Center for Centering

Analysis of a modular timber dome

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Introduction:

Over the past few years, individuals across countless communities have been emotionally, mentally, and physically displaced. The COVID-19 pandemic impeded many aspects of life and will have lasting impacts for years to come. Due to the social, environmental, and personal disruptions, it is paramount the individual restore balance to their lives and center themselves. Is it possible to create spaces for the individual to reflect on their hardships and experiences and discover their own creativity? Can a space offer internal stability and allow for re-centering?

Interdisciplinary artist Marcos Lutyens and arts educator Cynthia Campoy Brophy collaborated with an interdisciplinary team of architecture and engineering students from Cal Poly San Luis Obispo to create a prototype structure for the Center for Centering (C4C). The C4C dome was a continuation of work developed in a collaborative design studio led by Professors Tom Fowler and Kevin Dong during the 2020 - 2021 academic year.

Scope & Role:

The scope of this project team is to effectively transfer the concepts proposed by the initial master’s design student group into a structure that incorporates inductive, sensory, social, and environmental aspects. My role in the team is to analyze the dome under various loading conditions and guide the aesthetic design to ensure the safety of occupants inside. Researching and understanding the stresses that the structure will face informed the structural design throughout the project. Lateral loading of the dome had to be prevented by effectively transferring moments across the nodes and connections, which informed the team on what properties the structural design must uphold.

Design:

Using graphics and concepts from the previous master’s group, a 1/16th scale model dome was created to gauge initial feasibility (Figure 1). Consisting of 304 individual members, the original curvilinear dome proved difficult to build given the need for ease of construction and transportability. Alternative designs were explored for the overall structure, including an elastic geodesic grid shell approach (Figure 6) and a lamella (Zollinger roof) structure (Figure 7). Since the original concept was born from the purpose of the project and incorporates ideas of recentering, the team agreed to pursue a more efficient design of the original concept. Iterations of the dome were created using parametric design, focusing on stability and feasibility. The original curvilinear dome was modified into one consisting of bi-planar rhomboid openings. This narrowed the quantity of structural members in the dome from 304 to 156. The rhomboid openings were bisected with hoop ties, encasing the dome at each node level thus triangulating every space. This design ensured the straight wood members would take compressive loads while the ties resisted tension. At the base of the dome, diagonal outcrops are used for the lateral system while heavy benches weigh down the structure and offer more usage of the space. To streamline constructability, every 2x2 member is cut to the same length, however each connector type changes the pitch of the dome. This design localizes structural complexities to the nodes, which aids in construction, but increases manufacturing demands. To transfer loads across the nodes, the connectors must secure each member framing into it while maintaining ease of
assembly. Inspired by Japanese wood joinery, or Sashimono, the connectors feature an arrowhead opening that the 2x2 member slots into. A wooden dowel insert prevents the member from translating out of the slot and enables the connector and member to act as one.

Figure 1: 1/16th scale, 304-member model dome

Figure 2: 156-member dome

Figure 3: Annotated render of full structure
Figure 4: Japanese wood joinery (https://interestingengineering.com/)

Figure 5: Render of a Lanceleaf node

Figure 6: Elastic geodesic grid shell study
Experimentation:

To experiment with the connectors, desired structural properties had to be chosen. While gravity loads are taken axially through each member, moments may develop anywhere on the dome given lateral loading. Three connection shapes were created to determine the most feasible and structurally adequate profile. Three experiments were conducted to test the capacities of the connection: a strong axis bending test, weak axis bending test, and a tensile strength test. Each test loaded the specimen at a rate 0.5in/sec, with recordings of deflection and load data at 0.2 inches total deflection and rupture. A sample connector node was also tested in a similar manner (Figure 8). Tensile tests proved difficult to conduct as the bolt used to secure the connector to the test rig sheared through the 2x2 edge (Figure 5). However, one experiment granted upwards of 2,000lbs in tensile strength.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Arrowhead (lbs)</th>
<th>Rectangular (lbs)</th>
<th>Hammerhead (lbs)</th>
<th>Young Lance Leaf (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak Axis Bending Deformation (to 0.2 in)</td>
<td>515</td>
<td>617</td>
<td>425</td>
<td>400</td>
</tr>
<tr>
<td>Weak Axis Bending Rupture Failure</td>
<td>616</td>
<td>800</td>
<td>750</td>
<td>505</td>
</tr>
<tr>
<td>Strong Axis Bending Deformation (to 0.2 in)</td>
<td>638</td>
<td>595</td>
<td>580</td>
<td>N/A</td>
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<tr>
<td>Strong Axis Bending Rupture Failure</td>
<td>1120</td>
<td>1200</td>
<td>725</td>
<td>N/A</td>
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</tbody>
</table>
Figure 8: Prototype Young Lanceleaf in testing

Figure 9: Hammerhead profile in tensile test and bolt shear

Figure 10: The three connector profiles tested

Figure 11: Failure after a strong axis bend test

Figure 12: Rectangular profile in strong axis bend test

Figure 13: Hammerhead profile in weak axis bend test
Analysis:

The connector design creates two likely failure locations: the flange of the cut 2x4, and where the dowel intersects the 2x2. Both net areas are relatively small however they are linked by the dowel. The bending tests showed the 2x2 member yielding first, with the dowel ultimately shearing through the edge (Figure 11). In every test, the 2x4 flange yields after the 2x2. Typically, the connection cannot take more load at this point, however on one occasion the dowel ruptured in shear between each member. These tests showed the design allows both members to act compositely and ensures the connection is stronger than the member framing into it. In the event of extreme forces acting on the dome, the 2x2 will fail first and can be replaced.

Along with gravity loads, the structure was analyzed under wind loading using a directional procedure from ASCE 7-16. This produced positive and negative pressures that were applied to a RISA 3D computer model (Figure 14). While the computer model illustrates how forces may be taken given gravity loads (Figure 15), lateral loads can produce compression in the circumferential hoops – or ring levels (Figure 16). To resist both tension and compression at each ring level, the team opted to thread paracord through PVC pipe. This system combats gravity load with the paracord taking tension while also resisting nodal translation via each space being triangulated with PVC pipe. Load paths and maximum forces across nodes were compared to the experimental capacities of the connectors to determine if the structure can withstand the design forces. Experimental capacities were modified by a factor of safety of 0.5 to ensure demand-to-capacity ratios were still adequate. Wind loading could overturn the structure if insufficient weight is provided. A maximum overturning moment of 18.3 kft was established and a required weight of 1.14k would prevent the structure from toppling. This weight is easily stored in water filled containers within the blocks (see Figure 3). Approximately 4.5, 30ga bins are required to prevent overturning given the stringent code assumptions.
Figure 16: Birdseye view of dome. Highlighted members denote compression under lateral loading. Before the team knew if every ring level had to have compressive elements, experimental connector capacities ensured moments could be carried across nodes to ring levels that contained PVC. The piping also acted as a redundancy against machine tolerances or “wiggle room” in the connections.

**Interpretations:**

Because this structure is meant to be temporary and transportable, the team pushed for construction to be as easy as possible. Localizing structural complexities to the nodes was challenging given the connectors must effectively transfer loads, change angle, and secure each member slotting into it (Figure 18). Manufacturing techniques improved over each iteration of connector design, eventually producing connections that could easily withstand design forces. Because the structural composition of the connector does not change between each profile, differences in load capacity proved negligible. For this reason, the arrowhead profile was chosen due to its resemblance of a leaf which pairs well with the project’s theme. The rectangular profile used two dowels as links between each piece which resulted in a higher connection capacity, however this design would take twice as long to build and negatively impact constructability. Applying the code to this structure was challenging because of its ambiguous shape: an elevated dome with a sloped profile extending to the ground. Shape aside, the internal pressure coefficient (GCpi) varies between one of four enclosure classifications: enclosed building, partially enclosed buildings, partially open buildings, and open buildings. The team settled on a vinyl wrap as the structure’s skin, with a pattern of cutouts meant to cast shadows on the inside of the dome. The cutout densities were undecided during the time of analysis, so the structure was designated as an enclosed building for a worst-case scenario as this would attract the most lateral loading (Figure 17). To simplify code application further, the profile was assumed to be rectangular. With these assumptions, ASCE 7-16 equation 27.3-1 could be used to find wind pressures:

\[ p = qGc_p - q_i(GCpi) \]
Although these assumptions are conservative, a positive pressure of 12.5psf and a negative pressure of 6.3psf was placed on the computer model. Load paths and maximum moments were analyzed. The tables below show connector and nodal moment capacities are higher than design values.

<table>
<thead>
<tr>
<th>Arrowhead Connector</th>
<th>RISA3D Model</th>
<th>Myy Max - Dome (lbft)</th>
<th>Mzz Max - Dome (lbft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(lbft)</td>
<td>φ</td>
<td></td>
</tr>
<tr>
<td>Weak Axis Moment Capacity = PL/4</td>
<td>161</td>
<td>0.5</td>
<td>80.5</td>
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<tr>
<td>Strong Axis Moment Capacity = PL/4</td>
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<td>0.5</td>
<td>100</td>
</tr>
<tr>
<td>D/C</td>
<td></td>
<td>0.2</td>
<td>0.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Prototype Young Lanceleaf Node</th>
<th>RISA3D Model</th>
<th>Myy Max - Dome (lbft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(lbft)</td>
<td>φ</td>
</tr>
<tr>
<td>Weak Axis Moment Capacity = PL</td>
<td>126.5</td>
<td>0.5</td>
</tr>
<tr>
<td>D/C</td>
<td></td>
<td>0.25</td>
</tr>
</tbody>
</table>

Figure 17: Renders of varying panel densities
Conclusion:

Transforming ideas of balance and recentering into a structure was as complicated as it was explorative. Having a free range of ideas and methods permitted the project to evolve over iteration. Analyzing what worked and what didn’t informed the team on what the next steps should be. Construction and manufacturing techniques allowed the connectors to be an integral part of the structure. By experimenting with them, the safety of occupants inside could be ensured against design forces found using the code. Both form and function of the project can be seen in the structure and its safe, yet simple connections.
How did the project address global, cultural, social, environmental concerns and topics?

This project came about from issues that affect communities around the globe. The Center for Centering is a space for all to reflect on themselves and their experiences. Due to its transportability and construction process, the center is a tool that can be used by anyone, anywhere. It could literally be shipped and freighted virtually anywhere in the world and since the connections are designed to be a simple tab and slot, communities without construction knowledge can easily put together and take apart structure. The space is as versatile in its construction as it is in its function. Because the project addresses issues through the individual’s perspective, cultural and community barriers may be relaxed and, in turn, allow people to approach the space as themselves. Curiosity will drive people to explore the space, and this starts with the environment. The structure is made from wood—the only truly renewable construction material—and features very little metal. From the outside, the structure is visually self-contained. The white vinyl wrap paired with the timber structure produces an elegant space, however few sites would likely add to this appeal. Instead, the structure can pair with endless locations to create a unique appearance every time. The structure’s skin cast shadows on those inside the dome, emulating light shining through a forest canopy. The space promotes social practices as well, such as dance, ritual, and storytelling. Each dome member is the same, it is only the connections that change. Likewise, many approaching the Center will enter as themselves, but meet and share experiences with others. The Center can help repair and create connections with oneself and those they interact with under the dome.

Reflections:

Applying the code to this project was tricky because each assumption that was made could ultimately alter the design wind pressures and, thus, the analysis. Carefully changing terms and coefficients produces different pressures so the simple, overarching assumption that the structure is a rigid box made navigating the code easier and produced conservative values. While this was one approach to the structural analysis of this project, there were numerous approaches to every task the project faced. Due to the dynamic of the team, design possibilities were explored using parametric design and proved useful in scaling the structure. Manufacturing leads used design software to precisely model each connection. However, translating these possibilities into goals proved difficult. Having a deadline can make it easier to perceive the workload, but it can also be a stressor when problems are encountered and could not be solved timely. Patience is key when transforming ideas into reality and keeping calm within the team allowed us to stay on track. Working in an interdisciplinary team of students involved considering every idea even if it did not present itself as a feasible one. After all, each group member comes from a different background of skills and creativity. It is this diversity in capabilities that allowed the project to grow and ultimately be produced.