Teaching Digital Fabrication through Design

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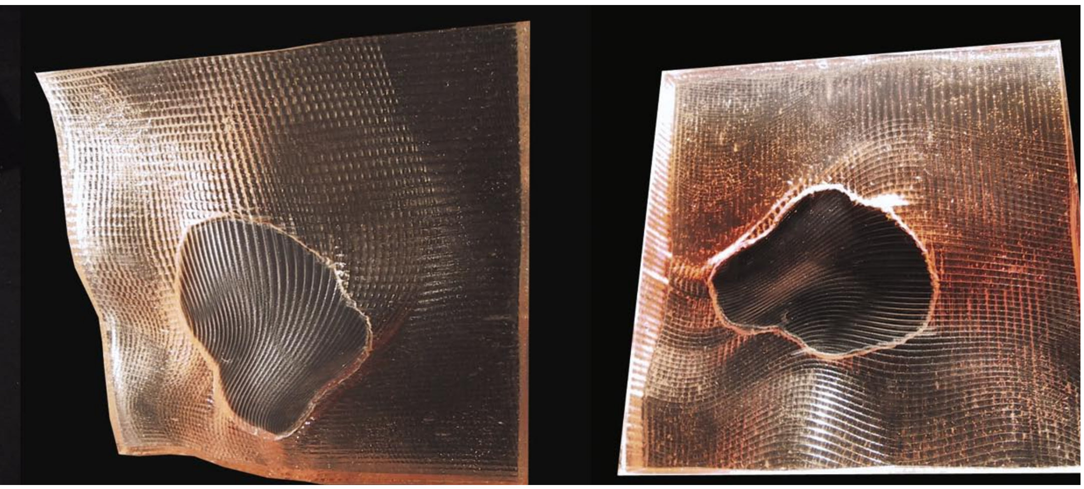

Abstract

This paper explains the development of a digital fabrication graduate seminar that has evolved over four semesters. The class attempts to teach at various levels between 'how to' considerations of learning hardware and software, while exploring a deeper understanding of the technological implications on design and digital fabrication. At the heart of the course is the belief that the limitations of hardware, software, and materials can be viewed as opportunities during the making of any artifact. A number of teaching models have been employed over the four semesters that include short, abstract, directed mini-projects, which teach one skill to the opposite extreme that develops longer, open-ended research / design projects focused on a technology or technique. The products of the class are used to compare the benefits and deficiencies of various pedagogies. The work is also used to further define the desires of the course related to strategies for materials and making.

Introduction

In 2001, the Taubman College of Architecture, in collaboration with the School of Art and Design, began a joint effort to develop a lab space that could extend many ideas that had been shared about developing a dedicated space for mock-ups and prototyping. The development of this lab space coincided with a paradigm shift within the College and collaborative grant funding available from the University of Michigan. The college decided to cease support for cluster computing (requiring students to purchase their own computers), but to develop higher end output and peripheral labs to augment the general computing provided by the students. The lab became both a place to house previously acquired equipment and soon-to-be-purchased equipment. The list of previously purchased but disparate equipment included a laser cutter, Microscribe digitizer, haptic modeler, and video digitizer. The University funding led to the purchase of a Z Corp 3D printer and Onsrud CNC Router with a bed of 4'x8'. A main goal of The FAB LAB, as it has come to be called, is to support student design work and research, and generate a renewed interest in the culture of making within the college.

To support and teach students about the FAB LAB equipment, a graduate Digital Fabrication seminar was started. The class needed to teach the students how to use the tools but also needed to produce work that could get more students interested in the tools. For the first year, the faculty member running the course was responsible for operating the equipment for course projects or other projects during the semester. While this provided an intense period for experience with the tools, it was not a model that could be scaled up to provide more service to the students. As the interest grew after the first year, the school needed to continue to foster interest in the tools and to support students beyond the students in the seminar. This next step was achieved through the hiring of a recent graduate to work 20 hours a week for the daily operation and management of the FAB LAB. This opened up the use from simply students enrolled in the digital fabrication course to any student with a relevant project. This model will be implemented again for the upcoming school year.

The logistics of setting up the shop and operating it create the conditions and impact the way in which the course can be run, and in many ways, frame its success. Having the tools is not enough; the goal is to get the students to use the tools repeatedly. The students are required to make and learn through iterations constantly feeding back their experiences into the next object they build, or project they design. This goal is best achieved through an accessible and user-friendly FAB LAB.

Course Background

The College's desires for the course needed to be coupled with the desires brought to the course by the faculty. The first desire was to connect students with materials. The course is viewed not only as a means of teaching advanced computer modeling skills or ideas about assembly, but is also a means to get students engaged with matter. The course in its current role within the curriculum is as a construction elective. The course is a synthesis of thinking about and making both digital and physical artifacts. A key component of the course and the technology is to make physical things that can be touched, held, and tested based on real and tangible stimuli. To these ends, digital fabrication is bringing about a renewed interest in sensuousness in architecture and design. The objects the students are designing and making are not conceptual or theoretical, but they are to be handled - in many cases fondled. In many of the projects produced during the seminar, a parallel investigation into material occurs to bring about a certain effect that couples the techniques of digital production with the materials of production.

A second desire brought to the table by the faculty is that an ethos of making exists that uses defined limits of materials and/or equipment to shape the design process. Of course, we can misuse technology and push the envelope, but we must understand that these tools have limits (basic parameters that influence the way we use them) e.g. bed size, maximum cutting area, maximum depth, etc. These limits push back, defining limits in the work in a way in which a rendering or representation does not. We can model and visualize extremes through visualization, which is useful, but not always productive. Once understood, these limitations can and should be viewed as design opportunities used to frame overall design thinking. While there are many examples of brute strength being used to make something (forcing a tool to do something it is not designed to do, or a material to take a specific shape), these limits can be a generative and positive aspect of the design process. An example of this thinking has to do with a 3-axis router; a 5-axis router can generate more complex forms, but the limitations of the 3-axis router (pedagogically speaking) makes casting or vacuum forming a logical next step. The 3- axis routers are unable to produce undercutting – limiting a design process in one trajectory opens up another.

While the students initially lament the loss of craft or of hand-making, they quickly find ways to embed the act of making within the objects they design and fabricate. Lectures and discussions present case studies to illustrate a renewed disciplinary interest in making, because designers are once again empowered to produce, not simply to visualize or draw. This aspect of making is amplified in the seminar; study goes back and forth between the digital and physical, each informing the other. Because the tools are accessible, the students are constantly challenged to make and remake something over again, allowing the process to become more sophisticated or more elegant. Having the equipment close and accessible allows for experimentation that would not occur if the student projects were cut or produced off-site.

Class 1: Fall 2002

The course developed for the first offering of Digital Fabrication foregrounded the tools in the development and course schedule. The basic premise was to investigate each tool coupled with its specific software for four weeks during the semester. This ambitious proposal produced three projects of equal value throughout the semester.

1. Laser Cutting: 2D Cutting Project

The first project was focused on the laser cutter. This assignment introduced the students to the idea of developing 3D forms or assemblies from 2D cut parts. The sheet size and material limitations of the laser cutter would frame their investigations. A simple program of a light fixture was used to stimulate the designs and investigations. The students used Rhino to model their projects, flatten their parts, and lay out their cut sheets. This data was imported into LaserCam for cutting. The benefit of having the laser cutting included in the course is that it was analogous to CNC cutting, like water jet or plasma arc cutting of larger materials – the process is scalable to architecturally sized elements. The included project begins by simply exploring cutting and scoring as a means of making components for a fixture assembly. Figure 1 shows the simple first iteration of a series of interlocking rings. The associated cut sheet shows strips that begin to explore the scoring and cutting as part of the design, including perforations to allow light through the surface, shaping the edges by cutting, and including notches for assembly.

Criticism of both design and technique are provided through both one-on-one interaction between professor and student (or student team) and through entire class pin-ups. The criticism for this first project pushed the development of product thinking such as allowing waste management to impact the design and shipping and assembly of the final product to a customer.

The final iteration of this project (Fig. 2) builds on the implications of the laser cutter. A double-sided material is used to exploit the creation of an inside and outside for the light fixture. The entire sheet is used; where the previous example showed waste at the edges, this example attempts to eliminate waste through using the entire sheet and maximum limits of the laser cutter. The proposal is a continuous wrapped piece, where the previous iteration was three separate rings. This example uses the notches to allow for various types of assembly, allowing a customer to adapt it, based on the multiple notches and scoring provided. The project is a successful example because it identified attributes of the tool and developed a product based on the limits, while allowing other factors to make the proposal richer, such as the use of color.

3.2 Digitizing / 3D Printing

The second assignment coupled the Microscribe digitizer with the Z Corp 3D printer and was much less of a design project than a simple technique exercise. Students were asked to digitize an object that they brought to class, but only to digitize a surface. To add to their Rhino skill sets, they were required to add thickness to the surface and make a closed, solid, digital model. This model was then 3D starch printed and the result could be compared with the original. Figure 3 shows the initial object, a piece of cloth over four eggs and the printed object. The student worked to model the draping of the fabric and the surface quality. The following images show the process of digitizing and model both wire frame and shaded to illustrate the increasing sophistication and complexity of the iterative process as the student explores various techniques of digitizing and modeling to achieve their desired results.

This project is harder to quantify than the first project where there is not a design consideration but the example included illustrates the student's development of both the use of the digitizer and their Rhino skills. The project was both about achieving a match of their original object but also manipulating the input data to achieve a desired output from the 3D printing.

Because this class was the first experience teaching the material, the projects tended to run longer, compressing the end of the semester. The CNC router was introduced as a series of demonstrations of both the hardware and software. The equipment was new at the time and occupied a less dominant role in the course as it would in subsequent offerings because the faculty was not as confident with its use. The students were given the option to use the CNC router for the development and production of their final projects.

3.3 Final Design / Research Project

The last project during the semester gave the students more freedom to use the technology for a design project. The process was stressed as a means to get them to use the tools to develop their design thinking. Students could revisit any of the tools that had been introduced during the term as they had

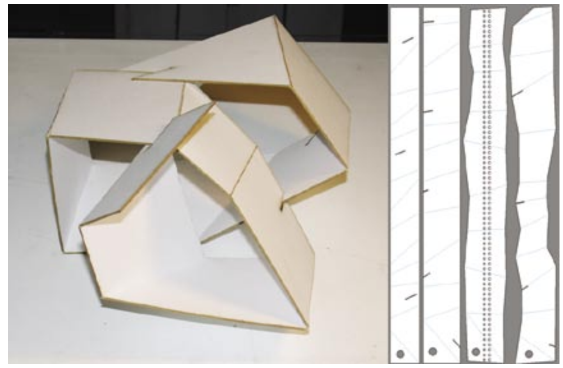

Figure 1. First Iteration for laser cutter project, Jeff Ponitz

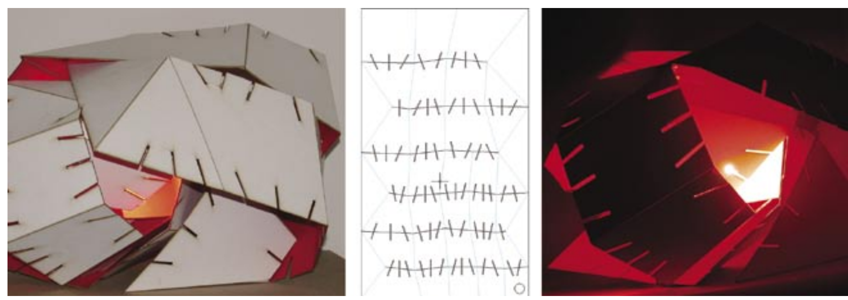

Figure 2. Final Proposal for laser cutter project, Jeff Ponitz

been covered quickly. There was a balance between laser cutter, 3D printer, and router, with about three or four projects on each. The included project developed a series of 'tipsy coasters' that could stack together into a solid block. The project began with a series of surfaces where the top would define the bottom surface of the adjacent coaster. This project gave each coaster a different tool path to add texture. The simulated surface from MasterCam was exported and 3D printed at a smaller scale to see and feel the texture of the final parts. Each coaster was routed on each side and then cut down in the wood shop with a band saw. The image shows a completed individual coaster, and the assembled block of coasters prior to finishing (Fig. 5).

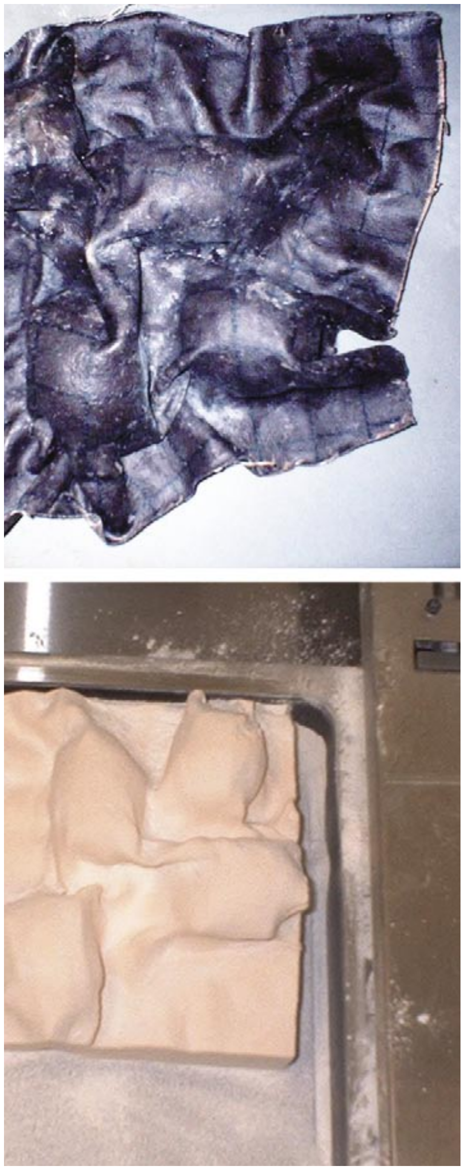

Figure 3. Digitizer / 3D Printer Project. Calder Spruill

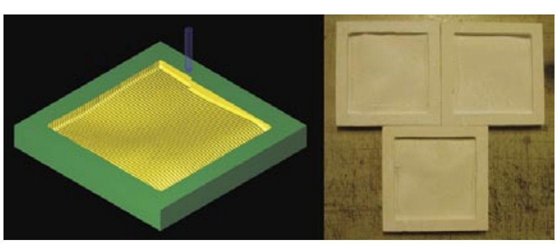

Figure 4. Simulated tool path used for 3D printing. Dennis Ng

The *tipsy coasters* project is included because of its complexity in making multiple parts that must fit together, and the ability to mill double sided parts. The multiples also allowed for an exploration of the textures using various toolpaths to create varied effects. The students mixed multiple tools such as the modeling and 3D printing to test the stated goals of the project prior to working at full-scale. This project is indicative of the scale of the final projects during the semester; most of them were finely crafted hand-held objects as a result of the limited time for the final project.

Class 2: Spring 2003

Building on the knowledge and experiences from the previous course and a more developed understanding of the use of the CNC router, this course focused on the use of the router. The course was divided into two halves, where the first half dealt with instruction of software and hardware and more broad lectures about construction and technology. The second half of the semester was used as an open lab environment with three teams of students developing a design project of their definition. Reviews and presentations were used to cross-fertilize the groups with various ideas, techniques, and strategies. The overall theme for the semester was on the production of formwork that would stress the design of something that would be made more than once. This was done to minimize the finality of something directly from the CNC router, forcing the students to modify and rework their digital creations into objects of production.

4.1 Project 1: 2D Tool Pathing

The first project of the semester used the CNC router to explore 2D cutting and tool pathing. This assignment was used instead of the laser cutter project from the previous semester, because the laser cutter had reached such a broad use within the school, and it did not need dedicated instruction. This simple (less design-oriented) assignment could also allow the students to focus on the various methods for 2D tool pathing within MasterCam, which develops the mind-set and similar workflow for more complex 3D tool pathing. This assignment also introduced a CSP (cross sectional prototyping) software application to make an egg crate prototype out of a solid model (Fig. 6). The software slices the solid model, notches the parts, and lays them flat. The students were asked to design a 4'x4' surface with a thickness and then decide on the number of parts used to make the piece. Having completed the CSP aspect of the project, they were required to lay out the cutsheet and tool paths. This assignment provided a key opportunity to begin the discussions of material efficiency and part layouts. The students were given the opportunity to go back and re-CSP their models to define more or fewer parts, to condense or add sheets to their production, and to make their surfaces more smooth or coarse. This iterative process was introduced and would continue throughout the semester as a means of intensifying design and making as a linked process. This project explored multiple iterations to arrive at a project that balanced the material use with what they felt was an appropriate approximation of their surface.

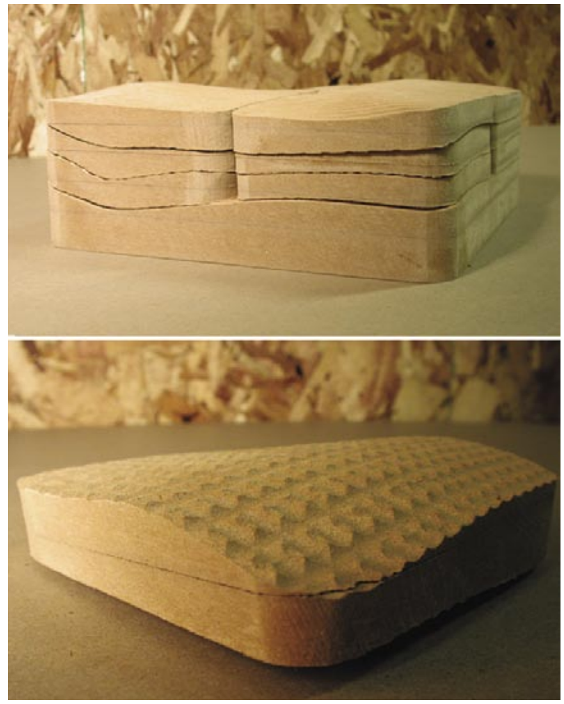

Figure 5. Texture / Tool Path Studies. Dennis Ng

4.2 Digitizing / 3D Tool Path Project

The second assignment began with the students making a quick 12"x12" surface from metal mesh. This was twisted or folded and then used to introduce the students to the Microscribe digitizer. This operation went through multiple iterations where the students refined their models through various techniques of capturing points on their surfaces. Once the students were satisfied with their digital surface, it was imported into MasterCam to begin 3D tool pathing (Fig. 7). This is always an exciting aspect of the semester, where students are free to explore the various parameters of tools, tool pathing geometry (parallel, flow surface, plunge, etc), speeds, and materials. The same surface geometry can result in various effects based on designers making decisions during the milling phase.

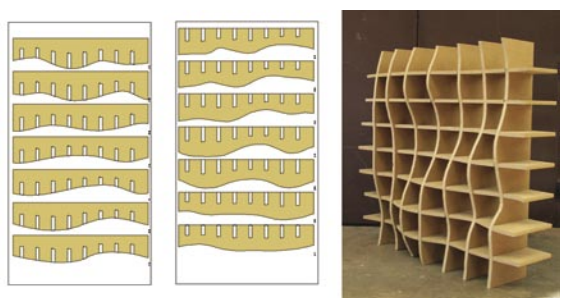

Figure 6. Cut Sheet and CSP Construction. Caroln Telgard, Shihjing Yen

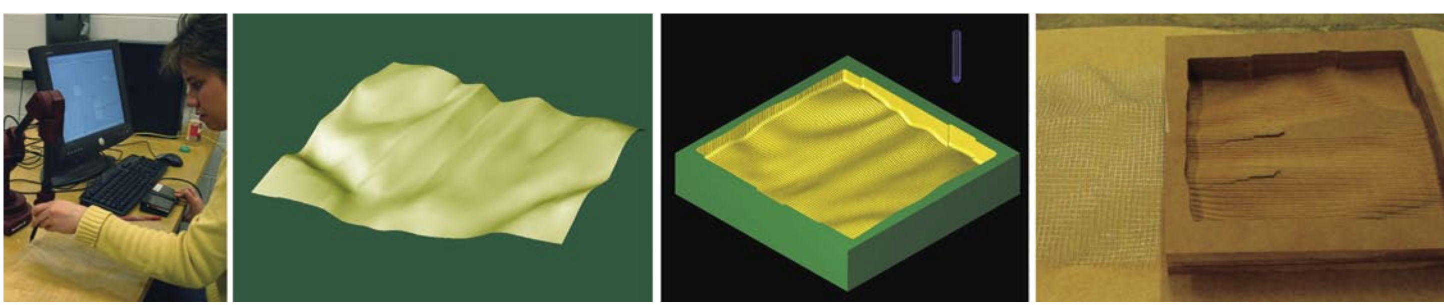

Figure 7. Workflow from Digitizing through to Final Milled Model. Caroln Telgard, Shih-Jing Yen

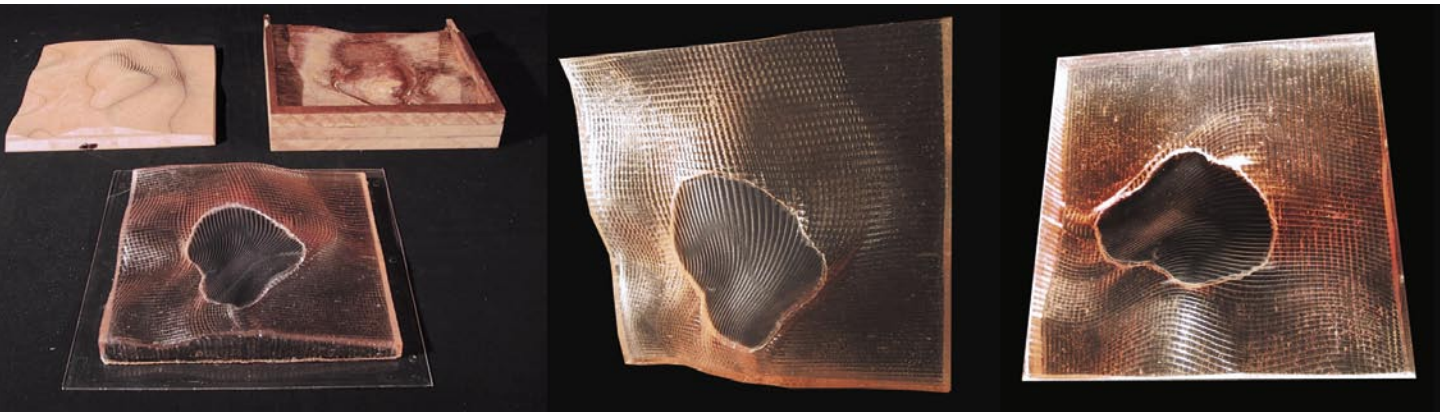

Figure 8. Vacuum Formed / Epoxy Final Project shown with molds Caroln Telgard, Shih-Jing Yen

4.3 Final Design Project

The final project gave the students much more freedom to propose the making of an object that could be made in multiples. The intention was to use the router to develop formwork that would make something else. Multiples needed to be made because the students were working in teams and each student would finish the course with something (the instructor could also keep one). An additional reason to propose the making of formwork is that the students had a tendency to treat anything made by the router as precious and final, never wanting to augment or adjust their 'final' piece. Making formwork would force a shift in their thinking between the positive and negative of component and mold, and require them to build more robustness into their digital and physical models.

One project that exceeded the expectations of the course was developed as a wall mounted light fixture. After a series of tests that explored thin concrete surfaces with vacuum formed molds, the vacuum formed surfaces took on more importance. The texture from the tool paths were used to catch and bounce light in combination with cast epoxy resin. The molds and final pieces are shown in Figure 8. The molds are used to develop varying thickness in the epoxy, varying the light transmission and color intensity. As is the case for much of the work from the seminar, the formal decisions are usually not explored as much as material choices. This emphasis holds true for this project where the actual surface geometry and form are not stressed as much as the effect of the epoxy depth and resulting light quality.

While the semester was successful for teaching the use of the CNC router, associated software, and broader ideas about assembly and making, the course felt quite limited in its ability to engage the other technologies of the FAB LAB. This class gave up the laser cutter and 3D printer to focus on making larger artifacts than the previous semester. The desire to scale up the ideas to engage more architectural implications continued to exert its pressures as thoughts focused on the coming semester.

Class 3 – Fall 2003

Having the summer to reflect on the successes and shortcomings of the previous class led to a major revision of the course content and structure. The summer also allowed for more time to develop expertise with the equipment. The major shift in the structure of the class spread design throughout the term and proposed a semester-long project. The course introduced all the equipment and tools but would capture them within the design of a 6' high by 4' wide exhibition wall. The students would again be required to work in teams, which was a major success from the previous term. The teamwork produced more work in a seminar setting and allowed the students to share ideas and knowledge outside the limits of the classroom. The other major advantage of teams is that more time was available per project on the equipment, which allows for more design iterations to be produced. The idea behind stretching design throughout the term would be to have the tools inform the design process. Unfortunately some of the students had an idea that their designs were fixed, and continually attempted to make the same object with different tools, never allowing the tool to participate in the making.

5.1 Course Structure / Schedule

The following list of activities was used to structure the overall design process. Many of the exercises were short, where one week would be used to develop a 3D print, while other exercises would run longer for the production of full-scale CSP prototypes.

- Physical models – each team starts with different materials (paper, clay, wood)
- Digitize a surface of the physical model
- Add second surface / refine model in Rhino
- 3D printing of digital model
- CSP – introduction to 2D tool path and CNC router
- Surface Mill – 3D surface tool path
- Unfold/Unroll/Flatten – Rhino and laser cutter
- Formwork: designed and fabricated for production

The student teams that engaged the structure of the semester developed their projects incrementally throughout the term. Figure 9 shows a milled surface from a two-week exercise. The project (throughout the semester) looked at permeable surfaces, so the surface is milled from both sides with intersections through the two surfaces that make clear openings. The students were both pushing a design idea while learning the tools and software. This team excelled within the structure of the course, where it seemed like they were picking up the tools without having to fully focus on the technical how-to considerations. The adjacent image shows their development of the unfolding / flattening exercise. They were required to take a surface from the previous exercise and flatten it for 2D cutting on the laser cutter. This group went one step further and used their milled surface as the formwork to assemble the 2D elements.

5.2 Final Design / Research Project

Once the technique-based exercises were completed, it was decided to open up the design projects to a bit more freedom. The designs were suffering because of the very strict structure to the course, so the students used the remaining two weeks to develop an aspect of their project that excited them the most. In some cases this included fabricating a portion of their wall; in other instances it meant creating a series of surface prototypes that explored texture. In each case they were asked to define their research interest and use the equipment to explore that interest. Figure 10 shows a series of surface screens developed using the laser cutter and sheet material and wood veneers. The project pushes the digital fabrication discussion into the benefits of rapid production and the feedback from the prototypes. The student team explored many variations of strategies for cutting, forming, and opening up a surface. This project again illustrates the focus of the seminar on the process and development of a prototypical system as opposed to a one-off perfect

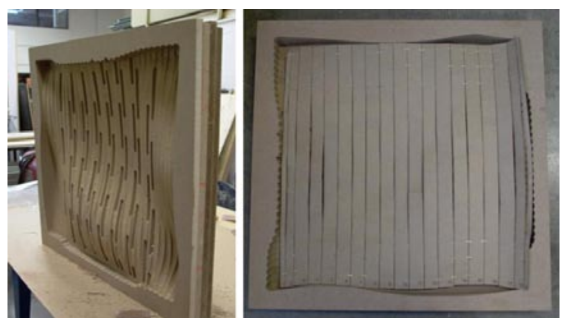

Figure 9. Milled surface model and flattened laser cut paper surface
Maria Walker, Brandon Andrezejczak, Julianna Lieu

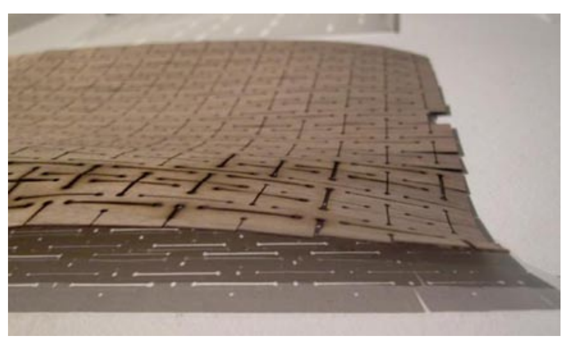

Figure 10. Detail from parametric / iterative studies
Maria Walker, Brandon Andrezejczak, Julianna Lieu

Figure 11. Screens developed on laser cutter for final research / design project.
Maria Walker, Brandon Andrezejczak, Julianna Lieu

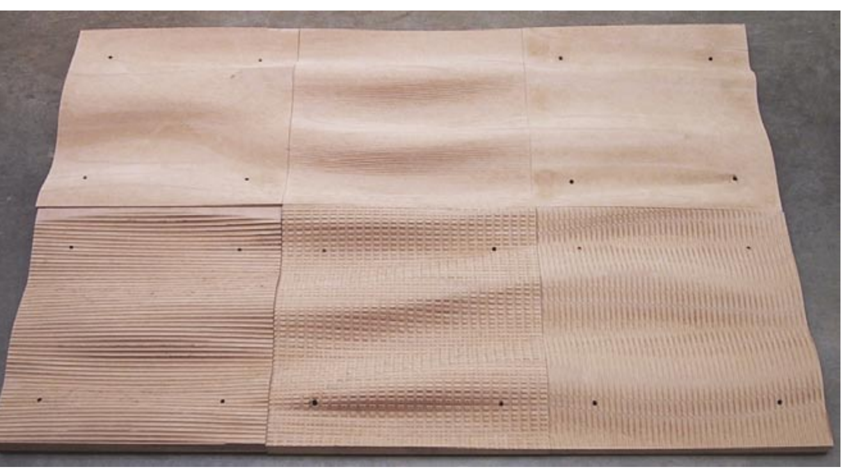

Figure 12. Each team was required to mill a surface that would fit next to another team's. Image shows all six surfaces arranged in order, each team using a different finish toolpath.

design. The work of the team explores geometry resulting from small-scale cutting without the influence of an explicit program, but instead, a simple screen wall. Figure 11 shows the final review and the body of work developed by this team in the last two weeks of the semester, again focused on the design process and the parameters they chose to explore, as opposed to the synthesis of all of their parts.

Class 4 – Spring 2004

The most recent changes to the course include compressing the exercises into the first half of the term, and allowing more time for a design/research phase. The exercises have become simpler and more directed toward efficiently presenting ideas or concepts, and to speed up the fluency and confidence of the students. Each exercise is scheduled for one week. The class during this term met on Tuesday and Thursday mornings, so the assignments would be given out on Thursday and due the following week. Thursday worked best with the hours of the FAB LAB, giving students the start of the week to work in the lab, with extended hours on Wednesday night. A hands-on demonstration would occur on Thursday when the assignment was handed out. This schedule left Tuesdays for lectures that included more general or broad discussions about the role of digital fabrication in architecture, topical presentations like *Flat Production Strategies*, or guest lectures to present relevant projects. Another change that grew out of more simple exercises was the removal of weekly pinups during class time. If the assignments were more directed and less design based, the work was simply handed in and class could continue, without having each team present their work.

6.1 Assignments/Schedule

The list of short exercises included the following tasks/skills which typically included both a hardware and a software component. The students were required to document their work with a PowerPoint journal of their process - the simplest way for them to document their work graphically. When the assignments were due, the students would hand in a CD, a process that also facilitates a thorough documentation of the work.

- **Digitized Physical Surface**: 12"x12" cloth, felt, chicken wire
- **Adding a Second Surface in Rhino**: make the surface a solid
- **3D Print**
- **CSP**: 2D CNC cutting of 3D printed model at 4'x4' scale
- **Surface Milling**: 3D tool pathing at 24"x24" (Figure 12)
- Unfolding and laser cutting of chipboard surface placed over CSP model

6.2 Final Design Projects

The work from this term included some of the strongest work to date from the digital fabrication classes. A range of interests, materials, techniques, and scales of investigation helped to round out many of the discussions and the overall experience.

Project A (Fig. 14) developed a series of screens/ panels that could be used as a cladding system. The panels included a series of interlocking *tongues* that could be used to bend the larger sheets into a specific form.

Project B (Fig. 15) began with an interest in the contouring effect of milling complex surfaces from a laminated material. This investigation moved in the direction of using complex shapes to mill surfaces, as a means to intensify the material/ lamination condition.

Project C (Fig. 16) explored the development of formwork to create *woven*/monolithic concrete surfaces. The formwork was seen as reusable, so it could adjust to a larger tiled pattern. This was also the most ambitious project related to scale in that it was seen as a larger structural system.

Project D (Fig.17) developed a series of milled formworks to support laminated chipboard surfaces. The project was to develop a chair prototype, but the exploration really centered on working with the material ripple, whether to incorporate it into the design, or to try and design it out.

Project E (Fig. 18) was called the *bubble wall*. It was a series of vacuum formed plastic panels that interlocked to make a room-scaled, translucent divider.

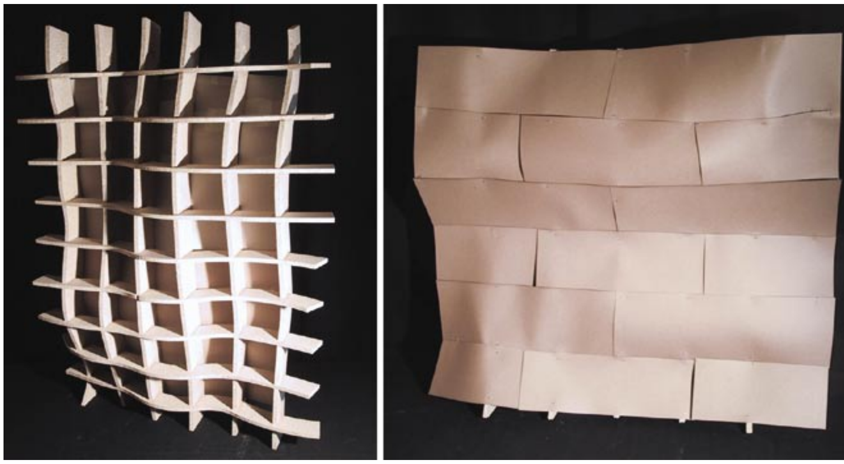

Figure 13. CSP Model (assignment 4) used as formwork for flattened laser cut paper surface (assignment 6). Image shown is one of six surfaces developed by the class

Figure 14. Interlocking, assembled panel system. Mike Brehmer, Chris Wilson

Figure 15. Milled complex plywood shapes. Jen Hinesman, Maggie Judge

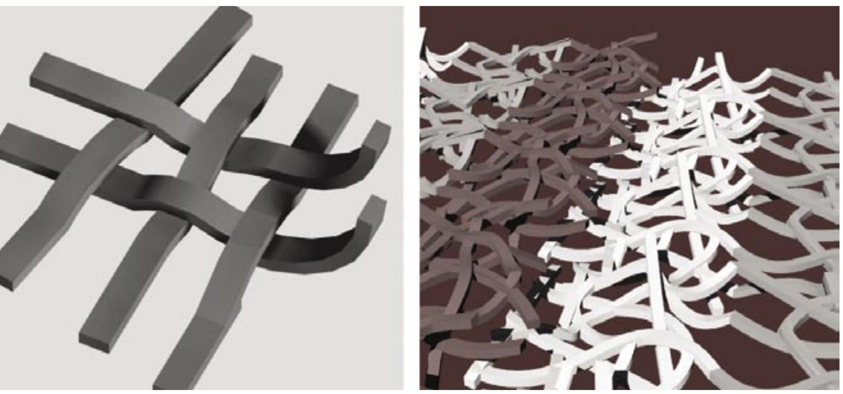

Figure 16. Formwork and renderings of the woven concrete structure. Jessie Allen-Young, Mark Lewis

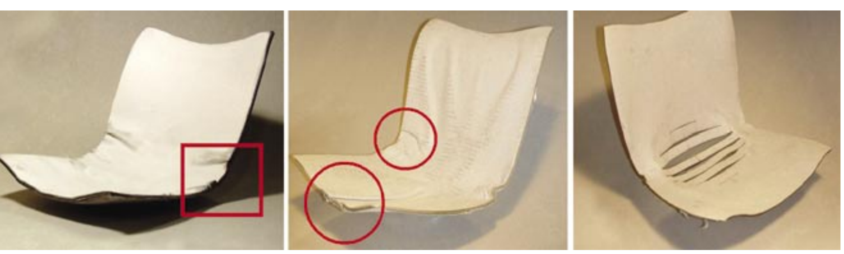

Figure 17. Three iterations for laminated chipboard chair shell. Alex Chu, Mark Davis

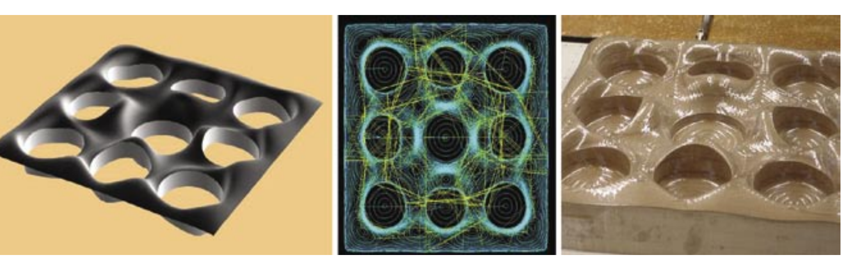

Figure 18. Digital model, tool path geometry, and mold for bubble wall. Sharad Sharma, Beth Jagnow, Emily Fischer

Conclusions

The course and ideas surrounding it have foregrounded material experimentation over form or geometry. The assumption is not that these aspects are unimportant, but that they are typically explored in a studio setting (where more time and credits are available), while the seminar can take on a detailed discussion of materiality without being tied to development of form and program. The work presented has been successful at coaxing form out of limited material studies and quick mock-ups. The belief is that students can take the knowledge gained from this course back to their studios and continue to synthesize the modes of working, the techniques, and the technology in their future work.

Having explored a series of teaching models for the education of digital fabrication, each model contains opportunities and limitations that affect the final products. The desire to teach the class as a design workshop has never been questioned because the students will only fully engage the equipment, and their skills and knowledge, to develop a project that they are passionate about. The downside to this method is that the students might focus on their designs too much and not expose themselves to all of the tools or techniques available during the seminar. The course has become a key course for introducing incoming students to the tools, with the intention that the students will continue to utilize the tools throughout their studio education.

Future Directions

The future for the Digital Fabrication course includes a second seminar that looks into larger scale forms of manufacturing from other industries and will be taught more as a research course, and be less hands-on. I will continue to scale up the projects to engage more building-sized proposals, and will explore more complex assemblies and the aggregation of parts. New software applications are being folded into the FAB LAB, such as parametric applications that will allow the students to rethink their design processes based on the production techniques and constraints. The course continues to develop a strong student pool and will continue to build skills and knowledge, which will be implemented throughout the design studio curriculum.

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