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Extremely Thin Concrete Shells in an Undergraduate Interdisciplinary Design Studio

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ABSTRACT

Brilliant structural engineers such as Pier Luigi Nervi [1] and Eduoardo Torroja [2] have convincingly argued that an understanding of the flow of forces in structures from a mathematical point of view can lead to aesthetically elegant structures from a design perspective. In a polytechnic university such as ours, we have a tremendous opportunity for not only LINKING such left brain and right brain thinking, but to TRIANGULATE the creative process by adding craft of construction to the design problem.

In this fourth year Interdisciplinary Design Studio, architectural engineering students are paired with architecture students with the goal of blending art and technology. The students were asked to negotiate the challenges of form finding based on solely programmatic concerns with form finding based on mathematical, compression-only algorithms. This way of working and teaching is not trivial or easy, it requires an attitudinal shift and guided mentoring in the studio. Some suggested pedagogy is presented to facilitate success in blending art and technology.

This paper concludes with descriptions of form-finding tools that were used in the design studio to create compression-only funiculars in 3D. Then, a brief description is provided of how the structural analysis was integrated into the design model. Finally, detailed visual explanations of two different construction methods will be given. These methods were used to build 2 to 3 meter scale models of the students' thin shells. The two construction methods are: 1) Inflatable formwork and 2) CNC cut cardboard waffle grid formwork with earthen infill.

The purpose of such descriptions is to encourage other faculty to delve deeply into the remarkable world of extremely thin shells that appear to be free-form, but are in fact, highly mathematically constrained. The principles described here form a loose rubric for a "Learn-By-Doing" means of teaching the integration of state-of-the-art design with highly efficient structures.

KEYWORDS Interdisciplinary education, thin shell design, thin shell analysis, thin shell construction

1. Introduction

The Interdisciplinary Studio described in this paper has been taught three times, each academic session lasting ten weeks. In each iteration, approximately twelve fourth-year architecture students were in a studio with approximately twelve fourth-year architectural engineering students. Extremely thin reinforced concrete shells were the centerpiece of each studio, yet the pedagogy improved during each iteration, as did the resulting student work. The following parameters guided each iteration of the Interdisciplinary Studio:

1. The focus of each studio was to Design, Analyze and Build a compression-only large scale model of an ultra-thin reinforced concrete shell.
2. Students had constrained freedom in choosing the site for their virtual shell, constrained freedom in determining the programmatic spaces of their shell, constrained freedom in the erection schemes for the on-campus model as well as for the site-specific virtual shell, constrained freedom in the structural analysis.
3. Teams were selected by the Instructors based on student skills.
4. The entire ten week schedule was presented to the studio on Day One, and the schedule was rigorously adhered to.
5. Small, but non-trivial financial support was provided by the Architectural Engineering department for each iteration, ranging from $1000 USD to $2500 USD.
6. Distinguished outside jurors critiqued the student work. This included video conferencing as well as visitors to campus.

Each of these principles will be described in further detail, including areas of strength and areas for improvement.

2. Pros and Cons of each studio principle

There are two philosophical reasons for focusing on the problem of thin shell concrete structures in our Interdisciplinary Studio. The first is that thin shell structures are somewhat unique in that for even an elementary understanding of these architectural wonders, much less mastery of them, they require deep immersion in three phases of planning: the architectural design, the structural analysis, and the constructability of the shell and of the shell's landing points to the ground. This tripartite approach has been eloquently defended by an important but little-known series of books by Hass [3], [4] from the 1960s. This tripartite approach is an ideal fit for an undergraduate interdisciplinary studio because it draws from a varied set of skills--no single discipline could execute such a project in a studio, several disciplines are needed. The second reason is slightly less tangible. In various great works of architectural engineering, the line between the Engineer and Architect was blurred. Felix Candela is a prime example of this porous boundary between Designer and Analyst. Candela also embodied the third leg of the tripartite triangle, namely he was a Builder as well. Our immersion into a thin-shell studio is a small attempt to rekindle that spirit of Designer/Analyst/Builder. We hope to strengthen the discipline-specific knowledge by immersing the students in an experience that draws from their own specialty, but requires them to negotiate and communicate with non-specialists.

Compression-only shell: Why?

The question of "why a shell" has already been partly answered in the previous section. Shells require a tripartite inquiry, Design/Analysis/Construction. Given that we wanted to work with shells, the choice of "compression-only" makes the most sense because the tools to find a 3D funicular are now readily available. To facilitate physics-based funiculars, tutorials were provided in Grasshopper/Kangaroo/WeaverBird and the majority of students used this process to create shells that appear to be freeform, but in fact, are strictly mathematically constrained to have no bending. This would allow for impossibly-thin structures to be created, were it not for buckling concerns.

An argument could be made for the study of gridshells, or the study of tensile fabric roofs. We rejected the idea of tension structures because of the fairly large armature or framework necessary to suspend the fabric, this would have been prohibitively expensive for a large undergraduate studio. The idea of gridshells remains appealing, and we may focus the interdisciplinary studio on these in the future. But we wanted to use reinforced concrete because our architecture undergraduates have very little experience designing or working with concrete. Consequently, we chose continuous, monolithic shells rather than piecewise-continuous gridshells, which could readily be constructed from timber.

Constraints vs. Freedom

The structural artist Robert Maillart exemplified “discipline and play” [5] in his work; there were enormous constraints on his designs, but he wilfully chose to celebrate playful aesthetic ideals in his highly disciplined bridges. Similarly, when Torroja described this design process, he was careful to emphasize that it was neither purely rational nor purely imaginative, "but rather both together." [2].

In that spirit of “discipline and play”, we chose to foster creativity within a tight set of constraints. Students were given choices, but the choices were limited:

- Sites were pre-determined by the Instructors
- Program was pre-determined by the Instructors
- Edge conditions (how the shell landed on the ground), was fairly prescribed
- The types of structural analyses were highly prescribed
- Lighting conditions were somewhat prescribed
- Construction schemes were highly prescribed

The highly constrained problems, and the extremely short schedule (10 weeks total) required the students to focus intensely on the studio, and to stay very organized and coordinated. Both instructors were impressed that the schedule was closely adhered to. Roughly 3 weeks were devoted to Design, 3 weeks to Analysis and 3 weeks to Construction Planning and Construction.

Teams Were Not Self-Selected

The Instructors joked that a computer algorithm was used to determine the teams, but something near to this did occur: we reviewed the students’ past performance in key courses. Since the Interdisciplinary Studio was a fourth year course, we had much data to draw from. We attempted to put one very strong architecture student and one very strong architectural engineering student on each team. Then we tried to evenly disperse the weaker students. The goal was to neither create a “Dream Team” nor a “Misfits Team”, but rather, to have leaders and followers on each team, hopefully setting each team up for success.

Day 1 Present the Entire Schedule

The entire scope of the project was presented on Day 1 to elicit strong responses from the students. We noticed that some of them were “shell shocked” and one student did indeed leave the class on the first day. This truth in advertising is recommended because it presents a realistic picture of the large amount of work needed to complete the studio.

Financial Support

The creation of reinforced concrete models, with spans on the order of 2m to 3m, requires financial support as well as professional assistance from Machine Shop personnel. Fortunately, the Architectural Engineering Department at Cal Poly was generous in providing funds. Each model cost between $200 USD and $400 USD to build, so if the studio is broken up into seven teams as it was in the winter of 2017, then the studio requires approximately $2500 USD to run.

Some criticism was levied against us for using so much concrete in the project, the argument being that this was not environmentally friendly and as such sets a bad example to our young designers. Our response to that criticism is twofold. First, the lessons learned from actually mixing and trowelling concrete over a reinforcement mesh was extremely valuable to our students, especially to the architecture students, some of whom had never handled concrete before. These benefits offset the cost somewhat. Second, we established a protocol of carefully piling up the debris at the end of the quarter when the models were demolished, and that debris pile was sold to an outside vendor who recycles the concrete into pavement projects locally.

Distinguished Jurors

Over the past three iterations of this studio, there have been many professional “outside” jurors who have devoted time and energy to attend the studio critiques. Representatives from small to medium sized firms have attended, as well as engineers and architects from powerhouse firms such as SOM, Buro Happold, Foster and Partners and MicroDesk. Having such distinguished jurors gives enormous credibility to the interdisciplinary approach and the students are extremely proud to present their work to outside critics. Recently we have introduced video conferencing in the critiques, using multiple computer screens with the software Zoom Meeting. This certainly does work--it opens up the world of potential jurors, and it costs practically nothing. Yet, there are technological hurdles to overcome. One issue we successfully resolved was ensuring a high-quality connection by using Ethernet cables instead of wireless internet, which is highly recommended. One issue we did not successfully resolve was to have an array of high quality microphones around the studio so video-conferencing jurors could hear all of the comments being made by participants of the critique.

3. Low-Cost Construction Techniques

With guidance from the instructors, the students tackled a few different strategies for constructing 2 to 3 meter partial models of their shell designs. In each iteration of the course, taking cues from Binishell, one team was encouraged to create inflatable formwork, which was constructed by “squishing” the digital model to produce a pattern, which was printed to scale and used to cut readily-available drop-cloth plastic. The plastic was heat-welded using an iron and the formwork was made to “bubble out” beyond the boundaries of the shell at openings so that the edges would not sag. In the most recent iteration of the course, large foam pool-noodle tubes were cut and glued along the edges of the openings to stop the concrete from slipping. After the creation of a custom-fit air nozzle, the plastic sheet-form was inflated with compressed air from the tool shop. The air pressure was somewhat regulated, but we found the air supply to be generally problematic. Once the form was inflated, the concrete was gently trowelled on, mixed with plastic fiber reinforcement or a plastic geo-textile and kept continuously inflated for three days. Because of the fluctuations of air pressure (from

0.55MPa to 0.83MPa), the topmost part of the shell model sagged over time, causing cracking. Despite this technical difficulty, we are eager to continue to develop this construction strategy in future iterations of the course, and plan to provide an air source with constant pressure, which will fortify the integrity of the formwork. A large volume blower, such as used in “bounce houses” will be used next time.

Another fabrication strategy, inspired by the construction of the Mercedes Benz Museum, was the use of lasercut cardboard waffle grids, which were either infilled with soil or overlaid with a membrane. The top surface of the waffle grid then supported the concrete that was thinly trowelled either over the soil or over the membrane. Metal wire mesh was used as a scaled-down version of full-scale mesh reinforcement. Students employing the waffle grid strategy usually had fairly evenly-distributed, reasonably thin concrete shells. The thinnest shell was achieved using an exaggerated vertical slope form and a membrane overtop the waffle composed of sprayed-on rubber. The resulting shell is 2 to 4 mm thick at its thinnest! Another successful example in terms of effect was achieved by a group that constructed the waffle grid out of medium density fibreboard (mdf), which enabled them to staple a sturdy, but thin film overtop as underlayment. After the formwork was removed, the underside of the shell was not only glossy-smooth, but it also had small pillows that were formed between each waffle, making the concrete appear soft. In future iterations, we hope to accurately include these undulating, thickened parts in the finite element model, to assess their influence on the stress patterns and buckling susceptibility of the overall shell.

4. Visual Descriptions of Details

The following images describe the funicular 3D form, the finite element models, the construction techniques and the resulting design after 10 weeks of interdisciplinary work.

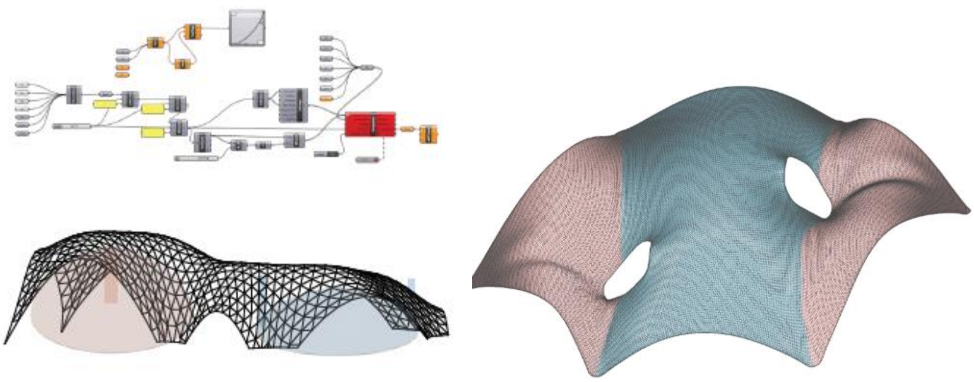

Figure 1a. One Funicular **1b. Another Funicular**

Stresses for self weight were comically low, on the order of 0.2 MPa. The high stiffness of the shell also resulted in extremely small deflections due to self weight, on the order of 4mm.

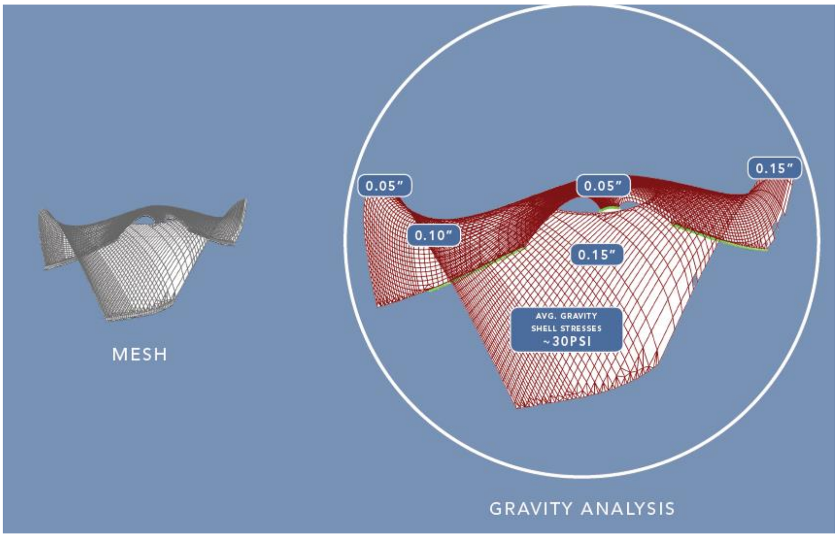

Figure 2. Gravity Load Finite Element Analysis

The shells were checked for Eigen Buckling, and the factors of safety against such buckling were on the order of 15 to 40. However, this was a LINEAR CHECK, we were not able to account for non-linear deformations which would cause the shell to stray from a funicular shape, and thus the buckling susceptibility would increase. This effect is currently being studied at Cal Poly.

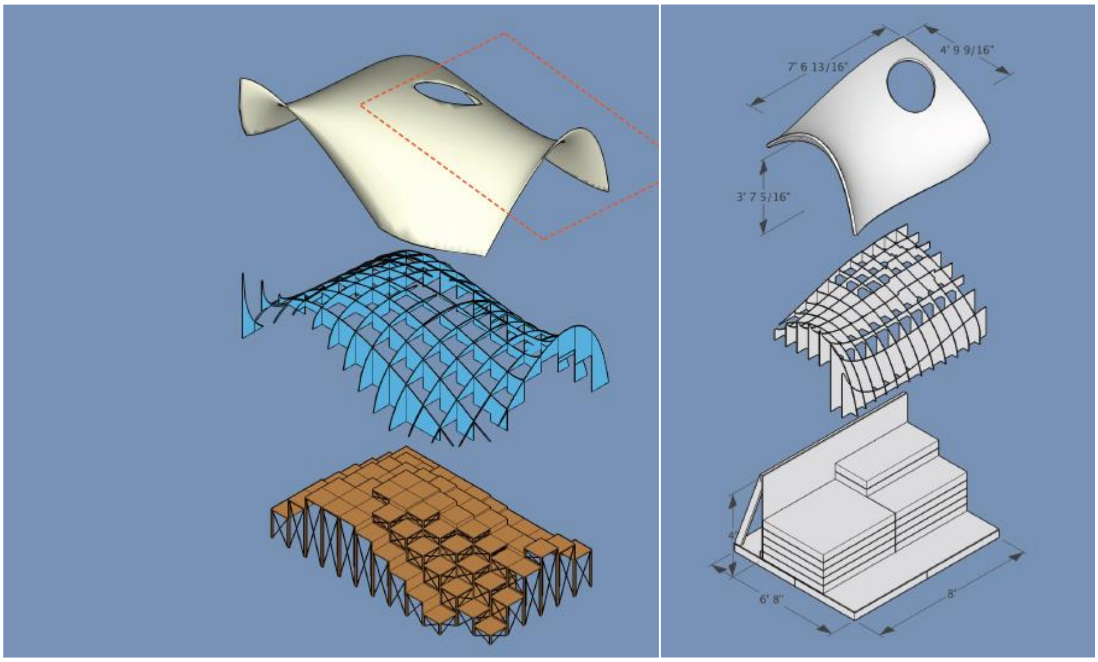

Figure 3a and b. Proposed Construction Method for Site on left and construction method of one section at Cal Poly on the right.

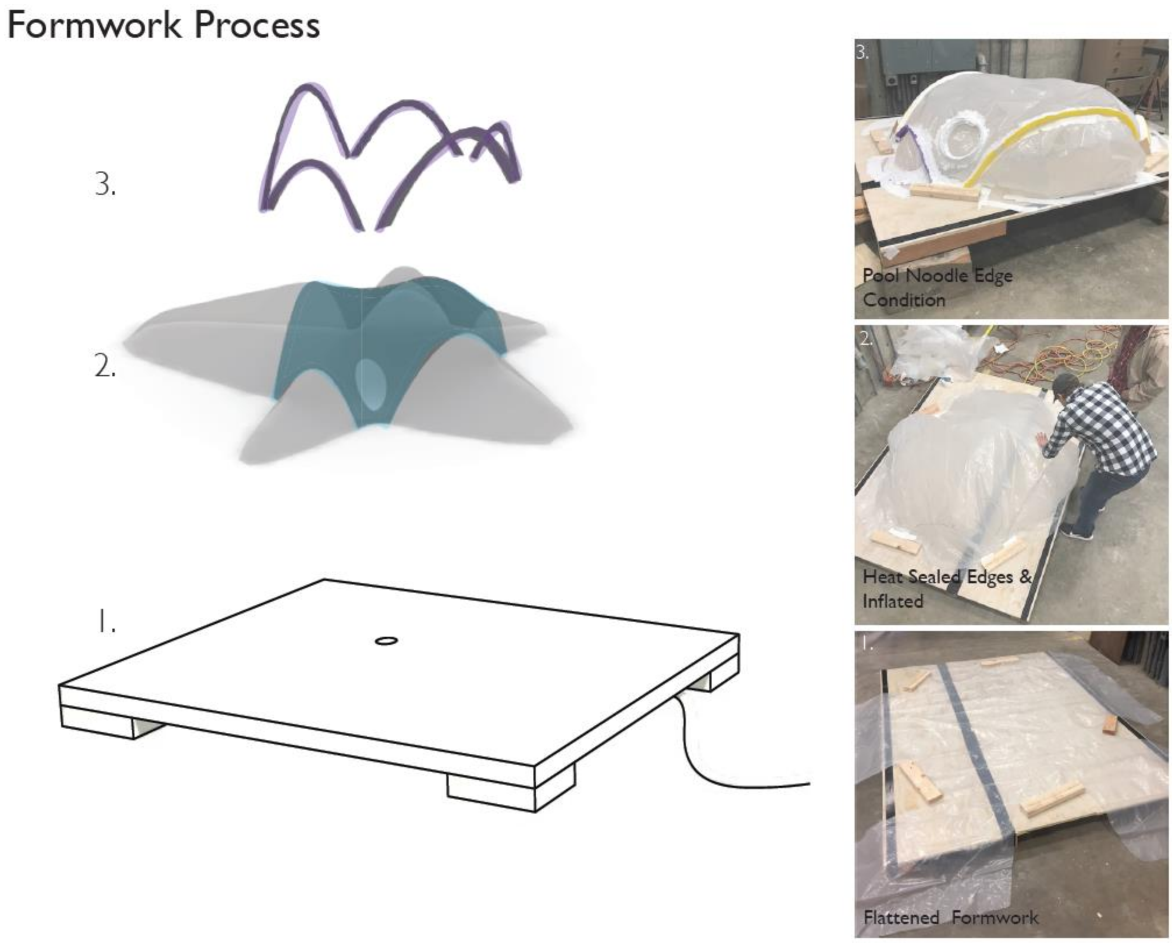

Figure 4. Inflatable Schematic at Cal Poly

Figure 5. Construction Using Inflatable Formwork

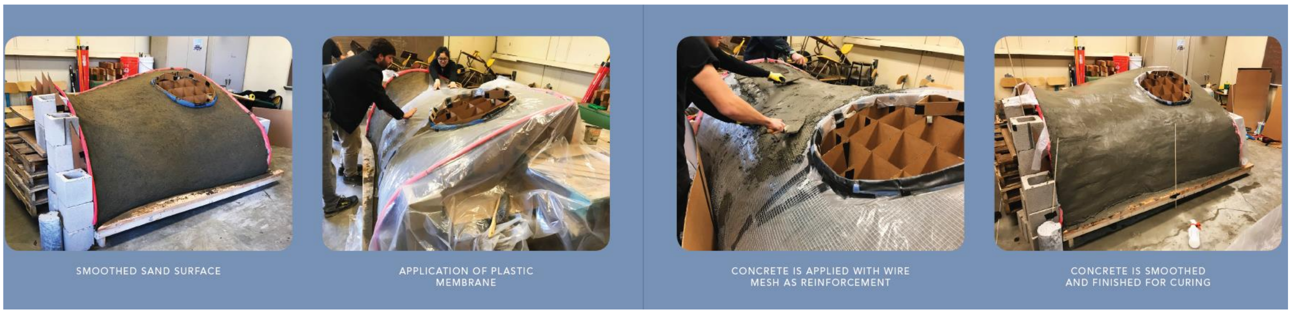

Figure 6. Construction Using Earthen Formwork

Figure 7. Visual Summary

5. References

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