Senior Project:
Innovating Concrete Shell Construction

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1.0 General Information

This section will cover the introduction/purpose of the project, a background on the design basis, as well as a brief description of the intended process.

1.1 Introduction/Purpose

The objective of this project was to explore and develop a cost effective concrete shell construction process that could be created with minimal skilled labor. By reducing the cost of construction, the goal of the design is to make structures of this kind more practical for use in third-world countries. One of the primary issues with building a concrete structure in under-developed countries is the lack of resources available to them. Paired with a higher level of poverty and the expensive nature of constructing formwork, concrete structures are oftentimes unachievable. In addition, the labor that is required to complete projects based in concrete is generally higher than that of timber or masonry. Due to this, a large obstacle of the design process was determining a way to make these structures economically competitive in a market of comparatively cheap alternatives. In order to accomplish this, the distinct characteristic of the project was to utilize dirt as a form for the concrete to be cast on top of. By utilizing dirt as a method of shaping the structure, the overall cost of construction goes down substantially, thanks to the use of a cheaper forming material and reduced need for skilled labor. Using dirt as formwork can become labor intensive, so another goal of the project was to develop a system of creating as much void space as possible.
1.2 Background
Thin-shelled concrete structures are unique in both their design and performance. Their intention is to minimize the amount of concrete used, without sacrificing their structural integrity in the process. The way this is accomplished is via the funicular shape of the finished product. A funicular structure is one that is able to distribute the loads applied to it solely due to its shape. An everyday example of this concept in effect is a net; having all fibers operating exclusively in tension. Conversely, the funicular structure operates in compression, using the weight of the building itself to sort of activate the load resistance.

Various other examples of funicular structures are used far more commonly, including arches, vaulted structures, and cabled systems, to name a few. The figure below illustrates the mechanics behind how these systems function.

Figure 1: Funicular Structure Load Variety
Because thin-shelled concrete structures are only able to resist compressive stresses, it is important that no tension is developed. However, in practice, that is not probable, especially when dealing with unskilled labor. As a result, reinforcing cables are required in order to mitigate the effects of any tensile stresses that manage to build up. In order to test the funicular shape of the shell, a structural analysis model was performed on the shell’s form using Rhinoceros 3D, Karamba and Grasshopper. The objective of this model was to verify the compressive nature of the structure and to act as a guide for the layout of the tensile reinforcing. This analysis, as depicted below in green, showed that the governing stresses acting on the shell are all compressive:

![Karamba Stress Distribution](image)

**Figure 2: Karamba Stress Distribution**

To account for these compressive stresses and any potential tensile stresses, reinforcement wiring would be placed along the perimeter of the shell from leg to leg, across the shell from leg to leg and transversely at each leg. By doing this, the shell itself is ensured to take responsibility solely for the compression stresses, as any tension will be resisted via the cabling.
1.3 Construction Process Schematics
To achieve the shape of the shell using this method, as shown in Figure 3 and 4, the construction of the formwork would begin with the placement of plywood walls to maintain the dirt. The plastic tube bundles would be feed through sockets of the plywood walls and locked into place with rebar stopped. The dirt would then be shoveled and molded into a mound of the desired shape for the shell. The process would be completed by placing the reinforcing wires and casting concrete.
Figure 4: Shell Formwork - Isometric
2.0 Experiment

This section will cover the equipment utilized for this construction, a brief description of building a practice model and the pre-construction process, a walkthrough of the construction process, and an outline of the excavation associated with the post-construction process.

2.1 Equipment

The nature of this project is to develop a process that minimizes the overall cost of constructing thin-shelled concrete structures. Because of this, the materials and equipment required to complete these buildings was also kept to a minimum. A list of equipment used in the construction of the shell is listed below:

Equipment:
- Shovel(s)
- Hammer/Nails
- Wheelbarrow(s)
- Trowel(s)
- Pool Noodles

Materials:
- Concrete Mix*
  - Aggregate (Sand/Gravel)
  - Water
  - Cement
- Formwork
  - 10 Cubic Yards of Soil
  - 2x Timber Members
  - Plywood
- 7 - 10’ long, 4” diameter pipes
- 2 - 2’ long #3 rebar
- 1/16”, 3/32”, and 1/8” Thick Reinforcing Cables

* Concrete mix consisted of a 1:3 cement to sand ratio, with enough water added to create a mashed-potato consistency.
2.2 Practice Model

Before constructing the final model, a test model was constructed to verify several aspects of the design, as well as to allow the members of the team to practice the process. The goals behind this model were to test the effectiveness of the plywood walls, determine the angle of internal friction of the soil, develop a system of establishing the cover requirements on the inside face of the shell, and verify the functionality of the void pipes. In order to accomplish this, the team received permission to have soil delivered to Poly Canyon’s Architecture Graveyard to construct the temporary model.

Before proceeding into the canyon, several steps had to be taken to prepare the materials and formwork. First, team members constructed the plywood walls pictured below:

![Figure 5: Plywood Formwork](image)

Each wall was constructed in two segments: one intended to establish the boundary of the shell, resist against the active bearing pressure of the soil, and house the bundles of pipe, while the top piece helped define the shape of the shell. The hole in the middle of the wall acts as a housing for the pipe bundles, allowing them to span the gap between the two walls.
Next, the pipe bundles themselves needed to be prepared. The team came up with several iterations of how the pipes were to be laid out. Initially, one bundle was to be created, its configuration shown below:

![Figure 6: Initial Pipe Bundle Configuration](image)

This configuration was shortly abandoned for a design that allowed the bundles to be removed more easily. To accomplish this, two rows of pipes were secured via a piece of rebar feeding horizontally through each one. The ends of the rebar were intentionally cut with several inches longer than necessary in order to bear against the walls, aiding in keeping the formwork contained. This final configuration can be seen below:

![Figure 7: Final Pipe Layout (With Rebar)](image)

![Figure 8: Wall/Pipe Configuration](image)
Several factors contributed to the redesign of the pipe bundles: primarily being to increase the ease with which they could be removed. Because much of the soil will be bearing on the pipes at the time of their removal, it was paramount to come up with a design that minimized the amount of friction acting on them. This prompted the two-tiers of pipes, allowing the first to be removed, while decreasing the amount of pressure on the latter.

Now that all of the components had been assembled, they were transported to Poly Canyon to begin the testing process. After the walls and pipes were assembled and soils was shoveled into place, it became clear that the initial estimation for the amount of soil required was less than necessary. This was attributed to the angle of internal friction of the soil being lower than expected: around 45°. Other than the behavior of the soil, the rest of the test went according to the team’s expectations. The walls performed as intended, with the only issue being the nails that secured the plywood to its 2x4 frame pulling out. Although this ultimately led to the test model underperforming, by reversing the orientation of the walls, the active bearing pressure of the soil will help keep the plywood in place, rather than make the pull out worse. The finalized test model can be seen below:

![Figure 9: Test Model](image_url)

The final objective of the Poly Canyon model was to determine how the bottom cover would be developed for the reinforcing cable that would be added before pouring the shell. Several iterations of this were considered before finally deciding to rest the cable on large
pieces of rock or concrete and allowing that to be cast into the final shell. Because this was done using the same material as the aggregate in the concrete mix, casting these pieces into the final shell did not result in a strength reduction. Initial concepts for the cable layout of the footings, as well as the cover conditions are depicted below:

![Figure 10: Reinforcing Cover](image)

With the confirmation that the team’s processes would work, it was time to move into Cal Poly CAED’s Support Shop where the final model would be constructed.
2.3 Construction
The construction process consisted of multiple steps ordered as follows: setting and bracing the bearing walls, adding the void space elements, adding the soil earthform, attaching the boundary elements, adding the reinforcement cables, and pouring the concrete mix. Initially, the bearing walls must be placed at the ends of the shell as coordinated with the architectural model and site location. The walls must be placed with the plywood facing the interior of the shell so that the soil pressure causes the plywood to bear onto the studs. When all of the bearing walls were braced and in the desired location, the team added the void space elements to the structure. Once these pipe bundles were locked into place using the #3 reinforcing bars, soil was placed on the structure to develop the desired shape of the shell interior. Soil was not placed onto the structure until the pipes and rebar were locked in because this configuration resisted active soil pressure and prevented the collapse of the walls.

Figure 12: Soil Mound Shoveled Between Bearing Walls
Once the soil was shoveled into place and molded to the desired form, the boundary elements to the shell were added to create the edge of the shell legs leading them into the foundation boxes. These boundary elements were simulated with pool noodles for this construction sequence and the diameter of these elements was determined according to the desired shell thickness. These boundary elements were held in position by threading through the ends of the pool noodles with wire and tying the wire to the plywood through drilled holes. Once the shell geometry was fully shaped, reinforcement cables were laid onto the structure using 3/4” diameter coarse aggregate for clear cover. Cables ran in bundles around each opening edge as well as across the top of the shell and acted as temperature and shrinkage reinforcement. Additionally, transverse reinforcement was added to pick up tension stresses at the shell legs where the structure was not completely

![Figure 13: Reinforcing Cable Layout](image)
funicular. The transverse reinforcement ran perpendicular to the compression cables and was tied in loops using wire rope clamps. Once all reinforcement cables were placed on the structure and tied off in the footing formwork, a concrete mix of one part cement to three parts fine aggregate was shoveled onto the structure. The concrete mix was troweled over the earthform with the desired thickness of shell in each location.

Figure 14: Troweling Concrete Onto the Shell

The thinnest cross section of the structure was troweled onto the top of the shell and the thickness gradually increased leading down into the foundations. Once all of the concrete was troweled into place, the structure was left to cure for three days before post-construction and testing began.
2.4 Post-Construction

Once the concrete shaping the shell cured, the excavation process began by removing the earthform and boundary elements from the structure. The initial step to the post-construction process is to remove the pipe bundle void space from the structure.

![Figure 15: Pipe Bundle Removal](image)

After the removal of the void space elements, much of the soil loosened and was easily removed using shovels. With an excess of void space, the soil active bearing pressure on the pipe bundles is minimized and removal of these elements becomes easier. Once the pipe bundles as well as a portion of the soil is excavated, the walls and boundary elements were uninstalled to allow for easier removal of the excess soil underneath the shell. Once the earthform was completely excavated, finishing of the shell faces and edges began.
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The interior face of the structure had soil removed using shovel edges to scrape and pressurized water to rinse. The edges of the shell were manually finished using a shovel edge to shape the contours of the shell boundary. Once the shell was excavated and finished, the walls, pipe bundles, and boundary elements were all reusable and were stored for future use on additional shell construction.

Figure 16: Shell Structure Post-Excavation

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3.0 Performance/Results
This section will cover the testing and performance of the model as well as the failure mode observed during the demolition process.

3.1 Shell Behavior
The Shell had to start resisting load once the first shovel of earth (dirt formwork) was removed from under the structure. As more dirt was removed, it became evident that the top layer of earth, that was flush with the understructure, had retained its water content and had adhered to the concrete. This added weight created an unintentional live load that the concrete shell had to resist from an early stage. Due to the minimal tension reinforcement, failure was predicted to occur in the legs, especially at each footing. While the concrete was curing, one such failure occurred as a tension crack developed across the length of one of the legs where it met the footing.

Figure 17: Tension Crack At Leg of Shell

This tension crack increased concern of failure due to slippage of the footings so ratchets and tie downs were tightened around the perimeter of the footings to act as containment.
With the new reinforcement, no new tension crack developed prior to loading. Another concern was that due to the shell's variability in thickness and extremely short cure time, it would not be able to withstand any substantial compressive load. However, even in the worst conditions, which were intentionally created, the shell survived a significant compressive dead load.

Figure 18: Shell Performance Under Live Load

Ultimately, the shell failed when a singular point load, from a sledge hammer, compromised the integrity of the entire structure. The shell failed at each footing, as expected, and the structure collapsed.
Figure 19: Shell After Demolition

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4.0 Discussion

This section will discuss potential corrections to this specific construction method for use in future structures.

4.1 Suggestions

The construction process of the concrete shell was considered to be successful considering the limited resources that were available. Some suggestions for the future are to create a larger void space, pipe bundles, to reduce the amount of dirt used for formwork. For the final model that was created, 10 yards of dirt were used to create the formwork. If a larger scale of the concrete shell were to be constructed, it would require an excessive amount of dirt. To reduce the volume of dirt needed for a larger model, it is suggested to create more void space. Another suggestion that should be taken into consideration is to have thickness markers to ensure a consistent thickness of the concrete shell. Due to a lack of consideration, the final concrete shell that was created varied in thickness all around, which lead to cracks and failures. To prevent such failures and for aesthetic purposes, the thickness of the shell should be kept consistent.

Edge elements, pool noodles, were used on the legs of the shell as a guide to pouring the concrete. It was used to provide a smooth edge face and as a boundary element for the concrete to run but not bulge out to creating an uneven edge face. Edge elements should be used all along the perimeter of the shell to ensure that there is a smooth, more defined edge face along the perimeter for aesthetic purposes. Another factor that needs to be taken into consideration is the concrete mix for the shell. The concrete mix used for the final model was a fairly dry mix for the purposes of better shaping the shell. However, due to the low water content of the concrete mix, the concrete dried rapidly after pouring and cracks started to form. It is suggested to use a higher slump concrete mix to avoid concrete from drying too quickly. However, with a higher slump concrete mix and the increase in water content, there is a higher chance of concrete slippage after pouring.

From the construction of the final model, it is proven that the concrete shell can be constructed with limited resources and unskilled labor forces. However, it is recommended to use equipments during the construction and excavation of soil process when creating a larger scale for efficiency. Another suggestion that should be considered is using a plastic membrane to separate the formwork and the concrete to prevent the concrete from sticking to dirt. A plastic membrane was not used for the model and the excavation process had to be done carefully because the concrete and dirt were stuck together. The interior
finish of the shell was not aesthetically pleasing because it did not have a smooth finish and it was not a perfectly curvilinear shape. With the use of a plastic membrane to separate the two materials, a smoother, more controlled interior curvilinear shape can be achieved.

For models of larger scale, the use of surveying tools would be highly suggested. With tools such a theodolites and a rod, the dirt mound can easily be molded and controlled to the desired profile. As done in the construction field, the elevation of several points throughout the dirt mound would have to surveyed and calculated, and simply marked with the needed cut or fill dirt amount.
5.0 Closing Remarks

This section will cover a few acknowledgements that we would like to make.

5.1 Acknowledgements

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