DESIGNING AND BUILDING THE CORK VAULT: REFLECTIONS ON A TWO-WEEK DIGITAL FABRICATION WORKSHOP

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ABSTRACT:

Thirty-five students took part in a two-week workshop intended to provide a hands on experience with digital tools for the design and fabrication of a 1:1 scale vault. The two instructors focused on theoretical concepts in arches, vaults, stereotomy, and led exercises of physical construction producing 2 arch experiments, 3 vault prototypes made from plywood, and 2 vaults made from expanded cork agglomerate. The final vault was the result of a competition between student groups and was based on an algorithm prepared by one of the instructors to design a structurally sound, compression-only vault shape with parts that were cut using a 5-axis waterjet cutter. We conducted interviews with the students and report on the resulting themes including reflections on the digital tools, stereotomy and related architectural theory. We recount positive as well as negative outcomes and provide suggestions for other design educators interested in conducting similar courses.

Keywords: vault, stereotomy, CNC, digital fabrication, architecture

1. INTRODUCTION

Architectural workshops rarely offer the opportunity to work in full 1:1 scale, however, with the tools of digital fabrication, CAD software, laser cutters, waterjet cutters and other CNC tools have made it possible to work in larger scales and to drastically speed up the design and construction process. There have not been many examples of research focused on reflections from architecture students on learning digital tools for architecture.

Kolaveric described a paradigm shift (Kolaveric 2001) in which the tools of computer-aided design (CAD) and computer-aided manufacturing (CAM) have empowered the architect to make advances in structure and materials. Architects are now equipped to break away from Euclidean geometries and explore the complexity of curved forms, mass customization, and new materials. Kolaveric proposes that architects are again becoming a "master-builder" (Kolaveric 2001), controlling aspects of the design that previously resided in the domain of structural, materials and process engineering. While digital tools are crucial to the architectural design process, the difficult interfaces and unfamiliar processes can intimidate the architecture student (Seely 2004). We seek to highlight the outcomes from an intensive course that exposed architecture students to the digital tools of fabrication in the hopes that we may encourage discussion in the design education community about how we embed the technology in meaningful ways into creative practices.

This paper is organized as follows: concepts of stereotomy and related design pedagogy is presented, the intensive workshop is described followed by research questions that formed the qualitative inquiry and discussion and suggestions for other design educators.

2. STEREOTOMY

Semper describes stereotomy as a system, which relies on parts that are held together by compression (Semper2004). Walls built out of blocks are an example of stereotomy, as each block exerts and supports forces on other blocks due to gravity, resulting in a stable system: a vertical wall. The addition of a horizontal dimension to this problem results in increased possibilities namely in the spanning of vaults, making stereotomy a key approach in complex construction systems.

There are records of vaults and domes in ancient Mesopotamia (Kawami 1982) and in other cultures such as Egyptian or Greek (Boyd 1978), but it is in the Roman empire that Vitruvius first writes on the theme around I BC. Romans make an extensive use of the arch and its more volumetric expressions, the barrel vault and dome, making this system pivotal to monumental constructions such as bridges, aqueducts or temples (Adam 1989).

True voussoirs - instead of corbel structures - passed on to Protoromanic, Romanic and ultimately to Gothic architecture where flying buttresses and ogives widen the structural and spatial possibilities given by this construction system. Single blocks of stone, precisely carved, describe surfaces that envelope strength flowing mechanisms.

A key figure in the history of stereotomy rises in the Reinassance through his most widely recognizable work, Château d'Anet. Philibert de l'Orme is also the author of *Le premier tome de l'Architecture* which seems to have set a tradition of stereotomic research in France. This research would lead to the development of a new science intended to provide tools for complex three dimensional drafting - the project of a vault and its independent voussoirs (Fallacara 2006). Gaspard Monge was the architect who would eventually put theories from Desargues down to paper and created Descriptive Geometry. Recently there is renewed interest in stereotomy due to the possibilities offered by digital technologies (Kolarevic 2003).

3. RELATED WORK

The introduction of digital fabrication tools in architecture schools has made complex design experimentation a tangible possibility. Structurally sound vaulting with thin tile structures have been explored recently including Vault201 (Davis 2010) or the Freeform Timbrel Vault (Davis, Rippman, Pawlofsky, and Block 2012). Design strategies devised by Ochsendorf and Block were applied in shell structures built with continuous inter layered thin tiles assembled with mortar. Larsen, Pedersen and Pigram directed a masterclass in which a true stereotomy is used in the form of specifically cast concrete voussoirs (Larsen, Pedersen, and Pigram

2012). MSc2 studio at Hyperbody TU Delft used subtractive processes of cutting styrofoam with a robot to create the vault components (Rippmann and Block 2013). The Cork Pavillion[1] built for Amorim Isolamentos S.A. in 2013 was the first example of spanning vaults with cork alone and the present workshop extends this research trajectory of fabrication using subtractive processes and CAD/CAM with Cork as a construction material (Sousa 2010).

4. HARDCO(U)R(S)E

The HardCo(u)r(s)e concept at the Aarhus School of Architecture presents a mix of "hard core" experimentation and intense, construction during a month long period of courses focused on digital tools. All students completing their second year of the bachelor program take part in this final series of courses before the Summer holiday and present their work in a group exhibition. We now provide details about the structure and timeline of the two-week Cork Vault HardCo(u)r(s)e.

The course began with an introduction of the design brief, which was to build a large vault structure with expanded cork agglomerate (ECA) using CAD/CAM tools. A lecture regarding the architectural concepts of stereotomy and vault construction was provided. Students were organized into 5 groups of roughly 7 students each, and were asked to sketch ideas for a vault in the planned site, which was an adjacent courtyard. These were then presented to the class and commented by the instructors and the students. The groups faced questions regarding the orientation of the openings, the height of the structure, how the planned location could affect the current use of the space by pedestrians entering the nearby buildings and other conceptual perspectives they chose to take with their designs.

The second day was dedicated to learning the software that would be used throughout the course to design the vault: Rhinoceros3D with the Grasshopper and Kangaroo plugins—Grasshopper for parametric design and Kangaroo for physics simulation. Students were led through an exercise of building a model by creating a simple Grasshopper definition. Then a prepared, more complex definition was provided that builds a complex vault and the instructions to cut the blocks that make up the vault. The prepared Grasshopper definition requires the student to draw lines to designate the two wall footprints and then make adjustments to the physical properties and simulated material in order to "inflate" the vault shape as desired.

A plywood model was fabricated by the instructors and given to the students so they could try and build the vault without the help of centering. After realizing that this task was very difficult and virtually impossible, the students were given the exercise of designing a centering system to support the blocks during construction. The centering and base plate were designed in Rhinoceros and fabricated by a laser cutter and a water-jet, respectively. The plywood vault was subsequently easily assembled, as shown in (Figure 1).

[1] Designed by architects Pedro de Azambuja Varela, Maria João de Oliveira and Emmanuel Novo under the coordination of professors Alexandra Paio and José Pedro Sousa.

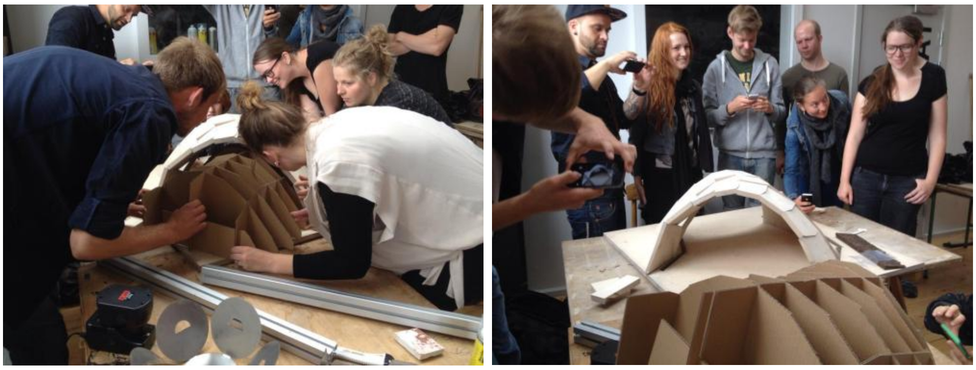

Figure 1: (Left) Centering being removed from the plywood vault. (Right) Free-standing plywood test vault with centering in foreground.

Considering the success in building the small plywood vault, we set the next challenge as the design and construction of a small cork vault using 100mm thick ECA sheets. The students chose a design, and then worked to realize it. A centering was designed, and a base was plotted on paper to allow for the vault blocks to be positioned easily on the wood floor. After waterjet cutting the blocks, the vault was assembled with the centering supported by a skid trolley. The centering was lowered evenly by the trolley enabling the individual blocks to settle correctly in place. An additional test was made involving the centering removal, which entailed softening the pieces with water for careful removal. The small test vault was loaded with weight, first by two students pushing evenly with their hands and then with by standing on top of the vault as shown in (Figure 2).

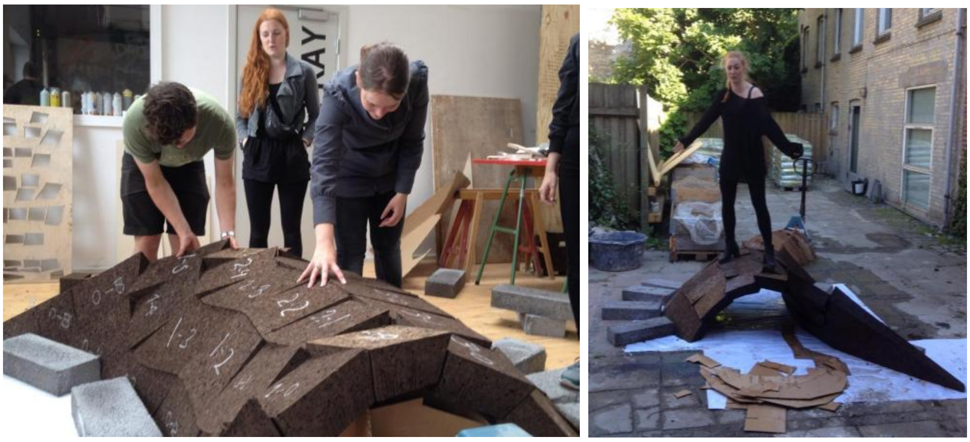

Figure 2: (Left) Students test strength of vault (Right) Standing on the vault to test its strength.

An arch was designed and cut so that its construction could be incremental, giving rise to a higher and wider arch with each iteration as shown in (Figure 3) to test for material limits. Students could again exert forces with their own hands against the structure to feel the stability and the reaction of the arch under uneven loads.

Figure 3: Benchmark strength test of simple arch.

The final design was the result of class competition. After having the design decided, each group was responsible for tasks necessary to complete the project. This included the centering system, design of a light concrete base, plotting a paper template with the plan for the base, preparation of the foundation, and presentation materials for the final exhibition. All participants helped in the construction process as shown in (Figure 4) leading to the freestanding vault (Figure 5).

Figure 4: Construction of the vault (Left) Test-fitting the voussoirs. (Right) Constructing the cardboard centering.

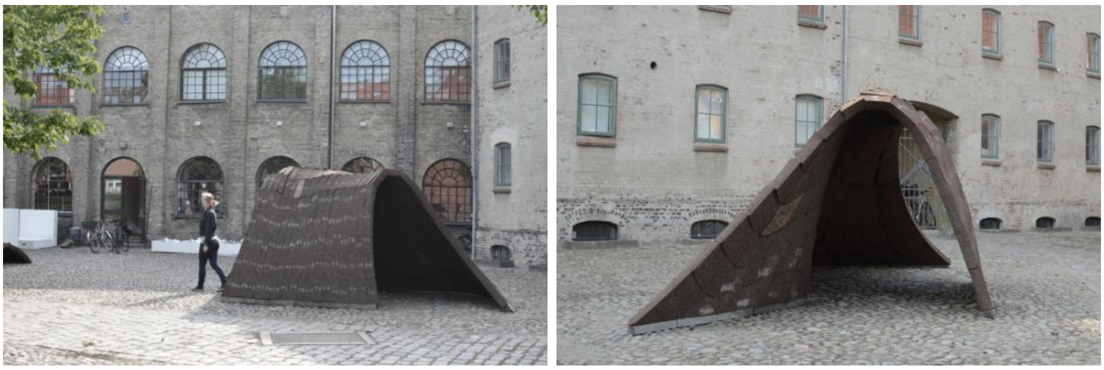

Figure 5: (Left) completed vault (Right) View of the interior of the vault structure.

5. INTERVIEWS

We conducted face-to-face interviews with 5 students primarily focused on the impact of the course and perspectives on the digital tools, course related reflections, and architectural concepts. The interviews took place three months after the workshop. The interviews were conducted using a questionnaire as guidance in a semi-structured approach and focused primarily on the 3 main topics including tools, course, and theory. Students were encouraged to provide other feedback they felt was relevant. The 12 initial questions are now provided.

Tools related questions:

1. Do digital fabrication tools (waterjet, laser cutter, CAD) change the way you think about or approach an architecture project?
2. What are the new possibilities in design that are enabled with a waterjet? How does it enable new forms for you to work with as an architect?
3. Do you see yourself exploring new materials with the waterjet?
4. What limitations do you see with the waterjet?

Course related questions:

1. What reflections do you have on the experiments during the course?
2. What are the challenges you encountered in working at 1:1 scale?
3. What worked well in the course?
4. What would you do differently if the course?

Theory related questions:

1. What are your thoughts about stereotomy as a construction technique? For example, do you have any feelings about the formal value of the voussoirs being chunks/blocks?
2. How about the "dragon wing effect" of the final vault shape, what are your thoughts about this?
3. Do you feel comfortable incorporating arches or vaults in your work?
4. How do you feel about using the lines that separate the blocks as a design resource?

6. RESULTS

The main themes that emerged include positive and negative aspects of the experience and suggestions for future refinement of the course.

6.1 REFLECTIONS ABOUT THE TOOLS

The overall impression was that the workshop provided some of the first experiences with parametric design and waterjet cutting. The majority reported that these complex tools were demystified, yet they still feel poorly skilled provided the limited time of the workshop.

Students reported that they now feel better equipped to make better choices about which tool to use in the workshop yet they claimed the user interface was tedious. Most agreed that the waterjet and CAD tools would enable new forms in their work, participant 1 (P1) noted,

"…now, ideas that would be cut off are now kept open because we know how easy it can be to construct these things."

P4 noted that parametric design with Grasshopper helped,

"…think differently than on paper. It helps you do more with Rhino… …a different type of thinking."

When asked about limitations of the tools, key differences between the waterjet, which cuts through the material and the laser cutter or 5-axis CNC milling machine were mentioned. These have the ability to engrave and to work on the surface of the material. P2 noted that the tools are complex and helpful, however,

"…if you can't design well in CAD, then the waterjet doesn't make up for it. It cuts exactly what you draw."

The questions related to the tools led to discussions about their design work *after* the course. The participants noted that in their current studios, they are not working on projects that force them to use the same tools. Most felt comfortable that they could envision using the tools in the future. P3 claimed that she would prefer to use the tools for 2 additional projects in order to feel comfortable and that she would need her instructors to provide more guidance in order to use them. One claimed that they would benefit from more workshop support staff so that they could more easily attain help when exploring the tools independently.

6.2 REFLECTIONS ABOUT THE COURSE

Feedback relating to the course revealed strong opinions about what worked well (and not so well) with the format, structure, and content. We now summarize this feedback including additional reflections on material and scale.

When asked what worked especially well in the course, most participants mentioned that there was some separation of duties in the workshop, especially when it came to the final construction, which made them feel more involved and responsible for the outcome. P2 noted that on the last day of construction, it was great to see people coming together to deliver the project.

When asked what they would improve about the course, feedback about the class size, workshop tasks and design case were discussed as well as practical concerns relating to the software availability and the scheduling of the course.

In relation to class size, the participants claimed that due to large groups, there was reduced responsibility for each individual leading to some members participating less in the discussions and design work. P4 suggested that more of the Grasshopper programming could be delegated to the students to,

"…solve some small parts of the definition and if they can't solve the problems, then the finished definition could be provided by the instructor"

so that they could "…follow the thought process" as stated by P2.

P4 went on to suggest that the design case could be provided as constraints with more decision making at the group level on how they would realize the project.

There were practical suggestions that the students had for improving the course. Since the vault was positioned in a high traffic area, and because it was not cordoned off with a fence, unknown people damaged it after standing for only 2 days. Another practical concern was that many of the students did not have functional copies of the software installed. This led to much time spent on troubleshooting and finding solutions. Another practical issue that impacted participation was the timing of the course, taking two weeks prior to the Summer vacation, led to low motivation from much of the group. P1 provided many suggestions for improving motivation, including focusing on giving strict grades for attendance, breaking up the project into smaller required tasks, and including a description in the course brief that would set the expectations of full participation for full workdays. P1 also suggested a focus on a final project that would be used in public , for example at a festival so that others could interact with their work.

The questions focused on the design experiments during the course were met with strong agreement that this was helpful for them in their learning process to start simple and then build up in complexity and scale. All recounted the enjoyment of using their hands to feel the forces supported by the ECA blocks. It helped them to see the stresses and loads working in the structure. P3 noted that with the final vault, they could push on the walls and test the strength and see the movement—

"…where it was more flat it was more bendy and would wobble if you push in that area, but where it was curved, it had strength, you could feel it!"

P2 reflected on using the new materials stating, "…using cork forces new perspective for us and for the others, it draws attention and creates a buzz around the project—it's entirely new."

As previously mentioned, we were interested in conducting the workshop focused on designing and building a full 1:1 scale vault with inspiration from Kolaveric that providing this opportunity to work in full scale in addition to model building would widen the perspective of the student designers. This did in fact resonate with them and provided rich opportunities beyond the smaller scale model building. P1 noted that there is a different relation to the materials in the large scale—they could understand more easily the material qualities of strength and performance. P3 noted that the scale forced them to develop solutions fast and it removed the "bag of tricks" they use when adjusting models. With model building, they could add glue, body filler, paint, or even tape to fill gaps and to smooth over problem areas, but in full scale, as P3 stated, "…parts have to be correct, the building has to stand or else it falls! Our centering had to work, there was no option!" On the cautionary side, may participants mentioned how the full scale required much more working space and to do the work.

6.3 REFLECTIONS ABOUT ARCHITECTURAL THEORY

During the design process and especially upon constructing the vaults, participants became excited about the visual impact of the alignment of the cut blocks, which they described as looking like scales. The final vault had a pronounced scale-like effect on the double curved wall that led to the students dubbing it, the "dragon wing." In the interviews, this also came up. The reflections revealed deeper thoughts from the participants. P4 commented that it seemed to reveal the nature of the construction and how the pieces were built. P3 claimed that it was a consequence of the tool and that it could be considered a limitation, but might be used in a positive way as a design element. P2 claimed that the effect shows where the form changes and accentuates the curves and stated,

"When you make more radical changes of the flow, it shows more of these overhangs."

When asked about using stereotomy as a construction technique, most claimed to have known something about the vault construction techniques prior to the course, however, they all claimed to be surprised that they could construct more organic complex forms. In regards to using the new knowledge, the students expressed concern that they would need to become more proficient users of CAD.

7. DISCUSSION

It is important that we consider how other design educators might benefit from the insights we have gained and perhaps avoid pitfalls when leading intensive workshops on digital fabrication. It is our hope that these findings can be helpful to educators outside the topic of architecture, digital fabrication and stereotomy; we encourage the similar sharing of outcomes to work toward more effective and rewarding educational experiences. The following suggestions include practical issues of running these courses as well as pedagogical concerns.

Practical issues

- Ensure students have software properly running on their computers prior to the course.
- Identify and avoid scheduling conflicts especially when it impacts the motivation levels of the students.
- Working in full scale requires considerable hardware and material support as well as incidental supplies, for example large rain covers, tape, power tools, etc. Having more than needed is a luxury; not having a rain cover when it is needed can be catastrophic.

Pedagogical issues

- Consider providing a balance between the number and depth of the experimentation as well as a final well developed final project to balance learning with results that students are excited to share.
- Consider the student journey after the course and find ways that the student can activate the new skills and knowledge with future projects.
- Similarly, consider ways that students can go through the learning process and become the experts who can then train others.
- Competition is a wonderful way to raise the effort level of students, however, it is necessary to ensure individuals working together on a final project feel committed and that they have a sense of ownership/authorship for the work.
- Dedicate time and energy to documentation. It is easy to let this fall to the wayside, but it is difficult or impossible to go back to take photos or video of stages that have been completed days earlier.

8. CONCLUSION

We provided a brief overview of an intensive architectural workshop focused on using digital tools for design and fabrication. We conducted post-workshop interviews with participants resulting in feedback about the experience and outcomes of the course, which we distilled into a set of concerns and suggestions for other design educators. We do not presume that this can be used prescriptively in all cases, but we hope that this contribution encourages deep discussions about how we teach design students the ever-changing tools and material possibilities available to them. With a fertile testing ground and effective support, the students of today could become the designers who innovate in architectural design and shape the future of the tools we use to design and shape the world.

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