Research-Build: Biomaterial Invention through Design Studio Pedagogy

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Academic design-build work provides an incredible opportunity for students to experience hands-on construction and see their work jump from the drawing board to reality. However, the inherent complexity and compressed timelines of these projects typically limit opportunities for material experimentation and invention, often biasing detailing and construction with proven conventional building systems for timely delivery of a project based on client and programmatic needs. At the same time, architectural innovation in academic scholarship is increasingly confronting technological and material needs necessitated by the climate crisis. This paper presents a research-build model via a studio that shifts the emphasis from program and client to material invention and experimental fabrication. The studio began with a series of physical fabrication exercises and material explorations, culminating in the design and construction of an experimental biomaterial pavilion that pilots three building systems: a double-layered woven bamboo wall with CNC-milled joinery and a shade canopy of bent greenwood lumber strips, both sourced from campus landscaping waste, as well as a façade of custom paper pulp shingles made with campus paper and wood waste. Salvaging material from the local environment and waste streams serves to improve equity and access to material — teaching students that good design does not necessarily demand expensive materials — and as an environmental strategy, asking students to consider the lifecycle and impacts of the materials with which they are working, and to design for end of life decommissioning.

INTRODUCTION

As the scale and immediacy of the climate crisis becomes ever more apparent, so does the need to develop sustainable building systems that radically rethink the materials with which the built environment is constructed. The curriculum of this design-build studio course combines established models of design-build pedagogy and material research methods such that students can develop hands-on fabrication projects which simultaneously advance novel material research. Students develop and deploy prototypical proof of concept installations which demonstrate new material possibilities and capture the public imagination.

The studio pedagogy and project presented in this paper is taught in the third year of a Bachelor of Science in Architecture program, in the Design Thinking Track. Because these students opt out of the Pre-Professional Track and may not be pursuing professional graduate studies in architecture, there is curricular leeway for alternate areas of emphasis. The studio empowers students to pilot carbon-sequestering construction techniques by working with local material streams to develop novel biomaterial systems, fabrication strategies, and a full-scale inhabitable space. Students work with a real-world client (university program leadership) to select their own site within 3,000+ acres on a nearby university-owned property. The client's priorities differed from traditional architectural clients, as they aimed not to achieve a specific programmatic goal, but to enable student research activities.

The studio pedagogy leads students through an introductory project to equip them with analog and digital fabrication and modeling skills focusing on emergent material properties. This is followed by a sequence of prompts in which students join together into progressively larger teams while focusing on materials and processes in which they are most interested. Finally, several material systems are assembled into a singular pavilion fabricated collectively by the class. The biomaterial systems developed include a structural double-layered woven bamboo wall with CNC-milled joinery, a façade of custom paper pulp shingles made with waste from the architecture school's plotting room and wood shop, and a shade canopy of bent greenwood lumber strips. The various systems required students to pioneer, test, and deploy novel strategies using particular material processes and digital modeling, simulation, and fabrication methods.

The focus on a temporary pavilion as opposed to a permanent structure releases the work from many of the pressures and liabilities that are often primary drivers in design-build pedagogy. By allowing the project to fail and emphasizing end of life decommissioning, the studio framing encourages students to

Figure 1. Results of Project I, conducted over the first five weeks of the semester by students working individually.

embrace experimentation and to test ideas at full-scale that would typically be deemed too risky in their durability or performance. Engaging with local and atypical material streams and designing for decommissioning encourages the interrogation of conventional material systems. This paper presents the methods of the pedagogical sequence, the specifics of the various material systems developed, and the results of and reflection on the process.

BACKGROUND

The methods deployed in this course are situated between established design-build pedagogies and academic material research operations, both typically housed within the academy and involving students in the production of innovative work at full scale.

A sampling of exemplary traditional design-build programs include Auburn University's Rural Studio, the Colorado Building Workshop, the University of Utah's DesignBuildBLUFF, Portland State University's Diversion Design-Build Studio and the Yale Building Project.[1] Such programs offer incredible opportunities for students to gain hands-on experience in construction and project delivery. Due to the various demands of real-world projects and clients, the pedagogy is often split over several semesters or courses, with teaching teams adhering to strict schedules to deliver projects on time.[2] The traditional vehicle of these programs are permanent projects, which present their own unique challenges and liabilities, focusing the work around the thoughtful deployment of proven building products and techniques rather than riskier experiments in material invention.[3]

There is also a long history of design-build programs being run outside the academy, often drawing students seeking practical learning experience over the summer. These include the Ghost Architectural Laboratory by MacKay-Lyons Sweetapple Architects, the Island|Mountain Design Assembly by McLeod Kredell Architects (www.islanddesignassembly.squarespace.com), and Studio North by Moskow Linn Architects (www.moskowlinn.com/studio-north).[4] These programs tend toward the permanent project model, and with it, typically rely on the expedient deployment of traditional material systems, ranging in scale from chicken coops to cabins. They are usually conducted on a particularly fast timeline, sometimes only a week or two from start to finish, meaning that material palettes are sometimes predetermined to avoid the challenges and delays of material sourcing and acquisition.

Figure 2. Results of Project II, in which students work in teams of two to design and fabricate prototypical biomaterial assemblies.

Exemplary programs focused on intensive material research include the Architectural Association's Hooke Park, University of Stuttgart's Institute for Computational Design and Construction, and ETH Zürich's Gramazio Kohler Research. These programs are often structured around more specialized Masters or PhD graduate programs, and often draw from significant support in the form of major research grants or funding from industry partnerships. Hooke Park's projects foreground student learning and experience, while simultaneously producing advanced research that results in refereed conferences, journals, and awards programs, while the Stuttgart and ETH programs tend to be longer in timeline and research-centered, with a greater number of PhD students working for longer periods of time on specific technologies and research foci.

Some traditional design-build studios have worked to integrate research methods, but remain constrained by pragmatic limitations of project delivery such as client needs, budget, and timeline.[5,6] The pedagogical and practical goals of these studios is subject to varying opinions — is the goal to teach practical construction methods, to serve a client and/or community, or to build a body of research within an academic context?[7] The studio presented in this paper seeks a middle ground between traditional academic design-build project delivery and advanced material research programs. Student learning, authorship and material innovation is foregrounded, but with a minimal budget (just over $900 for the entire course) and a fast timeline of just one semester. Students work with a real-world site and client, but the temporary nature of the final installation and lack of programmatic requirements allow for a level of experimentation and risk that would be irresponsible for a permanent building project.

PEDAGOGICAL SEQUENCE

The semester is structured in three parts: (1) an introductory fabrication and computation exercise, (2) a material research and prototyping project, and (3) the development and construction of an architectural demonstration pavilion.

PEDAGOGICAL SEQUENCE: PROJECT I

In the first project, students spend five weeks working individually to build both technical and conceptual skills using analog and digital methods. Students are provided with a log fragment and asked to first analyze it through digital modeling (one week) then modify it through a set of operations using woodshop tools (one week). Students then 3D scan their material and analyze it through Grasshopper (one week), before performing a second set of physical operations using digital fabrication tools (two weeks).

The project is aimed at developing a conceptual and practical framework for understanding and responding to specific material qualities or irregularities. The output is a sculptural object devoid of program or function, meaning that focus can instead be placed on material exploration and conveying a specific position relative to identified material qualities (Figure 1). A series of drawings produced in each of the four parts supplement the articulation of this position. The project also serves to equip students with an adequate level of skills in woodworking, digital fabrication, 3D modeling, and parametric modeling. This project sequence is presented in detail in the paper "Learning from Logs: Introductory Analog and Digital Pedagogy Addressing Material Irregularity".[8]

PEDAGOGICAL SEQUENCE: PROJECT II

In the second project, students work in teams of two and are tasked with developing a material system primarily using a biomaterial of their choosing. This system is to be used to develop a full-scale prototypical element in one of three form factors: linear (column or beam-like), planar (wall, floor, or roof-like), or volumetric (dealing with mass or poché).

Students are encouraged to be highly exploratory throughout this project by identifying local biomaterial sources, acquiring these materials, and experimenting to discover latent potentials or fabrication possibilities. A large portion of the effort is focused on developing ways of aggregating or assembling natural materials or fibers into one of the three assigned form factors. The focus on locally-sourced biomaterials — which are acquired largely for free through harvesting or salvaging — aims to focus on ideals of circular construction but also to level the playing field and reduce or eliminate student out-of-pocket material expenses,promoting an equitable and inclusive learning environment.

Students explore a wide array of materials, allowing the class as a whole to quickly gain exposure to a variety of material possibilities. The resulting elements and materials include: joined bamboo assemblies and natural timber-formed cob columns (linear), woven branch structures, paper-like layered surfaces, and woodchip-based layered assemblies with natural starch adhesives (planar), and grass-based bioplastics and 3D printed raw earth (volumetric) (Figure 2).

As in Project I, drawings are used to explain the processes and ideas present in the work. Specifically, the system diagram becomes a critical drawing articulating the workflow and negotiation of authorship between material agency, computational and fabrication methods, and design intent.[9]

Following a studio review and discussion with invited critics, students participate in a course wide discussion to identify the benefits and challenges associated with each method. This analysis is used to determine the most promising strategies to take forward into the final project.

PEDAGOGICAL SEQUENCE: PROJECT III

In the third project, the entire class of fourteen students works together to further refine the identified material systems, synthesize these into the design of a full-scale inhabitable pavilion for a specific site, and realize this project. The project is developed collaboratively over the course of the final six weeks of the semester. The site is Morven Farm, a university-owned property near the main campus. The development and results of Project III are presented and discussed in the following sections.

MATERIAL INVENTION

Three material innovations are selected by the class for development and are combined into the final research-build project: a double-layered woven bamboo wall, a paper pulp shingle façade, and a bent greenwood canopy (Figure 3).

Students are encouraged to source their biomaterials locally, with a focus on waste or non-traditional material streams, and to design for end-of-life decommissioning. This fosters a consideration of the entire lifecycle of the materials and a desire to produce aggregation and assembly strategies that can be accomplished exclusively with biodegradable materials.

MATERIAL INVENTION: BAMBOO WALL

The double-layered woven bamboo wall serves as a critical system, providing both the overall form and structure for the project. Students work in Rhinoceros and Grasshopper to iterate form and assembly strategies, selecting a simple form with a varying cross section: an asymmetrical inverted cone nested within a vertical cylinder.

Grasshopper is used to analyze the structure and generate joints. This joinery serves several purposes: it connects the inner and outer woven surfaces, it provides shear resistance within the wall, it delineates openings for a door and two windows, and it determines the overall form and thickness of the wall. The joinery is strategically deployed to eliminate the need for formwork — the walls are self-forming during assembly.

The door and window elements defined by the joinery are designed to situate the round pavilion relative to specific view corridors. The pavilion is sited near the top of a grassy hill visible from the rural property's architectural center, a historic house. A view back to this house down a hill and through a gap in the trees is framed by a thin vertical window. A second thin window is oriented horizontally on axis with the door, framing a view to distant mountains on the horizon.

To build the wall structure, students source material from a large bamboo grove adjacent to the project site and split the poles into thin and uniform strips. These strips are woven into large flat panels sized to fit in a cargo van for transport. Several weaving techniques and scales are prototyped and evaluated for stability, flexibility, and ease of assembly. The joinery system is made of plywood on a 3-axis CNC router using machine files generated in Grasshopper. The inner and outer layers of woven bamboo panels are assembled with the joinery pieces on site.

MATERIAL INVENTION: PAPER PULP SHINGLES

The woven cylindrical bamboo wall structure is clad in a custom multicolor paper shingle assembly. This cladding produces a visual weight from a distance that draws visitors to the site as well as a sense of interiority upon entry, reinforcing the two framed views.

Students work together to develop a method for casting waste paper and woodchips generated on campus without the use of adhesives. After testing various bioplastic strategies and adhesives, a paper making technique is deployed. The final process involves mixing shredded paper, woodchips, flour, and water into a relatively homogeneous pulp using a blender or food processor. Initial pulp tests vary in color, reflecting the dominant colors of the recycled and waste paper used. This effect was desirable but was relatively visually subtle, so milk paint is added to the pulp mixture to create shingles of varying color across the assembly.

Once prepared in batches, the pulp is spread in an even layer onto canvas sheets in a circular shape and pressed with a 3D printed mold to create surface texture. The canvas sheets are then hung vertically on a rack to dry. Once the pulp is dried and cured, the shingles can easily be peeled off the canvas backing.

The primary challenge for the shingle system is its durability and exposure to rain and moisture. Tests are conducted to determine the best way to extend the life of the shingles with various coatings including resins, oils, and waxes. Bioresins proved to be very effective at preventing degradation, but this coating prevents the shingles from being able to be completely composted upon decommissioning without the use of industrial composting equipment. Instead, a soy wax coating with a relatively high melting point is selected and applied by dipping each shingle into a pot of melted wax and hanging it until dry. It is important that the initial pulp forming is allowed to fully dry and cure before sealing in wax, so that moisture is not trapped within the material.

Given the labor-intensive processes of pulping paper and coating the shingles, the paper pulp shingle façade proved to be the most laborious and time-intensive component of the assembly.

MATERIAL INVENTION: BENT GREENWOOD CANOPY

A thin bent greenwood canopy tops off the biomaterial pavilion, made of undulating strips that form a very porous surface. The strips stand on edge, such that each acts as a very thin but proportionally deep beam. The canopy is designed not to divert rain, but to provide shade and patterned light within the structure. The form is designed using a Grasshopper script to

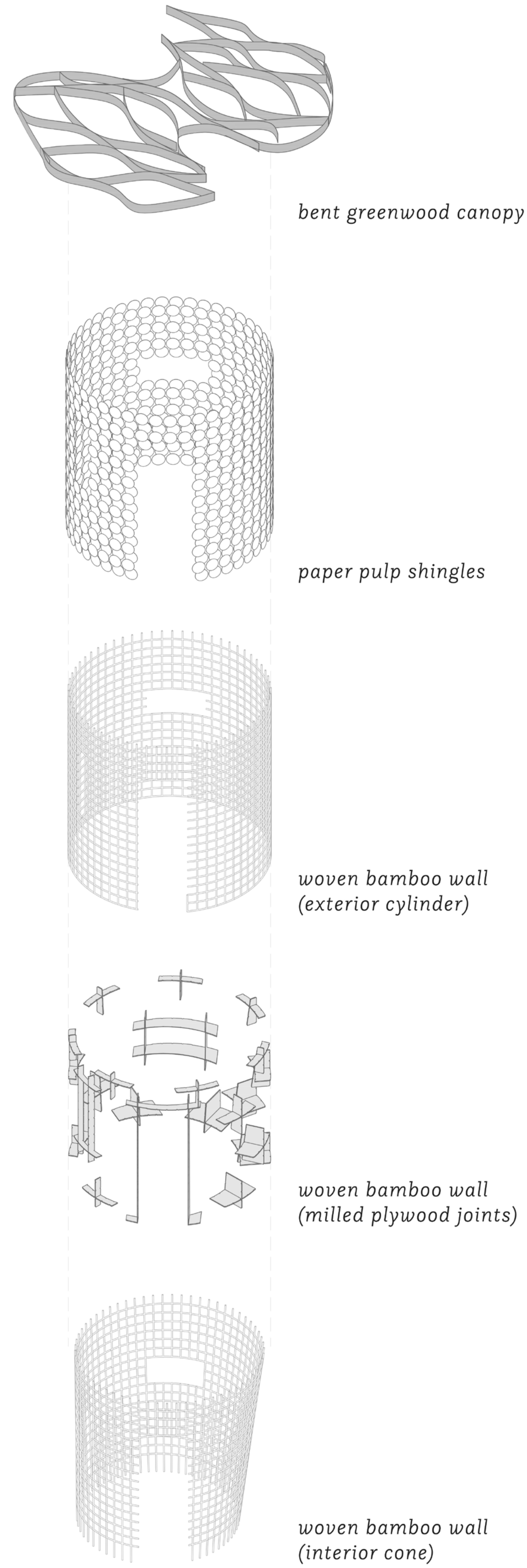

Figure 3. Exploded axonometric depicting material systems.

iteratively develop the sizing of openings within the surface, and to locate connections to the bamboo wall structure below.

Exposing students to the industrial tools that shape building material products is another opportunity within the course. To source material for the canopy, students were able to specify custom lumber dimensions (1/4" thick live edge pine) to be cut on a bandsaw sawmill housed at a local university facility.

A plan drawing is generated from the digital model and printed as a 1:1 template for the curving boards. The template is deployed during assembly to ensure the correct curvature of elements. Steam bending methods are developed and considered for obtaining the precise curvature required. However, the wood was still wet and green after milling, meaning that it had enough flexibility that steaming proved unnecessary. The pine strips are curved over the printed templates with a series of CMUs serving as weights to maintain proper curvature. The wood is allowed to dry in the sun for several days, at which point it is able to hold its shape (with some small degree of spring back as is typical of a steam bending process) and is assembled with pop rivets.

ASSEMBLY

Due to the compressed timeline of the project and the location of the site (requiring a fifteen-minute drive from campus), fabrication and assembly are planned to maximize off-site prefabrication, with pre-fabricated components being sized for the volume of a university cargo van. Work completed off-site includes weaving large panels of bamboo, CNC milling all wall joinery, bending wood strips and preassembling sections of the canopy, and fabricating and sealing all paper pulp shingles.

Once on location, the site is measured to accurately locate a series of helical pile earth anchors which serve as a removable foundation. The first row of wall joinery pieces are secured to these earth anchors. Meanwhile, the woven bamboo panels are combined into two large panels for the interior and exterior layers of the wall structure. These are assembled with the plywood joinery using a series of tied connections.

Once the wall is assembled, the structure is standing. The wood canopy is fully assembled at ground level with pop rivets, before being lifted to the top of the structure as a single unit and secured into place. Finally, the façade is installed by tying the pulp shingles into place, beginning at the bottom of the structure and working upward. Overall, assembly on site is largely completed over the course of two days (Figure 4).

DECOMMISSIONING

The installation is conceived from the beginning as a temporary exhibit that is disassembled at the end of its functional lifespan. This consideration led the students to develop material strategies for the various systems that are largely biodegradable, meaning that most of the installation is composted upon disassembly, which is completed with a small team of 1-2 people over two afternoons. Components that cannot be composted include only the earth anchors and a small quantity of metal hardware, which is gathered for use in future projects, and the plywood wall joinery elements. It was intended to use natural lumber for these components, but the quick fabrication timeline did not leave enough time for milling and drying the required lumber, so plywood was used instead. The rest of the installation is successfully composted together with other landscaping waste on site.

CONCLUSION

Material Invention

The three material strategies developed present several opportunities for future development. The double-layer bamboo wall is capable of forming lightweight self-forming structures in a variety of flat, angular, and curving geometries. The Grasshopper models developed allow for input surfaces to be analyzed and populated with joinery, which can easily be milled on a standard 3-axis CNC router.

The canopy structure is likely the closest to existing material systems, but the Grasshopper models produced prove efficient workflows for designing and fabricating lightweight structural and porous surfaces. The strategy for bending and drying greenwood suggests a less energy intensive method for bentwood structures and objects.

The paper pulp shingles present a low-cost, sustainable material strategy that has potential for use in architectural models as well as in larger-scale applications (Figure 5). The sealing and coating process would benefit from future development for long-term weather resistant applications, but the material strategy has proved effective at producing both thin surfaces and thicker volumes in a variety of geometries, suggesting possible applications in industrial and furniture design as well as in interior applications. During Project II, the material was also successfully piloted in a 3D printing application.

Material Economy

Throughout the course, efforts were made to increase access and affordability for all students. The studio was supported with a semester budget of just over $900 for materials and supplies provided by the Dean's Office. While this made it possible to conduct the course with near-zero material expenses for students, it is a modest budget for the construction of an inhabitable pavilion. Salvaging material from the local environment and waste streams served as both a way for improving equity and access to material — teaching students that good design does not necessarily demand expensive materials — and as an environmental strategy, asking students to consider the lifecycle and impacts of the materials with which they are working.

Figure 4. Completed pavilion on site at Morven Farm.

Figure 5. Paper pulp shingle and window detail, with woven bamboo wall visible on the interior.

Future work would benefit from more monitoring and documentation after installation to evaluate the efficacy of decommissioning and composting strategies. These strategies could be informed by recent work at the University of Tennessee Knoxville, which has focused on time-based processes in architecture.[10]

Course Development

This is the second iteration of the studio and was structured with some variations on the first version run the prior year. The introductory assignment proved very effective and was run the same way both years, while the second and third assignments were run differently in the first and second years. In the first year, this sequence began with a precedent study of recent novel material research projects and a study of the historical and cultural significance of the chosen site. Students then worked in groups of 4-5 to develop and build a series of modest full-scale installations. In the second year, a shift in the second assignment to designing and building a prototypical biomaterial element produced more exploration of possible materials and their properties. This productively shifted some agency in the design process to the materials themselves, as they became generative through these investigations. Students also became more acutely aware of and vocal about the need for the project to be sustainably decommissioned and for as many components as possible to be composted after the installation was deinstalled.

The shift from several smaller group projects to a single project constructed as a class played out in various ways. Several projects realized in smaller groups allowed individuals to have a sense of ownership over the entire project, and the range of approaches across the projects exposed students to a variety of materials and methodologies. This structuring stretched course resources and instructor time, as more projects running on various timelines with different material and fabrication needs proved somewhat complicated.

Challenges arose in synthesizing a cohesive project to be constructed by the entire class, such that each student could feel a sense of ownership and investment in the project. It was helpful to structure the class into teams that each led the development of a different material system. Within these teams, it was most productive for individual or pairs of students to take ownership of a specific component. For example, some students or pairs focused on leading Grasshopper modeling of the overall structure, CNC milling joinery, shingle production, testing shingle coatings, or canopy detailing. Students naturally began to focus on areas related to their experience in prior projects in the semester, but this structuring could be done more intentionally from the beginning of the third project in the future.

Research Pedagogy

Recent shifts in academia have placed increasing focus on exposing aspiring architects to rigorous research methodologies. Traditionally a focus of a terminal thesis or capstone studio, pedagogy on architectural research methods has the potential for earlier curricular implementation. This studio tested methods for introducing rigorous research into a design-build studio with the aim of training students to both develop and apply research. The prior version of the studio produced work that students were able to further develop as funded research with faculty.[11] A focus on the pavilion as a proof of concept for novel material research was discussed throughout the semester, with students working to convey the importance of their work to a broader public audience.

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