THINKING THROUGH MAKING:
Material and Process Intelligence Revealed in Architecture Through Design and Fabrication

by

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Submitted in partial fulfilment of the requirements
for the degree of Master of Architecture

at

Dalhousie University
Halifax, Nova Scotia
June 2017

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ABSTRACT

This thesis explores the potential for a detail or joint to be the generator of form. By thinking through making – this requires to create, to gain tacit knowledge (in addition to explicit knowledge), and to translate design intent through to built form. The ideas being tested here are realized in built form and studied to pull out information to submit back into the design and fabrication process via a feedback loop. The concept for this thesis is an exploration into how this methodology can contribute to the way architects think about and practice architecture. In addition, it is the exploration on how making can alter the way we think about and modify space. It also takes into account the new technologies we have that allow us to design, using parametric modeling, computational design and fabrication techniques to aid thinking and making (testing, prototyping, etc.).

How can the process of making inform the way we think about and create space, by the exploration of the Kawai-tsugite joint through the use of computational modeling and fabrication techniques?

ACKNOWLEDGEMENTS

My wife Christie, for the support, love and encouragement throughout this entire process.

My parents, for igniting my interest in building and architecture.

Brian Lilley for your dedication and continual interest in this thesis.

Regan Southcott for those ‘eureka’ moments in the shop.

My advisor Emanuel Jannasch for the numerous impromptu talks, guidance and inspiration.

My supervisor James Forren for continually pushing me to explore and discover with a critical outlook.

CHAPTER 1: INTRODUCTION

Thinking through making is a continual questioning and application of a methodology of how making can inform the design and fabrication process. In relation, the detail becomes an integral part in how spaces can be created and changed. Using Actor-Network Theory (ANT), an investigation into how animate and inanimate objects relate and influence one another becomes of importance. As the digital realm speaks directly to the tools of fabrication, the relationship between the two becomes extremely important and the investigation continues to the relationship to the artifact. Of great importance and contribution to this thesis is the constant feedback loops, using prototyping to inform the digital and fabrication processes and ultimately informing how space is generated and modified through the Kawai-tsugite joint.

Thesis Question

How can the process of making inform the way we think about and create space, by the exploration of the Kawai-tsugite joint through the use of computational modeling and fabrication techniques?

CHAPTER 2: THEORETICAL FRAMEWORK

Knowledge

Society has become increasingly accustom to explicit knowledge. An increasing disconnect has come from the world of tacit knowledge or that which cannot be explained explicitly. A common mistake made is using the term haptic knowledge for that of tacit. Indeed the two terms are similar and haptic is definitely informed by tacit and vice versa, however, the distinction here must be made that the terms tacit and haptic have different meanings in regards to knowledge.

Thus further defining these terms becomes important. Merriam-Webster defines explicit as "fully revealed or expressed without vagueness, implication, or ambiguity: leaving no question as to meaning or intent." (Merriam-Webster 2017, s.v. "explicit") By contrast, tacit is defined as being "expressed or carried on without words or speech." (Merriam-Webster 2017, s.v. "tacit") In relation to this definition, haptic refers to that of touch, that is relating or based on the sense of touch. (Merriam-Webster 2017, s.v. "haptic") It is easy to now draw the connection to tacit, as often haptic knowledge is also tacit knowledge.

However these alone do not start to give a holistic definition of the concepts at play, it is with the addition of knowledge that we start to see how the two terms are connected. Knowledge is defined as “the fact or condition of knowing something with familiarity gained through experience or association: acquaintance with or understanding of a science, art, or technique.” (Merriam-Webster 2017, s.v. “knowledge”) Therefore, we see that explicit knowledge is that which can be gained without doubt of meaning, to know exactly. Whereas tacit allows for those things: ambiguity, observation, interpretation of knowing something. The interesting part about language and the meaning of these particular words, is that the definition of knowledge already has inherent in it the ideas of explicit and tacit as articulated by experience or association.

Further explanation on the two definitions can be found that extends our understanding of the concepts.

> Explicit knowledge is articulated knowledge, expressed and recorded as words, numbers, codes, mathematical and scientific formulae, and musical notations. Explicit knowledge is easy to communicate, store, and distribute and is the knowledge found in books, on the web, and other visual and oral means. (BusinessDictionary.com 2017, s.v. “explicit knowledge”)

> Tacit knowledge is unwritten, unspoken, and hidden vast storehouse of knowledge held by practically every normal human being, based on his or her emotions, experiences, insights, intuition, observations and internalized information. Tacit knowledge is integral to the entirety of a person’s consciousness, is acquired largely through association with other people, and requires joint or shared activities to be imparted from on to another. Like the submerged part of an iceberg it constitutes the bulk of what one knows, and forms the underlying framework that makes explicit knowledge possible. (BusinessDictionary.com 2017, s.v. “tacit knowledge”)

Based on the further defined terms it would seem that one is able to separate explicit from tacit knowledge, however, this is not the case. In Angioni's 2011 book *Fare, Dire, Sentire: L'identico e il diverso nelle cuture* the importance of knowledge as a symbiotic aggregate of both explicit and tacit is outlined. Although we can distinguish with language the difference between explicit and tacit knowledge, they are not separate and discrete in practice; encoded in the modes of living and learning are the interaction between explicit and tacit which is vital for the creation of new knowledge. (Angioni 2011, 26-31) Thus, knowledge is comprised of two types from which our understanding is generated by symbiotically acquiring data from both explicit and tacit inputs. This definition of knowledge starts to provide the framework from which this thesis has developed.

Historically we can see how the two concepts have contributed to the transfer of knowledge from one generation to the next. Take for example an apprentice. He or she works alongside the master, listening to what is being taught (explicit) while simultaneously putting that knowledge to the test by doing (tacit). A common division in current society is that of the intellectual world, which can be seen as the explicit, and that of the practical world which is tacit or rooted in actually doing. The transfer of knowledge problem is not one that is new as Addington points out, scientific and engineering knowledge only enters the design realm in a 'dumbed down' state, keeping the architectural profession at arm's length. (Addington 2005, viii) This can easily be confirmed by walking into an architecture firm and seeing the numerous consultants used to carry out even a small job.

It is my intent to explore how tacit knowledge, we shall call it making, can contribute to explicit knowledge and is beneficial to learning architecture and indeed integral to contributing how we think about and make spaces as architects.

Making

If we define making as the embodiment of tacit knowledge, then making becomes the act of gaining knowledge which thus cannot be explicitly stated.

> […] architecture is only ever learned by getting your hands dirty – by discovering it one project at a time through mock-ups, installations or other kinds of 1:1 tests, by trying an idea out, by drawing, developing, testing and ultimately realizing an unknown or provisional idea. This is done through the making of prototypes and full-scale models whose working difficulties and eventual results offer the designers vital insight and understanding into how they might take a next tentative step forward. (Self 2011, 4)

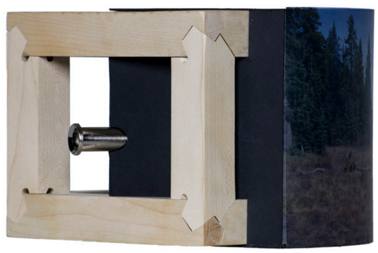
Self adds to this definition through the idea that making implies developing ideas in 3D form through prototypes and full-scale models. For now, we will define making as the fabrication of 3D artifacts that aid our explicit knowledge through the gaining of tacit knowledge as defined previously. 2D representations in this case are subdued to explore the potential of generating space in 3D. However, 2D representations such as drawing can still be used to explore making artifacts of three dimensions.

The making of architectural space has many facets, but in the context of this thesis we will constrict it to the definition and down to a minimum. By exploring what it means to create space, there is an implication of the relationship of the body to the construction and ultimately the built form. For the time being we can refer to this space as a building.

> Buildings that delight their users endeavor to enhance daily routines and timeless built landscapes. Buildings that provide reliable service ensure the safe, comfortable, reliable and durable shelter needed to fulfill the basic requirements of our species. Achieving this pair of conditions through time has been the driving force behind much of the architectural design and building construction. The balance between the two depends on the priorities of society and the flux of economic and cultural forces. (Fernandez 2006, 2)

The vernacular uses function as the driving force in creative problem solving, producing an architecture tied to place and idea transfer through tradition. (Fernandez 2006, 20) Yet the idea that we can use space to enhance our daily routine implies that space can affect the simplest of routines such as gazing out a window to admire the landscape or the way we move from the bedroom to the kitchen. In this case the space need not be complicated and can indeed be minimal, plain, and ordinary in appearance, yet have a profound effect on the way we see the landscape simply by framing it in a particular way. Thus the purpose of space is born out of a function.

Form Generator



Series of photographs showing a 3D model testing the ability of the Kawai-tsugite joint to be a form generator.

The detail, as Frascari indicates, can be a form generator, although it is a role typically ascribed to the plan. (Frascari 1996, 500) He also makes the distinction between details and joints as the former is defined as the relationship to the whole due to issues of scale and dimension, and the latter can still be defined despite scale and dimension. (Frascari 1996, 501) To distinguish between the two and provide clarity throughout this document, we will adopt his definitions.

Our ideas manifest themselves usually on paper first, then into scale models, and finally into built works. But the ability to think and create in three dimensions goes beyond pen and paper and starts to talk about architecture in the medium in which it arises. The Japanese layout is hands on, it is tacit information, and deals with the ability to visualize on a three-dimensional scale. (Brackett and Rao 2005, 9) It is this distinction between the two-dimensional and three-dimensional that the framework for this thesis evolves. I suggest that this visualization starts at the detail and allows for the visualization of space to occur.

Material Information

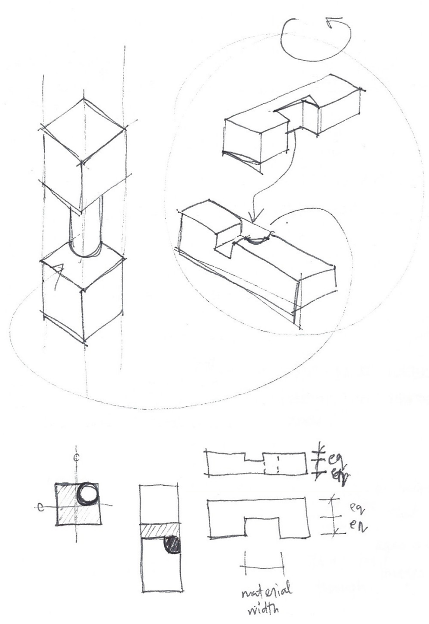
As the detail can be a generator of form, thinking in three dimensions in the medium which architecture is made, calls for additional information besides size and scale. Material plays a very important role that helps to determine the size and scale of the detail.

> Material design is a frame of mind. A deeper education unlearning one's first education. An attitude. Questioning. Inspiring: thinking, doing, and making. (Schröpfer and Carpenter 2011, 9)

Schröpfer and Carpenter in *Material Design* outline three verbs: thinking, doing, and making. These verbs actually form one stream of consciousness using Angioni's importance of knowledge as a symbiotic aggregate of both explicit and tacit as we established before. In the material design frame of mind, a material is needed to carry out the making process, to gain the tacit knowledge needed to inform design decisions. In the framework of thinking through making, material and design are dependent on each other, without one you cannot have the other.

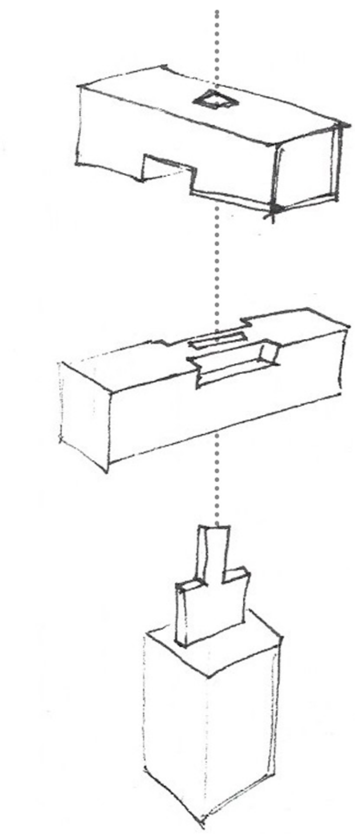
Japanese Joinery

As a culture of joinery rooted in a deep respect for the material and visualization in three dimensions, Japanese joinery is a suitable way to apply the theoretical framework of thinking through making. There is still belief that each tree has a soul, whom can be bestowed on pieces of wood, materializing on the surface in the form of the beauty of the wood. (Zwerger 2012, 11) It was only through the act of making that allowed a greater respect for the craft of Japanese joinery, as well as the time and effort required to fulfill the task of making a single joint.

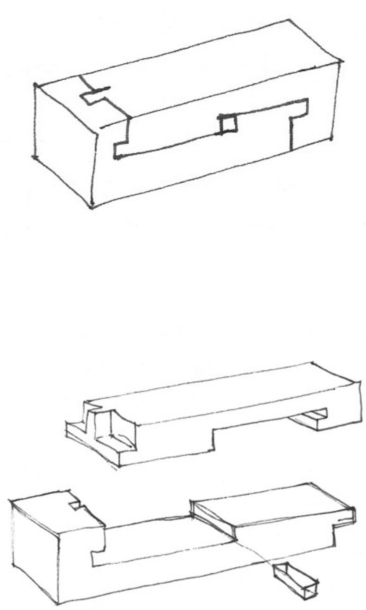


Visualizing in three dimensions through sketching of pieces and assembly technique.

Aesthetics and function of the joint start to play major roles simultaneously, giving the craft of joinery immense cultural value. Given that the framework



Sketching the Watari-ago-niju-hozo-shikuchi joint.



Sketching the Shippasami-tsugi joint to help with visualization.

requires some baseline on what is acceptable for making, the level of craft obtained within the Japanese culture as it applies to wood joinery serves a suitable baseline from which to progress.

Using tools commonly used to facilitate making Japanese joints, my investigation started applying the theoretical framework of thinking through making. First, explicit knowledge was gathered as to how the joint was to be made. Second, material was obtained and the layout transferred. Third, the making of the joint facilitated tacit feedback of which was used to further refine the joint and generate a working artifact. Careful attention was paid to the material itself, using the tools in such a way the material was guiding their movement.

> Japanese wood joinery exemplifies a deep-seated respect for the material and for the materials that work it. […] The tools themselves are referred to as dōgu, translated "instruments of the Way [of Carpentry]." While the instruments themselves have evolved to include both traditional and electric tools, the pride taken in them remains strong. The tools connect the carpenters to the material, the overall design intent, and to the cultural tradition. (Schröpfer and Carpenter 2011, 68)

This connection to the material through the tool lies at the heart of thinking through making. Although wood joints have not changed much in thousands of years, how we make them has changed drastically with the addition of power tools which can make the same joints in less time with greater accuracy. (Chan 2002, 9)This does not mean that the human element is completely disregarded, just that the bulk or all of the material can be removed through faster more accurate means than done ordinarily by hand. Yet because the tool is what connects the craftsman to the material, the addition of modern machinery was necessary to fit into the theoretical framework.

Computation and Machine

Now critical to the theoretical framework, the addition of computation and machine allows for the investigation to include modern methods and machinery for fabrication. If we consider these new elements as tools, then our connection to the material still holds true and allows for a deep investigation into the relationship we have with material and space which are modified by such tools.

> The explorations illustrate how parametric modeling and fabrication can contribute to the conception of new spaces, to everyday realities of commercial construction and to the transformation of the regional wood industry from a resource-based economy to one based in knowledge. (Beesley et al. 2007, 10)

Parametric modeling and fabrication can provide tools to the architect in which control of the outcome of fabrication is anticipated and even optimized. It is my intention here to explore the notion of computation and fabrication as additional tools with which the architect has control. By using these tools to design, create, and make, I will not only be exploring how these tools work for the architect but also the feasibility for the architect to use this way of working to produce architecture. This relationship between architect and machine thus becomes important to study, as the different tools, materials, and techniques will yield differing relationships.

Actor-Network Theory

To study the relationships created, Actor-Network Theory (ANT) is used as it allows a way to study animate and inanimate components on a level field. These components or actors are given equal value and the relationships between the different actors are valued and examined. Authored by Latour, Law, and Callon in the field of Sociology, ANT provides a unique way to look at the relationship of architect, machine, architecture and space.

> [...] when social scientists add the adjective 'social' to some phenomenon, they designate a stabilized state of affairs, a bundle of ties that, later, may be mobilized to account for some other phenomenon. There is nothing wrong with this use of the word as long as it designates what is already assembled together, without making any superfluous assumptions about the nature of what is assembled. Problems arise, however, when 'social' begins to mean a type of material, as if the adjective was roughly comparable to other terms like 'wooden', 'steely', 'biological', 'economical', 'mental', 'organizational', or 'linguistic'. At that point, the meaning of the word breaks down since it now designates two entirely different things: first, a movement during a process of assembling; and second, a specific type of ingredient that is supposed to differ from other materials. (Latour 2007, 1)

ANT provides a way to look at the ability of a detail to generate space that influences how we think, make, and experience the space based on the design around us. These relationships are not strictly person to person, but in fact are relationships of everyday life involving people, spaces, objects, and ideas.

> I find myself involved in relationships mediated by the particular design of the building [...]. (Yaneva 2009, 275)

Typical mapping looks at how the relationships between actors are formed rather than why they are formed. By looking at the relationships between actors (which can range from people to objects to ideas and even companies) the relative impact each actor has on another can fluctuate and change given the element of time. In one scenario, a person could have the most power within a network, yet when the network is mapped again, a software program could now hold this power.

> Actors come together to form temporary networks anchored by another actor creating assemblages of relations specific to an individual act or broader even and forming a collective (an 'actant'). An actant is a network comprising any actors - cell phones, blogs, people, etc. - that have the ability to act and do act within the network. (Potts, 8)

> ANT mapping is a method for understanding the context of workplace technologies, organizations, and people before documenting tasks, processes, and workflows. It is a way for researches to visualize their field-based research as assemblages of people, organizations, and technologies. (Potts, 9)

ANT mapping allows an architect to know the audience's context, relationships, and distribution before attempting to create innovative work. It enables communication between design collaborators to develop more quickly a shared understanding of the implications of the proposed designs, policies and services. (Potts, 10) Mapping is an ongoing process in which actors can and do change with time. By adding time into the mix, a better understanding of the contextual environment can be had, as each diagram network drawn will add some bit of information to the overall collective understanding of the design project.

Mapping occurs for a number of reasons: to understand the participants, to understand the relationship hierarchies, to understand the context - before, during and after design interventions.

Outlined below are the steps to ANT mapping:

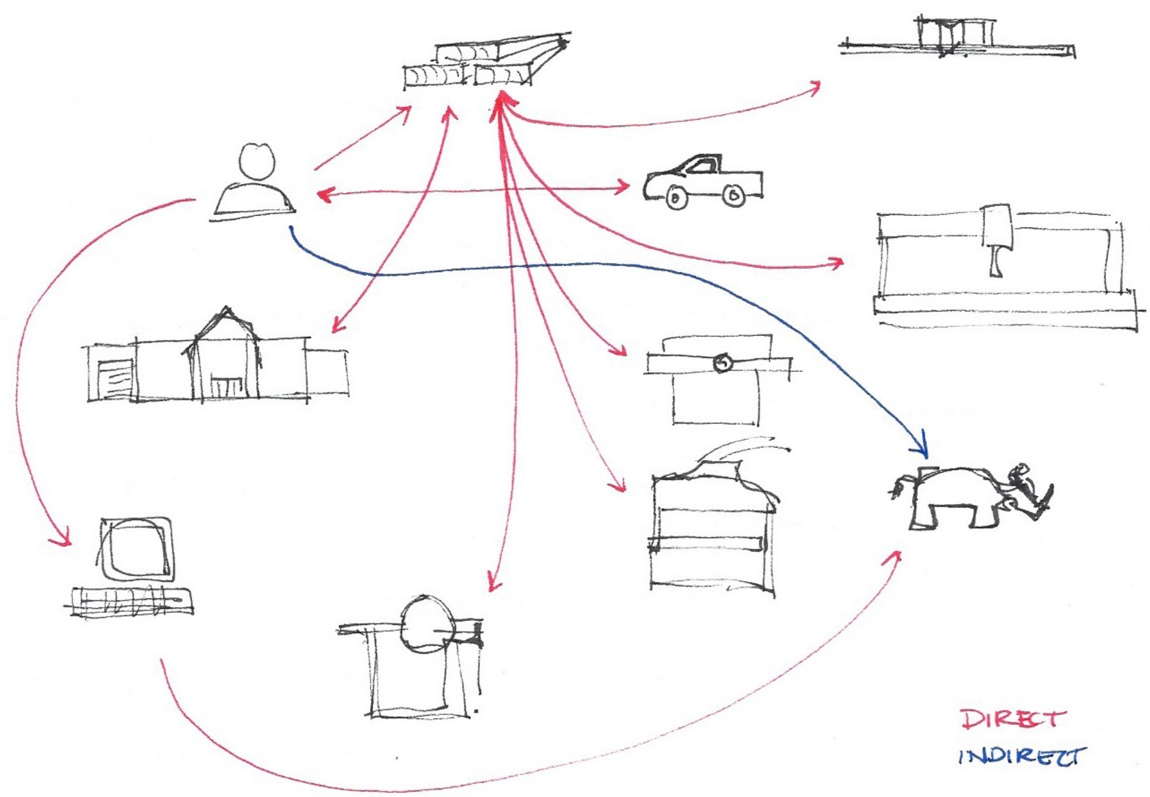
1. Look for actors within a network you would like to study. Limit the number of actors to those that are important to your study and research, this is not an all inclusive list.

2. Record only nouns: people, places, things, objects, technologies, ideas, etc.

3. Look for patterns and influences between actors.

4. Apply visual icons and distinguishing lines to show differing actors and relationships. This produces a visual that can be quickly read and understood as well as compared to other network diagrams.

Each actor is a network and each network could be an actor in a larger network. This powers of ten ability allows for mapping of actors to be very inclusive or exclusive. Choosing the right actors becomes the critical component to understanding the network being studied. By limiting the network actors to a selective number, the relationships and tracing of relationships can be studied more in depth than an all inclusive mapping strategy. Using this method of mapping allows for the inclusion of time within the network. Constantly changing, this gives a higher level of understanding the relationships at play and the influence associated with those relationships.



ANT map showing the actors as icons and the relationships between the actors as colored lines denoting a type of relationship.

CHAPTER 3: MATERIAL AND MACHINE

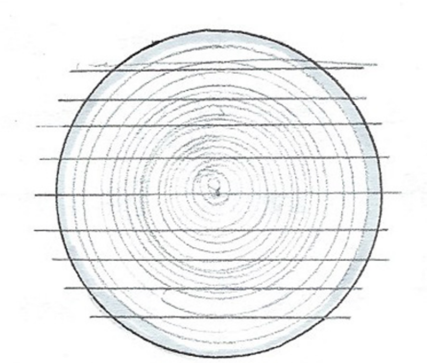
Raw log material waiting to be milled in the plant behind.

Wood: Raw Material

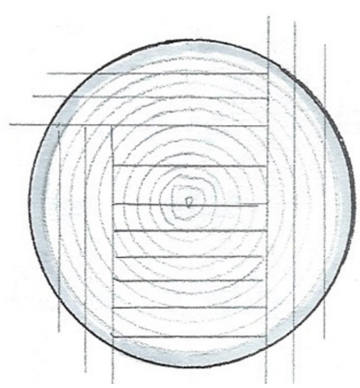
> Every material is distinguished by characteristics peculiar to itself. Knowledge of these is a necessary prerequisite for processing the material appropriately. (Zwerger 2012,10)

The choice of wood has stemmed from my years spent in the residential construction industry. It is a material that I frequently worked with, for a variety of different tasks: structure, furniture, sculpture. It is a material of wide diversity and versatility, which has many species all of which have a wide range of properties that gives way to a breadth of functions. This variety of characteristics and functions makes it an ideal material to work with and discover its limits and capabilities.

> Material in the raw is nothing much. Only worked with material has quality, and pieces of worked material are made to show their quality by men, or put together so that together they show a quality which singly they had not. (Pye 1968, 2)

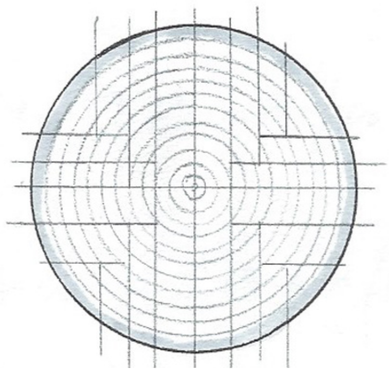


Plain sawn or flat sawn.

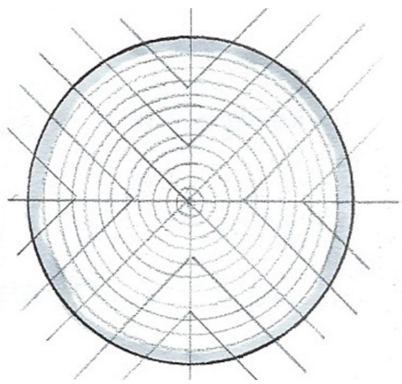


Sawing around or cant sawing.

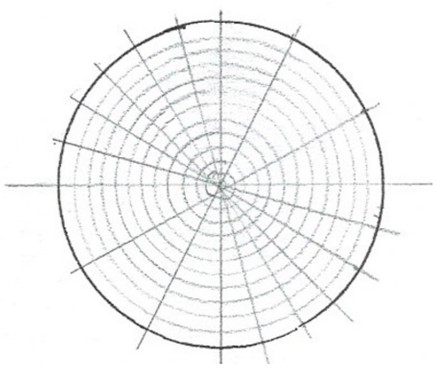
Raw wood is anisotropic, meaning its properties differ depending on its orientation. This is in relation to its fibrous wood grain and many different wood products take this into account for their function. Take for instance the way logs are cut for lumber: plain sawn, sawing around, quarter sawn, and rift sawn. Plain sawn or flat sawn (also known as through and through or live sawn) is the most common, in which the first cut is made tangent to the circumference of the log. The cuts in succession are parallel to the previous, producing the widest possible boards. This



Modern quarter sawn.



Traditional quarter sawn.



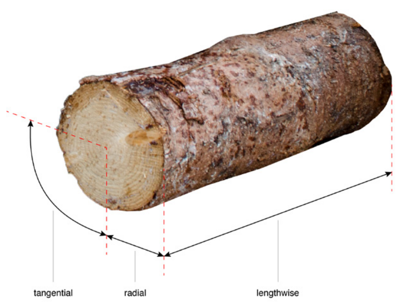
Rift sawn.

is the most economical for giving the most wood but also financially. Sawing around (cant sawing) refers to a sawing technique which uses the previous cut faces as flat surfaces to cut perpendicular pieces in succession. The name cant comes from the outer bark pieces being sawn off on all sides leaving a cant or square piece of wood from the center of the log with which to cut the remaining pieces from. Quarter sawn refers to a technique of cutting the circular cross section of a log into quarters, which then each quarter is sawn perpendicular to the growth rings with successive parallel cuts. Rift sawn is similar to quarter sawn, starting by cutting the log into quarters, then cutting pie shaped slices from the center of the log. This is not the only way to use the log either, as peeling the growth rings allows for sheets of thin wood to then be used as veneers and plywood. As you can see, just in the way a tree is milled, has impact and variety in the uses and functions it can achieve.

> The contributors to this book are explorers in this new world in which design and craft intertwine. But why wood? In contemporary design, it is but one of myriad of material choices. […] Wood is easy to work and form; it is accessible to many. […] Joining, laminating, carving, bending, cutting and finishing become sources of design ideas. (Beesley et al. 2007, preface)

There is still yet another way in which trees can be harvested as to make the most of a natural material. Trees grow by adding growth rings to its cross-sectional diameter. The grain shows the hard wood and the soft wood spring growth. But there are also outside forces which act upon the trees as they grow, producing reaction wood, which grows in opposition to the force acting upon it. This can be seen as curves, bows and bends which in local boat building practice has led to the use of these bent pieces called ships knees. This closer look and knowledge of how the tree grows led to the use of it in a similar way for bracing on ships.

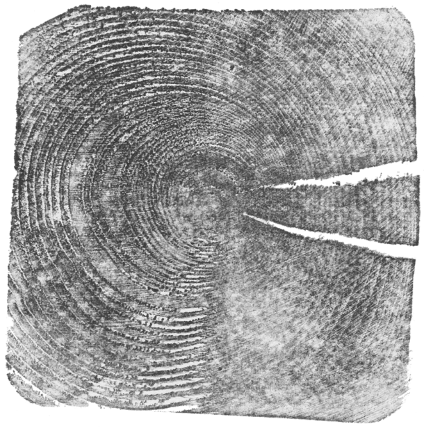
> Being an architect means being an intermediary, the connecting link between ideas and materials. This role of a go-between requires more than simple enquiry, it requires solid investigation and research: an exploration of what can be coaxed out of materials, what can be added, what the materials can support, what they can hide, what they can emit, what they can keep, what they can simulate, and in the final instance, what they can create and what they can destroy. (Schröpfer and Carpenter 2011, 8-9)



Types of shrinking and their direction in relation to the grain direction.

This understanding of wood was not learned in the way we learn today. Most current information can be found whether it be in books, articles or the web. But in the absence of making, this knowledge is not ‘good’. Wood is organic which means that it is hard to create a standardized product from it although our industry has managed to create some sort of standardized system in which lumber is graded according to the qualities it should contain. These qualities almost always have something to do with moisture content, as organic material is affected greatly by this. However, until you see the effects of moisture on wood in terms of warping, shrinking, cracking, etc., a diagram telling you the ways in which wood shrinks does not mean much and the full understanding is lost.

Historically, wood was used for its ease of malleability in proportion to its strength and size. In other words,



Ink print showing the end grain and the cracking occurring due to reducing moisture content.

it was a material readily available, easy to work with, and strong enough to be structure. Present day uses of wood as a modern material in new products such as glulam and cross laminated timber, make use of smaller dimensional lumber to create mass products with enhanced properties like strength and stability.

> Understanding and designing with an organized ecology of the built environment, and not just for a single project's needs, requires more information about the material flows for construction. Therefore, the ecology of the built environment becomes one aspect of the study of materials for buildings. (Fernandez 2006, 6)

An argument for the return of this material to the modern architect's palette comes at the expense of climate change in the interest of sustainability. Wood requires less energy to make into usable product as well as sequesters carbon. It can be reused and has a natural afterlife of decomposition thus completing the ecological cycle. A cause for concern is the call for wood to be used more extensively as building material, which could cause mass deforestation and hence reverse the sustainable properties that wood strives for. With advances in technology, we are able to grow wood (of smaller diameter) quicker than we can use it, which leaves wood as a renewable resource.

> Materials in most buildings – artifacts of large volumes wed to specific sites – have always been determined by local availability, current practice and experience, cost and construction expediency, and to a lesser extent, design and aesthetic preferences. (Fernandez 2006, 35)

Fernandez focuses on the economic values associated with using materials in general, however, it is easy to see how a material (in this case wood) is an actor within a larger network that contains other actors such as building culture, building practice, material availability, financial cost, ideas of aesthetics and design, as well as people. Using ANT mapping, the idea that material has agency and can influence other actors is proven in the above quote by Fernandez and shows the importance of mapping networks to understand the impact of design intentions before, during and after their implementation.

Machine: A Tool

> Decisions favouring one specific condition over the typical standard begin to change the motions of tooling upon a material. (Schröpfer and Carpenter 2011, 65)

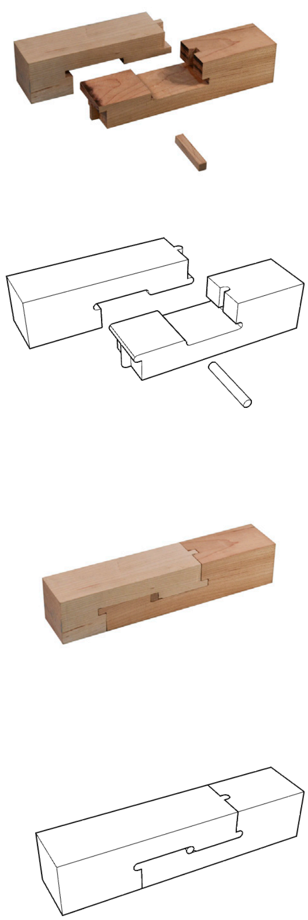
As established before, the tool is the way to connect the woodworker to the material, thus Schröpfer and Carpenter suggest that this connection allows for specific motions of tooling upon the material to change based on a specific condition or design intent. This tooling is then dependent on the machine used and as such will allow different marks depending on the tool to achieve the same design outcome. When using these tools, Pye outlines workmanship of risk and workmanship of certainty as the division between hand tools and machine tools.

> The difference between workmanship of risk and workmanship of certainty is that certainty has a predetermined quality, and the techniques used to apply are of economic value, and when it remakes our entire environment, it will also change the visible quality of it. (Pye 1968, 4-5)

If the inherent quality of the workmanship is based on the final object (for lack of a better term) and its aesthetics, then Pye suggests:

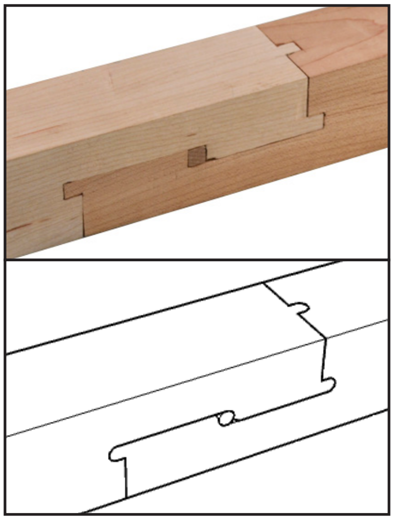
> The goodness or badness of workmanship is judged by two different criteria: soundness and comeliness. Soundness implies the ability to transmit and resist forces as the designer intended; there must be no hidden flaws or weak places. Comeliness implies the ability to give that aesthetic expression which the designer intended, or add to it. Thus the quality of workmanship is judged in either case by reference to the designer's intention, just as the quality of an instrumentalist's playing is judged by reference to the composer's. (Pye 1968, 13)

Yet if we take apart this explanation and look at the generation of a simple joint, say a lap joint, one can see the obvious flaw in separating the machine into a category of its own. The joint made by workmanship of risk, which includes the traditional machines and tools will make a precise and tight joint. The joint made by workmanship of certainty, in this case a CNC machine, will also make a precise and tight joint. Then if both workmanship methods produce the same joint, both are precise and fit tightly together, and one is indistinguishable from the other aesthetically, have we not just proved the workmanship of certainty can produce good workmanship? Yes, at least as good or better in both soundness and comeliness.



The difference in aesthetic between workmanship of risk and workmanship of certainty or a hand-crafted joint and a CNC milled Shippasami-tsugi joint.

Now if we consider a joint not so simple and straightforward, there becomes a different aesthetic when using the CNC than that of not. Take for instance the joint in figure left. The figures show the joint made from workmanship of risk – made by my hand using chisels and my knowledge to take away material and create flat, straight surfaces for the joint



Close up of the differences between the handmade (top) and CNC (bottom) made joints. Notice the addition of curved edges in the CNC rendition.

to come together. The precision and tolerance in each piece was guided by the other and their ability to fit together at the time of making. Now compare this to the model in the figure as a proposed CNC joint of the same language. Note how the curves are introduced as the bit in the CNC cannot produce square cuts (depending on the orientation). If the aesthetic of the joint and the intent of the designer was to have rounded edges, then we can assume that the CNC cut joint, made with the workmanship of certainty has good quality and is good workmanship. Both soundness and comeliness are accounted for and by comparison of comeliness to the joint created by workmanship of risk, we see that the latter fails in this department.

Coming back to the ideas of precision and tolerance in relation to the example above, it is easy to see how each type of workmanship for the joint can produce comparable results as each is calibrated to fit at the time of making. At the small scales of these models and for their demonstration purposes, it shows that each would produce a viable working joint, and any change to the environment (such as change in moisture content) would affect the soundness and comeliness of each joint regardless of how they were made. This shows that the CNC machine can be a tool for the workman, just as many tools have come before.

A close up of the jig being used to mill the joint with the CNC.

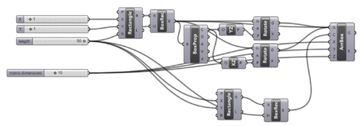
The jig holding material ready to be milled.

> In fact the workmanship of risk in most trades is hardly ever seen, and has hardly ever been known, in pure form, considering the ancient use of templates, jigs, machines and other shape-determining systems, which reduce risk. Yet in principle the distinction between the two different kinds of workmanship is clear and turns on the question: 'is the result predetermined and unalterable once production begins?' (Pye 1968, 6)

This is true even of machines as templates, jigs and machines that help define actions, are explorations in efficient ways to do a specific task. In my research of making, the forming of the jig is just as important as the formation of the object itself. Take for instance, the jig for making the Kawai-tsugite joint as pictured left. In the fabrication of the Kawai-tsugite joint, tooling marks are left which slightly alters the aesthetics of the joint, however, the workmanship of certainty provides a joint of quality, producing artifacts with low tolerance and high precision. In this case, the jig allows for repeated production of a specific part, whether this is by hand or by machine, both produce a viable joint.

The machine (although some are this way) does not allow for the material to be part of the machinery (self-clamping or self-holding). This requires the use of a jig or set-up in which to perform the required task with precision and accuracy. The jig in this case was milled as to provide an uninterrupted correlation of the geometry of the block material to the x, y, and z axis of the machine.

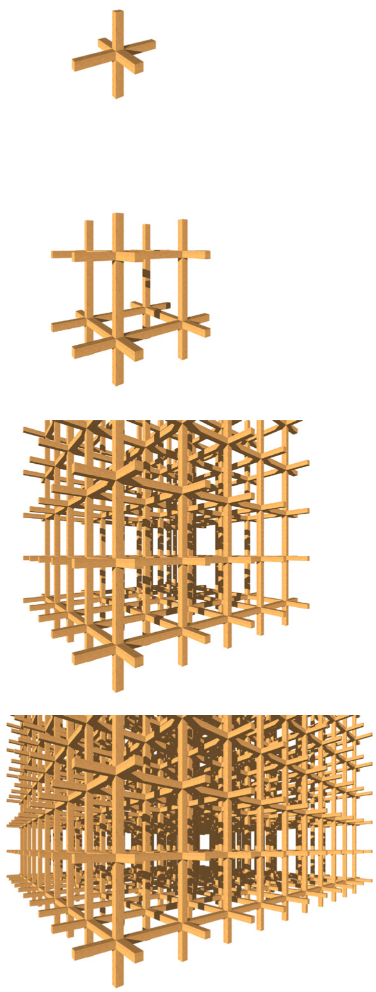
Machine: Computation



Simple grasshopper definition to control scale, size and dimension of the design detail.

The example of Kuma’s GC Prostho Museum Research Center, showed the potential for the detail to generate form. The joint was used as a building block to generate a form from which subtracting space out of yielded the intended design intent. The process is outlined at left in the diagram and shows how computational modeling with a simple Grasshopper script can generate a form and yet be robust enough to control the variables related to size, scale, and dimension as well as the matrix in which the building blocks interact.

This computational user interface relies on visual programming rather than coding. This is particularly good for architects as we communicate visually through drawings, diagrams, photographs, models, etc. The programing interface then becomes a sort of diagram of algorithm, explicitly telling the computer to run a piece of information through our written computational diagram. Thinking about it in this way allows for the computational tool to enhance our design process without much distance from our already formed knowledge.



Repeated joint as informed by the grasshopper script in the above figure.

CHAPTER 4: JOINT TO SURFACE

History of Joinery

For as long as man has been building, joinery has provided many solutions for a particular situation or function. One only need to admire a mitre joint in a picture frame to understand its purpose was to connect two pieces in an aesthetic manner. However, this contemporary example has a history that dates back thousands of years to which joints were the source for providing specific solutions to problems of defying gravity, spanning spaces, and meeting other materials. Of the human race, origins of joints can be traced back to the oldest civilizations in Japan.

Power Tools and the Joint

Power tools help the craftsman to manipulate material faster and more precisely than with hand tools. Jigs and fixtures extend the abilities of the power tool to make fast and accurate cuts with custom jigs able to solve specific problems. (Chan 2002, 20) A number of different tools are used based on their ability to manipulate material. For example, a table saw is good at providing planar cuts parallel to a material edge. With the addition of jigs the table saw still cuts material in a planar manner, now with the ability to cut angles, smaller pieces, and even joinery pieces.

The Detail

We have already established the difference between the detail and the joint. Whereas the detail is of a material nature, the joint is more conceptual in nature and not limited to factors such as scale and dimension. Frascari conforms to Jean Labatut's idea, "the detail tells the tale," (Labatut 1956, 37) of which this thesis attempts to explore. The detail holds the information on how we construct and build – this has cultural meaning and value.

There are the technical aspects to a detail that allow it to function. "We live in a world in which everyday objects have a size—we shall call it scale and give it the symbol L, for length—in the range of millimeters to meters. Scale has a profound effect on the behavior of structures made from materials." (Ashby et al 2009, 14) Indeed when talking about details, scale has an immense effect on the way we bring materials together to form the detail. A lot of the size and scale of objects has to do with resisting gravitational forces and as such are engineered in such a way that a minimum size is needed to withstand the pressures of gravity as well as carry the intended load.

Other external forces also shape the size, scale and material used when constructing the detail. Availability of materials as well as the cost of them has a huge impact on which ones we use for structure and the method in which we join them. "Joints and junctions of an architectural project are also expressive of an ingrained building culture in tension

Hand crafted Kawai-tsugite joint shown in its three different positions.

with a design intent as well as the design intent's struggle to express itself through communicative and operational tools." (Schröpfer and Carpenter 2011, 62) This suggests that the joint then is able to tell the story of how it was made. Frascari shows that Scarpa's adoration of the joint confirms this, in which "each detail tells us the story of its making, of its placing, and of its dimensioning." (Frascari 1996, 506) By searching for actual form and the perceived one, Scarpa uses the act of making to give rise to his details.

Ideas of tolerance and precision arise here as we discuss the elements of the detail in terms of scale and dimension. The scale on any detail has a proportional relationship to the tolerance it requires. Additionally, how a joint is assembled also has a great impact on the tolerance needed in its fabrication. One can see the need for greater tolerance to be allowed when movement is necessary to the joint as opposed to one that only need go together and not come apart.

The of precision is one that relates to that of tolerance in the way things are assembled. For instance, the fabrication of a joint that rotates concludes that each piece must have a precise rotation axis for the pieces to align and the rotation to occur.

> Degrees of tolerance necessitated between materials are deterministic of sequences of assembly, hierarchies of information and sometimes effect change on the original formal desire. Joints and junctions in architecture are the resultant balance of a process, form, structure, and desire. (Schröpfer and Carpenter 2011, 62)

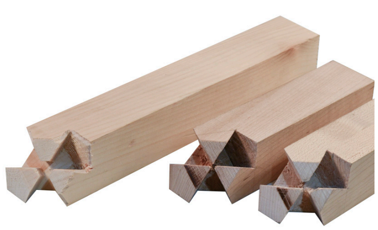
It is the process by which the joint is constructed, as well as the function that precision and tolerance play pivotal roles to the success of the joint. Both of these ideas are starting to be explored in the making of Japanese joints.

Japanese Joinery

Kawai-tsugite

This Japanese joint is called the “Kawai-tsugite” and was invented by a Japanese professor name Naohito Kawai when he was at Tokyo University. (Buzz-Net 2015) Found through the social network Instagram, this joint was of particular interest because of its recent invention and lack of knowledge throughout Western and Japanese culture.

> It is not popular Japanese joint and wanted to share to woodworker all over the world by Instagram. This joint has been invented by Japanese architectural professor 20-30 years ago for testing craftsman’s skills. Even we don’t find any details and informations from Japanese joinery books in Japanese. So it has been known between small amount of Japanese woodworkers in Japan. So it is almost impossible to find about this joinery for foreign woodworkers [...]. (Kobayashi 2014)



Kawai-tsugite joint. CNC milled joint on the left with the two hand carved joints on the right.

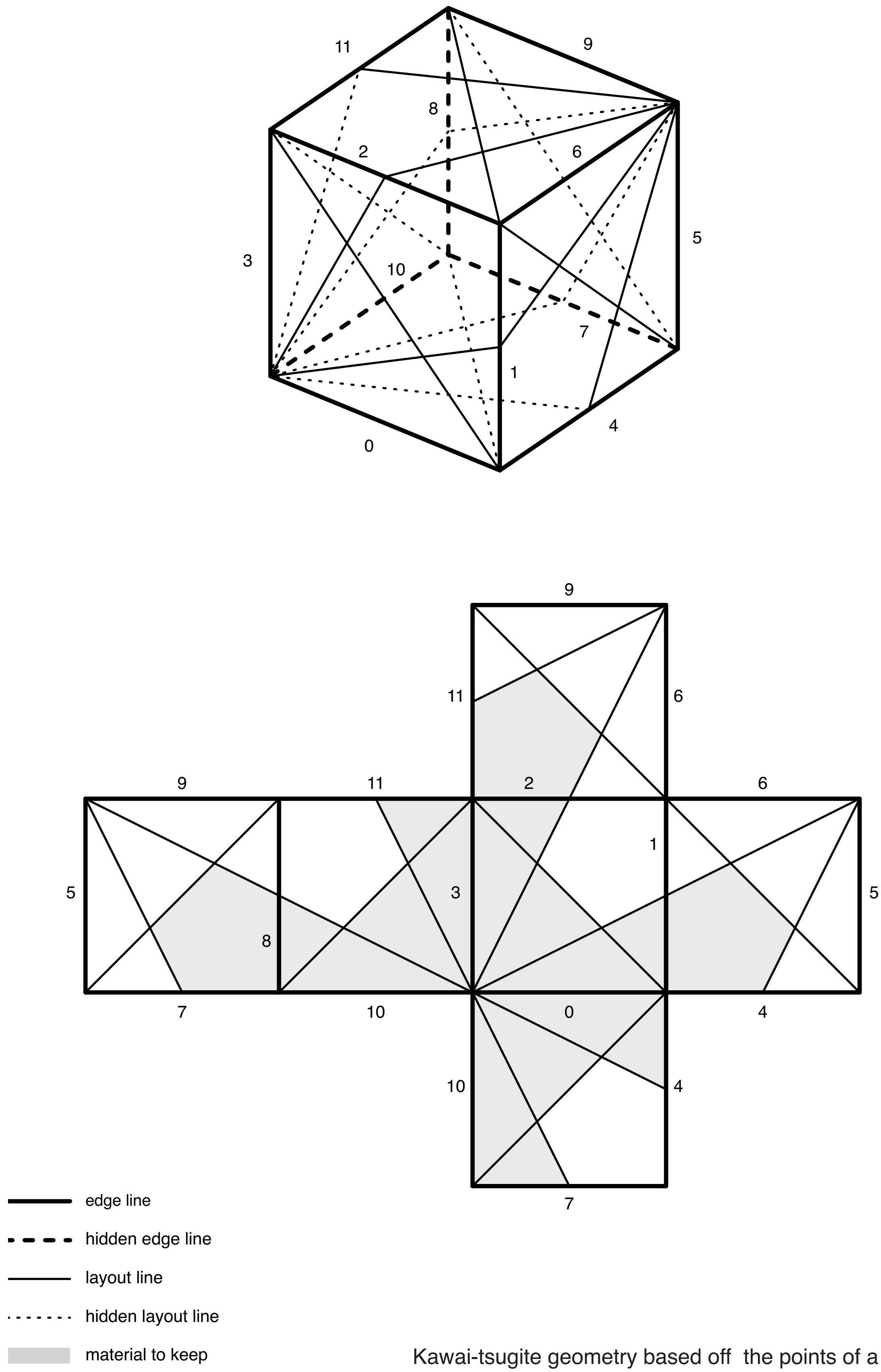
This joint is particularly hard to make, as each of the pockets do not intersect the outer faces at right angles. The one pocket has edge surfaces at less than 90 degrees so the ability to get a chisel in to remove the material decreases. However, because of the symmetrical geometry allowing for the same piece to make the joint as well as the verticality of the geometry itself, I was able to recreate the piece in digital form and mill it on the CNC machine. With the help of a jig to hold the material, the first iteration of the joint was able to fit together with the hand crafted pieces in much less time and effort and I would say to higher precision and tolerance. In the previous figure, the CNC machined part is on the left.

Cube Geometry

Kawai-tsugite geometry based off a cube.

The geometry is comprised of the rotational symmetry of a cube the cross sectional size of the joint. This rotational line that connects two points of a cube, allows for rotation of the joint at 120 degrees resulting in a column or one of two right angles. Using opposing points of the cube, a rotational axis is made by which the remaining geometry is based off of. Lines on each face connect to either corner points or edge midpoints to generate the cut lines for the geometry as shown in the figure on the next page.

Precision and tolerance in each part is critical to how the joint looks and functions. If one part is off in either of these categories, the joint becomes weak and fails to align as intended. Using the CNC as a tool, anyone can then make precise notches, cuts and holes, sometimes at the loss of the intended or original aesthetic form; in this case, the corners become rounded instead of square. A robust model can generate precisely and effectively a repeated joint with greater ease and less time. If these are the things needed to achieve the design intent, then the CNC machine has done the required task in which to complete the desired outcome and the quality of the



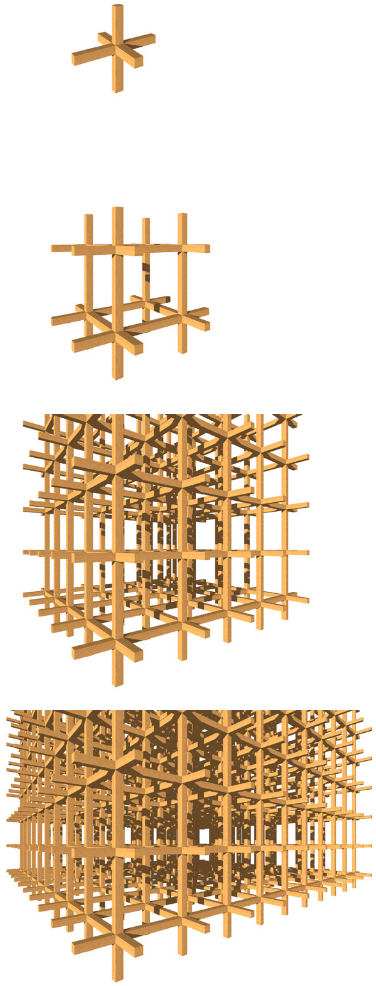
Kawai-tsugite geometry based off the points of a cube.

joint need not be called into question.

Thomas Schröpfer and James Carpenter suggest, “a truer investigation into architectural details asks us to consider the specific operations to which our tools subject materials. The part to the whole are elements of the discussion, but the root of any argument of material detailing lies in the act itself.” (Schröpfer and Carpenter 2011, 65) This has been intuitively explored in the iterations of making the Japanese joints, however, we will go into more depth in the next chapter which looks at the intersection of material and machine.

Detail as the Design Generator

The detail as a design generator asks an interesting question and challenges the norm in architecture to design from the general to the specific. A role typically ascribed to the plan, “the detail tells the tale.” (Labatut 1956, 37) Similar ways of informing a project start to inform the detail and suggest the ways in which the detail can generate architecture. Take for example a place in which both wood and steel are readily available, yet the knowledge and labor force for steel work is not. Then in thinking even about how one could construct a wall-roof detail, one immediately starts thinking in a material palette of wood as opposed to steel simply because the knowledge and labor force for working with wood is present. The implications can go on, suggesting that the detail being designed then is a subset of that of wood and a subset of that of the woodworking knowledge available.



Parametric model showing the idea of the detail Sampo-gumi-shikuchi generating a form through repetition. Study of the GC Prostho Museum.

One structural bay of the glulam structure detail.

With the making of the Japanese joints, it begs the question as to the space they imply. Additionally, the actions in which they are put together start to suggest the spaces in which they sit. For example, the Shihou-hozo-tsugi joint when thought about as a column detail implies a space which allows for the member to be placed together in a horizontal translation; one thinks of height in this case being limited, or to the idea of a renovation in which space for members cannot be inserted from the top or bottom. Another example starts to illustrate how space can be formed from the joint Sampo-gumi-shikuchi, in which the joint is repeated to create space. Kengo Kuma's GC Prostho Museum Research Center uses the joint to generate a form from which he subtracts from to create space.

My nature when designing or even looking at a piece of furniture, room, or building is to question: how is it built? The detail as a generator of form was explored in a previous term here at Dalhousie. A glulam structure was explored to create an undulating surface through triangulation creating a dynamic 'interior' space, that if it were to be repeated (as was the intention), one can envision a dynamic undulating interior space. (See appendix)

CHAPTER 5: DEVELOPING A METHODOLOGY

The design aspect of this thesis tests the theoretical framework outlined above, by developing a investigative making methodology. Using knowledge to guide the making process, the Kawai-tsugite joint is examined, tested, and machine fabricated to exploit its potential uses as well as understand its ability to be the detail which generates an architecture to create and modify space.

Process

Using the theoretical framework, the general process follows an investigative feedback system, starting with an idea, working through the digital environment and translating those digital models into files the CNC machine can read. Jigs are made to hold the stock in place as the machine mills out the part, and finally information is perceived, recorded and put back into the process to further refine and iterate. A continual curiosity and questioning of the methodology is required to stay motivated, deduce problems, and come up with solutions to build upon and add to the previous prototypes.

Principles Applied

Engrained within the methodology is the constant attention to craft, and how that applies to the modern age, digital environment, and architectural realms. There are certain principles that need to be asked at each stage of the process to ensure that the process can be followed methodically and to ensure craft is being maintained. As established in previous chapters, the workmanship of certainty as it pertains to the machine is considered the tool in which manipulation occurs before the fabrication rather than during the shaping of the material. The slight shift shows how this process can still be considered craft with modern methods of making.

Of the Digital Environment

The digital environment is the first step to iterating, as it allows for the quick testing of ideas. Creating a robust digital model is essential, simplifying the files to ensure no extraneous information is being kept that does not impact the specific goal in mind. This allows for the separation of the goal or problem into smaller pieces, thereby ensuring a robust foundation to build upon. Below are the principles asked of the digital environment:

1. Gather and apply input information pertaining to size, scale, material, machine, fabrication, assembler, and site. This is the most important step for the digital environment as it pertains all the information that can be changed and updated to refine and iterate.

2. Robust digital model. This may require the breaking down of a large model into smaller pieces to ensure that accurate information is being fed into the model as well as the programming that is done is achieving the desired outcome.

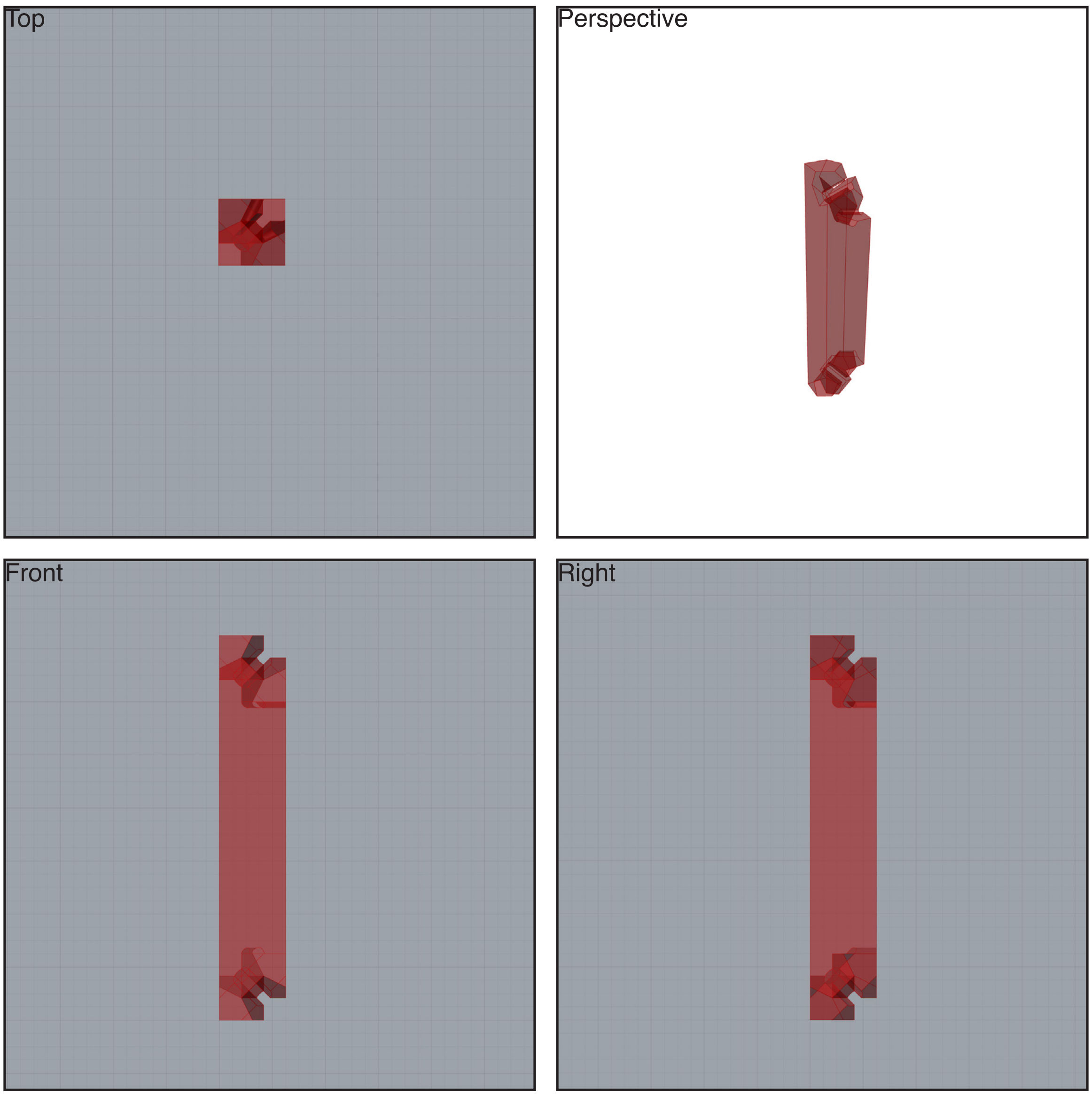
3. Understanding of the tool being used to modify the material. Since the digital model is used to create the machine files (be it for the CNC or the 3D printer) the model itself will reflect this allowing for the tool to do work on the material.

4. Understanding of the assembly technique with regards to size and scale and material. Smaller model size artifacts do not require as much thought on this principle as they can be manipulated by hand. The direct correlation between size, scale, and digital environment is crucial to understanding the pieces being generated by the model. Larger scale artifacts require different materials and assembly techniques therefore the digital environment must account for these changes.

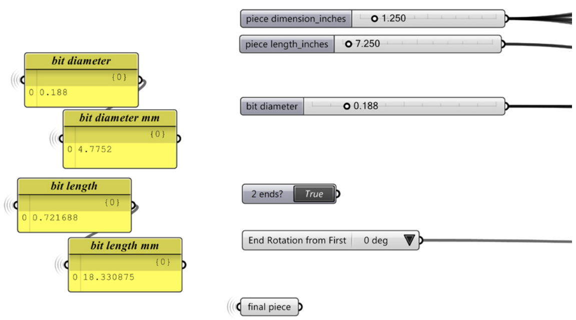
5. Consistent algorithm to generate machine code. This is of particular importance as the consistency of the output is required to be able to feed information back into the process and refine the artifact.

Creating a robust model for the Kawai-tsugite joint was tough as the geometry was having trouble being defined by the software. Breaking down the joint into smaller pieces helped to decipher the problems and fix them to achieve a working parametric model. The Grasshopper tool derived was intentionally made to allow for changes in material, bit sizes, and scale shifts. Knowing the CNC machine was being used for fabrication, additional material was removed from corners of the geometry to ensure no hand work was required after the part has been fabricated.

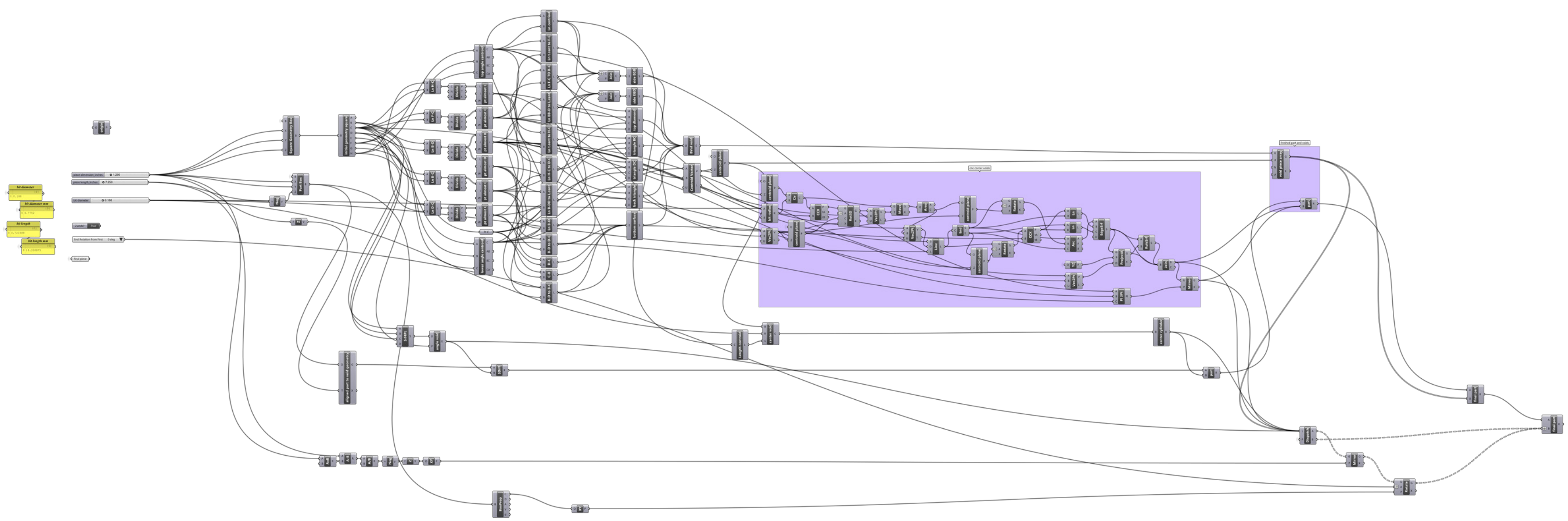
Using only input information essential to the model, the Grasshopper script created an artifact of dimension and size specified, knowing the diameter of the bit being used for fabrication. Then the plugin RhinoCAM was employed to generate tool paths and machine code for the CNC. It is here that most of the input data is manipulated to ensure the correct movement of the tool with regards to direction, amount of material being removed, bit diameter and bit RPM's.



Rhinoceros output of Kawai-tsugite Grasshopper definition.



Input data for the Grasshopper definition.



Complete grasshopper parametric definition of the Kawai-tsugite joint.

Of the Material

Knowing the material you are working with allows for the input of material information into the design and fabrication process. The digital environment uses this information to generate machine code to enable the tool to remove material accordingly. For example, milling an aluminum stock as opposed to wood stock will require a different bit, different router speed, and different amounts of material being removed. This is why material information is essential to the process, as it helps determine the outcome of the artifact and the detail. The principles asked of the material are:

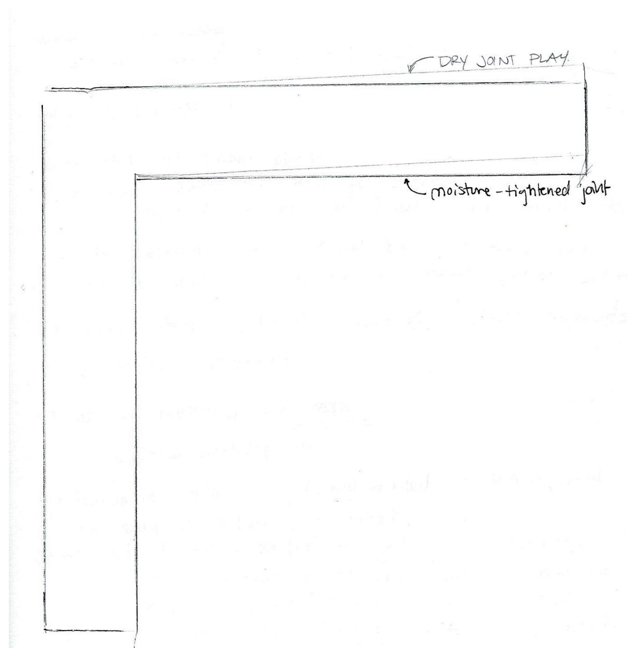
1. Some form of malleability. This means that tools are able to shape the raw material, to achieve the desired outcome.

2. Strength and durability to hold the shape of the joint itself, but also to connect to other members and support its connection with minimal deformation.

3. A dry and stable state. Acclimatized materials will work best in the environment they are in when an equilibrium has been reached within that environment.

Wood was my chosen material due to its accessibility, economy, and its relative ease to manipulate and allow the tool shape it. Other materials that could be explored here for example would be aluminum or casting metal. Within the realm of wood, a softwood of spruce and hardwood of maple were both utilized to allow for comparison and also to utilize the individual properties associated with each material. As shown in a previous chapter, the strength of the hardwood maple was double that of the softwood spruce, translating into a stronger joint when milled. It was also able to withstand more movement (assembly and disassembly) than its softwood spruce counterpart.

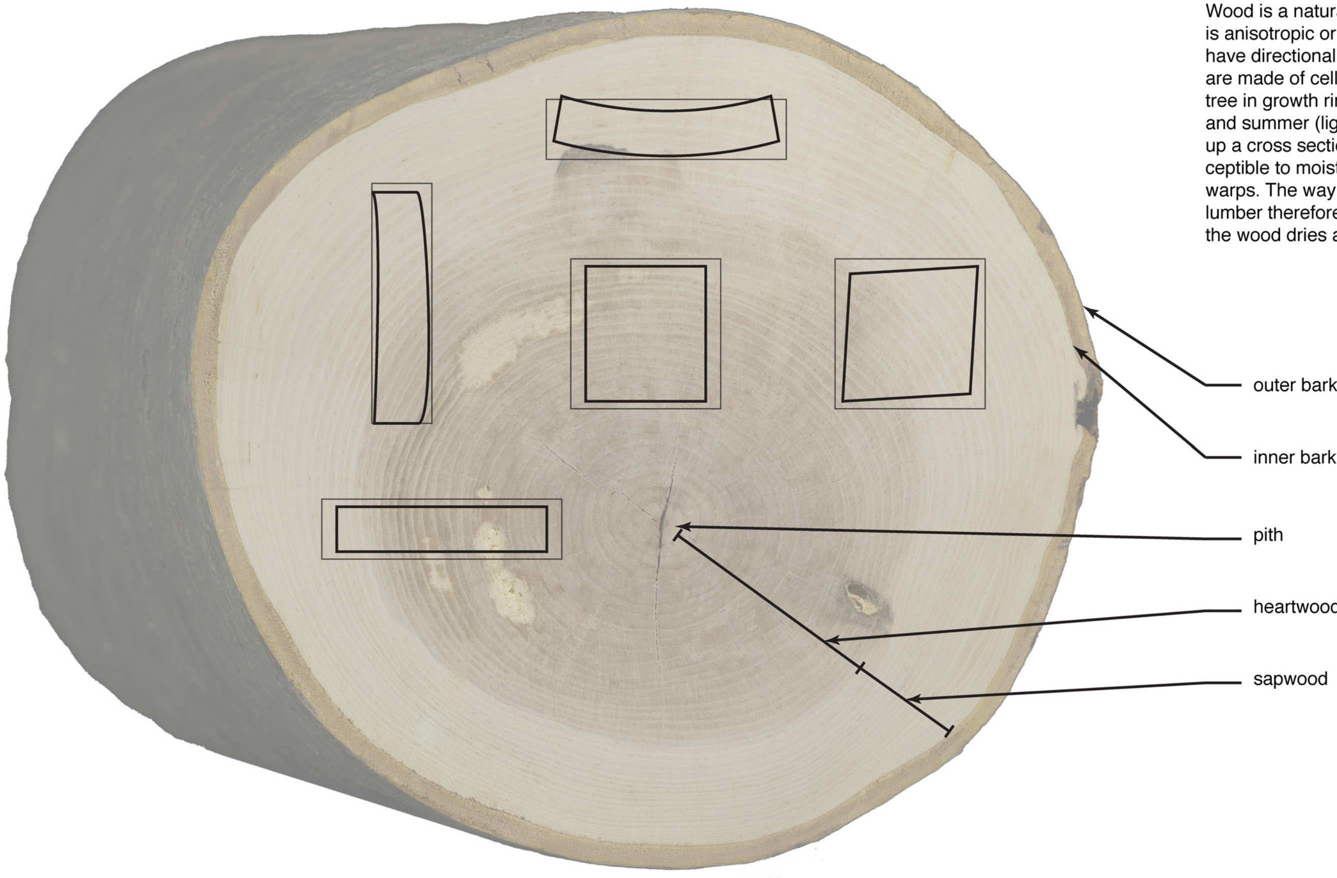
In this case, sliding together and apart connections loosened the joint over time, thus, minimal fitting of the pieces ensured the stability of the material and the joint. Affected by moisture, the wood was acclimatized and dried as much as possible to minimize shrinking, warping, and twisting. Material was milled when moisture content averaged 7%. A study of wood grain revealed the best milling technique to produce the strongest joint possible was with rift sawn lumber.



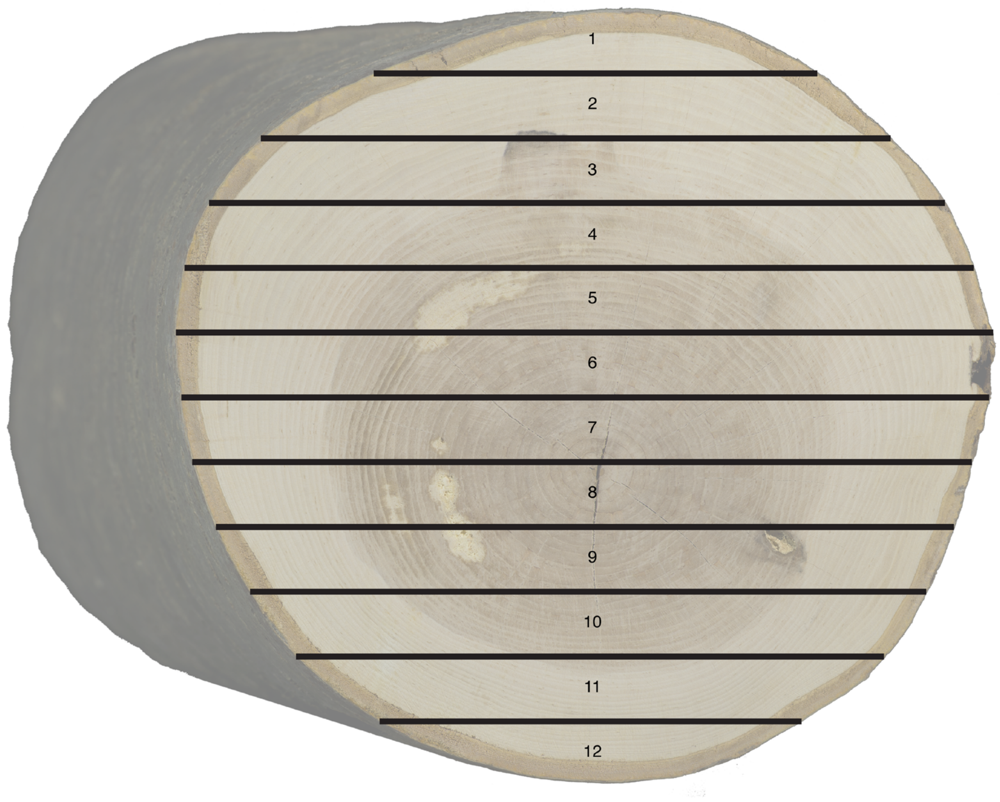
The change in moisture content affecting the shape of the joint.

Wood Anatomy

Wood is a naturally occuring resource that is anisotropic or its material properties have directionality. The grain of the wood are made of cells that run the length of the tree in growth rings made of spring (dark) and summer (light) rings. These rings make up a cross section of a log. Wood is susceptible to moisture which effects how it warps. The way that logs are cut into lumber therefore has great impact on how the wood dries and changes shape.



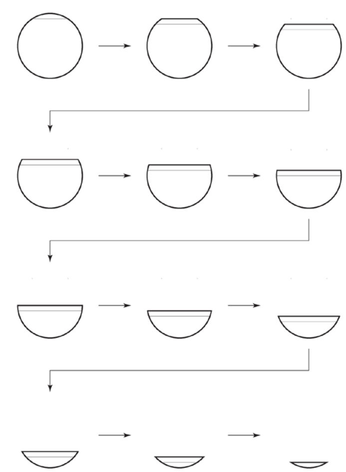
Wood log anatomy and different kinds of moisture shrinkage based on grain pattern.



Live sawn technique for milling a log.

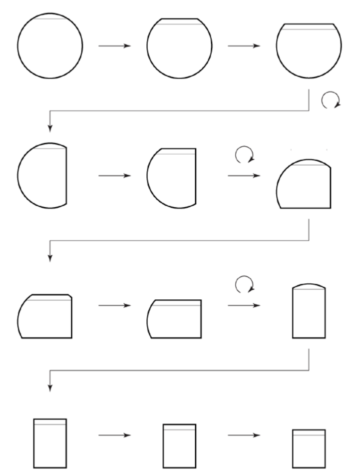
Through & Through (plain and/or live sawn)

This technique produces the most lumber and is the most economical. It also produces the least stable lumber of the four techniques, with boards prone to cupping, warping, and twisting. Sawing starts first by cutting off the top bark, and then proceding to cut the log by cutting slabs of a certain thickness. Slabs are cut over dimension to allow for shrinkage and finishing.

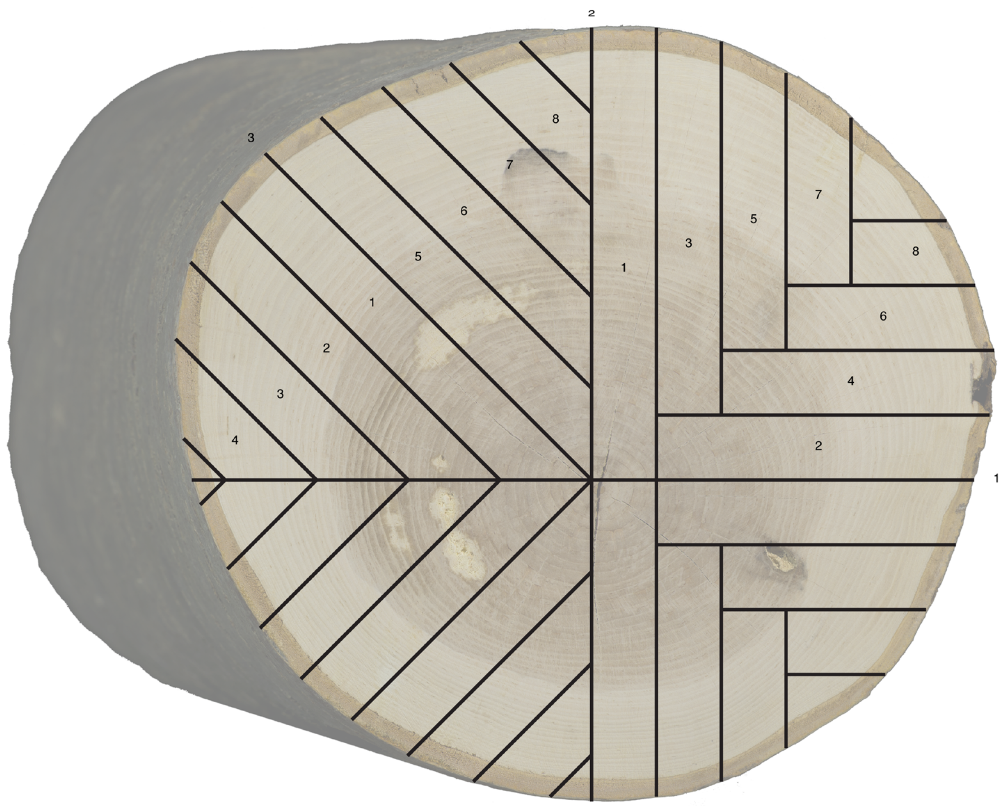


Sawing Around

This technique produces a wider range of possible lumber and still utilizes the log in an efficient manner. The process starts by cutting two or three slabs in succsion, followed by a rotating the log 90 degrees. few more slabs are then sawn off at which point another rotation occurs. Rotating the log another 90 degrees and a few more slabs are taken off. Now there are three sides square with each other. The remaing bark is turned up to be cut off, and slabs are taken until a dimension is reached or all the log has been cut. This is similar to cant sawing, and allows for multiple dimensions to be cut at the mill.

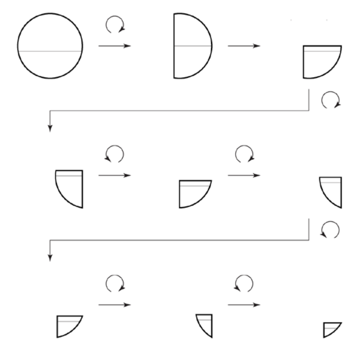


Cant sawing technique for milling a log.

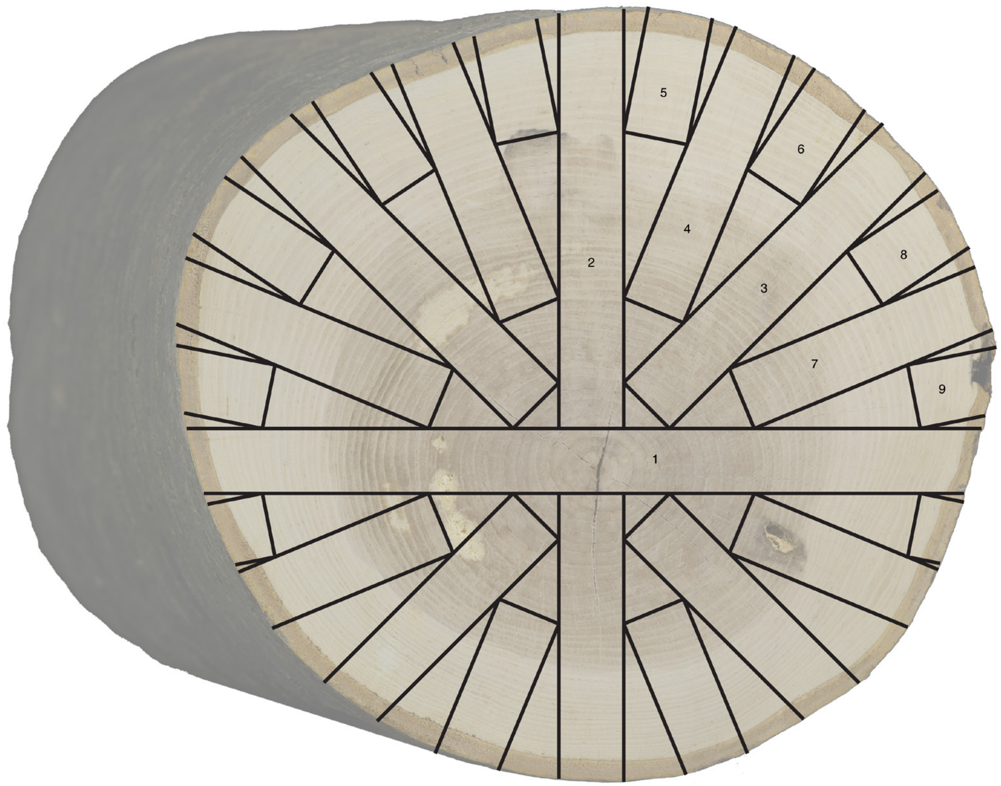


Quarter Sawn

This milling technique produces more desirable lumber than plain sawn, due to the grain direction in each board. Oriented between 60-90 degrees to the face of the board, quarter sawn has a reduced mois-true expansion rate and is more stable than live sawn and sawing around techniques. Two process are shown here, on the left is traditional quarter sawn, on the right is a modern version. The process starts first by quartering the log (cut lines numbered 1 & 2 and hence the name) and each quarter is then sawn accordingly to achieve the desired pieces. The modern quartering process requires a 90 degree rotation after each cut which adds time and expense. However, it is less wasteful than the tradi-tional method simply because the cutting is 90 degrees to each other and not 45 degrees. As the cuts progess away from the center of the log, some of the outer pieces may actually be rift sawn.

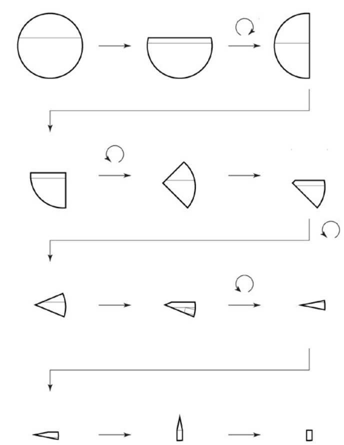


Quarter sawing technique for milling a log.



Rift Sawn

This is the most desirable cut from a log as the grain pattern runs perpendicular to the face and produces the most stable lumber. It is also the most wastefull, time consuming, and expensive of the techniques. The process starts by cutting the center portions out of the log, with the remaing portions rotated to achieve the desired grain pattern. With each cut a rotation and repositioning is requires which is what accounts for the time and cost increase over the other techniques.



Rift sawn technique for milling a log.

Of the Jig

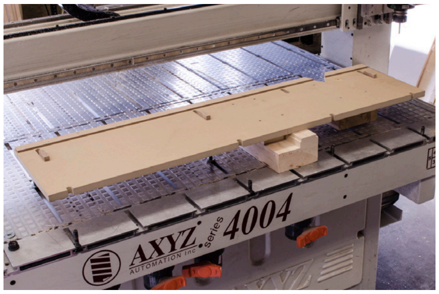
In order for the digital files to work properly, a jig is needed to correctly position the material stock so the CNC machine can accurately mill the artifact. Every jig is milled from the same digital file, so there is no lining up of the parts, thereby decreasing the introduction of human error. Still there are a few tasks required to ensure good results.

1. Consistent position of the jig stock material for machining. This requires the material to be stable and have low expansion and contraction rates.

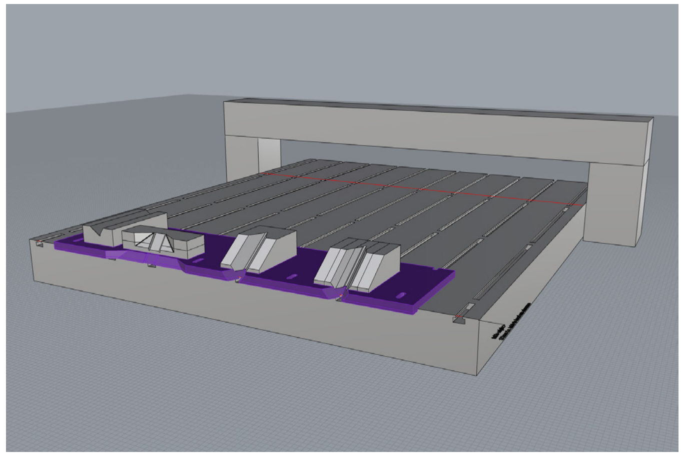
2. The jig itself must consistently position itself to the tool, again to ensure the correct consistent positioning of the stock material to be milled.

3. Sufficient holding of the stock material so that movement doesn't occur and the precision of the CNC translates to the part being milled.

MDF was used as the base jig material, using the digital file created to correctly position and align the jig to the tool and thus the stock material to the tool for fabrication. By modeling the CNC machine within the digital environment, precise measurements could be skipped as the machine would consistently precisely mill the jig pieces to accommodate the fabrication of the Kawai-tsugite parts.

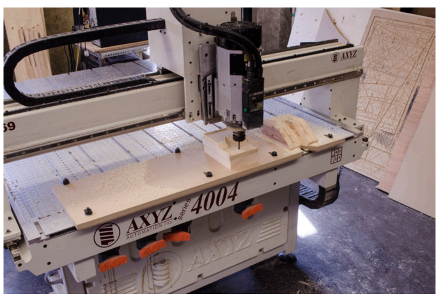


Jig overturned showing aligning pieces and jig stop.



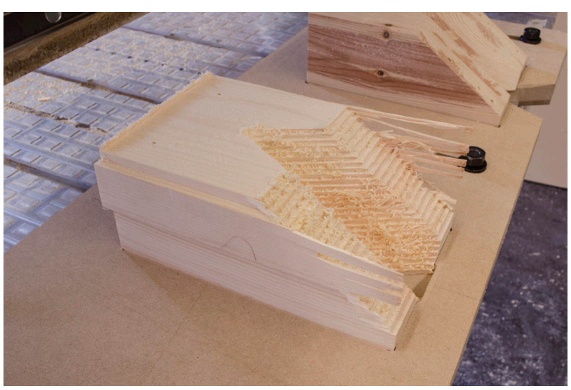
Digital model of the jig and CNC bed from which all NC files were generated.

Milling the MDF base for the jig stock material.



Milling the jig stock material to hold the part stock.

Ensuring the registration of the jig to the machine, hardwood pieces were glued to the bottom to align with the slots in the CNC bed. A stop was also glued to the bottom to align the front edge in the correct position. By using the self-aligning jig and the precision of the CNC machine, the parts milled on theses jigs ensured that stock placement error was minimized or even eliminated, ensuring the precision required for the Kawai-tsugite geometry was achieved.



The roughing of the jig stock.

Milling the final surface of the jig.

Of the Tool

Many factors here can be assumed without thought, however, careful consideration and research was done to ensure that the tool was in fact delivering what was required of it.

1. Consistent homing of the machine. Without this consistency, many errors develop which are hard to pinpoint and fix. The less room for error, the less errors there will be.

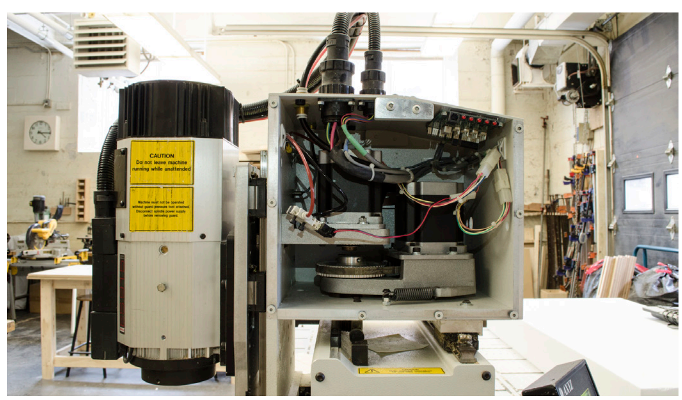
2. Consistent and accurate cutting of the file, repeatedly. This consistency we rely on so that fabrication production can happen quickly and accurately. Without this precision built into the machine, the time would increase significantly, drastically reducing the ability and desire to use this specific tool.

3. Accurate communication of the NC file to the machine. Sometimes software used to communicate with the machine can introduce new lines of code which were not present in the original file.

Several tests were done to ensure the tool was performing to its ability and that the tool itself was reliable in producing repeated accurate results. This was done by experimenting with the placement of the origin within the digital environment and repeated movements of the CNC head to measured locations. The result of this investigation leads to a confirmation on the machines ability to maintain its origin accurately when set. However, throughout the fabrication of artifacts, the setting of the origin introduced human error and would adjust the placement of the part in relation to the machine by thousandths of an inch. This error affected the outcome of the fabricated artifact so much so that a new origin was used. Testing as to the consistency of the table origin (or machine origin) was discovered to be extremely accurate and in turn further reduced the errors incurred from manually setting the origin. It was also found that this would allow for the machine to be used by other individuals and to be turned on and off without affecting the precision needed to accomplish a sound Kawai-tsugite joint.

The source of the error, slippage occurring due to failed bearings and not enough tolerance between plate and turning rod.

While using the CNC machine, the mechanical soundness came into question when the CNC head plunged through an artifact and into the jig. Discovery of the error was noticed when the machine z-axis was trying to mill the part well below the intended z-axis limit. Slippage was occurring and as a result repair work had to be done to ensure the principles asked of the machine would be maintained. This allowed for a better understanding of the mechanics of the CNC machine as well as the dependence of the principles on the regular machine maintenance.



Inside the mechanics of the CNC machine.

Of the Fabricator

The fabricator has a critical role to play in this making process as this is the stage where the digital craft, material, and machine overlap. Knowledge of all the previous categories and their principles is required because this information is evaluated and recorded for input back into the digital environment for future joint iterations.

The stock positioner.

1. Knowledge and experience on how the tool and material intersect, in the digital realm as well as the real world application. This allows for the continual striving for craft. It also leaves room for the process to be adjusted, should it need to be, to fix small errors on the fly. This is critical to ensuring the end result has achieved the desired goal, as well as critical information to put back into the making process.

Placing the stock positioner on the jig.

2. Positioning of the jig consistently and accurately to ensure the stock and machine meet in space exactly where they are supposed to.

3. Positioning of the stock material onto the jig consistently and accurately to ensure the stock and machine meet in space where they are supposed to.

Placing the piece stock against the stock positioner.

4. Accurate recording of data. This includes how long it took to fabricate one piece to observing how the machine shaped the material. This is where a lot of the feedback information is obtained, although not explicitly recordable, the tacit observation of the machine allows for adjustments to be made to the input data to change the output artifact.

Of the Assembler

The assembly of the joint is where most of the tacit information is recorded in this process. This is internal to the assembler themselves and requires explicit knowledge of the joint being fabricated prior to engaging in assembly.

1. Knowledge (explicit and tacit) to the simple assembly of the joint. This extends to an understanding of the size and scale of the members as that will directly influence the number of persons required to assemble a given joint.

2. Understanding of the ability of the detail to generate space and influence the people and networks around it.

3. Understanding of the joint network, its abilities to create and modify space, but also its structural capabilities.

Studying the Kawai-tsugite joint has allowed for much information internal to myself to be collected on the workings of this joint. Its assembly is one that I have learned to work with easily on a model scale level. A jump up in scale proved difficult as the members where larger and required different tacit information.

Of the Site

The site requires the least amount of principles as the variation and adaptation of the joint allows for it to change and modify almost any space. That being said, the principles asked of the site are:

1. Affordance for the creation of space. This includes some architectural environmental properties such as light, ground, foliage, etc. There are elements at play which allow for the creation of space.

2. Affordance for the modification of space. This implies an already created environment which can be modified. Again, qualities that allow an environment to change such as light, air, structure, material, etc., all contribute to the affordance for a space to allow modification.

A digital rendition of the empty site.

The site for this installation was the exhibition room defense space. Given the existing conditions of light, sound, movement and structure, the site afforded creation of new spaces as well as modification of the existing space to enable a thesis defense to occur. Due to the nature of the Kawai-tsugite network, defining the scale parameters of that network could allow for it to be adapted to suit almost any site. As larger members start forming, the limiting factor for the network would most likely be the size and scale of the individual members, as the structural qualities are not scalable.

A photograph of the empty site.

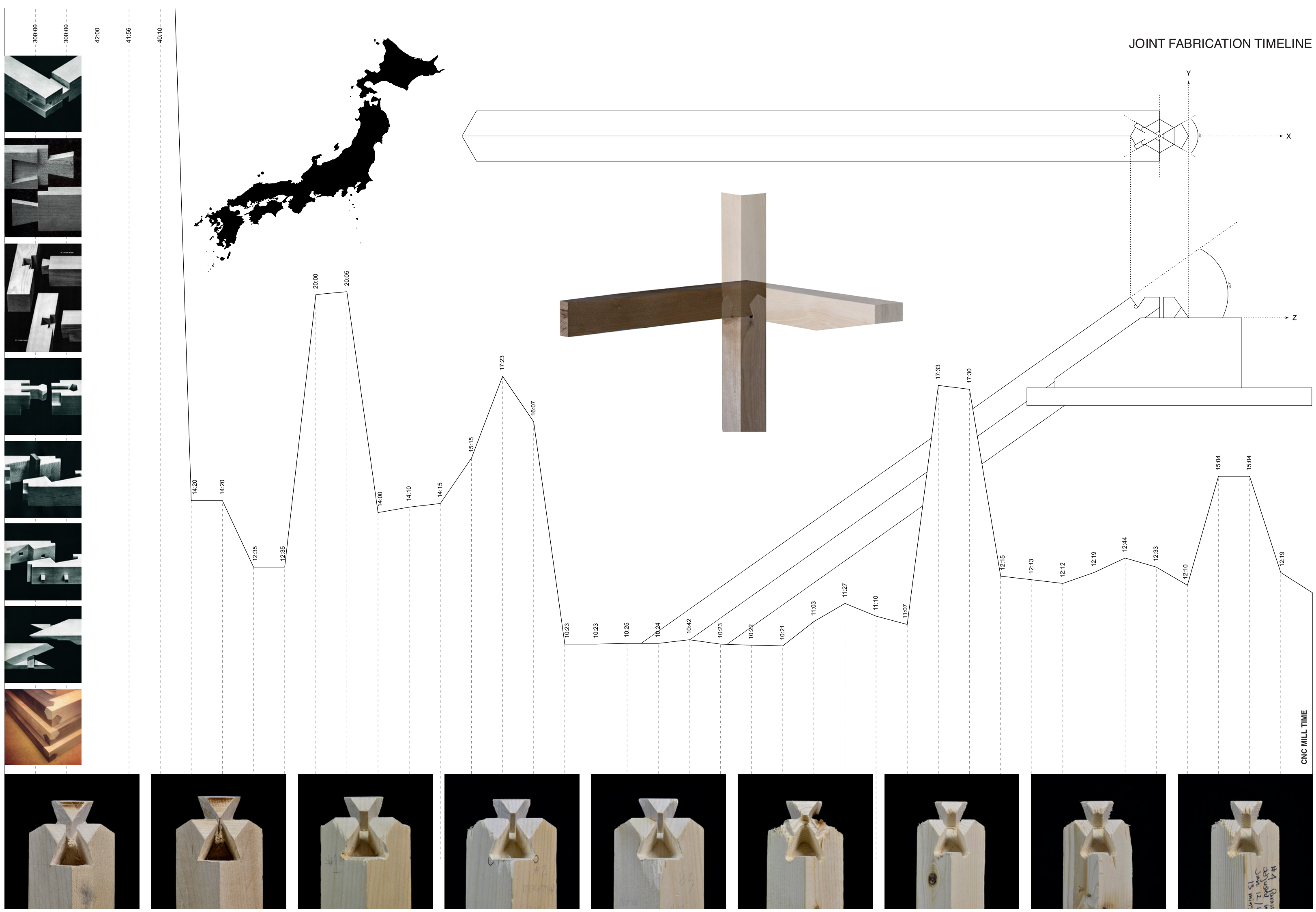
Kawai-tsugite Innovations

Using the making methodology, several iterations of the original Kawai-tsugite joint were fabricated, testing different materials, digital generation, and fabrication techniques. With each iteration, data was gathered to input back into the process to inform the next. After achieving successful iterations of the original Kawai-tsugite joint, innovations were explored to further the potential of the joint. By using the geometry of the original piece, several adaptations were tried and tested first in the digital environment, then carried through the to fabrication to a prototype. Applying the making methodology once again, the initial prototypes served as the base information which was input back into the process and used to refine subsequent iterations. Several of the innovations where feasible and used as details in the final installation.

The three variations of the Kawai-tsugite joint.

Original Joint

The Kawai-tsugite joint utilizes symmetrical properties of the cube from which its geometry is derived. By adding stock to the cube geometry, two members can connect together, being exact copies of one another, in three different variations.



Joint fabrication drawing showing timeline of fabrication, historical reference, and joint fabrication geometry. Historic images from Google images.

Assembly / Rotation

The assembly of the joint and the rotation axis around which the variations occur are one and the same. The model pictured below shows a wood dowel that acts as this axis, allowing movement along the axis to permit the members to separate, and the allowing rotational movement to alter the members position to one another producing a variation.

Sequence of variations that occur around the rotational axis as made with a wooden dowel.

Strength Testing

A number of tests were implemented to start to gain an understanding of the strength capabilities of the joint. A pneumatic shop press with a pressure gauge was utilized along with a simple holding jig to test the three positions of the Kawai-tsugite joint. The tests conducted where an acute angle, obtuse angle, straight joint, and portal frame. In each case two species were tested; spruce provided the control data and maple provided the test data. The pieces used for testing were fabricated out of one inch stock and fabricated with zero tolerance using a dry fit.

The holding jig comprised of a piece of 2x8 material with two 1/4” holes in it. In the case of the acute and obtuse tests, the same diameter hole was drilled in one of the members to facilitate its fixing to the jig. The jig was then clamped to the edge of the press and provided the positioning to test the various angles.

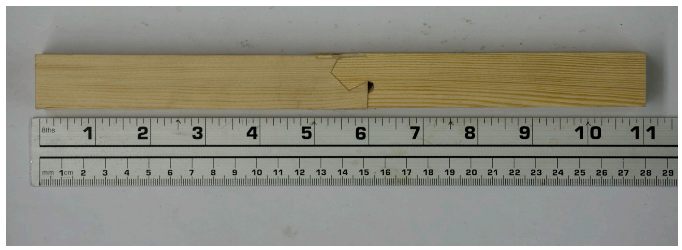
Straight Joint: Spruce

The test is set up with a straight joint supported on each end to apply a point load directly to the joint. This test did not yield a reading on the press and incurring a fractured element for each piece as seen below.

Pressure Reading: 0 MT

Setup to test the straight joint.

Aftermath of the point load applied to the straight spruce joint.



Showing size and scale of the joint being tested.

The results of the joint loaded to failure.

Elevation 1

Elevation 2

Elevation 3

Elevation 4

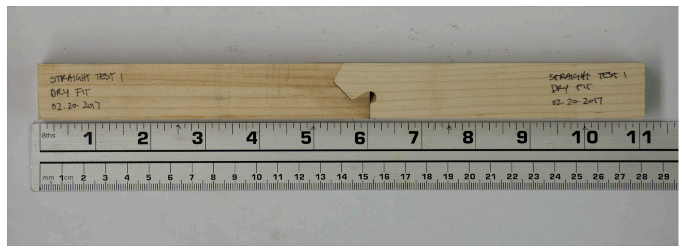
Straight Joint: Maple

Replicating the previous procedure, maple was noted to have a considerable advantage over the pine, yet no reading was able to be taken on the pressure gauge.

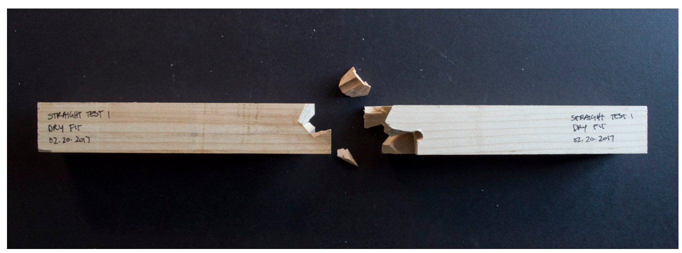
Pressure Reading: 0 MT

Setup to test the straight joint.

Aftermath of the point load applied to the straight maple joint.



Showing size and scale of the joint being tested.



The results of the joint loaded to failure.

Elevation 1

Elevation 2

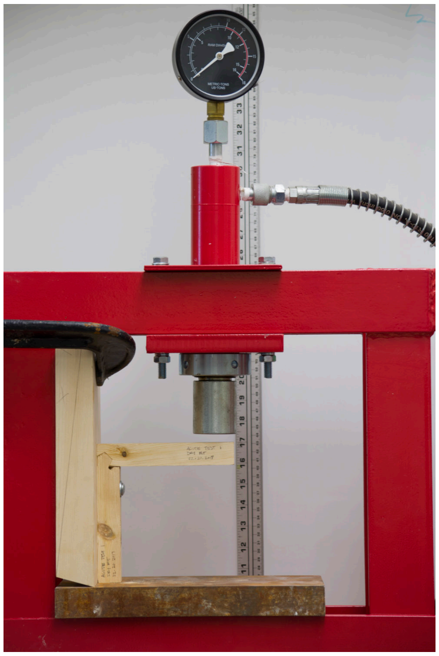
Elevation 3

Elevation 4

Acute Joint: Spruce

The acute joint tests the ability to resist rotation while at a 90 degree angle. The point load is applied in the direction that would make the angle less than 90 degrees or acute.

Pressure Reading: 0 MT

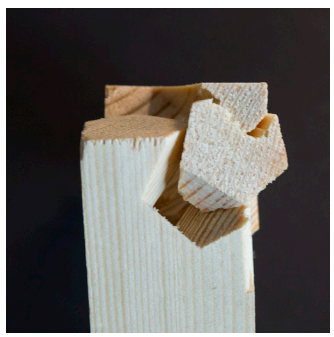


Setup to test the acute joint.

Setup of the acute test showing the jig used to anchor the joint.

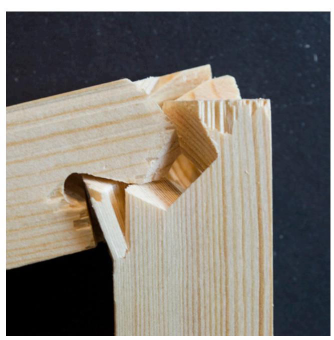
Size and scale before test.

Loaded to failure results.



Left Elevation

Top Elevation



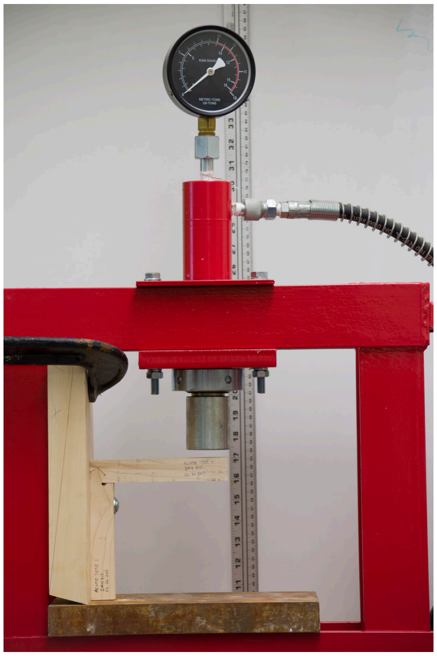
Back Elevation

Front Elevation

Acute Joint: Maple

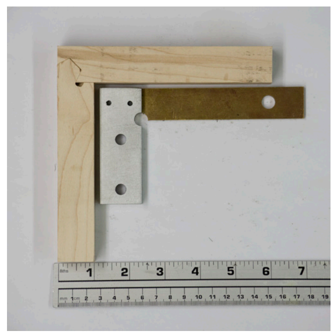
The same test performed as before, only now testing with maple. There is a noticeable increase in strength between the spruce and maple, however, not enough to register a pressure reading.

Pressure Reading: 0 MT



Setup to test the acute joint.

Results of the test still connected to the jig.

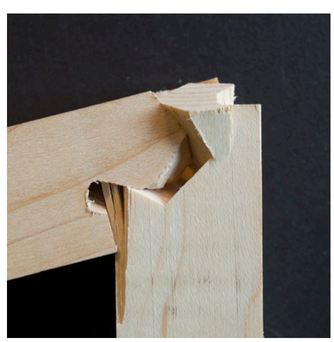


Size and scale before test.

Loaded to failure results.

Left Elevation

Top Elevation



Back Elevation

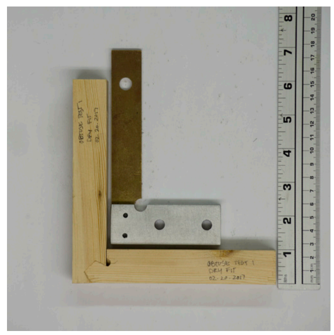
Front Elevation

Obtuse Joint: Spruce

The obtuse test mimics that of the acute only now the joint is being tested to resist rotational force when the point load is applied in the direction to cause deformation greater than 90 degrees.

Pressure Reading: 0 MT

Setup to test the obtuse joint.

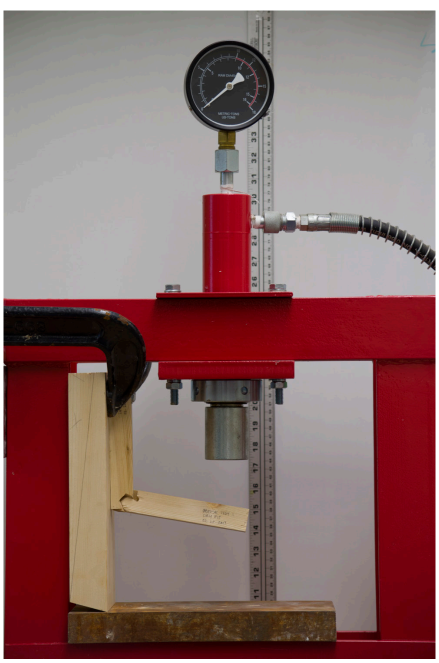


Size and scale before test.

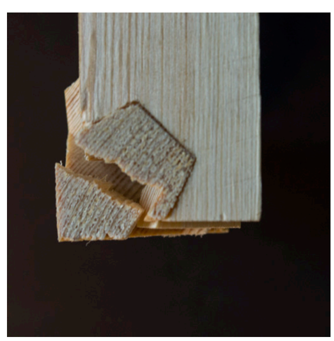
Loaded to failure results.

Back Elevation

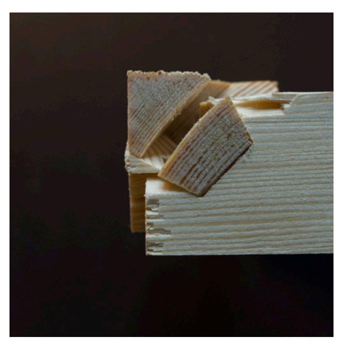
Front Elevation



Results of the test still connected to the jig.



Left Elevation

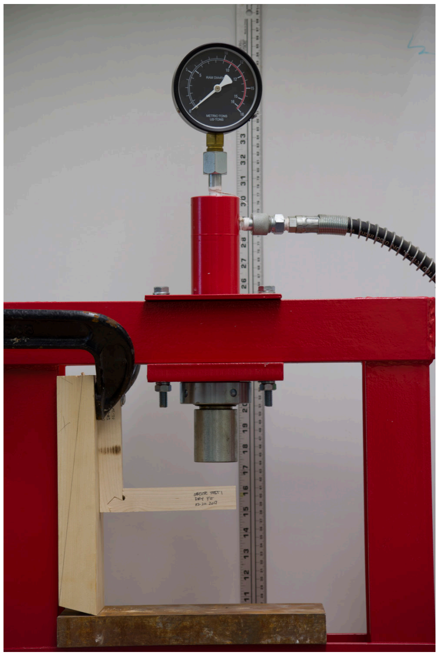


Bottom Elevation

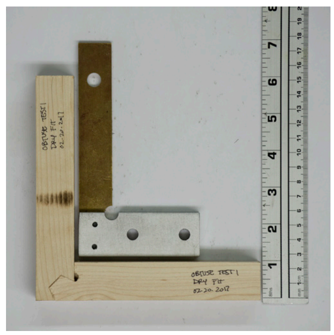
Obtuse Joint: Maple

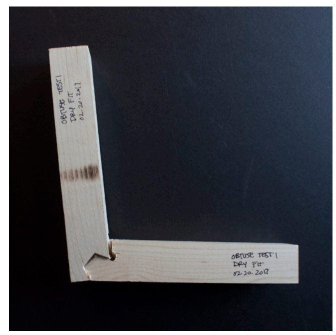
The same test as applied to the spruce now using maple. Once again, a noticeable increase in strength from the spruce test, with no reading on the pressure gauge.

Pressure Gauge: 0 MT


Setup to test the obtuse joint.


Results of the test still connected to the jig.

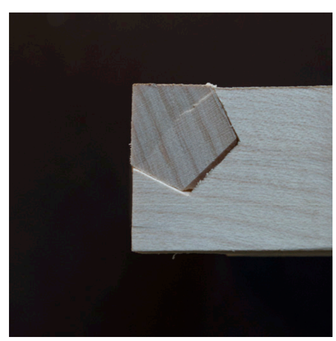

Size and scale before test.


Loaded to failure results.


Back Elevation


Front Elevation


Left Elevation

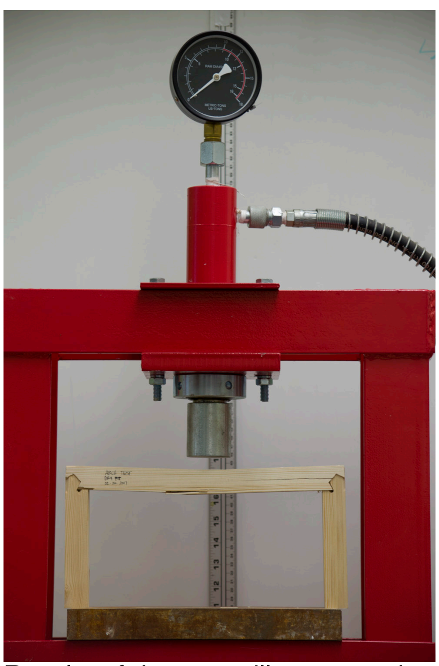

Bottom Elevation

Frame Joint: Spruce

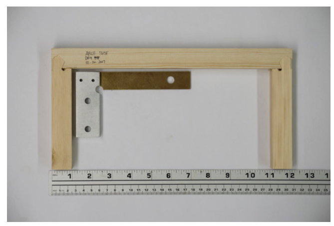
Using an architectural frame, the joint is tested to begin to understand its relationship to structure. A point load is applied to the center of a member, connect to columns on either end by use of the Kawai-tsugite joint.

Pressure Reading: 0.5 MT

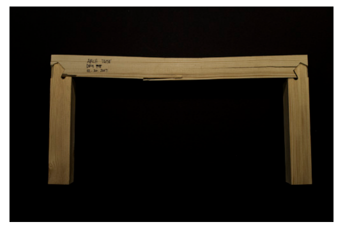
Frame in press, ready for testing.



Results of the test still connected to the jig.



Size and scale before test.



Loaded to failure results.

Top Elevation

Front Elevation

Bottom Elevation

Back Elevation

Frame Joint: Maple

A considerable increase in pressure was recorded when conducting the frame joint test with maple. Having a similar outcome to the spruce, the hardwood proved to have a drastic advantage over the softwood.

Pressure Gauge: 1.0 MT

Frame in press, ready for testing.

Results of the test still connected to the jig.

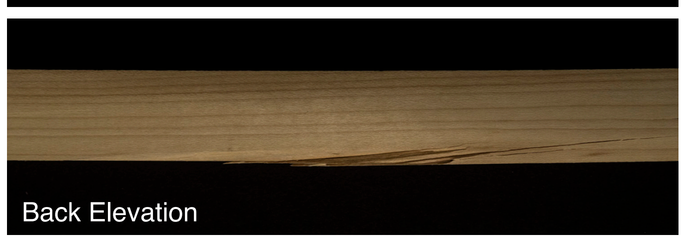
Size and scale before test.

Loaded to failure results.

Top Elevation

Front Elevation

Bottom Elevation



Back Elevation

Testing Outcomes

Side elevation representing the strength of the detail: green denotes strength and red denotes weakness.

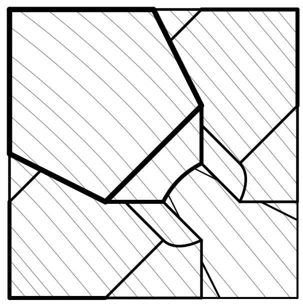
The results of the testing of the Kawai-tsugite joint show a pattern: the joint itself is not a strong one. Because wood is anisotropic, when the joint is milled, part of the detail becomes weak. This can be seen in the diagram to the left in which the green denotes a strong path through the wood and the red denotes the weak point prone to breaking. The strength of this particular part of the detail runs with the grain of the wood, as such, where the two sections meet is the line of breakage. This line of breakage is consistent throughout the tests performed whether the joint was in a 90 degree position or in the straight position.

Showing the greater void left by the tooling of the CNC machine (on the right) compared to the little void left by the pull saw blade (on the left).

If we compare the joint to a hand made version, we can see the extra material that is removed as a result of the CNC tool. Using the CNC requires a bit of certain size and therefore more material is taken out than needed for the joint to operate properly. However, the place where the material is taken out is where it is needed the most.

> The actions themselves are the result of a long history of choreographed movements enacted by a tool on a material. Each material inspires a specific set of movements. For instance, the grain of wood requires directionality to be considered when sanding, carving, or cutting in a manner that stone or brick would not. (Schröpfer and Carpenter 2011, 65)

It was this investigation of the movement of the CNC tool on the wood along with the results of load testing that caused for a greater understanding of the grain directionality in the detail. Understanding of the different log milling techniques, led to using



Plan view of a milled Kawai-tsugite joint showing the strongest wood grain direction.

stock that is rift sawn, or has the grain running from corner to corner to produce the strongest detail as shown in the diagram on the left. A plan view shows the milled part with imposed grain lines.

The tacit data collected revealed the relationship of softwood to hardwood showing a considerable strength increase when using hardwoods although no results were measured on the pressure gauge. The results can be seen summarized in the table below. To further understand the strength capabilities of the joint more testing is needed with a smaller pressure range that can measure the smaller pressure differences being exerted on the various testing configurations.

Test Configuration	Spruce	Maple
acute angle	0 MT	0 MT
obtuse angle	0 MT	0 MT
straight	0 MT	0 MT
portal frame	0.5 MT	1 MT

A later discovery proved to dismantle the idea of the portal frame joints being structure. Upon further investigation and study, the portal frame was in fact not testing the joint itself, but rather the member supported at each end. The test would have the same outcome without the Kawai-tsugite connections using solid straight members propped up on blocks. Solid pieces of spruce and maple were tested without any joints and confirm the theory above: both species registered a pressure of 0.5 MT and 1 MT respectively which matches the testing done on the portal frame.

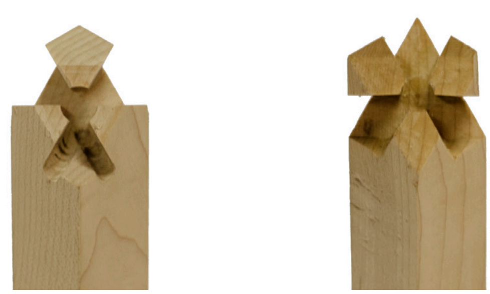
In addition, only one iteration was completed to get a sense of what the capabilities of the joint might be. To better understand the strength capabilities of the Kawai-tsugite joint, several more iterations are needed and more testing done. The next prototypes would use the data obtained from this testing as input data for subsequent prototypes and could test the possibilities of a less-than-zero tolerance, using an adhesive, additional wood species, alternate materials, and filling the void resultant of the fabrication process. Additionally given much time, testing could be done on the original joint as done with hand tools to compare and contrast the differences between the hand fabricated joint and the CNC fabricated joint.

Three variations of the inverse Kawai-tsugite joint.

Inverse Joint

The first adaptation derived was the inverse of the original joint, which was a simple switching of the solids and voids. This detail uses the exact same geometry as the original detail thus it has the same rotational variation properties. Upon closer inspection of the detail itself, it can be seen the weakness found in the original detail has now been multiplied by two, resulting in a weaker overall joint.

Comparison of the weak point between the original detail on the left to the inverse detail on the right.



Showing the difference between the original detail on the left and the inverse detail on the right.

Round Stock

Another adaptation of the original joint was to start looking at the relationship between the square stock and the geometry. Using the same CNC milling files, round stock was used to see if the properties that held true in the original did so also in the round stock. As can be seen, not all the properties transferred and the alignment of the outer faces is not consistently flush as is the case with the square stock. However, the rotational variations are the same as the original detail.

The detail milled in round stock still has the rotational variation of three positions

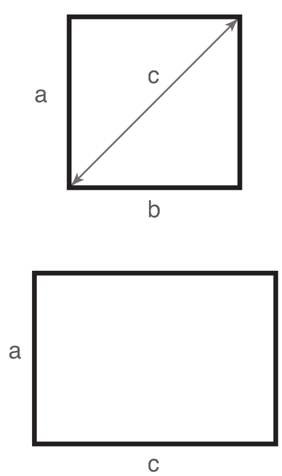
3-Way Joint

The components of the 3-way joint.

The original joint provided a way to connect only two members together, thereby limiting the spaces they could produce and creating somewhat of a closed network. Adding a third piece to the joint connection was the next innovation, allowing a more diverse network of possibilities. The joint is made by two pieces creating half of the joint and the third piece completing the other half.

The 4-way joint.

The surface joint.



The relationship between square stock and rectangular stock.

4-Way Joint

An extension of the 3-way joint, the 4-way joint utilizes the adaptation of the 45 degree angle in both sets of pieces, thereby reducing the number of rotational variations. This can be easily seen as the variation that does not work is one where the 45 degree mitre's in each set align, and nothing holds the two sides together. However, the other variations allow for the pieces to interlock in such a way that a joint is created with four members.

Surface Joint

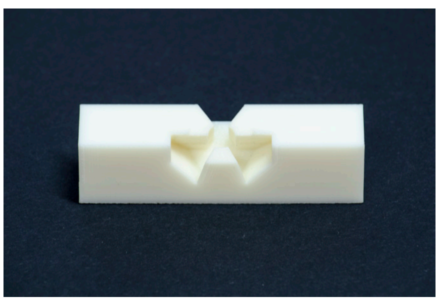
The surface joint innovation resembles that of stacking original joint members together. However, this joint was derived from a curiosity of a true solid surface, requiring new jig to position the material to be milled.

Rectangular Member

The rectangular member developed from a question of spatial capacity and the curiosity of the joint to allow for the shed typology. Derived to fit with the original joint, the rectangular member proved far more fruitful than just re-creating a typology. Having developed this piece in the digital environment, an alternate method of making was used, 3D printing the pieces. This allowed for quick prototyping and to understand the possibilities of this particular joint beyond the initial typology understanding. The proportions of the rectangle relate to the cube geometry, being the length of the diagonal of the square stock.

A 3D printed rectangular member on the left and a CNC milled member on the right.

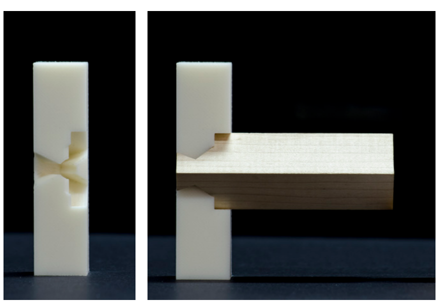
3D printing allowed for a quicker prototyping process, as there is no jig involved. Once the pieces were fabricated, additional properties started to reveal themselves only by playing with various pieces, assembling and reassembling, and making artifacts. Discovering what this joint could do beyond the initial re-creation of the shed typology, was a true outcome of the making methodology. Only by using the methodology and going through the process of making did the joint prove to hold the same variation properties as the original joint.



First T-Joint iteration.

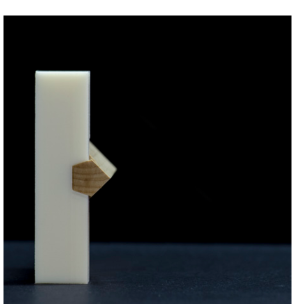
T-Joint

The T-joint went through several iterations before arriving at its current stage. Beginning in the digital environment, a simple T was formed and carried through using the 3D printed method as well. This afforded several iterations as the prototypes further developed at a quick pace, eliminating the need for multiple jigs. Once the joint was refined, a jig was made to produce the joint in wood using the CNC machine.

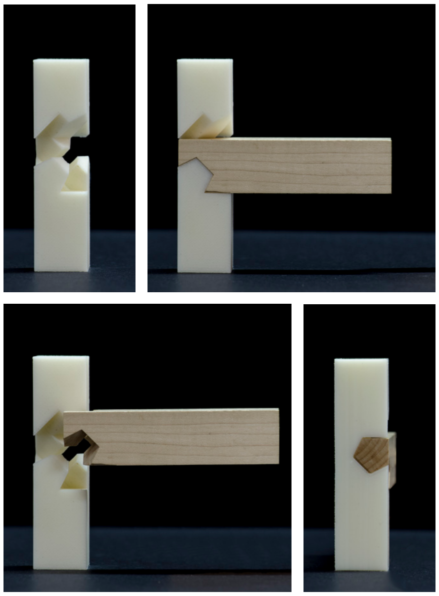


First T-joint iteration with no rotational variation, rotated joining member.

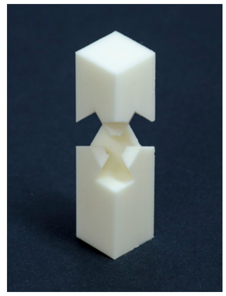
The first iteration allows for the connection of an original joint member, rotating it 45 degrees and aligning the outer most faces and edges. This iteration only allowed for one connection variation, leading to subsequent prototypes to further refine the joint.



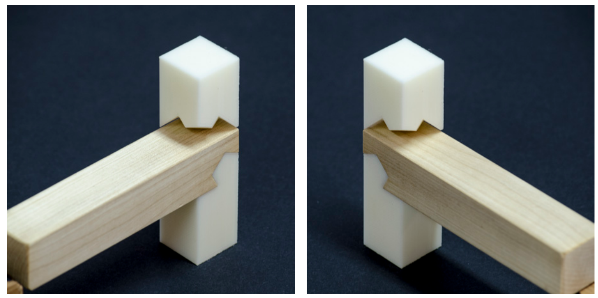
Elevation view showing adjoining member rotation 45 degrees.



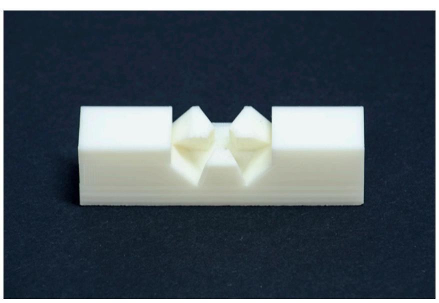
Second T-joint iteration showing movement of adjoining member and the flush nature of the faces.



The second iteration builds off the first iteration in two ways: it allows for 2 rotational variations of the adjoining member and aligns the faces of the members to be flush.

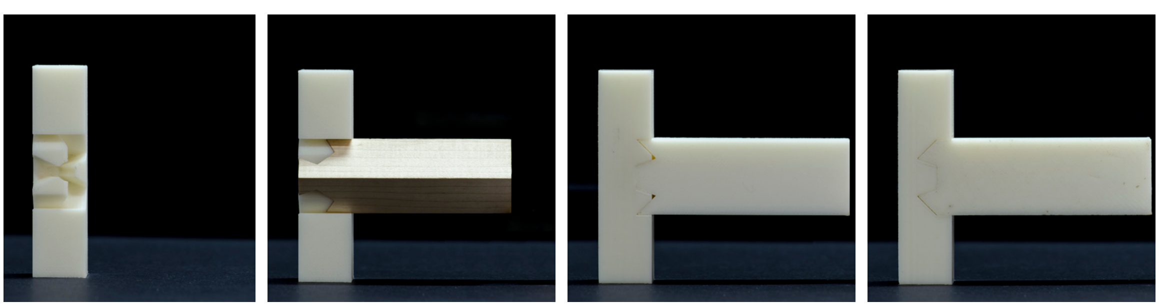


Second iteration T-Joint showing the two rotational variations possible.



Third T-joint iteration.

The third iteration developed by focusing on allowing other pieces to attach to it. This iteration returns to the rotating the adjoining member, but also allows for the attachment of a rectangular member. Although the rotated adjoining square stock does not align on all faces, the rectangular member does align on all faces giving it a more refined aesthetic and a greater possibility to be structural in some way do to the heightened stock depth.

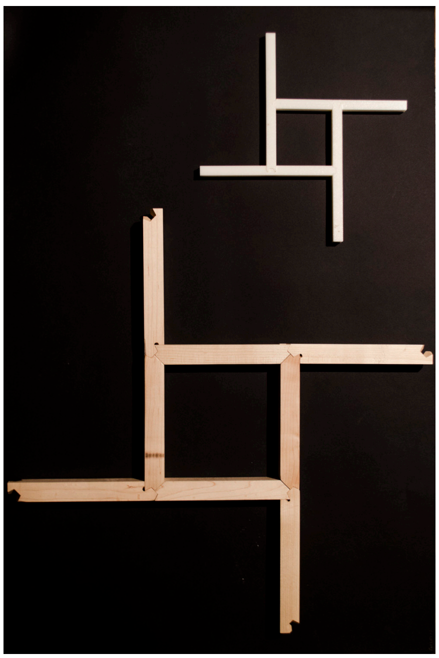


Third T-joint iteration with no rotational variation, but allows the rectangular member to connect.

Fourth iteration and refined T-joint.

The fourth and current T-joint combines the other iterations into one, allowing both square and rectangular members to adjoin, with full rotational variation.

Modified T-Joint

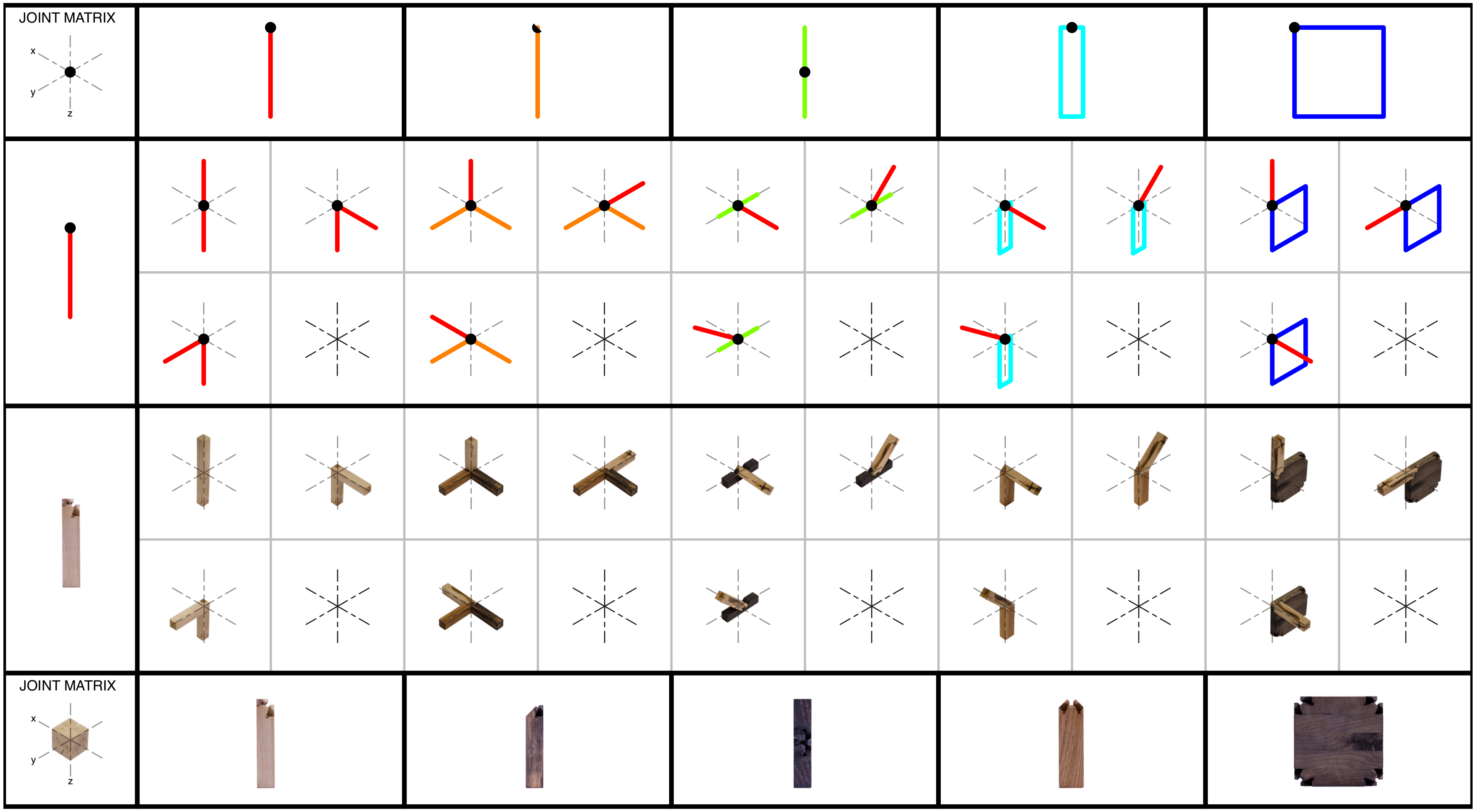


Modified T-joint and 3-way joint producing a reciprocal frame.

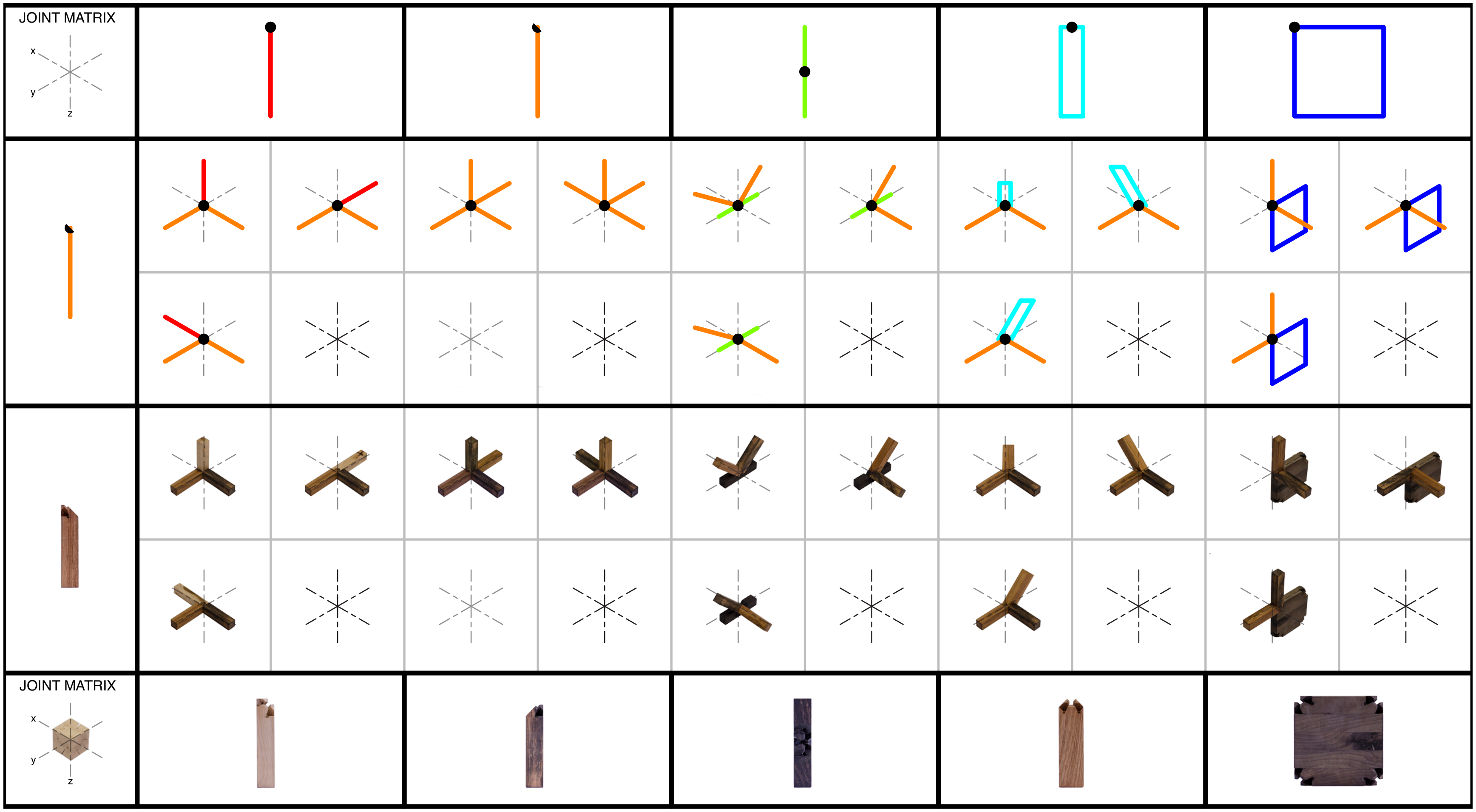
The modified T-joint builds on the idea of a network, providing an open ended way to continually connect pieces. By using the rectangular member with the joint milled in the end of it, the dimension is returned to a square. Similarly, the T-joint is adapted to only accept the modified square member which allows for the formation of a reciprocal frame. A similar effect can be created using the 3-way joint as the variation allows for a T-like connection as well.

Spatial Configurations

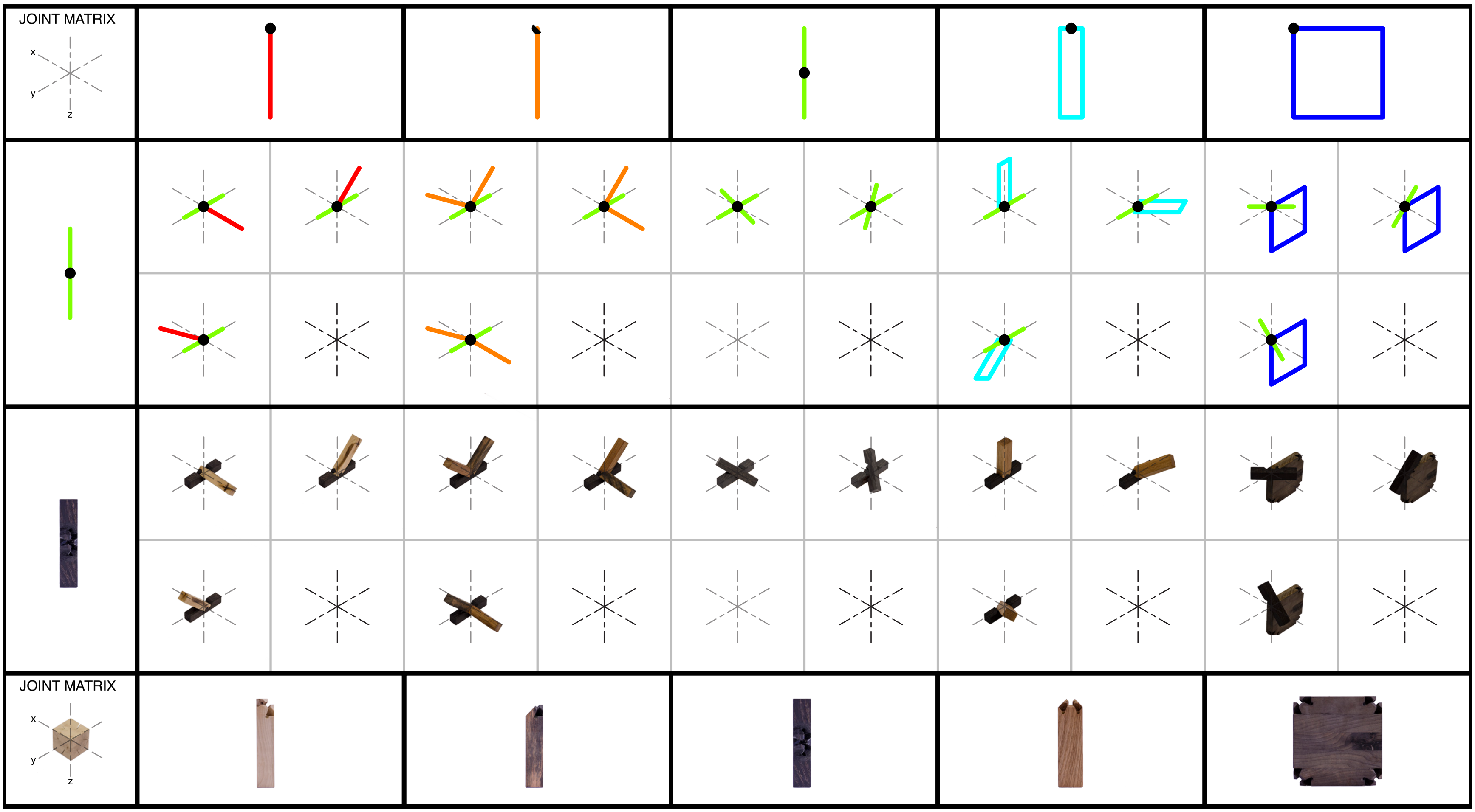
Having outlined the discovery and exploration of several innovative adaptations to the Kawai-tsugite joint, the assembly of those pieces create spatial configurations that can be used to create and modify space. On the following pages are a series of matrices that give the possible configurations when connecting any two given pieces. Each matrix is divided into an abstracted upper half and a photographic lower half.



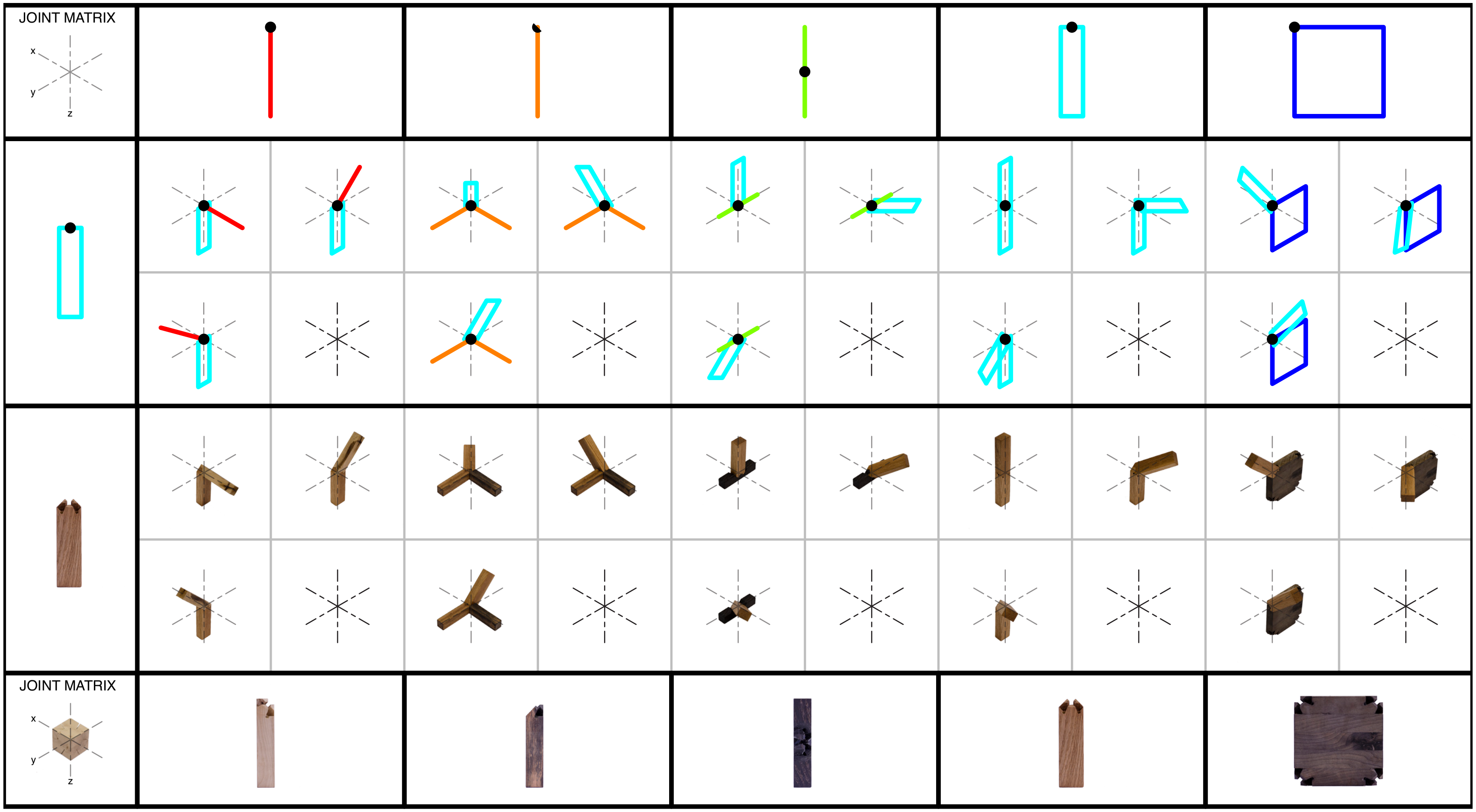
Joint Matrix: straight member.



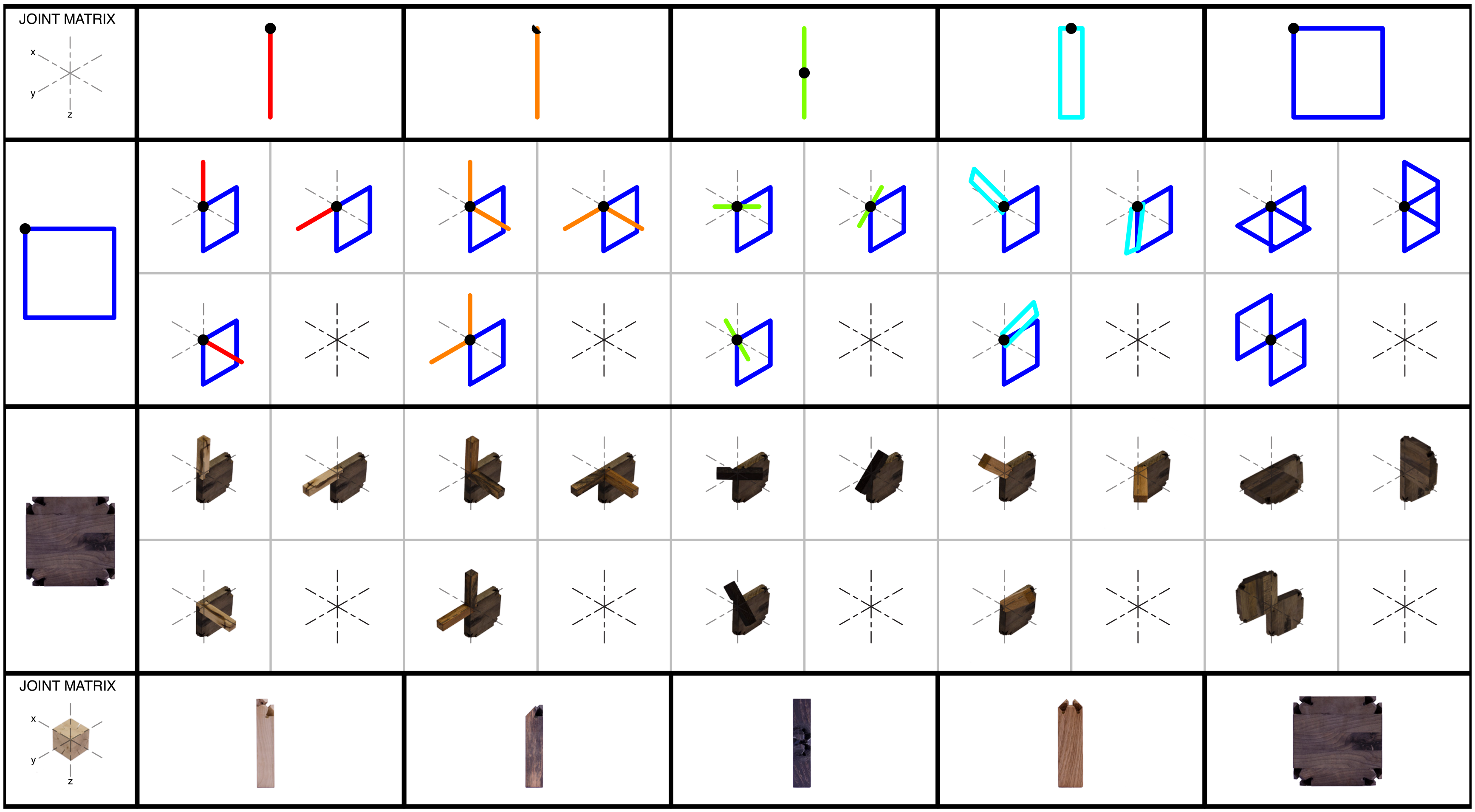
Joint Matrix: 45 degree mitered member.



Joint Matrix: T member.



Joint Matrix: rectangular member.



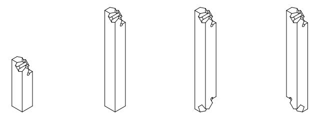
Joint Matrix: surface.

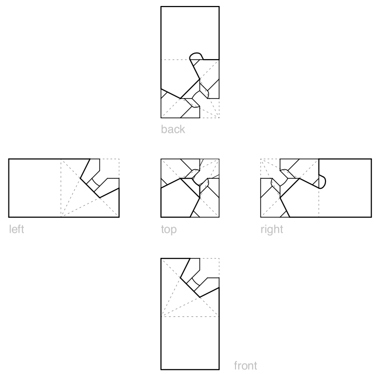
Kawai-tsugite Game

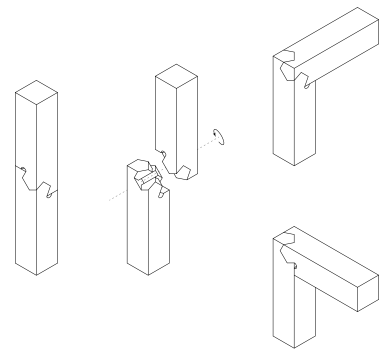
Using a few of the innovative pieces generated, a game was developed to start to understand how the joint could make and modify space. Additionally it provided information about the kinds of spaces the detail was making. The game was implemented in two phases; the first phase introduced the standard pieces, the second phase added to the repertoire. Each phase was documented through video and photography, focusing on the models that were made and how the pieces were used.

The goals of the game were to tease out the kinds of spaces the detail invoked and to determine how the detail could be used. What kind of structures would emerge? What types of spaces would the detail allow?

The first iteration of the game involved making a booklet with only the required information to properly use the system of joints to create some kind of structure. A series of drawings show the pieces allotted to the game, the geometry in orthographic views, and the three positions of the joint with the rotational axis. A set of instructions were given stating a sequence of information to obtain from becoming familiar with the joint and its motion to the entire structures restrictions. The structures that were meant to be created were a room, a dwelling, and a space of memory. The second iteration built on this first one by adding the ability to use the 3-way joint in the network.

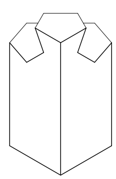






Instructions

- Become familiar with joint geometry & motion.
- The single pole of the geometry is fragile. Do not leverage the pieces against each other to pull them apart.
- The joint allows for two pieces to form either a straight line, or either of two 90 degree angles. There are only these three options per joint.
- Joints are strongest when members are supported at both ends.
- Not all the pieces must connect to one another, you can have multiple strands consisting of numerous pieces.
- Restrict building to 3 pieces long in the X, Y, & Z directions.
- Construct a room.
- Construct a dwelling.
- Construct a space of memory.



Created by professor Naohito Kawai of the Kohakuin University School of Architecture to test the skill of a craftsman.

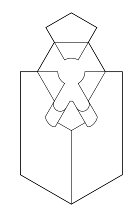
Data

Name:

What room did you make?

Briefly describe the space of memory you made:

What piece would you add to the system?

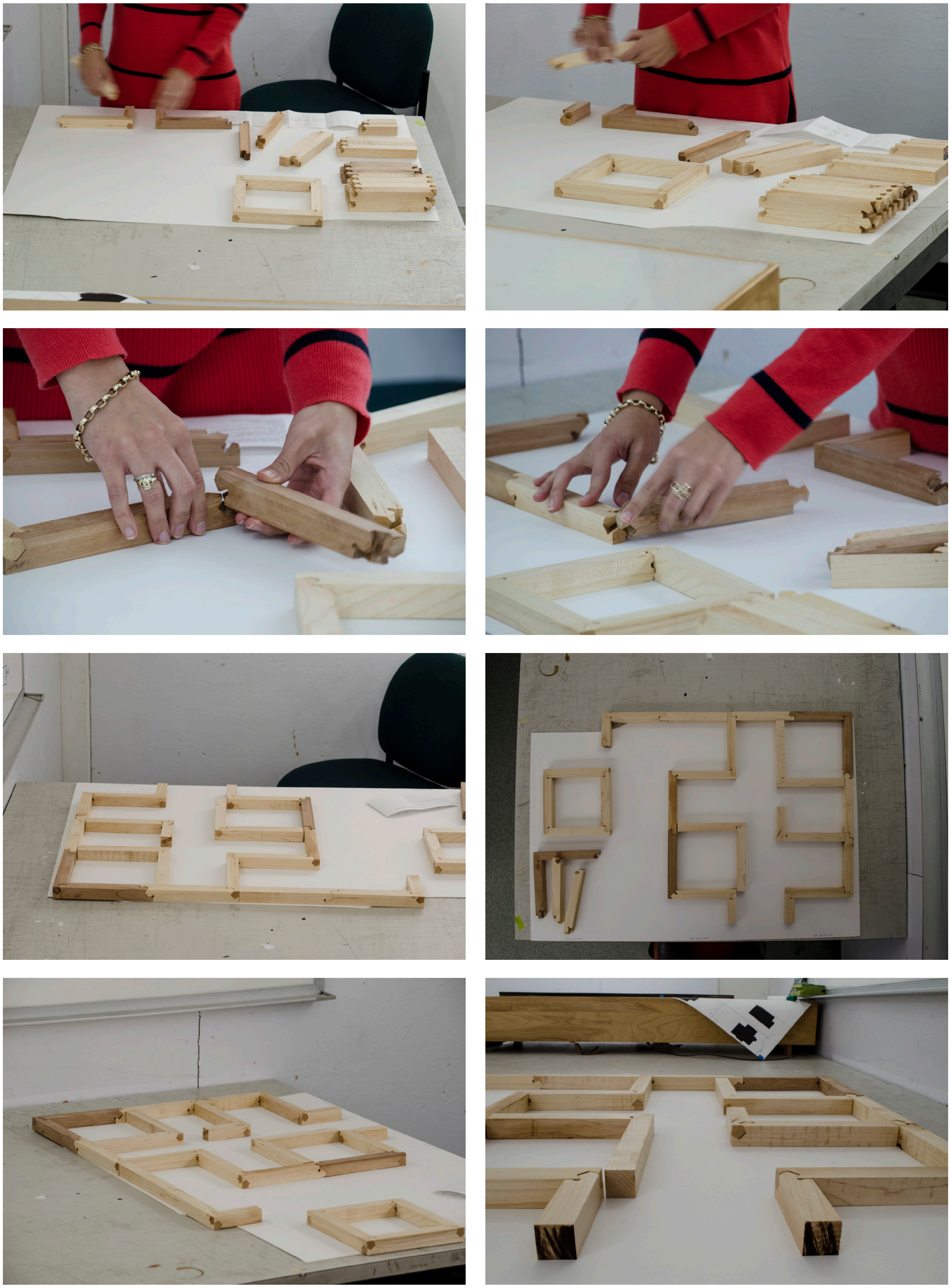


Kawai tsugite:
making space with one joint

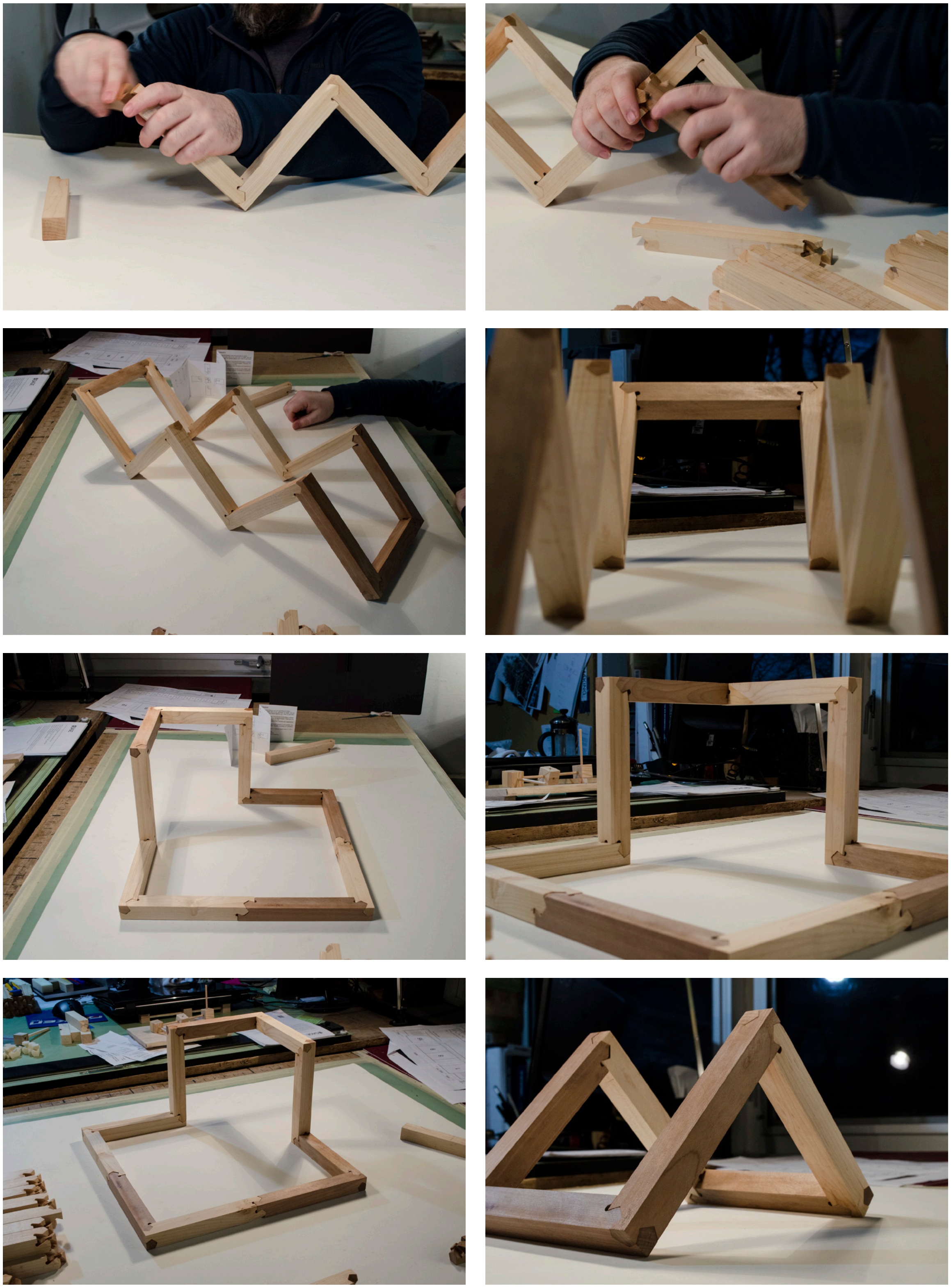
The booklet of the first iteration of the Kawai-tsugite game.

Photographs of one iteration as a result of the first instruction booklet.

Photographs of a second iteration as a result of the first instruction booklet.

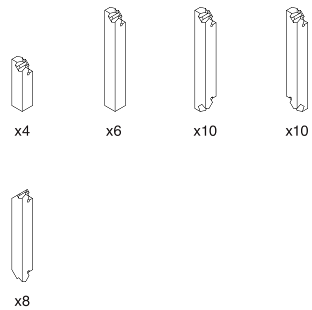


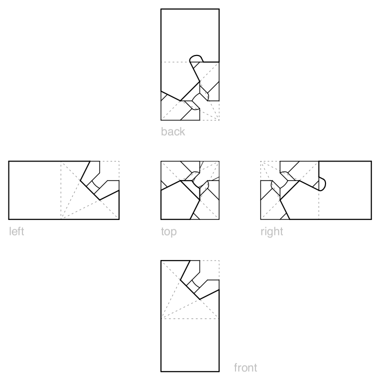
Photographs of a third iteration as a result of the first instruction booklet.

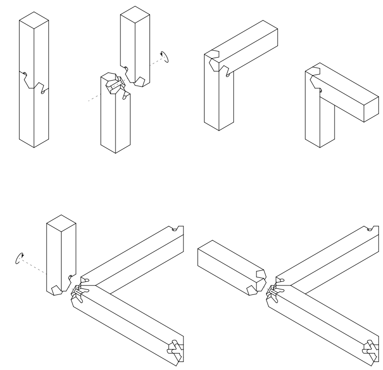


Photographs of a fourth iteration as a result of the first instruction booklet.

Photographs of a fifth iteration as a result of the first instruction booklet.

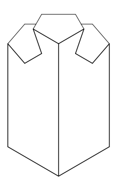






Instructions

1. On the white card in front of you, using the pieces provided in this kit, choose your least favorite piece and place it in the center.
2. Choose another piece and add it to the one in the center.
3. Continue choosing and pieces together with the joint until you are satisfied with the outcome.
4. You may choose to add a piece which is not connected to the last, at which time you are to start with the same least favorite piece, then subsequently add pieces in the same manner as above. You do not have to use all the pieces.
5. Record on the back of this booklet the space and its function that you have made.
6. Drastically alter the space simply by rotating one joint to a different direction.
7. Record on the back of this booklet the space and its function that you have made.



Created by professor Naohito Kawai of the Kohakuin University School of Architecture to test the skill of a craftsman.

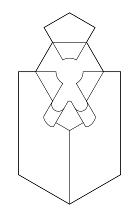
Name:

Record the first space and its function you have made.

Where is it located?

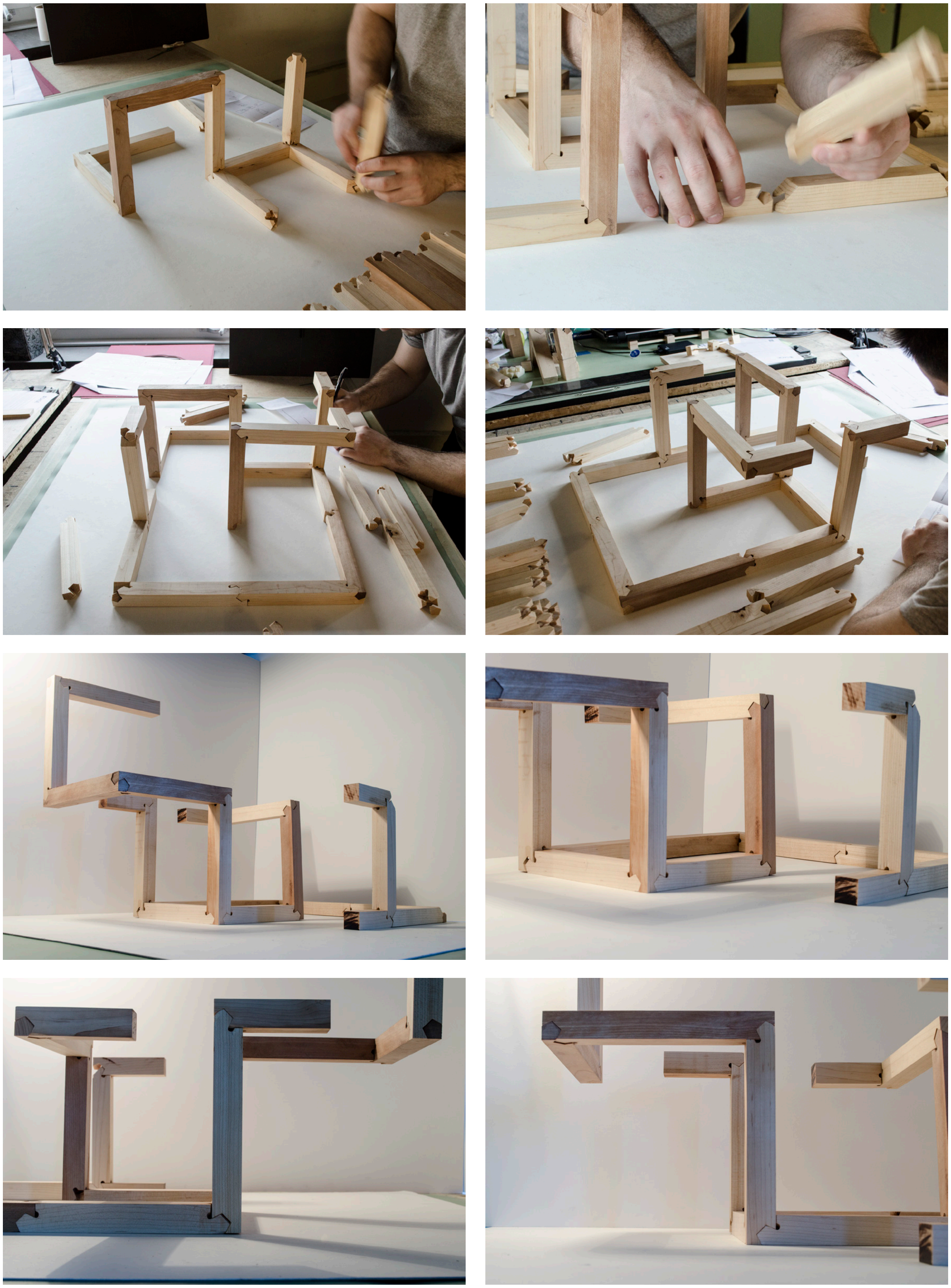
Record the second space and its function you have made.

Where is it located?



Kawai tsugite:
making space with one joint

The booklet of the second iteration of the Kawai-tsugite game.



Photographs of one iteration as a result of the second instruction booklet.

Photographs of a second iteration as a result of the second instruction booklet.

Much of the game consisted of individuals trying to gain the tacit knowledge required to assemble the joint. Once that happened, because there were only line-like pieces to create a network with, stacking of the pieces occurred to create a surface. This lead to an innovative surface member as seen previously.

Additionally, the ideas of the types of spaces that were generated covered a wide range, thereby the deduction can be made that the types of spaces the detail affords can vary and change depending on the network they are a part of. This is consistent with the spirit of the joint, as the variation within its geometrical position allow for adaptability to happen.

Further game testing could occur at a jump up in scale that would allow for the investigation of spaces created in relation to the body as well as the investigation of the structural capabilities of the network.

Defense Installation

In the educational realm, students disconnect with that of actual making inhibits their ability to design or to make architecture. In Jean Labatut's article, "An Approach to Architectural Composition," he discusses the expression of 'Architectural Composition' in which are embedded the meanings of the words design and construction that which are inseparable. (Labatut 1956, 33) With the focus on the ideas behind architecture, rarely is a student asked to detail or asked how the architecture is built. This does not mean that detail or the process of construction is completely lost, however, it often takes a back seat to the architectural concept and image rendition. When making objects, models, and doing physical research, there is an inherent haptic and tacit knowledge present for architecture. It is modeling how a space feels, it becomes experiential knowledge that can be used in the next project as acquired facts. This is not to say schools do not allow for making, models are greatly encouraged. Even Dalhousie has a free lab component every year which allows students to go through the process of design-fabricate-build and to gain crucial experience with materials, tools, and processes. This process should be the way in which we design on a regular basis. If architecture's medium is construction, why are students not constructing things? The digital world allows for a tool in which to utilize construction techniques and therefore should be used, however, process of building of making must be inherent in its DNA.

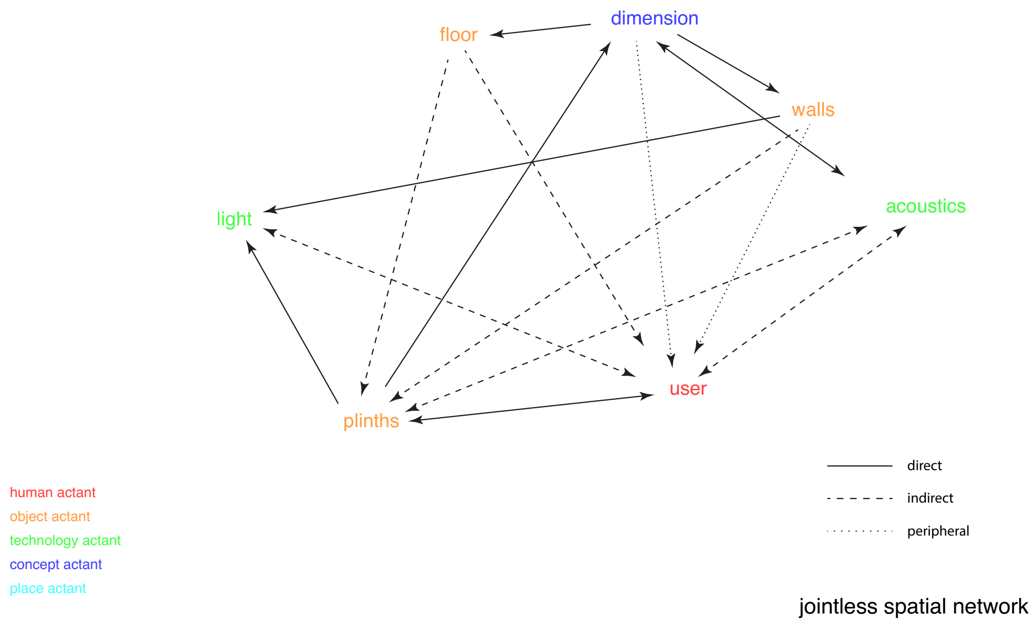
Having gone through the making methodology in producing one-inch stock pieces from which fabrication techniques, spatial qualities, and strength testing could be done, a jump in scale was needed to continually test the abilities of the Kawai-tsugite joint. If the smaller stock was related to the hand, a larger stock would relate to the body and therefore inform and change the spaces that we inhabit.

To test the abilities of the Kawai-tsugite network and to continually question the methodology at hand, a defense installation was constructed using the many different pieces produced earlier. Although it was previously determined that hardwood was a better material choice than softwood, the installation was made using spruce as it was financially economical, easily malleable, and sufficiently strong to construct with.

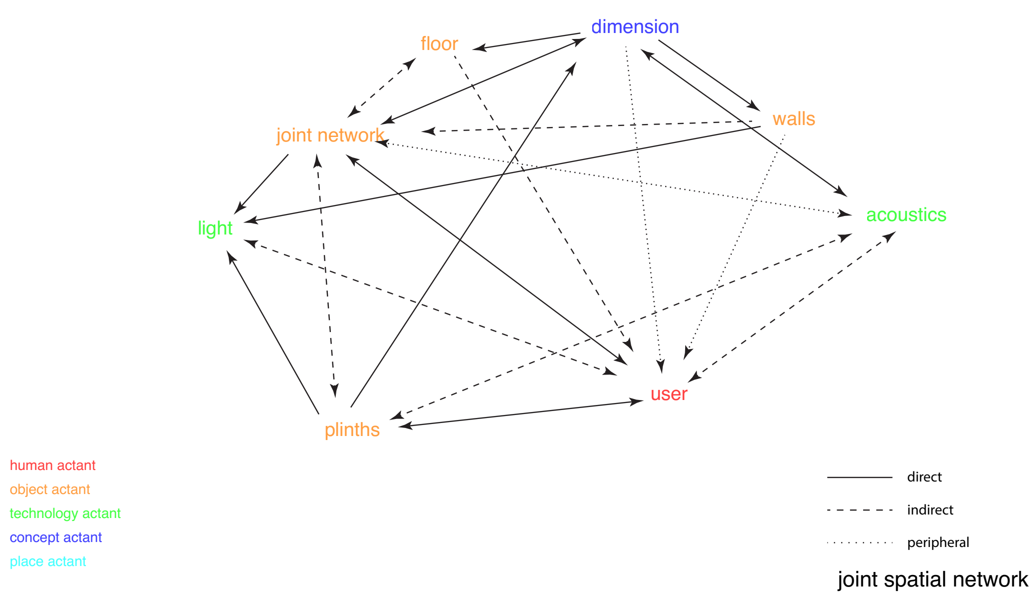
Moving through the defense installation. Photograph by Christie Kijewski.

The network created immediately modified the site by placing solid and voids throughout the space. This allowed for the application of drawings to the surfaces and gave specific movement throughout the space. Upon starting the thesis examination, those in attendance were required to move through the installation, engaging in the architecture the joint afforded. This network was mapped with ANT and are shown on the next page focusing on how the network changed when the Kawai-tsugite joint modified the defense space.

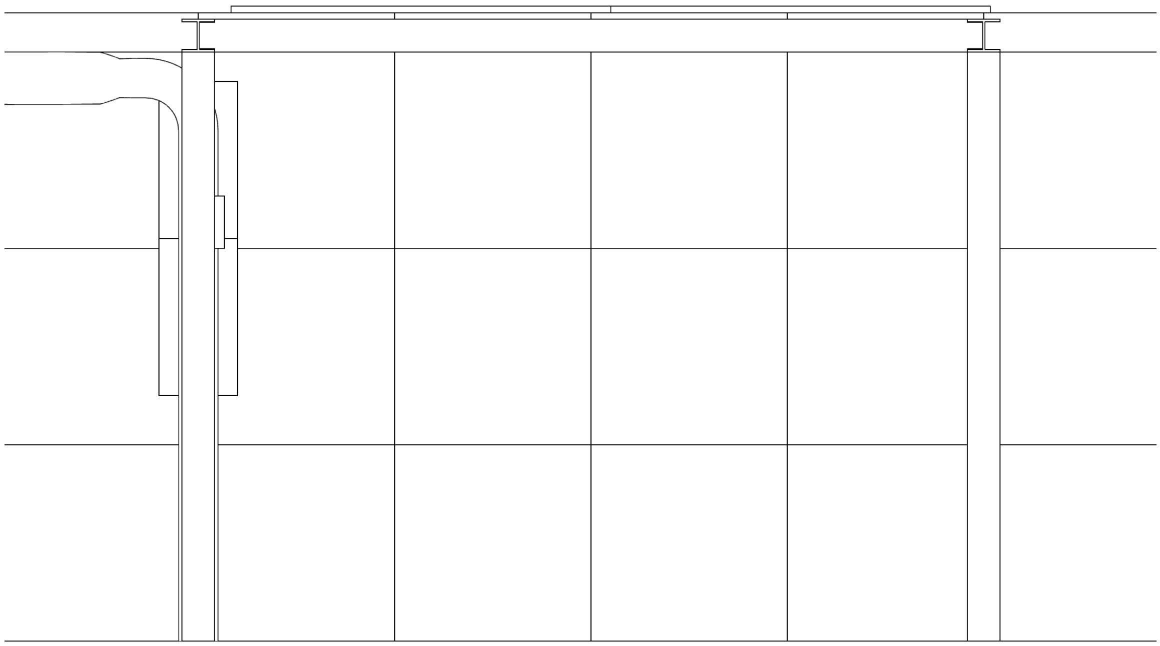
Thesis defense in progress showing how the examiners were part of the network. Photograph by Ken Kam.



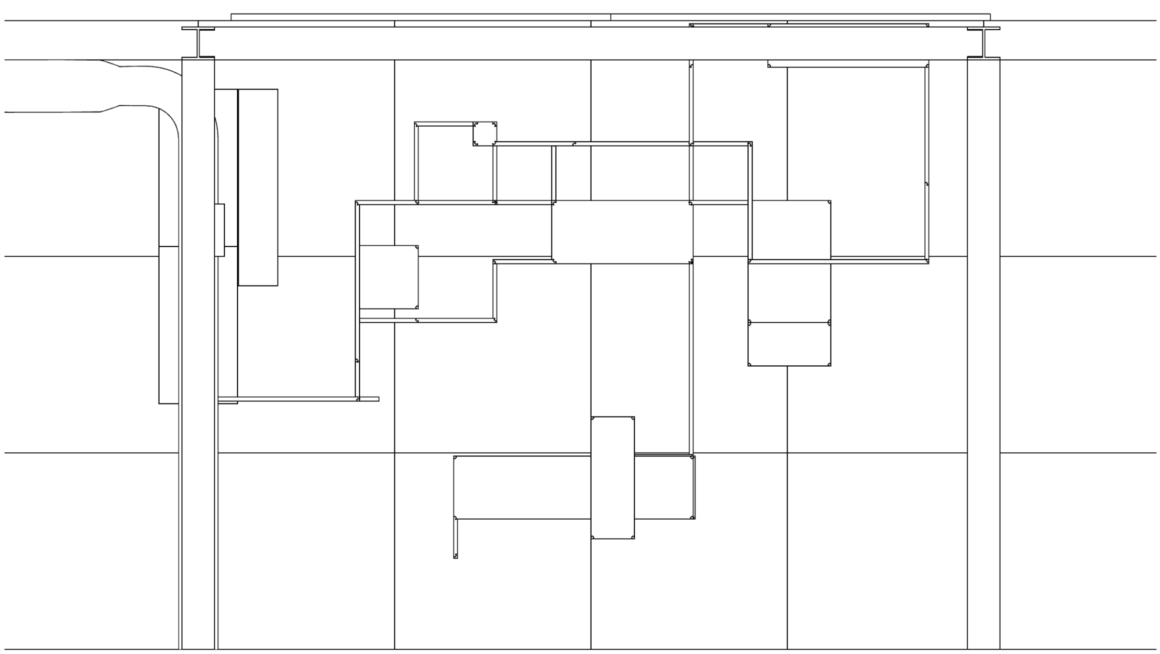
ANT map of the space before introducing the Kawai-tsugite architecture installation.



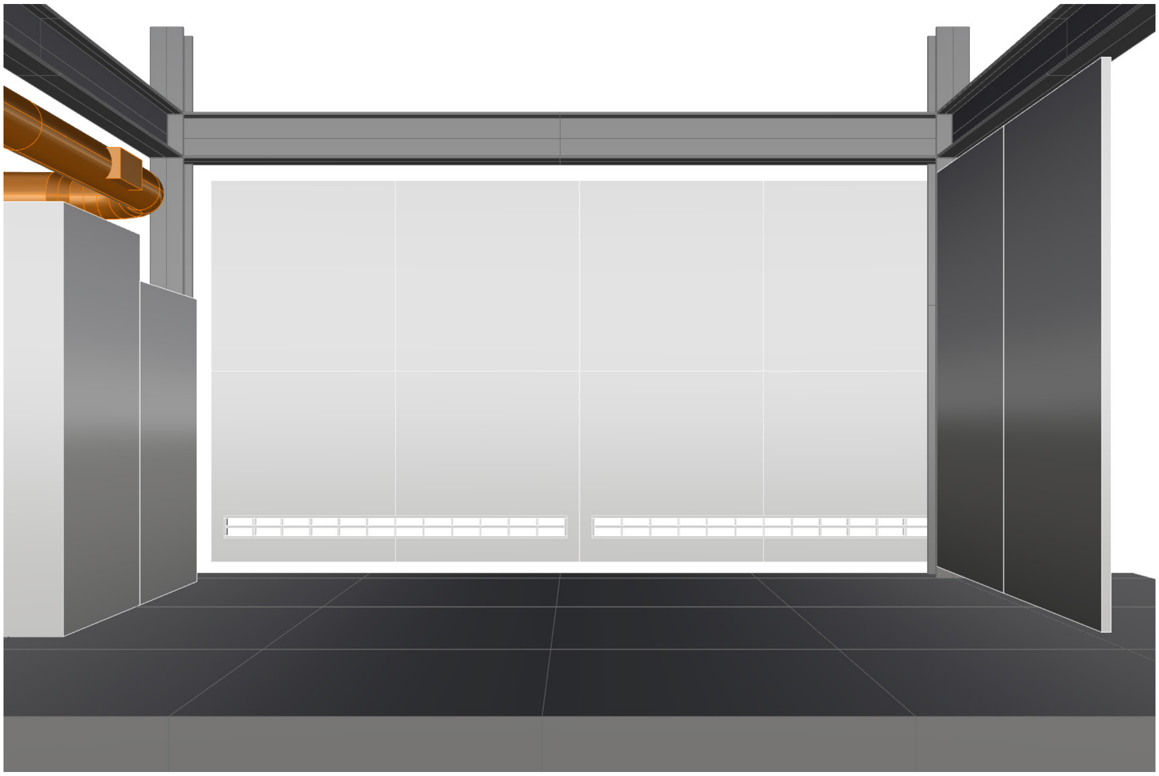
ANT map of how the Kawai-tsugite installation modified the defense space.



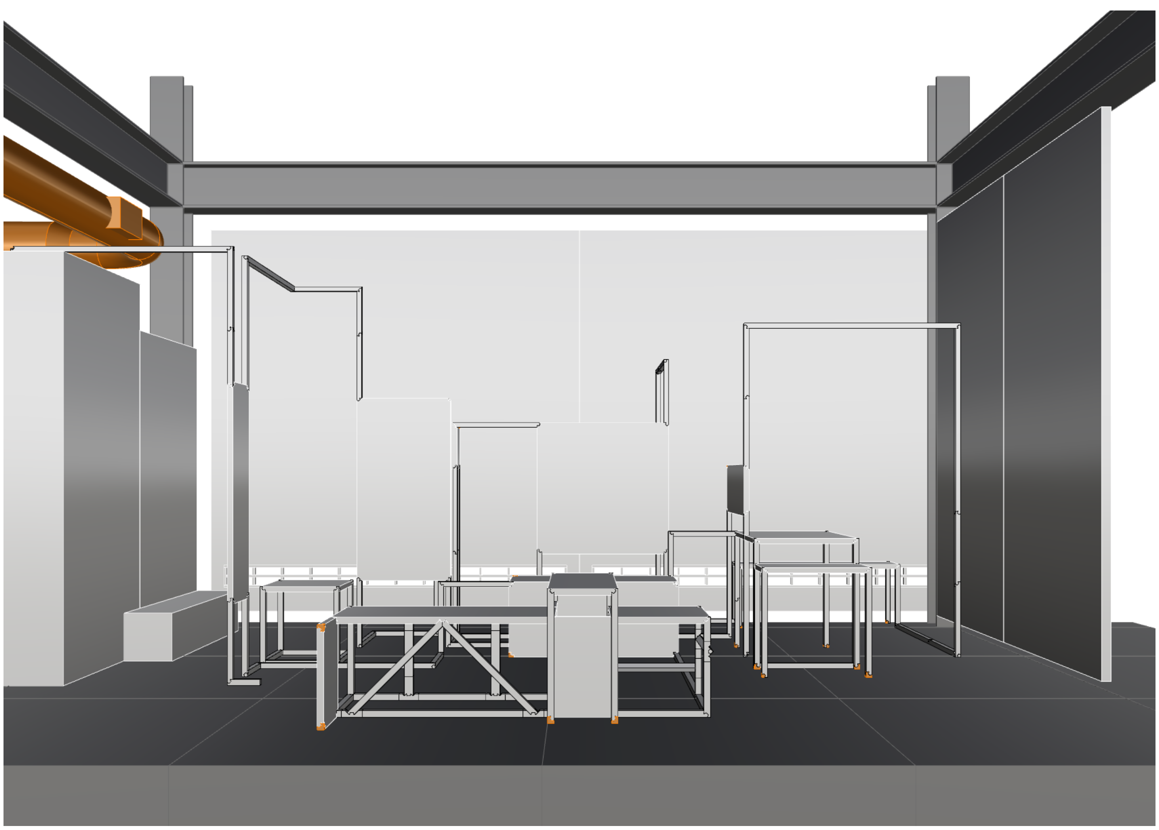
Plan of empty digital defense space.



Plan of modified digital defense space.



The empty digital defense space.



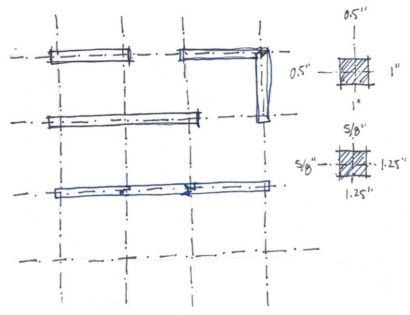
Modified digital defense space.

The empty defense space.

Installation modifying defense space.

Photographs showing the thesis installation and invoked movement throughout the structure.

Giving my thesis defense presentation, showing how the audience is part of the network.
Photograph by Ken Kam.



Kawai-tsugite overall grid structure.

It was shown that the ability of the Kawai-tsugite joint to generate an architecture to generate and modify space was successful. A network itself, the installation was part of a larger network consisting of thesis examiners as well as a relationship established with the audience. The installation proved its ability to create solids and voids which invoked movement throughout. It was also able to generate a stable structure on which the examining committee was able to sit for the duration of the exam.

Giving my thesis defense presentation, with examining committee seated within the network. Photograph by Ken Kam.

CHAPTER 6: CONCLUSION

With a persistence to investigate and develop the potential of the Kawai-tsugite joint, numerous innovations were fabricated and refined. Working within the theoretical framework of knowledge as informed by the process of making, a number of strategies were employed to investigate how the detail could be used as a form generator within a network. A working methodology was developed within the theoretical framework to provide an investigative approach to look at how details can generate architecture. By way of a feedback loop, information from each stage of the making process could and was fed back into the beginning of the process to ensure the refinement and advancing of the ideas and fabrication techniques engrained in the methodology. Actor-Network Theory provided a unique view by placing animate and inanimate objects on a level field and focusing on the relationships between the actors and how they formed. A unique thread was established throughout the thesis that focuses on the ability of the Kawai-tsugite joint to be a network but also be part of a larger network as shown through the defense installation.

Although relatively new, the Kawai-tsugite joint has yet to reach its full potential. From a pragmatic or mechanical point of view of joinery, the joint does not afford much. Ceremonious structures could be generated using this joinery and as shown in the defense, the joint has the ability to create small structures through the repetition of members. This repetition allows for strength within the network but also relies on the varying defined pieces to achieve stability. The investigation into its capabilities as a structure were started, showing that with a number of the different innovations placed strategically, a seat could be generated that would support the weight of the examiners. This shows potential for further structural capabilities.

However, the Kawai-tsugite joint falls heavily on the conceptual approach to joinery, with the joint network offering an organizational framework. Given only one iteration at a larger scale, on a spectrum from tectonic order through spatial order, the Kawai-tsugite joint falls closer to the spatial order. By contrast, Kengo Kuma’s GC Prostho Museum would lie somewhere in the middle, given the ability of the repetition of the joint to afford a structure that articulates a spatial configuration, yet falls short of providing a spatial hierarchy in which to work with. Given the additional adaptations derived from the original Kawai-tsugite joint, a spatial system of point, line and surface offer a spatial hierarchy with which an organizational structure can rest.

A successful architectural defense installation shows the ability of the investigative process and making methodology paired with digital process and fabrication techniques to yield a detail able to generate an architecture.

Further Study

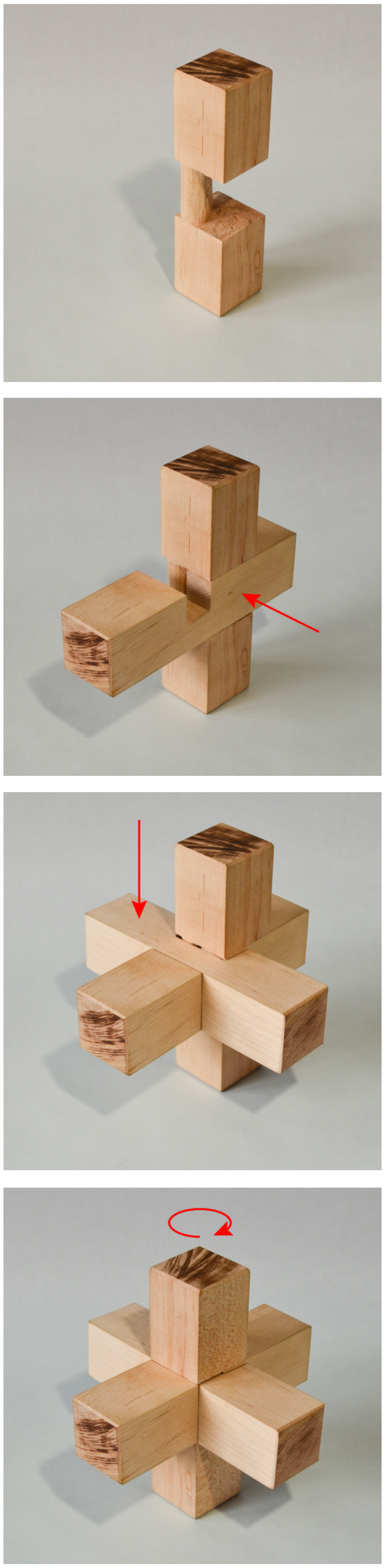
Further study is required to fill some gaps left within the investigation. Although a large part of the thesis was to explore through making, this occurred within the physical 3D realm with fabricated artifacts. Continuing this investigation within the digital realm would provide more indication as to the potential of the joint to generate and modify space. As the investigation was started by the abstraction of the connection of components, a script could be written using that abstraction data to explore further the abilities and possible capabilities of the Kawai-tsugite detail to generate space and architecture.

Similarly, new materials and techniques could be explored within the making methodology that could provide additional support to the network or alternative solutions. Such material investigations should include the ability to mill out of solid aluminum and the effect that has on the strength of the joint, as well as the assembly. Using ANT, the relationships between these actors would change and would be an interesting dialogue between the materials and methods discussed in this thesis.

APPENDIX

Japanese Joints

Sampo-gumi-shikuchi

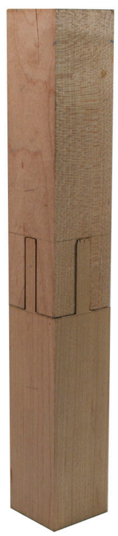


Sampo-gumi-shikuchi joint that shows its process of assembly.

The Sampo-gumi-shikuchi joint is the intersection of joining square sectional wood stock in the three directions of a Cartesian plane. The result of three individually cut and carved pieces, they go together in a specific order with the final twisting motion to lock all pieces into place. Working with the hardwood maple, getting clean pieces that had a sufficiently low tolerance of movement was difficult.

Three iterations were needed to arrive at an acceptable joint. Iteration one proved an exploration into the exact pieces and workings of the joint. The second iteration was to improve upon the starting piece with the quarter section of dowel using a mill drill and rotating jig to create the round surface. The third iteration used the table saw to optimize cutting straight and true cuts through each piece. The dowel piece was then shaped down using chisels (and a template) to achieve a round dowel piece.

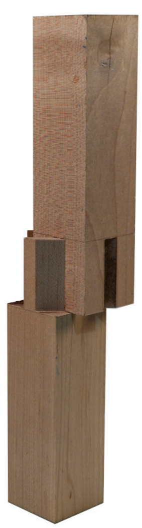
The result of this exercise embodies the thinking through making concept as each iteration informed the next 'prototype' by ways of working with the material, exploring alternative tools to forming the material and refining the use of these tools to produce a piece of craft and aesthetic quality. Although seemingly simple in principle, the act of using tools like the chisel starts to explain how wood is comprised. Moving the chisel with the grain of the wood is not always precise although it is easier than cross grain. Most important, however, is the sharpness of the chisel itself, as the sharper it is the easier it is to carve away the material. This leads to the next point, a question of time. It takes time to carve away the material by hand; using tools to get most of the way there is helpful, where the 'human hand' can finish the last 10% as is the case with the last iteration.



It should be noted now that at the time of making, the pieces that comprised this joint fit tight and snug so much so that the rotating action was hard to accomplish without great force. As the joint stands now, it is quite easy to rotate and in fact all the pieces show greater tolerance with each other. This is due to moisture content in the wood and starts to talk about one of the issues in using an organic material and attempting precise low tolerance joints. There will be more on this topic in the upcoming chapter.

Shihou-hozo-tsugi

This joint was a quick experiment using a table saw and jig to recreate. A simple form, this joint implies movement in a vertical direction, different to the direction of actual movement. Used for specific areas in which room above or below was not an option, this piece could slide in from the side to provide a secure joint.



Horizontal movement in the Shihou-hozo-tsugi joint.

> The knowledge (when not the mastery) of the building techniques was always implicit in the idea of producing architecture… The invention of form is also the invention of its construction. (Schröpfer and Carpenter 2011, 8)

It is clear this joint holds more information than meets the eye, but clearly one needs to see it and construct/deconstruct or move the parts in order to establish its true use and function.

Shippasami-tsugi

This joint uses the ship lap joint as a base and adds a key in which to lock it in place in all three dimensions; x, y, and z. Both pieces are identical in geometry, allowing for the symmetry of the joint to produce an nice aesthetic. At the same time the joint is designed to resist the forces applied to it in all directions.

The parts and the process of putting the Shippasami-tsugi joint together.


Glulam lamination made of 1/2" plywood strips.

Glulam Structure

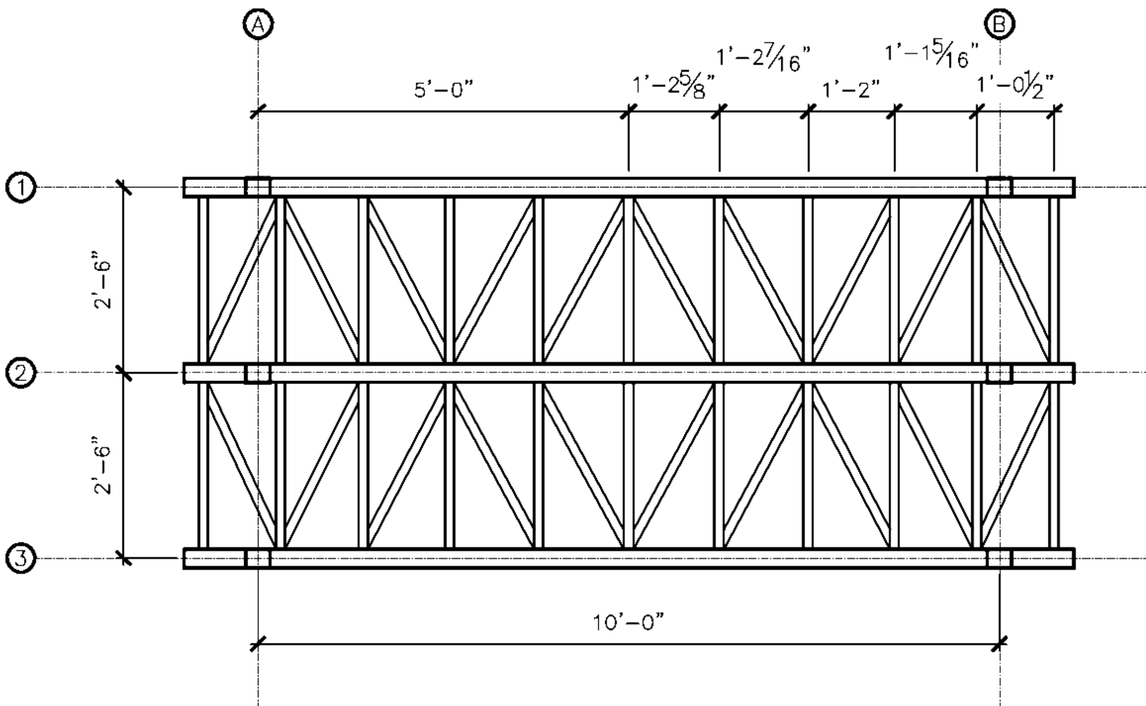
Group Members: Celine Cobenter, Eric MacDonald, Matthew Kijewski, Nahla Al Dhobaib, Sam Lai

1. Type of Structure and useful reference:

Bentwood glulam beams are a type of structural timber. They are made up of layers of plywood, bent into place, and held together by a durable structural adhesive. Glulam beams allow for larger spans than other woods or timber. Because of the strength of each member, we are in fact able to use less wood overall, and beams can be smaller in width, without compromising their structural value. Glulam beams are especially frequently used in sports structures, as they allow for large open spaces, and are quite light in comparison to structural steel.

2. Description of key dimensions and assembly

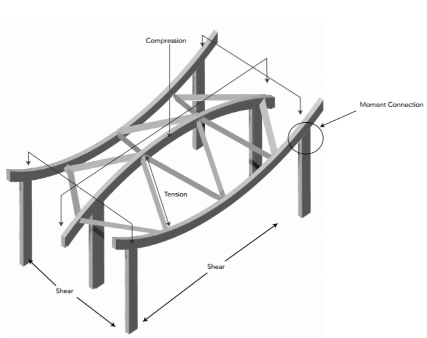
Our concept was designed to span 50' and included a bay of 12.5' (two bays were needed to complete the structural model. The model at 1:5 scale contained curved beams with a 2"x6" rectangular cross sectional profile. The columns on which the beams sat were also glulam, measuring 2" thick and 4" wide, which were created with a U-shaped connection to the beam and fixed a moment connection by 4 ¼" bolts. Triangulated bracing provided the diaphragm for the structure using 2x2 dimensional lumber. This triangulation was carried down through between the columns to provide the lateral shear. All the glulam components were made with ½" thick plywood strips that were glued together over a jig to create the curve. The 1:5 model was slightly over designed due to the dimensions to be able to work with, as the secondary structure members were slightly bigger than needed. These members were easily secured to the beams using a mitered edge and a screw to hold it in place.



Plan drawing of glulam structure.

3. Description of expected structural properties:

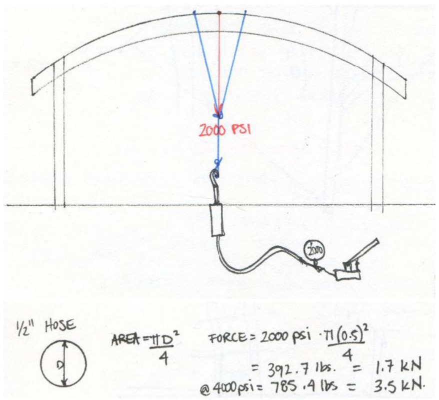
Our design consists of 3 glulam beams and 6 glulam columns, the columns are connected to the beams through moment connections. The beams, in turn, exert compression on to itself and the columns. The moment connections prevent the columns from torsion as the beams press down on them. Purlins are added to prevent shear within the structure.



Forces acting on the structure.

Tension forces are also acting on the purlins as they hold together the beams.

4. Testing Method



Pressure applied to the structure at its breaking point and the calculation as to the force applied.

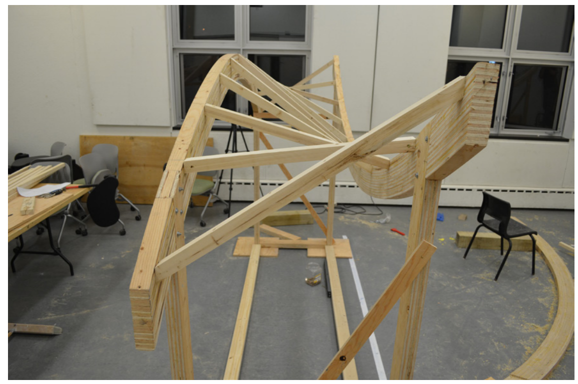
During the first round of testing, a chain was wrapped around the three beams; a collar tie was added to provide more support and help distribute the pressure more evenly. After removing the collar tie and focusing the loads on the central beam, the structure held up till 2,000 PSI and continued cracking to the point where we stopped the test at 3,000 PSI. In comparison with other structures, our project has held up fairly well. Since the central beam was stretching downwards, the side purlins/diagonal braces were pushing outwards and were detaching from the columns. However, the columns themselves were holding very well which is a testament to how strong the moment connection that we attempted to create was.

Our initial prediction was that the purlins were the weakest part of the structure as they were connecting to the beams in the middle, so we predicted that they would push the beams outwards and cause the structure to fall. We also assumed that the moment connections between the columns and beams would most likely fail; however, it was the most stable point of the structure.

We concluded that a reconsideration of the placing of the purlins was necessary in order to achieve a stronger structure.

Sketch models showing how triangulation of a surface can be achieved, allowing the resulting undulating surface to be coverable.

Formwork for all 3 bent glulams.



Halfway done structural triangulation.

Bay Elevation

Side Elevation

Interior Space

Exterior Perspective

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