plyAbility: New Parametric Models for Laminate Composite Material Manufacturing in Architecture

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INTRODUCTION

Advances in composite materials and corresponding manufacturing techniques, specifically computer numerical controlled (CNC) machining, necessitate new models for the instruction of digital fabrication in architectural education. With the ease of design and manufacturing platform development brought about by the emerging cultures of visual programming (e.g. Grasshopper and Dynamo) and more intuitive, dynamically typed scripting languages (e.g. Python and DesignScript), the applicability of precision toolpathing within a freeform parametric modeling environment needs to be reevaluated. The current climate of image-driven form-making has inadequately addressed the opportunities of downstream manufacturing, proving shortsighted in preparing students for the realities of a changing architectural profession increasingly allied with fabricators by means of shared models and data sets.

To this end, a graduate seminar on the topic of computer-aided construction has recently been developed that includes new computational models. In this seminar, Master of Architecture students at the Pratt Institute's Graduate Architecture and Urban Design (GAUD) program create speculative architectural assemblies from glue-laminated composite stock. The assemblies range in function from shading devices to structural bays, and in scope from individual masonry units to entire cladding modules. Once the base geometries and their parameters are formalized with a sufficient understanding of downstream fabrication constraints, material performance can be achieved solely through the manipulations of manufacturing-based analytical thresholds within the parametric definitions. This novel design-for-manufacturing process acknowledges both creative and analytic thinking at both ends of a complex workflow and is repeatedly tested in the context of ongoing CNC-machined prototypes.

CURRENT APPROACH

There is a tendency in academia toward repetitive, cellular patterning in CNC-fabricated work rising out of formal tendencies in parametric design, such as the ease with which isoparametric subsurface routines and related surface parameter space hosting methods can be achieved, and the logistical reali-

Figure 1: CNC router machining a mold for a bent wood chair back design driven by a single, unarticulated NURBS surface.

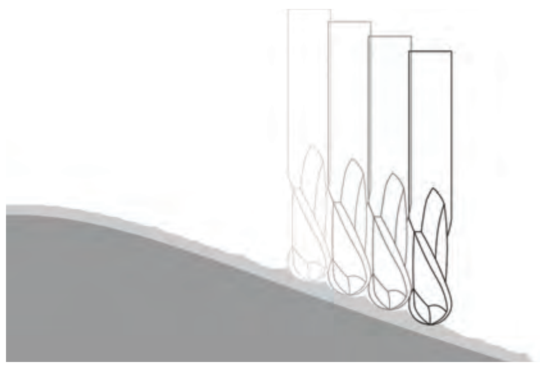


Figure 2: Diagram of end mill step over relative to stock artifact.

ties of construction, wherein design surfaces must be "broken down" or discretized into constructible units. What results from this may seem like simple patterning, but could perhaps be thought of as a hybrid of discretized (the repetitive patterning derived from parametric software) and monolithic (the volume of stock being machined) systems. The difficulty in describing these complex forms with toolpathing leads to manufacturing inefficiencies, particularly if the forms have not been designed with the means of manufacturing in mind.

Looking outside of architecture, academic programs in industrial design serve as good precedents for design-for-manufacturing curriculums, curriculums that emphasize the constraints and opportunities of downstream manufacturing as a primary design driver. However, the forms being machined in such programs are inherently different from those being pursued in architecture, tending toward monolithic forms, such as the body of a car (broken up into components like the hood and doors, but certainly not to the extent of a typical architectural panelization) or furniture. These unarticulated surfaces can be easily described by toolpathing, allowing manufacturing processes to be optimized (fig. 1). Furthermore, these objects are designed for mass

Figure 3: Isocurve-based stock artifact in Baltic birch plywood, revealing ply glue lines.

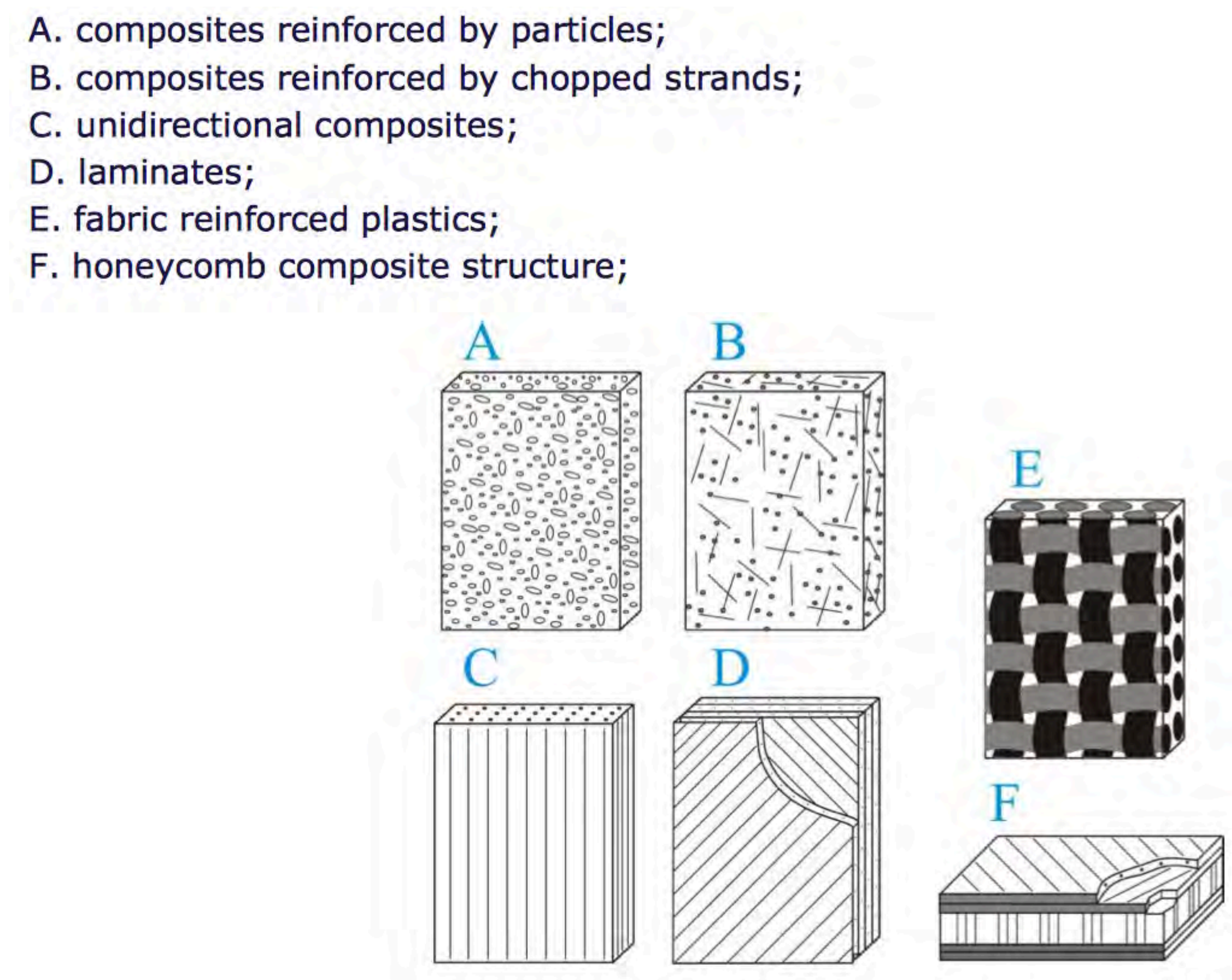


Figure 4: Common types of composites.

production (something that architecture generally is not), furthering efficiency and cost savings through repetitive production.

Therefore, it would seem that architecture is stuck between a particular aesthetic agenda and the unavoidable fact of its manufacturing inefficiency. This is where the classroom investigation typically ends—some small technological proficiency gained in the process, but lacking critical examination. For the "plyAbility" seminar, this is where the questions begin: How can we harness the unique capabilities of parametric software, not exclusively for formal generation, but also to define an explicit relationship between formal language and means of manufacture? How can such a workflow, in addition to potentially increasing manufacturing efficiency, push back on said formal approach; in other words, how might considering manufacturing limitations and opportunities impact aesthetic? And ultimately, how might we integrate architectural performance along the way?

Performance inherent to the material volume itself, when considered, has been something tacked on to the artifacts of the CNC machining process. While CNC artifacts, which are patterns of material volume intentionally left behind on a finished piece (fig. 2), could conceivably aid in phenomena like rainwater runoff directed by machined grooves, they're also liable to create additional problems. These include difficulty in cleaning and maintenance, animal perching and nesting, and thermal loss from increased surface area. Furthermore, the custom toolpathing that drives the CNC patterning motion, even if designed efficiently in the sense that it's inherent to the CAD model (such as extracted NURBS isocurves or subdivision surface face edge tessellations), is unlikely to be the most efficient and timely way to describe a surface for manufacture. In fact, it is only perceived as such due to its intentional coarseness, a timesaving strategy not intended to fully finish the part to a smooth condition. And there are other, more practical concerns: The pointing and cusping resulting from patterning is subject to

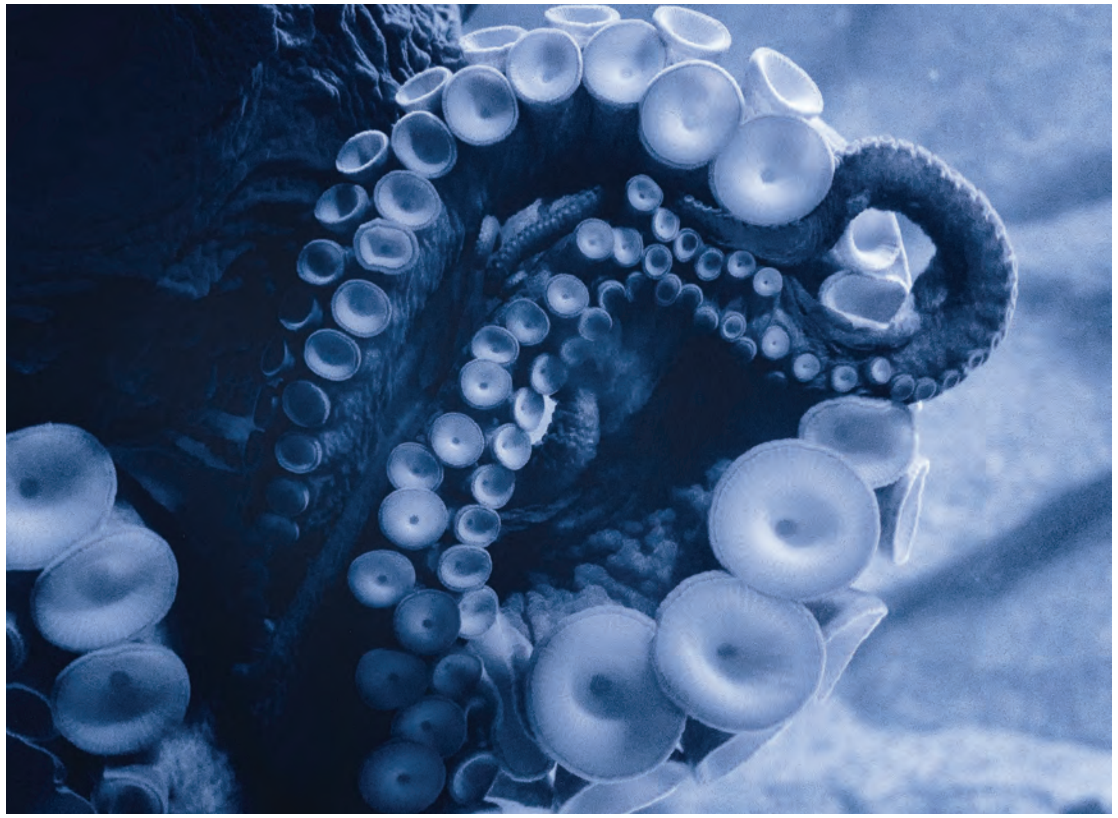


Figure 5: Suction cups of various sizes on an octopus's tentacle.

Figure 6: Gooseneck barnacles.

material damage, such as splintering and chipping; the finely articulated detail is nearly impossible to properly finish via sanding and coating (fig. 3); and the increased surface area makes secondary manufacturing processes, such as the release of casted forms from molds or vacuum-formed plastics from bucks, extremely difficult.

COMPOSITE MATERIALS

So what can be done differently? Composite materials may in fact be the additional factor necessary to extract performance from CNC-machined investigations. Composites are certainly not a new concept and can be found in contemporary manufacturing in products as diverse as fiber-reinforced sailcloth and the assembly of the iPhone, reliant more on adhesives and compression than traditional hardware.

Nor do composites have to be particularly complex (fig. 4). Though not typically discussed as such, plywood is a composite material, made up of thin layers of wood (birch, oak, maple, etc.) stacked with alternating grain direction and fused together with chemical adhesives and pressure. This yields performance (alternating grain direction creates two-way strength and reduces the chance of splintering and/or splitting the wood), aesthetics (the strata patterns of 3D forms machined in plywood are quite striking, particularly in contrast to the veneer), and practical economy (lower quality wood is layered in the interior with higher quality wood on the outside). In fact, the possibilities of composite materials are virtually limitless—any combination of two or more materials with matrix and reinforcement can be a composite.

For the purposes of the seminar, the composite material was to be a glue-lamination of any combination of:

1. Baltic birch plywood, for its aesthetic qualities as well as its relative rigidity.
2. Translucent white polycarbonate, for its light transmission quality as well as its ability to be bent with the assistance of a heating element.
3. High-durometer rubber, sufficiently rigid to CNC machine nicely, but pliable enough to allow for bending in the completed piece.

For even compression while the adhesives set, a vacuum bag is preferred to the inconsistent pressures offered by traditional board clamping. This change in approach is echoed in the words of Greg Lynn: "Assembly by chemical compounds doesn't involve the force of mechanical torque and pressure, instead it involves vacuums and cooking. There is a sea change going on in the world of construction and that is the shift from assemblage to fusion. In material terms this translates into a shift from mechanical to chemical attachments; more simply, things are built without bolts, screws, nails and pegs and are instead glued."[1] As Lynn mentions, no hardware is involved in making the laminated connections. This allows the entirety of the resultant composite stock to be CNC machined

Figure 7: Parts of a feather.

without concern that the cutters might collide with the fastening hardware, which can severely damage the tooling. The lack of an obvious connection detail also questions current paradigms in architectural tectonics. Turning again to Lynn: "Detail need not be the reduction or concentration of architectural design into a discrete moment. In an intricate network, there are not details per se. Detail is everywhere, ubiquitously distributed and continuously variegated in collaboration with formal and spatial effects."[2]

Compositing techniques such as lamination, thermoforming, vacuum forming, vacuum bags, pressing, and casting open up the ability for a designer to machine a single volume composed as strata of different materials. Detail is encapsulated in various intensities across the material volume while, tectonically speaking, present nowhere. These manifold details are ornamental as well as performative across multiple metrics. Tom Wiscombe defines this as "meta-seaming,"[3] a shifting articulation of surface not constrained to any one particular system (isocurves, structure, venation, etc.) but fluid between many. For example, a crease enhances a material's ability to span but may also serve as a channel for drainage. These systematic relationships need not be so obvious—the relationship between tattoos and musculature is both subtle and grotesque (in its proper sense) but remains undeniably captivating.

With composites, the traditional restriction of working within the static properties of a solitary material has given way to new investigations into the dynamic material properties of composite material volumes. At any given moment along matter being machined, there exists a sophisticated ecology of materials and methods. Fac-

Figure 8: Types of feathers.

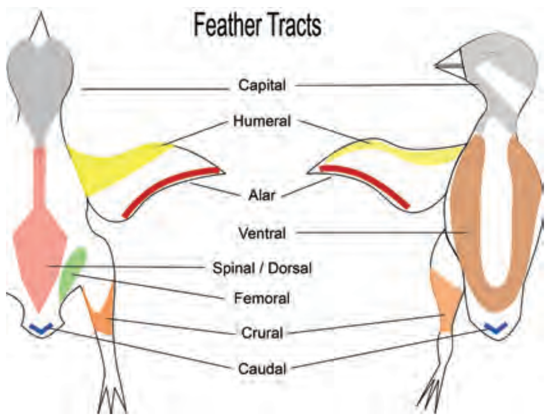


Figure 9: Feather tracts (pterylae) of a bird.

tors include cutting motion, cutter profile geometry, cutting depth, relative position of cutter tip to toolpath curve, material properties, material performance, and material aesthetic. Because the students' assemblies are machined from a laminate stock composed of a varying-property material stratum, they are capable of performing in both different manners (rigid flat vs. rigid fold vs. flexible bend/twist) and varying intensities (less to more folded, less to more flexible) at any given moment throughout the laminate, relative to the depth by which the stock is machined by CNC tooling. Parametric software like Grasshopper is the key to systematically controlling this depth and, by extension, the material's performance.

PARAMETRIC SYSTEM

In order to extract the maximum range of performance out of a single volume of composite stock, a design system needs to be established that privileges neither discrete components nor exclusive functions. This is where the formal and performative ambiguity of our discretized-monolithic hybrid systems may be of use. Stephen Kieran and James Timberlake recognize this when they write: "The product engineer needs to take the blinders off and focus on permutations of elements rather than on single parts and separate materials. A vital new responsibility of the product engineer is the development of integrated component assemblies—modules, chunks, grand blocks—that cut across all the separate categories of material and function."[4] While it is difficult to identify a constructed precedent that strictly adheres to what Kieran and Timberlake are suggesting, it's quite easy to look to nature, and more specifically to animal integumentary systems, to begin to address such "permutations" of material and function. In this vein, students begin by identifying biomorphic precedents for the unit-based fields of their parametric models. Examples of this include animal integumentary and follicular systems such as bird feathers or pangolin scales (fig. 5), as well as fields of organisms such as barnacles clustered on a rocky shore (fig. 6).

Thought is given to these systems in four parts, where the first is to consider how the physiological forms of these systems could perform in both a traditional architectural sense (gills as ventilation, scales as rain screen, etc.) and a speculative sense based in architectural performance (the ability for a building to "grow" something akin to layers of feathers for insulation and a moisture barrier, respectively). The varying intensities or gradation of performance across such natural systems lends itself to a certain ambiguity best captured by Tom Wiscombe when he suggests: "A much more interesting and contemporary idea is to embed technology so deeply into architectural surfaces that it cannot be unwound ... where it is not clear what features are doing the work and which are excess ... Such formations, as in all of nature, are never the best of all possible solutions but rather good enough."5 Nature helps us to remember that we should not fool ourselves into pursuing fully optimized solutions (if there even were such a thing), but rather pursue flexible systems that can be functional and efficient but not overwrought, excessive and exuberant but not wasteful, and beautiful as a performative solution rather than merely a satisfying image.

The second part is to examine how the individual units in the system (a single feather or follicle) respond to performance demands in both the aforementioned gradation of intensity as well as in threshold transformations. For example, a contour feather might undergo a gradated intensity change in length and width based on aerodynamic demands along the edge of a bird's wing. The basic topography of the feather, the vanes and the shaft (fig. 7), remain topologically the same, but their characteristics or parameters adjust along the bird's body based on performance demands, changing all the way from long, stiff flight feathers to short and fluffy insulating down feathers (fig. 8). This is in contrast to a threshold transformation, which represents a fundamental topological change, such as the transformation from

Figure 10: Scaled pangolin coiled for protection.

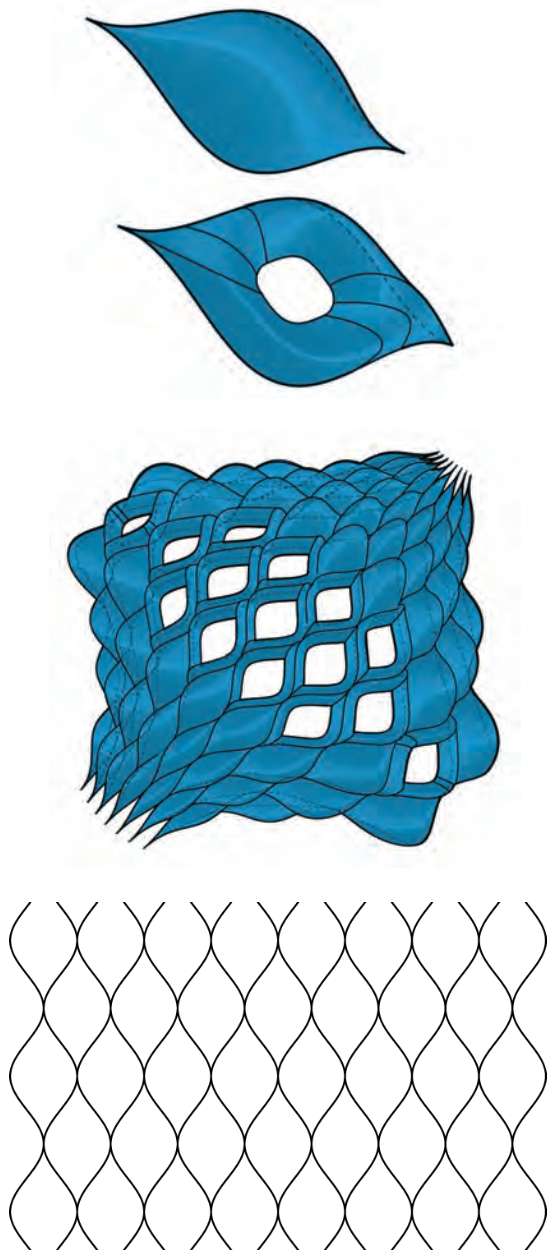


Figure 11: Parametric unit types, grid, and units structured within grid and hosted onto body with threshold-based transformation from one unit type to the other.

feathered to non-feathered integument like the beak or the feet, where blood circulation can approach the surface of the body for thermoregulation.[6]

The third part is to consider how unit distribution and density create a field. Again looking to the bird, feather follicles are clustered within tracts known as pterylae (fig. 9), whereas featherless areas between tracts, where the follicles become much less dense for purposes of grooming, thermoregulation, and ease of motion, are known as apteria.[7] "Apteria" in the seminar's architectural assemblies allow for ease of motion, and they can also help to reduce the complexity and machine time of assemblies through a strategic reduction in pattern articulation.

The fourth and final consideration is the shape of the host body in relation to the prior three considerations. Special attention must be given to how the system is impacted by the movement of the animal body host. While the end fabricated product is not necessarily kinetic, methods of animal motion relative to their integumentary systems may clue the students in to how the machined composite material could flex, bend, and twist most effectively. Examples of this include the coiled body of the pangolin relative to its scale overlay (fig. 10), and the inflation of a blowfish relative to its spike orientation.

Once students have a formal objective based on the above conditions, at least two unit types are parametrically modeled before being instantiated into a body-hosted grid, allowing for the generation of a field across which systematic gradation (within unit types) and threshold transformations (from one unit type to the other) may occur. Once the units are in place, the students analyze them for particular properties (surface area, volume, height, curvature, etc.) in order to get a sense of existing data ranges in the definition so they may set their thresholds accordingly.

The initial analysis is just a starting point, as these thresholds will eventually relate more directly to the CNC machining process. For example, if a CNC cutter is unable to fit within pockets under a certain diameter, units with apertures would automatically be transformed into more easily machined solid units (fig. 11). This avoids time-wasting formal idiosyncrasies, such as the tool only being able to partially machine out a pocket, leaving haphazard divots in the work piece. Using these thresholds, the designer now has an understanding of downstream manufacturing limitations and can control transformations relative to tool fit or reach, or even whether or not material will delaminate, warp, chip, splinter, burn, scuff, or otherwise fail given its geometric properties (tall, thin) relative to its material properties (directionality of lumber grain or thermoplastic extrusion). Design considerations, performance benchmarks, and manufacturing concerns are thus linked in both computational (design method) and tectonic (built product) fashion (fig. 12).

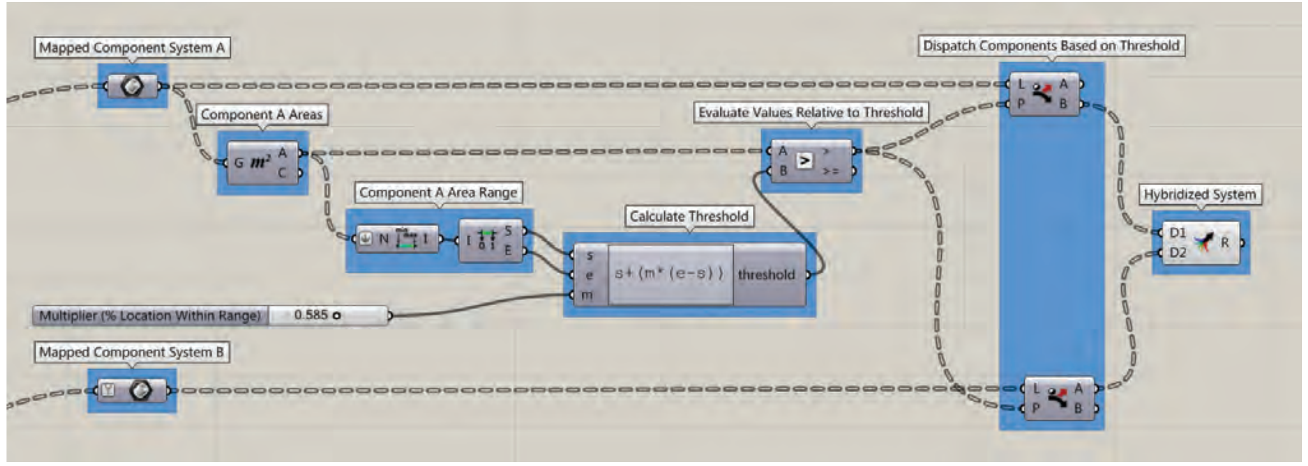


Figure 12: Grasshopper snippet describing the threshold-based transformation from one unit (or "component") system to another.

MACHINING PROCESS

There is a tendency among students to prototype the entire design straightaway; their desire for the completed image of the piece must be overcome so that they first concentrate on solving issues of material performance. Their objective should be to extract the maximum amount of knowledge possible each time they go to the CNC machine, establishing proof of concept prior to pursuing a complete machining of their design concept. If only a small portion of the prototype is expected to bend and the rest is rigid, the students are encouraged to limit their initial prototyping to that portion which is bent so that the bending performance of the material can be proven prior to spending a large amount of time prototyping the entire design, only for it to fail in key areas (fig. 13). This strategic approach, in which we are not simply pumping out physical recreations of a digital model but also learning how to investigate actual material performance, seems obvious, but it is perhaps the single most important aspect of the course—and one of the most difficult student habits to overcome.

When it comes time to glue up the materials, work must be done quickly so that the adhesives do not set prior to the material being placed in the vacuum bag. Wood-to-wood mating is easily done with wood glue, typically Titebond I, or Titebond II if increased set time is required for larger surface areas. The rubber and the polycarbonate, however, lack surface friction and are difficult to get to adhere. Therefore, it's recommended that the mating sides of both of these materials are scored with a knife in a diamond pattern and, in the case of the polycarbonate, additionally sanded with a high-grit sandpaper to increase surface area for adhesive grip. For wood-to-plastic adhesion, any two-part epoxy, such as Gorilla Glue, works quite well. However, cured epoxy is brittle and rigid, which does not work particularly well for the rubber, which is a much more malleable material than the others and requires a more flexible adhesive. Polyurethane construction adhesives, such as Liquid Nails, were tested to this end, but the glue line did not compress to the desired consistent hairline depth. Ultimately it was a general-use adhesive by Liquid Nails that proved to perform the best, both in the glue-up process and later when under the duress of CNC machining—the aptly named "Perfect Glue."

After the materials are laid up, the composite stock is wrapped in butcher paper (to prevent it from adhering itself to the inside of the vacuum bag) and placed within the bag on a grooved palette (fig. 14). This palette encourages air flow underneath the stock, while a plastic mesh drape assists air flow over top of the stock. The part is stabilized within the bag by creasing the bag at the corners of the stock with palms placed firmly against each side of the stock corners. This keeps the material layers from shifting while the glue is wet and has the added advantage of preventing the bag from dimpling over the top of the stock corners (it's also recommended to rasp the corners prior to glue-up). While this process can be quite precise when performed properly, it's recommended to leave a quarter to a half-inch tolerance between the dimensional extents of the part being machined and the dimensions of the stock.

In addition to the physical prototype, the deliverables for the course include diagrams illustrating the single parametric unit and its critical parameters, heat maps indicating the intensities of various parameter gradations across the field, Boolean diagrams of threshold changes, renderings or drawings of the field instantiated onto a host body or surface, and anything else required to explain the process. Perhaps the most critical drawing is when the students export the resultant stock from the CAM package, which is a different geometry than the initial surface input, and contour it relative to the locations of their glue lines (fig. 15). This verifies that the cutter is machining to the depth of stock required to release particular material strata in order to achieve the desired performance.

Figure 13: Prototype testing for possible bend angles.

SEMINAR CASE STUDIES

Students Ulrika Lindell and Erik Davin Nevala-Lee began their project by studying the intricate Radiolarian mineral skeleton (fig. 16), known for its efficient lightweight structure. An alternating cellular grid was instantiated across multiple surface strips (fig. 17), with individual units becoming more or less squeezed across the length of the strips by multiplying the deconstructed V domains of the isoparametric subsurfaces by the values of a willfully manipulated Bezier graph (fig. 18).

From this study they devised a concept for an architectural assembly in which cross-bracing elements could be constructed from two bendable strips of composite stock. Toward their extremities, the strips would be thick and rigid and the light apertures would be at their largest (fig. 19). Toward their midsections, the strips would taper to a thin layer of rubber and the apertures would flip from void to solid, providing a series of rigid islands to help structure the bend (fig. 20). A machined slit in the piece would allow for a portion of it to peel off and form the basis of a connection with a second strip, thus forming the cross-bracing member.

The strips needed to be machined on both sides, either via a flip-mill or by machining the two sides separately and joining them after the machining process. This meant that in order to machine a single cross-bracing element, there were a total of four CNC setups, consuming a massive amount of machine time despite the use of efficient toolpathing strategies. Machine time was the largest limitation of the projects from the first semester of the course, so in the second course, the concept of apteria would be reintroduced as a means of strategically reducing articulation in order to reduce machine time, with the goal that more substantial prototypes could be produced. Any articulation that appeared to be purely ornamental with no conceivable function would be eschewed for more straightforward manufacturing.

One project that was particularly successful in this respect was a cell phone privacy booth design by the student team of Linnéa Moore, Andrew Sutton, and Olivia Vien. The students were interested in how the instantiated units might splay as the rubber bent, much in the way scales might adjust as the pangolin rolls into a protective ball, or the manner in which the blowfish's spikes move from parallel to perpendicular to the fish's body upon inflation (fig. 21). In order to achieve splaying and assist with overall bending, a small cutter was used to trace the leading edges of the units to partially release them from the stock. This method of tracing islands of solid material laminated to the rubber, when used for scoring (partial depth piercing) rather than cutting, was also useful in reducing the tendency to delaminate via the shear forces occurring at the glue line between the rubber and the wood or plastic islands (fig. 22).

Figure 14: Students working to stabilize material within a vacuum bag.

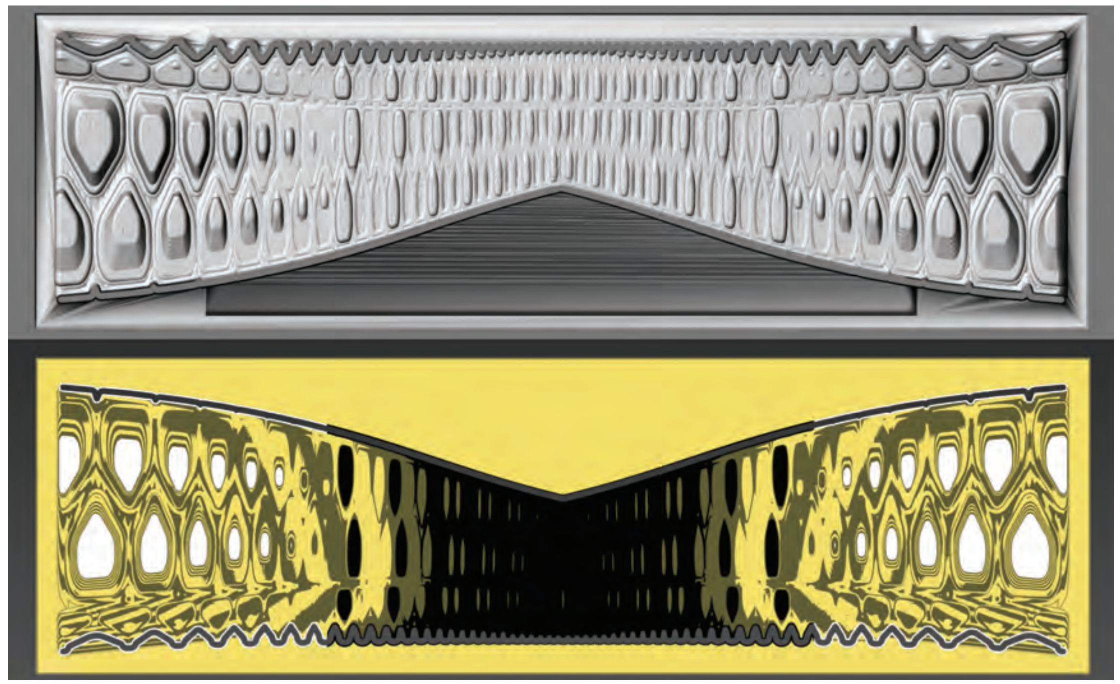


Figure 15: Contour drawing indicating glue line and material strata locations in exported RhinoCAM stock result.

Figure 16: Radiolarian mineral skeleton.

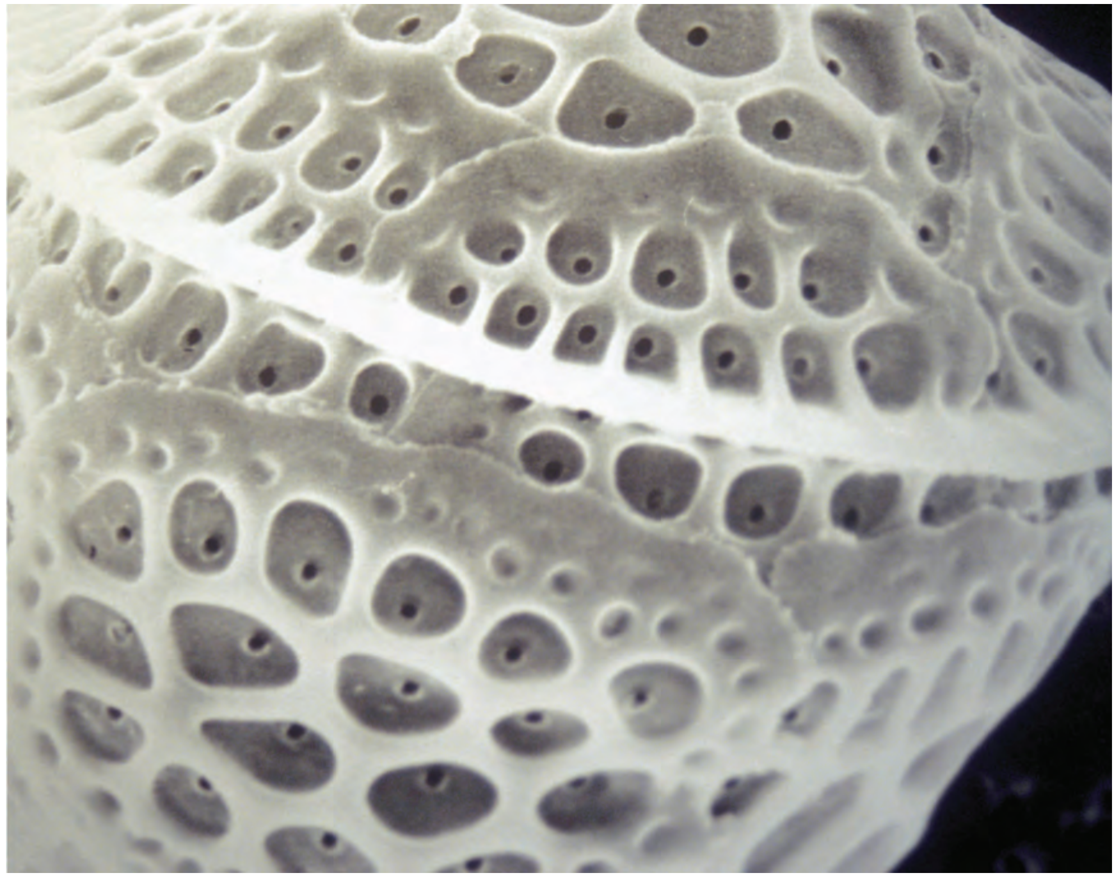
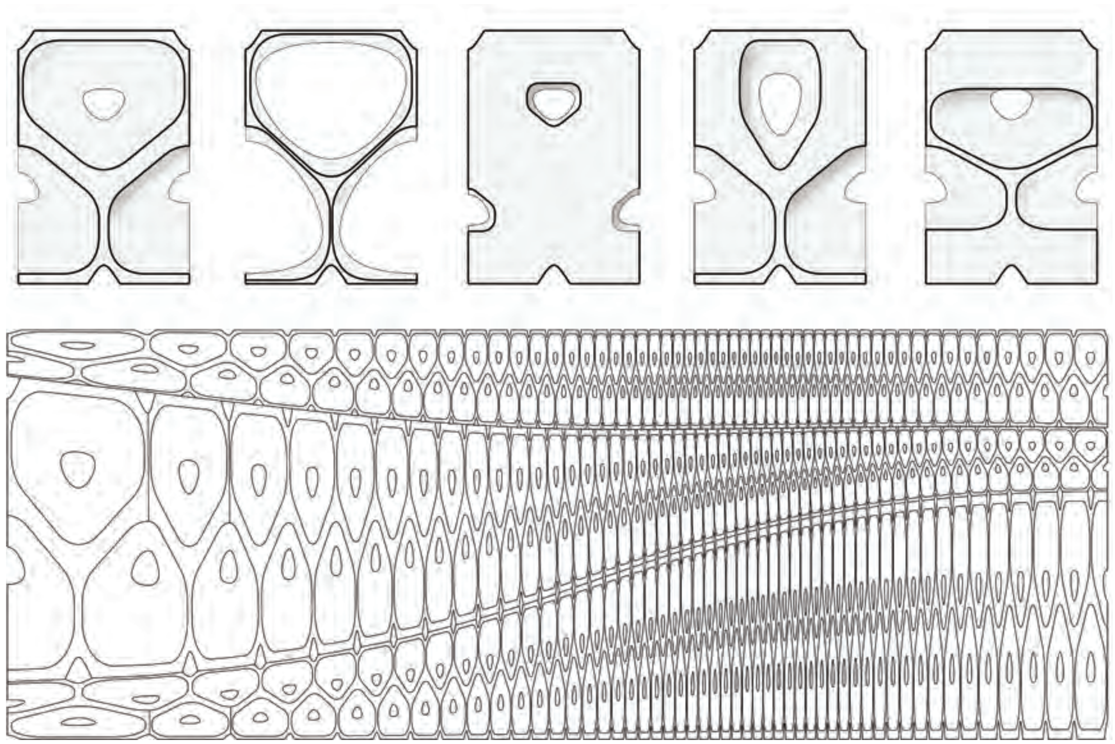


Figure 17: Initial parametric study.



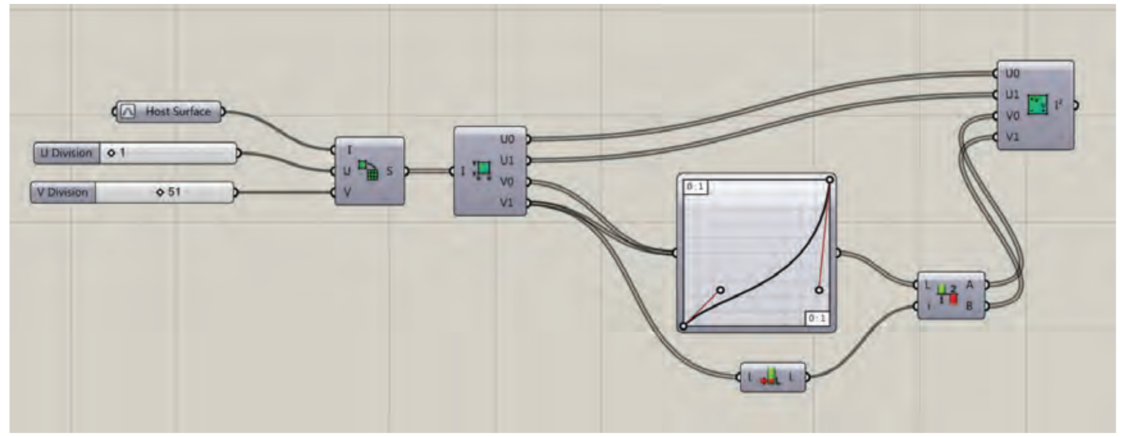


Figure 18: Grasshopper snippet showing Bezier-based isoparametric subsurface V domain gradation.

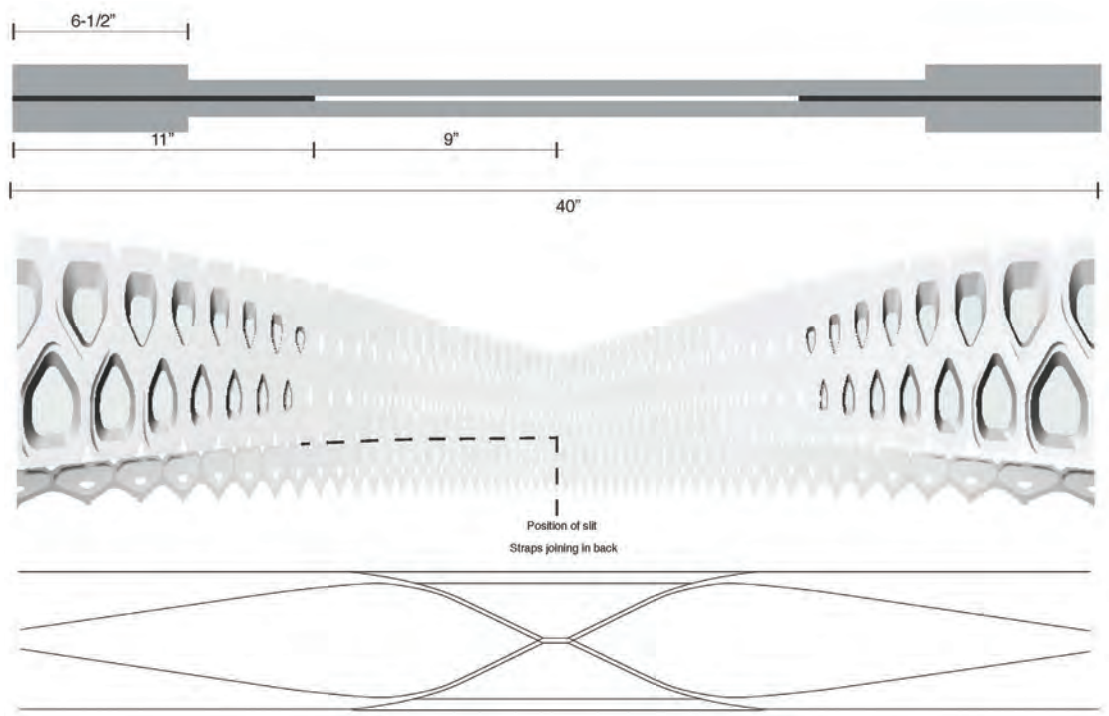


Figure 19: Composite material lay-up, machined stock result, and elevation of cross-bracing assembly.

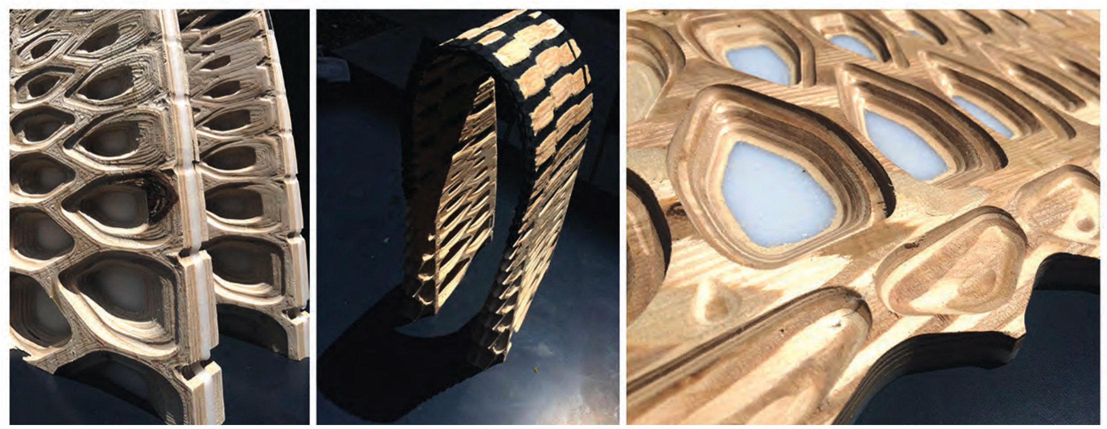


Figure 20: Machined composite stock strip.

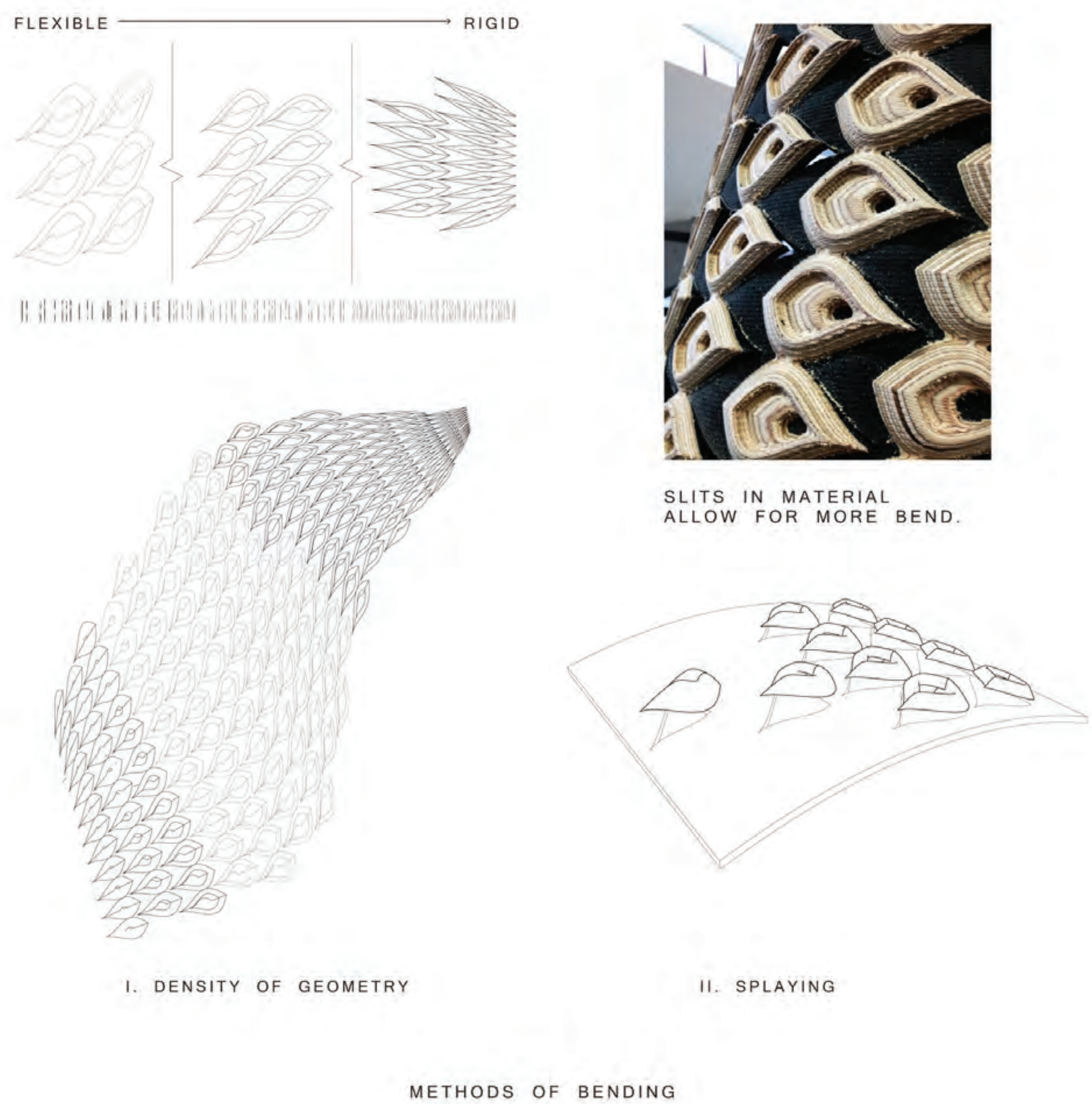


Figure 21: Unit density and splaying strategy.

Instead of articulating the entire booth, the students limited articulation to those areas that required cutting to release bending and/or light-filtering performance, and then faded into unarticulated, broad surfaces which served more of a structural or space-defining function. In this manner, they were able to produce a more substantial assembly than had previously been possible (fig. 23).

SUCCESSES AND LIMITATIONS

Successful projects were judged by a high output to machine time ratio, indicative of both efficient toolpathing practices and strategic distribution of articulation across the stock. Further efficiencies were gained when analytic thresholds were dialed in correctly such that no geometries existed which could not be fully reached and machined by tooling.

Material performance was another factor of success. Completed assemblies that were able to flex, bend, and twist along areas strategically milled to the depth of the rubber, and/or transmit light or be rigidly folded via a heating element along areas strategically milled to the depth of the polycarbonate are good examples of this. There has to be some restraint here—if too much of the rubber is released, the assemblies lack structural integrity.

Many of the limitations along the way relate to the materials themselves. As mentioned previously, the smooth surfaces of the plastic and rubber make them difficult to bond with other materials. This also hampers the stock's ability to be vacuum-held on the CNC router's spoil board, and in many cases, students had to resort to mechanically fastening their stock to the router bed. This reduces the range of material that can be machined safe from fastener collision. To an extent, vacuum holding could be assisted with double-stick tape and larger stock footprints, but any stock motion during a machining process is troubling indeed.

The flexibility of the rubber is also a challenge. Materials need to stay rigid while they are being cut, but rubber tends to flex under the cutter. If the cutter is rubbing against material rather than removing it, the increased friction leads to tool overheating, which in turn hampers its ability to cut cleanly, so the whole thing becomes an unfortunate feedback loop (not to mention the acrid smell). This can be overcome by switching to a specialized down cutter when machining the rubber, and limiting any toolpathing of the rubber to simple two-dimensional cuts rather than fully three-dimensional surface machining; however, specialized tools mean increased budget and setup time, so compromises are often made. The flexibility of the rubber also means that composites which have an interior rubber ply exposed by machining both sides of the composite stock cannot be flip-milled (machined in two positions), as the stock sags in those areas where it is not supported by other material plies. Therefore, assemblies with rubber cores are typically milled in two parts and joined after the machining so that the rubber strata can rest on the spoil board while machining.

Overall, it is difficult to obtain the kind of unfettered access to the lab that allows for sufficient fabrication iteration, meaning that students often have to take risks or test multiple aspects of their materials at once. However, as machine time is very expensive in the industry, this limitation likely mimics "real world" manufacturing constraints, and the ruthless time management efficiency it prompts in the students has educational value.

Future work in this area will look to materials and assemblies more suited to exterior construction and weather permeability, and will attempt to validate performance metrics with physical testing. Validation data would be integrated back into the computational model, effectively "teaching" it to simulate performance more accurately. Furthermore, this course would benefit from being removed from the seminar environment, which can focus too much on technological skills as a means to an end in themselves. Instead, the content could be situated within the context of the studio environment, where it could be critically applied to, and more directly driven by, issues of the constructed environment.

END NOTES

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2. Greg Lynn, "Intricacy," in *Intricacy*, ed. Greg Lynn, et al. (Philadelphia: ICA Philadelphia, 2003).

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Figure 22: Glue lamination and CNC machining process.

Figure 23: CNC machined stock and resulting assembly of cell phone booth.

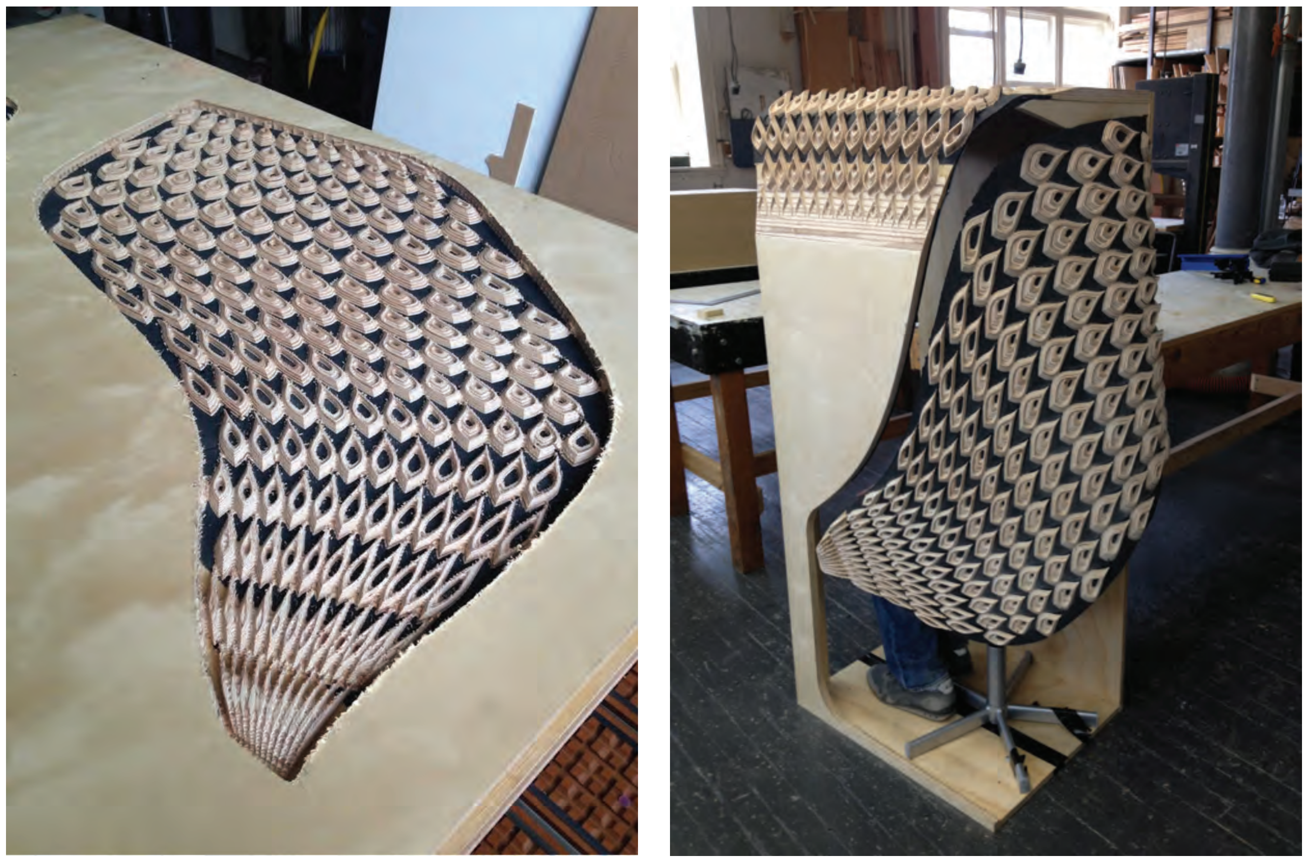

IMAGE CREDITS

Images by author unless otherwise specified below.

Title Image: Faroughi, Shahab and Sun Kim. plyAbility student work. Photograph. 2014.

Figure 3: Jordan, Trevor, Austin Weller, YoonJin Kim, and Brian Turcza. plyAbility student work. Photograph. 2012.

Figure 4: Kokcharov, Igor. "Classification of composites from book Structural Integrity Analysis." Diagram. 2010. Via Wikimedia Commons: Kokcharov, CC BY-SA 4.0, https://commons.wikimedia.org/wiki/File:Composites_Materials.png

Figure 5: Kilby, Eric. "Blue Tentacles." Photograph. 2015. Via Flickr: ekilby, CC BY-SA 2.0, https://www.flickr.com/photos/8749778@N06/17569669855

Figure 6: Pearsall, Peter/U.S. Fish and Wildlife Service. "Gooseneck barnacles (Pollicipes polymerus)." Photograph. 2015. Via Flickr: usfwspacific, CC BY 2.0, https://commons.wikimedia.org/wiki/File:Pollicipes_polymerus_(23812068786).jpg

Figure 7: "Parts of a feather." Diagram. 2006. Via Wikimedia Commons: Icea, Copyrighted free use, https://commons.wikimedia.org/wiki/File:Parts_of_feather_modified.jpg

Figure 8: "Types of feathers." Diagram. 2012. Via Wikimedia Commons: Anazxibia, CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Types_of_feathers.jpg

Figure 9: Shyamal, L. "Pterylosis or feather tracts of a bird." Diagram. 2007. Via Wikimedia Commons: Shyamal, CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Pterylae.svg

Figure 10: Wildlife Alliance. "Curled Pangolin." Photograph. 2010. Via Flickr: wildlifealliance, CC BY-SA 2.0, https://www.flickr.com/photos/wildlifealliance/9449651301

Figure 13: Sutton, Andrew. plyAbility student work. Photographs. 2014.

Figures 15-20: Lindell, Ulrika and Erik Davin Nevala-Lee. plyAbility student work. Photographs and Drawings. 2014.

Figures 21-23: Moore, Linnéa, Andrew Sutton, and Olivia Vien. plyAbility student work. Photographs and Drawings. 2014.

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