

Tooled

An Exploration of Craft, the Tool and Emergent Trends in Wooden Architecture

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Abstract

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Throughout all cultures and histories, we are linked by our need and desire to build. We construct homes and shelters, community buildings for meeting, storage and commerce as well as monuments to governments and gods. We have progressed from humble beginnings in vernacular dwellings to the complex edifices we dwell within today. Throughout history we have built with the materials that were available to us and that were made workable with the tools at hand. Wood has always been an obvious choice in communities and cultures where it was abundant. With an understanding of its basic material characteristics, pieces of wood can be worked with only the hands and body by stacking, breaking, bending or weaving it to shape a desired form. With the aid of the most basic of tools, wood can easily be transformed into more complex and beautiful structures that are expressive of its material properties and the processes that shaped them.

The tools we have used to manipulate wood as a material for construction have evolved dramatically since early civilizations first began to build. Each of these revisions, or additions, to the builder's toolkit have resulted in changes to the shape of wooden buildings and the wooden connections that make them possible. From tools of stone and bone, to technological advances and refinements of

tools of iron and steel, the evolution of our toolkit has historically marked changes in what we build and how we build it. In recent history, the implementation of computer aided design and drafting (CADD) software as well as computer aided manufacturing (CAM) has driven dramatic changes to wooden building shapes and assemblies. Changes to the tools we use to fabricate the elements of wooden buildings have enabled new building shapes to emerge, changed how we view wood as a material, and made building with heavy timber economical again. Understanding the evolution of wooden construction as it relates to the tools available to architects and builders is an essential part of understanding how to leverage new developments in wood technologies, re-interpret wooden joinery and traditional building methods and build more often and more expressively with wood.

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INTRODUCTION

I Background

In an essay entitled, "The Architect and the Machine", Frank Lloyd Wright asserts that "the Machine is the architect's tool – whether he likes it or not. Unless he masters it, the Machine has mastered him" (Wright 15). In this work, Wright discusses the prominence of automation and ubiquity of tools driven by electric motors and combustion engines at the turn of the 20th century. He supposes that embracing these emerging technologies is necessary as they are an unstoppable force that will inevitably be a part of the building industry whether they are adopted by architects or not. This sentiment can be useful in describing our relationship as builders and designers with any new tool (or technology) throughout history. The tools we use to make and build have served to both limit and enable our successful manipulation of any materials. Tools do what they have been designed to do well, and they do other things less well by the very nature of their design. Furthermore, by choosing a particular tool, we agree to view a material through the lens of how our chosen tool can act on that material; we thus tend to neglect other possible outcomes of our actions. As Malcolm McCullough describes in his book, *Abstracting Craft*, "A tool directs your attention. Its function becomes your focus: as the saying goes, when you hold a hammer, all the world looks like a nail. Its function extends some powers of your hand, and prevents the use of others" (McCullough 59). A tool requires us to understand both the physical properties of the material to be worked upon as well as the tool's strengths, weaknesses and capabilities; the specialization of that particular tool. As Wright suggests, we master our tools "by learning the nature of them and, by practice, finding out what and how they do, what they do best" (Wright 19). The evolution of the tools we use to shape, manipulate and manufacture wood and wood products in architecture and construction has had a distinct impact on the shape and form of wooden buildings present in our built environment.

For centuries, buildings have been constructed using wood as the primary structural and material constituent. From small vernacular structures to heavy timber halls, churches and homes; wooden

building technologies have been driven largely by the tools available for splitting, sawing, carving and shaping wooden members. Since the first use of primitive cutting tools, such as stone and bone, to act on wood as a material for craft and making, our built environment has evolved along side the evolution of our toolkit. New technologies initiated change, innovation and development of new forms from this primary material.

From the rise of steel and concrete as primary materials for modern construction with the introduction of modernism and minimalism in the 20th century, to the prevalence of balloon and stick framed buildings during the residential boom of the 1950s and 1960s, wood construction has been challenged by the economy of new technologically advanced processes and materials. The development of engineered timber and the implementation of computer numerically controlled (CNC) machines has changed the scale, speed and manner in which we build with wood as a building material as well as how we harvest and manufacture wood based products for construction. The incorporation of digital fabrication and representation into the workflow of architectural design, education and construction has changed our built environment and had a significant impact on what we deem possible and viable to build with wood. In the 21st century, we are experiencing a revolution of computer aided manufacturing and design that is revitalizing the timber building industry with new shapes, engineered materials and structures that would not have been realized without these changes to the architect's toolkit.

II Methodology

Computer numerically controlled (CNC) manufacturing has been around for over half a century. First adopted in the industrial manufacturing sectors and aerospace industry; architects and engineers were slower to make use of this next step in designing and building. As Don Norman evokes in his book, *The Design of Everyday Things*, "technology changes rapidly, but people and culture change slowly.... Much of daily life is dictated by conventions that are centuries old, that no longer make any sense, and whose origins have been forgotten by all except the historian" (Norman 268). The woodworker's

workshop has looked essentially the same since the 16th century. Until the introduction of steam, gas and electric tools, the nail and the two-by-four during the early 20th century, sawyers and builders manufactured wood as a material and constructed just as they had for hundreds of years. In order to fully understand the implications of digital design and fabrication in the wooden building industry, it is important to understand what has been lost and gained historically in building with wood. By developing both, a history of wooden construction as it relates to the tool, as well as a catalog of construction methods employed in timber framed buildings, the reciprocal relationship between the evolution of tools, making, culture and building can be illustrated. This thesis addresses the evolution of the tools employed in the fabrication of wooden building parts and joinery and seeks to draw correlations between the implementation of digital fabrication and manufacturing, the evolution of woodworking toolkit, and our modern relationship with wood as a building Material.

PART 1: MAN THE MAKER: *HOMO FABER*

1.1 Stone, Bone & Wood

Wood has been utilized by human civilizations since our early beginnings as an effective and plentiful building material. "Hand-eye coordination distinguishes humanity as the maker of things: *homo faber*. It is our talent to bring a mass of raw material into conformity with a vision. We fashion tools and coax materials" (McCullough 32). From humble beginnings in what we now call vernacular shelters of buried wooden post and lashed beam; tools and our emergence as *homo faber*, man the maker, has cultivated a growing relationship between man, wood and tool as they relate to our built environment. Beginning with chipped rock and bone, we first realized that we could affect the



Figure 1.1 - Frontispiece to Marc-Antoine Laugier's *Essay Sur L'Architecture*

world around us with more than just our hands. Our relationship to wood as a building material dates back thousands of years to the first shelters and community structures of early civilizations. As the Renaissance architectural theorist Marc-Antoine Laugier supposed in his *Essay sur L'Architecture* [1753], man's first wooden structures were most likely built with only our hands as tools, built from sticks and branches; "pieces of wood raised perpendicularly, give us the idea of columns. The horizontal pieces that are laid upon them, afford us the idea of entablatures." When human beings first buried a wooden post in the ground and lashed branches to the post to fashion a simple roof, they acted upon their environment in a way to form space, shelter, protection and community. Our use of wood as a material for structure has by nature always been related to the tools available to us to cut, split, weave, carve and shape wooden members to fit our desired purpose. Early humans split logs with stone, wood, antler or bone as wedges; used chipped bone and stone to carve and shape wood, utilizing the tools available to

them to improve on the basic vernacular shelter Laugier (allegorically) describes in his essays. The most basic of cutting tool, chipped pieces of bone or stone were used to chisel away at wood, to slowly carve and shape it into appropriate sizes and shapes for building elements. It is with these tools that we first began to join pieces of wood together to form progressively complex wooden structures and arrangements.

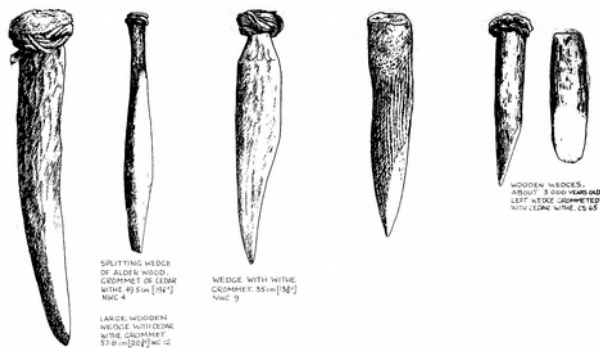


Figure 1.2 Native American Hardwood Wedges. (Source: Hillary Stewart's, *Cedar: Tree of Life of the Northwest Coast Indians*, pg. 31)

The shape and function of timber joinery is governed by both the tools available to the builder and their skill as a maker. The mark of a particular tool can often be seen in the form of a timber structure. A tool may leave its mark in the choice of a particular joint or connection, or literally in the striations and cuts left behind on the surface of the finished material. Before the invention of the saw, Neolithic craftsman used the edges of flint flakes to slice and carve material. These tools were useful for

skinning animals, cutting furs and cordage but were ineffective at sawing through thick materials such as large pieces of wood or hard materials such as stone (Jones & Simons 11). In place of the saw, early builders employed tools that benefited from sharpened or hammered edge of bone or stone: the axe and the adze.

Wooden structures in Native American cultures throughout North America serve as an ideal point of embarkation to discuss the development of tools in wood construction in stone age societies and primitive building technologies. Although there is evidence of metallurgy in Native American communities dating back thousands of years, these metals were not commonly used for tools. The primary metal available to them that was easily worked in a wood-coal fire was copper. Native Americans may have deemed copper too precious, retaining it for jewelry, ceremonial weapons and other crafts.

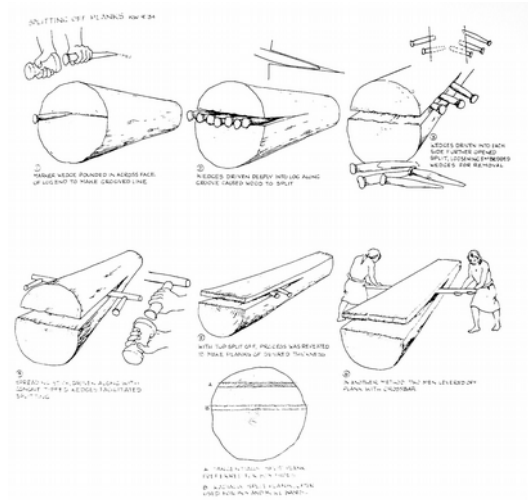


Figure 1.3 – Method for Splitting Cedar Logs (Source: Hillary Stewart's, *Cedar: Tree of Life of the Northwest Coast Indians*, pg. 41)

Woodworking implements found at archaeological sites of Northwest Coast plank houses are generally stone tools such as the axe or adze (Ames et al 14). Because of this, the methods employed in working with wood as a building material by tribal communities in North America used similar materials and tools; those readily available to them in nature to construct their homes and shelters for thousands of years. Archaeological evidence of their building practices is thus suggestive of how these stone and bone tools may have been employed to affect new ways of building and working with wood. In an article published in the *Field Journal of Archaeology*, "Household Archaeology of a Southern Northwest Coast Plank House", researchers from Portland State University assessed the cost of labor and time associated with building a Northwest Native American cedar plank house. The research revolves around the Meier site near the confluence of the Willamette and Columbia rivers, dating the dwelling to two periods of

construction in the 14th and 18th centuries (Ames et al 275). The plank houses of Northwest Native Americans exhibited a particular relationship between their structural form and the tools and practices utilized to build them. The primary structure was composed of buried post and beam construction that was lashed into place with woven cordage or roots. The cladding and roof construction was made possible by the particular technique used to split large cedar logs into long planks using stone, bone and wood wedges (Stewart 36). "The native peoples of the Pacific Northwest developed a rich tradition in the applied arts, fashioning artifacts from baskets to buildings using the products of the cedar tree. Monumental post and beam longhouses, incorporating towering totem poles, were potent symbols of status, kinship and the veneration of ancestors" (Taggart 14). The cedar tree was utilized by tribes throughout the Pacific Northwest as a material for all kinds of crafts. As botanist and author Hillary Stewart describes in her book, *Cedar: Tree of life to the Northwest Coast Indians*, "in a culture where so much of daily life depends on wood, all men – for woodworking was solely a task for them – acquire a well rounded knowledge of the art" (Stewart 29). Wood was utilized in all its forms as a building material. The bark was used as both cladding, cloth and cordage; cedar logs were used as structural posts or were split into planks using hardwood wedges. The wedge, chisel and adze were the primary shaping tools of Native Americans. "As a result of woodworking with the versatile cedar for thousands of years, generations of woodworkers devised and perfected various technologies for felling and transporting trees, splitting and cutting planks, joining pieces of wood together, steaming and bending

wood and sanding finished products" (Stewart 36).

These techniques relied on, and were made possible by, both the inherent properties of the splitting and cutting tools used, the techniques used, as well as the particular material properties of the pacific and yellow cedar used by Native American craftsmen.

Cedar and other wood products were also used to make cordage and textiles, woven into baskets,

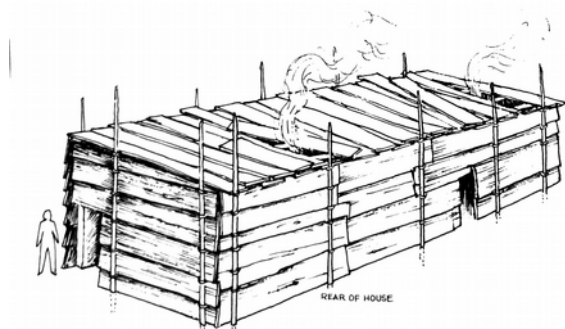


Figure 1.4. Coastal Salish Shed Roof Plank House (Source: Hillary Stewart's, *Cedar: Tree of Life of the Northwest Coast Indians*, pg. 64)

carved or burnt out to make canoes and a variety of other tools, decorative and useful items. Each technique and tool involved in the production of each of these products lent to the creation and development of the forms and shapes of the products that they created. In the case of plank houses, stone, bone and antler wedges were driven into cedar logs. The straight grain of the cedar lending particularly straight and flat planks that could be fixed as cladding to logs and poles buried in the ground (Ames at al 276). Early Native American cultures of the Pacific Northwest utilized rudimentary chisels and wedges to make complex, lasting and renewable structures out of wood. Their construction practices exhibiting many traits of ancient building techniques: Lashing and tying building elements together, splitting and forming joinery with stone and bone tools. The implementation of such tools allowed them to move beyond stick and debris shelters and create lasting, secure and arguably beautiful structures out of wood. The splitting and carving tools of the Pacific Northwest Native American tribes afforded their makers the ability to form straight planks from wood, carve post and beams with axe and adze and weave bark into cordage for lashing and weaving. The tools available to them not only dictated what they were able to build, but lent themselves to creating a type of building that was related to the processes and technologies that made it possible. Their tools suggested a building type related to the needs of their culture as well as the requirements of the materials available to them.

1.2 From Copper to Iron

The principles of abrasion man understood from making fire. The friction caused by rubbing two pieces of wood together will eventually make sparks and embers that can be used to start a small flame so that a fire can be kindled. Fire itself was used as a tool for boring into or hollowing out a piece of wood, a process useful in making products from bowls to boats. This principle of abrasion and eventually the principle of serration were the first thoughts that sparked the invention of the saw. In their book, *The Story of the Saw*, Peter d'Alroy Jones and Eric Norman Simons track the development of the saw throughout human history, noting that changes in this tool's technological capabilities had a great impact

on human life and cultural changes throughout history. "The basic principle of sawing was first devised in the pre-metal age. Neolithic man adapted as tools the objects he found around him; he cut crude and un-even notches or serrations in the edges of flint flakes" (Jones & Simons 1). The development of metallurgic processes was a necessary technological development across many fields of craft that broadened the scope of what man could make. The invention of the metal saw enabled the invention and realization of so many other technologies, particularly, one of the most important events in the evolution of technology; the wheel. The saw was necessary to cut complex and accurate shapes from wood. The invention of the wheel required the use of a saw in order to accurately process rough wood into particular shapes. Thus, as Jones and Simons suppose in their work, without effective timber saws, the wheel would not have been possible to construct. The development of the processes necessary to produce copper and iron were essential conditions that allowed the wheel to be imagined and realized (Jones & Simons 13).

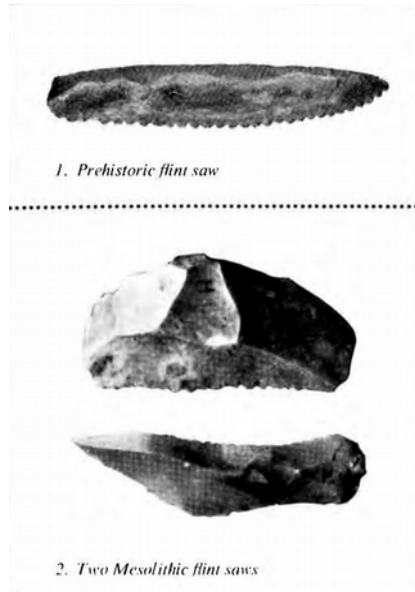


Figure 1.5 - Early Flint Saws (Source Jones and Simons, *Story of the Saw*, pg 12)

Early saws were made most commonly of copper. Copper was easily worked in wood-coal fires and could be hammered into desired shapes with the aid of a heavy rock or mallet. In Egypt, for example, the earliest saws "were made of hardened copper, and date back as far as the 3rd Dynasty (or roughly 4900 to 4700 BC). They began as large, round, crudely serrated copper knives with the teeth sloping in no particular direction, not raked, and therefore cutting in both directions" (Jones & Simons 13). As trade routes across the world became more traveled, the addition of tin and other metals made possible the development of more precise saws of bronze and more rarely of iron. It is important to note that both changes to the strength and hardness of the metal as well as the shape and arrangement of the teeth of the saw had a great impact on what they were useful for making. Although stone was a

more plentiful resource in ancient Egypt, evidence of advanced wood joinery such as tongue and groove and mortise and tenon joints can be seen in their shipbuilding and later in the complex carving associated with the making of wooden sarcophagi.

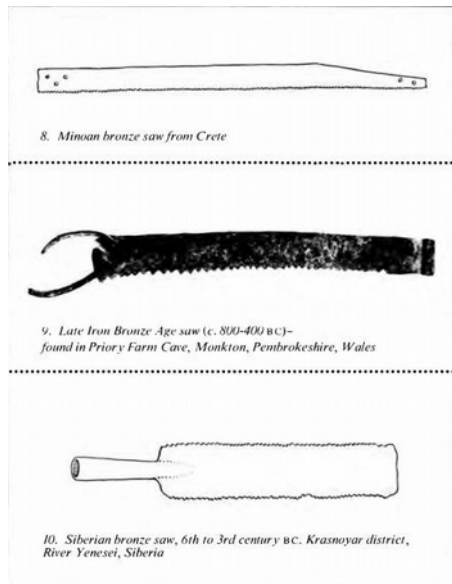


Figure 1.6 - Saws of the Bronze Age (Source: Jones and Simons, *Story of the Saw*, pg. 16)

The axe, adze and chisel as well as these hand held saws of copper and bronze changed little until nearly 500 BCE. Greek and Egyptian craftsman developed wooden joints for making ships and wooden members for roofs to cover their temples made of stone, but, when compared to the Romans the Greeks contributed little in terms of technological innovations (Jones & Simons 15-16). Innovation, when it came to technologies in metal and working with stone and wood, would come from the Romans. "In Western civilization, the Egyptians (as seen in their surviving wood furniture) and the Greeks (as seen in their roof structures) are known to have possessed

advanced wood joinery techniques. The Romans developed these further building complex wooden geared water wheels, arched wooden centering for the construction of vaults and domes, and complex catapults and other machines of war" (Brown 84). Although the Romans utilized traditional copper and bronze saws to cut both stone and wood, big changes to the shape, construction and use of the saw came with the introduction of iron production (Jones & Simons 16). Traditional copper and bronze saws of the Egyptians and Ancient Greeks saw little change until the advent of the Iron Age. "The Iron Age (from about 500 BC to 50AD) brought definite improvements at the time quite apart from that of future development in steel. First, the Iron Age saw the general introduction of the raking of teeth to give a cut in one direction only on the pull stroke, so the teeth were raked towards the handle" (Jones & Simons 17). This was a great advance over the haphazard un-raked teeth of early saws.

The development of iron and eventually carbon steel marked a new era in tool design and defined new shapes that could reliably be cut and shaped out of wood. New types of saws were developed, specifically suited to particular tasks to enable craftsmen to create and cut with a level of accuracy and efficiency not previously possible. During the Iron Age the parts of a saw were defined very much as they are today. The teeth were raked in one direction on a saw meant to rip along the grain of the wood; a saw which was meant to cut across the grain was made without raked teeth so that it could chisel away at the wood's fibers and be pulled from both sides, as in the case of a thwart saw or frame saw. The benefits of providing a channel for waste material to be removed from the cut, a kerf, were also identified. Without some means of removing waste material, whether cutting wood or stone, a saw will catch or clog the cut. "Three ways are known of tackling this problem: first, the kerf can be expanded with wedges (a method of the old pit-sawyers and of tree-fellers); second, the back of the saw blade can be made thinner than the toothed edge (as in 19th century compass and keyhole saws); and third, the teeth can be set or bent very slightly to right and left alternately." (Jones & Simons 18). These successive improvements to the saw sparked the development of types of saws suited to particular specializations. Tools specializing in a particular cut or task allowed builders to work with a level of precision in wood not previously possible with more crude copper, bronze or stone tools. These improvements to the saw were mirrored across all types of tools that could be refined as a result of the addition to iron and eventually carbon steel to the craftsman's toolkit

1.3 The Craftsman

Although changes to the saw had a broad impact on how we fundamentally work with wood during the iron age throughout Europe and the West, all tools benefited from the precision of newly honed technologies in metal production. Metal smiths continued to work with iron and "it is possible that when converting bloom into wrought iron, early craftsmen may have superficially carburised the iron by continual charcoal heatings between the hammerings, and made steel this way" (Jones & Simons 16).

The carbon from the coal fires was absorbed by the iron in this process and the first carbon steel tools were formed. Carbon steel is harder than iron but can still be sharpened to hold an edge quite easily.

This development, happening around the world throughout the Iron Age, brought on a new age of

specialization and development of tools already in existence. The saw had replaced the axe as the primary means of felling and processing a tree, creating a process for producing a number of uniform building elements quickly and economically. Straight, roughly planned rectilinear pieces of wood could be manufactured for building components. The axe and adze would still be used to shape and form large posts and beams while the chisel would be refined as a carving tool and the plane could be introduced as a new tool for surfacing and finishing wood. "In the earliest times wood was probably roughly trimmed with an adze and then smoothed with a stone, using sand as an abrasive. This method was the one most probably used by the Ancient Egyptians, skilled woodworkers who were familiar with the mortise and tenon joint" (Stanley 1). Early advances in planing, chiseling and shaping with iron and steel tools allowed for development of both more specialized and advanced tooling as well as more complex joinery between wooden elements. The earliest known planes were essentially a chisel-like tool inserted into a block of wood. Planes were found in Pompeii that date back to 79 CE. "The Pompeii planes had a wooden case sheathed with an iron plate about 1/4" thick. The mouth was cut about a third of the way back from the front, and the iron, set at an angle of about 50 degrees, was held with a wedge against a round iron bar across the opening" (Stanley 2). The woodworking tools employed by Roman craftsmen allowed for a new level of complexity not possible before these evolutions to the woodworker's toolkit.

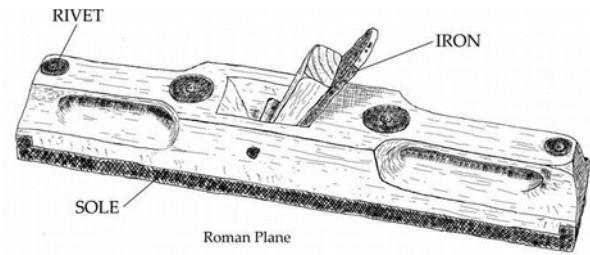


Figure 1.7 - Rendering of Roman Plane (Source: Stanley Works Ltd., A Brief History of the Woodworking Plane)

When attempting to study the effect and development of tools and technology on our built environment and our relationship with craft, it is important to note the particular case of Japan. The joinery seen in Japan today "represents the survival of an extremely archaic way of building, a kind of

living time capsule" (Brown 86). A culture cut off from the developments of the western world but influenced by technological changes in Chinese culture and other influences throughout Asia and the Middle East, Japan offers a unique snapshot into a culture that has not only worked with wood as a primary structural element in their buildings but also venerated and honored the material culturally as a way to remind oneself of our place in the natural world. "It may be argued that even in the millennium before Christ, Chinese joinery techniques were more advanced than their Western counterparts. Although dynasties changed frequently, there was a cultural continuity in all fields in China unmatched in European culture, reaching one peak during the Han dynasty (AD 0-200) and another during the Tang (AD 600-900)" (Brown 86). Japanese craftsmen have been influenced by the melting pot of Chinese and Korean culture in ancient Japan. "The complex joinery practiced by Japanese carpenters during the building of the early temples like Yakushiji represents the state of the art in early Tang China, as distilled once by contemporary Koreans and again by builders on Japanese soil" (Brown 86). Japan has culturally prized the work of the hand through various religious viewpoints that have their origins in Buddhist, Taoist and Shinto beliefs and has cultivated a particular relationship with craft and working with natural materials through these belief systems.

Wood has the ability to inspire a connection to our natural surroundings, remind us of the passage of time and our place as a part of nature that is unique among building materials. "This is nowhere more evident than in the traditional buildings of Japan, where the unique characteristics of timber contributed to the evolution of an architecture at once elemental and elegant that both reflected and shaped Japanese culture for more than 1,000 years" (Taggart 14). Outside of western culture, wood construction has been a staple and often a primary means of building for millennia wherever the material was plentiful. In Japan, wooden buildings have served as the major form of dwelling for thousands of years and the country has developed a rich culture of craft and construction around the beauty, durability and quality of wooden joinery and craftsmanship. Japanese temple construction has been documented as far back as 500 AD when Buddhist influences from China and Korea sparked a cultural renaissance in

the fine arts, including architecture. "Exactly how many of the early Japanese temple builders were native Japanese is open to debate.... Horyuji temple was based on an ancient Korean Shaku scale, and Yakushiji on a Chinese scale, their master carpenters may have been Korean and Chinese respectively" (Brown 86). Temple construction from this period took much of its influence from the Chinese architecture of the time but Japanese architecture developed on its own to embody a particular relationship with wood as a valued and honored material, and to develop tools, techniques and styles meant for shaping wood and wooden dwellings as a common means of construction.

Until the late 19th century, the Japanese carpenter employed tools that had remained fundamentally unchanged since the Tang dynasty. The axe, the adze, the chisel and block plane; saws specific to ripping, crosscutting or doing precision work, all contributed to the craft and design of the Japanese temple, tea room and home. Emerging from humble roots as pit dwellings and elevated storehouses, the Japanese house evolved into an elegant and open structure, that, during the late 19th and 20th centuries was praised by modernist and minimalist for its openness and modularity. In his book, *Japanese Homes and Their Surroundings*, Edward S. Morse catalogs his experience with the Japanese at the turn of the 20th century. "The frame-work of an ordinary Japanese dwelling is simple and primitive in structure; it consists of a number of upright beams which run from the ground to the transverse beams and inclines to the roof above. The vertical framing is held together by either shorts strips which are let in to appropriate notches in the uprights to which the bamboo lathing is fixed..." (Morse 14). Although Morse viewed Japanese carpentry as somehow still rooted in the primitive when compared to the rigor of English and American timber work of the early 19th century, it embraced certain qualities of wood that allowed it to express openness and highlight the connections of structure members throughout the frame in a way that western architecture did not. As stated by Malcolm McCullough in his book, *Abstracting Craft*, "in comparison with European practices, the Japanese crafts traditions held a simpler and more sympathetic relation with natural beauty. This was quite an important lesson to Westerners of the time, and many notable designers such as Frank Lloyd Wright were overtly affected" (McCullough 245). In

many ways it can be argued that Japanese carpentry surpassed that of its western counterparts when considering the expressive nature of both joinery and material. In Japan, the carpenter focused on his material, mainly Japanese cedar and cypress, and it's relationship with the tools necessary to work it. While the waterwheel powered saw mill had been prominent in Europe since the twelfth century (Lucas 10), Japanese carpentry relied in the use of hand tools and manual labor until the late 19th and early 20th centuries when steam engines entered the country due to westernization and trade. Due to this late onset of westernization and contact with the western world. Japanese carpentry developed independently from Europe and the United states and in doing so retained a level of roughness in natural form while perfecting the precision of wood joints beyond that of European craftsmen. The fact that Japan escaped industrialization until the late 19th century solidifies the idea that the nature of Japanese carpentry is at once derived from its tools as well as its material. The Japanese Cypress, particularly is not only "strong and resistant to decay but is easily workable, and has a fine grain, delicate color, and pleasant aroma" (Brown 24). Japanese carpentry survived without the advancement in tooling technologies experienced throughout the rest of the world. Because of this, they continued to develop and refine a complex relationship, driven by simplicity, between material, tool and maker.

1.4 Wind, Water, Animal

By the fall of the Roman Empire, the tools employed to harvest, process and build with wood had changed dramatically since the time of Greek and Egyptian craftsmen. The age of the axe was gone. Now the saw provided a means of converting roughly felled trees quickly into usable lumber with new found efficiency. The saw now enabled flat, straight and dimensional lumber to be produced by means of

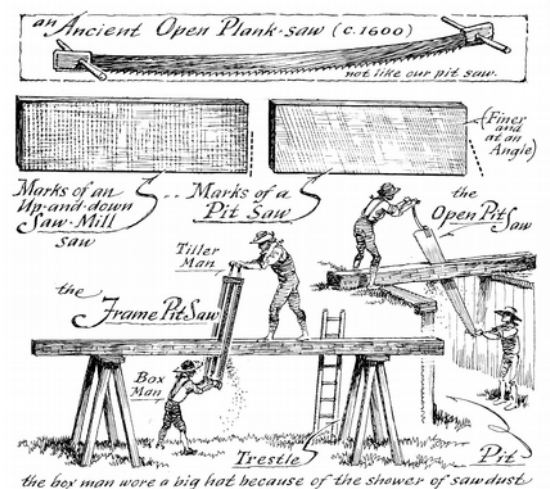


Figure 1.8 - The Pit and Frame Saws (Source: Sloane, E. (1964). A museum of early American tools, pg. 70)

efficient use of human energy. Changes to the application of this energy in the Middle Ages, Renaissance and Victorian Era would change how we define the terms tool, technology and machine and challenge what we believe to be man-made at its purest forms. Outside of the refinements to the nature of the saw's most basic parts, innovations also occurred in the size and arrangement of the saws used for processing raw timber. The development of the frame saw, that braced the blade at both ends to avoid buckling marked yet another improvement on the shape and use of the tool. "This was an ingenious way of avoiding the bending and buckling of soft metal blades by setting the blade either centrally in a frame or as one side of a frame" (Jones & Simons 19). The development of the frame saw marked a moment in history when the size and arrangement of saws used to process whole timber changes. As technology and innovation progressed through the middle ages the open pit saw and paneled pit saw were used widely to convert logs into planks, while early Romans began to employ machinery to convert rotary motion from windmills, water wheels or animal drawn turnstiles into the reciprocating or linear motion necessary to saw lumber (Jones & Simons 20).

The first sawmills began to appear around the world as innovations in metallurgic technology allowed for more precise gearing and mechanisms to be produced. "As for medieval machine saws, they depended for their motive-power, like all other machines of their age, on the treadmills, windmills or water-mills which gave a continuous rotary action" (Jones & Simons 22). Despite innovations in the saw mill, hand tools continued to be the primary method for most builders, as proximity to both the source of lumber and the mill was necessary to benefit from the increase in productivity. Most lumber was sawn close to where it would be used to build and thus the use of pit saws to process rough logs remained a common practice as late as the 18th century. The pit saw developed as a larger version of the panel saw, where both ends of the saw are braced in a rigid wooden panel and two men push and pull the saw to make a cut. The pit saw employed an arrangement where the man below did the majority of the work, using leverage and his body weight to perform its cuts. "The appellations 'top Sawyer' and 'pitman' survived for many years." (Jones & Simons 27). Over the course of medieval Europe, the use of saws

became general practice and were developed further in terms of specialization and variety. "The saw became, next to the axe, the most symbolic of tools. There were five main types of medieval saws, open handsaws, two-handled saws, frame-saws, pit-saws and machine saws" (Jones & Simons 21). The increasing ubiquity of the water, wind and rotary powered mill, dating as far back as the 1st Century, sparked a change in not only what we could make but how fast it could be produced. "It would appear that by the mid-twelfth century, the industrial use of water-power had spread from Islamic to Christian Spain, where fulling mills, paper mills, and forge mills are recorded for the first time in Catalonia. Archaeological evidence from the High Middle Ages suggests that industrial water mills were used in large factory complexes, and that water-powered sawmills were also widespread" (Lucas 10). As Jones and Simons point out in, *The Story of the Saw*, "we have already noticed two remarkable examples of sawmills long before the mid-15th century, one Roman and one Medieval. But like many other technical innovations sawmills were adopted only very gradually, and even as late as the 18th century the pit-saw was still in more general use" (Jones & Simons 23). While water, wind and animal power were innovative in the production of early milling machinery, it was not until the invention of the steam engine that the mill could be reliably and effectively implemented anywhere. "It was the advent of the steam-engine, in the late 18th century, that was the chief stimulus to the widespread employment of woodworking machinery" (Jones & Simons 23). These motive additions to the builder's toolkit began to change how we viewed wood as a material for building as well as how we viewed it as a commodity.

It was in the middle ages that the artisan gained their status more akin to artist than to laborers and we began to develop our modern ideas of craft and handiwork. "In the European early Middle Ages artisans gained rank, for as free men they took refuge in the monasteries... Later, amid expanding urbanization and trade, high Medieval guilds diversified and regulated the supply and demand for a great many crafts" (McCullough 7). It was in these first Medieval guilds that wood became a medium to be worked upon by the craftsman. In *Abstracting Craft*, Malcolm McCullough quotes Denis Diderot's

Encyclopédie (1751-80), a compendium of definitions and descriptions of material crafts from the mid-late 18th Century;

'CRAFT. This name is given to any profession that requires the use of the hands, and is limited to a certain number of mechanical operations to produce the same piece of work, made over and over again. I do not know why people have a low opinion of what this word implies: for we depend on the crafts for all the necessary things in life... The poet, the philosopher, the orator, the minister, the warrior, the hero would all be nude, and lack bread without the craftsman, the object of their cruel scorn'

The guilds embraced the specialization of skill that a set of tools required and focused the maker's energy on perfecting a type of craft. The introduction of machine work into the guild system in the 18th Century and continuing through the industrial revolution set industries against one another as sides formed in opposition and in favor of the machine in the role of the craftsman. One of the era's staunch supporters of handcraft was John Ruskin. As skill became less significant with the introduction of the machine into the world of handicrafts and making, design disciplines embraced the machine for its precision and economy. John Ruskin, stating in his *The Seven Lamps of Architecture*, "the last form of fallacy which it will be remembered we had to deprecate was the substitution of cast or machine work for that of the hand, generally expressed as Operative Deceit." Ruskin found two primary arguments against the practice of producing what had once been made by the hand by the machine; firstly, that all "machine work is bad, as work; the other, that it is dishonest." Ruskin found the work of industrial processes and the machine to be lacking in the basic requisite of human touch. "Ruskin was especially attentive to the role of hands: ' For it is not the material, but the absence of human labour, which makes the thing worthless; a piece of terra cotta, or of plaster of Paris, which has been wrought by the human hand, is worth all the stone in Carrara, cut by machinery'" (McCullough 14). Architects, builders and designers continue to argue about the role of the machine in the works they create up until the present day. Frank Lloyd Wright embraced the role of the machine as a tool of the future; one to be embraced by architects and builders or they would be left behind designing and building in the past. Wright wrote that "the machine has emancipated these beauties of nature in wood; made it possible to wipe out the mass of

meaningless torture to which wood has been subjected since the world began, for it has been universally abused and maltreated by all peoples but the Japanese" (Wright 6). In the 19th century, variants of the water-powered saw mill throughout Europe allowed relatively flat and efficient pieces of wood to be cut into lumber and used for timber framing. This type of wood material continued to evolve and become more precise and efficient with the advent of steam powered engines, and eventually electric tools in the 1920's. The age of the machine challenged the notion of traditional craft and allowed for the production of standardized and uniform lumber to be processed near urban development and be shipped across the united states and the rest of the world. As wind and water power evolved into steam, then the combustion engine and electric motor, the nature of the saw evolved to be both a tool of the hand while also a machine of industry.

PART 2: MAN & THE MACHINE

2.1 Machine Craft

The water and windmill continued to be the dominant sources of power driving the saws of Europe and the East until the development of the steam engine at the turn of the 18th century. The source of power was not limited to how much water or wind there was available at the time but instead driven by how much fuel could be procured; an economic problem as opposed to one of physical availability. The steam and

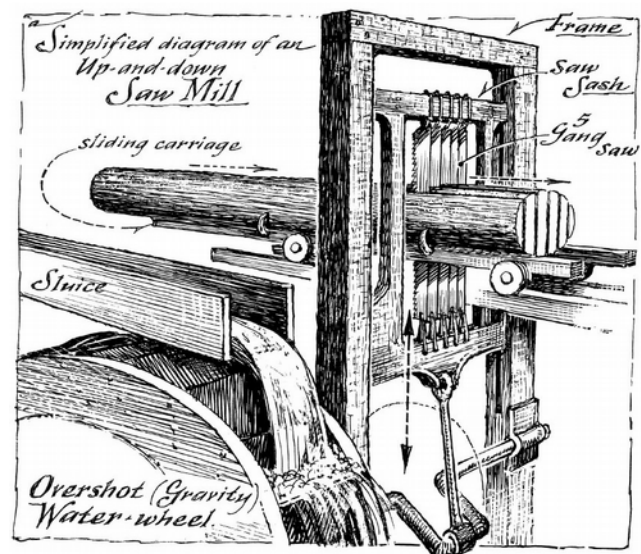


Figure 2.1 - Water Powered Gang Saw. (Source: Sloane E. (1965). *A reverence for wood*, pg. 78)

combustion engine changed the scale of the Western sawmill and furthered the role of the machine in the production of lumber and raw material for wooden construction. This new development in industrial sawmills and timber harvesting was fought tooth and nail by hand sawyers around the world. "In 1803, a

steam-powered sawmill in New Orleans was destroyed by hand sawyers, and about two years later they smashed a mill in Natchez, higher up the great Mississippi river” (Jones & Simons 24). The resistance of workers and craftsmen to embrace the machine mirrored the sentiments of Victorian England as a response to industrialization. “The Arts and Crafts Movement, whose start was signaled by Morris, became one of the more significant responses to industrialism. Its concern for the aesthetic consequences of hasty profiteering may have been socialist in its origins, but its appeal to amateur creativity and taste was ultimately quite democratic” (McCullough 15). People feared greed and unneeded material possessions, calling for a return to the handmade and handcraft while others championed the machine and its efficiency as the road to the future. As Frank Lloyd Wright describes in his essay, *The Art and Craft of the Machine*, “The machine these reformers protested, because the sort of luxury which is born of greed had usurped it and made of it a terrible engine of enslavement, deluging the civilized world with a murderous ubiquity, which plainly enough was the damnation of their art and craft” (Wright 1). The Arts and Crafts Movement fought back against the sentiment that the machine was the solution while Wright described the use of the machine as a craft in itself. “William Morris pleaded well for simplicity as the basis of all true art. Let us understand the significance to art of that word – SIMPLICITY – for it is vital to the Art of the Machine.” (Wright 5). The machine was embraced by many modernist architects and those that practiced the international style, for it made possible new typologies in construction like economy, modularity, and prefabrication but also made new levels of customization possible through advances in precision and production.

The industrial revolution sparked a change in how we procure goods. It changed the quantity of an item that could be produced in a day as well as affected material character, uniformity and challenged the notion of ‘hand-made’ and ‘man-made’. Although handcraft continued at small scales all across the world, the introduction of the machine and rotary engine changed the way in which human beings produced building materials and goods in general. This moment in time marked a divergence from making by hand exclusively and was a time of great controversy in regards to making, plenty, craft and

the economy of goods. These changes were often fought by craftsmen. "Even in the United States hand sawyers were ripping boards until the 1820s" (Jones & Simons 27). The transition from handcraft to machine-craft was a battle fraught with doubt, uncertainty and fear and a battle that is still present in discussions of the arts and crafts movement today.

2.2 Modernism and the World Wars

Architecture's relationship with modernism, technology and the international style is undoubtedly intertwined with the First and Second World Wars. As modernism embraced technology, buildings of metal, glass and concrete became the style of the times. Based on the new technologies that made building with concrete, steel and glass possible, Modernism rejected the decorative traditions of the Beaux-Arts styles and came to reign as the dominant architectural style until well after the Second World War. Wood construction during this time was mostly relegated to the balloon and stick framing made possible by the two-by-four and the nail. With the advent of Modernism in the early 20th Century to the suburban

boom of the 1950's following World War II, the modularity of two-by construction was embraced and building with wood as a structural centerpiece fell by the wayside. As Jim Taggart describes in an article for *The Canadian Architect* entitled "Modernizing Timber Design", "When the International Style caught hold in the 1950s, it brought with it new materials such as aluminum, and a new sleek industrial aesthetic. With the exception of glue-laminated beams, timber technology failed to advance with the times, and for the most part, wood was relegated to use in small, low-tech buildings" (Taggart 14). The role of wood in Architecture during this period was limited. Developments in engineered wood technologies, plywood and glue laminated beams began to emerge as new methods to use wood as a



Figure 2.2 - "Keep that lumber coming!"
Poster for the United States Army by Earle Winslow, 1884-1969. (Source: University of North Texas Libraries, Digital Library, digital.library.unt.edu)

material for building; but often modularity served mass construction and dimensional lumber and plywood were used for the sole purpose of economy and not architecture.

The construction boom of the 1950's only further established wood as a low-tech construction material, meant for quick construction of inexpensive residential and small commercial buildings. In the documentary film, *Modern Views: A Conversation on Northwest Modern Architecture (2015)*, Jeffery Ochsner, a professor of Architecture at the University of Washington discusses the nature of the construction boom following World War II as a culture where people were simply looking for a place of their own. He quotes Seattle Architect Fred Basetti, describing how "an architect could make a living after the war designing 1,200 square foot houses... any Architect who tried to do that today would go broke in 6 weeks" (*Modern Views, 2015*). Industrial building materials were established during wartime markets as the standard for light-framed construction. There were, however architects at the time that sought to embrace wood as an architectural material with interests rooted in the architecture and timber framing of Japan as well as traditional Western heavy timber framing. Architects like Greene and Greene in California embraced the Arts and Crafts Movement and focused on an integrated approach to wood while Northwest Regional Modernism took inspiration from both the Arts and Crafts Movement as well as Japanese influences to create a style that treated wood "not as a utilitarian building material, but as a material to be shown and to be joined in ways that revealed how it ought properly to go together" (Grant Hildebrandt, *Modern Views, 2015*). Northwest Regional Modernism as well as other regional styles of timber construction embraced a construction method where wooden structure was again exposed as it would have been in timber framing or the Japanese tradition. These architects sought to find new ways to work with wood, to join timber and to divorce themselves with the modular restraints of two-by-framing. Fred Basetti describes his reaction to wood as a building material; "I have a feeling in my heart, that a sloping ceiling with the rafters showing, and the texture of cedar boards between the rafters, the reflection off the water, create reflections that are bouncing across the ceiling; it does touch the heart, which the plaster board doesn't otherwise" (*Modern Views, 2015*). In response to the construction boom

of post war America, there was a resurgence of Architects and Builders who viewed wood as a material to be revered and revealed in architecture.

2.3 The Two-by-Four

It is difficult to discuss the progression and future of wooden architecture and the tools used to act on wood as a material without some study of the two-by-four. Before the industrial revolution and particularly before the first World War, lumber was generally sawn and delivered to building projects close to the site of the sawmill. The size and dimension of that lumber was usually not a problem because “the needs of builders in the locality were well understood and carpenters were accustomed to much more hand fitting on the job than they are today” (Smith and Wood 2). As urban centers grew and forest were cut back to make room for growing cities and suburban sprawl, lumber had to be shipped far greater distances. By the end of the 19th century, lumber was not a local commodity. “It then became apparent that the sizes used in different trading areas were not uniform and as a result sawmills had to cut lumber for the markets they wished to serve” (Smith and Wood 2). As the sawmill moved farther and farther from the city center, the lumber industry was dependent on rail cars to deliver vast quantities of timber across the country and the shipping industry to deliver timber internationally and along the coasts. “The lumber taken from old houses is revealing in its variety. By 1900, 2 inches was the most common thickness for joists, rafters, studs, and the like” (Smith and Wood 2). As rail shipments began to encroach on to local markets in the early 20th century, a standardization for lumber became necessary as the companies providing the material no longer understood the needs of their customers. Dimensional lumber sizes are a result of the need to come to a common understanding between lumber mills and distant lumber markets. The first national size standard was put into place in 1924 after World War I. Demand for lumber continued after World War II, leading to large shipments of lumber dressed green to standard sizes (Smith and Wood 1).

Much of our relationship with wood in our built environment today revolves around what we've come to know as lumber; the ubiquitous "two-by" dimensions of standard lumber sizes of spruce, fir, pine and hemlock available at lumberyards and home improvement retailers across the country. The standardization of lumber sizes provided protection and assurances for consumers, eventually resulting in the dimension we have today of 1/2" under nominal dimensions in both width and depth. Due to the standardization of nominal lumber sizes and the demand for lumber in the United States during, and after World War II, our relationship with wood as a material changed dramatically from the early 20th century to post War America. The story of the two-by-four has far reaching implications that relate wood as a natural, raw material for building with the consumer building product that is sold to us by retailers. Timber framing fell by the wayside in favor of two-by construction, metal fasteners, the hammer and the nail. "It is interesting to note that during this period, the economic viability of wood joinery depended upon its low relative cost to other means of connection – metal fasteners such as bolts, nails, and the like – which had existed since the earliest era but were often prohibitively expensive. In the West, this situation changed rapidly with the Industrial Revolution, when both cheaply milled lumber and mass-produced nails became common. By the early twentieth century, architectural wood joinery had virtually disappeared" (Brown 84). There is a semantic difference between purchasing lumber, timber and wood that has a real effect on how that material will be acted upon by a builder as well as by a designer. The nature of this state of wood will be considered at the earliest stages of design and different tools will be employed to manipulate and form these material products into parts of an edifice. Before the 20th Century, the saw would have been the tool most utilized by the timber framer while the introduction of standardized dimensional lumber and the nail championed the hammer as the most useful of tools.

2.4 Twentieth Century Timber Construction

The World Wars sparked a change in the way we produce and manufactured building products. "The United States needed an enormous amount of natural resources to fight World War II. Crude oil for

fuel, rubber for tires, and iron ore and other metals for everything from submarines and torpedoes to airplanes and aerial bombs” (Burns, 2016). Wood was needed for wartime efforts as well, “to build hangars, barracks, ships, trucks, planes, bridges and crates for shipping supplies and ammunition to Europe and the Pacific. It was a jolt to a timber industry hit hard by the Great Depression” (Burns, 2016). Lumber was produced quickly and cheaply with the use of new technologies developed during the War. The timber industry was quickly modernized. “Tree cutting became far quicker and easier because the war helped push the most iconic symbol of modern logging — the chainsaw — into the hands of the Northwest logger. It changed the industry forever” (Burns, 2016). New technologies in logging and milling were quickly employed to keep up with wartime demands and continued to be used after the war to meet the demands of a post-war construction boom.

Today, logging and industrial milling are completely changed from their early 20th Century origins. “With equipment like the feller buncher and the dangle-head processor, one logger can cut a tree down in just a few seconds. Then it only takes a few more to shear off the limbs and cut it to length. The relatively small and light back-hoe type vehicles can maneuver in dense forests, target



Figure 2.3 - Gasoline driven power saw. Tumble Creek fire near Detroit, Oregon. U.S. Forest Service Historic Photograph #409118

specific trees and control their fall” (Burns, 2016). Due to the logging practices of our past, the large trees available to timber framers at the turn of the 20th Century are no longer available. Forests must be expertly managed and cataloged in order to maintain profitability and sustainability for years to come. The smaller size of tree available to use to manufacture lumber and wood products has resulted in the need to rely not only on heavy timber as a means of wooden construction but also on engineered and laminated products in order to most effectively utilize the size of trees available to us for harvest. Traditional timber framing and heavy timber construction, although it experienced a resurgence and

renaissance in the late 1960's and 1970's faces the particular challenge of working with either small members and dimensional timbers or working with engineered or laminated wood. Engineered and laminated wood products offer the benefit of working with wooden members of nearly any size and shape while digital design and manufacturing make it possible to both digitally model and fabricate those members as unique parts of a design or as a prefabricated identical kit of parts.

PART 3: CONNECTION TYPOLOGIES

3.1 Material Properties of Wood

In his book, *The Complete Japanese Joinery*, Hideo Sato begins his discussion of Japanese joinery and woodwork, first, with an introduction to the properties of wood that make it good, or bad, to build with. "Wood is Alive" he starts, "even after trees have been cut, wood continues to respond to environmental conditions.

Before, during, and after construction, changes in the wood's characteristics can have serious consequences for the integrity of a structure" (Sato and Nakahara 33). The expansion and contraction of the cellular structure of wood can vary a great deal throughout a

piece of wood. As moisture moves into or out of a piece of wood it will have a tendency to shrink, warp, or swell. All of this is a function of its moisture content of the wood and will vary considerably as the moisture content of the air changes (Sato and Nakahara 36). How the lumber is sawn will have a great effect on its material properties, strength, and tendency to warp or move. "Lumber with the heart center, the core wood containing the initial annual ring, is the most affected by this. From a single tree, there is one piece with the heart center, the other pieces cut will suffer less distortion the further they are from the center" (Sato and Nakahara 36). The relationship between a board and where in the tree it was sawn from can be determined by examining its end grain.

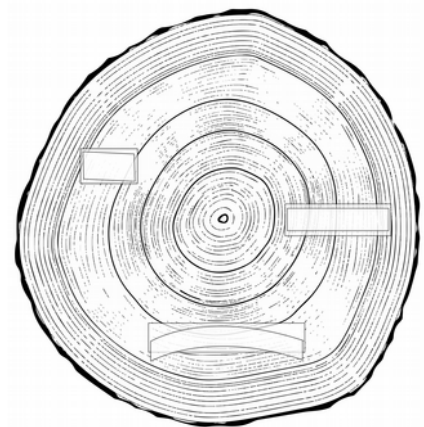


Figure 3.1 - Cupping, warping and shrinkage in tangential, rift and quarter sawn lumber

Today, there are several methods for limiting how much movement will be experienced by a particular board. Timber that has been recently felled is said to be *green*. Green wood is still saturated with water that remains trapped in the cell walls. Green wood is overly heavy, structurally weak and is more likely to fall victim to fungus and insect damage. “The amount of moisture the wood contains as a percentage of the oven-dry weight, is known as the moisture content (m. c.), and the process of reducing the m.c is termed drying” (Porter 18). In order for green wood to be turned into workable lumber it’s moisture content must be lowered to a reasonable level so that it is stable and workable. Historically, logs would be left to soak in water at the mill for as long as two years so that the sap could be removed through a slow interaction between the sap and water. Lumber left in water like this tends to dry more evenly and is more stable (Sato & Nakahara 37). Due to the relationship between moisture loss and a board’s grain pattern, board movements and warping can also be controlled through the method used to mill the lumber. When using wood as a structural element it is necessary to consider the grain direction and orientation of each building component. The most economical way to saw logs is plain, or through sawn, simply cutting the log into several boards in the same plane. These logs will have a grain pattern with an angle to the face of the board measuring between 0-30 degrees. Logs can also be quartered first for ‘quarter-sawn’ lumber that will have an angle of grain from 60-90 degrees and are less prone to warpage, cupping and shrinkage. Quarter-sawn logs also yield some rift sawn boards with a grain angle of between 30-60 degrees to the face of the board (Porter 14). How the log is processed will change how the lumber produced will react to changes in temperature and humidity and affect what the lumber is most useful for.

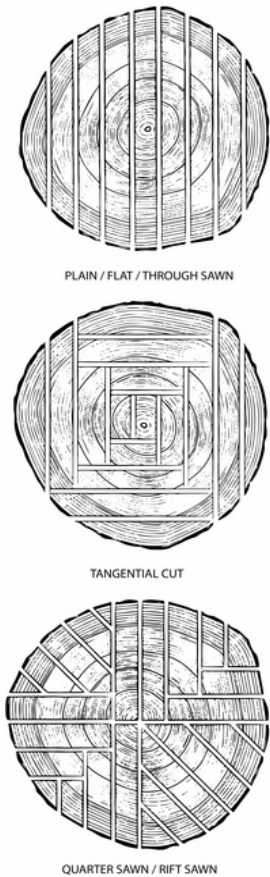


Figure 3.2 - Flat sawn, tangential cut and quarter sawn timber

Sawing techniques used to process lumber from logs can also affect a change in the appearance of the wood. "Figure is best described as the pattern or marking which is formed on the surface of processed timber as a result of wood tissue being cut through" (Porter 51). There is a difference worth noting in the figuring of sawn timber for heavy timber buildings and the homogeneous mixture of pieces formed by gluing together short cuts to make engineered lumber. Exposed heavy timber will display a grain pattern typical of its species, sawing technique and may show signs of checks and cracks as the wood shifts and ages. Engineered lumber conversely, will not display the grain pattern of a single tree, but showcase the manufacturing process that created it; giving clue to its manufacturing process through how the smaller pieces or particulates of wood are arranged and laminated together. Both applications of wood as a building material offer succinctly different but valuable structural and aesthetic qualities.

3.2 Engineered Wood Technologies

Engineered wood products changed the ways in which wood could be used at a variety of levels. From plywood and oriented-strand-board (OSB), to particle boards and glue laminated timbers (Glulam), the addition of engineered lumber made the CNC and other digital tools more viable when working with wood as they are generally stable, uniform in texture and internal forces are distributed evenly throughout the material. The kiln dried lumber used in the production of engineered lumber and sheet materials behaves as a more homogeneous material, well suited for the CNC. Working with lumber that had not been sufficiently kiln dried and stabilized is difficult to do with computer controlled milling machines as the wood will tend to change shape as its moisture content changes. The forces and stress housed within the fibers of the wood can vary based on moisture content and other conditions and are thus difficult to predict when working through a machine. In order to work effectively with a material, the craftsman must understand both the material properties of the material they are acting on as well as the capabilities of the tool they are using. Engineered wood products have been kiln dried and processed

to be structurally stable. They lack the inherent internal tensions that make working with raw lumber particularly difficult and are thus well suited to being processed with digital manufacturing technologies.

The particular type of engineered wood will have a significant impact on the process used to produce building components as well as on the strength and aesthetic of the finished product. The following types of engineered timber have already had a wide array of impacts on the building industry but may offer new opportunities for the pairing of digital fabrication with engineered wood products. Ulrich Dangel's book, *Turning point in timber construction : A new economy*, takes a comprehensive look at the state of wooden construction and engineered wood products in the construction industry and was used as the basis for these definitions.

Glue-laminated timber (Glulam): Glue laminated timber is one of the oldest types of engineered wood products. Structural timber members could be produced that are no longer constrained by the growth limits of trees due to lamination technologies introduced in the last half of the 19th Century. Glulam is produced by laminating three or more individual boards together. These lamination are kiln-dried prior to bonding and have been tested for stresses and joined at their ends with finger joints to form a strong beam or post of nearly any length and cross-section (Dangle 98).

Laminated Veneer Lumber (LVL): Veneer laminated lumber is produced with rotary-peeled veneers like plywood. LVL veneers are laminated so that the grain of the veneers runs in the same direction and the veneers are generally thicker. LVL is thus suitable for beams, trusses, planks and rafters (Dangle 100).

Oriented Strand Board (OSB): Oriented strand board is composed of a loose collection of thin strips of wood, usually lesser expensive softwoods such as spruce, fir and pine. Water resistant adhesives are used to bond the panels together under heat and pressure. OSB is less expensive to produce than veneer plywoods and is commonly used for sheathing, roofing and sub flooring in commercial and residential construction (Dangle 99).

Plywood: Plywood is a general term for any lamination of veneers that the grain direction of each layer is perpendicular to the adjacent layers. Plywood is generally assembled in an odd number of layers to ensure that the grain direction of the outside layers runs in the same direction (Dangle 99). Plywoods are stable panels that are useful in shear as sheathing but can also be manufactured with hardwood exterior for use as interior finishes as well as treated and manufactured to withstand exposure to the elements.

Parallel Strand Lumber (PSL): Parallel strand board is produced from strand of veneer, utilizing waste material from plywood and LVL production, the strands are laid parallel to each other and glued in a press. Species used for PSL commonly include Douglas Fir, Southern Pine, Western Hemlock, and Yellow Poplar. Structural Members of up to 66ft long can be produced using this method. This process produces a product with a large proportion of small voids between the strands, enabling a high degree of preservative penetration, making PSL a good product for exterior conditions. Parallel strand lumber has a high bending strength and is commonly used for large headers, beams, and heavily loaded columns (Dangle 100).

Laminated Strand Lumber (LSL): Laminated strand Lumber is similar to parallel strand lumber but the wooden strands are shorter, more irregular flakes. It can be manufactured using small-diameter trees of faster growing, low density hardwoods like aspen, poplar or basswood. These woods are generally not suitable for conventional sawn lumber. The chips are gathered loosely with a water proof adhesive and cured in a steam injection press (Dangle 101).

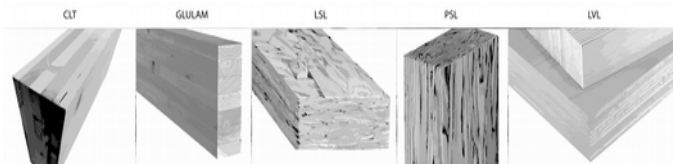


Figure 3.3 – Engineered Wood Products: Cross-Laminated Timber, Glulam, Laminated Strand Lumber, Parallel Strand Lumber, and Laminated Veneer Lumber

Cross Laminated Timber (CLT): Developed in Europe in the 1990s, cross-laminated timber is composed of layers of stacked lumber, each layer is rotated 90 degrees. When glued face-to-face, these layers form a large structural panels with bi-directional load-bearing

capabilities. Suitable for use as floors, walls and roofs, the individual boards are finger jointed together so that the panels can be manufactured in a variety of sizes. Openings for doors, windows, etc. are generally cut at the factory using CNC machinery so CLT is conducive to pre-fab and shop fabrication (Dangle 101).

Developments in engineered wood products have been necessary for wood to compete as a building material. Panels of ply-woods and compressed chip and particle boards offered solutions where large areas needed to be covered as well as provided some outlet for the waste material inherent in the milling of lumber. Further advancements in glue laminated timber and composite beams led to the development of glulam beams, laminated and parallel strand boards. Engineered lumber has many benefits over whole timber. It can generally span further per inch of depth than heavy timber due to a lack on inconsistencies in the stable kiln dried and laminated wood, it is more stable partly due to its behaviors as a more homogeneous material due to its make up of many parts of smaller strips of lumber that can be oriented with alternating grain orientation. Engineered timber is generally cheaper than heavy timber, a sustainable product as it is made from smaller trees or waste products from timber production, and offers a new and unique aesthetic possibility that is similar but primarily different from heavy timber in appearance and atmosphere.

3.3 Wooden Connections & Joinery

At the scales of both buildings and furniture, wood joinery connections typically fall within only a few typologies that have been developed throughout the evolution in wooden construction. Enabled by the development of more precise tools, these types of joints find similarities across cultures and time frames and have evolved little by little along with the tools and craftsmen that shaped them. In their book, *Building the Timber Frame House*, Ted Benson and James Gruber set out to instruct the novice timber framer in the types of joinery that are necessary to build a Western timber frame home. They

separate a variety of joints into overlapping categories dependent on their specific use or possible uses in timber framing, distinguishing the housed dovetail from the simple dovetail and the lapped dovetail. In order to fully understand the parts of these joints it is necessary to break them down into their simplest components. The *mortise and tenon* for example, is an extremely useful joint for joining two perpendicular pieces of wood, but its strength in shear and torsion will be limited by the depth and cross section of the tenon and not the total depth of the beam. By adding a *shoulder* for the beam to rest on, the tenon functions only to hold the beam in place while the entire cross-section can be acted upon by shear forces. The *shouldered mortise and tenon* can be secured by the addition of an offset wooden pin or peg. In some instances, particularly Japanese construction, this may also be a key or wedge designed to not only hold a joint in place but to provide additional force through leverage to pull the joint together. The *dovetail* is another joint that has a rich history of use across Western and Japanese carpentry but benefits from the additional support of a shoulder to carry any structural loads. In the case of bracing, the dovetail may also be *lapped or housed* in both the post and girt in order to provide a more rigid brace.

In, *The Complete Japanese Joinery*, Hideo Satao and Yasua Nakahara define the various members of axial framing as; mudsills, posts, beams, girders and headers. Ted Benson and James Gruber in, *Building the Timber Frame House*, identify the timber frame as being composed of bents and bays, these modules in turn being made up of of sills, posts, girts, braces, beams, struts and collar ties. The essential construction of the timber post and beam structure relies on similar elements in both cultures. Although the

joinery is cataloged under different names and slightly different arrangements of elements, the general principals are the same. In Japanese carpentry, how the members are joined has to do with their *Tsugite* or end joints. The type of end joint required is determined by the type of load the joint must resist as

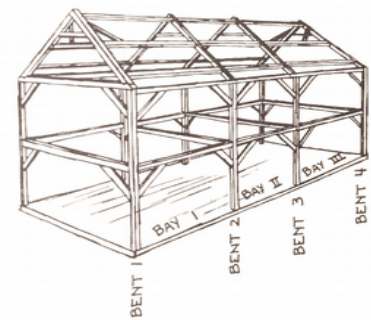


Figure 3.4 – The Timber Frame: A typical timber framed structure illustrating the difference between bents and bays. (Source: Ted Benson & James Gruber's, *Building the Timber Frame House*, pg. 15)

well as the quality and economy of the construction. In most Japanese construction the wood member bears a dual purpose of structure as well as a finishing material so the joint must be aesthetically pleasing as well as strong. While the end joint addresses how to join the ends of parallel beams, joists and columns. *The Complete Japanese Joinery* identifies the category of right angle joints or *shiguchi* for those that join between two perpendicular members. While the art of Western timber framing has been slowly revived throughout the second half of the 20th century, the art of Japanese carpentry has been passed along from craftsman to craftsman throughout history. This difference in the two styles can be seen in the simplicity and pragmatism of western joinery, a limited number of joints to complete an appropriate task; while in the Japanese style, many joints are available to accomplish a single task. The type of joint necessary is determined by the quality of the work desired based on the type of structure and quality of the material. The mudsill, for example, a moisture resistant wood, often Japanese Cypress or Fir that is placed on a stone foundation or raised on posts, can be joined in different ways based on the grade of wood or quality of construction desired. The end joints of a standard quality mudsill, as the book points out, should be *Koshikake ari tsugi* or *koshikake kama tsuri* (either lapped dovetail or gooseneck end joints). For select grade wood, or a higher quality construction, the sills should be *Okkake daisen tsugi* or *kanawa tsugi* (two versions of keyed scarf joint).

Both Western and Eastern timber joinery share several basic categories of joinery suited to specific structural and aesthetic needs as well additional modifications to these joints in order to allow for adaptation to specific circumstances. A *mortise and tenon*, for example, may be modified by the addition of both a shoulder and an offset or tapered pin in order to make it structurally suitable for post and beam timber construction. The joints necessary for building with heavy timber can be broken into the following types:

Scarf & Splice: Joints of this type are used to join two pieces of wood into a longer member. This may be two short beams that must be joined in order to span a distance greater than their independent length. The scarf and splice differ from one another in that the scarf joint will generally be used for a

structural purpose, such as joining to beams close to where they are supported by a column or post, while a splice will generally be used for non-structural applications such as sills and trim.

Dovetail & Gooseneck: The *dovetail* has a wide variety of applications. With a rich history of use in furniture making, it is still used to join sills and trim that are supported from below as well as used structurally for floor joists. The *house dovetail*, often combined with a *wedge* is often used for collar ties and bracing in Japanese construction. The *gooseneck* is a modification of the dovetail that offers greater structural performance than the *dovetail* and is used often with larger cross sections of wood (Sumiyoshi & Matsui).

Mortise and Tenon: The *mortise and tenon* is one of the oldest and most useful joints in woodworking. In timber framing it is arguable the most important joint used as it constitutes the majority of the structural work in a timber framed building. Further more, joint like the *dovetail* and *gooseneck* are simply a derivative of the mortise and tenon produced by changing the shape of the tenon and mortise. The *mortise and tenon* is generally modified with the addition of a *shoulder* or *housing* to carry the full cross section of spanning member and is generally secured with a *key*, *pin*, or *wedge* to bring the joint together.

Lap: The *lap joint* is one of the simplest joints in wood construction. Most *scarf* and *splice* joinery involve some form of a lap where equal amounts of wood are removed from two members so that they can rest flush together, used either longitudinally, or at corners and roof ridges. *Lap* joints generally must be secured by *pins* or by locking them with a *mortise and tenon* from an intersecting structural member.

Floating Tenon & Spline: The *floating tenon* and *spline* are important to note as although they are less common in heavy timber framing, they have commonly been applied in post and beam framing with steel splines. Their use in heavy timber is limited to when the post or column does not allow for both beams

intersecting it to have a *tenon*. Traditionally a hardwood spline would serve as the *tenon* for *mortises* in both beams. Engineered timber may lend to some new applications of *spline tenons* in heavy timber construction.

Each of these joints can be modified for a variety of different applications and scales by adding a *shoulder*, *rabbeted edge* or *housing*. They may also be affixed into position with the use of offset or tapered *pins*, *keys* or *wedges*. *Pin* and *key* placement in wooden joints is of great importance as it ensures that they will not fail under shear forces or cause splitting of the post or beam under stress making withdrawal of the joint possible. This is especially true in the case of *tie beams*, *collar ties* and other members that are put into tension. The structure and composition of these types of wooden connections have evolved over time with the cultures, craftsmen and tools that shaped them. In the author's preface of, *The Complete Japanese Joinery*, Yasua Nakahara suggest that although "there is a greater utilization of steel and reinforced concrete in modern structures, wood construction remains among the most important, maintaining its long tradition in Japanese Architecture. Regretfully however, with the passing of time, the splendid tradition of Japanese wood construction has become stagnant and is losing its driving force". Heavy timber, and the wood joinery that make it possible, has recently been challenged and arguably replaced by the economy of light timber framing and the structural stability and economy of metal fasteners and steel enabled post-and-beam construction. New types of wooden construction are currently being explored that, enabled by digital fabrication and a variety of engineered wood products, will continue to implement and build upon these age old principles of wood joinery.

3.4 New Connections: Intro to Digital Manufacturing

The evolution of woodworking tools generally followed a relatively linear process from tool to tool; chipped stones yielded to hammered copper, then harder metals and eventually a refinement in the individual classes of tools themselves once carbon steel was discovered. Occasionally, there is a jump, a moment when this linear progression is disrupted with the addition of something new. "There are two

major forms of product innovation: one follows a natural, slow evolutionary process; the other is achieved through radical new development” (Norman 279). The development of computer numerically controlled devices in the 1950’s was one such radical new development. The computer controlled machined at first offered manufacturing capabilities far greater than those of the assembly line. Tools could be automated to reproduce a variety of products quickly and efficiently.



Figure 3.5 – CNC Tool Heads: Various cutting tools for a 5-axis CNC router equipped with an automatic tool changer (Photograph by the Author)

As Kiel Moe, Associate Professor of Architecture and Energy at the Harvard University Graduate School of Design, notes in his essay, “Automation Takes Command: The Nonstandard, Unautomatic History of Standardization in America”, “Our current use of the term numerical control in digital fabrication was coined by the U.S. Air Force after World War II in their search for an elaborate manufacturing system capable of producing primarily repetitive and occasionally complex components for warplanes and weapon systems” (Moe 154). This new tool however, has a far greater capacity than to simply reproduce industrial products, and has a specific relationship to the evolution of tools that has been examined thus far. The primary applications of computer aided design and manufacturing in the architecture and construction industries employ a rapidly rotating tool. Most often this tool is a derivation of a milling or router bit, but recent applications of circular saws, grinders and sanders have become more common with 5 and 6-axis machines as well as robotic equipment. The modern hand held or stationary router itself is an evolution of both the electric motor and the hand held router plane. Moe explains further that, “the router bit is merely a refined application of the partial rotary motion tools, such as the fire drill, bow drill, and pump drill used as boring and cutting tools throughout the archaic world” (Moe 154). They are a continued evolution of the woodworker’s toolkit and, as in the past, must be understood by both the designer and the builder if those two are not one in the same.

Stephen Kieran and James Timberlake have argued in their book, *reFabricating Architecture*, that “handcraft is now an indulgence left over from another century” (Kieran and Timberlake 5). It is true that the transition from making by hand to machine-craft was the dream of modernists throughout the twentieth century. “Many of the most significant architects of the twentieth century pursued this dream of machine production. The goal was to make some architecture, especially housing, into a commodity for consumption by the masses.” (Kieran and Timberlake 5). It should be considered, however, that this requires us to believe that handcraft must require some investment in physical labor; that handcraft is impossible with the use of the mouse and computer screen. Many would not believe this to be true. Frank Lloyd Wright argued for the virtues of both the machine and the man behind it when he described the machine as either an “engine of emancipation or enslavement, according to the human direction and control given it, for it is unable to control itself... The Machine is no better than the mind that drives it or puts it to work and stops it” (Wright 16). New technologies in digital representation and fabrication offer a new tool for architects and craftsmen alike to create new forms or re-imagine forms of the past. Digital design and craft is an emerging field that can empower designers to think of new ways to work with wood or possibly reawaken old ways of building through economic viability and sustainability.

PART4: DIGITAL REPRESENTATION & FABRICATION

Computer aided design and manufacturing have made it possible to quickly create complex physical forms from digital representations. This development in architectural design and construction has two primary implications. Firstly, that shapes and connections that were not possible before due to constraints of labor, time and expense are now made viable through the efficiency of digital design and manufacturing; secondly, that traditional building techniques and crafts can be interpreted for digital manufacturing, making them an economically viable method of construction once again. These two factors have sparked visible changes in our built environment, such as the re-emergence of heavy timber construction, the appearance of large wooden buildings as an emerging and sustainable building

typology, the prefabrication of wooden building elements for economical and fast construction as well as enabling complex wooden shapes through engineered wooden structural elements and systems.

Wooden joints and connections require a high degree of skill from their craftsman due to the necessary precision required of all components. Traditional wood joinery thus comes with an economic cost of labor and extended construction timelines. Developments in CNC wood processing, digital design, fabrication and the prefabrication of building parts have made it possible to create wooden buildings of any scale in a cost effective and efficient manner. New construction types can be attempted due to the precision made possible by both digital representation and fabrication. New building types have emerged and old techniques have been re-imagined to integrate computer aided design and fabrication into the building process. These changes to the architect's and builder's toolkit have encouraged experimentation and innovation in wooden design and construction as well as revitalized interest in traditional techniques and craftsmanship.

4.1 Origins

Like computers themselves, the first computer numerically controlled machines of the 1940's and 50's were controlled by punched paper or magnetic tapes. "Beginning in the 1940's the U.S. Air Force developed the earliest numerical control systems for accurate and repeatable fabrication of aircraft components" (Corser 13). The goal of these first machines, was to quickly and accurately fabricate parts for military aircraft for the Second World War. After the war, other manufacturing industries adopted similar processes and the first computer numerically controlled (CNC) technologies were widely in use throughout various manufacturing industries. "In the 1960's digital computers began finding their way into the design of aircraft and so thereafter computers began to replace paper tape on the shop floor" (Corser 13). The increasing prevalence of the computer and the development of graphical user interfaces (GUI) for visualization and interaction with computer data sparked the beginnings of digital representation as we know it today. "The Servomechanisms Laboratory's Kludge system became the

basis of CADD software. The logic of the graphic display and the mouse-based input had its origins in this work. The development of solid modeling and parametric design in the French/British design of the Concord aircraft is another example of trickle-down technology from aeronautical enterprise” (Moe 160). Beginning in the aeronautical and military manufacturing industries, digital design, representation and now fabrication have made their way into design classrooms. These technologies have been controversial in architectural practice and design education. In architectural education today, learning representation by hand, graphite and ink, is no longer the norm. Computer-aided design has changed how we visualize new ideas, represent and communicate data between minds and how we design and fabricate building components. But, as Don Norman points out in his book, *The Design of Everyday Things*, “the same technology that simplifies life by providing more functions in each device also complicates life by making the device harder to learn, harder to use. This is the paradox of technology and the challenge for the designer” (Norman 34). The utilization of digital design and fabrication in the architectural workflow requires designers to learn new tools, adapt to a new skill-set of digital design and representation and utilize complex CAD/CAM software that may differ greatly from program to program and between building specializations. There are however, many benefits to learning these new tools. As William Massie describes in his essay, “Remaking in a Post-processed Culture”, advances in computer processing and the development of more advanced manufacturing tools and CNC technologies have allowed both the designer and builder to move from the virtual world of ideas and visual representations directly to the physical world of models, mock-ups and finished products. “This technology not only eliminates the distance between ‘virtual’ architectural hypotheses and the physical test of construction, but also forces us to examine our roles as architects in a condition allowing greater potential input into the processing of building construction” (Massie 101). The evolution of digital representation and fabrication have had an impressive impact on how we build already. While digital representation changed how architects recorded visualizations and iterations of their design, digital fabrication has slowly been revolutionizing what is possible in rapid prototyping and modeling in both education and the construction

industry as well as making new forms of both modular and custom prefabrication possible in modern construction.

4.2 Digital Representation (CADD)

Changes to the way in which architects and designers represent their designs have been rapid since the turn of the twenty first century. Early forms of computer-aided design and drafting (CADD) software moved the architect from a two-dimensional paper space to the computer screen. Two-dimensional representations of the lines created by pencil and ink were the architect's first introduction to digital representation. Although the implementation of 2-D digital representation workflows into architectural practice changed how architects produce their visualizations; programs like AutoCAD have done little to change the drawings themselves. Today, the primary way in which designers communicate their ideas is through traditional two dimensional construction drawings; renderings of plan, elevation, section and perspective views. More and more, however, architects and builders are leveraging the data available in three dimensional models to both visualize, design, and fabricate buildings and their component parts. A necessary step towards CNC machining a component is the transition from CAD to CAM (computer aided manufacturing) software. These forms of digital representation are necessary, not only for modeling a component accurately, but are an essential part of a workflow that transforms a digital model into a physical object. A computer numerically controlled machine must interpret its tool-path from G-code generated through both modeling and manufacturing software in order to complete a particular design. Each of these forms of representation will have an impact on the finished object. The skill of the operator and their knowledge of these tools is an essential component of the process. It is possible to generate G-code from scratch, given sufficient understanding of the tool and task at hand, but when working with complex shapes and systems, computer aided manufacturing software is necessary to move from digital representation to physical component as the complexity of the task makes coding by hand nearly impossible.

The transition from drawing programs to three dimensional modeling programs has transformed the architecture and construction industry. Most recently, the wide implementation of parametric modeling has sparked a shift from digital representation of buildings as traditional drawing sets, to building information modeling or BIM. Modeling software that can represent building components as parametrically related data has introduced a new way to communicate building information. As Achim Menges states in his essay, "Instrumental Geometry", "the arrival of parametric digital modeling changes digital representations of architectural design from explicit geometric notions to instrumental geometric relationships" (Menges 23). Parametric modeling and BIM have been influential in the industry, shifting the architectural workflow from drawings to the modeling of building components and systems. As these models get more and more precise, the opportunity to digitally fabricate building elements directly extracted from data becomes more and more realistic. "Parametric modeling has been understood as instrumental for its ability in improving workflow, its rapid adaptability to changing input and its delivery of precise geometric data for digital fabrication and performance analysis" (Menges 31). Digital representation and parametric modeling are the basis of what makes digital fabrication a useful evolution of the computer as a tool for architecture and construction. Three dimensional modeling programs have made it possible to model a component with enough accuracy to, in turn, simulate the path of a particular tool, modeling its route and orientation as it moves along a cutting surface. Digital models can now be made of both the cutting stock, cutting tool and machine in order to make complex and accurate simulation for CAM programs to interpret. These revolutionary tools remain to be implemented fully into architectural practice. "While emerging digital technologies offer architects radically new possibilities for designing and building, current architectural speculation remains largely confined to timid *evolutionary* steps" (Celento 57). The fields of architecture, construction and engineering have only begun to explore the full implications and possibilities of the integration of digital design and manufacturing technologies into the workflow of both designer, engineer and builder.

4.3 Typologies in Computer Aided Manufacturing (CAM)

The term digital fabrication is a general term for a variety of manufacturing processes that involve the use of CAD/CAM software at their core. It can generally be broken into two broad categories of *additive* and *subtractive* manufacturing. These broad terms encompass a variety of fabrication techniques but generally describe processes in which objects are produced by the *addition* of material, such as 3-D printing, or by means of cutting, carving, or *subtracting* material such as the CNC router, plasma cutter or laser cutter. Each of these digital fabrication typologies has benefits and limitations when compared to making by hand and also as they relate to each other. "Machines, after all, are conceived, designed, and constructed by people. By human standards, machines are pretty limited.... machines usually follow rather simple, rigid rules of behavior. If we get the rules wrong even slightly, the machine does what it is told, no matter how insensible or illogical" (Norman 5). These rigid rules, that Don Norman describes are the basis for the limitations of each machine, and what determines what it can and cannot do well. The 3-axis CNC router for example, can move horizontally in two directions as well as up and down along a vertical axis; it cannot rotate to undercut a relief unless it is given the additional freedom of another rotational axis. It is thus most suited to cut flat panel and sheet material, shallow contours and surfaces as limited by the length of the cutting tool and the size and shape of the tool's body.

The CNC router can be enabled with more capabilities to fabricate increasingly complex shapes with the addition of additional rotational axis. The 4-axis CNC will may rotate either the stock or cutting tool while the 5-axis and 6-axis machine will add additional rotational freedom to the tool head or stock. While the 3-axis machine is well suited for cutting sheet material and shallow surfaces, the 4-axis machine is capable of more complex rounded surfaces and relief. The 5 and 6-axis machines are suited for complete three-dimensional sculpture dependent of the level of sophistication of the cutting tools and tool changing ability of the machine. These tools are capable of quickly forming complex shapes out of whatever material they are designed to work with. They have made the rapid prototyping of designs

possible as well as enabled complex forms to be carved with ease and economy. CNC machining has changed what is viable in terms of scale and economy with wooden construction, allowing builders to revisit labor intensive traditional building methods through a digital lens as well as imagine new ways of building with wood that would have been unrealistic before. “Departures from basic geometries in architecture have historically often coincided with the development of new materials.... The lack of suitable design and manufacturing tools, however, frequently confined designers to regular geometries. Recent years have seen a renaissance of free forms – designers today are formally less constrained as a result of modern technology” (Kloft 111). From heavy timber to complex joinery and engineered wooden connections, the integration of the CNC machine into the toolkit of both the architect and builder marks a point of embarkation from the traditional machine tools used to process wood. No longer moved by hands or relegated to simple processes of automation, CNC machines have the ability to produce either many identical parts for a building or to produce an entire building where each component is unique; removing the constraints of considering wood as a material purely for post and beam assemblies.

Although not necessarily influential to the development of new wooden construction methods and joinery, it is worth noting here that additive manufacturing techniques like 3-D printing are changing the industry as well and offering new ways to prototype designs as well as experimenting with new ways of building with fluid building materials such as concrete and rammed earth. Developments in additive manufacturing have had little effect on the construction of wooden buildings but continue to change the industry alongside other methods of digital fabrication.

PART 5: DIGITAL CONSTRUCTIONS

The evolution of the tools used by both architects and builders to design, model and fabricate buildings has undoubtedly changed the fabric of our built environment. In wooden construction alone, digital design and fabrication has made building with wood a favorable option economically as well as enabled builders to think and design with wood in ways not formerly viable. Developments in engineered

wood products have led to the renewed availability of large quantities of wood for construction and freed the size and shape of building elements from the restrictions of the age or height of a tree. Wooden members for both, structural and aesthetic applications can now be fabricated from stable, structurally uniform engineered wood products of nearly any size and shape. The implementation of computer aided manufacturing and digital design has aided in ensuring that wood maintains a prevalent place in both architectural and structural applications in our built environment. It has made heavy timber construction economical again, allowed new forms to emerge from timber construction that challenge how we think of wood as a building material, as well as enabled the design of highly engineered building elements and wooden connections.

5.1 Tradition and Economy of Craft

Heavy timber framing has a long history in the United States and Europe but has been challenged as a viable means of construction moving forward as the trees required to build in such a way have become scarce. Building with heavy timber relies on several necessities that make it difficult to accomplish today. Firstly, building in heavy timber requires timber in dimensions that are not readily available. Today, the trees needed to produce large quantities of heavy timber for building are limited and thus the number of buildings that have access to this type of material are limited as well. Engineered wood products have offered a solution to this as large wooden members can be produced using smaller pieces of wood, enabling the building elements necessary for heavy timber construction but in material with inherently different physical and aesthetic properties. Secondly, the cost involved in building a heavy timber structure is significant. Requiring skilled labor and handcraft, each



Figure 5.1 – Construction Crew Raising a Timber Frame
(Source: Truini, J. (2007, March 22) *Popular Mechanics: A House With No Nails: Building a Timber-Frame Home*)

joint must be carefully cut and measured to ensure a perfect fit. Ted Benson of Bensonwood Homes in New Hampshire has been building with heavy timber for decades. His book, *Building the Timber Framed Home*, was instrumental in the revival of timber framing. Bensonwood built their first homes under the name Benson Woodworking Company, specializing in timber framing. By 1974 they were prefabricating parts in their shop in order to expedite on site construction (Truini, 2007). Today, the shop prefabrication



Figure 5.2 - CNC Cut Timber Joinery (Source: Truini, J. (2007, March 22) *Popular Mechanics: A House With No Nails: Building a Timber-Frame Home*)

of their timber frames is further expedited by the full integration of digital design and fabrication of the heavy timber joinery. Moving from hand-made timber frames to CNC fabricated timber parts has enabled them to remain competitive in the building industry.

By the mid 1980s, Benson Woodworking had begun to integrate AutoCAD into their prefabrication workflow in order to produce accurate templates for more complex joinery, such as compound joints for

roofs. By the 1990s, 3D representation was integrated in order to facilitate quick changes and iterations during design. Today, computer aided representation and manufacturing are a necessary part of timber frame construction, allowing builders to create designs and move to production rapidly (Truini, 2007).

The process of constructing the home remains more or less similar to how it would have been done at the end of the 19th Century. What has changed is that today “workers assemble a frame out of the factory-shaped timbers on-site. The mortise-and-tenon joints are secured with wooden pegs in the traditional way — by boring holes and pounding the pegs in... Accurate machining produces joints to within 1/32” that generally slip together with a light tapping” (Truini, 2007). The entire home is cut in the factory, the pieces assembled, then disassembled and shipped to the job site. Timber framing has remained a relevant form of wooden construction through the use of digital design and fabrication to streamline developments in prefabrication and digital manufacturing. In an article for *Popular Mechanics*,

"A House with No Nails: Building a Timber Frame Home," Joseph Truini describes that, although the majority of the manufacturing work is accomplished on the CNC machinery, there is still a great deal of finishing work that is best accomplished "the old-fashioned way — with a mallet and chisel."

Bensonwood's model of adapting digital design and fabrication to timber frame construction has allowed them to continue practicing this traditional craft in the modern world. Although many of the joints remain identical to how they would have been produced by hand, some, like the rounded dovetail or the rounded mortise and tenon, show evidence of the evolution from chisel, saw and hand plane to the CNC machine in their structure and shape.

5.2 Carving

One of the most interesting developments in digital fabrication with wood is the ability to realize complex surfaces in solid wood. To move from representation to reality and carve complex free-form surfaces from solid wood without limit of scope or scale. Carving, as an action for effecting the appearance and shape of wood has generally been limited in scope as part of the modern construction process due to the high level of skill and human labor necessary to produce a single carved artifact. In architecture, carved elements, beyond the

roughly hewn beams of early timber framing, have been limited to decorative elements such as moulding and furniture. The wood lathe offered the ability to shape wood as though it had been carved but is limited to a single axis of rotation, a rotary motion that will lend itself useful to only certain types of objects. With the addition of

digital fabrication and CNC machinery as a tool to carve solid pieces of wood, we have enabled builders and designers to imagine wood as a sculptural material in ways they have not been able to before. Not



Figure 5.3 - Entrance to Snøhetta's Reindeer Viewing Pavilion
© Ketil Jacobsen

only can large quantities of material be removed with accuracy and precision with the CNC mill, but complex shapes can be modeled before milling and studied in detail. The CNC mill has enabled us to carve and sculpt wood into nearly any shape desired, and worked upon in mass, assuming it can be broken down into parts small enough to fit on the CNC machine available for the task.

The Reindeer Pavilion at the Norwegian Wild Reindeer Center is located on the outskirts of Dovrefjell National Park and serves as an observation point for the Wild Reindeer Foundation and their educational programs. Designed by the Norwegian Architecture and Design Firm Snøhetta Oslo AS, the Wild Reindeer Pavilion is essentially a box of glass and steel that is filled with wood. On the outside the glass and steel patina reflect the landscape that surrounds it while the wood interior has been sculpted to act as a point of intrigue and warmth. Snøhetta describes the project as such; "This unique natural, cultural and mythical landscape has formed the basis of the architectural idea. The building design is based on a rigid outer shell and an organic inner core. The south facing exterior wall and the interior create a protected and warm gathering place, while still preserving the visitor's view of the spectacular panorama" (Tverrfjellhytta / Snøhetta, Archdaily, 2001). At 900 sf, the Reindeer Pavilion is a small project. The building is key-less so that it can be accessed by park visitors all year round. The wooden interior has been carved away to give the impression of erosion by wind or water, a treatment that one might reserve for stone or concrete, made possible by the CNC router. The interior wood structure and



Figure 5.4 - Interior view of Snøhetta's Reindeer Viewing Pavilion © Ketil Jacobsen

ceiling have been CNC fabricated out of 10"x10" local pine timbers. "The simple form and use of natural materials references local building traditions. However, advanced technologies have been utilized both in the design and the fabrication process. Using digital 3D-models to drive the milling machines, Norwegian shipbuilders in Hardangerfjord created the organic shape

from 10-inch square pine timber beams. The wood was then assembled in a traditional way using only wood pegs as fasteners” (Tverrfjellhytta / Snøhetta, Archdaily, 2001).

Snøhetta’s Raindeer Pavillion offers an investigation into the ability of CAD/CAM technologies to both explore free form structures through digital representation but also realize those structures in wood using computer controlled manufacturing techniques. It is important to note a few points of interest surrounding this project. Although a complex digital model was created to represent the surface of the wooden interior, and the pieces were manufactured through computer aided manufacturing processes, the joinery used was a traditional process of wooden peg fasteners. There is a blending of traditional craftsmanship with digital technologies in this project that speaks to the traditions inherent in wooden joinery. Choices were made to both highlight and hide the use of CNC manufacturing techniques. Although the benches on the interior are smoothed and sanded to invite touch, comfort and warmth; the ceiling and the walls are textured with the router’s tool-path. The grooved markings of the router’s offset path leaves a hint of the tools and techniques used in both manufacturing and modeling.

5.3 Engineered & Free-Form Structures

Free-form architecture has been part of the conversations around digital representation and fabrication since the introduction of post-modernism and “blob” architecture. Digital representation has been at the heart of these developments. While Frank Gehry has made free-form structures that treat their metal shells almost as fabric, explorations in new ways of joining and configuring complex structural systems from



Figure 5.5 - Engineered wooden joint at the Tamedia office building © Shigeru Ban Architects

wooden components have been less frequent. Although complex shapes can be formed out of metal, wood and stone by hand, digital representation and fabrication allow for complex models of whole



Figure 5.6 - Interior of the Tamedia Office Building © Didier Boy de la Tour

systems as well as individual elements to be modeled and in turn, prefabricated away from the job site, making assembly of complex systems more efficient and organized through digital tools. Digital representation and fabrication have allowed for complex shapes and joinery to be modeled accurately so that their construction in the real world can be accomplished in an organized and economical fashion.

One architect, whose innovative use of wood in several projects has influenced the way in which we imagine building with wood is Shigeru Ban. Shigeru Ban's Tamedia Office Building in Zurich Switzerland presents a unique case study for wooden joinery at a much larger scale and level of engineering. The Tamedia building incorporated wooden building technologies that do not simply refine and strengthen traditional building joinery and building elements but that re-define what is possible with wood as a building material. Situated on a 1,000 square meter site, the main structural systems for the building are designed entirely of timber. Timber was chosen due to its low contributions to CO₂ production and the projects focus on sustainability in design. "Timber structures are increasingly applauded as a sustainable alternative to the carbon-heavy production of concrete and steel. No longer the domain of houses and other small-scale buildings, wood now frames mid-sized buildings of various types and potentially high-rises in the near future" (Hill, 2014). The Tamedia building pushes the boundary of what was thought possible in wooden buildings of this scale. The structure is composed of a spruce-pine frame of post and beam inspiration but with all wood connections that form mechanical connections with each other. Each post and beam forms a mechanical wood-to-wood connection at each node, interacting with ovular plates of beech-wood that nest between each connection piece; a beech-wood spline secures this connection and is pinned into a mortise in the adjacent connection (Tamedia

Office Building / Shigeru Ban Architects, Archdaily, 2014). Without digital design and fabrication, a building like this would be nearly impossible to build. "Today, thanks to CNC milling, the elements can be cut down to the last millimeter, sections prefabricated and then assembled on site" (Ernst, 2013). The parts were manufactured on CNC milling machines to tolerances of 1/32". The connections are engineered to withstand the structural forces of a building this size and their size and shape is integral in that design. The general function of the joinery takes its basic shape and form from timber joinery present in Eastern and Western timber buildings already. The shouldered mortise and tenon and mortised spline connection are seen in similar constructions of heavy timber and engineered wood. But the size, shape and arrangement of the connecting parts is unique here and new to the world of timber design.

The owners wanted to exhibit wood as both a symbol of sustainability and for its warmth and positive effect on the mental health of building occupants. As John Hill describes in his article about the building, "Tamedia's Timber Structure", wood is a natural choice for the project given there is a context of building with wood in Switzerland, but, the choice also "responds well to Tamedia chairman Pietro Supino's mandate for a 'pleasant working environment'. The exposed wood members have a wider range of positive sensory [sic] qualities than steel and concrete, be it their warm appearance, their (lack of) noise, their distinctive smell, and even their natural touch. These characteristics unite the material with the chairman's desire to give his employees a quality working environment" (Hill, 2014). The expertise of wood engineer Hermann Blumer was essential when realizing the Tamedia building. "It was Blumer who proposed the special connections and the type of wood to us: pine from Styria in Austria, felled some 1,000-1,500 meters above sea level" (Ernst, 2013). Shigeru Ban's design for the Tamedia building is an example

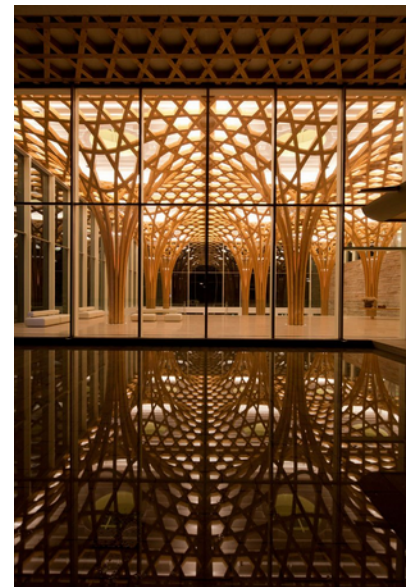


Figure 5.7 - Nine Bridges Golf Course Clubhouse © Hiroyuki Hirai

of an emerging type of wooden construction in architecture today. Rooted in the traditions of wooden joinery, but fully reliant on digital tools and engineering, the Tamedia building presents a case for the development of new engineered wooden joints to explore the possibility of returning to wood-to-wood connections as a viable structural system in heavy timber construction moving forward.



Figure 5.8 - Nine Bridges Clubhouse Roof Structure Under Construction
© Shigeru Ban Architects

Another project of Shigeru Ban's that has stretched what we thought was possible to accomplish with wood is the club house at the Nine Bridges Golf Course in South Korea. Located two hours from Seoul by car, it is made up of three separate buildings, each of the buildings highlights a different structural system that reflect the traditional construction methods of South

Korea (Nine Bridges Country Club / Shigeru Ban Architects, Archdaily, 2014). The main clubhouse features a hexagonal wood lattice shell, while the two other buildings are of wood and concrete respectively. The laminated timber columns are arranged radially, becoming the horizontal structural members for the roof as the hexagonal lattice extends from each column. "The lower podium is constructed as a wall of large local stone built like traditional stone setting of South Korea, gradually slanting inwards towards the top" (Shigeru Ban Architects, 2010). The three-story timber structure is a visual center point for the entire club house and the texture and warmth of the wood's natural finish is a focal point of the design. The design, inspired by a traditional type of woven Korean basket, a type of construction that would not be possible out of rigid wooden members if not for the utilization of digital representation and fabrication in producing the doubly curved glulam shell. The joints at each intersection are essentially lap joints that have been laminated in two directions, providing strength in much the same way as cross laminated timbers do in mass-timber construction. The structure, although

inspired by weaving, does not act as though it is woven, instead it relies on the strength of these laminated lap joints to create a rigid structure that carries the weight of the roof and delivers loads evenly to the wooden columns. Although a structure such as this may have been possible without the use of digital fabrication and design; its cost would have been prohibitive due to the time and labor necessary. Digital design and fabrication have made the construction of free-form or complex structural systems from wood a viable choice for architects and builders who would choose to incorporate wood into their designs.

PART 6: MATERIAL INVESTIGATIONS

In order to fully illustrate how changes to the tools we use to build have affected changes in what we design and make, as well as understand the implications and potentials of computer aided design and manufacturing on wooden architecture and buildings, some material investigations were undertaken to study both wood as a material, the traditions that surround it, and the tools used to shape it. I began by approaching timber construction from its beginnings, working to understand how the hand worked with both wood and tools to shape it to a desired form. Investigations into how the joinery used in timber framing might be interpreted for production by the 3-axis CNC router were meant to better understand how the use of digital fabrication might change how we are choosing to work with wood as a medium for architecture and building. "Making by hand was the only way we had of fabricating artifacts for most of our history. It required a great expenditure of human energy. When things were made by hand, economies in the expenditure of this energy came about naturally. The designer was often one and the same with the maker" (Kieran and Timberlake 5).

6.1 – Traditional Joinery – Models and Explorations

When describing the current state of wood construction in his introduction to *The Complete Japanese Joinery*, Yasua Nakahara states, that although there are numerous new ways of connecting wood members from steel fasteners, glued and engineered connections, it's necessary to first understand the developments that brought about these new ways of working with wood. "As in the proverb, 'onko chishin' (not to throw the baby out with the bath water), it is first necessary to review the past development and progress of wood construction before creating new methods" (Nakahara 1). In order to more completely understand why and how we join wood in certain ways today, it is necessary to understand how and why it was joined in the past. By studying the joinery of both Western and Japanese timber construction, a more complete understanding of wood, wooden connections and the nature of the tools used to shape them can be achieved.

As stated earlier, the joinery necessary to construct a timber framed home or building, in both the Western and Eastern traditions can be distilled into their most basic of parts for better understanding. The *Scarf*, *Dovetail*, *Mortise and Tenon*, *Lap*, and *Splice*, all embody the most basic elements of timber joinery. Augmented by a *Shoulder*, *Rabbet* or *Housing*, to provide additional strength and bearing potential, as well as a *Pin*, *Key* and *Wedge* to lock the joints into place and hold them secure; combinations of these elements make up the building blocks for timber joinery. Some time was invested in using traditional woodworking tools, some Western and some Japanese, to construct study models of traditional timber joints. These models were cut from 2-inch-square lengths of poplar and were meant to study the layout of the joint, the tools necessary to complete each joint with relative ease and accuracy as well as to judge the complexity and utility of the joinery. The timber joints included in these study models were a variant of the *Stop Splayed Wedged Scarf*, *Half Rabbeted Oblique Scarf (Crossbill)*, *Housed Wedged Dovetail*, *Mortise & Tenon*, and the *Bladed Scarf*. Each of these joints may come under a variety of names, but for the purpose of this study, layout and procedure was derived from Ted Benson

and James Gruber's, *Building the Timber Frame House* as well as, *The Complete Japanese Joinery*, by Hideo Sato and Yasua Nakaraha.

Stop Splayed Scarf with Through Wedge

The *Stop Splayed Scarf* is one of the more common joints in timber construction to join two beams or girts together. Used when a girt of sufficient length is not available for a given span, one side of this end joint extends past a column support to meet the shorter, unsupported end. A wedge is driven in from both sides in order to pull the joint into compression.

This joint can be accurately cut with relative efficiency with just a saw, chisel, and square making it a common choice in timber framing.



Figure 6.1 - Stop Splayed Oblique Scarf with Through Wedge

Halved Rabbeted Oblique Splice

This end joint is used in traditional Japanese construction for joining roof purlins as well as on non-structural and decorative elements such as trim and moulding. It was often used on fence headers in the Japanese house (Sato and Nakaraha 185).

Not notable for its structural strength, it's simplicity can be appreciated and relative strength when

compared to *butt*, *bevel*, and other simple end joints. The cutting of a channel for the pin requires the use of a chisel, however the pin can be omitted as it may cause the joint to pull apart over time. Without



Figure 6.2 – Half Rabbeted Oblique Splice

the pinned connection as a simple splice this elegant joint can be cut with only a saw and marking tools, making it a good choice when balancing speed, strength and aesthetic concerns.

Mortise and Tenon

The *Mortise and Tenon* is one of the most common joints in timber construction for joining two perpendicular members. This example is modeled after a common shouldered mortise and tenon commonly used in girt and post connections and is generally pinned in place but can also be locked in place with a wedge at the top of the joint or a key or



Figure 6.3 - Shouldered Mortise and Tenon

wedge through the tenon if it passes all the way through the column in the case of a *Through Tenon*.

Housed Sliding Wedged Dovetail

Both the *Dovetail* and *Mortise & Tenon* can benefit from a hardwood wedge instead of a pin or through tenon key. In this variation used in furniture as well as timber construction, a tapered and slotted mortise is carved out of the post such that the halved-dovetail tenon can be slid into the mortise and locked in place by driving the wedge into the slot. This joint is not as



Figure 6.4 – Housed Sliding Wedged Dovetail Tenon

commonly used as the more straight forward shouldered mortise and tenon as it requires additional skilled work to carve the sloped mortise with appropriate accuracy. It does, however, provide the benefit of improved resistance to withdrawal, a primary concern in the structural arrangement of timber joints.

Bladed Scarf

The *Bladed Scarf* can be used to connect two linear elements, often being used in as a beam-post-beam connection where the post above can lock the scarf into place by use of a through tenon. This end joint can also be employed with column-to-column connections with the addition of pins inserted into holes bored perpendicular to the face of the scarf; often an additional tenon is added to the end to provide additional lateral resistance.



Figure 6.5 - Bladed Scarf Joint

These joinery investigations were helpful in confirm some of the conclusions reached thus far concerning the nature of hand tools and the material properties of wood in affecting the ways in which we approach wooden joinery when building. A product of generations of carpenter's skill and craft, these timber joints are a result of generations of refinement and distillation of the possible outcomes one might encounter when seeking to join two pieces of wood together for a particular task. These joints represent only a fraction of the catalog of types of joinery methods present in wooden construction, but their parts make up a portion of a language of joinery that is useful in describing new or innovative ways one might join multiple pieces of wood to resist structural forces.

6.2 – Joinery Interpretations for the CNC

There is no doubt of the inherent beauty in the craftsmanship of traditional wood joinery. When executed correctly, the joinery reflects the relationships between stresses, scales and material characteristics of the two joined pieces; likewise communicating the skill and often the cultural influence of

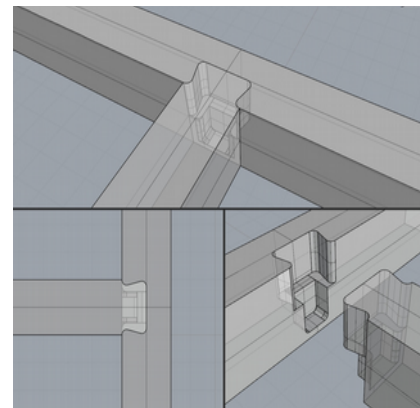


Figure 6.6 - Dovetail Joist to Beam Connection, Modeled in Rhinoceros 5 for for digital fabrication

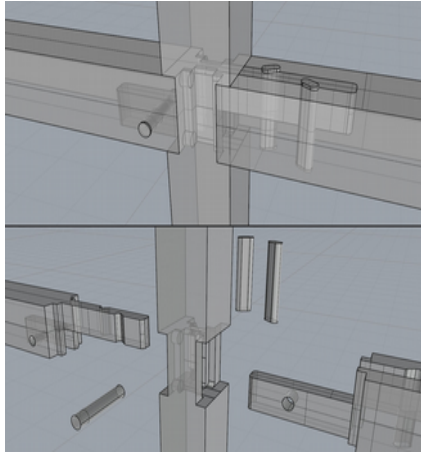


Figure 6.7 - Model of Column-Beam Connection with Pin and Key

the craftsman. The joint's layout is often telling of its purpose, the nature of the materials used as well as the motives of the designers, builders and inhabitants of a building. The traditional joinery of Japanese and Western carpenters arose through years of evolution, changing along with technology, tools and culture. Although, traditional joinery methods in wood have lost their viability in modern construction due to concerns of cost and labor, digital design and fabrication offers a means of affecting the economy of timber joinery for wooden construction and bringing

new life to old forms. The following investigations into CNC interpretations of traditional joinery sought to understand how the basic components of a timber framed structure can be replicated for production on a 3-axis CNC router. Although much of this joinery could be produced on industrial grade CNC manufacturing equipment with both 5-axis of rotation as well as tool changing capabilities, this investigation sought to understand what is possible with the particular tools at hand, a 3-axis CNC router. Though the understanding of the capabilities of this particular tool it is possible to begin to understand the implications of mass adoption of CNC manufacturing and the possibilities for change in the realm of wooden construction going forward.

Four connection types were studied, revisiting, in some cases, several of the types previously studied with traditional hand tools. A beam-beam scarf, girder-joist connection, post-beam connection, and column splice; these four joinery methods being present throughout the design of a timber structure and illustrative of the basic joinery necessary to design and build a timber structure on many scales. The workflow for designing and fabricating each of these parts was three-fold: Firstly, to create a digital representation of the part, secondly, to generate G-code

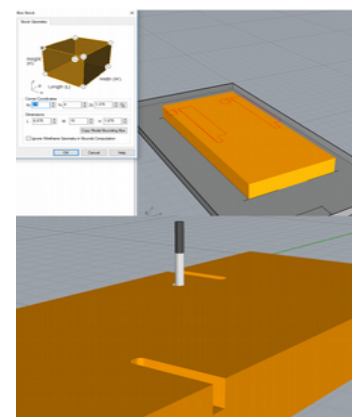


Figure 6.8 - Simulating and Cutting Stock Tool Geometry in Rhinoceros 5 and RhinoCAM

for the CNC machine through the use of CAM software and lastly to manufacture the part on the CNC router. Software used in these particular experiments included McNeel and Associates Rhinoceros 5 or 3D modeling of the parts, MecSoft's *Rhino CAM* as a manufacturing software to model tool geometry, tool paths and produce G-code as well as *Flashcut CNC* to interact with the CNC router and interpret each G-code script.

Several challenges became clear through the fabrication of these parts. Limited by the movements of the 3-axis CNC router available for use for fabrication, each of these objects was designed so that it could be 'flip-milled', or turned between passes on the CNC router, such that each face of the joint could be unique if desired. This process complicated the overall fabrication of the pieces as any difference in placement when turning and securing the pieces to the CNC bed would result in imperfections in the alignment of the parts when the joint was assembled. A template was created to ease in indexing and securing the pieces to the CNC in the exact location necessary. The cutting stock was modeled in Rhino CAM to allow for two pieces to be cut at once. The tool geometry was modeled and G-Code was generated for each face of the piece so that a separate file could be run with each pass. Once G-code was created for each face of a joint the files could be sent to the CNC router for cutting.

Oblique Scarf with Through Wedge

This end joint, explored previously in a hand-made version, is one of the most common beam-to-beam connections in timber construction and proved a good point of embarkation into the process of fabricating a timber joint on the 3-axis CNC router.

Fabrication of this piece would be completed with a 3/8"

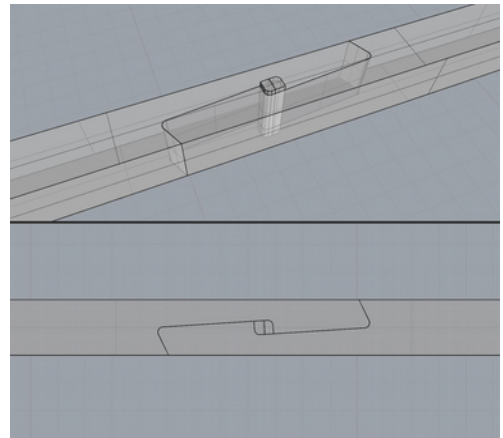


Figure 6.9 – Physical Model - Stop Splayed Scarf. Cut on a 3-axis CNC Router

down-cut spiral router bit and this each inside corner was given a radius of 3/16" to accommodate the shape of the cutting tool. This difference between using the round, rotating bit of a router instead of the straight blade of a saw for these cuts was immediately apparent, particularly in the case of the wedge. This joint is generally pulled together by tapping in a wedge from opposite sides. Without 90 degree inside corners, a split wedge is a difficult thing to replicate. There are a variety of possible solutions for this; putting a radius on two of the four edges of the wedge, choosing instead a tapered channel with ovalular pin, or lastly, to drill out the radius of the inside corners leaving a void in that area. For this joint, I chose the first method but the third is commonly used in CNC fabrication especially with sheet materials.

Dovetailed Joist

One of the most frequently used connections in timber construction is that between floor joists and beams. Timber framing generally uses three types of connections when joining floor joists with beams; the shouldered-tusk tenon, a sliding-housed dovetail, or a simple cut-away mortise for the joist to rest in (Benson and Gruber 44-46). The sliding dovetail offers a solution to fixing floor joist in place without the need for boring holes for pins, the shape of the mortise and tenon is the locking mechanism for the joinery when combined with the dead-load of the flooring system and structure above. By deepening the tenon and providing a shoulder for the dovetail to rest on this joint increases



Figure 6.10 - Physical Model - Dovetail Joist-Beam Connection. 3-axis CNC Router

the depth and cross-sectional area of the beam capable of resisting shear at the connection as well as locking the joint in place with the dovetail geometry.

This model was designed to be cut by flip-milling each piece twice on the CNC router. Challenges arise in a joint like this from the material left behind by the radius of the router at the edge of the mortise. This was solved by making a second pass with the router to remove a small channel of material from the face of the mortise so that the inside corner of the tenon wouldn't intersect with any left over material.

Mortise and Tenon (Pinned and Keyed)

This exploration on the *mortise and tenon* combined elements of both Western and Japanese timber framing by utilizing the Japanese *pole tenon* connection that is held in place by two rectangular keys with the *shouldered mortise and tenon* that is most often pinned with a round trunnel and commonly used for post and beam connections. The process for milling this joint was relatively time consuming. Each beam had to be milled on each of its 4 sides while the post had to be flip-milled twice to cut both the shoulders and the mortise. Each of these flip-milling procedures created an opportunity for error and inaccuracy in the final product, however, a joint such as this could be cut on an industrial 5 or 6-axis mill with relative ease. There is a beauty in the mechanics of a joint such as this that would be a pleasure to see at full scale in a modern timber frame.



Figure 6.11 – Physical Model – Pinned and Keyed, Shouldered Mortise and Tenon for Post and Beam Connection

Column Scarf

This joint explores the possibility of using variations on the bladed scarf joint to splice columns. Although column splices are used infrequently in Western timber construction where designs usually favor connections that either terminate at a girt or continue to the next horizontal member, Japanese construction has employed the spliced column occasionally, usually in low-rise buildings below the mudsill where the post meets the foundation. This joint is similar to the horizontal scarf joints used for beam-to-beam connections but benefits from both a stub tenon that prevents the joint from twisting as well as two trunnels or pins.

The work and skill required to fabricate traditional timber frame joinery with traditional tools is beyond what the majority of builders today can accomplish. Traditional joinery can be interpreted for the CNC router and other computer numerically controlled milling machines in order to continue the tradition of heavy timber framing in modern heavy timber construction. There is a beauty in the ways timber frame joints go together and to continue to use and improve on them through digital design and fabrication would allow us to continue to enjoy all of the interesting ways in which wood has been joined to shelter us throughout history. Although not studied in this investigation, some effort might be invested in determining new ways of joining timber with CNC joinery that build upon and improves the traditional joinery of timber framing.

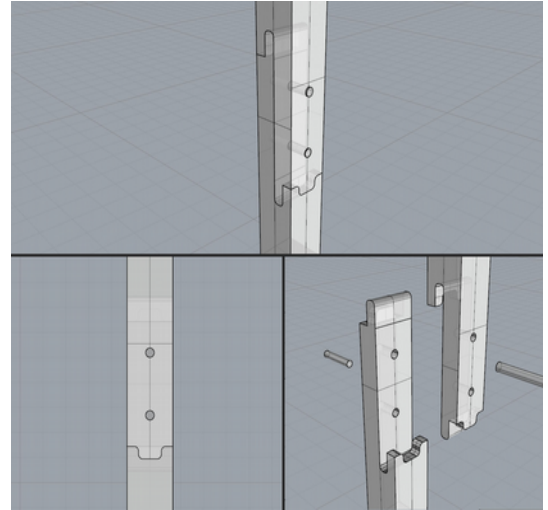


Figure 6.12 - Physical Model - Column Scarf with Stub Tenon (Photograph by the Author)

CONCLUSION

At the root of this investigation was a desire to unearth the reciprocal relationship between material, tool and maker. In his book, *The Craftsman*, Richard Sennet distinguishes between craftsmanship and skilled labor; the difference between man as *homo faber* and *animal laborans*. He claims that "*animal laborans* takes the work as an end in itself" (Sennett 6). Craftsmanship, he continues "cuts a far wider swath than skilled manual labor; it serves the computer programmer, the doctor, and the artist... Every good craftsman conducts a dialogue between concrete practices and thinking; this dialogue evolves into sustaining habits, and these habits establish a rhythm between problem solving and problem finding" (Sennett 9). When we first began to work with tools, beyond simply our hands, we set out on a purposeful journey to seek a means of doing something better. We produced things more quickly, things that lasted longer or were more beautiful or more useful. Craft, as it relates to the tool, is at the heart of this argument. To again quote Malcolm McCullough's, *Abstracting Craft*, "A tool directs your attention. Its function becomes your focus: as the saying goes, when you hold a hammer, all the world looks like a nail" (McCullough 59). Throughout the evolution of the various tools we have used to work with and manipulate wood, these tools have both enabled us to create new shapes and forms from a raw material but also determined what we envision possible from that material through a variety of social, cultural and economic factors. As digital design and manufacturing technologies continue to influence the design and building industry's relationship with wood, new shapes and arrangements of wooden building elements will continue to emerge; changing, fundamentally, how we view wood as a material for construction.

The material nature of wood and its relationship to the tools we use to work it are of particular importance. Our modern view of wood as a material for construction is built out of centuries of habit. The evolution of the saw from its humble stone age beginnings has seen a solidification in our opinion of wood as a material for straight, planar, orthogonal geometries. These inclinations are linked to the tools used to work this natural material. As digital design and manufacturing continue to infiltrate the design and construction industries, wood construction has taken on new forms not previously imagined. In Kiel

Moe's essay, "Automation Takes Command: The Nonstandard, Unautomatic History of Standardization in America", he illustrates how Benedictine Monks changed our relationship with time by introducing the bell tower to their daily practices.

"With the clock and bell, the Benedictine monasteries at the beginning of the last millennium synchronized liturgical rites with the bell tower. This regularized the spatial and temporal behavior of the monks – in doing so, also fundamentally transformed their experience of duration. Our physiological systems – no longer synchronized to the rhythms of the sun, seasons, and free morphogenesis – became increasingly determined by numbers" (Moe 155).

As we introduce seemingly benign technology into our daily practices, it has a tendency the shape how we view the world as generations pass; eventually, not seen as technology but simply as part of the natural world. Digital design and fabrication have freed the designer from thinking of wooden construction with a linear mind, "the control of a tool along a path no longer guided by the neurological-muscular feedback loop of a human technician. Instead, it is now controlled by a path in a numerically defined blanket of points" (Moe 154). Projects like Snøhetta's Reindeer Viewing Pavilion, Shigeru Ban's Nine Bridges Clubhouse and the Tamedia Office Building all embrace digital fabrication as a new method for working with, and exploring new possibilities with wood. These projects show ways in which digital fabrication with wood as a building material can be leveraged to explore new a vernacular in wooden buildings. Snøhetta's Reindeer Viewing Pavilion is not beyond the scope of human ability to build by hand, it would simply be exceedingly difficult, time consuming and expensive. As Frank Lloyd Wright puts it, "perfected machines are startlingly like the mechanism of ourselves" (Wright 15). These projects are specific examples of carving, of weaving, and of re-imagining timber joinery in the new light of digital fabrication and design.

Through these investigations into traditional tools, timber framing and new interpretations of timber joinery through digital fabrication, this thesis has explored how our relationship with our toolkit affects what we deem viable and even possible to build. By learning from past examples of joinery and

past builder's relationship to their tools, we can learn much about how new additions to our toolkit may effect how we view wood as a building material going forward. "The joinery seen in Japan today thus represents the survival of an extremely archaic way of building, a kind of living time capsule" (Brown 86). By learning from this time capsule of traditional joinery and methods of construction we can start to envision new ways of building with wood, leveraging digital design and fabrication, engineered wood and new and emergent trends in wooden building technologies. Wood as an architectural material, has an innate ability to remind us of our state in the natural world. Japanese architecture has, throughout history, honored wood as a spiritual symbol of nature. "Natural materials" as described by Juhani Pallasmaa in, *The Eyes of the Skin*, "allow our vision to penetrate their surface and enable us to become convinced of the veracity of matter. Natural materials express their age and history, as well as the story of their origins and their history of human use" (Pallasmaa 31). When trying to understand our relationship with these natural materials, our 'history of use', as Pallasmaa puts it, is not only limited to the life of a particular material, but linked to our use of that material throughout time. The tools we've used to shape and form wood as a material for building have left their markings, not only on the edifices of the past, but also on our modern view of wood as a medium for architecture; and thus our built environment today. Digital design and fabrication seem to be permanent additions to the architect's toolkit. For over half a century already, our built environment, and our relationship with wood as a material for building has been shaped by these new tools. To evoke Frank Lloyd Wright's assertion once again, "the Machine is the architect's tool – whether he likes it or not. Unless he masters it, the Machine has mastered him"

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