Playing with Geometry and Physics: Designing and Constructing Ultra-Thin Shells

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An interdisciplinary architecture-engineering design studio focused on ultra-thin shell structures was co-taught to fourth-year students at Cal Poly San Luis Obispo. Teams of four or five designed, analyzed, and constructed a play-house size model of their shells in just 10 weeks. In the pursuit of ultra-thinness, students were asked to develop funicular-based, compression-only shells using Kangaroo and analyses were conducted using SAP 2000. A construction scheme was designed for the full-scale shell at the chosen site, and an analogous construction scheme was developed for a play-house sized model built on campus. The triangulation of design, analysis, and construction proved critical for understanding form-efficient structure, and performing these varied steps made learning comprehensive.

INTRODUCTION

The thinnest concrete shell designed and realized by pioneering engineer-architect Felix Candela, the Cosmic Rays Laboratory, was a mere 5/8" thick.[1] Using hyperbolic paraboloid geometry with extreme efficiency, the resulting form is mostly in compression allowing the reinforced concrete to appear almost paper-thin. Candela used hypar geometry for the first time in Cosmic Rays because the roof had to be only 5/8" to enable cosmic rays to penetrate concrete and be measured. Given the requirement of ultra-thinness, Candela was faced with a challenge: In the high seismic zone of Mexico City, how thin can concrete be constructed and still stand up? As this canonical work demonstrates, shell structures are fertile (play)grounds for design, geometry and construction. Two iterations of an interdisciplinary architecture-engineering design studio taught to fourth-year students at Cal Poly San Luis Obispo asked the same daring question. Student teams of four or five designed, analyzed and constructed a play-house size model of their shell structures in just 10 weeks. Through the studio, students learned the significance of collaboration, developed new digital form-finding and analyses skills, and learned the value of considering geometry, material, and constructability early in the design process.

BACKGROUND AND ACKNOWLEDGMENTS

This paper discusses the studio co-taught by the authors based on previous iterations of courses taught with other colleagues. Clare Olsen co-taught a shells structures interdisciplinary design seminar with engineer Sinead Mac Namara at Syracuse University and Ed Saliklis co-taught the first iteration of this studio at Cal Poly with architect Ansgar Killing. These courses derive from a long history of teaching architecture and engineering students the value of integrating structural rationalism with architectural expression. Moreover, designing shell forms is well suited to the integration of disciplines because the architectural and structural designs cannot be separated from one another. Since integration is inevitable with shell structures, this subject serves as a perfect vehicle for teaching integration to architecture and engineering students and teaches them to value the contributions and expertise of other members of the design team.

In this iteration of the course, the faculty discussed the importance of communication from the start, and this was a regular topic of conversation during desk critiques. Since the Architectural Engineering (ARCE) program is four years, the engineering students were completing this studio to fulfill their senior project, which requires a final report and project book. Knowing this from the beginning helped to instill a sense of seriousness and dedication, not only on the part of the engineering students, but also from the architecture students who remarked numerous times that they wanted to support their colleagues' in their final undergraduate endeavor. It also helped that since the course had been taught on campus the previous year, the faculty and students knew exactly what to expect from the quarter-long experience and recognized the need for continual dedication to the effort and pace. Although not without predictable hiccups in design and team-work along the way, the studio proved to be a growing experience not just in terms of skills learned, but also through the growth that is inevitably part of a large collaborative project.

METHODOLOGY

The 10-week long schedule involved about three and a half weeks for research and design development, three weeks for analysis and design refinement and three and a half weeks for construction of a large-scale playhouse-size model in the high bay concrete lab. Students and faculty recognized the rewards of material experimentation with concrete and formwork, and the time it takes for concrete to cure. Working backwards from the final presentation with formwork removed, the faculty maintained a rigorous schedule, which the students were eager to fulfill. The ambitious timeline was achieved by setting regular progress deadlines with weekly "milestones", which included small and formal presentations, sometimes using digital projections only and sometimes also with physical boards and models.

Figure 1: Saliklis-Olsen Interdisciplinary Studio: Day and night lighting by Meller, Hirrata, Price, Nune.

THE TEAMS

The teams were pre-selected by the faculty before the start of the quarter based on grades in their previous courses to attempt to start everyone on an equal footing. There were 12 engineering and 14 architecture students, so some of the teams included more architecture students. This methodology of choosing the teams simulates a work experience in which designers are assigned to projects; one often doesn't get to choose one's teammates on the job. Out of the six teams in the studio, two teams had communication difficulties, but in the end, all the teams stayed together and completed the studio projects on time and on budget.

THE PROGRAMS AND SITES

Given the tight schedule and limits of shells, there were numerous constraints at play. Teams were given the choice of sites and programs in four cities around the world, all with high risk of lateral movement. The options included a spa in Japan, a museum in Miami, a skate park in Madrid or a pub in Portland. The program complexity and scale, about 1,000 square meters, required interior partitions, which are not intrinsic to shell structures. The spa in Japan was the most popular choice, but diversity in the studio was encouraged, so two teams focused on the spa, two on the pub and one team each worked on the skatepark and museum. The students researched the sites in terms of climate, population and surrounding circulation. All the sites were many times larger than the program, so in the field contexts, students made siting decisions based on access, solar and wind (a design driver at the Miami site).

FORM-FINDING AND ANALYSIS

In the pursuit of ultra-thinness, material and structural efficiency, students were required to develop funicular, compression-only shells. Funicular forms were facilitated using physics-based digital form-finding with Kangaroo, a plug-in for Rhino's Grasshopper. The students were given a video tutorial specifically created for the course by a former student and also directed to other online resources to learn how to use Kangaroo for the design of shell structures. About four architecture students in the studio had already been familiar with Grasshopper, so the process of learning Kangaroo was a small step, but for those not familiar with Grasshopper, learning the software represented a hurdle, although a rewarding one since the software enabled the rational efficiency of Candela's Cosmic Rays, but with greater geometric possibility. In Kangaroo, "anchor points" were placed according to plan ideas and degree of openness desired—the more points at which the shell was anchored to the ground, the more enclosed the shell became. (Fig. 2) Two student groups (out of six) used other means of simulating funiculars in the Rhino modeling environment. Most of the modeling was designed and executed by the architecture students, although many worked with the engineers at their side providing feedback.

After initial designs were developed (about two weeks into the quarter), the students were asked to develop the shells with greater detail, considering natural and artificial lighting, hydrology (water run-off), footing designs, edge conditions, shell thickness and texture variations. (Fig. 1) Of course, these aspects were expected to fully integrate into a fluid form. Makerbot rapid prototyping machines were offered to our studio (by a colleague who was not using them that quarter) and most teams made very small study models and sites to study form and apertures. Weekly reviews provided feedback on the details of the teams' designs. Collaboratively, the students developed day and night lighting strategies, which impacted the footing and edge condition details. The engineering students developed detail drawings in AutoCAD to describe rebar locations and footing sizes. Some teams also discussed concrete mixtures and specifications, demonstrating the desire to comprehensively design and execute the project.

Overall, the use of Kangaroo proved to be crucial in ensuring that the shell forms were efficient. The finite element analyses conducted by the engineering students with SAP 2000 revealed few major problems in students' initial designs using Kangaroo, but teams that had only used Rhino needed to

Figure 2: Saliklis-Olsen Interdisciplinary Studio: Kangaroo employed in form-finding to create a spa by Dias, Shafer, Dung, Guevera.

return to Rhino to further refine the geometries to be more efficient. The analyses conducted by every shell included dead and lateral loads and time-history lateral response. Linear elastic buckling analyses were also conducted, as extreme thinness is not a concern for stresses, but it is a major concern for buckling safety. Over a two-week period, the student teams refined their designs by moving back and forth between Rhino and SAP until all team members were comfortable with moving forward with construction. While the engineering students were in the computer lab working on SAP 2000 and AutoCAD, the architecture students developed presentation drawings and renderings in Rhino and VRay.

CONSTRUCTION

Even basic facility with the design of reinforced concrete shells requires a third discipline, the art of construction to fully realize design goals.[2] After the midreview, faculty presented multiple construction possibilities and students also conducted their own research to develop formwork strategies for their designs. The strategies suggested by faculty included (1) inflatable formwork, (2) sheathed waffle grids sitting on scaffolding, (3) waffle grids filled with dirt, and (4) a panelized, modularized system, temporarily placed on a lattice and then reinforced with a topping slab. In addition to these strategies, one team introduced CNC milling to create the formwork for panels, which were lined with fabric for removal from the foam molds. These low- and medium-tech strategies for construction enabled a combination of machine and hand construction, thereby simulating large-scale means of building. A construction scheme was designed for the full-scale shell at the chosen site, and an analogous construction scheme was developed for a play-house sized model built on campus. In other words, if a waffle grid at the site would be constructed out of wood, the scaled-down version could be constructed out of cardboard but maintained the same proportions and geometries. The play-house size model, about three meters squared, was a selected portion of the whole shell, and was required to include at least one oculus.

The construction of the shells required the most time outside of class, but the teams were eager to see their designs constructed. The College of Architecture and Environmental Design has a concrete high bay laboratory, which was made available to the studio and each team commandeered a section of the shop for the three-week construction period. The lessons learned from the large-scale model were multifold. One of the biggest challenges was the creation of a base that could simulate the footings required for the model. Several teams built a simple platform out of plywood, neglecting the footing requirement. Two of the teams constructed sandwich platforms to contain pits for footings and other teams used various methods of shoring including small metal angles or wood blocks, which kept the walls of the shells from splaying outwards.

The most playful aspect of the construction was the slathering of concrete, which required attention to water content, pacing and teamwork. Due to the time constraints, all members of each team needed to participate in laying concrete, which further bonded some groups and frustrated others. In the end, however, every team presented their designs at the final review with the formwork removed. A week later, the teams tested the strength of the shells by standing on top of them before destroying them with sledge hammers. The pieces were discarded in the concrete recycle bin and a road construction company purchased the concrete remains from the shop.

LESSONS LEARNED FOR FUTURE STUDIOS

Another iteration (at least) of the course will be taught by the authors, so the paper enables reflection on the pedagogical goals, skills learned and sequence of the course. The ambitious three-part experience of design, analysis and construction proved not only doable in 10 weeks, but also critical to students' learning. Each phase of the project enabled refinements to the form, structural efficiency and experience of the space. Fundamentally, students learned the critical leap and translation of design into built form. Knowing the details, edges and textures of their designs in drawings and models, inevitably did not translate exactly as expected into concrete. The faculty plan to mitigate surprises by encouraging more material play and construction research earlier in the quarter. This way, fabrication techniques can inform the shell design and anticipate construction.

Four of the teams used a waffle grid and quickly learned lessons about kerf and construction tolerances. However, similar lessons about tolerances were also learned by the two remaining teams who used an inflatable and milled formwork. The air supply in the shop varied throughout the

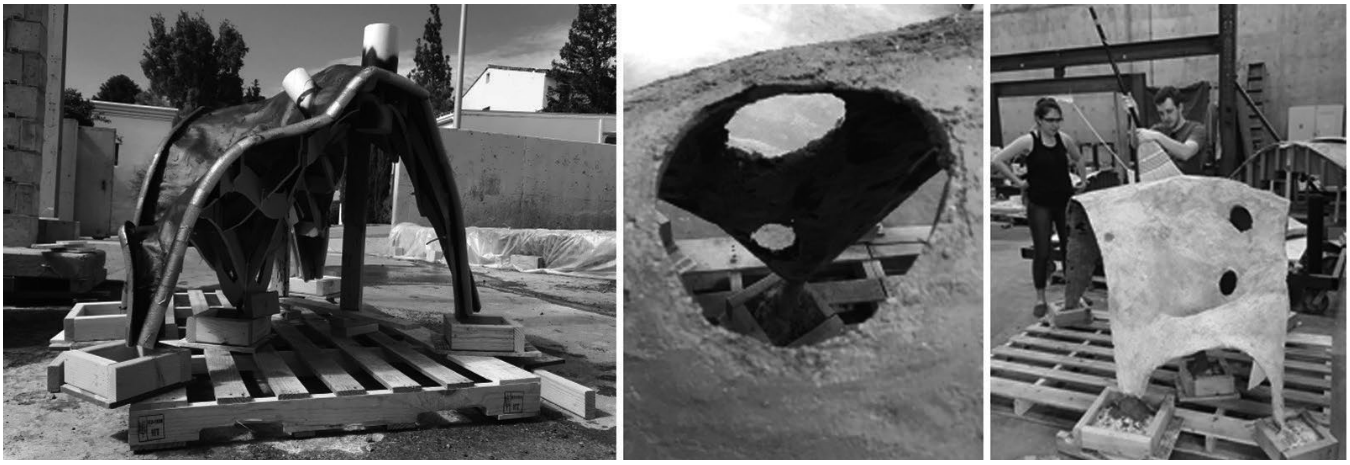

Figure 3: Saliklis-Olsen Interdisciplinary Studio: Material savings achieved through geometry, formwork and ultra-thin concrete by Berridge, Cano, Choy, Ojalvo.

week, resulting in fluttering of the inflatable and cracks in the concrete. Although the inflatable is a promising strategy for sustainably saving material in formwork, as Dante Bini advocated with Binishells[3], the technology available on campus is not reliable. Future attempts at the inflatable will require more partitioning (i.e. smaller inflatables) and a steady air supply.

The most time-consuming construction strategy, by far, was the creation of milled modules, mostly because the group selected a huge portion of their design to construct, but also because they did not properly account for drying time and removal angles in the molds. As a result, they were not able to reuse molds as had originally been one of the sustainability drivers for the strategy. One other team used a modular approach, but with lasercut molds that sandwiched wire mesh to serve as both reinforcement and to connect the modules together. Both teams using these modulated strategies applied a topping slab (similar to the construction sequence used by the Queen Alia International Airport[4]), but both teams used the topping slab as a way of hiding tolerance errors and resulted in overly thick shells.

The thinnest shell, by far, created in the studio was achieved for a shell with practically vertical walls—a tall shell with high arches. (Fig. 3) The team employed a waffle grid strategy by milling wood into four-inch wide parts and then gluing the lattice together. They skinned the lattice in a thin metal mesh and then painted it with liquid rubber. With thinness in mind, the students troweled a ¼” thick layer of concrete over the entire model. The structure maintained its integrity even after removal of the formwork. The team achieved multiple course goals including saving material in formwork and saving concrete through efficient geometry and attention to craft.

Each team used a different method of skinning the waffle to create a surface to support the concrete. The faculty supported experimentation in this area, although not all strategies are elegantly scalable to the actual site. One team working with a scalable system stretched smooth plastic from rib to rib and stapled the plastic to the wood waffle. Despite tightly skinning the surface, the weight of the concrete caused the plastic to sag, thereby creating a quilted effect on the interior of the shell. (Fig. 4) Although a happy accident, this strategy, considering a different interior texture than the exterior smoothness, will be one that faculty discuss with future teams.

Another aspect of the course that will evolve in the next iteration is the cultivation of teamwork. Although all teams were a success in that they designed and constructed shell models on time, it was clear that not everyone in the studio pulled equal weight. Part of this imbalance of work started early in the quarter when the pacing of the studio was established. The expectation became that some students would be doing things in their expertise, which varied the workload and timing. For example, Kangaroo was only used by the architecture students, which limited some of the dialogue and collaboration about initial form-making. In future iterations of the course, the faculty plan to conduct a hand-modeling charrette and pin-up on the day the brief is released so that engineering students are encouraged to participate in the design conversation from the start. Also, use of RhinoVault, which may be more accessible for all students, will help to level the playing field during the design process. Similarly, only the engineering students conducted the finite element analyses. The architecture students would also benefit from the SAP 2000 tutorials and will participate in those in future iterations.

Along these lines, the faculty plan to start the new studio with team-building games as a quick assessment of synergies and personalities. A focused workshop on collaboration strategies will also help students to discuss difficulties as they arise or avoid them altogether. Students were encouraged to present their projects from multiple perspectives (not just their own or their discipline’s) so this stimulated team dialogue

Saliklis-Olsen Interdisciplinary Studio: Interior quilted texture through
plastic stretched over wood waffle grid by Cordova, Da Silva, Franco, Roth.

about the decisions they were making so that every member could advocate for the work during a presentation. This was an important component of the collaboration strategy that faculty will continue to instill in the future.

PEDAGOGICAL VALUE

Research and practice in the design and construction of shells helps to blur the boundary between the Architect and the Engineer, nurturing a shared sense of accomplishment in the integration of geometry, form and structure. Students develop collaboration skills, design and software skills and hone construction techniques. The resulting shell structures provided palatable lessons about teamwork, form-efficient geometry and the best water-cement ratios for concrete.

This learn-by-doing project also benefits students by providing a full design-build experience, from ideation to construction. Students at Cal Poly have several opportunities for large-scale construction, especially in the first year in which architecture and architecture engineering students take studios together. This fourth-year studio enables students to build upon those skills at a much higher level of sophistication, thereby spring-boarding students into their professional careers. The triangulation of design, analysis and construction proved critical for understanding form-efficient structure, and performing these varied steps made learning comprehensive, but perhaps more importantly for the Play Conference, fun for all involved.

ACKNOWLEDGEMENTS

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ENDNOTES

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