Timber Structure For Cycling by 2+0.5D Digital Fabrication

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Wood and tools. They bring to mind the cabinetmaker’s factory, boat builder’s jigs, the residential construction site, concrete forms and the amateur’s workshop. Each is at the end of conception, where already set ideas become reality. Mostly what is made are the ideas of others—the hand holding the tool is not that of the designer. The history of design would appear to force such a separation between design and its realization. Modern artifacts are complex and demand specialized knowledge and machines for their production. It is easy, or at least expedient, for designers to leave tools and materials to others. Sadly, the common view that designers are ungrounded in practical reality may be simple historical necessity.

-FUTURE WOOD
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0. Abstract

The recent development of architecture comes with some key words, such as curvy, non-standard, and non-regular. New architecture asks for complex geometry. To materialize such complex form, digital work flow-from design to production has been employed with all kinds of new techniques. Wood and wood products have been main construction materials for a long period. In traditional wood construction, carpenters had already achieved fruitful works of timber by their excellent skill. In new complex digitally fabricated architecture, wood becomes an ideal choice again due to its number of advantages, such as sustainable, easily fabricated, standard products. Through CNC milling and other CNC machines, wood and wood joints can be used to realize any complex geometry. As a new requirement, building for cycling is a kind of complex form architecture. This paper is mainly about how to use wood and digital fabrication and digital work flow to achieve a timber structure for cycling.

Key Words: timber structure, digital fabrication, wood-wood connection
1. Introduction

1.1 Origin of cycling building

1.1.1 Cyclists need building
As a sustainable, clean efficient and healthy transportation system, cycling is becoming more and more popular all over the world, especially in the Netherlands. Bicycle is used for more than a quarter of all journeys here. A statistics getting from a search in 2006 shows that the average amount of the bicycle share in all journeys in the Netherlands is 26%. As people cycle so much and so often, buildings for bicycle appears in recent years. Most of them are bike storage facilities, such as Fietsflat next to Amsterdam Central Station. (Figure 1-1) To some extent, this kind of building complements lack of parking space for bikes, however, it cannot meet the other needs of cyclists. A survey focusing on people who do not ride in Amsterdam shows that distance and danger are the top reasons. Other reasons include riding with friends, package carry or storage space, a reasonable trip length. So, cycling facilities with consideration of these aspects are necessary, especially in the suburban area with long distance cycling route.

Brettenzone is an in-between area leading from Amsterdam downtown to Harriem. (Figure 1-2) A cycling route running through the whole long stripe is used frequently by daily commuters, cycling fans and students for daily commute, recreation and sports. Moreover, as a preferred way of networking for the modern professional, long distance cycling is considered as a sharing experience. All these several kinds of cyclists need cycling facilities to serve them during their cycling along this area.

1.1.2 Complex structure for cycling building
The cycling facilities should be designed mainly for cyclists, considering the requirements of cycling in it. It should locate next to cycling route, directly connecting with the existing cycling way. The cycling building should be temporary due to the variation of the situation of cycling route and the location. Cycling in a building also set constraints for the geometry of the structure. In suburban areas like Brettenzone, good sightseeing is an important character of such cycling structure, so a curved ramp which can guide cyclists to the upper level is necessary. This is also necessary due to the movement of cycling in a building. (Figure 1-3) The curved ramp running through the whole building will lead to certain complexity of the structure.
1.2 Timber structure in 2+0.5D digital fabrication

1.2.1 Wood as a suitable material
In order to materialize this kind of cycling building, a sustainable and economic construction way should be employed. As a reproducible and environment friendly material, wood and wood products are quite suitable for such temporary light weight structure. There are a lot of other advantages of wood, such as regularized components, easy and affordable machine processing, and a multitude connection types. By the Industrial era mechanized timber prefabrication, timber construction can be built easily and quickly with those standard components and industrially fabricated steel connectors. In digital manufacturing, wood products are excellent material selection. Off-the-shelf wood products come in manageable dimensions, capable of being easily and accurately cut. Rather than concrete and metal, wood components can be digitally fabricated easily and cheaply. The potential of wood-wood connection is explored by digital fabrication as well.

1.2.2 2+0.5D digital fabrication in timber
For a complex structure, as the components of the structure vary gradually to address different structural loads in the most optimal way, mass-customization through digital fabrication is needed. “Mass-customization” by digital fabrication is to produce differentiated building components with the same facility as standardized parts, by which we can achieve unique mass-produced components efficiently. 2+0.5D digital fabrication is the most commonly used and economic fabrication technique for wood, which mainly contains CNC cutting, like CNC Laser Cut and CNC 3-axis Router. There are some differences between these wood fabrication technologies in the kind of maximum thickness that could be cut. For example, Laser-cutters can cut material up to 16mm cost-effectively, while for CNC Router, the maximum cut length of the router bit determines the thickness of wood components, normally it can achieve 150mm. The radius of the bit defines half the width of the cut, meanwhile, it leaves a radial or fillet at any corner. Another constraint of 3-axis CNC Router is that undercuts cannot be accomplished. (Figure1-4)

The technique research questions is:
How to design and material a complex cycling timber structure by 2+0.5D digital fabrication?
2. New timber construction by digital fabrication

2.1 Choice of wood products

A number of inherent characteristics of timber make it an ideal construction material, including high strength to weight ratio, impressive record for durability and performance and good insulating properties against heat and sound. There are more than ten different kinds of wood products, which can be mainly separated into two groups: solid sawn timbers and engineered wood products. Solid sawn timbers contain products of softwood and hardwood, which come from sawing of logs. Engineered wood products are developed to overcome the limitations of solid timber in size and quality. Generally speaking, engineered wood products can be divided into Glued-laminated timber (glulam), plywood, Laminated veneer lumber (LVL), solid wood panels (SWP), oriented strand board (OSB), medium density fiber board (MDF). (Figure2-1)

For CNC cutting, on one hand, the thickness and size of wood products are limited, normally for CNC Router, 200mm thick, 1500mm wide and 3000mm length are the maximum dimensions it can cut effectively and economically. On the other hand, laminated wood is preferred to solid wood because of warping. The characteristic of solid timber is influenced by its grain, knot; however, plywood (a kind of laminated wood product) which is made by banding together and pressing a number of thin layers of veneer, (Figure) has an even properties and strength in each direction, so its structural performance depend mainly on the number of layers and the thickness of each layer. Besides various kinds of thickness, the plywood sheet sizes are 1200mm*2400mm or 1220mm* 2440mm, which is flexible and suitable for CNC Router manufacturing as well. The homogeneity of laminated wood products as well as their producing sizes make it a suitable choice for digital fabricated timber structure. Here are some nomal wood products with homogeneity that are suitable for digital fabrication, in which MDF is not stable in high moisture environment, which is not suitable for external use., For different application, plywood has different kinds of products in several grades, such as structural plywood, plywood in different thickness, plywood in different raw materials.(Figure2-2,Figure2-3)
2.2 Timber construction system

2.2.1 Traditional timber construction system

Basically, there are four kinds of construction systems in timber construction, including log construction, traditional timbered structures, timber frame construction (also known as “balloon frame” in America, and “timber stud” in Europe), frame (skeleton) construction and panel construction. (Figure2-4)

Log construction needs a large amount of timbers, which is not economic comparing to other construction systems. Traditional timbered structure is seldom used today, which is not suitable for CNC cutting due to its large structural members. In timber frame construction, the character of replacement of larger cross-section members by nailing several smaller squared sections together is suitable for CNC manufacturing. However, the members of standard sizes are not necessary. Panel construction and skeleton construction systems also employ large timber panels and posts and beams, which does not fit the restriction of economic CNC manufacturing. These timber construction systems have different logics of load transferring: log construction transfers load from log to log; timber frame construction mainly uses vertical elements, and horizontal ones as secondary elements; frame construction has horizontal and vertical elements of the same structural importance; panel construction transfers load by large solid wood boards. (Figure2-5)

2.2.2 New complex timber construction system

Many different timber construction systems are using in traditional wood construction, such as light frame construction, stressed-skin panels, box beams, heavy timber, special trusses, folded plates, arches and lamella construction. In 2+0.5D digital timber fabrication, the elements are basically timber sticks and plates cutting from timber plywood panels. To achieve complex form timber structure, basically, three of the construction systems are employed frequently after the study of a great amount of cases. They are Timber Lattice construction, Timber Frame (sectioning) construction and Folding Timber plate construction.

(1) Timber Lattice Construction

In this system, 2D timber plates or sticks cutting from laminated wooden panels are connected based on some logic to form the whole structural system. This structural system has an isotropical characteristic, so each element has the same degree of importance. Sometimes, the timber elements will be bended in the final structure. (Figure2-6)

2005 Serpentine Gallery Pavilion

“what if elements are equal and evenly distributed? what if they can only work in collaboration, relying on mutual support to create a spanning system?”

The design start with the answers of these questions. The reciprocal grid provided the solution. Each discrete element is two grid-bays long. It is supported by locking its ends into neighboring elements, and at the same time supports its neighbors. This construction is composed of 427 different components, cutting by the 3-axes CNC Router. The connection detail was precisely fabricated yet crudely assembled. (Figure2-7)
(2) New Timber Frame (Including sectioning) Construction
Timber frame is frequently used in timber structures. The basic idea to achieve complex form timber structure by timber fame construction system is to find a group of vertical section frames of the complex geometry, then to connect them transversely by secondary structural elements. Sectioning can be understood as a special kind of timber frame, in which the transverse connection is replaced by adding more section frames. (Figure 2-8)
Dunescape
This whole structure is composed of a great amount of 2”*2” cedar wood members. It can be understood as the combination of a group of section frames, each of which has several truss-like profiles. Set of section frames were constructed directly on top of each plot, and all the wood members are connected ed by 3” screws at each joints. Entire sets were placed aside and screwed together in place to create the final construction. (Figure 2-9)

(3) Folding Timber Plate construction
Folding, as a traditional structure principle, is quite suitable to explore the potential of structural performance of timber plates (especially cross laminated timber panels). The basic structural element-timber plates connect with each other edge to edge. The folded patterns are important for folding structure, which can be studied by Origami. The IBOIS research laboratory has studied timber folding structure for a period with fruitful findings. (Figure 2-10)
Temporary Chapel, 2008
This folded plate timber structure were constructed with folded laminated wood sheeting, allowing the spatial enclosure, the load-bearing structure and the internal finishings to be combined in a single layer.
Conclusion: From the reference projects studied above, the effective and economic digitally fabricated timber construction should employ a great amount of small timber members as a group or integrity to play the structural role. The small timber members can be timber plates or timber sticks. With a trapezoidal cross-section, the structure has basic three folded segments composed by groups of planar panels, which can be fabricated by the direct planning data. (Figure 2-11)

Conclusion:
a. In timber lattice system, we can find that timber construction in digital fabrication employs small interconnecting structural elements, in case one of the elements fails, the whole structure will not be collapse since the load of the failed element will be carried by adjacent elements.
b. New timber frame construction has less restriction for openning than lattice system and folding plate system.
c. Structural members will be timber plates or timber sticks or the combination; There are some restrictions for the dimension of the members.
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Figure 2-12

Figure 2-14
2.3 Wood Joints

Joints always play a critical role in any timber construction, no matter if it is a historical wooden house or a new digitally fabricated pavilion. The whole development of timber construction can be divided into three production technologies: hand-tool-technology, machine-tool-technology, information-tool-technology. These three technologies are related to each other more like “waves” than “steps”. As they both have overlapping parts. (Figure 2.12) From the first phase to the second one, the wood-wood joints made by high skilled carpenters were gradually replaced by the standard industrially fabricated steel connector. In information-tool-technology phase, the CNC production of a wooden detail is simultaneously both a manufacturing process and marking. A big benefit of building with wood-wood connector is that it can avoid the structural failures of wood building due to fire caused by weakening of metal connectors. The digital work flow (design to production) has re-introduced wood-wood joints with more potential and relevance.

2.3.1 Traditional wood-wood Joints

There have been numbers of ways of classification for wood joints, but there are always missing types in any classification system. Based on the usage of joints, they can be defined as vertical or horizontal applications, tension and/or compression resistance. Here, from construction point of view, I classify the wood-wood joints listed in “wood and wood joints” by Klaus Zwerger into three groups: end-end, end-edge, edge-edge. (Figure 2.13)

2.3.1 New wood-wood Joints in digital fabrication

Application of traditional wood-wood joints has been showed in digital fabricated projects, which promotes expressive horizons of assembly methods and expand the possibilities of digital fabrication.

CNC timber framing, University of British Columbia, 2006

This outdoor theater roof is a research project designed and fabricated in the University of British Columbia. The main focus of the project is the application of CNC design to production workflow in timber framing methods and traditional wood-to wood joints. The final complex interlock truss employs 2”x4” square lumber fabricated by CNC beam processor connected by customized timber joinery. (Figure 2.14) The trusses had to be reconfigured frequently to test if the joints achieve as small load as possible.
**Parawood—Non standard wood construction, CITA, 2008**

Parawood is a collaborative project between Center for IT and Architecture and companies of machining and software. Within this project a parametric design system was used to create production data for all the elements and joints. The construction geometry was parametrically controlled, so that all the mass customized beams were allowed to adjust location due to specific requirements of the chosen joints. In Parawood, 72 unique elements and 6 different types of traditional joints were employed, among those tenon, half rafter, double cut and dovetail joints. **(Figure 2-15)** By this project, the potential of combination of traditional craft and digital fabrication for complex geometry architecture has been explored.

**The Ripple Wall, Digital arts center, University of North Carolina, ?**

This wall is an installation in the Digital fabrication Lab in the university. The whole project used no mechanical or adhesive connections, employing only the precision of a 2.5-axis CNC Router to define built-in connection details. The diameter of the CNC router bit is 25", cutting a 25" wide slot on the structural ribs cut from 75" birch-veneer plywood. The panels which cut from 25" birch veneer plywood can nest cleanly into the 25" wide slot. This connection detail is a clear demonstration of how to introduce the machine’s parameter into the design. **(Figure 2-16)**

**Other cases:**

Digitally fabricated timber connection is studied and applied in furniture as well, some of which can provide inspiration to architecture. The Naked chair is a good example. Two structural elements as two chair legs interlock with each other, and the seat and back are cut to fit the in between space in the two legs. The principle can be applied to architecture, as the cladding is assembled in between interlocked structural elements. **(Figure 2-17)**
Conclusion:

a. With CNC milling or Router, the bit diameter will generate rounded corners and the machine vibration will create slight fluctuations in the cutting surface. The size of the elements cutting by CNC Mill/Router is a bit (offsetting in a depth of bit radius) smaller than the dimension designed. So, we should be aware of this. (Figure 2-18)

b. Choosing or designing the types of wood-wood joints, basic force analysis should be done. Based on different configurations, wood-wood connections have functions as tension resisting, compression resisting or both, some can resist upper loads. (Figure 2-19)

c. Interlock is frequently used in wood-wood connections. One of its advantages is that the interlocking joints can be easily assembled and disassembled; besides, by the strength it gets after joining without other structural element like wood butt, the connection becomes tighter.

Some simple practices of timber digital fabrication mainly on wood-wood connection did by Yusef Patel can tell some further information. Here are some images. (Figure 2-20)
2.4 Materialization of new timber building

2.4.1 Envelope of complex timber building

For timber buildings in complex form, the cladding can be timber elements, such as timber planks, panels and shingles. Geometry transformation is necessary when planks and panels are used. In “Peoples Meeting Dome”, the triangulated surfaces are covered by groups of planks from old boards. In ICD/ITKE research pavilion at the University of Stuttgart, polygonal timber sheets with finger joints produced by the seven-axis robot are employed. Larch shingles used in Chesa Futura can be another choice of cladding with consideration of water-draining characteristics. (Figure 2-21) Although they were cut by hand, it is possible to digitally cut shingles laterally and radially by CNC machine. The cladding system should be separated from the timber structure by a ventilated and drained cavity. Due to waterproof requirement, membrane can be an option for cladding of lightweight timber structure. Kreed pavilion and Center Pompidou in Metz both use membrane (PVC tensile membrane and pre-tensioned glass-fiber mesh membrane) as cladding. (Figure 2-22)

2.4.2 Production and Assembly

Optimization for production

After getting the exact geometry of all the single parts (the structural elements, the connections and the cladding elements), they will be arranged on boards of raw timber materials. In order to guarantee the waste of materials should be minimized, several options of the arrangement of elements should be studied, meanwhile, take the parameters of machine, process and raw materials into account. To crate the cut sheet of the Ripple Wall, all the panels were nested with a distance equal to the diameter of the router bit. The Ripple wall in Swissbau pavilion, even the additional details for production, the wholes for fixing boards on the table of CNC Router, were placed exactly in order to be used for connecting adjacent frames. (Figure 2-23)

Naming system

For a complex structure, all the elements should be in the exactly the correct placement with its neighbors, so a naming system is necessary, furthermore, they should be marked on each single element during the production phase. In the project GSAPP Trussset, the naming system of each connection node corresponded to its location in the UV grid, and the name of the structural member tells the nodes it connects and the direction. To mark each element, relief cutting on surface of timber elements by router bit is automatic and easy, using data from digital model. (Figure 2-24)

Customized falsework

For site construction, a falsework system may be needed, which also have to be customized in order to support the complex structure. In the research project “full scale timber prototype”, a group of labelled profiles were fabricated and assembled first to secure the position of the timber panels. (Figure 2-25)
Other factors
The weather condition is another important factor that should be considered for site assembly. For timber construction, because humidity changes the volume of wood, assembly should take place in dry weather. Big complex timber structure can be divided into several parts. So they can be assembled partly somewhere (maybe interior), then transported to site. In this condition, the constraints of the transportation should be considered. Besides, assembly order is parameter which can be introduced in the design process. In Ripple wall, each trunk should be assembled atop its neighbor in a serial construction process. (Figure 2-26)

2.4.3 Durability

Moisture Resistance
The plywood itself is required to be painted, full acrylic latex paint systems are recommended for structural plywood, which can tolerate expansion and contraction due to moisture change in exterior environment.
In Dutch environment, especially in wet condition, it is important to have cavity for draining and ventilation behind the cladding, keeping the timbers form long time wetting. For structural timber, the bottom side of the timber structural elements should be at least 150mm above the finished ground level to prevent the splashing rain from it.

Long-term shortening
Long-term is caused by moisture content reduction, joint tightening and elastic load effects. The deformation of the timbers is related to the direction of the grain. Due to the veneers running in two directions, the whole plywood elements can resist against shrinkage than normal timber.
3. Design and materialization of timber structure for cycling

For materialization of complex geometry architecture, a “digital process chain” should be implemented. For one thing, digital work flow allowing CNC manufacturing can fill the gap between the designer and manufacturer, for another thing, the digitally fabricated elements varying one by one can be automatically arranged and easily assembled, which fills another gap between skilled works and unskilled ones.

To materialize a complex structure for cycling, the design requirements on function, form, the materials and construction method should be defined, then, the whole parameterized digital model should be set up with clear geometry of each structural part as well. As the research is about digital fabrication in timber, wood and timber construction as well as economic digital fabrication has been studied, in which I can find input of material and construction method for the cycling structure.

3.1 Definition for the cycling structure

The first step of the “digital process chain” is to identify the requirements of architecture including shape, function and construction. As in the suburban context like Brettzone, a cycling structure with its facilities should be highly accessible by cyclists, provide a shelter from bad weather, and add spice to the cycling journey. These design aims guide to a curved lifted bridge like structure with a main cycling ramp in it, which can let the cyclist bike in and through and provide a nicer view on a higher level. Based on the regulation, the suitable gradient of a cycling slope should be gentle than 1/8th, guiding to a long span of the structure (for a 3m high structure, 24m2 as the total cycling route length is needed). The width of the cycling route is 3.5m more or less for adjacent cycling. The attached facilities including info room, bike-renting & parking, cycling-in restaurant, rest room, small club, storage require some over-sailing spaces along the cycling route, thus the curvilinear structure will have some protruding parts. (Figure3-1)

Along the long cycling route in Brettzone, Several this kind of cycling structure are going to be designed to fit different sites. The design of new adding cycling structures will respond to different constraints of the choosing sites. One of the sites (Site D) is just sitting across a motor road, which requires the structure lifted with only supports at two ends. So for site D, a digital model of the certain cycling structure can be set up based on these design input. (Figure3-2)
3.2 Construction system for the cycling structure

3.2.1 New Timber Frame structure (Figure 3.3)

Due to the form and the span, a reasonable structural system is a timber truss, normally achieving a span up to 50ms. Normally, to achieve a complex form building, sectioning in digital fabrication can be an easy approach. Combined with timber frame construction, which is a traditional way of constructing a timber building, the new timber frame construction system is employed. For the curvilinear cycling structure, the complex geometry can be understood as rigid connections of a group of sections. (Figure 3.4) The curved profile of each section can be converted into polylines for materialization of cladding. All the polyline profiles will be the main frame of the structure, then using transverse beams to connect them to form the rigid body. To study this structural idea, a physical model of part of the whole structure is employed to explore the possibility of this complex timber frame structure. (Figure 3.5)

For this approach, even the whole geometry is a rigid body, but the load transfer is not efficient. The reason is that the vertical elements do not take any role in transferring loads to the two end supports, which will make the horizontal frames too much bigger.

3.2.2 Case study for timber lattice construction system

Qingpu Pedestrian Bridge (Figure 3.6)

This winding bridge is using a metal truss as structural model. In order to resist the strong torsion stress associated with the support-less shape of the bridge, we need to activate structurally all the sides of its distorted volume. Not only the vertical, but also the horizontal surfaces of the bridge behave like a three-dimensional beam, working as a whole, like a tube, and deformed following the direction of the zigzag. The design of the bars that form each surface expresses the results of another important structural analysis, in this case the diagram of shear stress. For the layout of the profiles, instead of using a regular pattern whose bars become thicker when the stress is higher, the designers prefer to make the pattern denser, but still using the structural elements with the same section. Based on the site conditions, the two ends the bridge truss connect the concrete foundation in two different ways: simple support on the North, rigid connection on the South. This also guides to an asymmetric diagram of bending momentum, and the condition is also translated to the design of the lateral surface.

Form the study of this curved lifted mental truss, we can get some basic structural principle:

a. The structural concept of this kind of curved lifted mental truss can be understood as arch plus truss. For arch, the middle part of this structure should higher than the two ends, which is the requirement of the design as well. For truss, each surface of the geometry should be transferred to nets of structural elements.

b. At the supporting ends, on one side, the structure should be connected with ground rigidly; on the other side, the structure only needs a support, in order to release the strength from structural deformation.

c. The density of the structural pattern has relationship with the distance between the part of the structure and the supporting ends, the closer, the higher.
3.3 Structural Pattern

Density variation
For digital fabricated timber truss structure, the dimension of the elements is restricted to some extent, thus varying the pattern density is an efficient way to deal with the structure of the complex form. Based on economic and efficient reasons, one constraint for the size of structural element is the restriction of the maximum cutting size of the normal CNC machine, for CNC router, the size of 1.5m*3m*200mm can be achieved. Another factor is the size of the suitable wood products. Like for plywood, the custom sheet sizes are 1200mm*2400mm or 1220mm*2440mm, and thickness is always 50mm more or less. (Figure3-7)

Joint displacement
The construction of timber truss is quite different from metal truss. In metal truss, the joints of metal truss elements are usually made by welding to get stiff. In timber truss construction, especially in a 3D structure, it is not a durable solution to join several wooden elements together at the same location by wood-wood connection, which will make the wood joints too complicated that simple fabrication tool can not achieve, even weaken the connection due to wood cutting. (Figure3-8) So, an efficient way to avoid these weak nodes is to stagger the connection position. It is clearly showed in several projects. Additive Robotic Fabrication of Complex Timber Structures is a research project in ETH. The intersection nodes of the cross quadrilateral pattern have been transferred into two half cross connections. Another example using the same method is the small pavilion in Native Child and Family Services of Toronto. The timber structure is even covered totally by birch heartwood. In Kreod Pavilion located in Greenwich Peninsula, 3 in 1 intersection nodes of hexagonal structure were converted into three 1-1 simple connections. (Figure3-9) Other patterns can be transferred to 2-elements joint pattern as well. Here are two study cases made by author to transfer complex joints of triangular and Hexagonal pattern into 2-elements joint pattern by shifiting the joint. (Figure 3-10)

Interlocking wood-wood connection
Through this kind of joint displacement for a certain pattern, complex form can be achieved by simple 2-elements joint system. An efficient way to connect two wood elements is to have interlock between these two timber elements. Further research on what kind of interlocked joint can be achieved by simple digitally fabricated wood elements should be conducted.
3.4 Conclusion

a. To design a structure of timber complex geometry architecture, the first step is to define the geometry, and then a certain construction system should be chosen. Based on this, the constructive details should be studied.
b. For architecture of complex geometries, timber lattice structure system has more flexibility to realize it than other systems.
c. The pattern of timber lattice structure is defined by architectural input and structural calculation, as well as the design of construction details.
d. Instead of joining several structural elements at one point, 2 elements-joint getting from shift pattern is more durable and suitable for timber complex structure.
4. Conclusion and recommendations for the graduation project

Wood is a suitable choice to materialize architecture with complex form with the benefit of digital fabrication. There are a great many of practical works by digital fabrication in wood. To study these works as well as the related literatures, I get lots of useful knowledge about timber complex architecture. The basic conclusions which can give inspiration to my graduation project are listed as below:

a. New complex architecture asks for new timber structure systems.
b. Different wood products have different properties. For CNC cutting, laminated wood products are more suitable for structural uses.
c. In new complex structure system, rather than define the main structural system, to give full play of the structural role of small elements can be an efficient way. This is also an constraint of economic CNC cutting.
d. With the benefit of digital fabrication, wood-wood joint comes back to timber structure as an economic and architonic joint system. Research of the traditional wood joints can give us a lot of inspiration for new timber joints.
e. In order to form the timber structure system, certain constructive details should be explored and defined based on the constraints from CNC machine and force analysis.
f. For any timber construction, certain treatment to resist moisture and insect is necessary, like coating.
g. Timber lattice structure is a flexible structure system for architecture in different complex forms. To design a timber lattice structure, the construction details and the pattern are two important factors. Undoubtedly, structural analysis and calculation should be conducted.
5. Bibliography


Oliver Neumann, CNC timber framing-Innovative applications of digital wood fabrication technology. [pdf]. Available at: http://cumincades.scix.net/data/works/att/sigradi2006_e151c.content.pdf


Approximate span ranges for timber systems

<table>
<thead>
<tr>
<th>Material</th>
<th>Minimum span</th>
<th>Possible span range</th>
<th>Maximum span</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planking</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Joists</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stressed-skin panels</td>
<td>L/24–L/30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laminated beams</td>
<td>L/18–L/20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Box beams</td>
<td>L/18–L/20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trussed rafters</td>
<td>L/5–L/7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open-web joists</td>
<td>L/18–L/20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat trusses</td>
<td>L/10–L/15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaped trusses</td>
<td>L/7–L/10</td>
<td></td>
<td></td>
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<tr>
<td>Plywood folded plates</td>
<td>L/7–L/12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laminated arches</td>
<td>L/4–L/6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Structural pattern cases