Fab+Craft: Synthesis of Maker, Machine, & Material

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School of Architecture
University of Hawaiʻi at Mānoa

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We certify that we have read this Doctorate Project and that, in our opinion, it is satisfactory in scope and quality in fulfillment as a Doctorate Project for the degree of Doctor of Architecture in the school of Architecture, University of Hawai'i at Mānoa.

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Contents

I. Abstract

Within contemporary architecture a fundamental disjunction exists between design and building facilitated by the use of advanced computational methods, and the relationship between form, material, and maker. The making of buildings demands an expertise that is familiar with the physical and involves a level of skill that many designers cannot claim to fully possess or practice. This doctorate project presents a study of a *design-through-making* methodology that incorporates craft with the material exploration of sandwich panels, digital technology and fabrication in the process of 'making' architecture. A focus is placed on the development of a specific design intent through the manipulation of materials, using skills and techniques guided by the practiced hand. This interaction between technology, material, and the designer-maker referred to as "fab+craft" creates a narrative that allows for the physical translation of ideas into the built environment.

II. Introduction

2.1 Background

Contemporary architecture is heavy influenced by advancements in generative, algorithmic "bottom-up" digital design methods. These bottom-up methods draw upon material properties, fabrication, and construction processes to influence the development of a design. Typically, architecture uses a "top-down" approach with design being largely determined prior to fabrication and construction.[1] This bottom-up approach focuses on first, developing a single detail, or module, and then using variations of the module to form a component-based system. As a result, form creation inscribed by internal rules and scripting drawn from production his resulted in an abundance of component-based geometric systems. Perhaps the most well-known example of this method is seen in work done by Andrew Kudless and his Honeycomb Morphologies.[2] Parallel to this has been design prototyping which has risen due to computer-numeric-controlled (CNC) manufacturing resulting in a fabrication culture that encounters the use of tooling, processing, and limitations of material systems. An architecture as a composite practice is being encouraged with an integration of traditional craft-based practices with a culture of advanced CNC fabrication. This integration combines computational virtuosity, human skill, and material logics, and the understanding of digital manufacturing tools. These manufacturing processes are available to the architect during both the initial design research phase and one-to-one scale production of component systems.[3] This hybrid practice of craft and CNC technology coined by Santiago R. Pérez is known as 'fab+craft.' According to Branko Kolarevic, "digital technologies are enabling a direct correlation between what can be designed and what can be built, thus bringing to the forefront the issue of the significance of information,

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[1] Jeremy Ficca, "Material Resistance" in *Matter: Material Processes in Architectural Production,* ed. Gail Peter Borden and Michael Meredith (New York: Routledge, 2012), 344

[2] Lisa Iwamoto, *Digital Fabrications: Architectural and Material Techniques,* (New York, Princeton Architectural Press, 2009), 86-87

[3] Santiago R. Pérez, "Towards an Ecology of Making," in *Matter: Material Processes in Architectural Production*, 379

i.e. the issues of production, communication, application, and control of information in the building industry."[4]

Similar to traditional drawing, digital production as a generative medium encounters its own hosts of restraints and possibilities within which lie its potential to narrow the gap between representation and building. A fundamental disjunction exists between the instrumental control and determination of form within contemporary craft and advanced fabrication. This is facilitated by the use of advanced computational methods between the relationship of form, material, and maker. This disjunction or gap between computer-aided design, (CAD) and making may stem from both a rapidly developing over-reliance on software as well as overall job specialization. Though this gap is not new to architecture as a material practice, its approach to design is predominately characterized by prioritizing the elaboration of form first, then selecting materials later. Since the Renaissance, the division between the processes of designing and making has led to the development of, and increasing dependence on, representational tools used that simultaneously serve as instructions for the translation from drawing to building.[5] Contemporary design and advanced fabrication stresses the relation describe in the equation of:

Constructability = Computability[6]

These new digital processes of production facilitate the constructability of a building design, with constructability becoming a function of computability. Some argue that the use of advanced fabrication, where the relationship of 'Constructability = Computability' results in a loss of improvisation, skilled craft, detail, and material diversity from a human-centered activity to a mathematical and computational form of making.[7] This accounts for buildings composed of larger modules to respond to economic constraints leading to buildings with fewer details and less variety in the ways that they are made. The corresponding faction of digital fabrication known as the "culture of making" counters this criticism of detail through the use of parallel

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[4] Branko Kolarevic, ed., preface to *Architecture in the Digital Age: Design and Manufacturing* (New York: Spon Press, 2003), v

[5] Achimmenges.net, "Design Research Agenda," Achimmeges.net, http://www.achimmenges.net/?p=4897 (accessed March 21, 2012).

[6] Daniel Willis and Todd Woodward, "Diminishing difficulty," *Harvard Design Magazine,* ed. William S. Saunders (Cam bridge, MA: Harvard University Press, 2008), 71-83

[7] Russell Nordmeyer, "A Fetish for Fabrication," *Architectural Record*, no. 10 (2011), 97

development of digital strategies and fabrication. This is in conjunction with the exploration of multiple material systems.[8] As a direct result of the fab+craft techniques used, there is a collective knowledge framework that combines parametric workflows and traditional crafts of forming, folding, and assembly with advanced rapid-prototyping and manufacturing processes.[9] This results in a renewed culture of open-source and shared knowledge capitalizing on composite strategies of milling, mold-making and casting techniques borrowed from traditional crafts. This is known as Material Intelligence (MI) where typical traditional craft practices are re-engineered into the system of logistics of machine production and material performance.[10]

Similar to the master builders of the past, designers of this modality are acting as resurrected master craftspeople with the use of digital techniques to explore material effects and properties (as means) that will manifest the design intent. In this vein, craft is no longer relegated to the realm of production, but rather used as a process to find new unanticipated solutions between designing and making. As these digital technologies bring about changes in the fields of design and construction, architects are embracing the "craftsmanship of risk" or the risk involved in making.[11] Craftsmanship of risk can also be referred to as the "workmanship of risk," as used by David Pye to describe the process of making where the outcome is continually at risk as discussed more in detail in later sections[12] Risk as a discovery process allows for an opportunity to bring about new research in material selection and assemblies. A master builder with their knowledge of making allowed them to design buildings, formulate construction sequences, and engineer building practices. The master builder represented a designer and a maker who was able to orchestrate the design and construction processes into unison. But as other professionals are making their way into what once was the sole domain of the architects, we begin to see a loss of control over the craft and see ourselves further from realizing the capabilities of the master builder.

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[8] Pérez, "Towards an Ecology of Making," 383

[9] Nordmeyer, "A Fetish for Fabrication," 97

[10] Pérez, "Towards an Ecology of Making," 384

[11] Branko Kolarevic, "Between Conception and Production," in *Building in the Future: Recasting Labor in Architecture,* ed. Peggy Deamer and Phillip G. Bernstein (New York: Princeton Architectural Press, 2010), 68

[12] David Pye, *The Nature and Art of Workmanship* (London: The Herbert Press, 1995), 20

The capabilities now provided by furniture designers, sustainability consultants, construction managers, and engineers of all stripes have become so advanced that Martin Simpson of Arup suggests that “architects may eventually become unnecessary—except, perhaps, as [an] exterior stylist.”[13] Some feel that as we shift to digitally-driven fabrication tools by designing specifically for the capabilities of machines we will fall into the same unproductive relationship between the means of representation and production. As observed by William Mitchell, “architects drew what they could build, and built what they could draw.”[14] However, it is through these machines that we are able to bring craft back as a process in making buildings. “Machines will lead to a new order of both work and leisure,” as stated by Le Corbusier in *Towards a New Architecture*.[15] Throughout history architects have always looked for new materials and new processes. With the use of today’s digital fabrication tools such as CNC machines, we are able, to fully realize the capabilities of “liquid” materials (known as composites), which have been used by aviation and marine designers for years. Composites, or reinforced polymers, are similar to concrete in that they can be molded in a form but are far superior in their strength-to-weight ratio. And it is through the use of computer numerical processes that ship builders are able to efficiently create new compound curve molds to form composite materials.

The use of digital design and manufacturing processes are poised to close the current separation between designing and producing that results when designers begin to make drawings. Through an integrated approach to these processes, one is able to interact with materials as they are assembled together to form larger wholes that define space. A number of architectural firms have recently explored this union of 3-D design with 3-D fabrication including SHoP Architects, William Massie Architecture, and Byoung Soo Cho. Massie states, “When [an] author produces a drawing that becomes the information that drives the machine, it compasses the world of design and fabrication into a single process, thereby yielding efficiencies not realized in the

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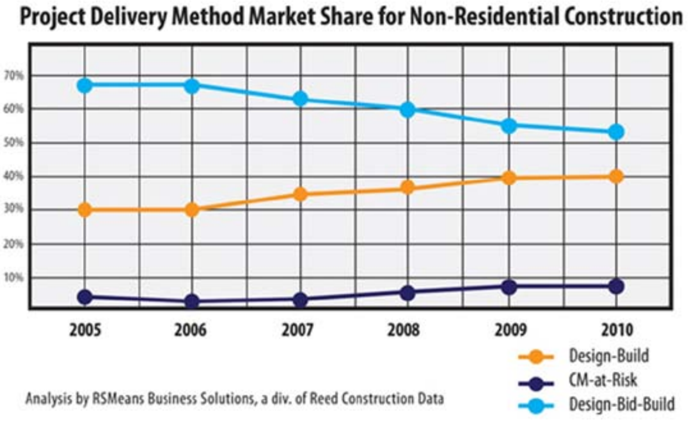
[13] David Celento, ”Innovate or Perish: New Technologies and Architecture’s Future,” in *Fabricating Architecture: Selected Readings in Digital Design and Manufacturing,* ed. Robert Corser (New York: Princeton Architectural Press, 2010), 57

[14] Branko Kolarevic, ed. “Digital Production” in *Architecture in the Digital Age: Design and Manufacturing,* 32-33

[15] Robert Corser ed., introduction to *Fabricating Architecture: Selected Readings in Digital Design and Manufacturing*, 11

industrial era."[16] Therefore jobsite actions and construction process become drawn back into the digital world as new constraints. These constraints are then used as tools in the quest to further develop a design achieving the precision and quality associated with craft.

Though design-build is not a new principle in the realms of architecture and construction, as the Jersey Devil Architects popularized 30 years ago, it can be used as a process for the architect to design and fabricate assemblies. Emerging designers are once again excited about the possibilities inherent in varying levels of participation in the actual making of a design. Design-build is a method of project delivery in which one entity, the design-build team, works under a single contract with the project owner to provide design and construction services. Design-build, or simply D-B, is an alternative to the design-bid-build (D-B-B) process. Under design-bid-build process, design and construction are split into separate entities of work and separate contracts with the owner. People tend to see more of the profit optimization side of D-B ran mostly by contractors whereas the product optimization side is more design driven, resulting in interesting assemblies of materials. The advantages of D-B are the following: one entity, one contract, and one unified flow of work from initial concept through completion. Design-build is also known as design/construct and single-source responsibility. Design-bid-build, construction management, and design-build, are the three project delivery systems most commonly employed in North America. Design-build has greatly accelerated in the United States over the past 15 years, making this delivery method one of the most significant trends in design and construction today. According to the Design-Build Institute of America (DBIA), design-build project



Analysis by RSMeans Business Solutions, a div. of Reed Construction Data

Figure 1 Project Delivery Market Share

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[16] William Massie, "Remaking in a Postprocessed Culture," in *Fabricating Architecture: Selected Readings in Digital Design and Manufacturing*, 103-104

delivery is expected to surpass traditional design-bid-build methods in the near future, as of 2010 it accounted for 40% of non-residential projects completed (fig 1).[17]

2.2 Doctorate Project Statement

As the line between design and construction continues to be obscured, there is evidence that the evolving technologies of digital design and fabrication are being embraced in all aspects of contemporary architecture. Within this evidence emerges a resurgence of craft know as fab+craft—the hybridization of practices of craft and CNC technology absorbed and re-integrated into traditional craft knowledge with advanced fabrication techniques as a composite practice. Taking this as the starting point of the status of craft within the role of contemporary design, this project examines material properties as design parameters and workmanship of risk as they relate to craft as a practice centered on the manipulation of a physical material by the machine along with the skilled, knowing hand.

Research shows that it is accurate to state that the activities of the designer and craftsperson are not completely different from one another nor are they completely the same. They share parallels in the methods by which they operate. Knowing what, why, and how to design and make requires deep knowledge of the processes, tools and techniques used in creation. The designer not only solves problems of functional shape, he or she also invents, elaborates, and refines the design during the process of creating it. However the craftsperson ends up with a finished functioning object, where as the designer ends up with an abstract notation that may be made into an actual object at a later time. There is evidence that the integration of designing and fabricating will develop a new master craftsperson like those of the past. Such a new craftsperson or *designer-maker* may be more able to achieve a synthesis between, architecture, technology, and fabrication, resulting in more well crafted environment.

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[17] DBIA, "What is Design-Build?," Design-Build Institute of America, http://www.dbia.org/about/designbuild/

This study will investigate the relationship of craft to contemporary design by understanding the importance of the act of ‘making’ as a process contributing to a higher quality built environment.

In summation, this project seeks to manifest a two-fold fab+crafted environment that involves:

1.) A finely crafted digital fabrication technique, that pays respect to traditional methods to be utilized by the modern ‘designer-maker’.

2.) A process that seamlessly links form, structure, and material properties to create a material system tested at the scale of an architectural application—a self-supporting wall.

2.3 Scope & Limits of Research

This project examines the importance of making within design. It represents an exploration into looking at the back and forth flow relationships between designer and craftsperson, materials, tools, and machines. The goal is to produce a crafted object that promotes a certain quality of life to be infused into the built environment.

Fab+craft examines traditional and digital craft within an age of digital fabrication where machines and tools share a very close relationship to one another. The architect, with the use of digital fabrication is able to build once again. Drawing along parallels to analogue counterparts of past craftspeople consisting of the Daiku, Filippo Brunelleschi, and the Eames, the architect, as a designer and maker is positioned at the center of the construction process, controlling the flow of information and formal generative geometry. Case studies of digital tools and processes are presented to demonstrate the ‘file-to-factory’ of computer controlled processes (CNC) that allow for quick and interactive prototyping through the use of ‘do it yourself’ (DIY)design method of Flash Research. Flash research is the quick exploration of an architectural idea using applied research tested through one-to-one scale prototyping.

Typically, a tool is something that extends one’s power through a piece of technology or applied knowledge to overcome the limitations of the body. Whereas, a machine is a mechanism—a device with multiple moving parts—for the transfer of power.[18] With the advent of computer-aided-design (CAD), computer-aided-manufacturing software, and CNC technology, tool s and machines have become interchangeable. At times, machines and tools are presented as separate entities, while at other times they are presented as one in the same. A tool can be a machine, just as a machine can be a tool. Design-through-making necessitates a medium, either a tool or a machine. Through this analysis it becomes apparent that the two are one in the same.

To illustrate the relationship between making and design, architectural sandwich panel prototypes were created using an iterative workflow of 'Research = Design = Construction' engaging craft and technology. This workflow places material properties, traditional craft, and digital fabrication techniques as inputs into the initial design process, which results in formal geometries being realize through physical material. Each prototype was produced using the Rhinoceros 3D, as it allowed for direct transition of digital data and shape into MasterCAM without any file conversions. Although other 3D and CAM software is available, Rhinoceros 3D and MasterCAM were chosen based upon user experience. MasterCAM was used to produce the G-code, which controlled the Techno CNC router located in the School of Architecture's shop. Due to the cutting limits of this router, other conventional tools of the shop were used to complete the various tasks of cutting, bending, and laminating components of the prototypes.

Each prototype is evaluated on its own performative capacity, (i.e., its reciprocity between material and form, craftsperson and designer, and aesthetic and functional utility within its environment). Finally, future research based on the outcomes of orchestrating these methods of digital representation and tools of execution is suggested to form a strong connection between architectural design and making.

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[18] Malcolm McCullough, *Abstracting Craft: The Practiced Digital Hand* (Cambridge, MA: MIT Press, 1996), 59, 64

2.4 Organization

This doctoral project begins by introducing digital fabrication and craft by explaining the existing conditions and boundaries that separate design and construction. From here it is suggested that architecture needs to embrace the act of making and use it as a design tool through fab+craft.

From here, Chapter three breaks down and explains the various components that define Fab+craft. Fab+craft, in simple terms is the blending of traditional methods of making with digital design and fabrication. This chapter begins with the fundamental tool—the hand—and how it gains accountability through the process of craft. Craft is examined and discussed in conjunction with craftsmanship, workmanship, and digital technology.

This section continues by looking to our past counterparts and drawing upon their abilities to build and design, control construction, and invent or use new methods as a means of tooling to create a crafted environment through digital fabrication. The chapter concludes by examining case studies of existing manufacturing methods and fabrication techniques used as tools for designing via making.

Chapter Four describes the making methodology of Flash Research or ‘Research = Design = Making’ and where testing of the conventional building material of plywood is introduced.

Chapter Five describes the various processes of bending plywood and the prototypes created based upon the properties discovered from the tools and methods involved. From there, prototyped sandwich panels are suggested as a performative building system. The system investigates various configurations based upon fabrication methods, performance values and design intentions. After each prototype is constructed, it is analyzed and compared to each other in order to see if the process of constructing it can be improved.

The last chapter concludes with future applications and areas of fab+craft by applying a broader or culturally contextual approach. It examines the act of making and designing or ‘architecture’ as cooperative endeavor among clients, designers, and makers with the architect at the center of control. From here it questions and summarizes the findings and suggests future areas of studies.

III. Fab+craft

3.1 The thinking hand: The origin of maker, hand and tool

The phrase, 'the thinking hand' refers to the ability to create and the ability to transform an idea into a physical object through mechanical actions. It is an interpretation of the "thought of the hand" used by Oswald Spengler in *Man and Technics.*[19] Yet hands are frequently underappreciated—"eyes are in charge, mind gets all the study, and heads do all the talking."[20] Hands act as conduits as we extend our willpower in the world—hands can contribute to working and knowing by pointing, pushing, pulling, and picking up tools. They allow us to gather knowledge from the world as they feel, probe, and practice through their intimacy with direct contact of material.

When at work, hands show the most life. They just don't hold—they grasp, pinch, press and guide as they apply a force of action into the physical world. Work of force takes on a different form than work that exercises precision, however all this work is fast as the hand is quicker than eye.[21] It is through the endless versatility of the hand as a tool—the ability to execute a physical mechanical action—that allows a maker to manipulate the physical environment. Yet, the hand by itself can only execute an action within its physical range of movement. It is through "the thought of the hand"—the thinking hand—where the eye seeks out cause and effect while the hand works on the principle of means and an end that allows for the hand to use tools to convey a plan of action. [22] Hence, the tools used by a maker become an extension of the body to take part in the act of making. A maker is only as good as the tool and the tool is only as good as the maker. Therefore, to distinguish a maker's ability in making, craft is applied as a measurement of his or hers ability to produce. Therefore, in the modern world it is meaningless to attempt to divide the hand from the tool, machine, and action as the hand accepts technology rather than rejecting it.

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[19] Oswald Spengler, *Man and Technics: A Contribution to a Philosophy of life,*(New York: Alfred A. Knopf Inc., 1932), 39-40

[20] Malcolm McCullough, *Abstracting Craft: The Practiced Digital Hand* (Cambridge, MA: MIT Press, 1996), 1

[21] McCullough, *Abstracting Craft: The Practiced Digital Hand*, 2

[22] Spengler, *Man and Technics: A Contribution to a Philosophy of life*, 39-40

3.2 Craft

Historically, craft is categorized according to material, working methods, and techniques, and by the type of object produced. This definition traces its roots back to the medieval guild system and further to the Roman system of *collegia*.[23]

The very root of the word 'craft' illustrate this focus on materials and technique as it defines the requirements demanded from a craft practitioner—later becoming known as a craftsman. According to the *Oxford English Dictionary,* the original word 'craft' was related to strength, force, power, and virtue.[24] As the word evolved it came to mean "Skill, skillfulness, art; ability in planning or performing, ingenuity in constructing, dexterity."[25] Within the range of this usage, craft emphasizes the kind of technical knowledge and skill required to make an actual object come into being—a practical physical function.[26]

Hence, the term craftsmanship can be applied when referring to the skilled activity with which *and* through a crafted object is made. Craftsmanship is defined as the skill of making something well.[27] This becomes a way to separate objects from the skills that were engaged to make them while reinforcing the connection between craft and the skilled hand. These distinctions about how objects are made play an important role because the process of making is closely tied to the meaning of the object. Before the Industrial Revolution, the skilled hand carried out activities of making, whereas today this is not the case. Today, with the use of machines and digital fabrication techniques the skilled hand is relegated to computer specific tasks. With the development of machines, craft and craftsmanship still retain qualitative dimension by referring to the "well-made-ness" of objects and things.[28] In fact, craft has always been mediated through a relationship between humans and technology. From hand tools to industrialized machines, the quality of craft in an object has been measured by human input.

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[23] Howard Risatti, *A theory of Craf*t (Chapel Hill, NC: University of North Carolina Press, 2007), 16

[24] *Oxford English Dictionary,* online ed., s.v. "craft," http://www.oed.com/view/Entry/43694 (accessed May 3, 2012).

[25] *Oxford English Dictionary,* "Craft."

[26] Risatti, *A theory of Craf*t, 17

[27] Richard Sennett, *The Craftsperson* (New Haven, CT: Yale University Press, 2008) 8

[28] Risatti, *A theory of Craf*t, 14

Digital craft first emerged in 1983 when the software designer Ben Schneiderman introduced computational pointing, termed "direct manipulation." This term describes the act of pointing at our work with a mouse. Direct manipulation more specifically refers to the combination of three activities: (1) uninterrupted visibility of the object of interest; (2) rapid, incremental, reversible, physical actions on the object; and (3) immediately visible results.[29] With this ability, the computer, combined with software, becomes a medium as a "means for combining the skillful hand with the reasoning mind."[30] As a tool, software can give visible form and action to a logical operation. Similar to a physical tool, the software modifies the effect of the hand through the visible cursor controlled by the pointing device. Therefore a tool can be conceptual and indirectly controlled; whether direct or indirect what matters is the ability to manipulate. Similar to a physical tool, software becomes the medium for the operation it performs. To employ a tool, you have to look around for it, pick it up, and move it in relation to the object being worked. Its use is initiated and guided by the user's intentions and ultimately by the hand. "Representing particular abstract operations as tools is the best way yet developed for engaging the kinds of action and intents that traditionally motivated the craftsman."[31]

Therefore a crafted object, digitally or physically constructed, can be defined by applying the following four principles or causes described by Aristotle:

The Four Causes:

- The material cause: "that out of which", e.g., the bronze of a statue.
- The formal cause: "the form", "the account of what-it-is-to-be", e.g., the shape of a statue.
- The efficient cause: "the primary source of the change or rest", e.g., the artisan, the art of bronze-casting the statue, the maker who gives advice, the parent of the child.

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[29] Ben Schneiderman, "Direct Manipulation: A step beyond Programming Languages," *Computer* 16, no 8 (1983): 57-69, quoted in Malcolm McCullough, *Abstracting Craft: The Practiced Digital Hand* (Cambridge, MA: MIT Press, 1996), 23

[30] McCullough, *Abstracting Craft: The Practiced Digital Hand, 81*

[31] McCullough, *Abstracting Craft: The Practiced Digital Hand*, 80

- The final cause: “the end, that for the sake of which a thing is done”, e.g., health is the end of walking, losing weight, purging, drugs, and surgical tools.[32]

3.2.1 Manual Skill, Workmanship, & Craftsmanship

Both workmanship and craftsmanship imply a function done with the hand and they involve a high degree of technical manual skill. But there are many different kinds of manual skills that do not involve workmanship or craftsmanship. Traditionally, manual skill implies the manipulating of physical materials with the hand. This connection between technical skill and to actual physical materials is fundamental to the basic concept of workmanship and craftsmanship as they relate to craft.[33] Without this, one will not understand the importance of crafted objects in the face of industrially produced design objects.

Workmanship—as being the product of the hand to work a physical material—is different from design. The more skillful the hand, the greater the skill can be, and the better the workmanship can be. This determines the quality of workmanship based on the output of manual skill that is directly dependent among the following factors: the degree of actual skill possessed by the hand, the technical knowledge of how to manipulate materials using tools by the worker, and the standards of quality the worker is committed to. Compare to a designer, who conceives and creates a design that is a product of the creative imagination using representation; the worker realizes a design by producing it by technical manipulation of a physical material. A design can communicate a sense of workmanship even if the worker already knows the conventions in making it. Hence, a worker’s workmanship is predictable regardless of how skilled he or she is as they are required to follow the parameters set forth by the design. Basically, workmanship is a rote process of making and is not to be confused with that of craftsmanship.[34]

Craftsmanship is difficult to distinguish from both workmanship and design as modern technology and machines have altered our views and expectations of production. Many people

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[32] Falcon, Andrea, "Aristotle on Causality", *The Stanford Encyclopedia of Philosophy*, Fall 2011 rev. ed. ed. Edward N. Zalta, http://plato.stanford.edu/archives/fall2011/entries/aristotle-causality

[33] Risatti, *A theory of Craft*, 157

[34] Risatti, *A theory of Craft*, 163

today see craftsmanship equated with that of workmanship. In his book *Medieval Craftsman*, John Harvey argues that technology is nothing more than craftsmanship. David Pye refers to craftsmanship as an "honorific way" for describing workmanship and is an activity that is qualitatively different. As mentioned earlier, he refers to craftsmanship as "the workmanship of risk" and workmanship as "the workmanship of certainty." Basically, the "idea is that the quality of the result is continuously at risk during the process of making."[35]

3.2.2 Labor, Work, & Craft

Labor as employed in a process of working is not just about the power of technology but also its effect on technologically-engaged subjects. Each generation of design, construction and fabrication professionals have had to harness the innovations of their time in the age-old task of shaping the environment. The Industrial Age gave rise to the belief that craft and machine manufacturing were locked in combat with each other. The computer has the potential and offers a means to end this battle. So what is the effect of digital fabrication on how we as designers and builders conceive our work? The traditional definition of designer, architect, and builder come under attack as their relationship to one another shifts. The designer is no longer equated solely with the architect due to the fact that fabricators, engineers, and programmers lay equal claim to authorial designation. The expanding technology of computer software and digital fabrication techniques have the potential to expand a professional's control over the world of built form by linking designers with contractors more closely now. Architects have the ability to regain their role not only as a designer but also as a maker with the generation of construction documents and fabrication of the finished product. Therefore critical control paths become mingled with the control of form. This collaboration among design, fabricators, and constructors entails a great deal of risk.[36] So how will design, fabrication and construction professionals reposition themselves and their relationships to each other as digital technology disrupts the known patterns of behavior?

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[35] Pye, *The Nature and Art of Workmanship*, 20-21

[36] Robert A. M. Stern, preface to *Building in the Future: Recasting Labor in Architecture,* ed. Peggy Deamer and Phillip G. Berstein (New York: Princeton Architectural Press, 2010), 15

The architect Renzo Piano emphasizes craft as the common unifying principle in team-based work. He seeks to expand the notion of craftsmanship to embrace the idea of a continually integrated exchange of manual and intellectual work. This renounces the split between the arts and sciences through the term *techne* defined by Martin Heidegger. *Techne* is a mode of knowing that is inseparable from design and construction.[37] Yet very few are able to cross over this divide between designing and building except for a select few due to the specialization of labor that realizes the work.

Craft acts as the process of technique resulting in the digital processes of architecture to follow one of three directions. The first is the use, or replacement of geometry, with formal logic based on mathematics using scripts or codes to generate topological relationships. The second is a drive towards organizational complexity where information about a building is linked, imputed and managed. The third is the development of digital fabrications in which craft has gained a new life as a tool to directly link machines that make designs a reality. Stan Allen, suggests, "today even construction has come to rely on tools of abstraction as computer technology is increasingly used during the production of buildings."[38]

In architecture, craft is closely connected to detail, which is being redefined with the use of digital design. It is through detail that architects are able to bring craft into buildings as a product of the relationship of design to construction. Today's details are being based on management and the organization of information. It is through these CNC assembly procedures and tolerances that the architect is able to reconnect with making as a relationship between human and machine intelligences. Craft expands to include not only the act of making, but design processes by which the knowledge is ascertained through the resistance of materials associated with traditional craft.

With the integration of digital design and fabrication processes, the disjunction between fabricators and designers, happening since the industrial age, is dissolving into the past. Drawings and models were once used as guidelines to represent design intent and are now

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[37] Kenneth Frampton, "Intention, Craft, and Rationality," in *Building in the future*, 35

[38] Stan Allen, "Artificial Ecologies," in *Reading MVRDV*, ed. Véronique Patteeuw (Rotterdam: NAi, 2003), 82-87

being used to communicate information precisely on how to fabricate the assortment of materials within a project. As a result, the control data, developed with digital 3D modeling information, drives the machines and is directly translated by fabricators. This gives rise to a new relationship between design and fabrication processes

3.3 State of Architecture: Designer & Craftsperson

The tradition of the master builder did not survive the cultural, societal, and economical shifts of the Renaissance. According to Leon Battista Alberti, architecture became separated from construction.[39] This differentiated and departed architects from the roles of the master builder and craftsperson. In a way this cessation is a sign of an expanding specialized society. A society that essentially relegated 'Architect' to an irony where they were first to perfect their intellectual training so as to properly provide the aesthetic essence of architecture instead of displaying the practical knowledge of construction. The combination of theoretical knowledge, new descriptive geometries of technical representation, with the development of perspective and orthographic drawings transformed architecture into a formalized discipline.[40] These technical drawings became the medium of communication of building information and design intentions; architects no longer had to be present on the jobsite to supervise construction of a building. Thus, the disjunction between designer, production, and the process of making evolved from this moment in time.

The Enlightenment Period is often regarded as the great turning point that has shaped the world we live in today. During the 17th century, the disjunction between designing and making would continue to grow as designers and builders were no longer limited to locally produced materials. Advanced material production and transportation infrastructures combined with large urban working populations created a convincing illusion of an endless supply of materials that could be moved and employed with ease, without the regard for regional application traditions. With a

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[39] Branko Kolarevic, "Information Master Builders," *Architecture in the Digital Age: Design and Manufacturing,* 57

[40] Dalibor Vesely, *Architecture in the Age of Divided Representation: The Question of Creativity; in the shadow of Production* (Cambridge, MA: MIT Press, 2004), 236-237

growing reliance on theoretical knowledge, and the increase in material production and labor, came a fundamental shift in human consciousness. As a result, architecture, engineering, and construction spilt into specialized disciplines. Traditional guilds were replaced by new technical institutions. Architecture, civil engineering, and other disciplines of surveying were now being taught at universities such as the Ecole *des* Ponts *et* Chausses founded in 1747.[41]

With the introduction of the general contractor and professional engineer in mid-19th century England, the disjunction continued to evolve. As with earlier off shoots to the field, each new job title necessitated a common language between them. Orthographic drawings became the primary instruments of communication between the owners, architect, engineer, and contractor just as is practiced today.

Further separation occurred between design and construction during the 20th century. The emergence of various design and engineering consultants came with the increase in complexity of the built form. But as complexity was added to the process of design and construction, the time to execute an entire project has become shorter. The fact that time could be saved on the construction end meant money could be saved thereby providing leverage to the other, 'non-architect' project constituents. This gives rise to the need for more precise legal definition of the roles of each constituent involved in the design and construction. As a consequence, the architect relinquished more to the construction team thus becoming further separated from the rest of the building industry. As a direct result of specialization, standardization and faster production times, the craft of building gave way to assembly. As an example of the current situation, American Institute of Architects (AIA) in the their owner-architect agreement states, "the architect will not have control over or charge of and will not be responsible for the construction means, methods, techniques, sequences, or procedures."[42] This leads to further marginalization of the architectural design specialist, which results in the inability of an architect to be a craftsperson with respect to a more fully integrated methodology of design and construction.

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[41] Kenneth Frampton, *Modern Architecture: A Critical History,* 3rd ed. (London: Thames and Hudson Ltd., 1992), 12

[42] AIA, "Architect's Administration of the Contract" in *AIA document A201-1997: General Conditions of the contract for Construction,* (Washington, DC: AIA, 1997), 22

3.3.1 Japanese Craftsperson—the Daiku

During medieval Japan the architect did not exist and the profession would not emerge until westernization of the country during the Meiji Period. The Japanese medieval master builder was the master carpenter—the daiku meaning great craftsperson. Over time, the carpenters would form guilds similar to that of medieval Europe.

During the middle of the seventh century, a large guild of artisans made up of master craftspeople—the daiko and common carpenters, or shoko, formed under the Ritsuryo system. This system would gradually be undermined by the landed aristocracy. Because of this carpenters would become nomadic in the eleventh century, but they would reorganize themselves into official guild structures during the following century. They divided into a hierarchy based on their skill which included the daiko—the chief carpenter, indo—the master carpenter, and otona and tsura carpenters. Each carpenter worked together in collaborative teams to complete tasks that specialized in their skills.

The evolution of Japanese carpentry tools and methods is inseparable from the emergence of social classes, building types, technology, and material availability. The availability of straight-grained structural timber wood became exhausted during the Kamakura period resulting in builders being forced to use inferior timber. This situation led to the development of new joint methods and in turn led to the evolution of new tools. As these tools evolved, basic structures became lighter and finishes became more refined.

Many traditional Japanese tools were in place during the fifth century. Adzes, chisels, gimlets, mallets, and planing knife or yari-ganna were used to construct the Horyu-ji Temple. However these crude techniques involved an enormous amount of time and wasted as much as nine-tenths of the lumber in the process of dressing. Thick saws with blades of 5 millimeters thick or more were first used during the eight century, as well as crosscut saws imported from China, but these were very cumbersome to use. Learning from the two-person rip saw imported from China during the Muromaci period from 1333-1573, the Japanese invented the maebiki-oga—one-person saw at the beginning of the Momoyama period from 1568-1600. This allowed for one carpenter to efficiently cut as much timber as two using a frame saw. Another advantage of this saw was the ability to cut boards as thin as 3.5 millimeters. As timber became a precious commodity, minimizing waste was a critical skill for a sawyer. The ability to cut 12 boards instead of 10 meant the difference between providing ceiling panels for an eight-mat or six-mat tatami room from a log of the same size.[43]

The Japanese would continue to refine their tools to create ever-more stylish results for the aristocratic elite but this changed during the seventeenth century, as the building practice would be employed by the state and mercantile urban class. As result, a division of labor in wooden-construction would occur to meet these new demands leading to a new range of special skills. With carpenters specializing in the production of frames, doors, shoji screens, the making of wooden boxes and chests, a proliferation of tools of every kind occurred. This led to the invention of particular tools for special classes of work, thus the diversity of the carpenter's tools became a symbol of the subtlety and the range of his practice.

The building of the Sogakudo in Ueno Park Tokyo in 1890, displays the range of hybrid Western and Japanese carpentry methods that would become the standard practice in urban Japan. Thus the Sogakudo contains Western styles, roof, trusses and connectors and framing methods as Japanese carpenters continue to evolve their tools from western influence. An example of this is the shift from the single-blade plane to the Western plane with a cutting edge and a chip breaker. The Japanese would perfect this by blending these two designs together to form a hybrid version. This allowed for the lower quality of wood that was available during this time to be worked without tear outs by the carpenter, due to the higher angle of 45 degrees compared to the traditional angle of 37 degrees. Even though this new plane did not leave the same type of polished finish, the operation of the plane remained the same of working wood against wood through the use of steel. Plane blocks are made with regard to the growth pattern of the tree, so that the sole of plane is made from surface wood—the wood closest to the bark. This places the hardest portion of each growth ring downwards which requires the sole to be adjusted and leveled out with the scraper plane in regards to climatic conditions.

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[43] Kenneth Frampton, Kunio Kudo and Keith Vincent, *Japanese Building Practice: From Ancient Times to the Meiji Period,* (New York: John Wiley & Sons, 1997), 26

3.3.2 Early Renaissance Craftsperson—the Capomaestro: Filippo Brunelleschi

As design processes have transitioned into the digital realm, it has been suggested it will reinstate architects to the status of the master builder. It was the master builder, who facilitated the smooth flow between design and construction during many projects of the middle Ages.[44] These master builders were exceptionally talented craftspeople trained in guilds that crossed over into architecture from an allied field of construction. Their knowledge of making allowed them to envision the design of buildings, formulate the construction sequence, and engineer building practices.

During the 15th century, the capomaestro Filippo Brunelleschi—initially trained as a goldsmith designed and constructed the vaulting of the dome of Santa Maria del Fiore in Florence without the traditional use of centering wood scaffolding.[45] Brunelleschi used the latest building technology of *modelli* or large scale physical model to convey his intention of the dome. These *modelli* were similar to today's prototype models as they were large enough to be entered and inspected by clients, conveyed spatial organization, material information, and construction techniques. On larger models, individual craftspeople from the various guilds were employed to construct the portions of the scaled model that they would build and be responsible for in the field.

The model dome of the Santa Maria del Fiore was 60 feet in length and was constructed by four bricklayers lent to Brunelleschi. A series of wooden tension chains were set at equal lengths within the interior cavity of the dome itself (fig 3). This supported the structure without using buttresses and internal armature, or scaffolding, as seen in Gothic cathedrals a century prior (fig 2). This model allowed for production discussions and feedback from the various trades people before the actual vaulting of the dome which eased concerns as to whether such construction techniques would actually work. This type of working model allow for the ability of systemically testing construction techniques and sequencing. This is to be contrasted representing a

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[44] Richard Garber, "Alberti's Paradigm," in "Closing the Gap," special issue, *Architectural Design* 79, no 2 (March 2009): 89

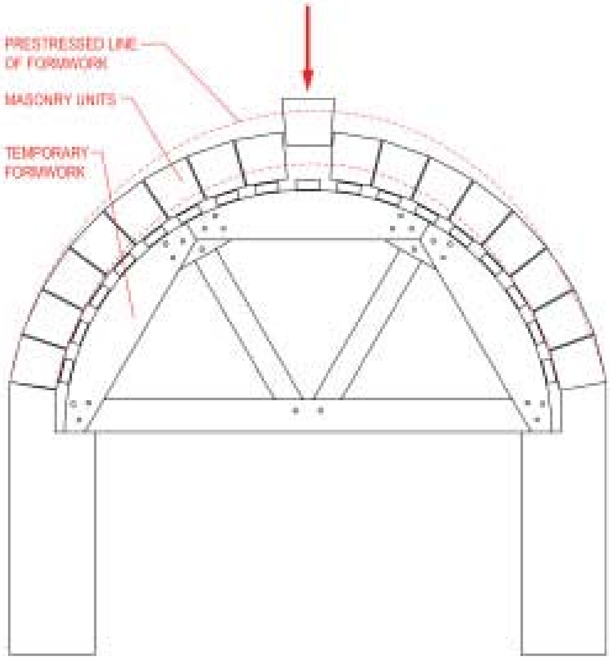
[45] Garber, "Alberti's Paradigm," 89

designer's intention. These working models became more complex as more three-dimensional awareness emerged within the guilds.

Brunelleschi designed and engineered many innovative tools and techniques in the process of construction that would be used throughout the Renaissance. His greatest invention among dome construction was the oxen driven hoist or crane (fig 4). This machine delivered materials several hundred feet in the air to the masons laying the dome's complex brickwork. The hoist was able to reach heights that were not possible by workers with pulleys of the past—buildings could now be taller. It is estimated that the oxen driven hoist had lifted 70 million pounds of building material to masons during its years of service.

Traditional Vaulting Drawings

The conventional method of vaulting an arch or dome prior to Brunelleschi’s plan to vault the dome of the Florence cathedral was to first construct and erect a temporary support structure, usually of timber frame members, that was then hoisted into place (1).Next, masonry was installed on top of a series of wooden slats that formed sheathing on top of the timber frames (2). Once the final center course of masonry was installed, the centering could be removed (3).The only practical way to remove the timber frame was to dismantle while standing on the ground (4).[46]



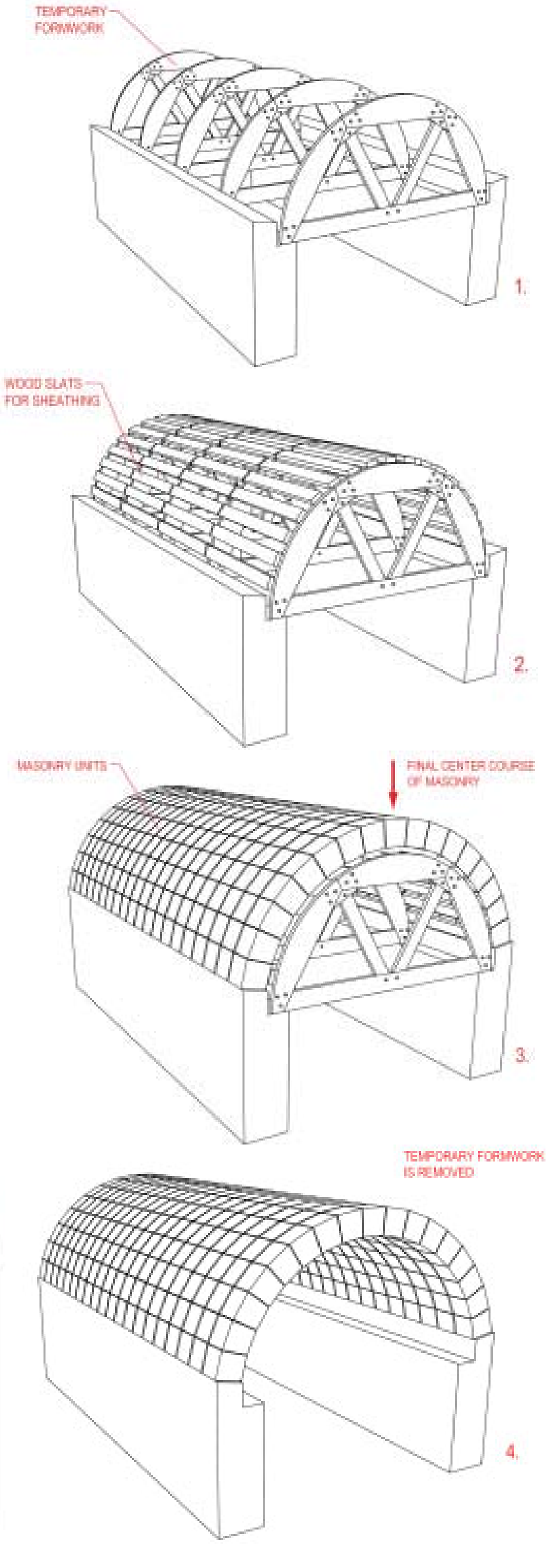


Figure 2 Typical Scaffolding for a masonry arch.

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[46] Garber, “Alberti’s Paradigm,” 88-93

Construction of the Dome of Santa Maria del Fiore

The innovations in the construction of the dome included a two-shell system between which a series of wooden chain tension rings were installed within the cavity to resist the outward pressures of dome. This allowed for construction of the dome without external buttressing or internal structural centering frames (fig 4). In addition to the interior scaffolding, a series of exterior platforms were designed to fit into the exterior masonry of the dome.

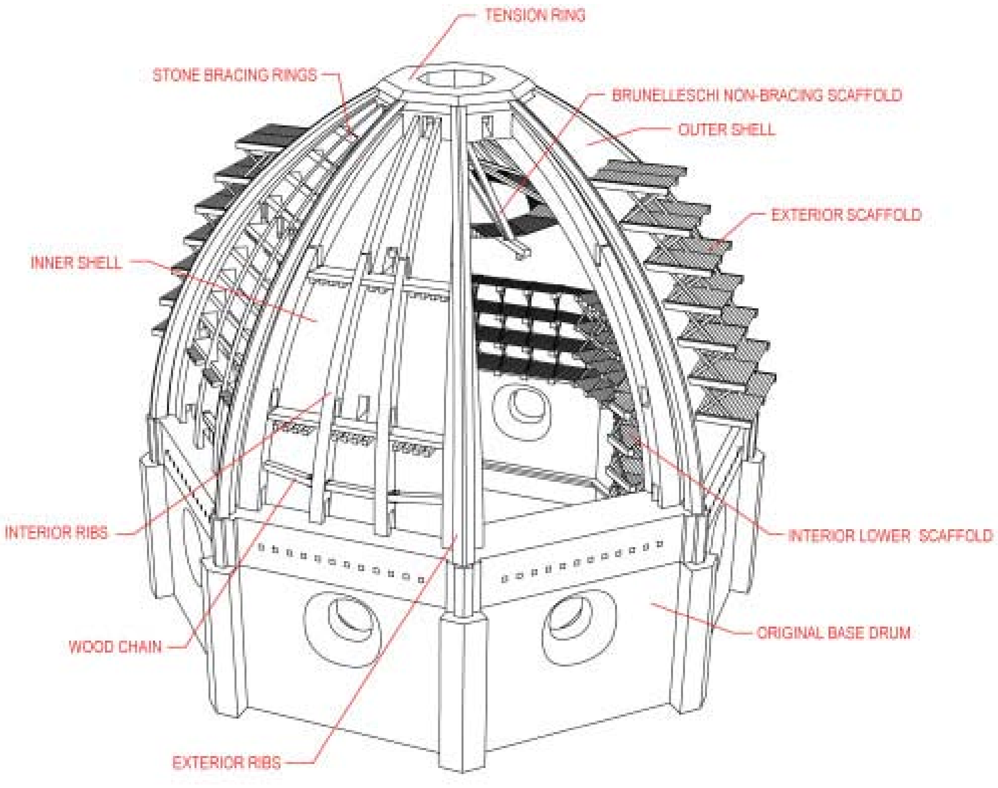
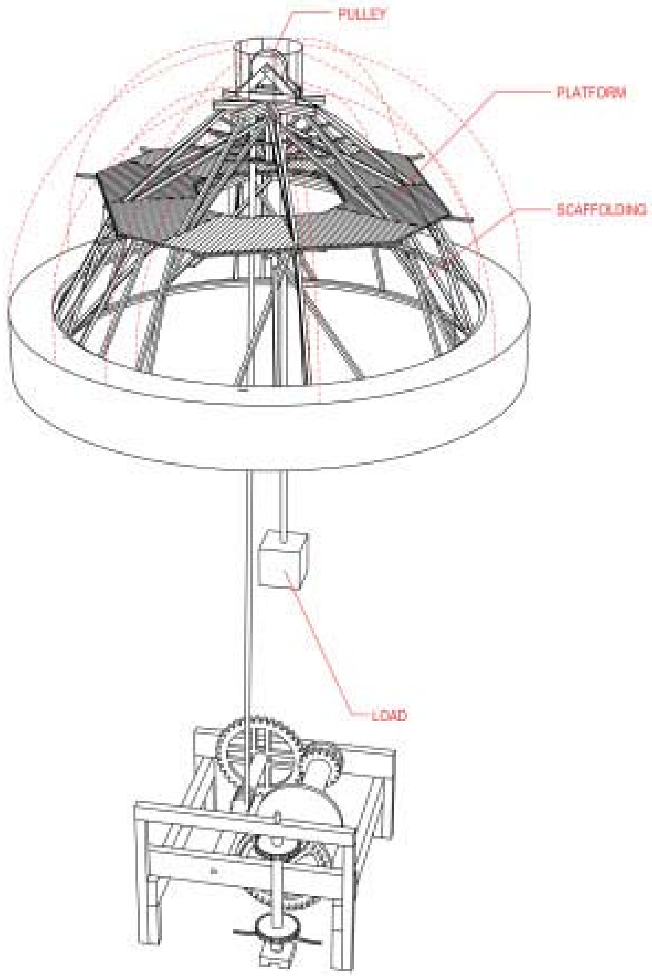


Figure 3 Construction and Vaulting of the Dome of Santa Maria del Fiore

Brunelleschi's Hoist

The relationship of the oxen-driven hoisting device invented by Brunelleschi and the scaffolding that was erected at the level of the dome's cupola was carefully coordinated. At the top was a pulley that brought materials through the scaffolding to a series of levels where the tradesmen were working. At the base of the hoisting device were gears that allowed it to be move forward or in reverse by way of a reversing clutch and screw-controlled load positioner without changing the direction of travel of the oxen that were tied to it.



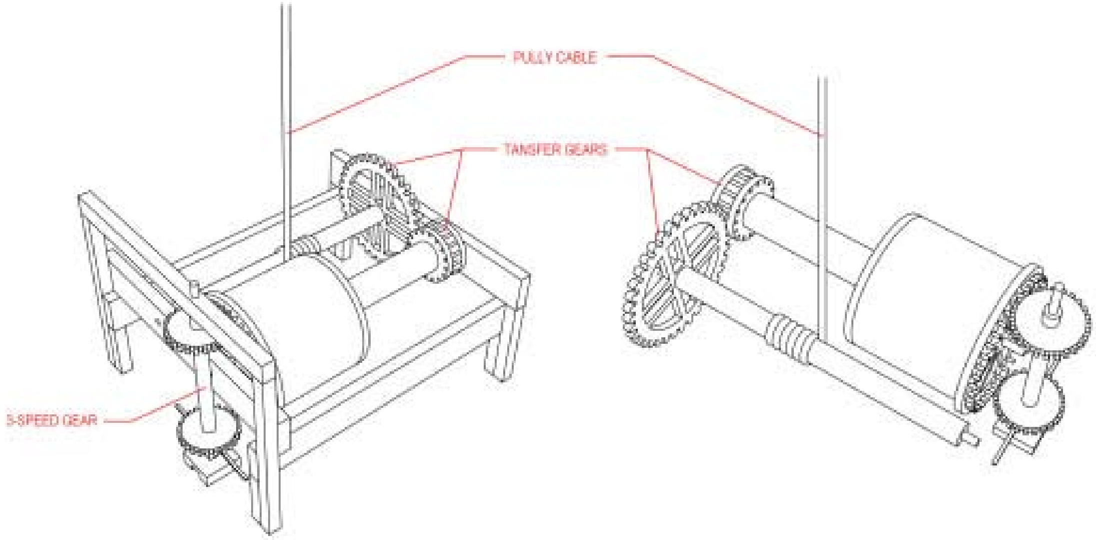


Figure 4 Oxen-driven hoist with mechanical Gear & Clutch

3.3.3 Designer & Maker—the Eames

With the advent of digital design and fabrication, we have entered a time where the expertise in making is becoming repositioned at the center of the architectural practice. Drawing parallels between analogous counterparts of the past, twentieth century designers and makers such as Charles and Ray Eames understood the value connecting material innovation with available craft skills and material processes. They were at the forefront of reaching equilibrium between the merger of production and assembly with design. This serves as a model for contemporary design and making as seen with the development of the plywood molded chair. According to Donald Albrecht it is considered a brilliant failure in finding of a solution to the challenge of making a chair from a single, body-fitting shell.[47]

The exploration—designing, making, and refinement of the Eames chair was a thirty year undertaking. It began with the Kleinhans chair, designed by Eero Saarinen and Charles Eames for the Kleinhans Music Hall in 1939. It continued with the development of a fiberglass chair in the early 1950's and ended with the Eames exploring ideas for a two-piece secretarial chair. This is an example of the design and making process that Eames followed in their office. "There was a constant working out of each issue one by one, a kind of learning by doing until a solution was revealed." According to Eames Demetrios, "as the solution then became the starting point for the next part of the journey" of a project.[48] The Eames were acting as craftspeople in finding a solution based on how to overcome resistance.

The Kleinhans chair was the starting point for the Eames in their search of a single body chair. The curve for the chair was developed by using an array of dowels to trace the shape of the human back and bottom. Although this chair was not mass-produced, the chair was constructed from a single curved slab with simple curves.

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[47] Donald Albrecht, "Evolving forms: A photographic Essay of Eames Furniture, Prototypes, Experiments," in *The Work of Charles and Ray Eames: A legacy of Invention,* Harry N. Abrams, Inc., Library of Congress, and Vitra Design Museum, (New York: Harry N. Abrams, Inc., 1997), 74

[48] Eames Demetrios, *An Eames Primer* (New York: Universe Publishing, 2001), 35

The idea for a plywood chair would come into play in 1940, as Charles Eames with Saarinen would enter the Museum of Modern Art (MoMA) competition of *Organic Designs in Home Furnishings*. The first attempt of a full-scale mockup, a single-mold made with plaster, did not turn out the way Charles would have liked. With the help of students, the Eames, began working with wood using a patented idea for wooden trays. This too failed. The first wooden shell was made in April but was not to any one's satisfaction. In order to fix these problems, Charles decided to explore cast iron casts of which the results were more failures. The problem was that the wood splintered after the molding process. Fixing this required that fabric be used on the chair that Eames submitted to MoMA. The Eames learned from this process that if you are designing for mass-production, it is necessary to discover how to make both the tooling and the end product.

As the journey of forming plywood continued, the Eames developed the *Kazam! Machine* to gain knowledge about fabrication processes (fig 5). These processes would determine the appearance and form of the plywood chair. This machine was a custom made press by Charles Eames to learn how to mass-produce molded plywood with compound curves in order to get single-piece shell made. With this machine, they could mold plywood within their own home. The press had curving plaster molds with electrical coils running through them which require a large amount of voltage. Instead of using conventional plywood, the Eames layered sheets of veneer or plies on top of one another with layers of glue in between them. Early experiments included molded-plywood sculptures that tested the capabilities of the plywood and machine. From here they tested different one-piece molded shells of plywood exploring the limits of technology and material. The one-piece molds splinter in one way or another. To fix theses failures, the Eames cut a slit or hole into them to relieve the tension created from forming a single-piece shell with compound curves (fig 5).

From all of the different tests conducted the Eames evolved their process, to consider the honest use of the material—spinoff of form follows function that acknowledges that there is more than one path to a given design choice. From the lessons learned from the plywood chair, the Eames began production of molded plywood splints. These splints fashioned with symmetrical holes, relieve the preset tension in the bent plywood and provided access to thread bandages and wrappings. These also reduce the vibrations associated into the body from movement.

After five years of exploring and pushing the limits of plywood, the Eames were still asking themselves what was the honest use of molded plywood and could a single piece shell in complex curves be made? [49] After years of frustration, the Eames decided to abandon the single-piece mold and turned it into a two-piece mold—a back and a seat. The result was the LCW chair of 1945.

Figure 5 Single mold Prototypes & Eames Kazam! Machine

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[49] Demetrios , *An Eames Primer,* 44

Craftsperson, designer, and maker Comparison:

Japanese Craftsperson

Profession: the Daiku—master craftsperson, chief carpenter

Object: Horyu-ji \Temple* Sogakudo, Uneo Park Tokyo (1890)

Material: Timber high & low grades

Tools: Yari-ganna-planing knife –cylindrical columns* Adze & chisels-mortises*

Inventions: maebiki-oga—one-maker rip saw (1568-1600, Momoyama period)

45 ° Hybrid plane (western and Japanese Styles)

Result: Speed: one maker=2 makers

Material waste decease: 10 boards = 12 board

Less-grade timber could be processed and planed

Filippo Brunelleschi

Profession: the Capomaestro—master builder

Object: Dome of Santa Maria del Fiore

60’ modelli showing construction & material techniques

Material: Spiral Brick Masonry

Tools: Modelli – Modern large scale physical model use to convey ideas

Inventions: Wooden tension ring chains

Oxen driven hoist w/clutch

Interior scaffolding with exterior platforms in relation to dome & Hoist

Result: No need for buttresses or internal formwork.

Taller building heights could be achieved.

Charles & Ray Eames

Profession: ‘Architect’—designers and makers

Object: Single piece Plywood molded chairs 1940-1946—‘Brilliant failure’

1945 LCW

Material: Honest use of molded plywood & Veneer Sheets

Tools: Plaster Cast = failed Cast iron cast & dies = failed

Inventions: Kazam! Machine- hot press for veneer sheets

Techniques: Holes & splits reduce splintering

Spin offs: Plywood molded leg splint

Result: 1945 LCW – Two piece shell & mold.

Single piece mold failed.

Plywood shapes need to be composed of multiple Curves/pieces

3.3.4 Conclusions of master builder/craftsperson

Similar to these past master craftspeople, the ‘architect’ as a CAD/CAM operator is neither a designer nor a maker, but both with an array of new tools that draw and make. This is a result of the convergence in the properties of digital drawing and the automated techniques of manufacturing into a hybrid practice with the adaptive technologies of CAD/CAM. The design and production of form is dependent upon the three following factors: (1) finding and using the right tool; (2) understanding the construction or fabrication processes; and (3) the material being used. In order to act as innovative architects or designers and makers we must design appropriate tools as a continual by-product of the investigation. As seen from comparing the Daiku or master Japanese craftsperson, Filippo Brunelleschi, and Charles and Ray Eames they were all constantly, changing and improving their tools to accommodate material and current technology. As a result, their designs reflect the tools, and construction techniques available to them. The Japanese craftsperson was able to increase production, while using a lower quality material with his ability to adopt and perfect the rip saw and plane. Filippo was able to convey his design intentions through mock-up models that showed the construction sequence and techniques similar to modern 3D information modeling. His scaffolding and hoist system allowed for taller buildings to be designed and built out of new material techniques. The Eames with their fascination with fabrication techniques pushed plywood design and construction to its limits with the development of their custom hot press.

3.3.5 Fab+craft Designer & Builder,

Computers are touted as opportunities to expand the designer's tool box and to solve technical problems by delivering accurate plans while looking at every imaginative angle at hand for a solution. The demarcation between design and fabrication is no longer feasible, if indeed it ever was. This has resulted in design functions being divided and assigned to specialized locations outside the professional firm and deep in the artisanal trade structure. As Paolo Tombesi points out, "more and more building needs to be thought of as a branch of architecture, rather than keeping architecture a privileged but inward-looking subset of building."[50] For over forty years the architect's role in building in the United Sates has been diminishing with their role in the built environment limited to the luxury housing niche and brand-name corporate towers. Surprisingly, with the introduction of digital design and fabrication, architects are conspicuously 90 percent absent from the annual built production completed.[51] As the architect's influence has dwindled, the cultural power of select high profile designer names has skyrocketed. Architecture has been taught and represented as an insider's profession and has been less subject to change due to its monopoly of expertise from outsiders or laypersons compared to the other professions of law, religion, and medicine. This is chiefly due to the confirmed detachment from labor and fabrication as an essential component of the architectural profession's self-image.

The design-build movement is the most aggressive counter response to the division of labor by promoting services by waving greater efficiency and authentic quality control. Its raison d'être is firmly rooted in the present day integration of design, engineering, and construction under a single entity. The underlying pragmatic advantage is an ongoing battle to reclaim the profession's own freedom to build.[52] With this new collaboration among design professionals and fabricators, the following questions arise. "Who will control the process of design and fabrication, and who is willing to take the risk?" Is it architecture that has to change or is it the way that it is practiced? A new paradigm of integrated design and construction is upon us.

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[50] Frampton, "Intention, Craft, and Rationality," 32
[51] Frampton, "Intention, Craft, and Rationality," 32
[52] Andrew Ross- Deamer, forward to *Building (in) The Future: Recasting of labor,* 13

Can one make and have ideas at the same time? Furthermore, what is the relationship between idea and fabrication in the digital age? The age old question of “can it be built” reappears.[53] What if architects define themselves by saying they make buildings instead of saying they *design* them? With digital fabrication, the information is presented not as singular bits but rather interconnected bits that allow us to organize them into innumerable relationships. We can introduce variations, change the order or interfacing of the connections and form different worlds. However, as projects increase in complexity, the knowledge required to bring the design through to completion also increases. How will this increase be met? Will it be a new type of project manager, architect or engineer, or a mixture of the three in one, or a team of multi-skilled individuals? I hypothesize that there is resurgence of craft with a new demand for the convergence of accurate digital design and crafted objects.

The utilization of digital information systems or the concept of working through the use of numerically controlled processes of bits to atoms allows for an individual to move directly from abstraction to object without typical meditation. Through the use of computer and CNC technologies, complex information travels from idea to product with the individual obtaining an increase in control relative to the production of ideas. The direct dialogue between virtual and the actual increases artistic autonomy resulting in the architect gaining greater onus of accountability. This is the result of the removal of the technological and sociopolitical gulf that has existed between abstraction and making.[54]

Fab+craft is similar to a digital arts & crafts movement, shifting from the making of the final product to making of a whole design.[55] Techniques developed through experimenting with fabrication are resulting in materials being detailed and constructed with machine-like precision. However, digital fabrication is not a substitute for the material imagination, nor necessarily does it inspire it. Material imagination is developed through the fluidity of material play and focuses on constraints. Through a rigorous process of translation and abstraction, digital fabrication

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[53] Brennan MacFarlane, “Making Ideas,” in *Architecture in the Digital Age: Design and Manufacturing*, 183

[54] William Massie, “Remaking in a Postprocessed Culture,” in *Fabricating Architecture: Selected Readings in Digital Design and Manufacturing* 108

[55] Lars Spuybroek. *Research & Design: The Architecture of Variation*. (New York: Thames & Hudson Inc, 2009) 7

enables the development of material systems which may be derived from the material imagination. This process of translation and abstraction is an informative opportunity to connect the material imagination with a disciplinary development of material systems.

The plan in architecture is thought of as the surface of action and the wall as the surface of perception. Lars Spuybroek rejects this distinction of action and perception and argues for a definition of the relationship between making and the made through different modeling strategies. He states, “the link between action and perception, movement, image, is the act of construction”[56] The bodily experience of touch, movement and sensual fulfillment of materials let us confront the world of consciousness. When the design process is based upon the act of making, space can be touched; thoughts are transformed to one’s hands resulting in sensorial and tactile objects coming into existence. John Dewey encourages this hands-on approach arguing, that things are learned best through action, with concern for context with requisite reflection upon the experience. Today, this idea is the core of action learning that contains threads of constructional thinking and can be seen as one of the more positive forms of inductive learning.[57]

No doubt the formal image has dominated digital discourse due to the geometric structure and screen-based interface of digital media. Through the inseparability between identity and skill, it should be no surprise that architecture has become so focused on visual imagery, and in turn, the identity of the design student is the image-maker. The first step is to explore how we use materials and the nature of the information about materials that we inquire. The second is to explore methods, and, ultimately design tools that “weave these strands of thinking, making, and producing into an integrated fabric.[58]

Through the process of specialization and division of labor in industrial standardization, building methods, types, and materiality have been reduced to the lowest common denominators in order to make production cheaper and optimized in design and construction. With the advent of digital design and fabrication, new processes of manufacturing and designing have entered

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[56] Asterios Agkathidis, *Modular Structures in Design and Architecture,*(Amsterdam, Bispublishers 2009) 78
[57] John Dewey. *Experience and Education, Late Works,* vol. 13 (New York: MacMillan, 1938) 59
[58] Mike Ashby and Kara Johnson, *Materials and Design,* (Oxford, Elsevier Butterworth-Heineman, 2002), 3

the realm of architecture. Can we theoretically replace 'handcrafted' with 'computer manufactured' to insinuate quality? This doctorate project seeks to explore the benefits of an integrated learning through-making process.

Digital fabrication is shaping the materials that once were done by hand and is blurring the discontinuities between conception and production established during the 20th century. Computers in conjunction with CNC-processing machines are being used as an efficient instrumentation of industrialization, but they have the potential to be used as an artisan tool. Although these tools are feared to be degrading they are innovative in reutilizing the skills of the self-reliant artisan. The industrial age gave way to a locked in battle of *craft verses the machine* with no true victor, yet the computer offers the means to conquer this battle with its power to expand the control over the built world by linking designers with contractors. The question becomes, can digital fabrication be used to reinstate the notion of craft in a world that relies heavily on the standardization of materials with the factors of time and cost determining the outcome? Craft needs to be rethought as the act of the go-between tools, objects produced, design as the process of imagination, and production as the process of technique. We are now entering a time when new master-builder-craftsperson is being revived as Ruskin sought to revive but in a way he could imagine. Digital fabrication techniques promise to make it possible for architects to regain their power and effective role, in design and in the fabrication of the finished product. The architect using CNC fabrication and assembly procedures will reconnect with the act of making establishing a relationship between maker and machine. As a result craft expands to include the act of making and design process as the resistance of materials is learned. This process puts the control information back into the designer's hands.

Craft can be defined as a skill developed or obtained over time through the direct relationship of making and working with materials. Architects have been disconnected from this relationship by working with the abstract processes of representation that become the instructions for the act of making to follow. As a result, the quality of craft has been measured and has been bestowed onto the builders and fabricators to carry out. But the demarcation of labor among the construction industry, and the steady increase of the cost of labor has resulted in very little craft produced. This can be attributed to the use of standardized materials and processes of the past several decades.

It is conceived that this will bring about a new role for the architect who will then act as a master-craftsperson in a seamless digital collaborative enterprise made up of the professional realms of architecture, engineering, and construction integrated together. Renzo Piano reinforces this idea that an architect must be a craftsperson—"the work of someone who does not separate the work of the mind from the work of hand."[59] Since the industrial age, each new generation of architects has had to harness the innovations of its time to the task of shaping the ever-changing built environment. The current impact of digital design is no different.

3.4 Technology & Architecture

In 1950, Ludwig Mies van der Rohe delivered the following speech to the Illinois Institute of Technology (IIT) where he was commissioned to redesign the university campus.

> *Technology is rooted in the past. It dominates the present and tends into the future. It is a real historical movement—one of the great movements which shape and repeat which shape and represent their epoch. It can be compared only with the Classic discovery of man as a person, the Roman will to power, and the religious movement of the Middle Ages. Technology is far more than a method; it is a world in itself. As a method it is superior in almost every respect. But only where it is left to itself, as in gigantic structures of engineering, there technology reveals its true nature. There is evidence that it is not only a useful means, but that it is something, something in itself, something that has a meaning and a powerful form—so powerful in fact, that it is not easy to name it. Is that still technology or is it architecture? And that may be the reason why some people are convinced that architecture will be outmoded and replaced by technology. Such a conviction is not based on clear thinking. The opposite happens. Wherever technology reaches its real fulfillment, it transcends architecture. It is true that architecture depends*

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[59] Branko Kolarevic, " Between Conception and Production," In *Building in The Future: Recasting Labor in Architecture*, 67

> *on facts, but it's a real field activity is in the realm of significance. I hope you will understand that architecture has nothing to do with the inventions of forms. It is not a playground for children, young or old. Architecture is the real battleground of the spirit. Architecture wrote the history of the epochs and gave them their names. Architecture depends on time. It is the crystallization of its inner structure, the slow unfolding of its form. That is the reason why technology and architecture are so closely related. Our real hope is that they will grow together, that someday that the one will be expression of the other. Only then will we have architecture worthy of its name: architecture as a true symbol of our time.*[60]

Historically, design follows technology because technological change has driven innovation. Technology makes invention possible. Production methods and technologies are now directly informing architectural construction. The challenge for the designer is to speculate how to exploit new possibilities that understand the technology, its promise, and its utility beyond expectations.

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[60] Ulrich Conrads, ed. Programs and Manifestoes on the 2oth Century Architecture (Cambridge: MIT Press, 1971), 154

3.4.1 Machine Fetishism

According to Karl Marx, technology is deployed for maximizing profit and value rather than for improving the material conditions for all. Within capitalism, workers apparently neither own nor understand the means of production, or the tools with which they work. As complex machines were increasingly introduced they absorbed the worker's functionality and as claimed by Marx deprived them from acquiring skills of assembly and production. [61] As result of machines taking over, human skill is reduced to a simple rote act. This act requires no thinking as it the same repetitive act over and over.

Humans are influence by the objects they produce and by the very tools that they use to perform laborious tasks. According to Marx, machine automation deprives the work of interest and character of the worker. As a result of performing the same rote action over and over, the worker is unable to gain new knowledge or skill sets. As time moves on, workers are reduced to more and more partial operations as automation takes place within the fields of production.

Machine fetishism becomes a product of technological alienation where machines increasingly display the very functions of which the worker is deprived of mobility, diversification of task, and skill. Therefore machines are optimized by capitalists who seek to maximize their production of material wealth.

Although Karl Marx argues against technology in his early writing he goes on in his later writings to accept machines and the transformation of work. He states that humans, nature, and machines all operate according to a single model of energetic flow by following the rule of energy transforming itself.[62] Yet Marx asserts a dualism between the human and the natural in order to describe the production of machinery as progressively conquering Nature by Spirit. As he describes in the *Grundrisse,* "nature builds no machines, no locomotives, railways, electric telegraphs, self-acting mules etc."[63] These are products of human industry; natural material transformed into organs through human's will over nature and of human participation in nature.

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[61] Amy E. Wendling, *Karl Marx on Technology and Alienation, (*New York: Palgrave Macmillan, 2009), 197
[62] Wendling, *Karl Marx on Technology and Alienation*, 204
[63] Wendling, *Karl Marx on Technology and Alienation,* 205

3.4.2 Design Technology

Potential implications of the digital revolution foretell that cities will increasingly disperse, that humans will have less interaction with one another, and that direct tactile experience of the physical world will be replaced by virtual constructions created within information-processing systems.[64] At the same time, computer technology used is creating a new understanding of exposing, displaying, and interacting with physical phenomena. Architects can use this new technology to build a new radically constructed world. However, architecture has to act in a broad, cross-disciplinary manner to merge into the flow of overwhelming future change, such to reveal its new potential. It can serve as a committed bearer of materiality and physical experience through the transformations of a new age of digital making.

The development of digital tools has acted as a catalyst for an emerging paradigm shift in architecture. Within today's world, it is possible to produce all effects and visions in the virtual world but the challenge is to bring the virtual world into physical reality and into architecture. In digital design infinite options of form can be produced without any connection to material properties. With this lack of material properties, contemporary architecture has no reasons of logic to form. According to Peter Eisenman, form without reason has no meaning, resulting in no architecture.[65] With the introduction of material properties and manufacturing limitations to the digital process of form generation, the digital world becomes connected to the physical world. As a result, an efficient building culture emerges with nonstandard constructions using new arrangements and compositions of materials.

3.4.3 NURBS & Parametric Design

A departure of Euclidean geometry of distinct volumes has occurred with the introduction of digital modeling software of 3D-Rihoincerous. Instead NURBS — (Non-Uniform Rational B-

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[64] Anderson Anderson, *Architecture and Construction,* 172

[65] Harald Kloft, "Engineering of freeform Architecture," in *Fabricating Architecture,* 126

Splines)—are used to present the geometry of continuous curves and surfaces prominently feature in contemporary design, NURBS are mathematical representations of 3-D geometry that can accurately describe any shape from a simple 2-D line, object, or 3-D surface.[66] NURBS are a highly appealing modeling tool with their ability to easily control their shape by interactively manipulating control points, weights, and knots. As a 3-D modeling tool, NURBS provide for an efficient representation of geometric forms using a minimum amount of data with very few steps in constructing a shape. Hence, today's modeling programs rely on NURBS as the means for constructing complex surface and solid models. NURBS are the digital equivalent of drafting splines used to draw complex curves for the cross-sections of ship hulls and airplane bodies. Because of their flexibility and accuracy, NURBS models can be used in any process from illustration and animation to manufacturing.

The most important property associated with NURBS, is the ability to produce 'smooth' curves. Curves produce by splines have curvature continuity as the radius of the curve changes smoothly along their lengths as compared to curves made from tangent circles and arcs. These curves despite their smooth appearance have discrete points at which the radius of the curve changes abruptly. The location of control points of a curve can affect its continuity curvature locally, meaning that segments of the curve can different levels of smoothness.[67] The use and organization of control points of complex curves and surfaces are expressed through sets of equations. These sets of equations are used to express certain quantities as functions of number variables or parameters which can be independent or dependent. The organization and use of parametric description of form is referred to as parametrics or *parametric design*.

Parametric design is a type of generative computer modeling. Parametric design and modeling focuses on the relationship of objects contained within a system. Parametric modeling allows for individual or group changes within the system. Depending on the parameters set, the entire system adjusts accordingly. In parametric design the manipulation of the entire system is referred to as the "global," and the manipulation of a single object is referred to as the "local." Parametric design can also be called associative geometry and views a digital model as single a

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[66] *What is NURBS?* http://www.rhino3d.com/nurbs.htm

[67] Branko Kolarevic, "Digital Morphogenesis," in *Architecture in the Digital Age,* 16

database. A digital object has embedded histories and data that allow it to react to itself as well as the rest of the model. As a result, associations are created between individual components, which are useful in designing and making, as various changes or variations can be made into a single component and the entire system will reflect the change.

3.4.4 Digital Fabrication

Digital Fabrication has spurred a design revolution yielding a wealth of architectural invention and innovation in expanding what we conceive to be formally, spatially, and materially possible. Similar to traditional drawing, digital production as a generative medium encounters its own hosts of restraints and possibilities with the potential to narrow the gap between representation and building. These digital processes of production facilitate the constructability of a building design, with constructability becoming a function of computability.

This direct link between what can be conceived and what can be constructed has resulted in projects realized through “file-to-factory”—CAD/CAM and CNC fabrication processes. As construction becomes a function of computability, the question as to whether a particular form is buildable is shifted to what new instruments of practice are needed to take advantage of these opportunities opened up by digital modes of production and construction. Moving from digital to physical via CNC tools opens numerous design opportunities for investigating the transitions between form, machine, and material.

CNC multi-axis milling is the oldest of all digital fabrication processes. CNC systems trace their origins back to the military and their effort to assure uniformity and control in the manufacturing of weapons. Their main concern was to eliminate errors in weapon production.[68] A back-and-forth play between humans and machine has become the challenging aspect in the transfer of knowledge from maker to the computer. A maker’s intelligence is transferred through computer code to the machine as a quantitative precision.

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[68] Andrew Ross, forward in *Building in The Future: Recasting of labor,* ed. Peggy Deamer and Philip G. Berstein, (New York: Princeton Architectural Press, 2010), 13

Digital fabrication is a process of transforming digital data of a design model into a physical object using various manufacturing technologies. Currently, four different fabrication methods are used to explore new geometric shapes and forms. These methods express the formal component in relation to the assembly of which it is a part.

Two-Dimensional

Two-dimensional fabrication is perhaps most commonly used fabrication technique. The primary cutting tools for two-dimensional fabrication are milling machines, plasma-arc, water-jet, and laser beam. These involve two axis motion of the sheet material relative to the cutting head and are executed by a moving head, a moving bed, or the combination of both. Wood routing and water-jet procedures actually cut a material by the removal of the material in contact with the head. Laser cutters melt or burn away material. The water-jet CNC machine is able to cut up to 15 inch thick titanium with very clean and accurate cuts. Laser cutters can cut materials such as wood and plastic up to 5/8 inch, while maintaining effectiveness.

Subtractive

Subtractive fabrication involves the removal of a precise volume of material from solids using electro, chemical, or mechanical processes which can be surface and volume constrained. Axially controlled machines can be associated with lathes that [relieve on one direction rotation of a material]. Surface controlled milling is two-dimensional fabrication with a rotating drill bit moved along the X and Y-axes with the removal of material which creates two-dimensional patterns. The milling of three-dimensional solids is an extension of two-dimensional milling. The Z-axis is added to the milling process to have the ability to lower and raise the cutting bit resulting in the volumetric removal of material. Yet there are limitations to this type of three-axial milling such as the ability to produce undercuts. In order to produce such cuts, a four or five-axial milling machine must be used. In quad-axis milling an additional axis of rotation is added to the cutting head or the cutting bed that holds the material known as the A-Axis. In a five-axis milling one more axis of rotation is added, called the B-axis.[69] This allows for the cutting head to perform undercuts as well increase the applications of the milling machine. All milling machines take an assortment of different diameter bits depending on the desired function at hand. Also the rate at which the machine cuts depends on the properties of the material.

In CNC milling, dedicated computer software such as MasterCAM performs the controlling functions over the movement of a machine tool using a set of coded instructions. Depending on the function at hand this type of software generates the instructions for the milling process for the imported digital geometries which control the motion, feedrate, operation of the spindle and other parameters of the milling machine. Depending on the instructions, which hold the tool paths, to be generated, milling of shapes can be accomplished in a variety of ways. These tool paths can become very complex when using four and five machines and need to be performed by a skilled operator. A tool path is the CNC program of coded instructions for the machine to execute, these commands made from words that contain a letter and a numeral value. The letter ‘G’ designates these codes hence, CNC codes are referred to as the “G-codes.”[70]

Additive

In a kind of reverse milling process, additive fabrication entails incremental forming by adding material in a layer-by-layer. This type of fabrication process is often referred to as layered manufacturing, desktop manufacturing, and rapid prototyping. Basically it could be referred to as digital sectioning of an object. Rapid prototyping is defined as the automatic construction of physical objects by the sequential delivery of energy to solidify material to specified points in space to produce an object. This is known as Stereo-lithography. The digital model is sliced into two-dimensional layers and the information of each layer is transferred to the processing head of the manufacturing machine. Powder-based printing & Fused Decomposition Modeling (FDM)-

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[69] Kolarevic, “Digital Production,” in *Architecture in the Digital Age,* 34
[70] Kolarevic, “Digital Production,” in *Architecture in the Digital Age,* 35

consists of melting plastic filament that solidifies upon cooling through the use of a 3D printer.[71] Due to the cost of machines, material type and strength properties, and the limited size of objects produced this type of fabrication has very limited application in building design and production.

Formative

Formative fabrication involves applying [heat, steam, restricting forms, or mechanical forces] to a material in order to change the physical form of the material into a desired shape. These are axially and surface constrained through the use of height-adjustable numerically control (CNC) pins for compound planes and numerically control bending for plane curves. Testing the limit of the material, a designer is able to explore a variety of formal variations keeping a high degree of freedom in design. This process reshapes material by deforming it permanently by stressing it past the elastic limit by heating and then bending it while in a softened state. Steam bending boards and bending metal in softened states are examples of these methods. These new digitally-enabled processes offer rich opportunities for the exploration of new geometries. Also, these new processes allow a designer to increase the creativity and the productivity of their design work.

3.4.5 Digital & Material Techniques

This section breaks down the five basic digital material techniques used in Digital fabrication.

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[71] Kolarevic , “Digital Production,” in *Architecture in the Digital Age,* 36

Sectioning

The best representational tools at an architect's disposal have been that of orthographic projections of plans and sections. As a design device, both plans and sections are indispensable communication. These traditional representational methods can also be applied and used as methods of building. Sectioning is a two-dimensional drawing exercise involving taking cuts through a three-dimensional object. This cross-sectional method has been proven to be an effective technique. Current 3D modeling software typically includes sectioning tools that can instantaneously cut parallel sections through an object at desired intervals.

Sectioning is not new in the construction industry, as it is commonly used in the airplane and shipbuilding to make compound and doubly curved surfaces. Ship hulls and airplane bodies are defined first through the sectioning of a series of ribs within which are latter cladded with outer surface materials. These outer and inner skins are lofted over these ribs to enclose space. Lofting is the method that determines the shape of cladding or surface panels by building in-between curved section profiles; this is comparable to lofting using 3D computer modeling software. Lofted 3D surfaces are unrolled into flat surfaces or re-described in section as curves to be fabricated.

Tessellating

In architecture, tessellating refers to tiled patterns on buildings and digitally defined mesh patterns that are a collection of triangular geometries that fit together without gaps to from a plane or surface. Due to the inherent economy of means of digital technologies new interest has begun in patterning due to the increase of variation and modulation in manufacturing. One is able to move with ease from a digital model to a vector-line file straight to fabrication. This type of process allows for a fluid transaction between the stages while reducing labor involved in transferring data between different types of mediums. With the use of digital design, architects are tiling larger-scale materials into patterns similar to bricklayers of the past. This has resulted in unique abilities for architects to modulate, design, and build custom panels from larger stock in many different sizes and configurations. Currently there are two primary ways to model three-dimensional forms in digital format of NURBS and meshes.

The tessellating technique, discretization—"the digital definition of surface as a coordinated set of discrete parts," has rapidly accelerated in use to gradate surface and skin within non-orthogonal forms. [72] This technique helps architects to modulate surface and skin in a logical way of points, grids, and networks.

Folding

Just as the name suggests, this technique induces folds into a planar material in order for the material to gain stiffness and rigidity which allows the material to span distance and be self-supporting. Folding is effective at multiple scales and often produces visually appealing results. The technique allows for new spaces to emerge without losing their characteristics.

As a material operation, folding becomes a generative design method that creates fluidity and multi-functionality with a continuous plane or surface. Folding is able to expand the three-dimensional use of a surface through deformation and inflection, which add stiffness. The early and mid-twentieth century saw the use and experimentation of the structural potential of folding which consisted mostly of creased forms and hyperbolic curvatures to create various roof structures that utilized geometry to aid structural performance.

Within digital fabrication, folding is taking on a new role in that building materials are folded into place. Folding has a wide range of forms that it consists of, including: creased surfaces, folded plates, and wrapped volumes. These share similar fabrication processes with three-dimensional surfaces in that they unfold into two-dimensional templates for cutting.

Material selection is restricted to those that are pliable, easily scored, and capable of bending without breaking. Various materials consist of sheet-metal, thick paper, and fabric. Unlike

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[72] Lisa Iwamoto, *Digital Fabrications: Architectural and Material Techniques,* 37

sectioning, folding relies on the characteristics of the original material as it adds new spatial, visual, and tectonic dimension.

Contouring

Since a majority of construction materials such as plywood, stone slabs, medium-density fiberboard (MDF), and cast composites are two-dimensional sheet materials, contouring can be used as a technique that reshapes these surfaces into three-dimensional reliefs through the subtractive process. Basically, contouring is carving or the removal of material from virgin sheets or blocks to make parts and regulated patterns and form into various sheet materials.

Digital fabrication has enabled architects to transcend carving practices that have exclusively resided in traditional handcrafted practice. Digital craft is gaining ground though the use of CNC routers and mills as a way to revive the carved, ornamented, and articulated surfaces of the past. Through the use of data translated from digital models into tool-paths, these machines are acting as computer-controlled versions of traditional hand tools. The routing process is used to experiment by generating surface texture.

Contouring, as subtractive process is a *highly* material and time intensive procedure to use. But architects are able to elevate ordinary standardized building materials to new extraordinary uses and levels. As result of this process, there is a large amount of material wasted as well as time spent on this type fabrication compared to others. Yet contouring as a fabrication technique is able to closely match the smooth, fluid nature of NURBS forms and surfaces. Therefore, contouring offers the most direct and precise means of achieving curved geometries compared to the other techniques of tessellating and sectioning. Generally, contouring is used at smaller scales to make parts where as sectioning is used at larger scales to produce building components. At a larger scale, contouring has been used and maximized through the milling of molds for shaping planar materials for building components. This is commonly referred to as Forming.

Forming

Forming is the process of generating multiple parts from a number of molds or forms. It is generally used as a mass-production process. Within building construction, forming is a common practice of producing structural members consisting of cast-in-place slabs, walls, precast panels, entire buildings depending on their size.

In mass-produced formwork, each unit is identical resulting in repetitive patterns as seen in common concrete construction. For non-standardized mold making, digital fabrication of formwork yields new possibilities for conceiving and designing customized formwork in a cost-effective manner. But not all applications can be cost effective, such as stamped sheet metal panels because producing unique dyes for limited use is highly expensive. Concrete formwork currently yields the greatest flexibility in using digital technology and other fluid materials through the use of milling form work out of plywood and foam. With this type of atypical construction process, formwork can be digitally modeled and produced directly through a CNC router. This eliminates the need for construction drawings that can result in on-site errors.

Industrial design formwork is referred to as molds and plugs and is made from milling machines and rapid-prototyping machines that are used to cast parts. Based off solid void relationships, the process involves the use of negative molds positive molds referred to as female and male molds respectively. Female molding uses the processes of casting, vacuum and thermo forming, and injection and rotor molding. Male molding strictly uses vacuum and thermal forming. These female and male molds are used in various different methods and combinations with a lot a time and design innovation going into making the mold itself.

The third type of molding is similar to that of surf board production where resin-coated fiberglass fabric is applied over shaped molds. In this case, the final outcome does not always resemble the mold, but they yield flowing smooth surfaces with the mold becoming an integral structural component of the object produced.

3.5 Case Studies

This section explains the case studies chosen to explore existing work along the lines of digital fabrication methods and techniques as discussed in the precious sections. Projects were chosen based upon their varying material exploration, fabrication method, and technique.

3.5.1 Zero Fold Screen-2010

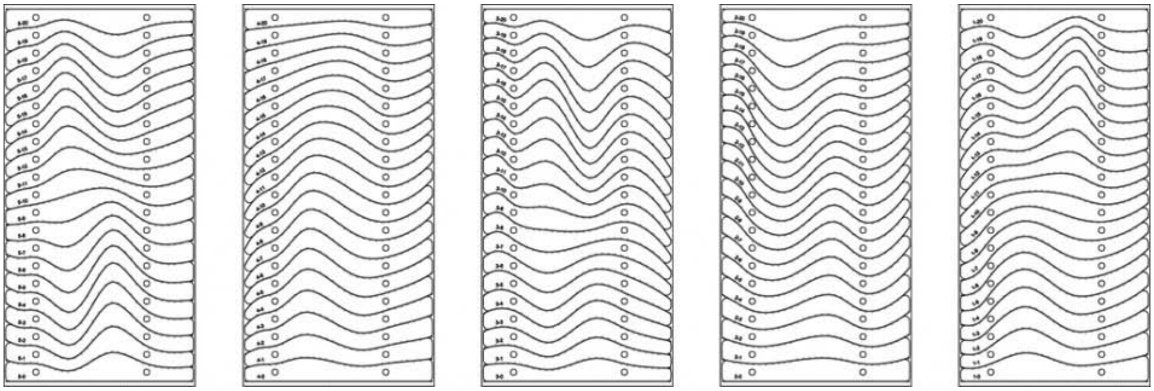
MATYS

Kasian Gallery, University of Calgary, Canada

Size: 10′ x 10′ x 3′

Figure 6 MATSYS, Zero Fold Screen

Digital fabrication has allowed many architects and designers to explore various complex geometries with little or no attention to the amount of material waste they are producing in their projects. Similar to traditional design approaches many digitally fabricated projects are generated with typical sheet material parameters being subordinated to the end of the process. This results in a significant amount of new material being wasted and is no different than traditional building design and erection within relation to large amounts of cut offs being thrown out. This project reverses that logic by starting from the basic material dimensions and then generating a series of components that will minimize material waste during CNC cutting while still producing an undulating, light-filtering screen.



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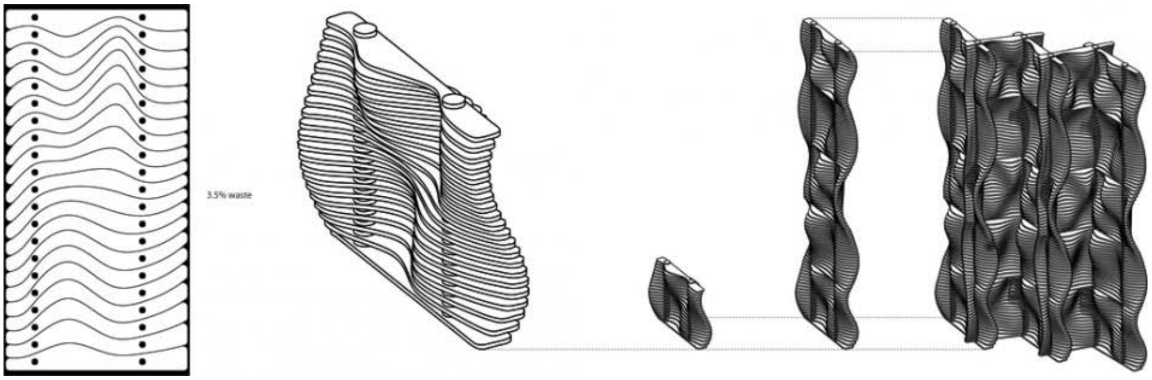


Figure 7 Zero Fold Screen Assembly & Sheet Layouts

Materials: (30) 3/4" x 4' x 8' plywood sheets

Waste from cutting: 3.5% 1 sheet =1.12 ft^2 30 Sheets = 33.6 ft^2

Fabrication Techniques: Sectioning and Folding

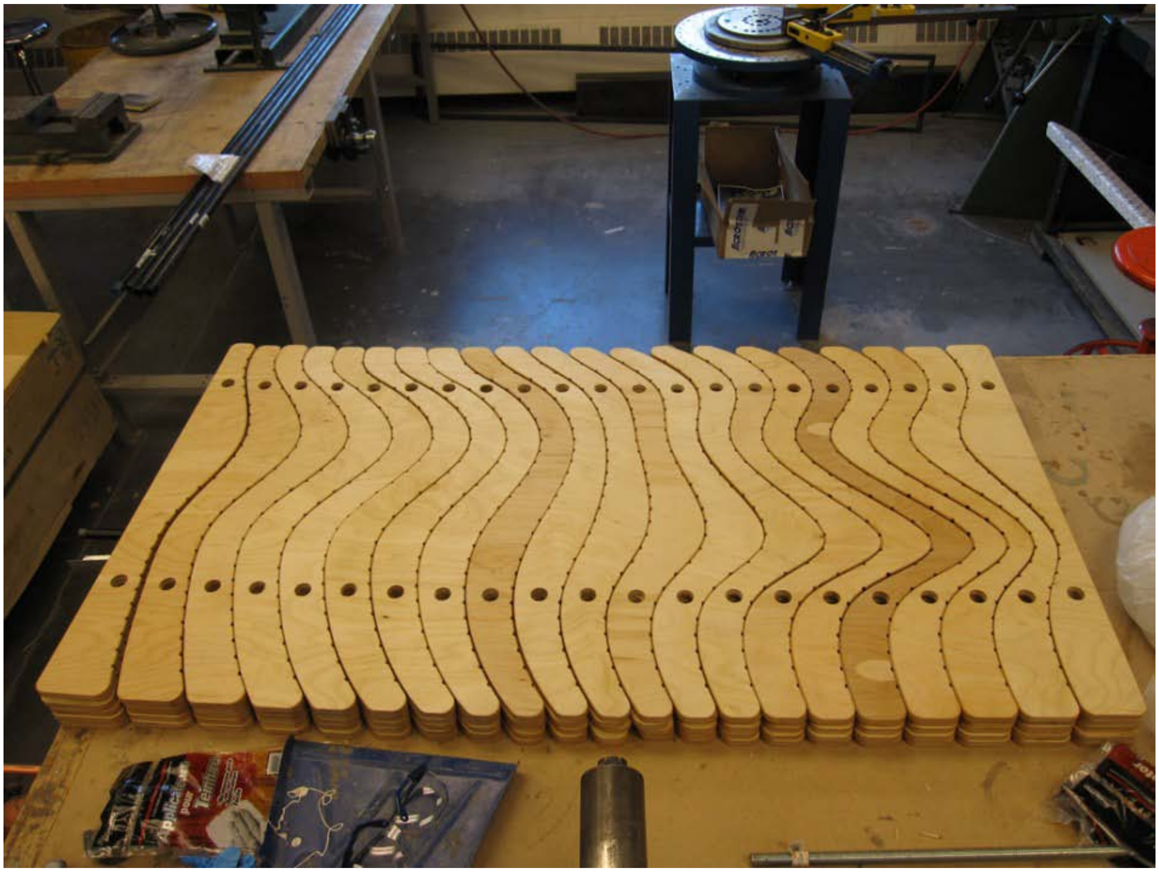


Figure 8 Zero Fold Screen Part Arrangement to Reduce Waste

3.5.2 p_wall -2006

MATYS

Banvard Gallery, Knowlton School of Architecture,
Ohio State University, Columbus, Ohio
Size: 15′ x 9′ x 1′

This project investigates the self-organization of two materials, plaster and elastic fabric, to produce evocative visual and acoustic effects. Inspired by the work of the Spanish architect Miguel Fisac and his experiments with flexible concrete formwork in the 1960-70s, p _wall attempts to continue this line of research and add to it the ability to generate larger and more differentiated patterns. Starting from an image, a cloud of points is generated based on the image's grayscale values. These control points are then used to mark the positions of dowels which constrain the elasticity in the fabric formwork. Plaster is then poured into the mold and the fabric expands under the weight of the plaster. The resultant plaster tile has a certain resonance with the body as it sags, expands, and stretches in its own relationship with gravity and structure. Assembled into a larger surface, a pattern emerges between the initial image's grayscale tones and the shadows produce by the wall.

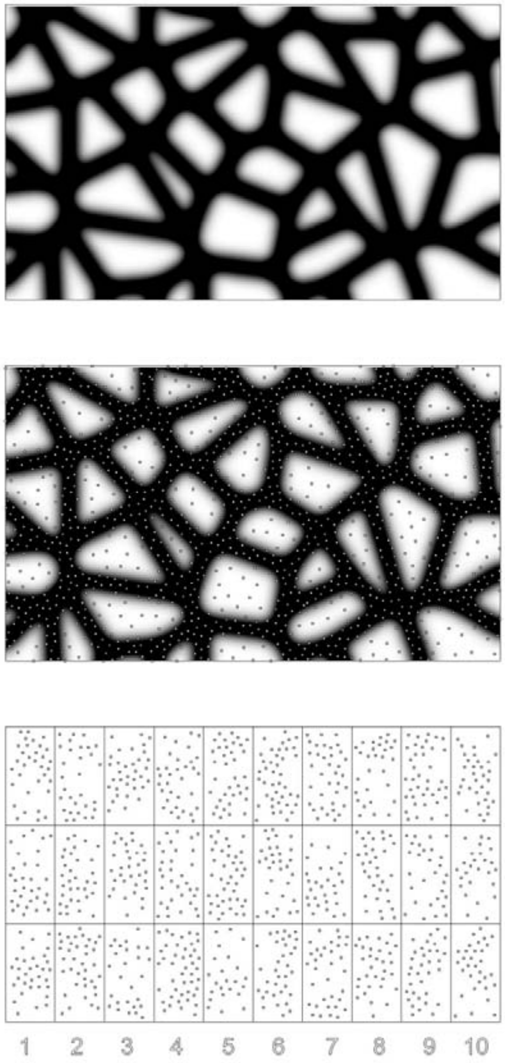


Figure 9 P_Wall 2006 Script

Figure 10 MATSYS P_Wall 2006

3.5.2 p_wall 2009

MATYS

Location: San Francisco Museum of Modern Art
Size: 45′ x 12′ x 1.5′

P _Wall (2009) was commissioned by the SFMOMA Architecture and Design Curator Henry Urbach for the exhibition Sensate: Bodies and Design. The wall is an evolution of the earlier work exploring the self-organization of material under force. Using nylon fabric and wooden dowels as form-work, the weight of the liquid plaster slurry causes the fabric to sag, expand, and wrinkle.

Fabrication Techniques: Tessellating and Forming

Materials: Plaster

Form materials: plywood frames with elastic fabric sketched over them. This project shows how a project can use digital fabrication and traditional methods of forming a fluid material to create a simple procedure of casting resulting in a complex material effect. P_Wall 2009 with its geometric shape module is assembled similar in fashion to that of a typical masonry block wall.

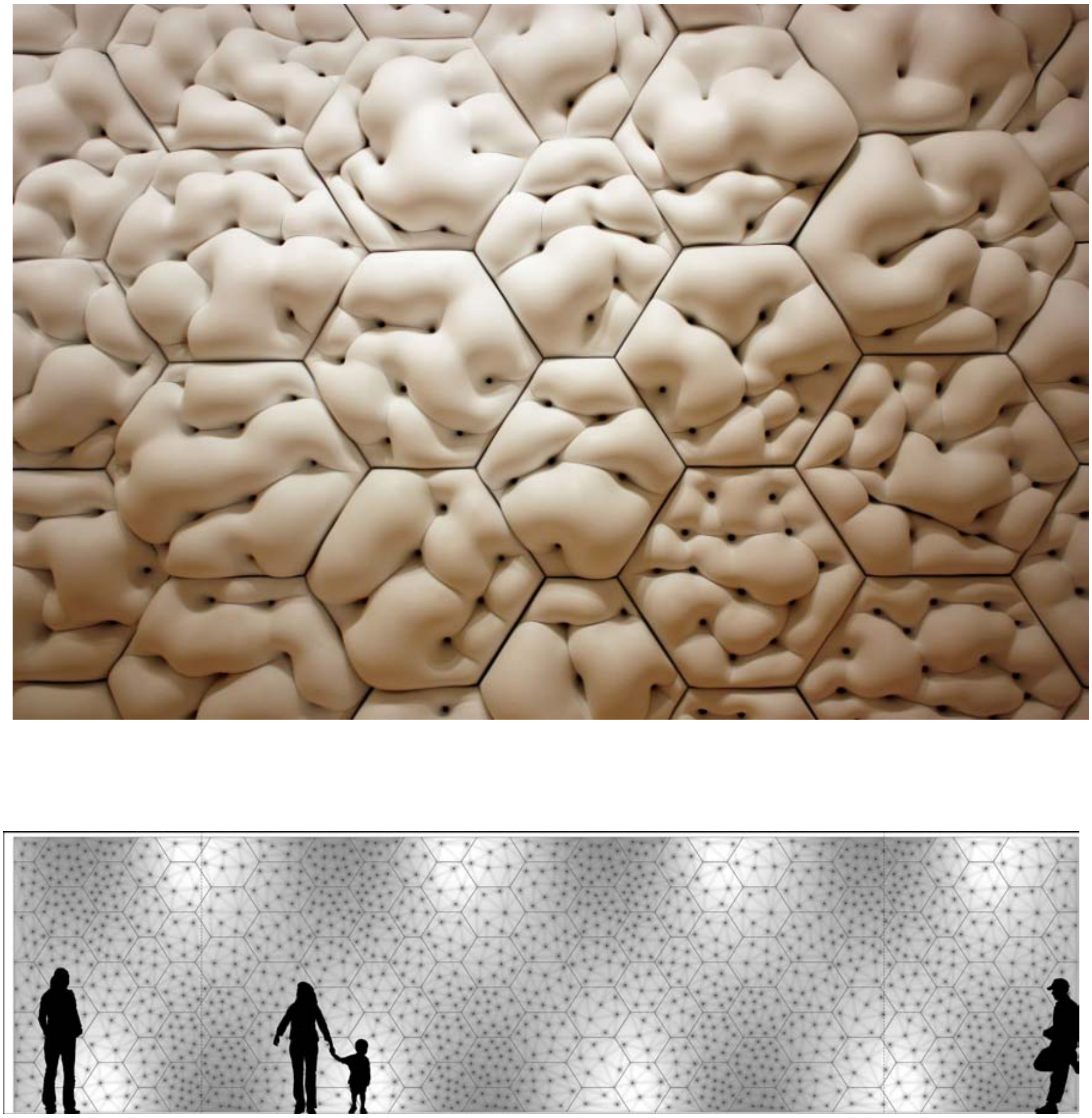


Figure 11 P_Wall 2009 Wall Script & Form Work

3.5.4 RICD/ITKE Research Pavilion-2010

Universität Stuttgart

Achim Menges, Jan Knippers

This innovative structure demonstrates the latest developments in material-oriented computational design and production processes in architecture. The result is a bending-active structure made entirely of extremely thin, elastically-bent plywood strips.

Its physical form is determined from a system of internal and external pressures and constraints. However, in architecture, digital design processes are rarely able to reflect these intricate relations. Whereas in the physical world material form is always inseparably connected to external forces, in the virtual processes of computational design form and force are usually treated as separate entities that are divided into processes of geometric form generation and subsequent simulation based on specific material properties.

The research pavilion exhibits an alternative approach to computational design where the computational generation of form is directly driven and informed by physical material characteristics and behaviors. The structure is entirely based on the elastic bending behavior of birch plywood strips. The strips are robotically-CNC manufactured as planar elements, and subsequently connected so that elastically bent and tensioned regions alternate along their length. The force that is stored locally in each bent region of the strip, and maintained by the corresponding tensioned region of the neighboring strip, greatly increases the structural capacity of the system. The changing of the connection points along the structure results in 80 different strip patterns constructed from more than 500 geometrically unique parts In order to prevent points of concentrated bending moments. The differentiation of the joint locations enables an extremely lightweight system. The entire structure, with a diameter of about 40 feet is constructed using only 5/16-inch birch plywood sheets.

Based on 6400 lines of code one integral computational process derives all relevant geometric information and directly outputs the data required for both the structural analysis model and the manufacturing with a 6-axis industrial robot with milling attachment. This type of robot can be compared to the human arm as the robot and the milling attachment act as the hand which allows it to swivel and perform various cuts that typical tri-axis CNC machines cannot perform.

Fabrication techniques: Sectioning and Folding

Materials: 5/16” birch plywood

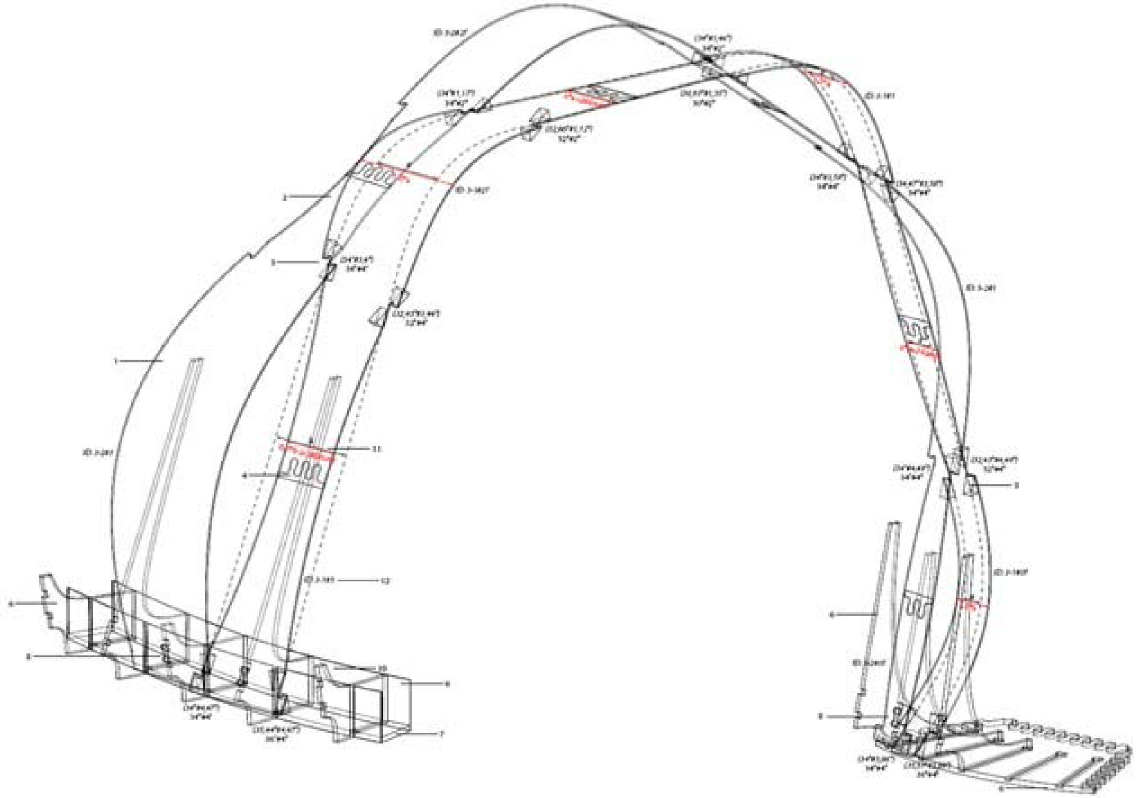


Figure 12 Research Pavilion Plywood Structure

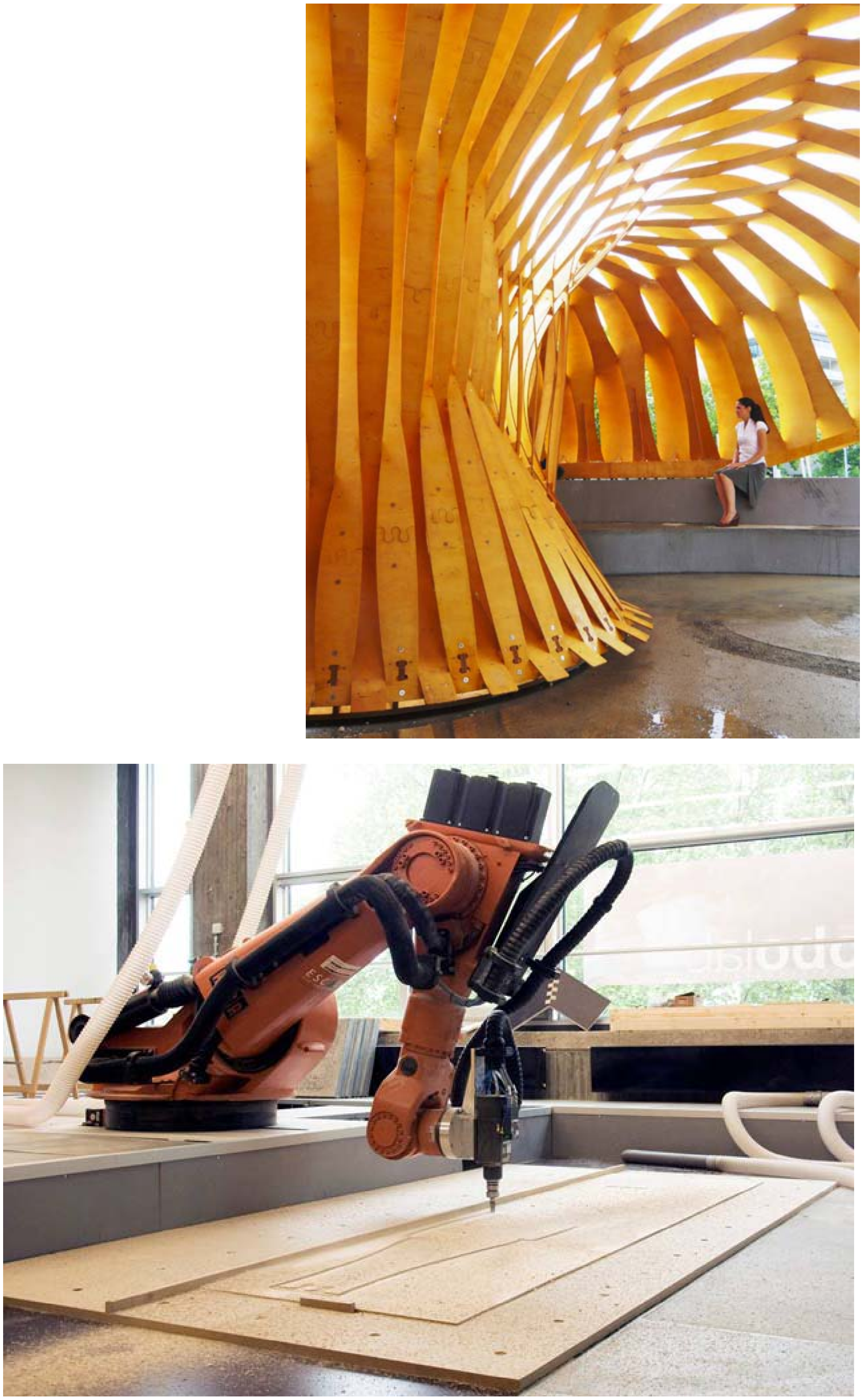


Figure 13 Research Pavilion

3.5.5 Bone Wall 2006

Urban U & O

Figure 14 Urban A& O Bone Wall Half Cell

The Bone Wall explores the relationship between surface and depth of pattern making. Thought geometry, it aims to demonstrate, structure, materiality and spatial configuration. As a result, patterning is shown to be a multi-dimensional method capable of occupying complex deep and spatial geometries. The bone wall began with the modeling of a base half cell that when inverted and rotated combines to form a cellular unit. The base cell has a total of 18 corners known as control points. There are a total of seventy-two cells resulting in 2,592 control points linked in the wall. Any change made to the geometry of the splines will regenerate the shape of each cell, which demonstrates the nonlinear and reciprocal relationship between computer software programs and the designer. This is referred to as parametric modeling.

Fabrication Techniques: Contouring and Sectioning

Materials: 4' x 8' x 4" sheet of 15lb high-density foam

Five cells are arranged per sheet with each cell divided, or "*sectioned*" into three slices so that they can fit on the bed of the CNC milling machine. Upon close inspection, the trace of the router's tool path can be seen on the surface of the wall at a step-over of 1/32." This adds to the overall effect of the wall as is does not have a smooth finished look. In this case the machine left its mark similarly to that of a craftsperson living his mark on a material. Each milled piece was glued and assembled by hand to construct the wall. The final assembly was then painted.

As the bone Wall demonstrates, a new opportunity for designers to participate in the processes of fabrication and making that resuscitates the debate over ornament's contingency in contemporary architecture.

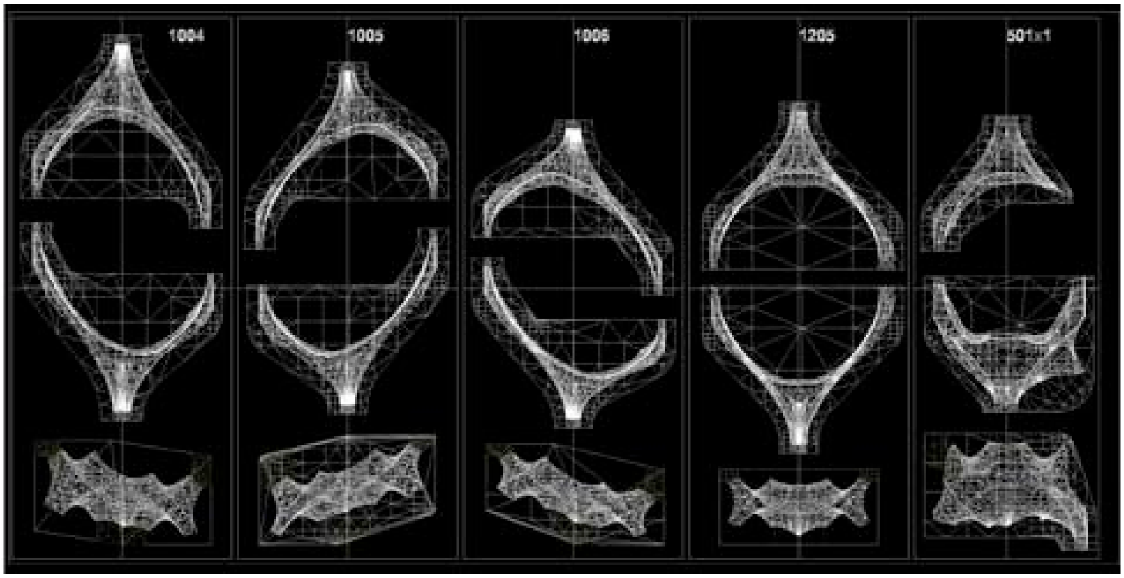
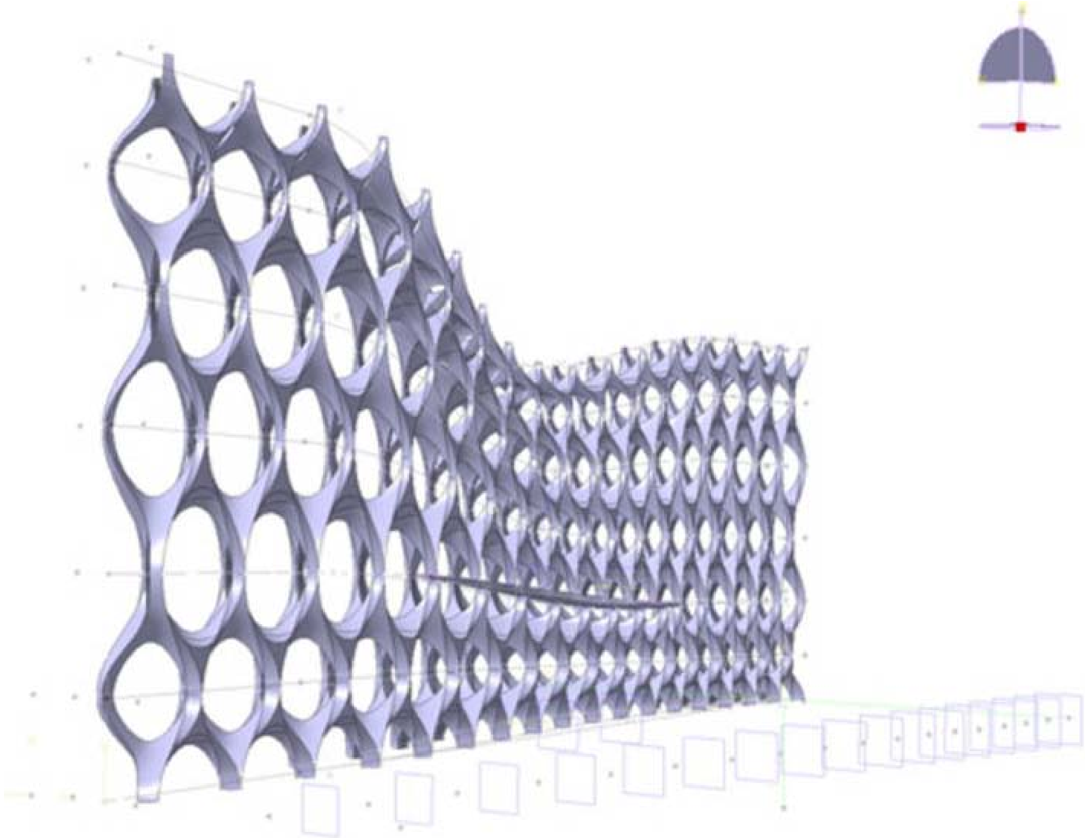


Figure 15 Bone Wall Module Arrangement



3.5.6 Hale Pili<u>h</u>onua

Team Hawaii-University of Hawaii-U.S. Department of Energy Solar Decathlon 2011

Designed to function in harmony with naturally available resources, Hale Pilihonua, is a holistic approach to sustainable living. The shape of the shell, or semi-*monocoque*, structure is made of bio-based, fiber-reinforced polymer (FRP) providing resistance to damage from corrosion, termites, rot, and floods. Within the walls of the shell is the primary structure of laminated plywood ribs that are reinforced with ¼" built-up angles to support the various live, dead, and seismic loads to the house. This rib system consists of two rib profiles—an end rib and an intermediate rib with blocking and steel cables in-between to provide lateral support. Each end rib has an added ¼" built-up steel angle to allow for each module to be bolted to both the substructure and one another. Due to the cross-section shape of house, each plywood rib, and the various steel angles associated with the rib profile are cut through CNC processes to maintain the tolerance in the curvature in the profile of the house.

Fabrication Techniques: Sectioning

Materials: ½" x 4' x 8'-layered structural-I grade plywood sheet

The plywood rib is composed of two layers – an A and B rib of ½" plywood laminated together. Each "A" and "B" sub-layers is made up of eight members each that overlap one another to ensure that no single joint falls onto another so as to ensure structural integrity. There are a total of 16 members per rib, and 36 identical total ribs in the house which results in 576 members that need to be cut precisely to match each other. Each rib is cut in half horizontally, to create an upper and lower module. This was done in order to transport the preassembled ribs in a shipping container.

With the use of the Nesting tool in MasterCAM, the total number of sheets of plywood was reduced from the initial 144 sheets to 91 with a total of 18 different arrangements of parts. Each arrangement required three different tool paths in order to be cut out by the CNC router. One layout consists of marking holes to allow for screwing the sheet of plywood down to the bed of the router to ensure that each part and cutoff will not move during the process. The second tool path is the etching, or *carving* of each part number into each member to ensure proper assembly sequence once cut. The last tool path consists of actually cutting the various parts from the plywood sheet. These three tool paths combine together to form the “G”-code which amounts to, on average 20 minutes of fabrication time. Therefore in order to cut out 91 sheets, it will take approximately 1,820 minutes or 30 hours of cut time.

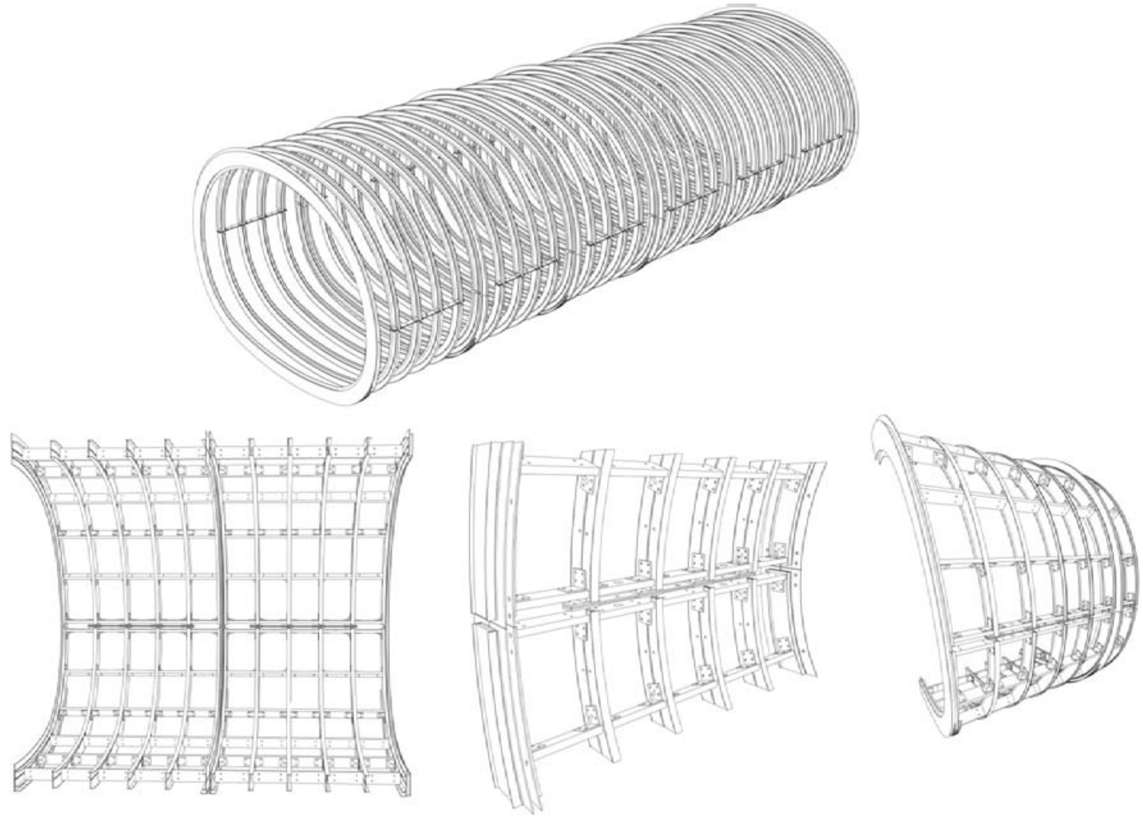


Figure 16 Hale Pilihonua Framing layout

Partial “G”- Code for one layout (Code is 72 pages long)

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(PROGRAM NAME - 2011_04_19_CNC RIBS 1)
(   3/8 STRAIGHT BIT   TOOL - 2 DIA. - .375)
T2 M6
S18000 M3
G0 G90 X11.5324 Y24.3986 Z1.
G81 Z-.025 R1. P0. F200.
G80
G0 Z1.
X20.1107 Y24.7109
Z1.
G81 Z-.025 R1. P0. F200.
G80
G0 Z1.
X35.4475 Y14.6786
Z1.
G81 Z-.025 R1. P0. F200.
G80
G0 Z1.
X34.7091 Y74.2983
Z1.
G81 Z-.025 R1. P0. F200.
G80
G0 Z1.
X20.575 Y66.0634
Z1.
G81 Z-.025 R1. P0. F200.
G80
G0 Z1.
X13.7919 Y70.0101
Z1.
G81 Z-.025 R1. P0. F200.
G80
G0 X.9813 Y48.774 Z1.
G1 Z-.025 F100.
X3.1892 Y50.1016 F200.
X1.8652 Y47.8901
Z.975 F100.
G0 Z1.
X2.5272 Y48.9958
G1 Z-.025
X2.087 Y49.4361 F200.
Z.975 F100.
G0 Z1.
X3.2744 Y47.5177
G1 Z-.025
X3.191 Y47.4482 F200.
X3.1214 Y47.3648
X3.0657 Y47.2675
X3.0289 Y47.1683
X3.0145 Y47.0637
```

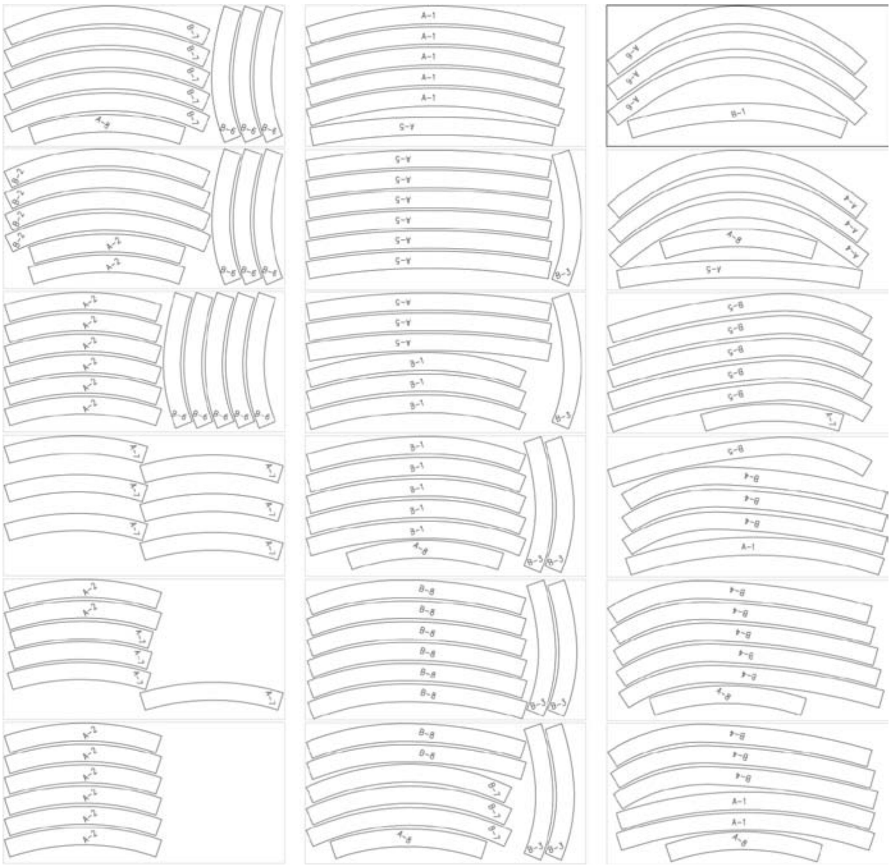
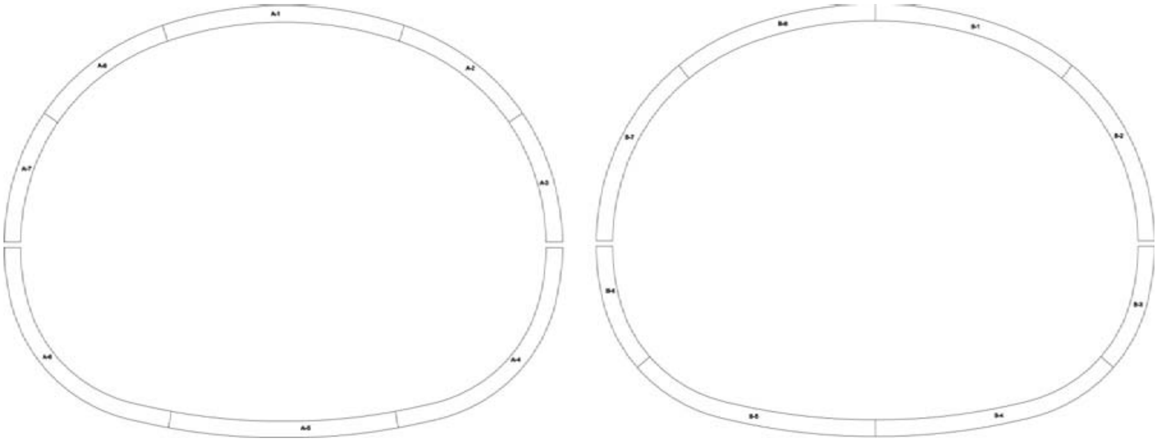


Figure 17 Hale Pilihonua 18 different Sheet Layouts



3.5.6 Conclusions

The common thread within these projects was that digital design and fabrication allowed for the exploration of design-through-making as a designer-maker. Each project used multiple fabrication techniques in conjunction with conventional methods of assembly. Hence, to achieve a desired outcome, no one project can be solely designed and built using either one fabrication technique or method but requires the expertise of using a combination. As seen through each case study, the form and design reflects the method of making used to conceive it. The Zero Fold Screen, using a "bottom-up" approach of designing to a full sheet of plywood was able to reduce material waste while producing a custom undulating, simple yet complex screen. The p_walls used digital design as a tool to generate patterns to make flexible form work. The different variations reflect the forces of gravity on the wall as they revealed the honest use of plaster as a fluid material. The bending-active RICD/ITKE Research Pavilion structure demonstrates the use of applied external stresses as design parameters within digital design and fabrication. The Bone wall verified the use of parametric modeling within mass-customization. The CNC-machine milling marks were reflected in the unfinished wall similar to the mark of a craftsperson. Also, the ability to fabricate individual custom parts from simple stock material is presented in Hale Pilihonua. This project illustrated the ability of CAD/CAM technology to nest material parts together to reduce cut-offs and waste.

IV. Making Methodology

4.1 Introduction

> *"Most Architects do not make buildings—they make information for buildings. They turn ideas into drawings, models, text and data where many results inform the production of buildings and others do not." – Bob Sheil*[73]

The act of making demands a know-how that is rationally connected with the tactile and the physical. This body of understanding and perception goes beyond the generation of information. It involves a skill that many designers cannot proclaim or practice. During the transition of realizing ideas in built form, some qualities are gained and others lost. The question of how things are made generates a phase of opportunity. As the tools of fabrication are put into play, architectural design does not end. Making is discipline that can instigate rather than simply solve ideas. It is a design process.

Architects need to be hands-on by making the places they design by using their tools available to manipulate things and study how they work. According to Kenneth Frampton, one learns architecture by doing. He insists that "architecture is a craft-based practice closely tied to the life world," where learning and making are different aspects of the same activity[74]. This process never stops—as every stage of a building is a moment in which one learns how to build. Frampton believes the real tectonic comes into being at the position where the pressures and tensions of a structure meet. By having an inventive curiosity, architects will become compassionate collaborators for people who like to explore, resulting in projects that search beyond the boundaries of expectation.

Hands-on architects, Mark and Peter Anderson use the term "making" as a description for their architecture and construction practice instead of "designing and building".[75] They are both designers and makers. However, but are not a part of the world of design-build which typically consists of profit optimization and produces results that are not particularly good examples of

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[73] Bob Sheil, ed.,"Design through Making: An Introduction," in "Design Through Making," special issue, *Architectural Design* 75, no 4 (July/August 2005): 6

[74] Glenn Adamson, *Thinking Through Craft,* 99

[75]Anderson Anderson, *Architecture and Construction,* (New York: Princeton Architecture Press, 2000), 14

either designing or building. According to the Andersons, “Sculptors and painters ‘make art’; one rarely hears the term ‘designing’ or ‘building’ in relation to these creative disciplines.”[76] Making can be defined by the characteristic of place making – “of human settlement or invention in the existing environment,” with design and construction being broken up into three strands by relating them to the three sequential phases in building construction: Earthwork, Framing, and Plumbing.[77] These three specific physical actions in the sequence of building comprehensively represent the construction process in the principal stages of: preparing the site and foundations, erecting the building, and finally connecting it into a larger infrastructure.

Architects need to be always reassessing the typical top-down hierarchy of the design-bid-build process where traditional formats for working drawings and specifications are produced first, followed by bidding and construction last. Learning from the construction process and by using the engaged mind of an experienced construction worker “is critical to a good design and building. “[78] On the other hand, if the architect is not doing this phase of the design work, then a contractor or an industry person is doing it. At a minimum, architects need to understand how all of these decision making processes work. A more intriguing possibility is to move architects into the depths of industrial processes and the systems of production, so that they are drawing upward the creative ingenuity they are experiencing the act of making. There is never a shortage of people who know how to do things. The Andersons rely heavily on this belief of making and searching for new processes as they state, “There isn’t much room for us to operate, and we have the impression that if you want something made you have to start out already sure of what you want. That’s where we got started in the business, knowing that we knew nothing at all. Of course we always start with some idea of what we’re trying to do, but then we set things into motion and ski along with the flow of who-knows-who, who-knows-what, and how can we do something we don’t already know using the limited time and money

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[76] Anderson, *Architecture and Construction,* 14

[77] Anderson, *Architecture and Construction,* 21

[78] Anderson, *Architecture and Construction*, 35

available. This is a building as a learning process, rather than a specifying and ordering process."[79]

4.1.1 Process: Flash Research

The process of the investigation of this project will follow the do it yourself or D.I.Y. design method of Flash Research developed by David Benjamin and Soo-in Yang. Flash research entails targeted, precise and intense explorations of an architectural idea. This process combines detailed knowledge of materials with direct engagement of making through testing. This allows for the designer maker to experience and learn from the craft processes of making with the linking of hand and eye, and the use of one's intellect or 'know-how' to control a physical outcome. While many architectural projects involve exploration through rendered images, Flash Research explores design through full-scale mock-ups and prototypes. As stated by Michael Stacey , "The importance of physical testing cannot be overstated; although we now have access to very sophisticated computational analysis, it is vital for architects, engineers and designers to remain grounded by physical reality."[80] The witnessing of physical testing is a source of confidence for designers and engineers. The physical observation of seeing a wall system undergo and survive a load or wind test takes one beyond the abstract. The work developed from this method is raw, quick, and rough and explores unknown territory, but this is where discovery happens at its truest nature. Many design projects follow a linear path of research first, and then design, and finally construction. The flash research method entails all three at once where Research = Design = Construction—it does not count unless it can be built. It looks deeper into the equation of *Constructability = Computability* where making is used as a design tool.

This type of research involves self-imposed limits of time and budgets that test a host of design possibilities through full scale, functioning prototypes. Another important aspect of Flash Research is that is presents itself to be swappable modules in new and within old

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[79] Anderson, *Architecture and Construction*, 35

[80] Michael Stacey, "In my Craft and Sullen Art or Sketching the Future by drawing on the Past," in "Design Through Making," ed. Bob Sheil, special issue, *Architectural Design* 75, no 4 (July/August 2005): 41

structures. These modules are precise and immediate as they can upgrade old systems without replacing entire structures. Therefore projects are not stand alone building designs but rather they have their own weight and significance. They are a part of an open source research endeavor being conducted, jointly, and loosely by others.

Rapidly changing conditions occurring in our environment requires new architectural propositions and solutions. These propositions call for testing physical conditions and properties. Testing constructions call for iterative prototyping. Prototyping and testing is the core of flash research with material processes adding to it. “Matter, here and now matters”[81]

Matter can be viewed as raw material, a unit of measurement, and a tool in understanding the relationship between the body, force and material. Material is the matter of ‘architecture’ as it makes the form, the space, the performance and the experience that is architecture.

4.2.1 Wood: ½” Plywood Sheathing

Digital design challenges typical form making with infinite options of forms being produced without any connection to material properties, but relies heavy on surfaces—sheets that twist, bend and form into complex shapes. These shapes—due to the complexities of curvature—do not translate well into the actual. So how can we achieve defined curves and shapes? The answer lays in our ability to translate a material’s properties by conducting real life tests under actual external forces in which the results can be transferred back into the digital model as a design parameter.

Plywood is an engineered wood panel manufactured from thin sheets of cross-laminated veneer and bonded under heat and pressure with adhesives. It has been one of the most ubiquitous building materials used for decades. Plywood is available in a dozen common thicknesses and over twenty different grades. Half-inch plywood (actual 15/32”) is cheap, common, and is used in everyday building construction from subflooring as a diaphragm, vertical shear walls, and roofing underlayment. It gains its strength by being mechanically fastened with nails to a frame.

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[81] David Benjamin, “Open,” in *Matter: Material Processes in Architectural Production,* 144

Platform framing is usually made from dimensional lumber arranged on one way grids. But within this traditional construction of walls, floors and roofs, ½” plywood is used as a flat panel that is a part of larger assemblies. These assemblies tend to be redundant in material use and often consist of overlapping of material in which is not needed. Usually plywood is used as the base panel that seals a wall cavity while providing rigidity to the wall or roof. Depending on the structural and performance of the wall, the initial layer of plywood is overlapped with various materials to build the wall up to meet the desired results. Therefore, how can plywood as a manufactured material be *tectonic* and useful in producing a performative wall assembly within an environment to promote a quality of life? Plywood as a sheet material similar to a piece of paper allows for it to bend into various shapes. Using digital fabrication methods and techniques researched and examined in this project, in conjunction with traditional craft techniques of making, variations of curvature can be introduced into a plywood panel.

Although, Plywood is composed of sheets of veneers that are cross laminated for strength, stiffness, and dimensional stability it carries the elastic bending behavior of wood along with it. Due to its grain structure wood is stronger in one direction than the other. This allows wood to flex or bend. But there are limits as to how far wood can be bent as it will split or break.

Bending solid wood is a traditional woodworking technique. As a forming process it has considerable advantages for producing curved wooden parts. Bending wood is materially very efficient and structurally advantageous, as it reorients the grain direction to follow the part’s curvature. This avoids excessive fiber run-out on the edges and cross-grain weaknesses.[82]

In boat construction, furniture making, and musical instrument making, the well known subtractive technique of kerfing is used to bend wood.[83] The properties of wood grain orientation allow for the removal or cutting of material perpendicular to the main grain direction without overly compromising the overall structural capacity of a wood member.

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[82] Jeffrey Niemasz, Jon Sargent, and Laura Viklund, “Steam-Bent Wood Lattice Morphology,” Achimenges.net, http://www.achimmenges.net/?p=5003 (accessed February 16, 2012).

[83] Jeffrey Niemasz, Jon Sargent, and Laura Viklund, “Steam-Bent Wood Lattice Morphology,” http://www.achimmenges.net/?p=5003 (accessed February 16, 2012).

As mentioned before, plywood is manufactured through the additive process of laminating and stacking an odd number of layers of wood together. This gives each sheet of plywood a consistent structural capacity, but as single unit it is weak. By using the same additive process that creates a single sheet, it is possible to overlay one sheet of ½" plywood onto to another, therefore increasing its structural capacity even further. With two layers, ½" plywood becomes stiffer and able to carry larger structural loads.

4.3 Prototype Assembly & Fabrication

In order to bring all of this together, prototypes using ½ inch plywood need to be explored to address the various material properties, fabrication methods and techniques used to make a performative wall assembly. The prototypes draw upon the fabrication methods discussed earlier of formative, additive, subtractive, and two-dimensional as each test explores the bending capacity of plywood.

Prototypes at the scale of 1:2 using the CNC router will allow for the exploration of joints, rhythm and system strength.

Full scale prototyping using CNC routing will allowed further exploration into the relationship between individual crafting of unit parts, the collective assembly, and performance of the aggregate system—system strength, material strength, stability and detailing.

The initial tests will address the following:

Sufficient load /curvature limits of plywood

- the elastic ability of ½ plywood (1) single layer, (2) kerfing,
- Grain direction/profile flat verves edge.

V. Prototype Investigation

5.1 Introduction

In chapter 5, the creation and testing of plywood prototypes are applied to the equation of *Constructability = Computability.* These prototypes are designed with a focus on material and assembly properties of plywood as design parameters.

Plywood is a conventional wood-based composite panel built up primarily of sheets of veneer called plies. It is classified into the categories of: (1) construction and industrial plywood, and (2) hardwood and decorative. Plywood is constructed with an odd number of layers with grain direction of each adjoining layer oriented perpendicular to one another. A plywood layer can consist of one ply or of two or more plies lamented with parallel grain direction. Within a sheet of plywood, there can be an odd or even amount of plies, but always contains an odd number of layers. The outside plies are referred to as faces with a front and back ply. The outer layers and odd-numbered layers within have their grain direction placed parallel to the long dimension of the sheet. The grain in even numbered layers is placed perpendicular to the length of the sheet. Inner plies with grain running parallel to the faces are called centers where as inner plies with perpendicular grain direction to that of the faces are called crossbands. In order to distinguish the number of plies (individual sheets of veneer in a sheet, the number of layers, number of times the grain orientation changes), sheets are described as three ply, three layered or four ply, three-layered, etc. (fig 18).

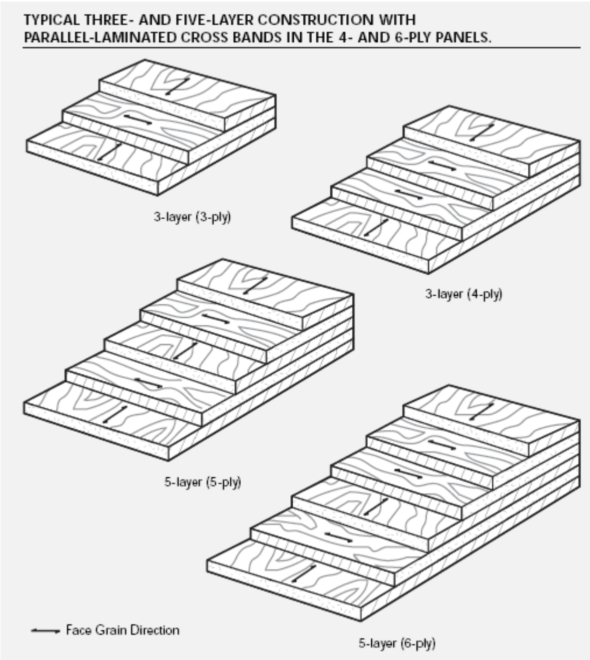

Figure 18 APA plywood composition

5.1.1 Construction and Industrial Plywood

Generally, construction and industrial plywood is used where performance in more important than appearance. If desired, grades of construction and industrial plywood are made with faces selected for appearance and are used with clear natural or lightly pigmented finishes. Sheets of construction and industrial plywood are typically made from the softwoods of douglas-fir and southern yellow pine but true firs, western hemlock, and western pines are also used.

Construction and industrial plywood is categorized by exposure capability and grade using the Voluntary Product Standard PS 1-07.[84] It is denoted as either Exposure 1 or Exterior. *Exposure 1 plywood* is used in applications not permanently exposed to weather, whereas *Exterior plywood* is intended for applications with repeated wetting and drying, or long-term exposure. The bond quality of these types is evaluated by the same test procedure, but a higher level of performance is required for Exterior plywood.

The primary adhesive type used in the manufacturing of construction and industrial plywood is Phenol-Formaldehyde or PF resins. These resins are used in applications exposed to weather during construction and other moisture situations such as occasional pluming leaks, wet foot traffic, etc. PF resins are commonly known as *phenolic resins* which are relatively slow curing as compared with other thermosetting resins. The heat exposure associated with the pressing Phenolic-bonded composites result in a reduction in their hyrgroscopicity—the ability to hold water. Because of this, phenolic bonds are believed to be boil-proof, as they maintain their composite material dimensional and mechanical properties under wet conditions. Due to the inherently darker color of the resin, they tend to be aesthetically unsuitable for interior paneling and furniture. [85]

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[84] Nicole M. Stark, Ziyong Cai, and Charles Cai, "Wood-Based Composite Materials: Panel products, Glue-Laminated Timber, Structural Composite Lumber, and Wood-Nonwood Composite Materials.", In *Wood Handbook: Woods as an Engineering Material*, *Wood Handbook*, Centennial ed. by Forest Products Laboratory(Madison, WI: United States Department of Agriculture Forest Service, 2010) 11-7

[85] Nicole M. Stark, Ziyong Cai, and Charles Cai, "Wood-Based Composite Materials: Panel products, Glue-Laminated Timber, Structural Composite Lumber, and Wood-Nonwood Composite Materials," 11-3

5.1.2 Hardwood and Decorative Plywood

Hardwood and Decorative plywood is made from many different species of wood from all over the world. Well over half of the panels used in the United States are from overseas. Hardwood plywood is used in applications that include decorative wall panels, furniture, and cabinet panels where appearance is more important than strength as it is available completely finished. The production of this type of plywood is intended for interior or other weather protected uses. A very small amount is manufactured with adhesives suitable for exterior service, such as marine applications. Hardwood and decorative plywood is categorized by species as well as it's characteristics of face veneer, bond durability, and composition of center layers. These center layers can be veneer, lumber, particleboard, MDF, or hardboard.

The exposure capability of hardwood and decorative plywood is denoted as Exterior and Interior. Exterior exposure is divided into *Technical* and *Type I*, but both of these classes share the same bond requirements.

Urea-Formaldehyde or UF resins are used in the manufacturing of hardwood and decorative plywood for interior applications. Unlike PF resins, UF resins break down with moisture and excessive heat exposure; therefore UF-bonded panels are cooled after emergence from the press. The advantages of using UF resins include lower curing temperatures, ease of use, and light color. UF resins are the lowest cost thermosetting adhesive resins used in manufacturing composite sheets. When greater water resistance and appearance is desired, UF resins are combined with Melamine-Formaldehyde or MF resins because of their light color.[86]

5.1.3 Plywood Grading & Species

Plywood grades indicate intended use, span rating, and the grades of the face and back veneers. A plywood sheet can be a combination of different graded veneers for the front and back faces. Veneer quality is based on visually observable characteristics of knots, decay, splits, insect holes,

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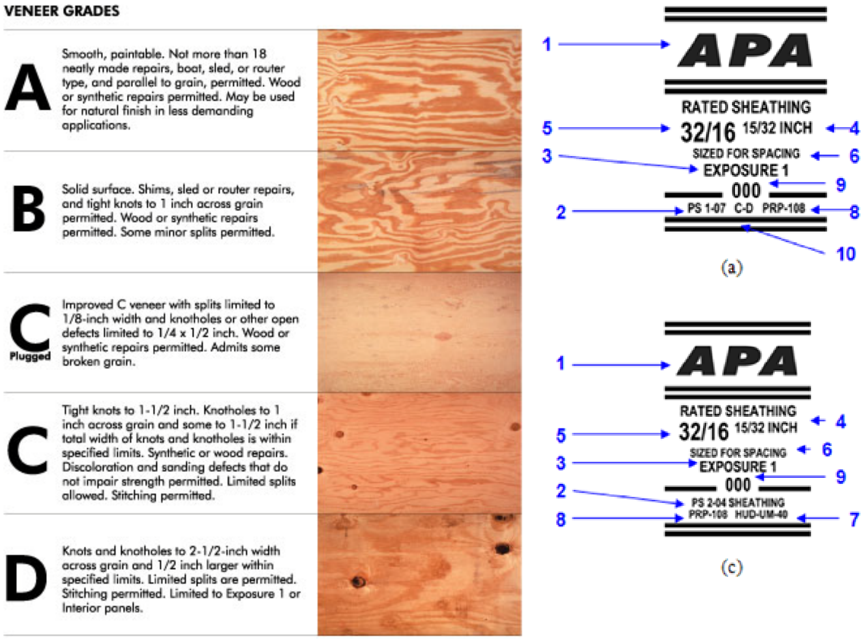
[86] Nicole M. Stark, Ziyong Cai, and Charles Cai, "Wood-Based Composite Materials: Panel products, Glue-Laminated Timber, Structural Composite Lumber, and Wood-Nonwood Composite Materials", 11-3, 11-4

surface roughness, number of surface repairs, and other defects. Veneer is divided into five levels or grades ranging from N and A, B, C, and D. N and A being the highest grade, while level C and D are the lowest allowable grades. N stands for natural finish whereas A is intended as a paintable surface. Usually all construction Grades of plywood come with a stamp on the back side denoting the grade and type (fig 19).



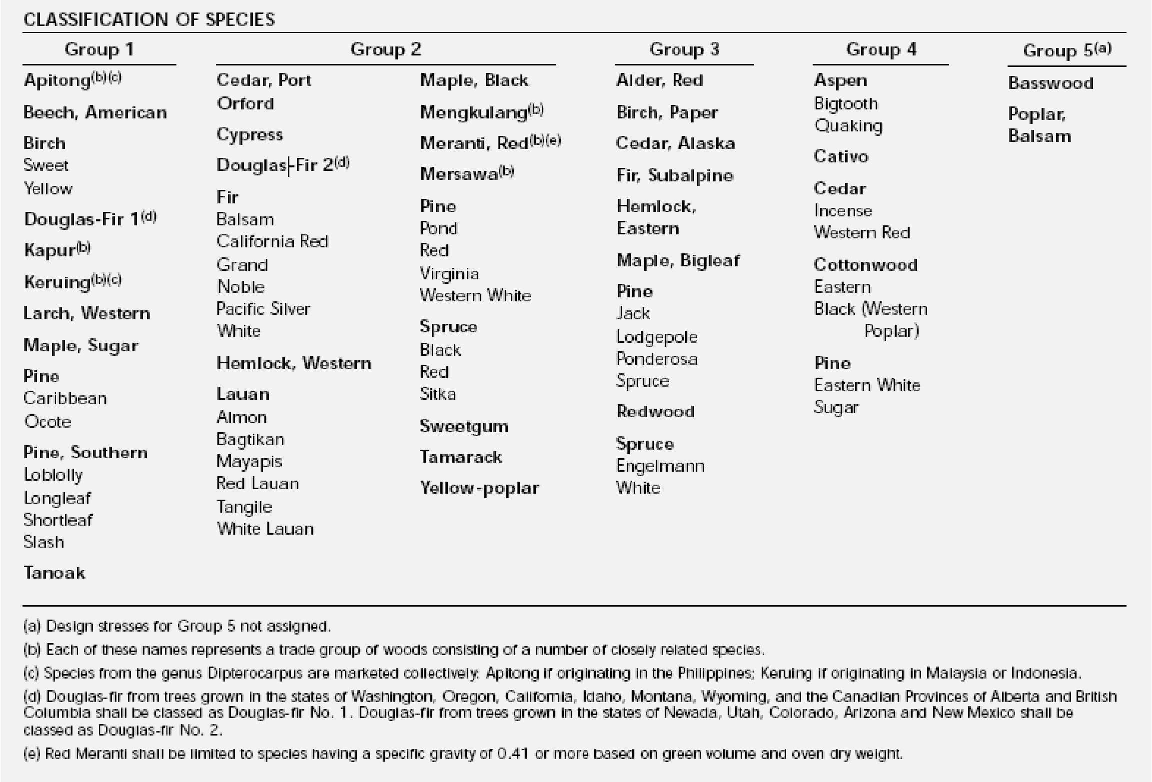
VENEER GRADES

A	Smooth, paintable. Not more than 18 neatly made repairs, boat, sled, or router type, and parallel to grain, permitted. Wood or synthetic repairs permitted. May be used for natural finish in less demanding applications.
B	Solid surface. Shims, sled or router repairs, and tight knots to 1 inch across grain permitted. Wood or synthetic repairs permitted. Some minor splits permitted.
C Plugged	Improved C veneer with splits limited to 1/8-inch width and knotholes or other open defects limited to 1/4 x 1/2 inch. Wood or synthetic repairs permitted. Admits some broken grain.
C	Tight knots to 1-1/2 inch. Knotholes to 1 inch across grain and some to 1-1/2 inch if total width of knots and knotholes is within specified limits. Synthetic or wood repairs. Discoloration and sanding defects that do not impair strength permitted. Limited splits allowed. Stitching permitted.
D	Knots and knotholes to 2-1/2-inch width across grain and 1/2 inch larger within specified limits. Limited splits are permitted. Stitching permitted. Limited to Exposure 1 or Interior panels.

Figure 19 Plywood Stamp & Grading

1) Third party agency
2) Conformance to product standard
3) Exposure Classification
4) Thickness
5) Span rating
6) Denotes for spacing of panel edges during installation to reduce buckling
7) Recognition as a quality assurance agency
8) Performance rated standard indicating structural-use panel test procedures
9) Manufacturing mill identification number
10) Strength axis (OSB only)

Due to the large selection, comprised of over seventy species and trade groups, that can be used for construction and hardwood plywood, the APA—the Engineered Wood Association (used to be referred to as the American Plywood Association)—categorizes plywood veneer species into five groups based on the structural properties of clear wood set forth in the ASTM D-2555 standard of establishing clear wood strength values.[87]



CLASSIFICATION OF SPECIES

Group 1

- **Apitong**(b)(c)
- **Beech, American**
- **Birch**
  - Sweet
  - Yellow
- **Douglas-Fir 1**(d)
- **Kapur**(b)
- **Keruing**(b)(c)
- **Larch, Western**
- **Maple, Sugar**
- **Pine**
  - Caribbean
  - Ocote
- **Pine, Southern**
  - Loblolly
  - Longleaf
  - Shortleaf
  - Slash
- **Tanoak**

Group 2

- **Cedar, Port Orford**
- **Cypress**
- **Douglas-Fir 2**(d)
- **Fir**
  - Balsam
  - California Red
  - Grand
  - Noble
  - Pacific Silver
  - White
- **Hemlock, Western**
- **Lauan**
  - Almon
  - Bagtikan
  - Mayapis
  - Red Lauan
  - Tangile
  - White Lauan
- **Maple, Black**
- **Mengkulang**(b)
- **Meranti, Red**(b)(e)
- **Mersawa**(b)
- **Pine**
  - Pond
  - Red
  - Virginia
  - Western White
- **Spruce**
  - Black
  - Red
  - Sitka
- **Sweetgum**
- **Tamarack**
- **Yellow-poplar**

Group 3

- **Alder, Red**
- **Birch, Paper**
- **Cedar, Alaska**
- **Fir, Subalpine**
- **Hemlock, Eastern**
- **Maple, Bigleaf**
- **Pine**
  - Jack
  - Lodgepole
  - Ponderosa
  - Spruce
- **Redwood**
- **Spruce**
  - Engelmann
  - White

Group 4

- **Aspen**
  - Bigtooth
  - Quaking
- **Cativo**
- **Cedar**
  - Incense
  - Western Red
- **Cottonwood**
  - Eastern
  - Black (Western Poplar)
- **Pine**
  - Eastern White
  - Sugar

Group 5(a)

- **Basswood**
- **Poplar, Balsam**

(a) Design stresses for Group 5 not assigned.

(b) Each of these names represents a trade group of woods consisting of a number of closely related species.

(c) Species from the genus Dipterocarpus are marketed collectively: Apitong if originating in the Philippines; Keruing if originating in Malaysia or Indonesia.

(d) Douglas-fir from trees grown in the states of Washington, Oregon, California, Idaho, Montana, Wyoming, and the Canadian Provinces of Alberta and British Columbia shall be classed as Douglas-fir No. 1. Douglas-fir from trees grown in the states of Nevada, Utah, Colorado, Arizona and New Mexico shall be classed as Douglas-fir No. 2.

(e) Red Meranti shall be limited to species having a specific gravity of 0.41 or more based on green volume and oven dry weight.

Figure 20 Plywood Species

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[87] APA-The Engineered Wood Association. *Plywood Design Specification.* (Tacoma, WA: APA- The Engineered Wood Association, 1998), 7

5.2 Bending

Bending or folding is a method that brings 3D geometries into planar sheet material such as plywood. These geometries not only give form to a sheet, but provide structural stiffing as described in the *3.4.5 Digital & Material Techniques s*ection on *Folding*. Bending can be used as an operative language that radiates throughout a design scheme formally and functionally. An effective way of constructing demands that a design take the physical world into account from the start.

Bending wood can be a challenging process that requires an understanding of the pressures being exerted on the wood fibers being bent. Under typical structural loading, wood is stronger in compression than it is in tension. Wood fiber can compress, without failing, but there is limit to as how far it can be stretched without cracking or splitting.[88]

Wood bending involves simultaneously application of two pressures. The fibers on the outside of a curve are under tension and need to stretch while the fibers on the inside need to compress. Common failure found in wood bending is splitting on the outside of the curve because wood cells compress more easily than they stretch. Splitting or breakage along the outside of a curve has a significant factor. For example, a steam bent piece of oak to a radius of 15” had an initial length of 34 ½”. After bending, the outside surface measured 36 ⅛” with an inside surface measurement of 34 ⅜” with a difference of 1 ¾”. This means that the outside fibers had to stretch [by each other] ¾” while the interior fibers compressed 1 ⅛”[89]. The center line of the force in wood or where the fibers do not move occur two-thirds the way in form the concave side or 1/3 from the outside of the curve.

Similar factors of bending wood can be applied to bending plywood. ½” Plywood panels have significant bending strength both along and across the panel, and the differences in strength and stiffness along the panel length as opposed to those cross the panel which are much smaller than those differences in solid wood. One of the most important items to consider is the

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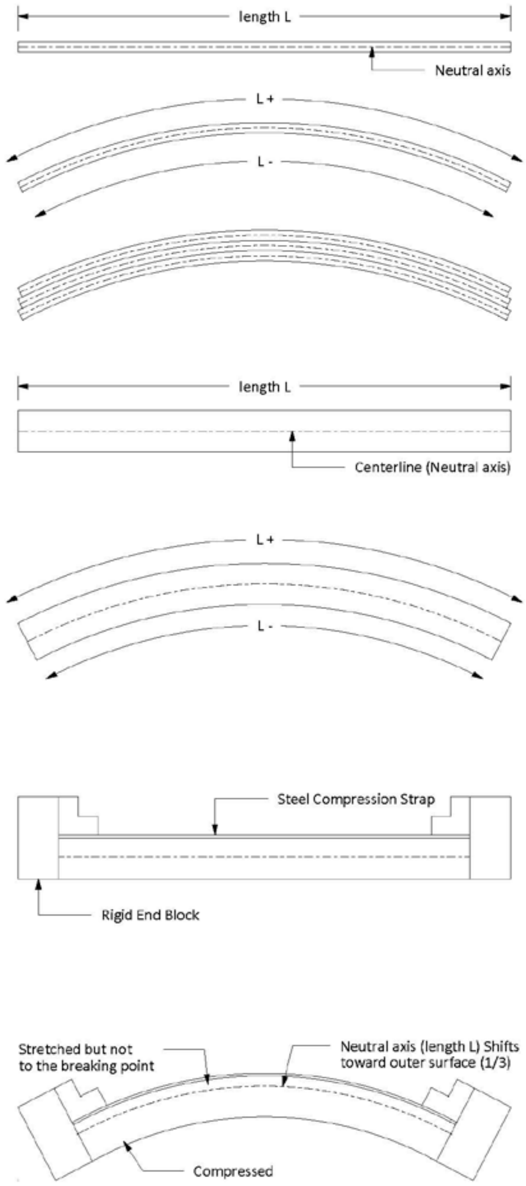
[88] Jonathan Benson, *Woodworkers’ Guide to Bending Wood: Techniques, projects, and expert advice for fine Woodworking,* (East Petersburg, PA: Fox Chapel Publishing, 2008), 16

[89] Benson, *Woodworkers’ Guide to Bending Wood,* 17-18

smallest or limiting radius of curvature that can be attained before the tension face of the bend is stretched to the breaking point.



A thin piece of wood is flexible and easy ro bend without breaking.

The difference is small between length L+ on the ouside of the curve, and the lenght L- on the inside of the curve. The Wood fibers don't have to strech very far.

Laminte bending of glueing thin layers of wood together.

A thick piece of wood is diffcult to bend.

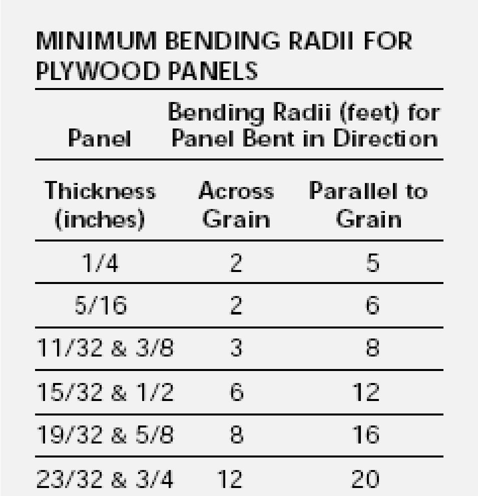
The difference is large between L+ on the outside of the curve and length L- on the inside when bending a thick piece of wood. The wood fibers most stretch alotand most likely break,

A steel compression strap with end blocks prevents wood fibers from stretching. Length L+ on the oustide of the curve remains close to the original length L. The neutral axis shifts from the center toward the outside surface (outer 1/3).

Figure 21 Wood Bending Principles

Factors affecting plywood bending:

Similar to that of clear grain wood, the type of species used in the construction of plywood has an influence on the limiting radius of curvature. In general, plywood made from temperate-grown hardwoods appears to have better bending properties than those from softwood and tropical woods. However there are no hard and fast facts that prove this, so preliminary practical tests need to be made to test each type of plywood used.



MINIMUM BENDING RADII FOR PLYWOOD PANELS

Panel	Bending Radii (feet) for Panel Bent in Direction	
Thickness (inches)	Across Grain	Parallel to Grain
1/4	2	5
5/16	2	6
11/32 & 3/8	3	8
15/32 & 1/2	6	12
19/32 & 5/8	8	16
23/32 & 3/4	12	20

Figure 22 APA Bending Radii

Similar to solid wood laminations, the ratio of radius of curvature to the thickness of plywood tends to increase with the use of thicker plywood.

Plywood as a manufacture sheet material is able to bend in both grain directions; across the grain, and along the grain. The extent to which it can be compressed and stretched across the grain varies from that of which is tolerable along the grain. This results in different limiting radii of curvature, which depends mostly on the grain direction of the wood core or middle layers of which plywood is composed. Plywood bent across the grain is found to bend to a smaller radius than with the grain. This is true for three-ply panels where the ratio of bending across the grain to bending along the grain is 2:1 with low curvature radii. As the number of plies increases to seven, the ratio for bending across the grain to bend along is reduced to 1 ⅓:1, with larger radii.[90] Plywood strips with face and back grain, and 45-degree angles, have a bending ratio and radii between those bent in the other two directions. These strips with a 45 degree angle face grain tend to take on helical shapes.

The APA has found appropriate minimums for mill-run (construction and industrial) panels of plywood (fig 22). Shorter radii can be achieved by selecting plywood free of knots, and short

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[90] W. C. Stevens and N. Turner. *Wood bending Handbook.* (East Petersburg, PA: Fox Chapel Publishing, 1970), 75-78

grain, or by wetting or steaming plywood. According to the APA, exterior-type plywood needs to be used for such processes of wetting or steaming plywood and dried before gluing.

5.2.1 Plywood bending across the grain:

The following tests examine the bending capability of different types of ½” construction and industrial plywood. The following tests focus on plywood’s ability to bend further across the grain as compared to along the grain. The outcome of the tests is to determine how far plywood can be bent within its formal state. As seen in the chart (fig 29) by the APA, we known that a 15/32,” or ½” panel can be bent to a radius of 6’ along the grain. As mention before, according to the *Wood Bending Handbook,* there are no hard facts on how far different types of plywood can bend and testing should be conducted in order to achieve the proper result.

The following plywood tests were conducted in a custom made jig that used two pipe clamps which allowed for each plywood strip to be compressed and form an arch under stress (fig 30). The plywood was compressed at a standard increment of two inches until it failed. During each increment the plywood arch was measured and recorded.

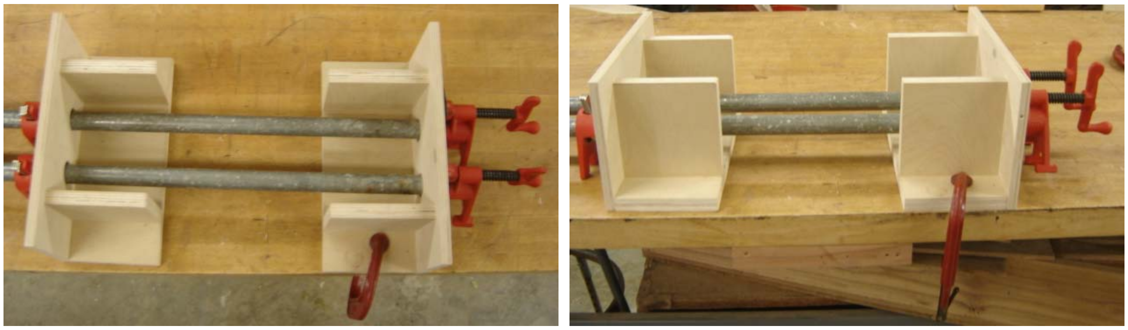


Figure 23 Testing Device

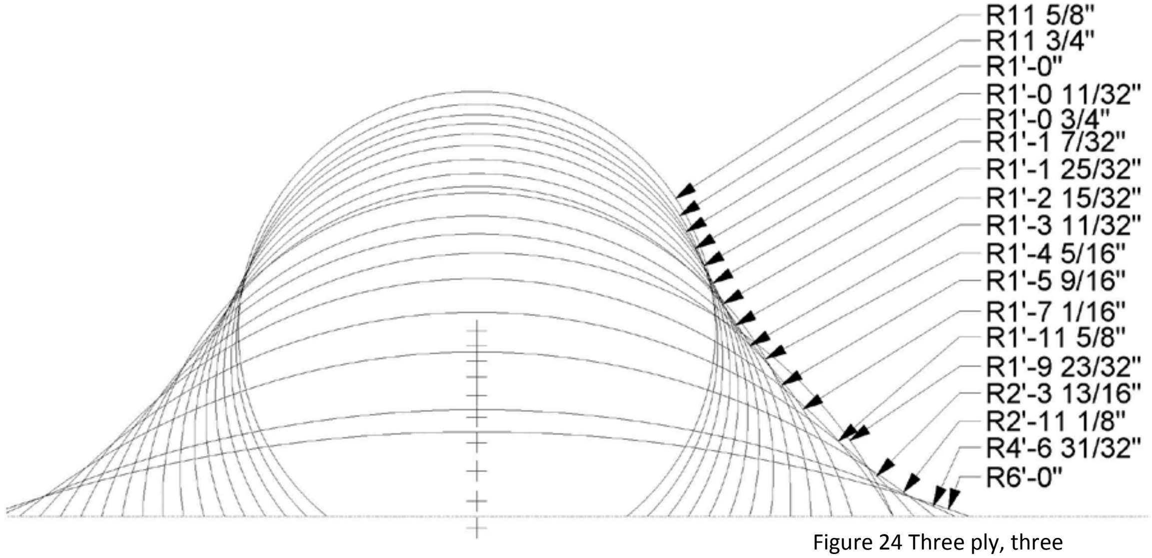


Figure 24 Three ply, three layered plywood radii bending results

Test One

This test examined a two and one-half-inch wide strip of three-ply, three-layered plywood. As seen by the following chart below (fig 31) this type of plywood was able to be bent to a radius of 11-5/8” before it broke. As compared to the APA recommendation of a six-feet bending radius, three-ply, three-layered plywood is capable of being bent to a variety of tighter radii.

Test Two

This test examined a four-inch wide strip of five-ply, five-layered ½”plywood. Although, this test subject is not the same width as the previous, when bending plywood in one-direction, the width has very little effect on the results. Plywood is similar to a sheet a paper for i.e.; a strip of paper and a sheet of paper are able to bend in the same direction at the same radius yet they are different widths, therefore a four-inch piece of plywood can bend to the same radius as a one-foot wide strip and vice versa. As seen by the following chart below (fig 32) this type of plywood was able to be bent to a radius of two-foot, ten and five-sixteenths before it broke. As compared to the APA recommendation of a bending radius of six-feet, it was able to bend a little more than twice as tight. But five-layer, five ply plywood cannot achieve the tightness as compared to that of three-ply, three-layered plywood, therefore the greater number of plies and layers a sheet has, the less of a bend it can achieve in its formal state.

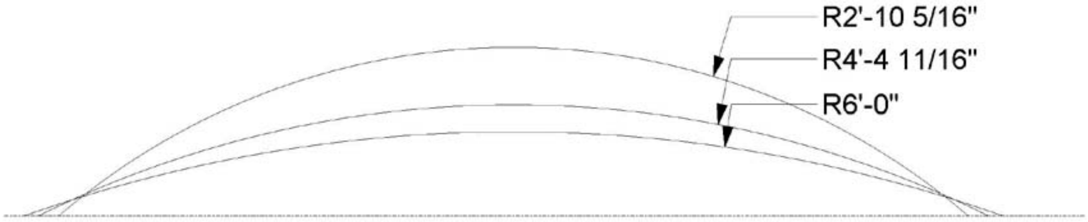


Figure 25 Five-ply, five-layered plywood bending radii results

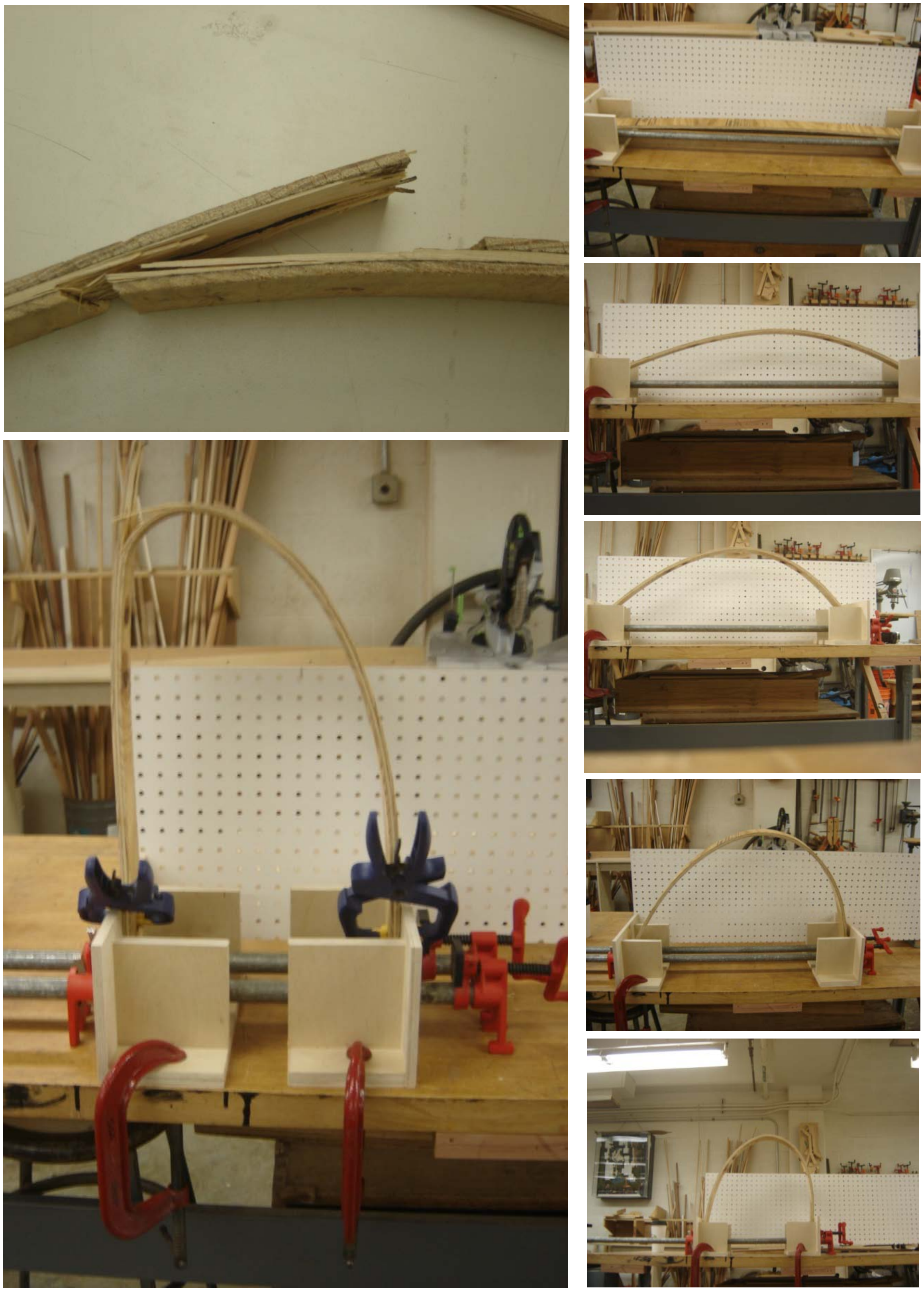


Figure 26 Three-ply, three-layered plywood bending test

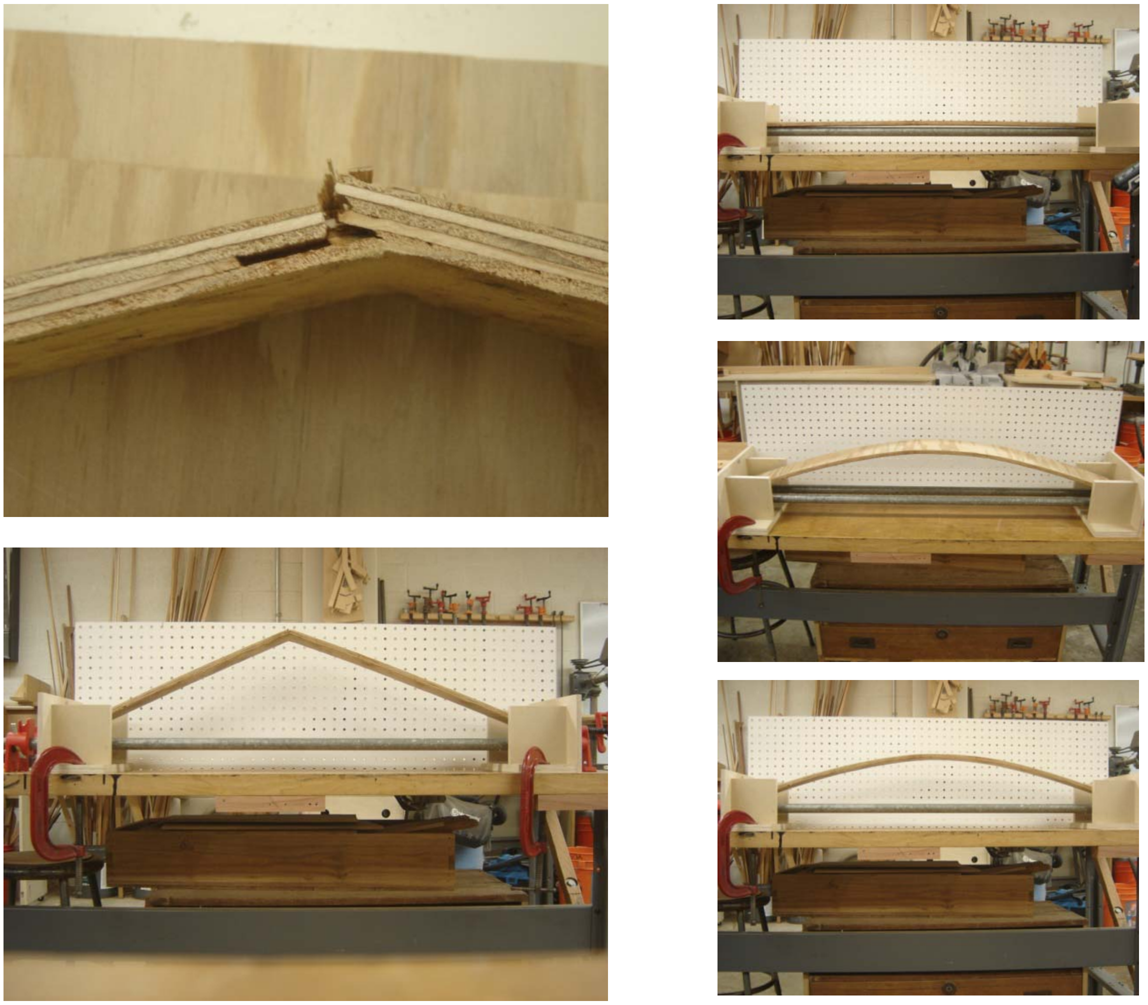
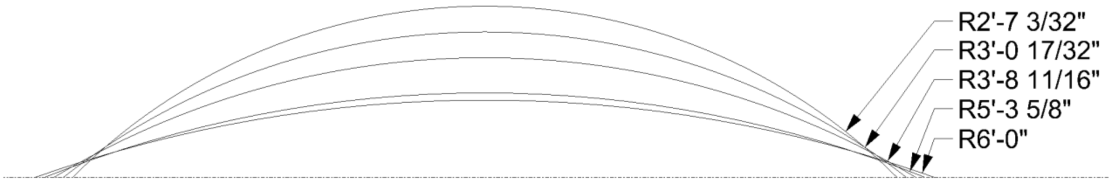


Figure 27 Five-ply. Five-layered plywood bending Test

Test three

This test examined a four inch wide strip of four-ply (two-ply inner core), three-layered ½”plywood. As seen by the following chart below (fig 35) this type of plywood was able to be bent to a radius of two-feet, seven and three thirty-seconds before it broke. As compared to the APA recommendation of a bending radius of six-feet, it was able to bend a little more than twice as tight. But surprisingly, four-ply, three-layer plywood bent just three inches tighter as compared to the five-ply, five-layer plywood. Although this four-ply, is manufactured in three layers, it cannot achieve the tightness as compared to that of three-ply, three-layered plywood. The thickness and the number of plies within a core of a sheet of plywood determines the radius that the sheet can be bent to.

Figure 28 Four-ply, three- layered bending Radii Results



Test four

This test examined a two-feet long, four inch wide strip of four-ply, four-layered ½” plywood to determine the limits of bending plywood into a “S”-shape across the grain. By bending plywood into an S-shape, the center becomes a neutral point where tension and compression change direction within a panel. Therefore, a four-foot wide panel or strip can be broken up into two smaller identical sections (based upon centering midpoint). A two-foot length strip of four-ply, three-layer plywood was able to bend to a maximum of two-feet and four one-half inches (fig 36).

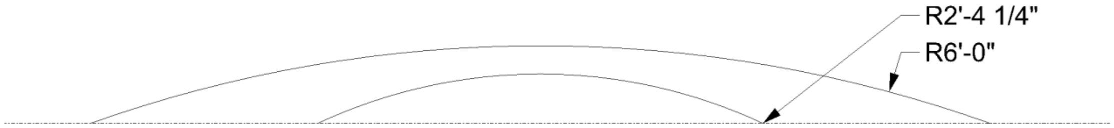


Figure 29 Four-ply, four-layered of a two-foot in length section

½" plywood bending radii across the grain (Radii in feet and inches)

3-ply, 3-layer(a)	**4-ply, 3-layer(a)**	**4-ply, 3-layer(b)**	**5-ply, 5-layer(a)**
Minimum to Maximum			
6'-0"(c)	6'-0"(c)	6'-0"(c)	6'-0"(c)
4'-6 31/32"	5'-3 5/8"	2'-4 ¼"	4'-4 11/16"
2'-11 1/8"	3'-8 11/16"		2'-10 5/16"
2'-3 13/16"	3'-0 17/32"		
1'-11 5/8"	2'-7 3/32"		
1'-9 23/32"			
1'-7 1/16"			
1'-5 9/16"			
1'-4 5/16"			
1'-3 11/32"			
1'-2 15/32"			
1'-1 25/32"			
1'-1 7/32"			
1'-0 ¾"			
1'-0 11/32"			
1'-0"			
11 ¾"			
11 5/8"			

Figure 30 ½ Plywood cold bending Radii

(a) Four-foot strip length
(b) Two-foot strip length
(c) APA minimum radius

5.2.2 Kerfing

Curved panels and bends can be created using the traditional method of kerf cutting. The principle is to cut partially through the concave face of the bend of a sheet in a pattern of parallel cuts. The depth of the cut extends to within two piles of the opposite face. When plywood with a decorative veneer is used, the veneer face counts as one of the plies. The amount of material to be removed will depend on the thickness of the plywood and the radius of curvature desired.[91] To obtain the smoothest curve on the convex or outside surface, the slots need to be to cut in a tight pattern on the concave side of the curve.

The thin layer of material left on the convex side allows for easy bending of the sheet. When bent and glued together, the blocks left over on the cut side compress to give the panel structural integrity. A disadvantage of this method is that it is difficult to maintain a smooth outer surface as flats tend to form opposite the tongues and ridges of kerf slots. In order to counter this, plywood can be stacked in two or more layers to create a smooth surface on both sides of a panel or to add additional strength. Also, if a free-standing bend is desired, additional layers of veneer can be added over the convex and concave kerf surfaces for a smooth finish and added strength.

Kerfing formula one:[92]

1. Take the Outside Perimeter of the radius and subtract the Inside Perimeter. This gives the amount of frame to be removed.
2. Divide this amount by the thickness of the saw blade. This gives the number of saw cuts.
3. Last, divide the Outside Perimeter of the radius by the number of saw cuts. This gives the distance between saw cuts.

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[91] Benson, *Woodworker's Guide to Bending Wood*, 83

[92] Tai-Workshop, "The bending Wood: Kerfing," http://www.tai-workshop.com/english/tech-2(b)-e.html (Accessed March 15,2012)

Kerfing formula two:

To calculate the number of cuts, first find the circumference of the circle that will form the corner of the project. Divide this number by the total number of corners on the project. This will be the length of one corner. Divide the length of the corner by the total width of the saw kerf plus the spacing between the kerfs. This will give you the number of cuts you'll need to make.[93]

The formula for this is:

Circumference ÷ Number of Corners = Corner Length
Corner Length ÷ (Kerf Width + Kerf Spacing) = Number of Cuts
Example: Calculating the number of cuts for a 12" dia. circle, used on a four corner project, with a saw kerf of 1/8", and kerf spacing of 3/4".
Circumference = 3.14 x 12" = 37.68"
37.68" ÷ 4 = 9.42"
9.42" ÷ (1/8" + 3/4") = 9.42" ÷ 7/8"(.875) = 10.77 or 11 cuts

The following tests examine ½" plywood's elastic bending ability and structural strength through various kerf patterns. Each series of tests analyzes the factors of kerfing and bending plywood.

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[93] Shopsmith, "Power Tool Woodworking Online for Everyone," http://www.shopsmith.com/academy/tblsaw_spops/index.htm (Accessed March 15, 2012)

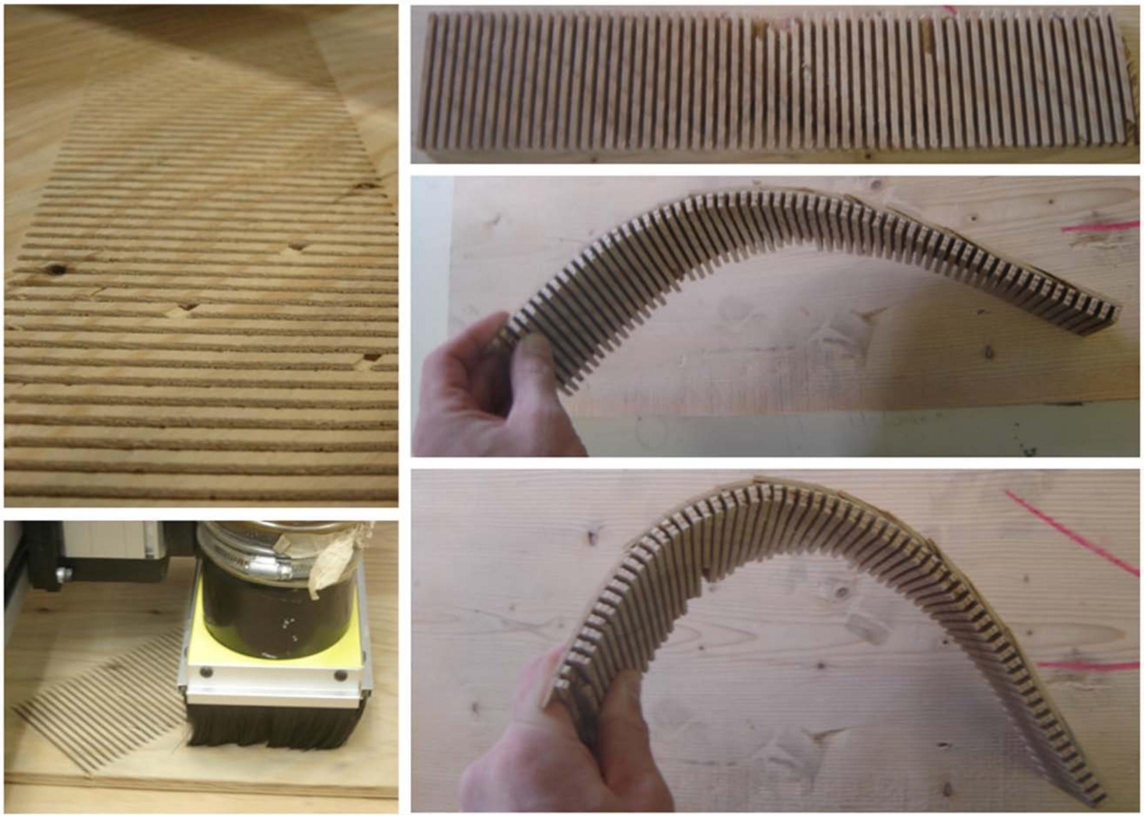

Figure 31 Kerf Testing of 1/2" plywood

Left Column: Fabrication of kerfing; *right column:* bending of plywood by hand

5.3 Joints applied to plywood

Any built object is usually composed of multiple elements. How do we connect one element to the next? As seen in lightwood construction, ½” plywood is connected to a stud frame through the use of fasteners. In this case the plywood is made to take structural loads by transferring the load from the fasteners to the studs. So how can we connect two planar pieces of plywood based on wood joints with digital fabrication?

Edge-Grain Joining

Edge-grain joints occur along the grain or long side of a panel or board (fig 32 A). They can be almost as strong as the wood in shear parallel to the grain, tension, and cleavage. There is a misconception that the tongue-and-groove joint (fig 32 B) and other shaped edge-grain joints have strength advantage over straight, plain joints. In the theoretical sense, the tongue-and groove has a strength advantage because of greater surface area compared to the plain joint. This strength advantage is lost because the shaped sides of the two mating surfaces cannot be machined precisely enough to produce a perfect fit that will distribute pressure uniformly over the entire joint. With a poor contact area, the effective bonding area and strength of a shaped joint can actually be less than a plain flat surface. The advantage of tongue-and-groove and other various shaped joints is their ability for quick assembly in presses, clamps, and by hand. Therefore a shallow cut tongue-and groove is just as useful as a deep, one with less material being wasted.

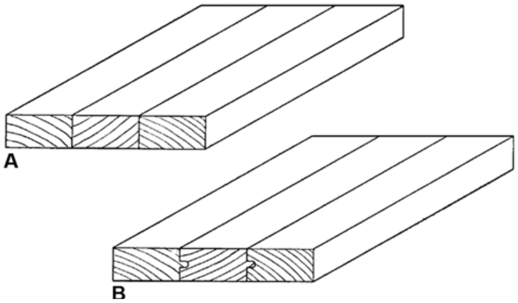

Figure 32 Edge-grain joints: A, Plain; B, tongue-and-groove.

End-Grain Joining

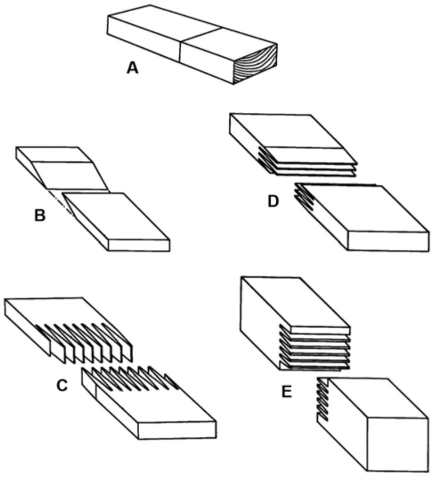

Figure 33 End Grain joints: A, butt: B, plain scarf; C, vertical structural finger joint; D, horizontal structural finger joint; e, nonstructural joint.

End-grain joints occur across the grain or the short side of a panel or board. End –grain butt joints (fig 33) are similar to a plain joint, in that they are not very strong and seldom do they meet the structural limits with conventional bonding techniques. Butt joints reach about 25% of tensile strength of wood parallel to the grain. In order to achieve proper structural transfer, a scarf or finger joint should be used with a surface area at least 10 times greater than the cross-section of the piece being used. Wood is approximately 10 times stronger in tension than in shear. In plywood scarf and finger joints with a slope of 1 in 8 or 8 times the cross-sectional area are used for structural pieces. For nonstructural or low-strength joints these requirements are not needed.

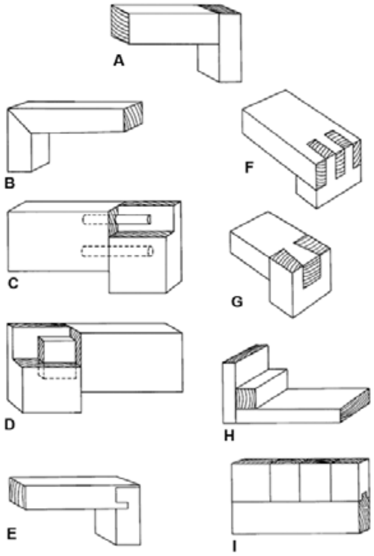

Figure 34 End-to-edge-grain joints: A, plain; B, miter; C dowel; D, mortise and tenon; E dado tongue and rabbet; F, slip or lock corner; G, dovetail; H, Blocked; I, tongue-and-groove.

Finger joints can be cut on a wide face—vertical joint, or on the edge—horizontal joint. Vertical joints have a greater area than horizontal joints, which allows for the design of the fingers' shapes. A well-manufactured scarf, finger or lap joint in the end grain can have up to 90% tension strength of

End-to-Edge-Grain Joining

Plain end-to-edge-grain joints capable of carrying appreciable loading are difficult to design. Therefore, these types of joints need to be designed with interlocking surfaces so that the edge grain of the interlocking member bonds to the edge grain of the adjoining piece. Increasing the joint surface area helps in transferring more load over the bond. Strong connection examples include dowels, mortise and tenons, and rabbets. Being that wood swells across the grain more than along it, changes in moisture can produce large internal stresses.

5.4 Performative panel: Sandwich construction and SIPS

A sandwich panel is a component assembly consisting of a lightweight core laminated between two thin strong facings. The engineered *structural insulated panel* (SIP) is the most common configuration of a sandwich panel in use today. The SIPS in use today draw upon the development and research conducted by Frank Lloyd Wright. In the 1950's one of Wright's students expanded on his sandwich panel concept by developing a structural panel with an insulating core.[94] SIPs are produced by a wide range of manufactures and consist of a layered construction made up of plywood or *oriented strand board* (OSB) panel faces known as "skins." These skins are attached to both sides of a core insulating material. A variety of core materials can be used. Among these are polystyrene foams, polyurethane foams, and paper honey comb fillers. Other outer structural skins such as steel, cement, and gypsum can be used. Plywood tends to be the ideal face material of a sandwich panel due to its strength, light weight, ability to be easily finished, dimensional stability, and is easily repairable if damaged.[95]

SIPs provide very high levels of insulation for their thickness, are inexpensive, and avoid trapped air spaces where moisture can build up and condense. In light wood framing batt-insulation in structural roofs, floors, and wall cavities, needs to be properly ventilated to avoid mold and rot. With the use of polystyrene core, a SIP eliminates trapped air pockets. This allows SIPs to be used in flat roof, or low-pitched-roof constructions and other structures, which tend to be very difficult to ventilate.[96]

Since SIPs are structural in and of themselves, they can be used as the main structural system or be a part of larger system as an infill panel. They are able to support spanning loads in horizontal applications and compressive loads when used vertically, which allows for them to be

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[94] Mark Anderson and Peter Anderson. *Prefab Prototypes: Site Specific Design for Offsite Construction.* (New York: Princeton Architectural Press, 2007), 147

[95] APA-The Engineered Wood Association. "Supplement 4: Design and Fabrication of Plywood Sandwich Panels" in *Plywood Design Specification.* (Tacoma, WA: APA-The Engineered Wood association, 1993), 4

[96] Mark Anderson and Peter Anderson. *Prefab Prototypes* 148

used in floors, roofs, and walls. SIPs achieve their structural properties from their design which is similar to that of an "I" beam. The faces of the panel carry compressive and tensile stresses as the top and bottom flanges of a steel I-beam do with the foam core resisting shear similar to that of the central steel web. The foam core needs to be thick enough to space the faces from each so that they can provide bending stiffness and support the faces against buckling.[97]

Typically, SIPs are manufactured to the dimensions of the plywood or OSB face material used. They generally, they come in four-foot widths and variable lengths with a maximum standard of twenty-four feet. Depending on the manufacturer, some panels are even available in six or eight-foot widths. The desired thickness of the panel depends on the structural loading in combination with the amount of insulation required by local building codes. The thickness of panels tends to range from four to twelve inches, but some manufacturers will fabricate panels to exact specifications and cut openings for doors and windows. In most cases, manufacturers fabricate panels in two-foot length increments, which will meet most applications but require additional cutting and assembling in the field.[98]

5.4.1 Sandwich assembly: bonds and adhesives

Plywood skins used in sandwich panel construction are structural members that depend on glued joints to integrate separate components into an efficient module capable of carrying design loads. Materials made from these components are able to be stressed to a higher level as compared to non-engineered construction. Therefore, the structural performance of entire assemble depends on its integrity of the bond between the faces of the skins and the core. Generally, glues are used to attach the plywood faces directly to the core. In other cases, direct adhesion of the foam core to the faces is achieved during expansion of the foam. In exterior wall types, the bond between the core and faces needs to be waterproof. The combination of

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[97] APA-The Engineered Wood Association. "Supplement 4: Design and Fabrication of Plywood Sandwich Panels" in *Plywood Design Specification.*, 4

[98] Anderson. *Prefab Prototypes*, 148

core material and bond should not creep too excessively under long-term loading and temperatures.

All glues used need to meet exposure, structural loading, and be compatible with the core material being used. Interior-type glue needs to conform to ASTM Specification D3024 and exterior-type glues shall conform to ASTM Specification D2559.[99] In order to achieve a proper bond, the plywood skins needs to be roughed, as by a light sanding before being glued to the foam core. During the assembly process, the plywood skins are glued to the core material over their full contact area using mechanical pressure or contact gluing in a press. The required pressure on the net contact area needs to provide adequate contact and ensure a good glue bond. A pressure of 100psi to 150 psi is recommended for wood-to-wood joints as a pressure equal to 40% to 60% of the compressive yield strength of the core. Pressure can be applied from any point but should progress and be applied uniformly to the ends of a panel to produce a continuous glue bond.

5.5 Fab+craft Fabrication: SIP Prototype

Currently, built architectural structures and material systems rely heavily on an assembly of varying, and often opposing systems, to solve issues of performance, geometry, and structure at different scales. This investigation studies the relationship between physical material properties and localized geometric manipulations in order to create a material system tested at the scale of architectural application—a self-supporting wall system. The process will always be closely connected to a hybrid between design processes and fabrication.

The overall design intent focused on producing a modular curved sandwich panel with a simple spline joint system. This system was developed to meet the current thermal performance requirements and to be easily assembled in the field. Although the following parameters were not addressed due to the time constraint of the project, they should be taken into consideration when designing a sandwich panel wall system.

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[99] APA-The Engineered Wood Association. “Supplement 4: Design and Fabrication of Plywood Sandwich Panels” in *Plywood Design Specification.* (Tacoma, WA: APA-The Engineered Wood association, 1993), 8-9

- Exterior cladding system to protect structural skins and performative values of the sandwich panel from weather.
- Waterproofing between panel joints to prevent moisture build-up. Constant moisture exposure can lead to delimitation of structural plywood skins over long periods of time resulting in structural failure.
- Penetrations for electrical, plumbing, and HVAC (heating, ventilation, & air conditioning) services.
- Additional Thermal enhancements consisting of vapor barriers and membranes.
- Roof & floor connections.
- Additional variations & applications: i.e. an interior acoustical panel system.

The sandwich panel developed in this project consisted of using ½” four ply, three layered APA plywood for the skins. This type of plywood was manufactured with C-D faces and used glue rated for Exposure I conditions. This type of construction grade plywood is generally specified in lightwood construction for shear walls.

Two inch thick Dow Styrofoam Band Utilityfit XPS 15 PSI was chosen as the core material due to its R-Value, light weight, and its workability as an extruded polystyrene foam insulation or XPS. This type of rigid insulation has an R-value of five per inch of thickness.

According to the R-value tale developed by ColoradoENERGY.org, ½” plywood sheathing has an R-value of .63 per sheet thickness.[100] Therefore when added to the R-value of an XPS core of four inches the wall panel had an R-value of: 4(5)(XPS) +2[.63(2)](plywood) = 21. 26.

According to the Revised Ordinances of Honolulu (ROH) the following table shows (fig 42) the required R-Values per climate zone found under Chapter 32: Building Energy Conservation Code.

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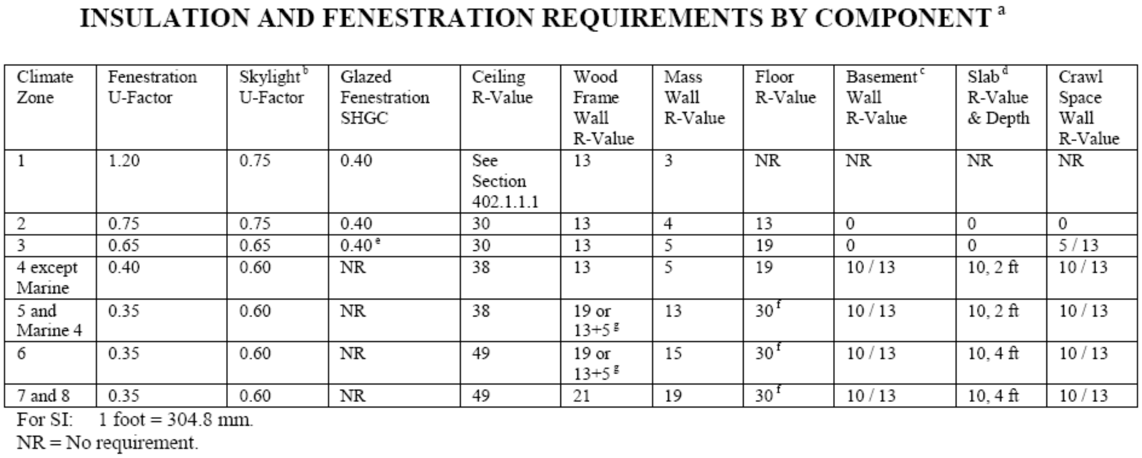
[100] Randy L. Martin, “R-Value Table: Insulation Values For Selected Materials,” (ColoradoENERGY.org, 2011)



INSULATION AND FENESTRATION REQUIREMENTS BY COMPONENT [a]

Climate Zone	Fenestration U-Factor	Skylight [b] U-Factor	Glazed Fenestration SHGC	Ceiling R-Value	Wood Frame Wall R-Value	Mass Wall R-Value	Floor R-Value	Basement [c] Wall R-Value	Slab [d] R-Value & Depth	Crawl Space Wall R-Value
1	1.20	0.75	0.40	See Section 402.1.1.1	13	3	NR	NR	NR	NR
2	0.75	0.75	0.40	30	13	4	13	0	0	0
3	0.65	0.65	0.40 [e]	30	13	5	19	0	0	5 / 13
4 except Marine	0.40	0.60	NR	38	13	5	19	10 / 13	10, 2 ft	10 / 13
5 and Marine 4	0.35	0.60	NR	38	19 or 13+5 [g]	13	30 [f]	10 / 13	10, 2 ft	10 / 13
6	0.35	0.60	NR	49	19 or 13+5 [g]	15	30 [f]	10 / 13	10, 4 ft	10 / 13
7 and 8	0.35	0.60	NR	49	21	19	30 [f]	10 / 13	10, 4 ft	10 / 13

For SI: 1 foot = 304.8 mm.

NR = No requirement.

Figure 35 ROH Insulation and Fenestration Requirements

a. R-values are minimums. U-factors and SHGC are maximums. R-19 shall be permitted to be compressed into a 2 × 6 cavity.

b. The fenestration U-factor column excludes skylights. The SHGC column applies to all glazed fenestration.

c. The first R-value applies to continuous insulation, the second to framing cavity insulation; either insulation meets the requirement.

d. R-5 shall be added to the required slab edge R-values for heated slabs.

e. There are no SHGC requirements in the Marine zone.

f. Insulation sufficient to fill the framing cavity, R-19 minimum.

g. "13+5" means R-13 cavity insulation plus R-5 insulated sheathing. If structural sheathing covers 25 percent or less of the exterior, insulating sheathing is not required where structural sheathing is used. If structural sheathing covers more than 25 percent of exterior, structural sheathing shall be supplemented with insulated sheathing of at least R-2.

All prototypes were constructed using standard woodworking glue due to its workability and health concerns. Initial tests were conducted with Titebond II Premium Wood Glue and Titebond III Ultimate Wood Glue glues. Although these glues, according to the manufacturer, should not be used in structural or load bearing applications they performed very well in adhering the plywood faces to the foam cores. That is as long as there was a strong contact pressure. Titebond II has a bonding strength of 3,750 psi and Titebond III has a bonding strength of 4,000 psi at room temperature for a wood to wood glued connection.

Under a controlled factory setting, wood glue would not be used. Instead, an adhesive would be specified from within the two groups of: MOR-AD laminating adhesives and MOR-MELT reactive hot melt laminating adhesives designed by Dow to be used in SIP fabrication with foam insulation cores. MOR-MELT reactive hot melt laminating adhesive is a moisture curing polyurethane reactive hot melt adhesive designed for laminating applications and is available in six different variations where as MOR-AD is a moisture cure, one-part non-sag urethane laminate adhesive. MOD-AD has twenty-three different variations to choose from based upon color, strength, curing and set time.

5.5.1 Design, fabrication, assembly, and craft

The prototype sandwich panels were design and fabricated based upon maximum and minimum bending radii of plywood discovered earlier. Although, SIPs can be manufactured at larger lengths, these panels were developed along a two-foot wide by four-foot long module. This allows for easy transportation and assembly of individual modules into a bigger wall system. Two construction workers are able to assemble the wall system with ease. Other benefits of this panel would include their use on remote sites and remodeling of existing buildings where cranes generally have limited access. Construction workers would be able to carry the panels through the jobsite without interfering with other operations associated with building.

Each panel investigated and built was developed through sketching, 3D-modeling, and fabrication. The initial panel and wall system was developed from the following sketches.

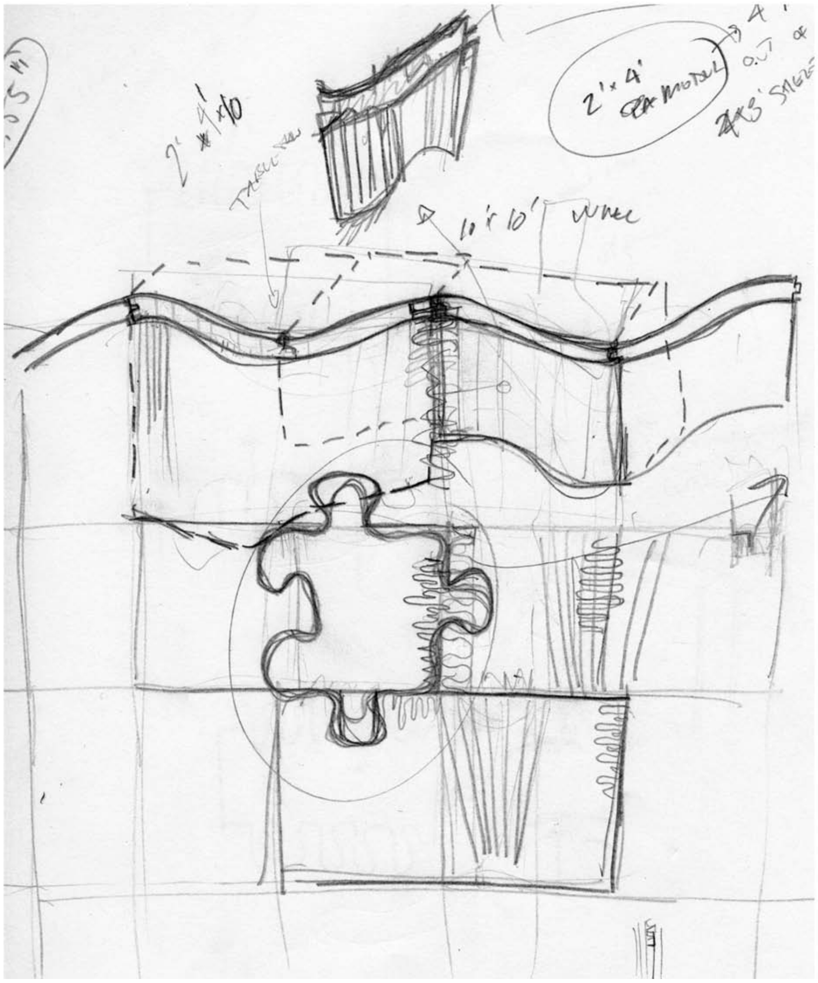
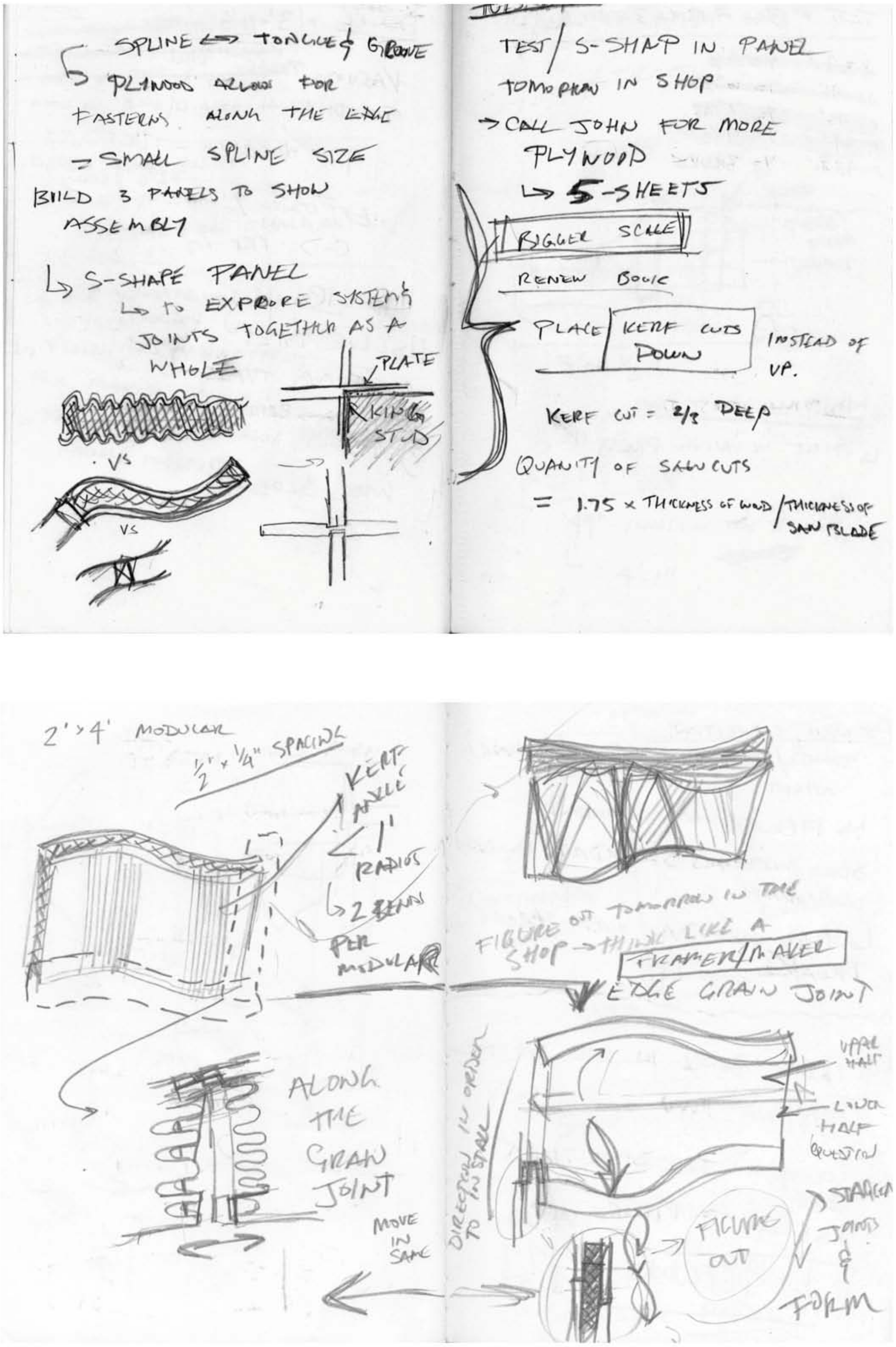


Figure 36 Initial wall system sketch

The sketches above and below (fig 43 and 44) begin to look at the modular size of each panel, the curvature of an individual panel, and the overall wall system. As a result it was determined that the plywood should have an overlapping and alternating "S"-shape with the radius of 4'-0" taken from the ½" plywood cold bending radii chart for 4-ply, 3-layered plywood. This was based upon the bending radius of 2-foot in length piece of plywood. The bending radius of a 2-foot piece can be applied to a 4-foot in length "S"-shape piece as the center point becomes a neutral point where compression and tension within the plywood canceled each other out resulting in mirror forces acting upon it.


SPLINE ⟷ TONGUE & GROOVE

PLYWOOD ALLOWS FOR FASTERNS ALONG THE EDGE

= SMALL SPLINE SIZE

BUILD 3 PANELS TO SHOW ASSEMBLY

↳ S-SHAPE PANEL

↳ TO EXPRORE SYSTEMS & JOINTS TOGETHER AS A WHOLE

TEST/ S-SHAP IN PANEL TOMORROW IN SHOP

→ CALL JOHN FOR MORE PLYWOOD

↳ 5-SHEETS

BIGGER SCALE

RENEW BOOK

PLACE KERF CUTS DOWN INSTEAD OF UP.

KERF CUT = 2/3 DEEP

QUANITY OF SAW CUTS = 1.75 × THICKNESS OF WOOD / THICKNESS OF SAW BLADE

2' × 4' MODULAR

1/2" × 1/4" SPACING

FIGURE OUT TOMORROW IN THE SHOP → THINK LIKE A FRAMER/MAKER

Figure 37 Sandwich panel development

5.5.2 Half scale Prototype panels

Prototypes were designed and built at half-scale to learn the fabrication and assembly steps that would be involved in producing the full-scale panel system. The first panel was designed to the maximum bending radii of plywood discovered in the precious tests. A radius of six inches was chosen assuming that ¼” plywood was able to bend twice as far as the ½” plywood. The second panel consisted of bending radius of 24-inches to study and contrast the two different radii. Each half-scale prototype consisted of ¼” three-ply, three-layered plywood and 2” thick XPS foam cores. In the process of designing and fabricating these panels basic MasterCAM skills were acquired in addition to learning how to set up and used the Techno CNC router to mill the curve profiles digitally modeled. The most important knowledge gain from producing these panels was that in order to fabricate with a CNC router, the components that make up a single panel need to be modeled and assembled part by part in the computer as it would be in the physical environment. MasterCAM serves as a second set of eyes with its ability to demonstrate to the CAD/CAM operator through simulation, of each cutting or milling step involved. From here, CAM operator can check for any conflicts within the 3D-molded part.

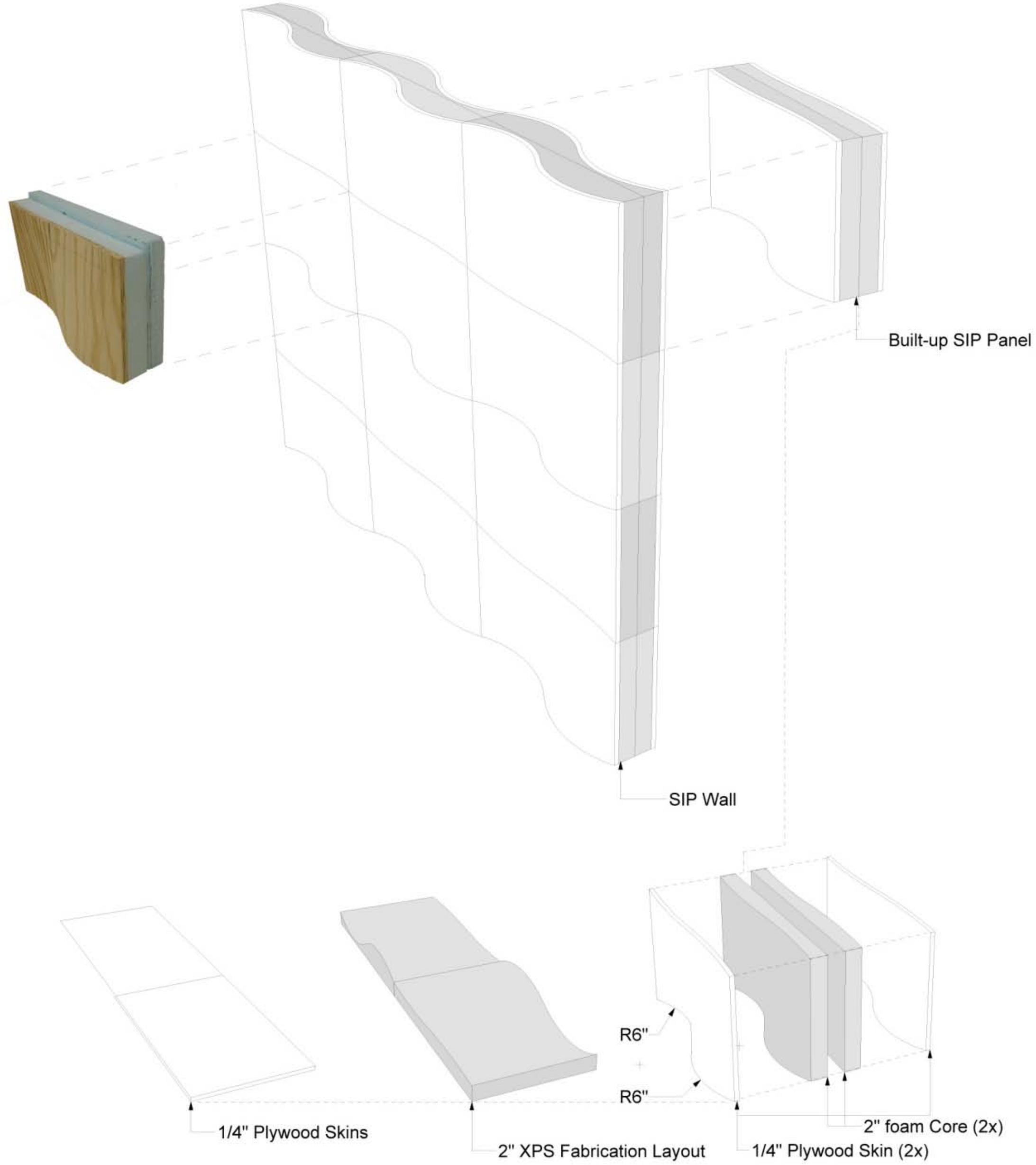


Figure 38 Half-scale prototype fabrication and assembly diagram

Upper: Exploded sandwich wall with tested built-up panel, *lower:* Exploded perspective of assembly sequence

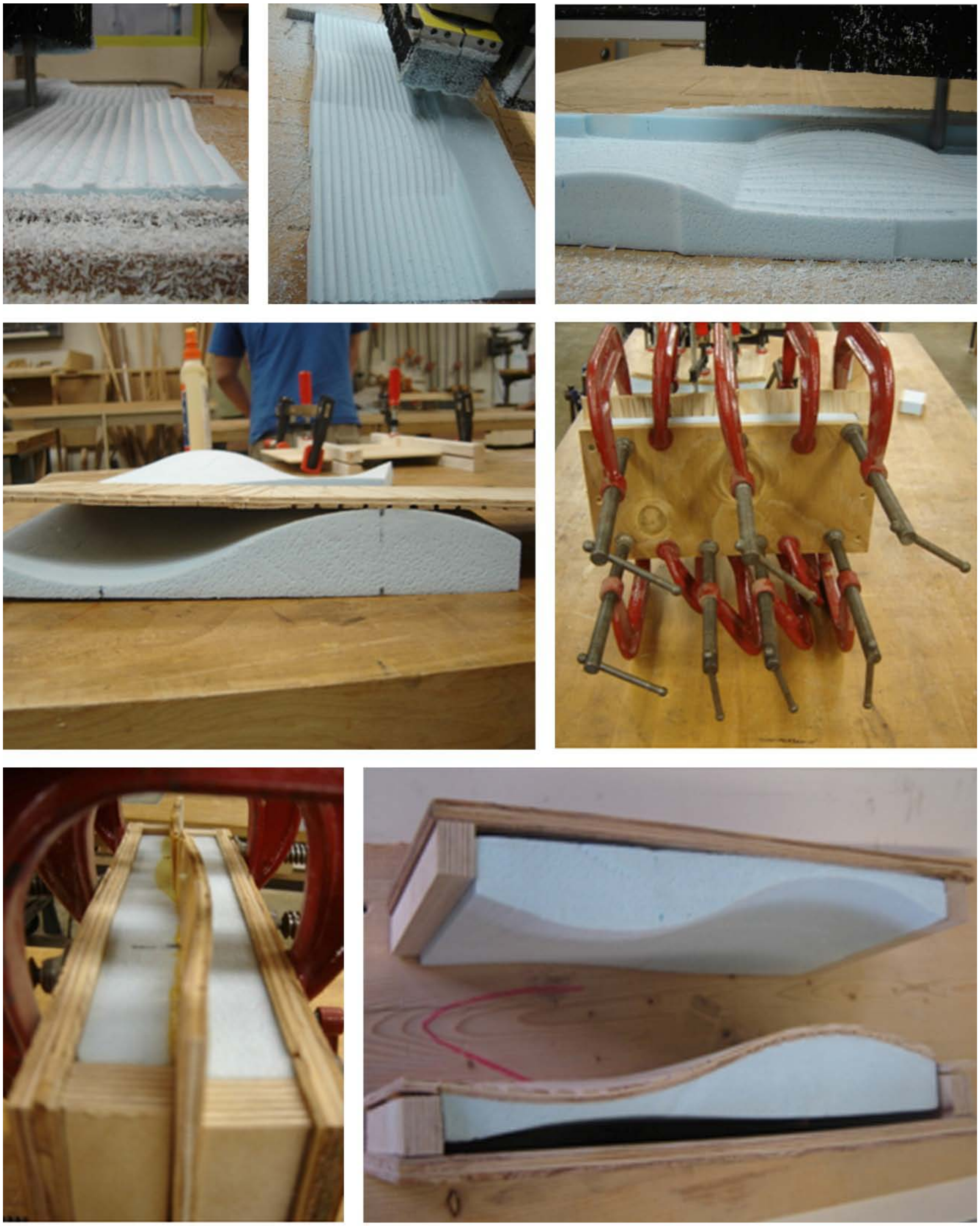


Figure 39 Half-scale fabrication & assembly

Upper: CNC Milling of Foam core; *middle:* forming and clamping of kerfed-plywood; *lower:* Mold with assembled panel demonstrating the spring back associated with elastic bending.

5.5.3 Full-scale Prototype panel 1

Full-scale Panel one was developed along a similar process as the half-scaled prototypes. This panel was fabricated to have an undulating ‘S’-shape profile. A radius of 3’-10” was chosen based upon the knowledge gained from the bending exercises mentioned earlier. This panel consisted of two ½” plywood skins with different kerf patterns: (1) parallel vertical kerfing spaced on 1” centers across the skin; (2) fan kerfing aligning to the bending radius space on 2” centers. Both kerf patterns were cut to a ¼” depth or through two plies of the plywood on the outer exposed surface of each plywood skin. The vertical kerfing was cut traditionally using a table saw which took a great amount of time to layout and produce. To speed up this process, a track saw was used to cut the fan bracing. A track saw allows for any angle to be cut without having to adjust a gauge or use clamps. The track in which the saw rides in is easily adjusted to the desired angle by simply moving it from one point to another. This reduced the time to produce a skin by half.

As discovered with the half-scale prototypes, to reduce programming and set up time on the router, the entire foam core was nested together so that it could be milled from one piece of foam. As it was discovered in the process of making, it is faster to mill all the parts at once as compared to milling them as separate components. To speed up milling, a 2” ball cutter was used instead of a 5/8” ball cutter used in the earlier prototypes. Therefore the 2” bit was able to increase amount of material removed during the ‘rough’ milling. But due to the tight nesting of the foam core components to reduce the amount of material milled, a 5/8” ball cutter still had to be used which required a tool change during the milling process.

MasterCAM has the ability to check clearances and conflicts with files. Ignoring conflicts can have negative milling results as the router can become stuck in one place. To prevent the router from burning holes in material, one has to be carefully watching the router at all times. If a mishap occurs during the ‘rough’ tool path the object still can turn out ok as the ‘finished’ tool path can correctly mill over the rough.

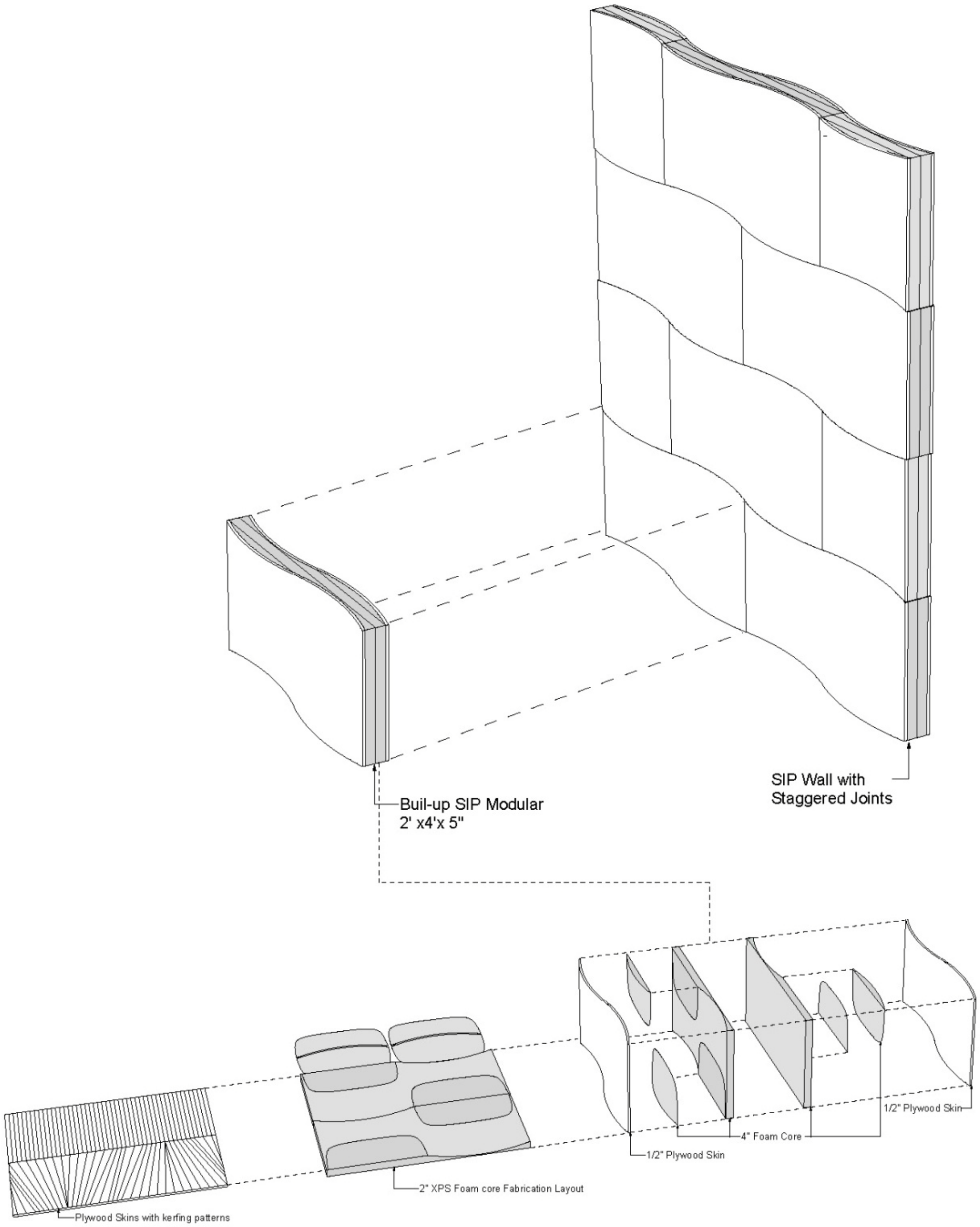


Figure 40 Full-scale Prototype fabrication and assembly diagram.

Upper: Exploded perspective of wall pattern; *lower:* Exploded perspective of fabrication layout and built up panel

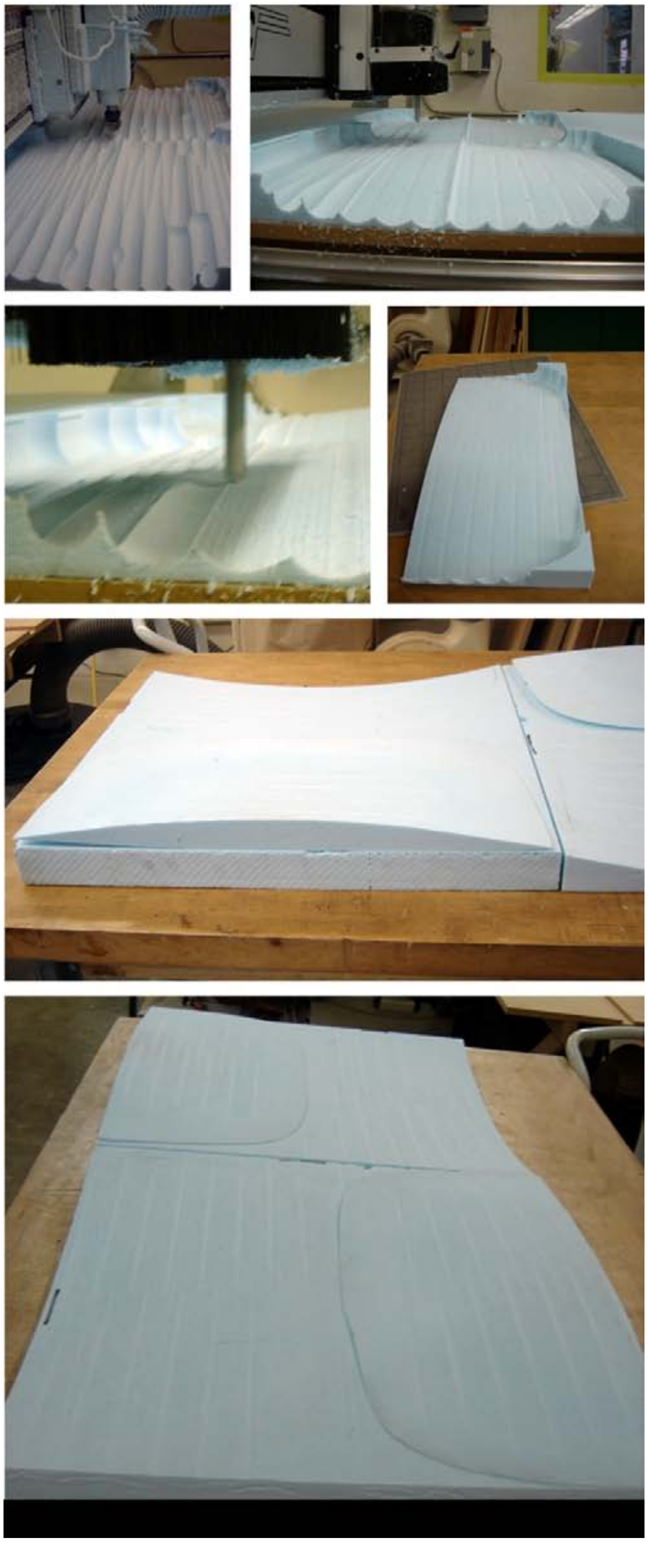
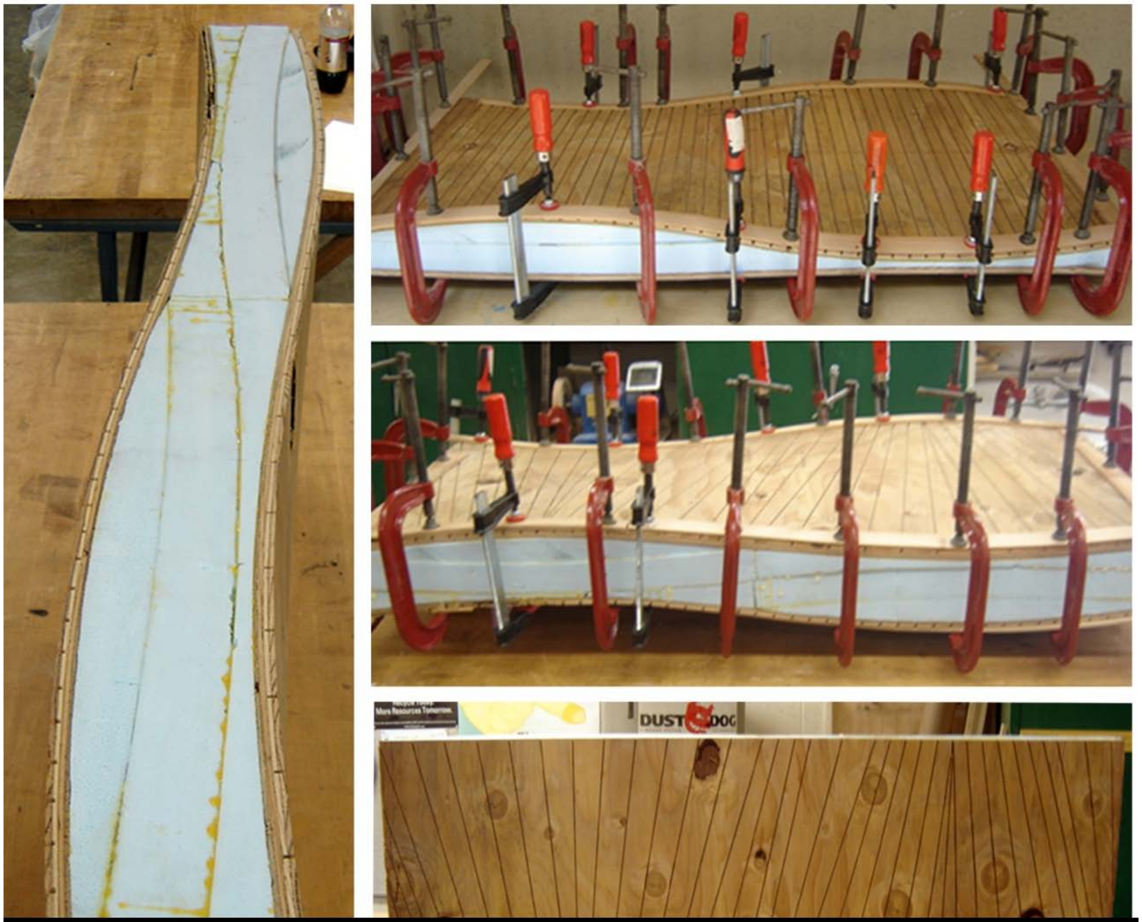


Figure 41 Fabrication of foam core



[redacted]

Figure 42 Assembly of panel II

5.5.4 SIP Mold-making

Learning from the process of assembling the one-to-one scale prototype panel 1, it was determined that a mold needed to be designed and built to address the following: (1) speed up assembly sequence; (2) ensure a proper unified-glue bond between the layers of foam and the plywood skins; (3) reduce elastic spring back within the plywood skins; and (4) provide uniform pressure during bending to reduce the splitting of plywood skins during clamping. The goal of the mold was to be able to produce one fully assembled panel per day. This would cut down on assembly time by half, as it was currently taking two whole days for one panel to be glued, assembled, camped, and cured.

Although clamping the panels together seemed to be a simple way of assembling, it was revealed that the individual layered-components within the panel were not in contact with one another. This resulted in a hollow air-section within the center of the panel as clamps applied pressure to the perimeter edges of the plywood skins. This resulted in the plywood to spring back, once the clamps were removed, reducing the degree of curvature within the panel. The use of clamps caused the plywood to split as they did not allow for uniform pressure to be applied across the plywood skin and allow for movement. The plywood skins need to be able slide and compressed into the milled foam core.

A two-part mold was developed to ensure uniform bonding pressures across the plywood skins to reduce the amount of spring back after curing. This mold would also allow the plywood to compress without splitting. The two-part mold was design with a top ‘A,’ and bottom ‘B,’ from twenty CNC cut ½” plywood plates assembled together with threaded rod. The use of threaded rod allows for the plywood plates to be spaced at different intervals to transfer pressure uniformly. Three tie lashes with ratchets were used to clamp the two halves together. The top ‘A’ mold was fabricated with an arch profile. This allows for a greater clamping pressure as the tie lashes are pulling down on the entire mold instead of just on the corners. The diagram below shows the fabrication and assembly sequence of constructing the mold.

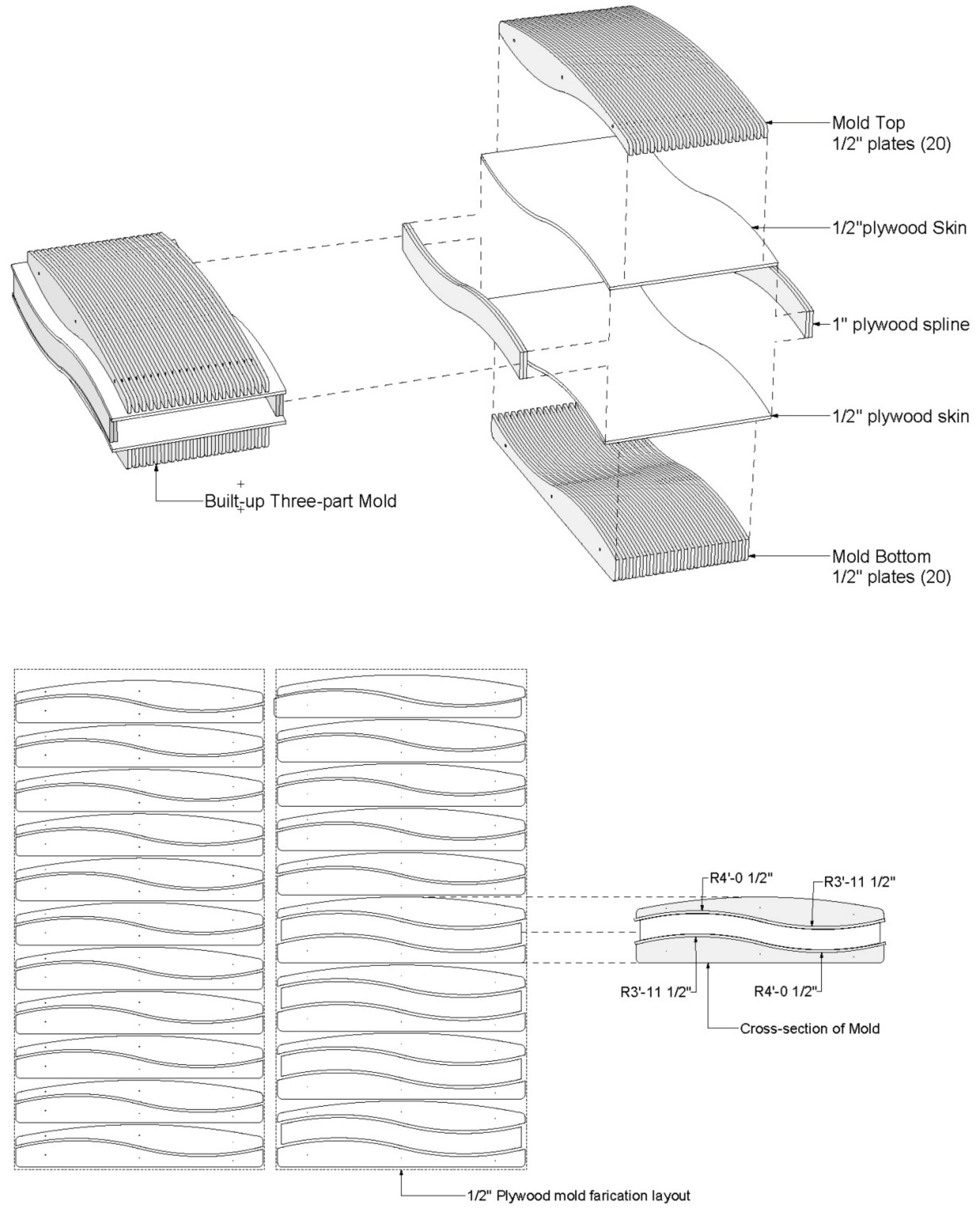


Figure 43 SIP mold fabrication and assembly

Upper: Perspective and exploded view of mold assembly; *lower:* CNC fabrication layout with mold cross-section

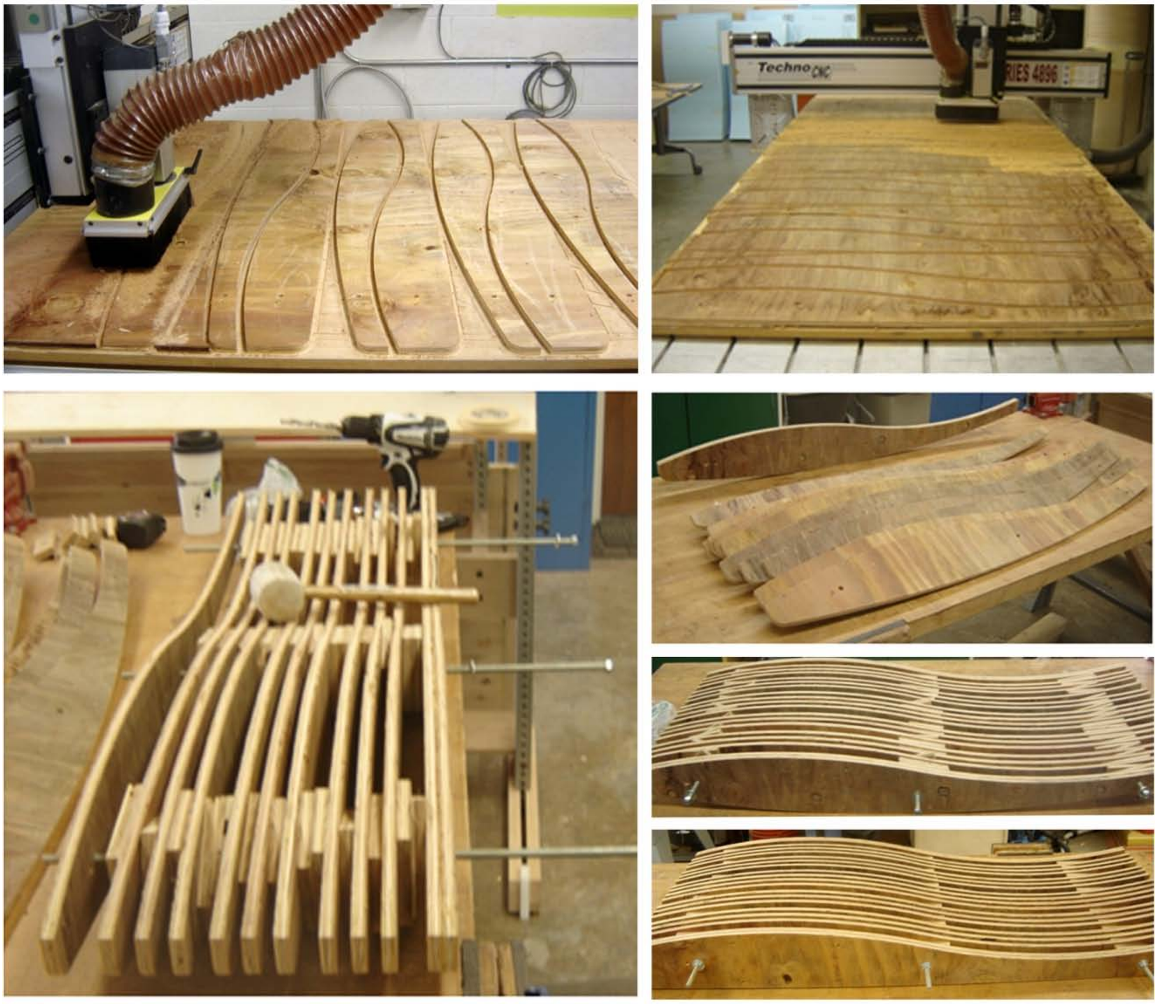


Figure 44 Mold fabrication and assembly

5.5.5 One-to-One Scale: Panel II

The design for Panel II was refined to a simple ‘S’-shape with a radius of four-feet, to explore a self-supporting wall system. This panel included a simple joint intended to speed up production given that previous panel one took one full work week in the shop to fabricate and assemble. After researching various SIP connection details, it was determined that a spline joint would be the most appropriate for the application of a curve panel. With the simple ‘S’-Shape the joints were the same either horizontally or vertically as compared to panel one where they were at various angles and widths. The splines developed consisted of three built-up layers of plywood forming a 1-1/2” in thickness. This allows for ¾” or half of the spline to be inserted into each panel with the plywood skin of each panel being screwed off at a spacing of 4” on center. This is similar to conventional light-wood construction framing practices and SIPs.

Four wall panels were developed to demonstrate the wall assembly and system. With a constant bake and forth exchange between design and fabrication the design of the panels was continually redefined. To align and stop the individual layers of foam from sliding during clamping, the foam cores were designed with foam plugs to be indexes. These plugs allowed for easy assembly during gluing without the panels moving. This resulted in higher quality panel construction. As this design-through-making process evolved, craft began to be reflected in the work produced. Fabrication, assembly, and digital modeling skills greatly increase.

The bending a four-foot long piece plywood to a radius of four-feet, results in a length of 3’-11 ½.” A ½” of material is lost to the area covered by the plywood. This ½” plus the ¾” for the spline to be inserted into the panel needs to be accounted for when milling the foam cores. As a result, three different cores had to be designed and fabricated for proper fit within the system. These three types were comprised of (1) bottom panel, (2) top panel, and (3) intermediate panel. These as part of an overall assembly were modeled exactly as to how they were to be assembled resulting in less material needed to be mill. With the use of nesting, or aligning similar panels up to reduce cut-offs, the time to mill these panels was reduced significantly with the use of full power of the router. The first two fabrication layouts were able to be milled around two and half hours, whereas the last layout took a little over three hours to mill. Therefore it took approximately a total of 8 hours to fabricate 48 components as compared to panel one, which took a little over five hours to mill six components. This increase in production rate was a result of learning the parameters of MasterCAM and CNC router while choosing the proper tool bit for the job at hand.

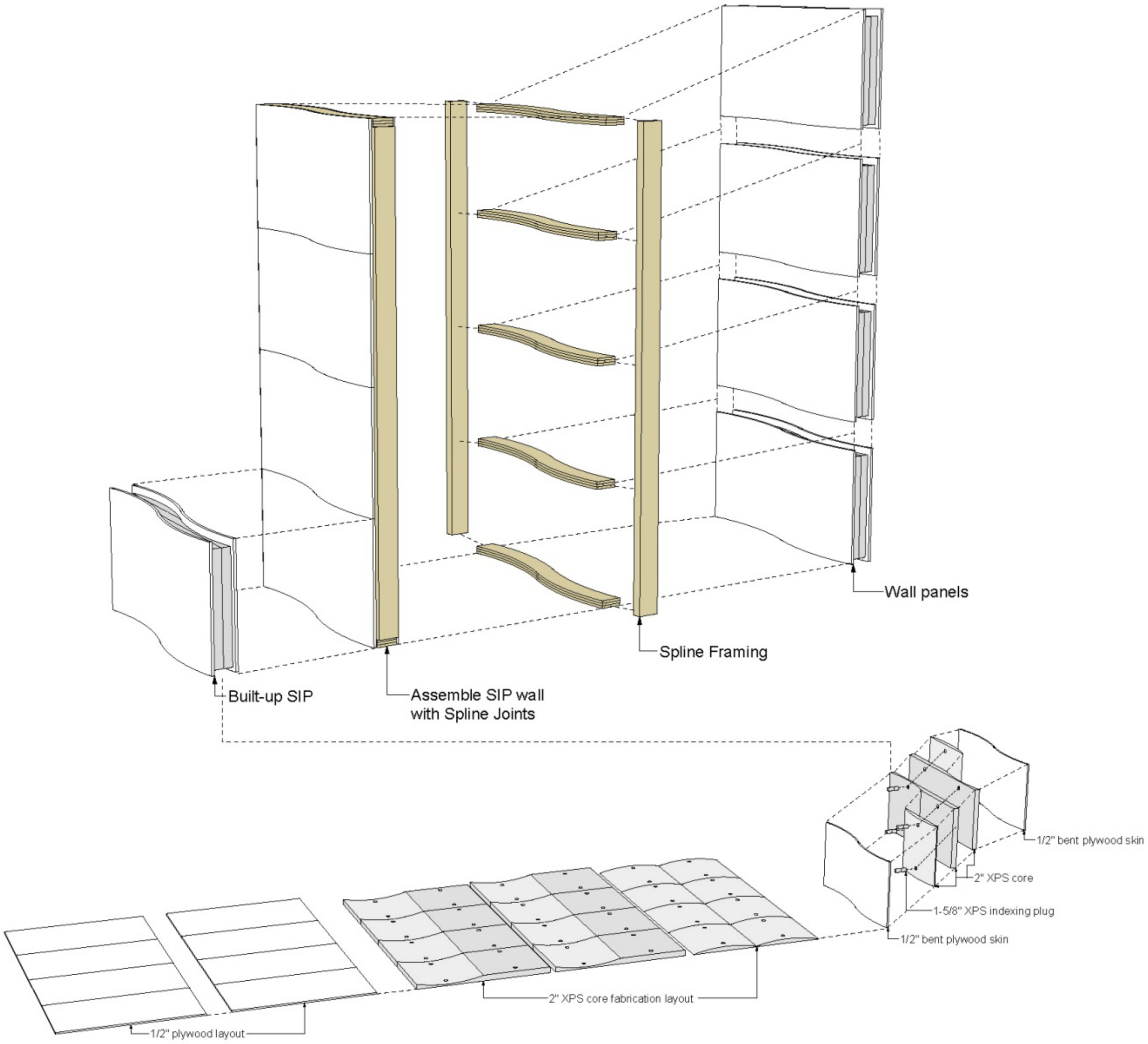


Figure 45 Panel II fabrication and assembly

Upper: Exploded perspective view of wall system with spine joints and panels; *lower:* exploded perspective view of fabrication and wall sandwich panel

Figure 46 Mold Fabrication and assembly

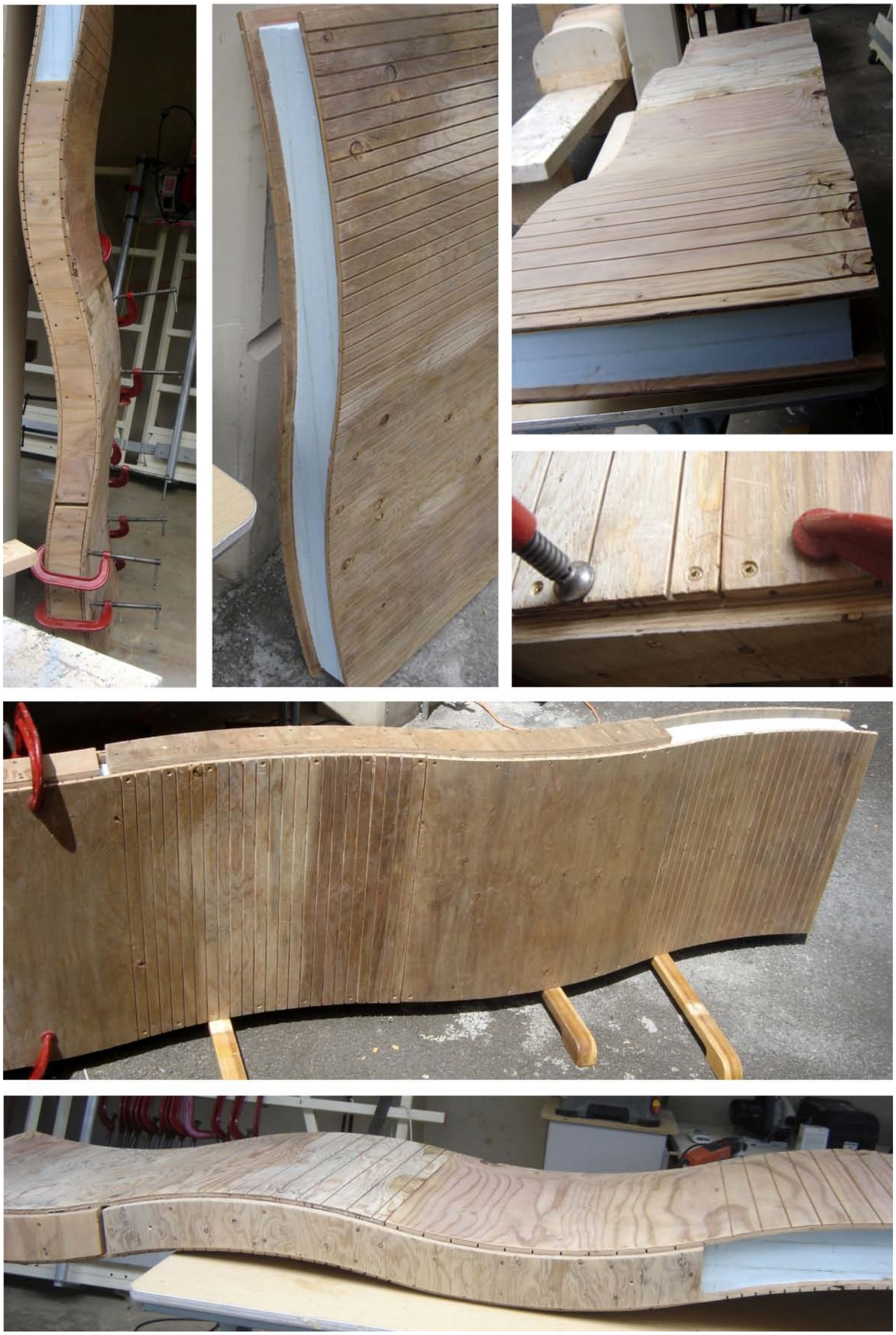


Figure 47 SIP wall assembly

Figure 48 Horizontal SIP wall assembly

Figure 49 Vertical SIP wall assembly

5.5.6 Tolerances of Machine, Material & Craft

Although the “file-to-factory” capability of using 3D-modeling programs of Rhinoceros in conjunction with MasterCAM allows for a smooth transition of precise data sharing, the proper use of MasterCAM requires its own set of machinist craft skills. As discovered in this project, craft deals with the processes to design and make an object well. The quality and precision of an object made depends on the designer-maker’s understanding of tolerances of the materials and the parameters of the tools used. With the use of CAD/CAM software the designer-maker is able to achieve superior accuracy with the ability to set the allowable tolerance within the program. With the software programs of AutoCAD and 3D-Rhinoceros, the display tolerances range from being from within 1” to 1/128.” The absolute tolerance for these programs is 7 values right of the decimal or 0.0000001. MasterCAM can be set to these tolerances as well, but the actual Techno CNC router cannot achieve this precision due to following factors: the natural properties of materials being milled; the zeroing of the machine to the spoil board in the X and Y directions, the zeroing of different length tools in the z direction, and rotation of the tool bits used. Therefore the designer-maker as a machinist has to learn these variable tolerances, in conjunction with the tool paths, and parameters available to efficiently fabricate a crafted object.

As a designer-maker using MasterCAM the following parameters were discovered to efficiently fabricate. These parameters and tolerances were based on the material used, maximizing cut time, and achieving a high quality of precision within the limits of the machine.

2” XPS Foam milling:

Tool	**Tool path**	**Step-over**	**Step-down**	**Breakthrough** (a)	**Check** (b)	**Cut path**	**Cut Rate**	**Plunge Rate**	**Feed Rate**
2” Ball cutter	Rough	1”	1”	0”	.02	Zigzag	181	256	256
5/8” Ball cutter	Finish	.01	0”	0”	0”	Zigzag	181	256	256
½” flat down	Contour	0”	¼”	.01”	0	right	181	256	256

Figure 50 CNC Foam Milling

1/2” Construction and hardwood plywood:

Tool	Tool path	Step-over	Step-down	Breakthrough(a)	Check	Cut path	Cut Rate	Plunge Rate	Feed Rate
½” Flat down	contour	0”	¼”	.01 (.02”)	0”	right	100-120	100-120	100-120
3/8” Compression	contour	0”	3/16”	.01 (.02”)	0”	right	100-110	110	110
¼” Flat down	contour	0”	1/8”	.01 (.02”)	0”	right	100	100	100
1/8” flat	contour					tip	80-100	100	100

Figure 51 CNC plywood milling

Figure 52 CNC router tool bits

Left: 3/8” ball cutter; *center:* 5/8” ball cutter; *right*: 2” ball cutter

Hardwood Milling:

Tool	Tool path	Step-over	Step-down	Breakthrough	Check	Cut path (c)	Cut Rate	Plunge Rate	Feed Rate
5/8” Ball cutter	rough	0”	5/16”	0”	.02”	One-way	100	100	100
½” flat down	contour	0”	¼”	.01”	0”	Right Left	100	100	100
3/8” Ball cutter	rough	3/16”	3/16”	0”	.02	One-Way	80-100	100	100
3/8” Ball cutter	Finish	.05”	0”	0”	0”	One-way	100		
¼” Ball cutter	rough	1/8”	1/8”	.01”	.01”	One-way	75-100	100	100
¼” Ball cutter	finish	.05”	0”	0”	0”	One-way	100		
¼” flat down	contour	0”	1/8”	.01”	0”	tip	75-100	100	100

Figure 53 Hardwood milling

As seen from the various charts, general parameters can be followed based upon the material being milled by the CNC router. Generally, to stay within the working limits of the machine the following should be followed:

- The maximum step over and step down for a rough tool-path or any tool-path should be ½ of the diameter of the tool bit.
- Rough milling is done with the larger tools bits as they remove the greatest amount of material with a single pass.
- Rough milling requires a minimum check of .02" and no breakthrough as they tend to cut deeper than finished tool paths.
- Breakthrough for finished materials (sanded hardwood, foam, interior plywood) needs to be .01" This requires for the actual stock dimension to be used. This ensures a clean cut without milling the spoil board on the CNC router.
- When quality is of concern, stock material should be milled in one direction with the router bit in compression against the material, versus zigzag cutting in both directions. This reduces tear outs.
- Construction plywood due to its varying thinness can be cut by two different ways:
    1. Used the normal size for the stock set with a .01 break through or
    2. Used the actual size for the stock set up with a .02 break through
- Plywood and hardwoods tend to mill at 80 to 120 % cut rate, plunge rate, and feed rate.
- Easy cutting materials such as foam can be mill at full power for cut rate, plunge rate, and feed rate without any difficultly.

During the fabrication of the components of the SIP wall assembly and mold-making the following and tolerances were found to be allowable. The foam cores were milled a 1/4" smaller to allow for 1/8" movement either way during the gluing assembly process to take in account for alignment issues later in the wall. The horizontal splines were initially milled 1/8" smaller than needed, but this turn out to be enough compensation, as the mold was able to compress the components tighter so the splines needed to be milled another 3/32" of which resulted in the proper fit. The vertical splines were deemed to have a 1/8” of tolerance to ensure proper fit, as the curvature of the wall seem no to affect the vertical joints as much compared to the horizontal joints.

With the experience, knowledge, and skills gain during this four week investigation the quality of walls panels has greatly increased to produce a high performance wall system. As seen through studies, the speed, quality, and craft have been steadily increased from designing-through-making exercise. Although it took four weeks to produce this system, it could easily be now reduce a quarter of the time. The construction schedule would follow as the following:

- Day one: Programming and milling of foam cores
- Day two: Programming, milling, and assembly of mold & horizontal splines
- Day three: fabrication of all plywood skins (kerfing, cutting to size), and the assembly of panel 1
- Day four: Assembly of Panel 2, and gluing of ½ the splines
- Day five: Assembly of Panel 3, fabrication of vertical splines
- Day six: Assembly of panel 4, and fabrication, assembly of misc., components
- Day seven: Assembly of Wall

The knowledge, skills, and the capabilities presented here reflect that of single designer-maker at the scale of architectural-wall. The capabilities of an integrated design-make team would be able to take on a bigger project and be able to it to new levels of designing and making.

VI. Conclusion

7.1 Maker, Machine, Material, and Craft

This doctorate project examined the gap that has evolved between the designer and maker within designing and building. This disjunction—due to specialization and legal restraints—has resulted in a lack of quality craftsmanship of the built environment. The advancements in digital design and fabrication methods of fab+craft promise to merge these disciplines into an integrated process where the line between designing and construction fades away. As a result, fab+craft combined craft and the act of making into a design-through-making narrative. This narrative integrates design and construction to contribute to a higher quality built environment. Research presented through the proliferation of digital design and fabrication methods of CAD/CAM software show that the designer and the maker share methods in by which they operate. This results in the ability for a new version of *designer-makers* and *designer-maker-teams* to emerge and to harness and achieve synthesis between, design, technology, and fabrication to produce a well crafted environment. This new designer-maker team has the ability to cross over conventional lines of separation as they are able to take part in the 'file-to-factory' process so as to engage in the processes of building and making through digital technologies. Within the culture of making there is a constant dialogue between drawing, computer modeling, physical modeling, and the transfer of data.

This doctorate project, as a means to investigate this dialogue, demonstrates this methodology through prototyping. Prototyping was conducted through the first-hand experience of an individual *designer-maker* guided by the practiced hand. Sandwich panel construction prototypes were developed linking form, structure, and material properties within a geometric rule base. This is seen through the design, fabrication, and assembly of the full-scaled curved SIP wall system. As revealed in the project, design-through-making involves a great amount of responsibility, risk, and skill. This requires considerable effort by an individual. But the availability of CAD/CAM technologies, along with the use of conventional tools, helps to lessen the burden. Digital tools in conjunction with conventional tools made it possible to design and fabricate the wall assembly using the traditional method of kerfing. This allowed for the bending of plywood skins and the milling of the insulation core to be completed by a single designer-maker. In the process, the designer-maker gains new insights as how to properly digitally model, because every component has to be accounted during fabrication. During the stages of design, the use of MasterCAM allows checking for tolerances and conflicts within the 3D-modeling software. The designer-maker is able to see conflicts in advance. These conflicts are immediately fixed as the designer-maker is present during all stages of fabrication and assembly. This was experienced firsthand during the fabrication of the insulation core as it took several revisions until it was modeled correctly before it was produced. This firsthand experience is important because it can help solve conflicts before they reach the job-site, as they are still within grasp of the designer and maker. Conflicts and missed tolerances discovered on the jobsite can cost thousands of dollars to be properly fixed or redone. Therefore the use of digital design and fabrication technologies provide a platform where knowledge and data can be exchanged between machines working in conjunction with other designer-maker constituents. As result, a flow of knowledge is transferred through the act of making an object, refining a design, or process, to contribute to the overall quality of cultural life, as it happens within the environment, it happens through craft.

Illustrations

Bibliography

Achimmenges.net, "Design Research Agenda," Achimmeges.net, http://www.achimmenges.net/?p=4897 (accessed March 21, 2012).

Adamson, Glenn. *Thinking Through Craft.* New York: Berg, 2007

Agkathidis, Asterios. *Modular Structures in Design and Architecture.* Amsterdam: Bispublishers Amsterdam, 2009.

AIA. "Architect's Administration of the Contract." In *AIA document A201-1997: General Conditions of the contract for Construction.* Washington, DC: AIA, 1997.

Anderson, Mark and Peter Anderson. *Architecture and Construction.* New York: Princeton Architecture Press, 2000.

Anderson, Mark and Peter Anderson. *Prefab Prototypes: Site Specific Design for Offsite Construction.* New York: Princeton Architectural Press, 2007.

APA-The Engineered Wood Association. *Plywood Design Specification.* Tacoma, WA: APA- The Engineered Wood Association, 1998.

APA-The Engineered Wood Association. "Supplement 4: Design and Fabrication of Plywood Sandwich Panels." in *Plywood Design Specification.* Tacoma, WA: APA-The Engineered Wood association, 1993.

Ashby, Mike and Kara Johnson. *Materials and Design.* Oxford: Elsevier Butterwoth-Heineman, 2002.

Benson, Jonathan. *Woodworkers' Guide to Bending Wood: Techniques, projects, and expert advice for fine Woodworking.* East Petersburg, PA: Fox Chapel Publishing, 2008.

Borden, Gail Peter, Michael Meredith, eds., *Matter: Material Processes in Architectural Production.* New York: Routledge, 2012.

Conrads, Ulrich ed. *Programs and Manifestoes on the 2oth Century Architecture.* Cambridge: MIT Press, 1971.

Corser, Robert, ed., *Fabricating Architecture: Selected Readings in Digital Design and Manufacturing*. New York: Princeton Architectural Press, 2010.

DBIA. "What is Design-Build?." Design-Build Institute of America, http://www.dbia.org/about/designbuild/ (Accessed March 24, 2012).

Deamer, Peggy and Phillip G. Bernsein, eds., *Building (in) The Future: Recasting Labor in Architecture.* New York: Princeton Architectural Press, 2010.

Demetrios, Eames. *An Eames Primer.* New York: Universe Publishing, 2001.

Dewey, John. *Experience and Education, Late Works, Vol. 13*. New York: MacMillan, 1938.

Frampton, Kenneth, Kunio Kudo and Keith Vincent. *Japanese Building Practice: From Ancient Times to the Meiji Period.* New York: John Wiley & Sons, 1997.

Frampton, Kenneth. *Labour, Work and Architecture: collected Essays on Architecture and Design.* London: Phaidon Press Limited, 2002.

Garber, Richard. “Alberti’s Paradigm.” in “Closing the Gap.” Special issue, *Architectural Design* 79, no 2 (March 2009).

Harry N. Abrams, Inc., Library of Congress, and Vitra Design Museum. *The Work of Charles and Ray Eames: A legacy of Invention.* New York: Harry N. Abrams, Inc., 1997.

Iwamoto, Lisa. *Digital Fabrications: Architectural and Material Techniques.* New York: Princeton Architectural Press, 2009.

Kieran, Stephen and James Timberlake. *Refabricating Architecture: How Manufacturing Methodologies are poised to transform building Construction.* New York: McGraw-hill Companies, 2004.

Kolarevic, Branko, ed., *Architecture in the Digital Age: Design and Manufacturing.* New York: Spon Press, 2003.

Martin, Randy L. “R-Value Table: Insulation Values For Selected Materials.”ColoradoENERGY.org. http://www.coloradoenergy.org/procorner/stuff/r-values.htm (accessed April 4, 2012)

MATSYS. “P_Wall(2006).” MATSYS. http://matsysdesign.com/category/projects/p_wall2006/ (accessed April 26, 2011).

MATSYS. “P_Wall(2009).” MATSYS. http://matsysdesign.com/category/projects/p_wall2009/ (accessed April 26, 2011).

MATSYS. “Zero/Fold Screen.” MATSYS. http://matsysdesign.com/category/projects/zerofold-screen/ (accessed April 26, 2011).

McCullough, Malcolm. *Abstracting Craft: The Practiced Digital Hand.* Cambridge, MA: MIT Press, 1996.

Niemasz, Jeffrey, Jon Sargent, and Laura Viklund. “Steam-Bent Wood Lattice Morphology,” Achimenges.net, http://www.achimmenges.net/?p=5003 (accessed February 16, 2012).

Nordmeyer, Russell. “A Fetish for Fabrication.” *Architectural Record*, no. 10 (2011):

Patteeuw, Véronique, ed. *Reading MVRDV*. Rotterdam: NAi, 2003.

Pye, David. *The Nature and Art of Workmanship.* London: The Herbert Press, 1995.

Risatti, Howard. *A theory of Craf*t. Chapel Hill, NC: University of North Carolina Press, 2007.

Sennett, Richard. *The Craftsperson.* New Haven, CT: Yale University Press, 2008.

Sheil, Bob."Design through Making: An Introduction." in "Design Through Making," Special issue, *Architectural Design* 75, no 4 (July/August 2005):

Shopsmith. "Power Tool Woodworking Online for Everyone." http://www.shopsmith.com/academy/tblsaw_spops/index.htm (Accessed March 15, 2012)

Spengler, Oswald. *Makerand Technics: A Contribution to a Philosophy of Life. New York: Alfred A. Knopf* Inc., 1932.

Spuybroek Lars. *Research & Design: The Architecture of Variation*. New York: Thames & Hudson Inc, 2009.

Stacey, Michael. "In my Craft and Sullen Art or Sketching the Future by drawing on the Past," in "Design Through Making," ed. Bob Sheil. Special issue, *Architectural Design* 75, no 4 (July/August 2005):

Stark, Nicole M., Ziyong Cai, and Charles Cai. "Wood-Based Composite Materials: Panel products, Glue-Laminated Timber, Structural Composite Lumber, and Wood-Nonwood Composite Materials." In *Wood Handbook: Woods as an Engineering Material*, *Wood Handbook*, Centennial ed. by Forest Products Laboratory. Madison, WI: United States Department of Agriculture Forest Service, 2010.

Stevens, W. C. and N. Turner. *Wood bending Handbook.* East Petersburg, PA: Fox Chapel Publishing, 1970.

Tai-Workshop. "The bending Wood: Kerfing." http://www.tai-workshop.com/english/tech-2(b)-e.html (Accessed March 15,2012)

Urbano A&O. "Bone Wall" Urbano A&O. http://www.urbanao.com/ (Accessed April 24, 2011)

Universität Stuttgart. "Research Pavilion ICD/ITKE." Universität Stuttgart. http://icd.uni-stuttgart.de/?p=4458 (accessed April 26, 2011).

Vesely, Dalibor. *Architecture in the Age of Divided Representation: The Question of Creativity; In the shadow of Production.* Cambridge, MA: MIT Press, 2004

Wendling, Amy E. *Karl Marx on Technology and Alienation.* New York: Palgrave Macmillan, 2009.

Willis, Daniel and Todd Woodward. "Diminishing difficulty." *Harvard Design Magazine,* ed. William S. Saunders. Cam bridge, MA: Harvard University Press, 2008.

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Figure 2, 3, 4	Garber, Richard. “Alberti’s Paradigm.” in “Closing the Gap.”
Figure 5	http://www.eamesoffice.com/
Figure 6, 7, 8	MATSYS. “Zero/Fold Screen.” http://matsysdesign.com/category/projects/zerofold-screen/
Figure 9, 10	MATSYS. “P_Wall(2006).” http://matsysdesign.com/category/projects/p_wall2006/ (accessed April 26, 2011).
Figure 11	MATSYS. “P_Wall(2009).” http://matsysdesign.com/category/projects/p_wall2009/ (accessed April 26, 2011).
Figure 12, 13	Universität Stuttgart. “Research Pavilion ICD/ITKE.” http://icd.uni-stuttgart.de/?p=4458 (accessed April 26, 2011).
Figure 14,15	Urbano A&O. “Bone Wall” http://www.urbanao.com/ (Accessed April 24, 2011)
Figure 16, 17	Courtesy of Team Hawaii, & Hale Pilihonua
Figure 18,19,20	APA-The Engineered Wood Association. *Plywood Design Specification.* 1998.
Figure 21	Benson, Jonathan. *Woodworkers’ Guide to Bending Wood: Techniques, projects, and expert advice for fine Woodworking.* 2008.
Figure 22	APA-The Engineered Wood Association. *Plywood Design Specification.* 1998.
Figure 32,33,34	Stark, Nicole M., Ziyong Cai, and Charles Cai. “Wood-Based Composite Materials: Panel products, Glue-Laminated Timber, Structural Composite Lumber, and Wood-Nonwood Composite Materials.” In *Wood Handbook: Woods as an Engineering Material*, *Wood Handbook*,2010.
Figure 35	Revised Ordinances of Honolulu. http://www1.honolulu.gov/council/ocs/roh/