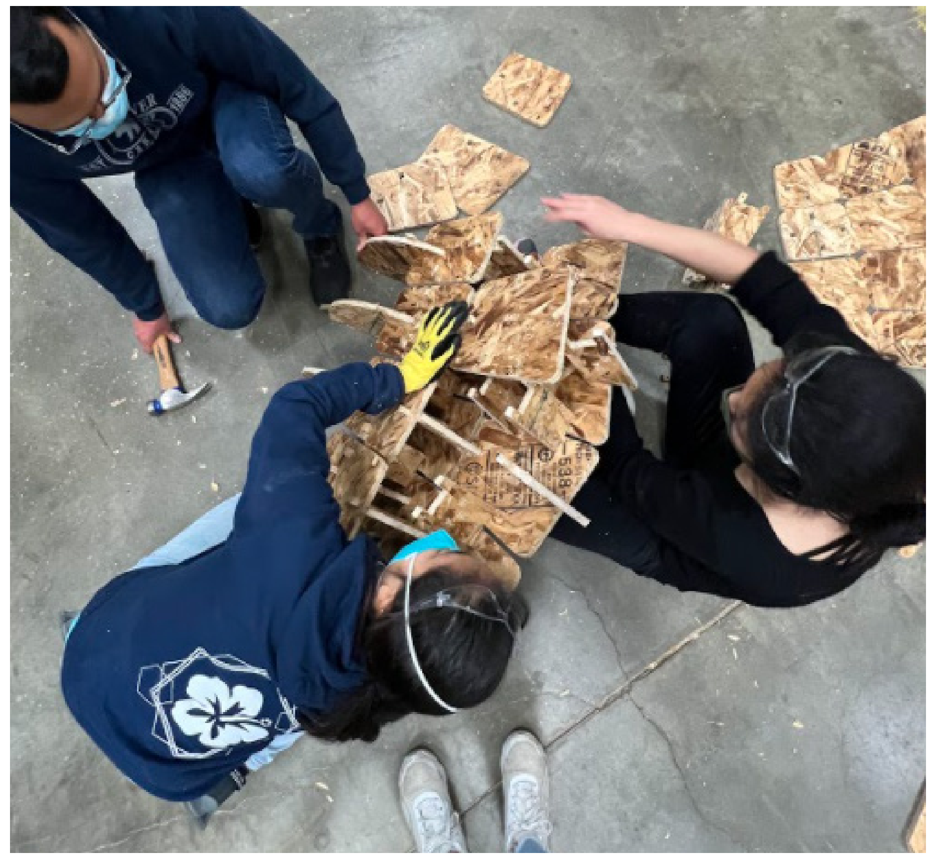
The CNC machine cut the G-Code onto OSB panels, leaving only a few bridges behind.

Bridges were routed, and later sanded off, leaving only the panels behind.

Quadrilateral panels were sorted by the numbering system etched onto them by the CNC machine,

to be assembled.

Small panel sizes, thick bridges, and faceted H-Connectors slowed down assembly. The shell took around four weeks to build.



The G-Code utilized a Quadrilateral mesh, and thus panels were quadrilateral shapes.

The shell is made from OSB, with a top and bottom layer "double-skin."

Ratchet straps were utilized as thrust containment between the footings of the shell.

H-Connectors attached the top and bottom layers through prefabricated slits.

Wooden dowels are inserted into the ends of the H-Connectors after they have been assembled, so that the layers stay together.

SHELL ONE QUADRILATERAL MESH

The completed shell was a success!

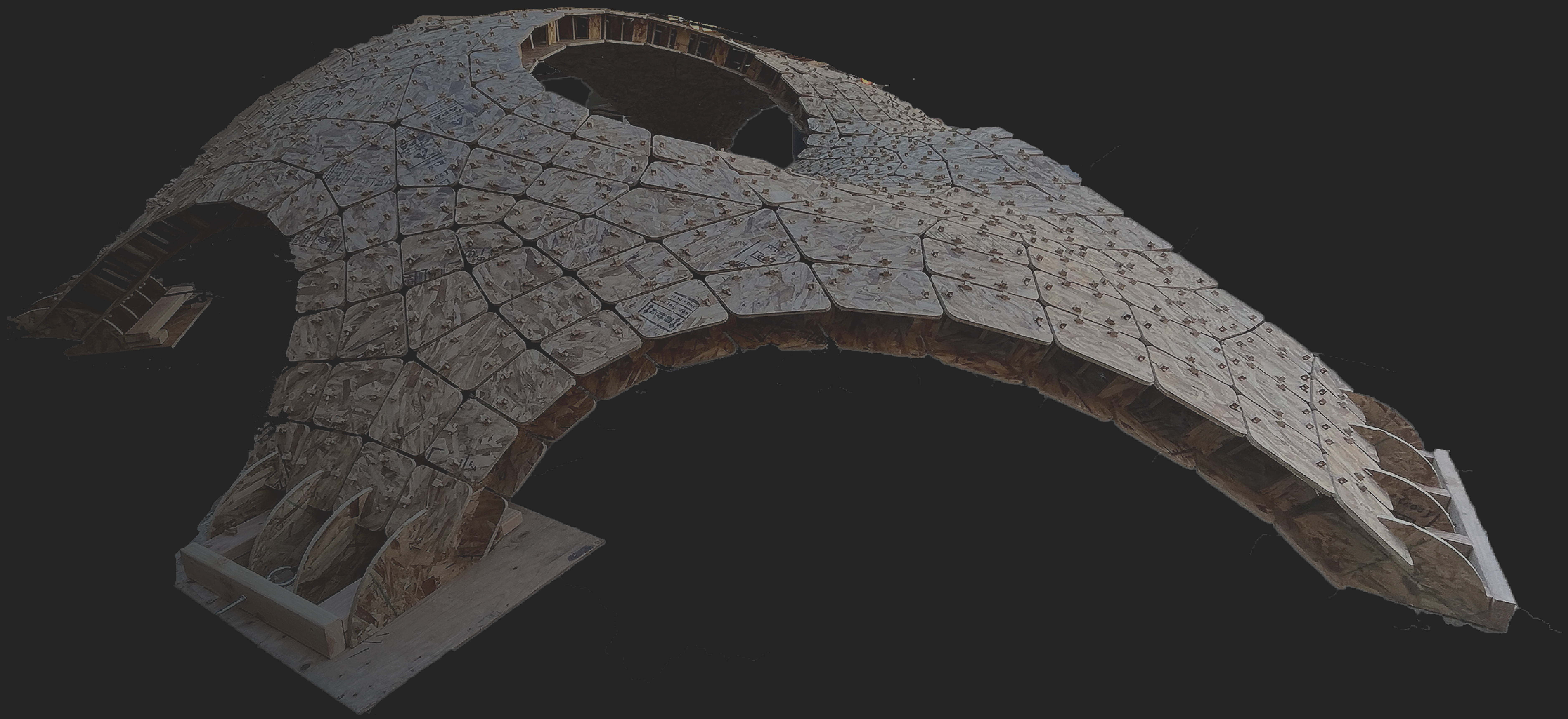


SHELL ONE LOADING

Loading fails -- the next shell will need some improvements

In order to mimic a distributed load, bags of concrete (94 lbs each) were craned onto the structure. Initial analysis on SAP-2000 projected the shell could withstand about 12,000 lbs. However, the footing design was underdeveloped and the thrust containment failed prematurely, after being loaded to about 10% of the expected capacity.

For the next shell, larger panels, improved footings, and improved H-Connectors are desired to achieve greater strength, and quicker assembly.



MATERIAL TESTING

Understanding the individual materials used to construct the large scale shells

H-CONNECTOR TESTING
PROCEDURE & RESULTS

Testing Group: Ethan Mach, Adria Burton, Lindsey Brophy
Machinery: Tinius Olsen, Riehle, clamps, bolts, screws
Additional Advising: Vince Pauschek, CAED Support Shop

1

GOALS

Find the strengths of the tabs as designed in the initial quadrilateral shell. Learn how to improve H-Connectors

2

TESTS

OSB: Compression, initial H-Connector design
OSB: Compression, configured H-Connector design
OSB: Tension, intial H-Connector design
OSB: Tension, configured H-Connector design
PLYWOOD: Compression

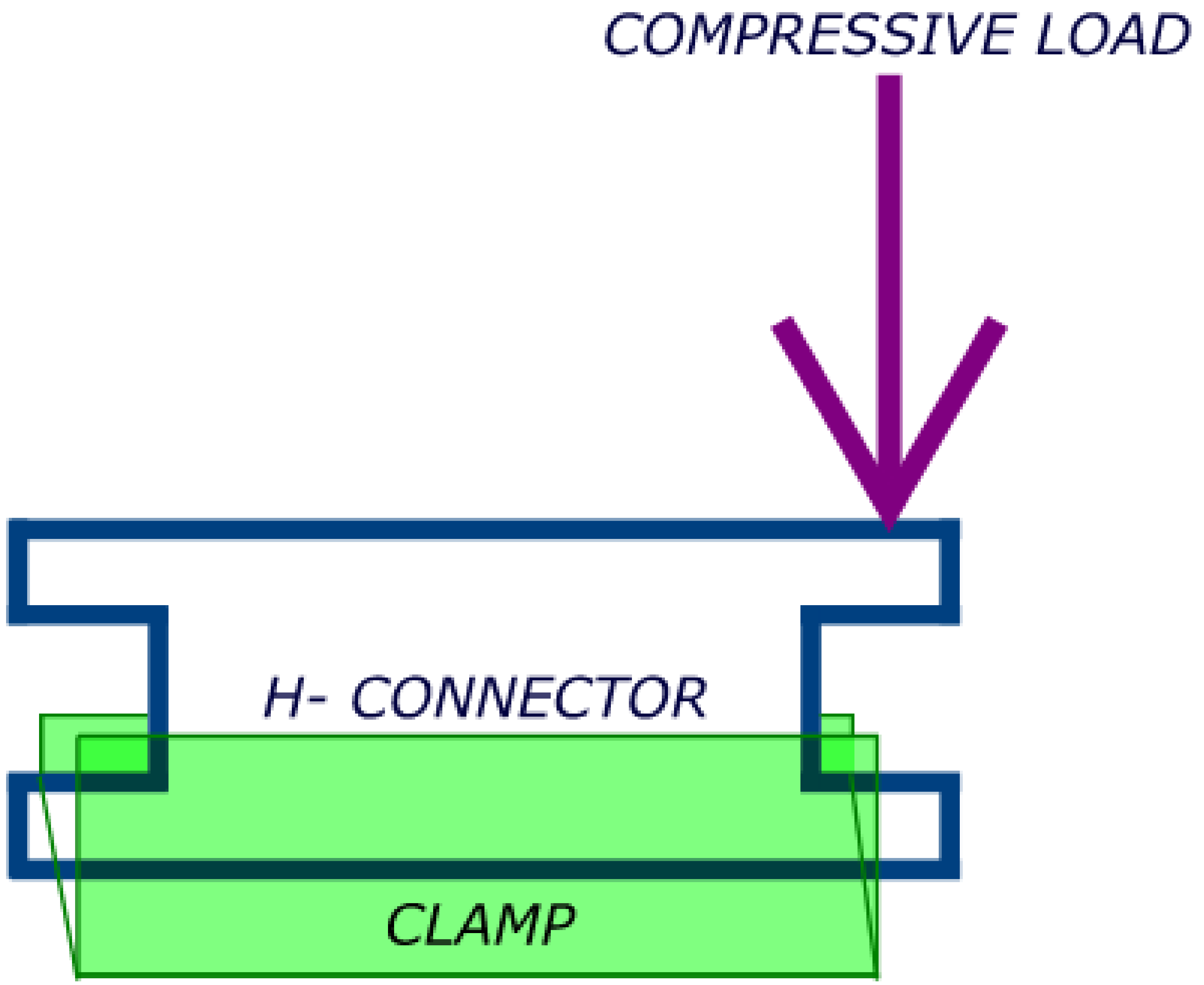
3

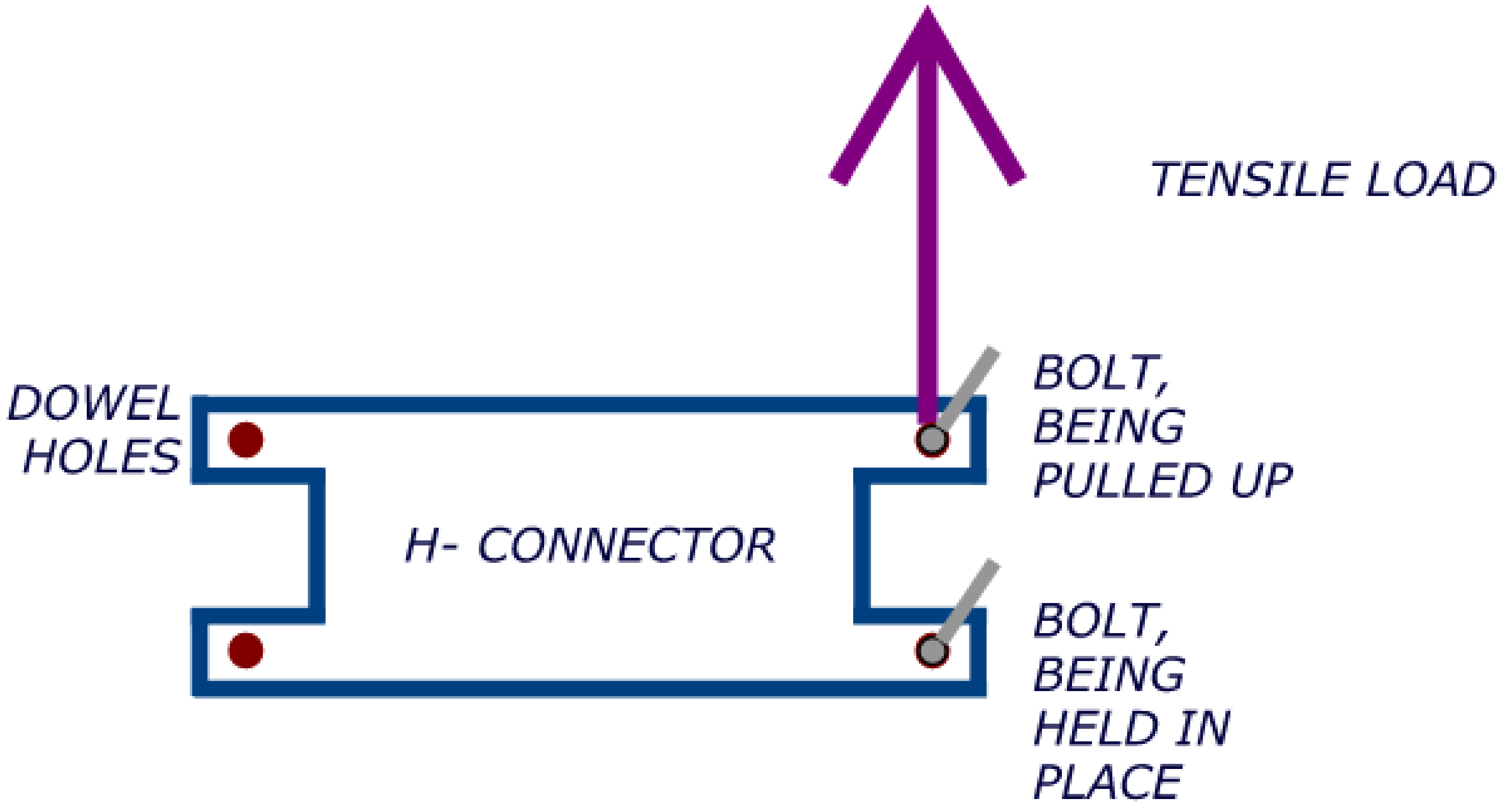
DISCOVERIES

Increasing tab thickness increased tab capacity in compression, but not as much as desired.
The blowout distance from the edge the tab to the dowel holes had greatest impact on capacity in tension.
Tabs are stronger in compression.

MATERIAL TESTING: H - CONNECTORS

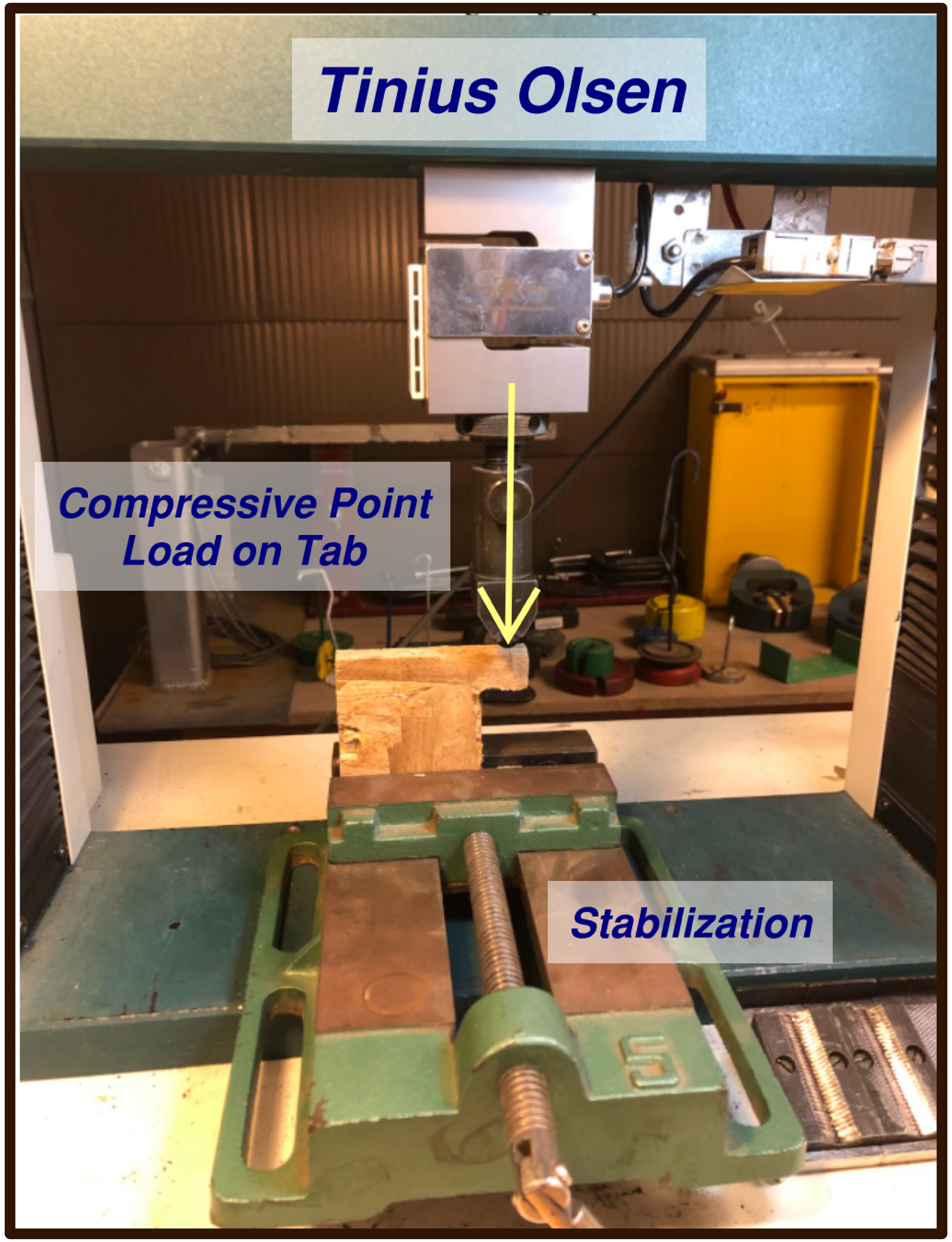
“H” shaped couplings connect the top and bottom skins of the shell togther. The (4) tabs on the H-Connectors fit into pre-cut slots on the tri or quadrilateral panels. Each H is unique, and numbered so that it can be placed in it’s designated location. Dowels are inserted into a hole located in the center of each tab after the skins are assembled, to prevent the H-Connectors





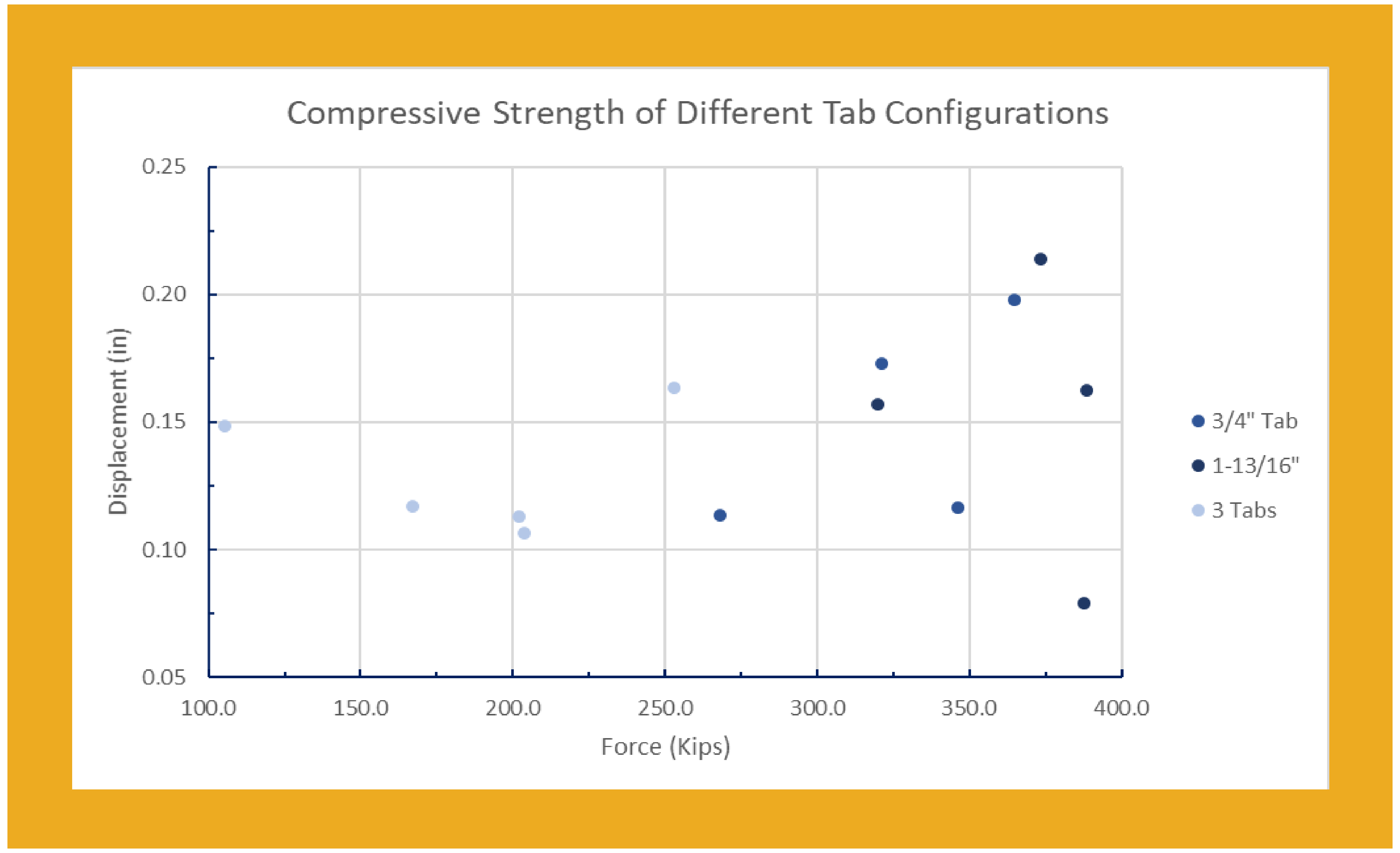
Since shell structures perform best in compression, H-Connectors are expected to perform best in compression as well.

In order to do comprehensive testing on H-Connectors, tensile tests were also performed. The main objective was to discover how dowel-holes in tabs affect H-Connector strength.



COMPRESSIVE H-TESTING

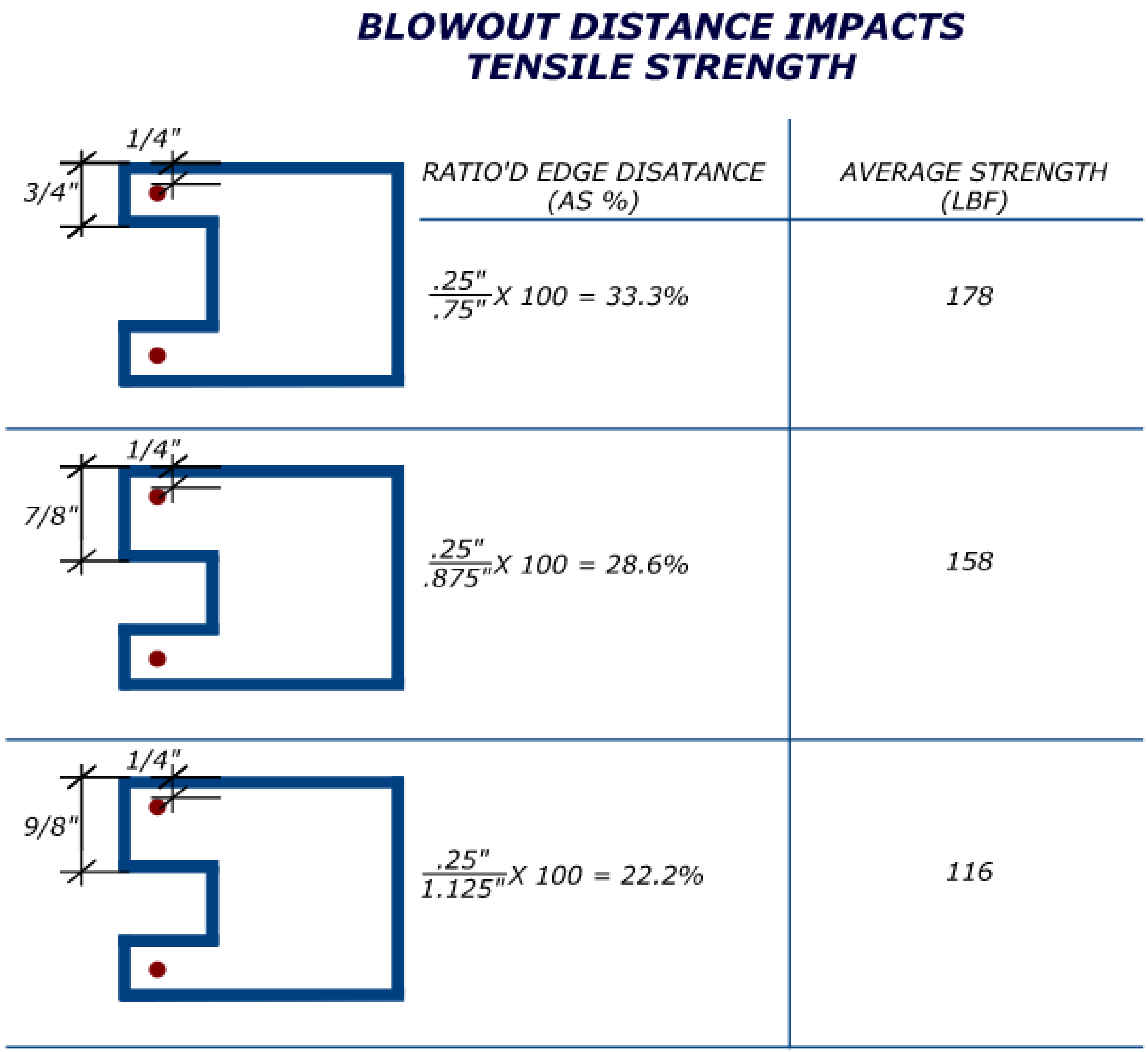
Compressive strength of H-connectors increased as tab with increased.

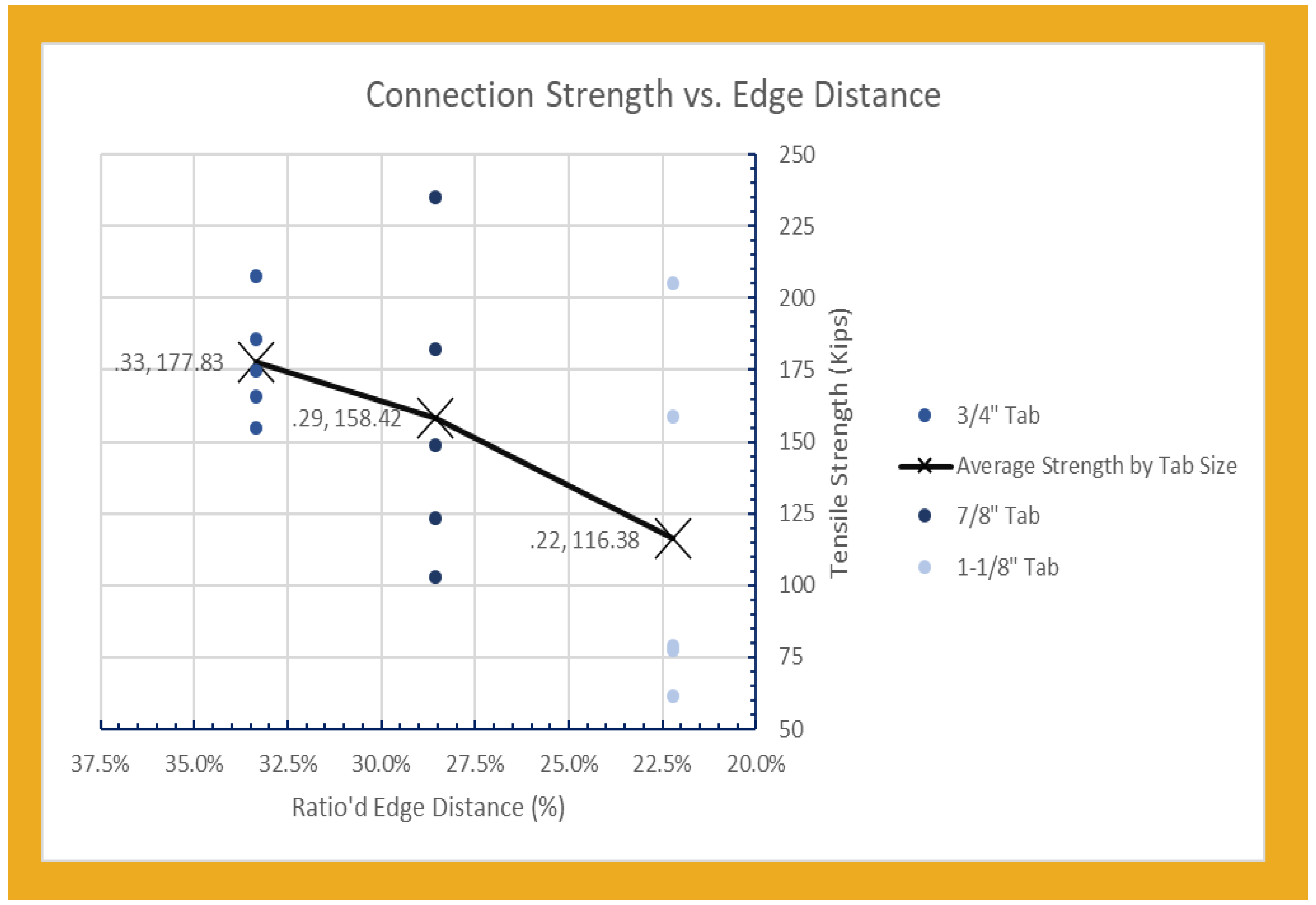


Trial	Compression Force (lbf)	Displacement (in)
1	321.102	0.17309
2	268.272	0.11343
3	409.152	0.20276
4	346.206	0.11669
5	364.940	0.19799
Average	**341.9344**	**0.16079**

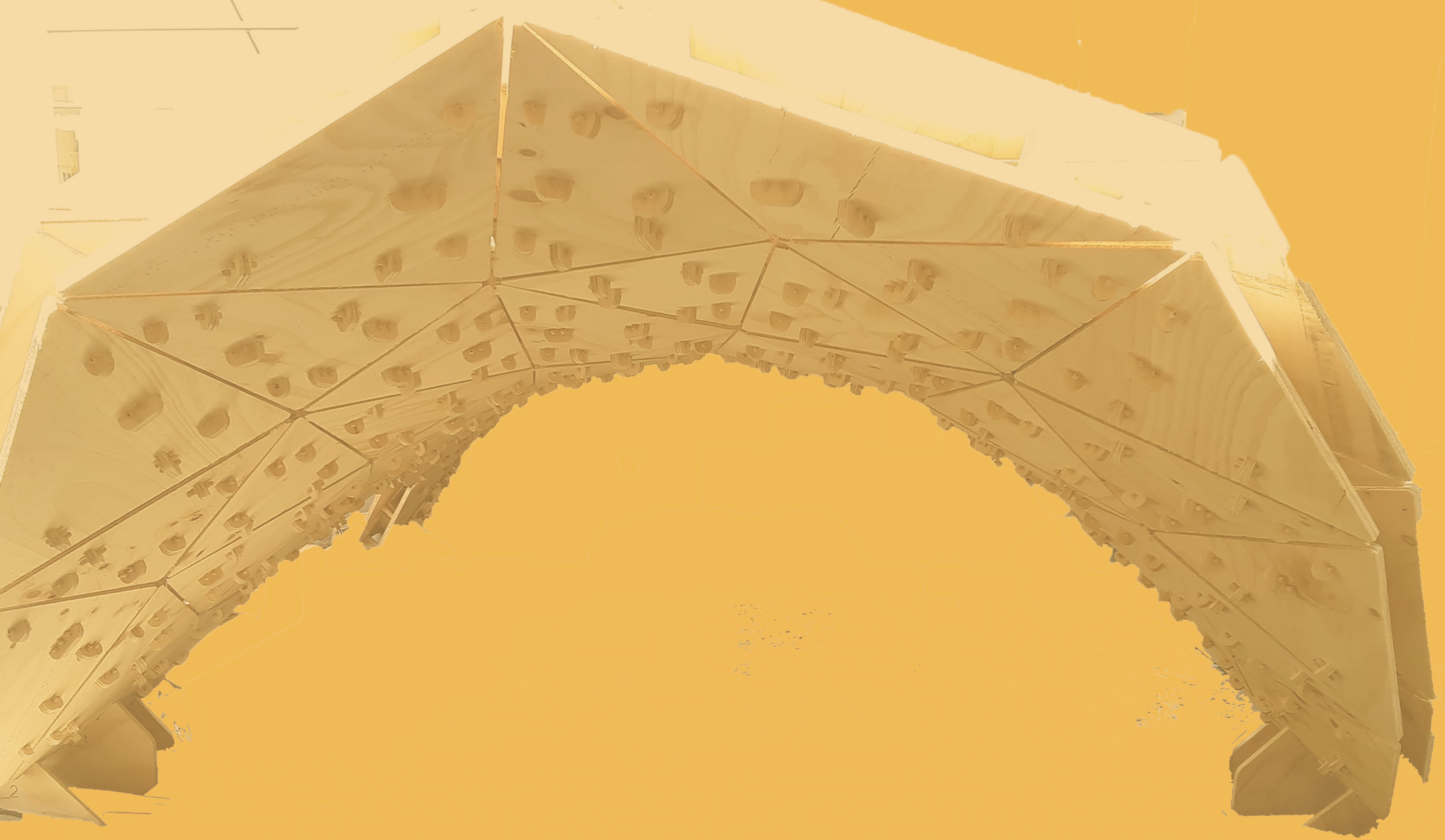
TENSILE H-TESTING

Tensile strength of H-connectors depended the MOST on how centered the dowel-hole was within the tab.





3/4" Tab		
Trial	**Tension Force (lbf)**	**Displacement (in)**
1	185.8	0.05
2	166.0	0.16
3	175.0	0.09
4	207.6	0.28
5	154.8	0.13
Average	**177.8**	**0.14**



SHELL TWO

PLYWOOD TRIANGULAR MESH

The redesigned shell that was constructed by the entire class

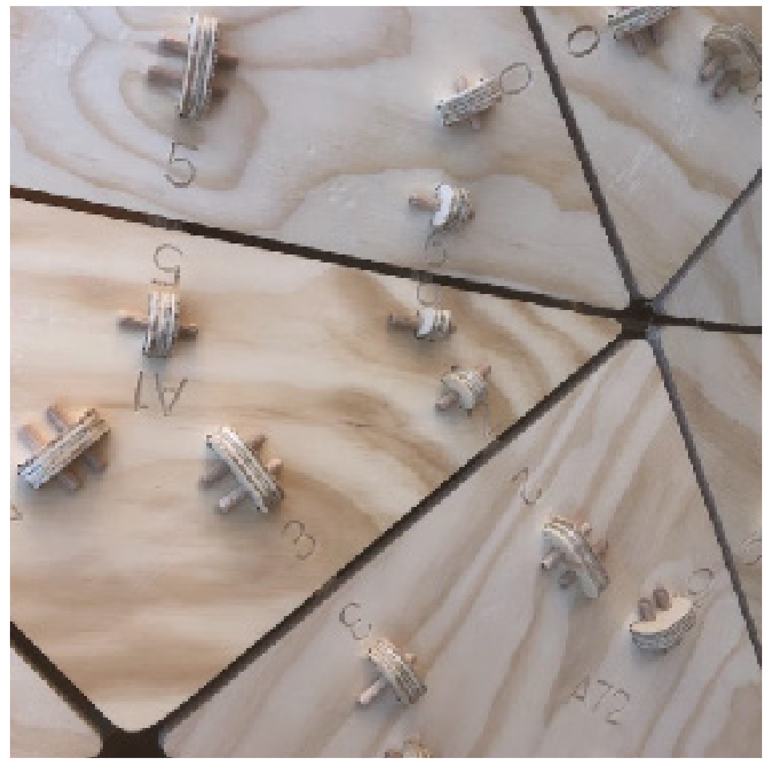
NEW AND IMPROVED

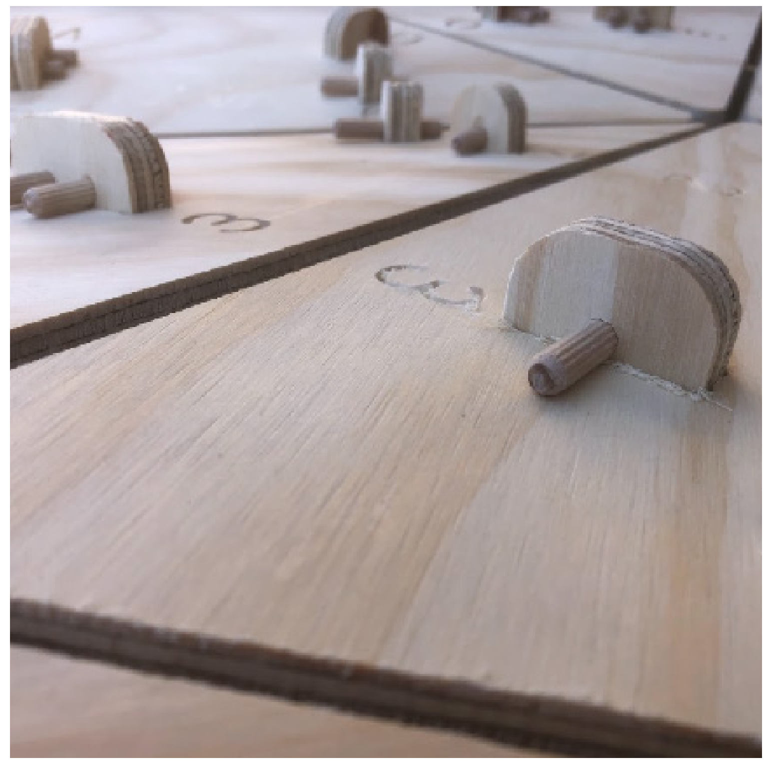
Observations made from the construction of the first shell were taken into consideration while developing the design for the second class shell. One of the first modificationsincluded the altering of both the shell panels and the H connections that held them together.

The shell panels were made into triangular shapes rather than quadrilateral shapes. In addition, the size of the panels was increased, resulting in a reduction of the total number of panels.

Similarly, many of the H connections increased in size as well, with larger tabs with rounded edges to facilitate the insertion of the couplings into the triangular panels. Arrows were etched into the connections in order to provide clarity regarding the orientation of the pieces.

LEARN BY DOWELING





The same doweling system as the OSB structure was utilized for this shell. However, rather than each connection having a single hole bored into it, a few couplings had multiple holes to accommodate more than one dowel pin.

The dowel pins were effective in keeping the H connections secure and prevented them from slipping out of the panel slots. The increase in dowel pins per coupling allowed for a more secure and sound panel connection.

FRESH FOOTINGS

Since the previous class shell failed because of the footings, a significant amount of modification occurred with this component of the plywood shell.

The shape of the footings was altered into a polygon with straight edges. The reason for this configuration was to allow the footings to beflush with the sides of the concrete blocks and beams, resulting in the stabilization of the shell. With the tremendous weight of the concrete blocks, any potential movement would be prevented.

THRUST CONTAINMENT REIMAGINED

In addition to the failure of the shell footings, poor thrust containment was also a reason for the quick collapse of the initial OSB model.

Aside from the support of the concrete blocks, the footings were placed directly across from each other, allowing the multiple ratchet straps to connect each corresponding footing to provide a stronger form of thrust containment.

PLYWOOD PARADISE

After 8 hours of construction, the second class shell was complete.

Inspired by Félix Candela's Lomas de Cuernavaca pictured on the bottom right hand corner of this page, this shell highlights the hyperbolic paraboloid form, with its signature saddle-like shape and unique curvature.

reddit.com

CLADDING

Understanding the individual materials used to construct the large scale shells

CLADDING EXPERIMENTATION
PROCEDURE & RESULTS

Testing Group: Ethan Mach, Adria Burton, Lindsey Brophy
Materials: HYDROCAL, Monk's Cloth

1 **GOALS**

Waterproof the shell structure with draped cladding.

2 **METHODS**

Dip Monk's Cloth in HYDROCAL and drape over shell.

3 **DISCOVERIES**

While our method works, an additional layer of strength will need to be added overtop of the dipped cloth. This should be further experimented with in the future, perhaps there is a way to not clad the structure at all?

CLADDING EXPERIMENTATION

If the structure is going to be a temperary fixture, then it will need to be waterproofed to withstand weather.

HYDROCAL TESTING
PROCEDURE & RESULTS

Testing Group: Adria Burton, Lindsey Brophy
Machinery: Riehle
Additional Advising: Vince Pauschek, CAED Support Shop

1 **GOALS**

Find the strengths of the HYDROCAL used in cladding explorations.

2 **TESTS**

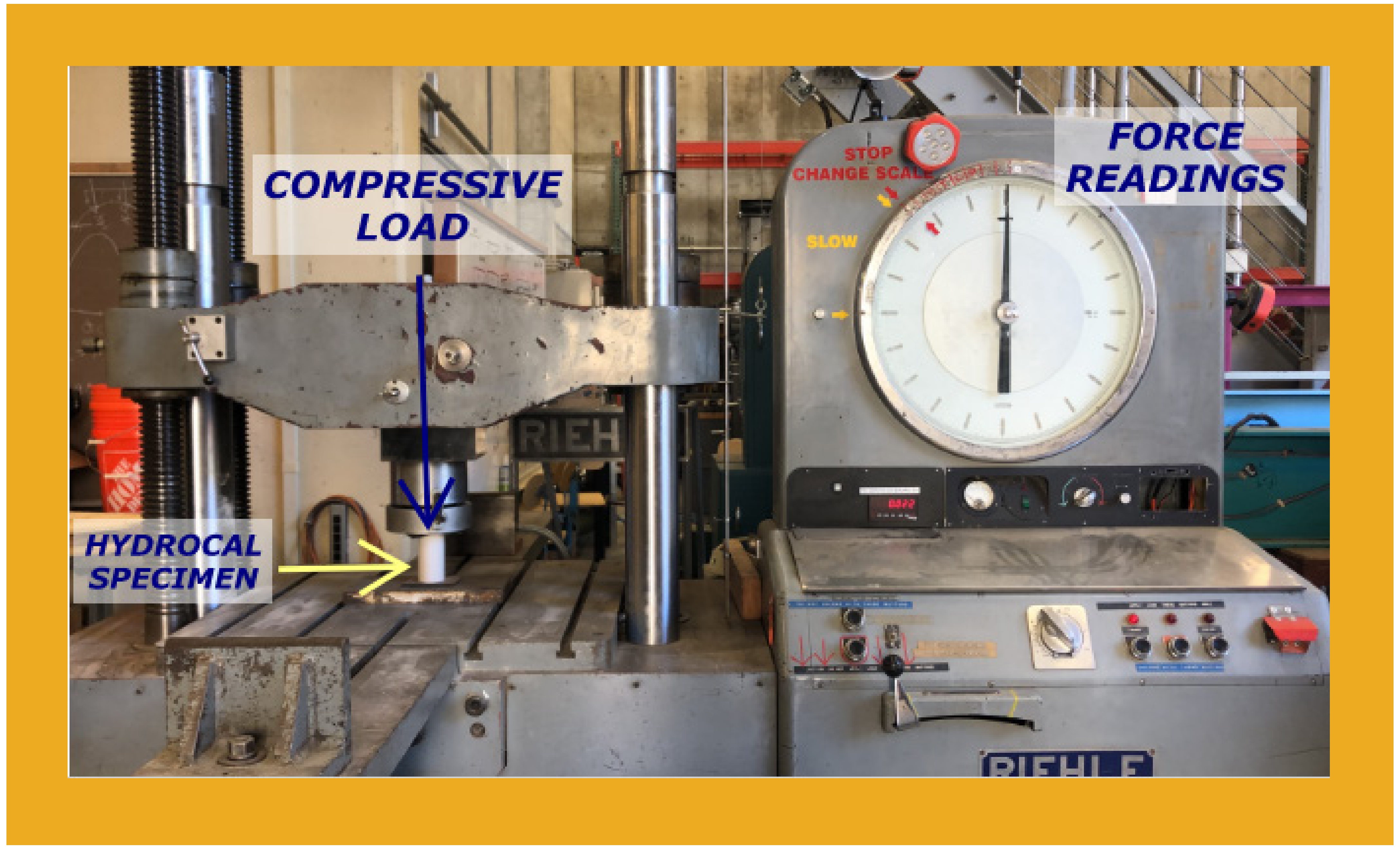
HYDROCAL: Compression, 2x4 Cylinders - left in a water bath prior to testing.

3 **DISCOVERIES**

7-day test yielded advertised wet strength of HYDROCAL. Small cylinders were used to not overwhelm the Riehle Testing Machine

HYDROCAL TESTING

If the structure is going to be a temperary fixture, then it will need to be water-proofed to withstand weather.



Trial	Expected Maximum Strength (psi)	Force (lbs)	Area (in²)	Strength (psi)	Difference (%)
1	1000	3875	3.14	1233	23
2	1000	3150	3.14	1003	0
Average	**1000**	**3513**	**3.14**	**1118**	**12**

APPENDIX

H-Connection Strength Testing

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.

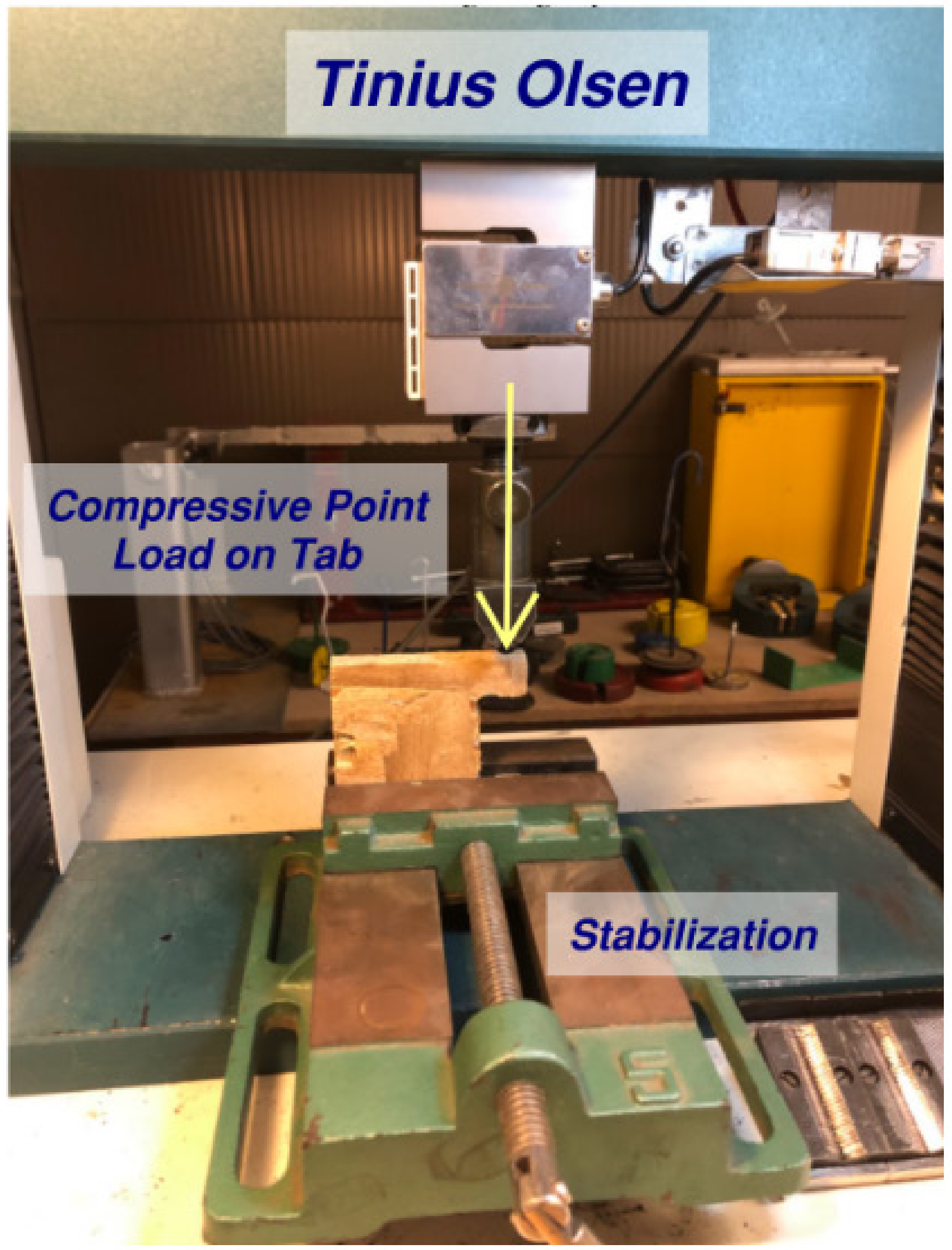


Figure 1.1.1: Compression Test Set-Up

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

Trial	Compression Force (lbf)	Displacement (in)
1	321	0.173
2	268	0.113
3	409	0.203
4	346	0.117
5	365	0.198
Average	**342**	**0.161**

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).

Figure 1.3.1: Crushing in Compression

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 1.4.1: Compression Strength Test of 3/4" Tab

3/4" Tab		
Trial	**Compression Force (lbf)**	**Displacement (in)**
1	321	0.173
2	268	0.113
3	409	0.203
4	346	0.117
5	365	0.198
Average	**342**	**0.161**

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

1-13/16 Tab		
Trial	**Compression Force (lbf)**	**Displacement (in)**
1	369	0.423
2	389	0.163
3	388	0.079
4	320	0.157
5	374	0.214
Average	**368**	**0.207**

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

3/4" 3-Tabs		
Trial	**Compression Force (lbf)**	**Displacement (in)**
1	204	0.106
2	167	0.117
3	105	0.148
4	253	0.163
5	202	0.113
Average	**186**	**0.130**

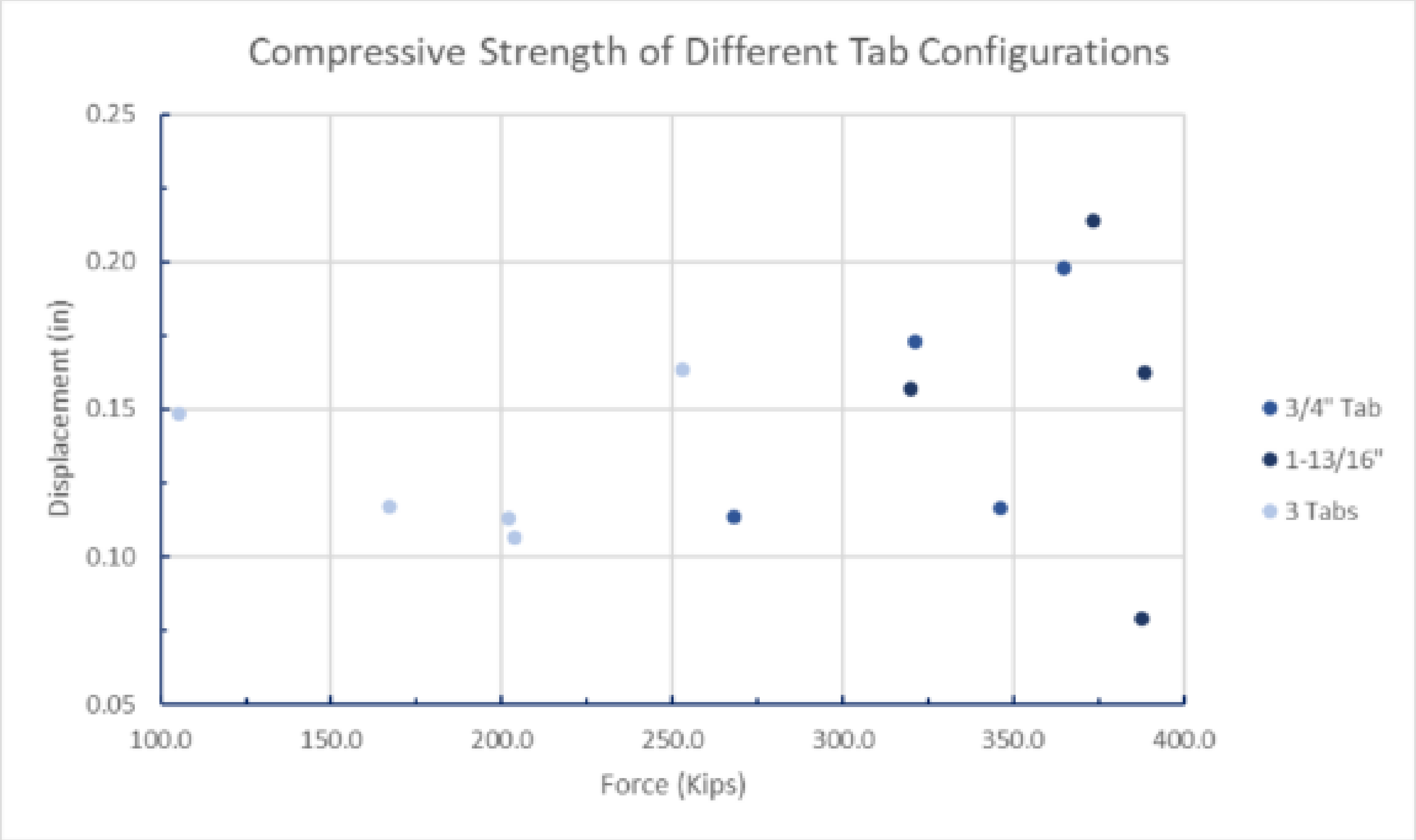


Figure 1.2.1: Compressive Strength Related to Tab Thickness Summary

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

Plywood Tab		
Trial	**Compression Force (lbf)**	**Displacement (in)**
1	207	0.819
2	312	0.291
3	870	0.456
4	375	0.093
5	467	0.210
Average	**446**	**0.374**

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).*

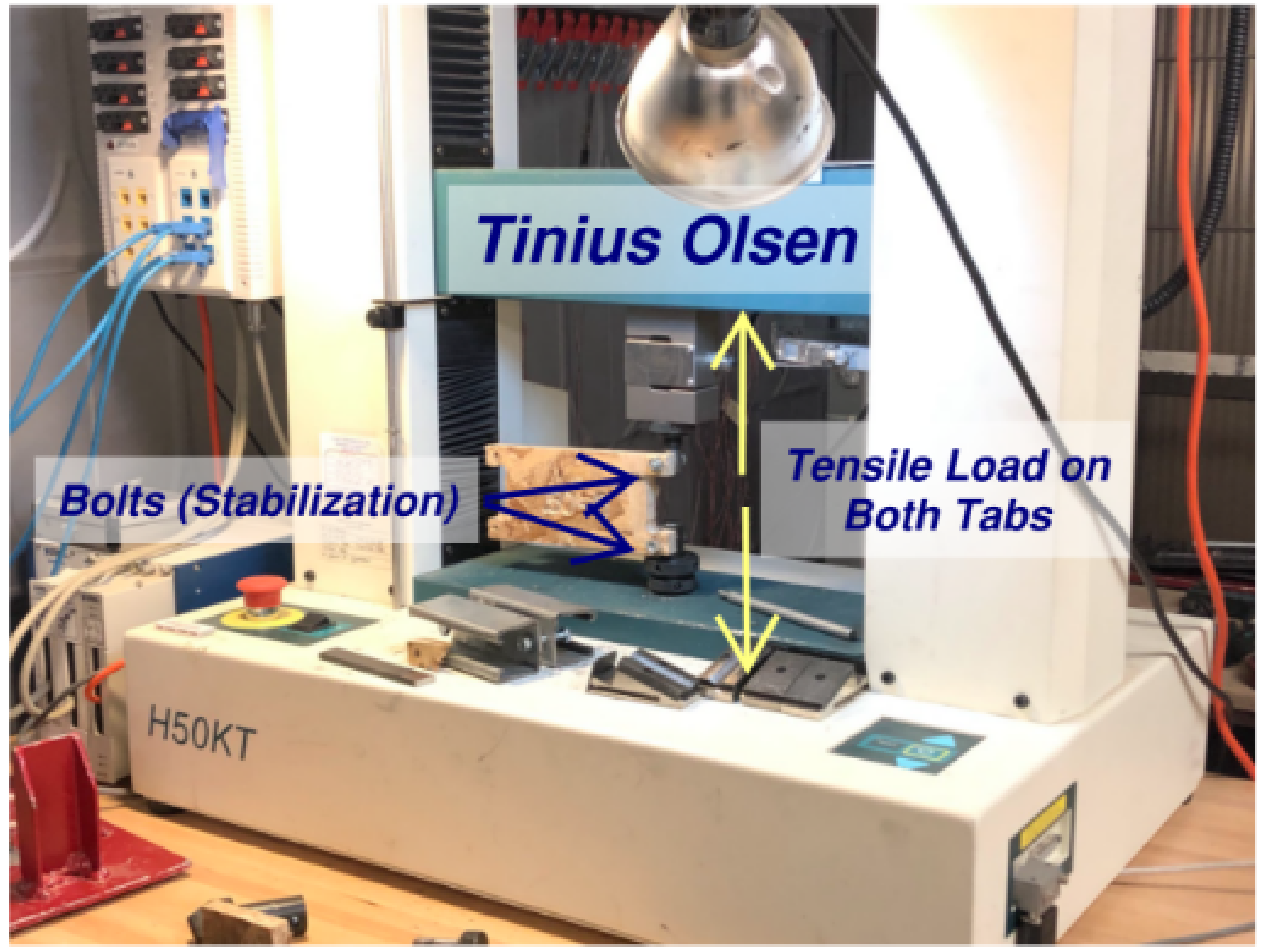


Figure 2.1.1: Tinus Olsen Tensile Test Set-Up

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

3/4" Tab		
Trial	**Tension Force (lbf)**	**Displacement (in)**
1	186	0.051
2	166	0.161
3	175	0.089
4	208	0.281
5	155	0.134
Average	**178**	**0.143**

Table 2.1.2: Tensile Strength Test of 7/8" Tab

7/8" Tab		
Trial	**Tension Force (lbf)**	**Displacement (in)**
1	182	0.420
2	149	0.359
3	103	0.225
4	235	0.245
5	123	0.192
Average	**158**	**0.288**

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

1-1/8" Tab		
Trial	**Tension Force (lbf)**	**Displacement (in)**
1	61	0.193
2	79	0.265
3	205	0.367
4	78	0.254
5	159	0.313
Average	**116**	**0.278**

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*).

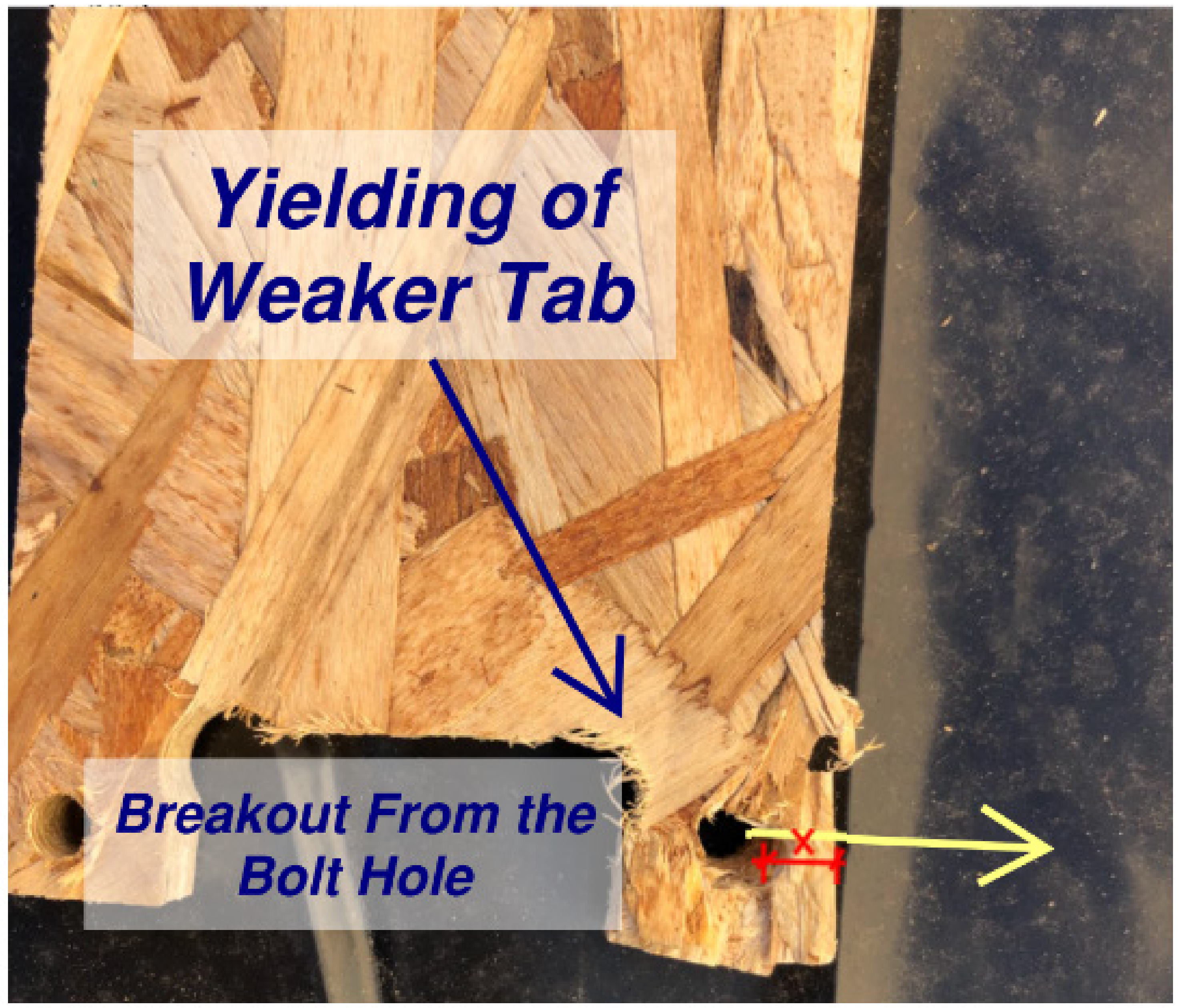


Figure 2.1.2: Tensile Test Failure Mode with "x" Distance

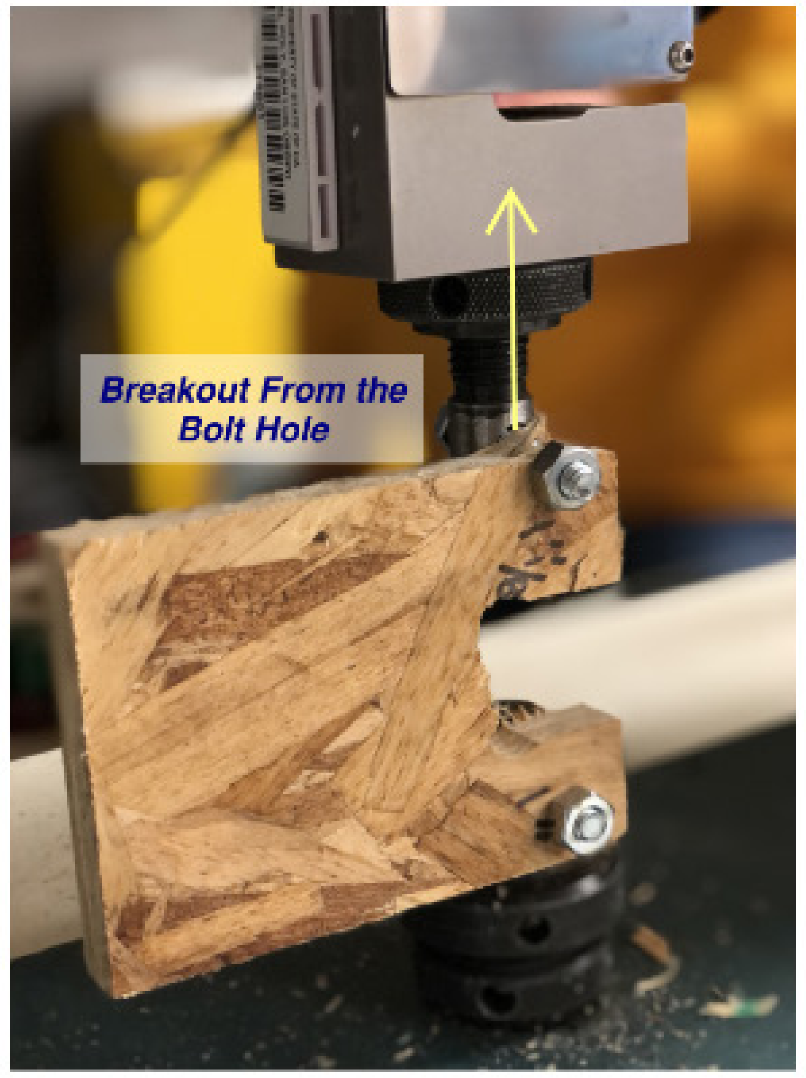


Figure 2.1.4: Bolt Hole Breakout

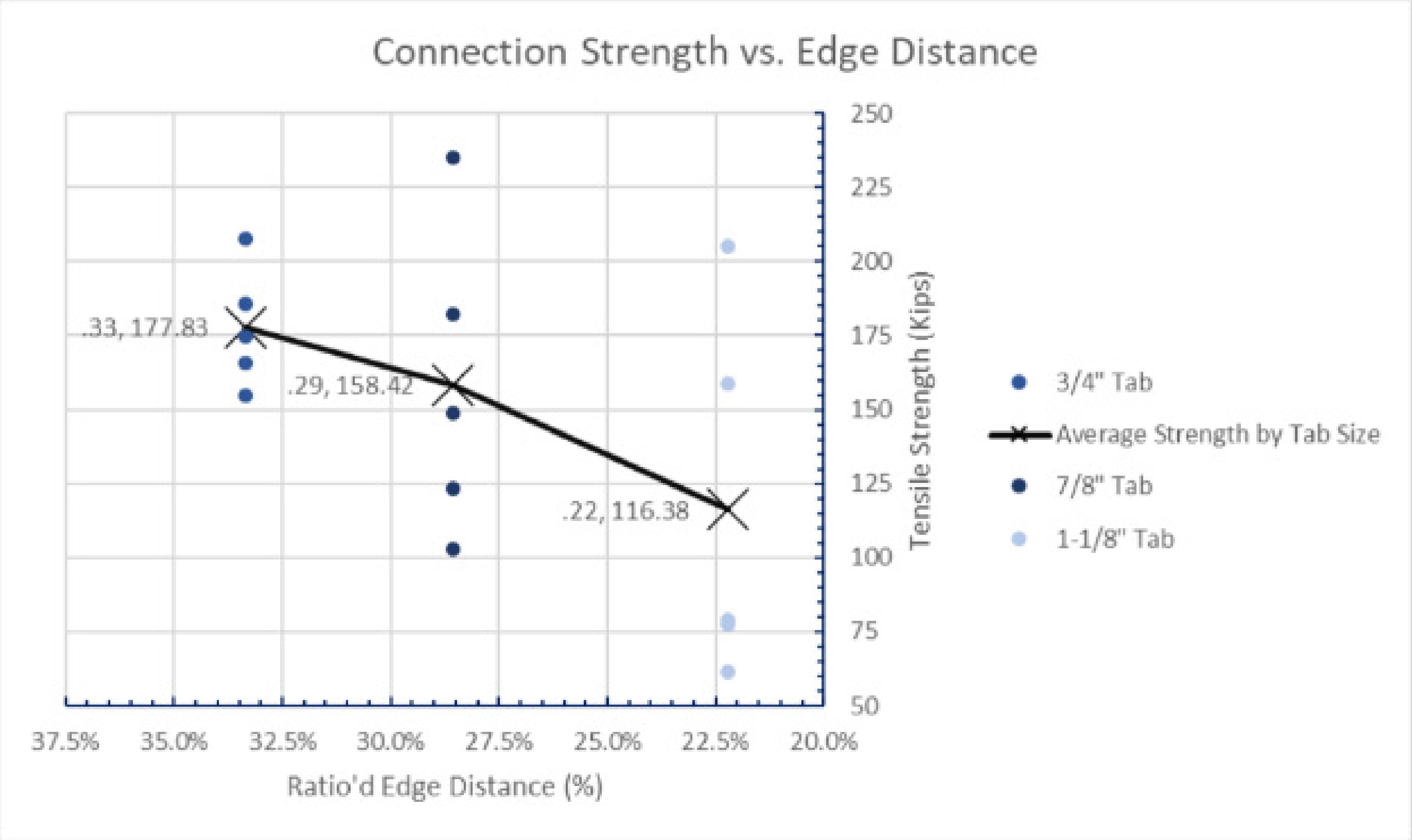


Figure 2.1.3: Tensile Test Connection Strength Relation with Edge Distance

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

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. Small cylinders were used to not overwhelm the RIEHLE Testing Machine

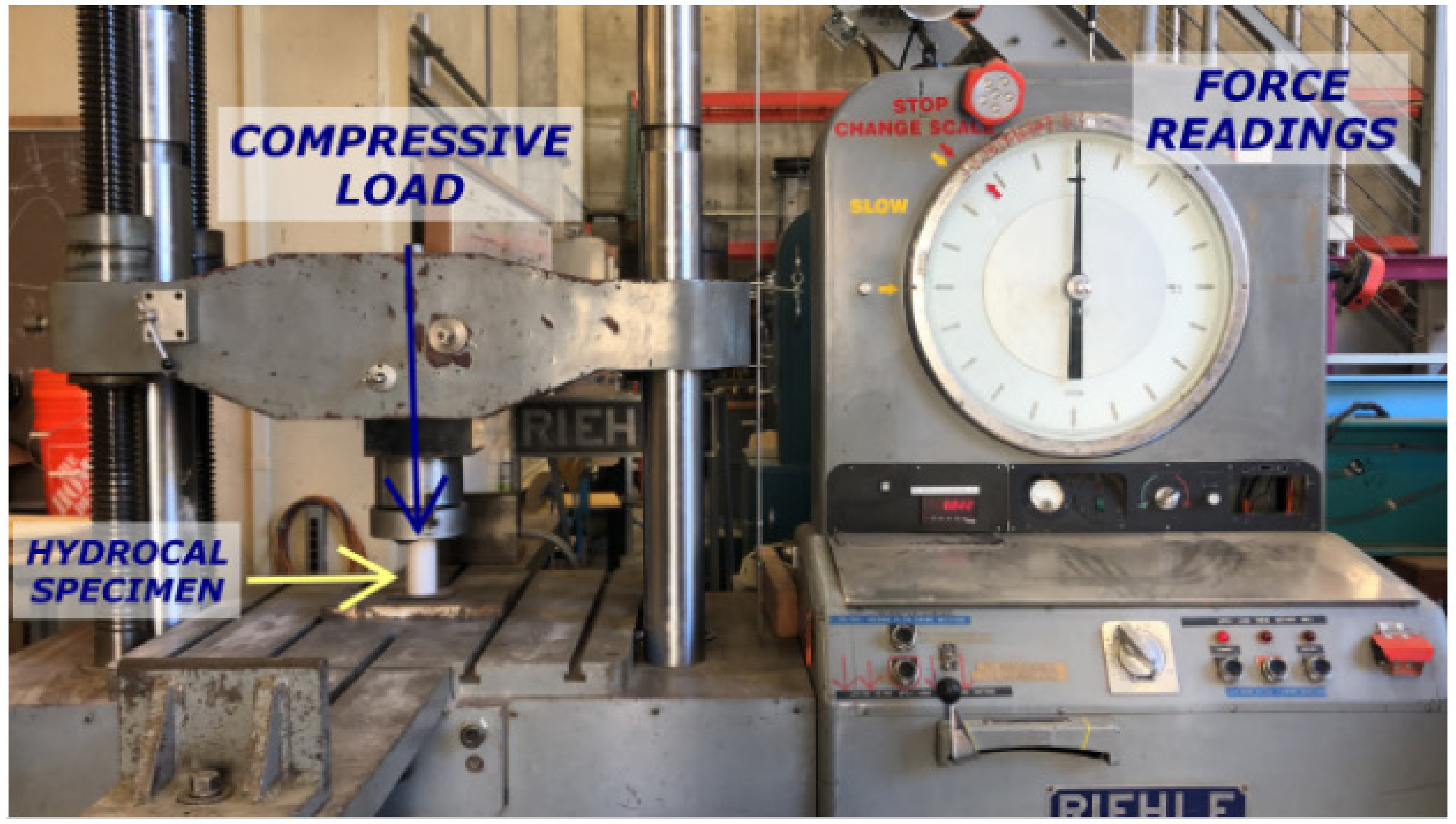


Figure 1.1.1: Test Set-Up on RIEHLE Testing Machine

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

Trial	Expected Maximum Strength (psi)	Force (lbs)	Area (in²)	Strength (psi)	Difference (%)
1	1000	3875	3.14	1233	23
2	1000	3150	3.14	1003	0
Average	**1000**	**3513**	**3.14**	**1118**	**12**

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 *Figure 1.3.2*).

Figure 1.3.1: Spalding at Yielding

Figure 1.3.2: Tensile Rupture

2.0 Conclusion:

The seven-day compression test yielded advertised wet strength of HYDROCAL. Since the advertised dry strength of HYDROCAL is 5000 psi, further testing should be done.