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MEET THE TEAM

MAKING THE DREAM WORK
SHELBY HOLMQUIST
• LAKESIDE, CA
• PICKLEBALL QUEEN
• PROUD TORTOISE (x2) OWNER

ANDREW DUONG
• ANAHEIM, CA
• DABBLLES IN ILLUSTRATION
• PROUD TORTOISE OWNER

MARIA BOYLE
• SAN RAMON, CA
• LIKES TO CRACK UP
• PROUD BLACK LAB OWNER
PROJECT SCOPE

PUTTING THE "ARCHITECTURAL" IN ARCE
The goal of this ARCE 415 senior project course was to create a shade structure that could be incorporated into The Leaning Pine Arboretum, located on campus at Cal Poly, San Luis Obispo. From start to finish, these three ARCE students took on the role of form-finders to form-testers to form-makers. We are putting the "architectural" back in architectural engineering as we reclaim the historical tradition of the engineer as the form finder. In many of our design labs we focused primarily on sizing members and analysis, just using a structure that the architect already had established. In this one-of-a-kind studio, we started with nothing and ended with a fully realized concept.
As a class, we visited the arboretum so that we could really get a sense of the environment we were working with. This arboretum includes various types of plants and unique areas to explore, and we wanted to take the time to capture some of its beauty. By sitting down and sketching, we were able to focus on the many details that have gone into this space. With that in mind, we want to respect the area and to create a structure that will not disrupt all this beauty. Sitting down and visualizing where the structure would peek through, or walking around the path and scouting locations, we were able to get a sense of where to place our structure.
This project is unique because as ARCEs, we were able to take on multiple roles throughout the project. We started with Form Finding, working with shapes in GeoGebra to create our forms. Then we moved to SAP 2000 for Form Testing, where we analyzed the performance and safety of the structure. Finally, we became Form Makers, placing our form into Rhino and Grasshopper to produce renderings as well as laser cut and assemble scale physical models.

Inspired by Iannis Xenakis’ 1958 Philips Pavilion, our studio sought out to create stable and determinate forms respectfully named “Xenaforms”.

Form Testing
Form Making
Form Finding
In GeoGebra we start by placing points on the 2D surface. Sliders are also created to act as variable radii that will control the size of the spheres (Figure 1). The spheres are placed on each ground point and the radius is assigned based off the radius on the slider (Figure 2). Because each sphere has its own radius assignment, each sphere can be a different size (Figure 3). Each of the spheres are named based on the base point’s name to keep consistent. From there intersections of two spheres are found by writing equations, which forms a circle (Figure 4). Then another intersection equation is written (Figure 5) to find the intersection of the circle and the remaining sphere. This creates a point in space that will become stable with the three segments connecting it to the ground (Figure 6), with the inputted radii representing member lengths for the structure. We use this approach in all our models to create stable and determinate structures.
We wanted to be creative with our forms but keep the technique of using the spheres to create our points. There was some strategy of symmetry, or lack thereof, with each of the forms. We wanted to avoid just placing points randomly in space and connecting them with lines. By having the spheres to control the “floating” points, forms could easily change just by sliding one of the radius sliders.

It is a constant balance between discipline and play, but both mindsets work together to eventually generate visually appealing and controlled forms. Some of the stronger iterations came from placing and moving points freely before eventually incorporating sliders.
Here is an example of “continuing the loop” where we jumped from GeoGebra to Rhino. We exported our form from GeoGebra and placed it into Rhino and rendered it. We even placed one of our renderings onto an area of the arboretum to get a sense of the space and what this structure will look like there.
Additional examples of our process from GeoGebra to Rhino are shown. They were great practice to move closer towards great ideas. At this point in the form finding process, there was added emphasis on directed views, as seen through the openings and panels placed in the models.
Moving forward with a focused idea, our group chose the natural form of a fallen leaf. Weightless yet self-supporting, a fallen leaf is a beautiful structural precedent to take inspiration from.

The curved shell surface matches the main body of the leaf while the stem is represented with a strut to the ground.
Version 1 was the first and most abstract form of the leaf. The stable tripod began in the center and supports the two nodes on either side. With this iteration, there was a distinct lack of traditional hypars. Instead, there were triangular planes with circular openings, which brought up discussion about tessellation. However, they were ultimately planar and not curved, requiring further investigation and adjustments.
Version 2 incorporates two hyperbolic paraboloid surfaces that intersect at the stable center point. One issue that arose was the limits on curvature that the planes could sustain, given that they would eventually have to be physical.
For the third iteration, the stable tripod was moved from the center to the side, serving as a stem. The form now incorporates one curved surface for the body of the leaf. We went forward with Version 3 for our mid-review presentation.
We cut out the pieces of the shell using the Grasshopper script that Nathan Lundberg of Poly Shells LLC created. Each piece has multiple numbers on it. For the shell pieces, there is a letter (A or B) followed by which piece number it is located at the center. Then the other numbers that are next to the cutouts corresponds to the coupling number that will join the A and B pieces together. This entire shell fit together like a puzzle. At full scale, these pieces will fit together, and dowels will be inserted through the outer side of the shells using the “tap tap tap” process. There will be no glue necessary. For this model, we used glue just for constructability ease because we did not have dowels, because they would be too small to keep track of.
Here is that shell placed on our Version 3 model. The shell is to scale to match the supporting struts, however the shell thickness was too large. Realistically, the plywood pieces would be thinner in relation to the struts, and the couplings would not be as long. This was a helpful model to make those realizations, as well as make improvements on our form.
After feedback from our mid-review presentation, we approached our final form that we moved forward with. We added another shell in the back to provide more shade and extended the ground strut to the outside to act as the “stem of the leaf.” This form felt more enclosed, yet still inviting to visitors to enter the space.
Modern Muller Breslau Method (MMB)

Unknown*Perturbation + Σ Force*Loft = 0

Material
Lodgepole Pine
Density = 40 PCF
E = 1,000,000 PSI

Strut
6” Dia. Strut
A = 28.27 sq. in

Shell
3” Thin Shell

Joints
Pinned

Our first analysis with MMB involved verifying the axial loading with SAP2000. Here, the concentrated weight of the struts connecting at the three floating nodes is applied as a downwards force at each node. This creates a loft when an axial deformation is prescribed at the stem, highlighted by the green box. Using the MMB equation, we can find the unknown force of the perturbed member, which is the axial force within the member. Comparing with SAP2000, the results are nearly identical.

As an additional check, we made sure that the concentrated weight matched the weight calculated by SAP2000. The weights are nearly identical as well.

<table>
<thead>
<tr>
<th>Axial MMB</th>
<th>Axial SAP</th>
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<tr>
<td>919.68 lb</td>
<td>919.94 lb</td>
</tr>
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</table>

<table>
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<tr>
<th>Total Wt. MMB</th>
<th>Total Wt. SAP</th>
</tr>
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<tbody>
<tr>
<td>1899.71 lb</td>
<td>1900.52 lb</td>
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Now that we trust our axial output from SAP2000, we looked at the risk of buckling under self weight. With buckling being a function of both force and length, we looked at the governing compression member. Comparing the axial output with the critical buckling load, our factor of safety came out to be about 12, which deems it safe from buckling.
Analyzing bending with MMB is very similar to axial analysis. Instead of an axial deformation, there is a relative angle between two halves of a member due to a kink. The unknown is the bending moment within the member. The forces and lofts are at the midspan of each half, being created from the concentrated weights of each half. Again, the bending moments are nearly identical, so we can trust our SAP2000 output.
Before advanced lateral analysis, we applied 30% of the dead load as gravity frame loading to get a rough estimate at the forces within the structure. Upon investigation, the forces and stresses are low and reasonable given the weight of the structure.
Our advanced lateral analysis involved running two time-histories and a response spectra based on the building code.

El Centro

Northridge

IBC 2012 RSA
The axial loading and bending moments weren’t alarming in their magnitude. The Northridge Earthquake ended up governing for axial loading and the El Centro Earthquake governed for bending moment.
MAXIMUM SHELL STRESSES

El Centro

Northridge

IBC 2012 RSA

S11

40.7 PSI

66.4 PSI

34.4 PSI

S12

60.3 PSI

73.8 PSI

35.2 PSI

Envelope Min.

Envelope Min.

Envelope Max.
After turning to the NDS, we recognized that some of our member sizes did not satisfy the slenderness requirement in section 3.7.1.4. The 40' member needed to be resized to have a 10" diameter, the 25' member could remain the original 6" diameter, and the 32' member needed to be resized to an 8" diameter. This was under the assumption that the shells did not provide bracing for the struts.

In terms of strength under combined axial and tension, our estimated size of 6 in. diameter struts was already sufficient.
Resultant Base Reaction (Northridge) = 7954 lb

Estimated Allowable Bearing Pressure = 2000 PSF

As an estimate for our required foundation, we compared the resultant base reaction from the governing Northridge Earthquake to an estimated allowable soil bearing pressure to find the required footing area. The preliminary foundation size would be smaller than what would be practically used.
Our site locations were determined on our circulation from when we visited the arboretum. Upon entry there was a very nice open grassy area, but we ultimately decided to proceed with location 2 for our placement renders.
This location of the structure acts as a “destination” that will be inviting to bring more visitors all the way through the arboretum. It will be an area that people can come relax in the shade and gather. Tables, benches, or even some sort of floor can be incorporated too. This combination of location and structure acts as a beautiful backdrop for graduation pictures and photoshoots.
The oculus allows sunlight to shine through and splash onto the inside portion of the shell, providing light to illuminate the interior space.
We conducted a sun study, specifically in the month of May, tracking the sun’s path. This showed us what types of shadows we can expect from our structure, depending on its orientation. We decided to have the largest opening of our structure face approximately west so that there will be long casted shade in the morning, plenty of shade still around noon, and a view of the sunset in the evening.
A long, pointed shadow is casted at 7 AM, looming far and forward around the opening hours of the arboretum.

Around noon, the sun is above the structure, casting sunlight through the oculus and allowing a thin strip of light in the center space.

During the closing hours of the arboretum, a shadow is cast in the direction of the stem, still providing shade around the structure.
To keep the leaf from crumbling or flying away, we needed 3 different types of connections:
- Strut to strut connects the axial lodgepole pine members
- Foundation connection attaches the lodgepole pine struts into a concrete foundation
- Shell to strut connects the double-skinned plywood shell to the lodgepole pine struts

A priority for all connections was to make a high tech but low construction solution that could work for any shell structure with any geometry.
One preliminary idea involved a simple pin connection. Our group quickly realized this was an extreme limit on how many struts could come into the hub and at what angle they could be received. We continued to iterate ideas...
With more thought, we imagined a steel hub where struts from any location and any angle could be received with tabs extending from the cylindrical hub. There would be wood caps and slats for architectural detailing.

We discovered beautiful Cast Connex Timber End Connectors (TEC) and decided to incorporate this into the hub design.
After correspondence with the Cast Connex Vice President, Jennifer Pazdon, we altered the design to a custom casting. This violates our initial priority of a universal hub connection, but since we had the attention of the VP, we figured it would be worth proceeding with this idea.

The connection simplified to the cylindrical hub with TEC fins to accept the strut from any angle. We did not want to cover up a gorgeous connection, so the timber caps and slats were removed. This also provides for an interesting view through the oculus of The Leaf.
The strut-to-strut TEC connection can also be used for the foundation. With anchor rods extending from the base of the connection, they can be doweled into a concrete foundation.

The sleek TEC foundation creates an undistracting solution for anchoring our structure to the ground and containing axial forces from the lodgepole pine strut members. Time constraints meant our group could not analyze the capacity of this connection in depth, but with datasheets provided by Cast Connex, we are confident that this is a robust connection for our shell structure.
FOUNDATION
An all-wood shell-to-strut connection was an initial priority to get the ideas rolling. As shown above, an iterative approach was taken to refine all-wood connection ideas as a universal connector that could work on any structure with any shell geometry. In all cases, cut plywood is layered onto the strut and then secured with “tap-tap-tap” dowels through both the shell and the strut.

Our group liked this chamfered clip idea, however the materiality of it remained a big question for us. We revised it as an all-wood connection, similar to those on the left of the page. However, there are fewer tap-tap dowels. Instead, the outer layers of the plywood pieces have a coupling system similar to that in the rest of the shell structure. Then tap-tap dowels are used to secure the interior plywood pieces as well as closing the clip around the strut.
Moving away from an all-wood connection, the idea of a minimal metal sleeve arose. Preliminary sketches and renders were mocked-up for our mid-review presentation.

We ultimately chose to move forward with this design because of the clunkiness of the all-wood connectors and how they would interfere with extreme shell geometries. At the oculus location the shells are at extreme angles, and the sleek steel sleeve allows for any geometry.

After the critique, we modified the design. Right angles are easy, but they are not always the right thing to do, so we incorporated a beautiful architectural taper to the end of our connectors. Additionally, the finish matches that of the strut-to-strut and foundation TECs.
A suggestion that got brought forward was to fill the open space under the "stem" of the "leaf." One thought was to fill that area with trees or plants that would include spikes or thorns that would keep the public away...

However, we felt that it distracted from the structure. We believe that the incorporation of the foundation seating will fill the area efficiently.
The capacity of all connections still needs to be checked with the axial forces in our struts as well as the shear forces that the shell causes on the struts. Since the connections are steel, we would check with AISC360 code as well as Cast Connex datasheets.

At geometric transitions, it would be better to have radiused chamfers (smoother transitions), as sharp right angles are impossible to cast and create stress concentrations.

It is possible that the sleeves need more bolt holes to deal with the shear forces of the shell on the strut. Also, we may need to add bolt holes on the middle sleeve.

This rear “stem” strut member experiences 920 lbs of force in tension. To properly design this connection, we would need to look at yielding, tear out, and block shear of the fin plate. Additionally, the shape of this fin would probably change as it is probably not sufficient to have a singular spindly fin to support this rear member.
GLOBAL CONCERNS

With a goal of high-tech design and low-tech construction, our goal is that structures like The Leaf can be built anywhere in the world. Issues regarding materiality become of concern when potentially building in a location where timber is not easily accessible. In those circumstances, perhaps the materiality of the structure would be reconsidered, or the possibility of shipping timber and plywood would be an option depending on the size of the structure.

ENVIRONMENTAL CONCERNS

Sustainability is a buzz word in architectural and structural design today. For our structure, the main shell is comprised of CNC’d plywood sheets. The production of this material should not be much of an environmental concern. Similarly, the lodgepole pine struts are a sustainable material as it is grown for length. We have very few connections requiring steel and concrete. With only 3 ground points, the foundation is repurposed into seating and a part of The Leaf experience. There are also only 3 steel strut-to-strut connections which are unobtrusive and do not cause significant environmental concern.

ECONOMIC CONCERNS

For this project, economic concerns might be comprised of building labor, maintenance or repair labor, and upgrade labor. Our structure does not require high-skill workers to construct. The one economic factor that might demerit the structure is the custom Cast Connex TECs, however since we have the attention of the Vice President of the company, we are hopeful there would be a way to make it work. As for maintenance and repairs, we believe this structure would generate foot traffic to the arboretum, and hopefully pay these off in time. We envision that future upgrades to the structure would be other student projects, such as the architecture studio that designs the wooden slat seating around the buildings on Dexter Lawn. These additions would not give economic burden to the arboretum.

CULTURAL CONCERNS

It is important to honor and respect the land that any structure is built on. For our case, the Leaning Pine Arboretum (all of Cal Poly campus for that matter) sits on the traditional lands of the yak titu titu yak tithini Northern Chumash Tribe of San Luis Obispo County and Region.