HOW TO USE TIMBER STRUCTURES TO CREATE LARGE-SPAN ARCHITECTURE SPACE

Jing Qi
Faculty of Architecture & the Built Environment, Delft University of Technology
Julianalaan 134, 2628BL Delft

ABSTRACT

Wood is a renewable material with good ecological properties, and its widespread use helps to reduce energy consumption during construction activities. In addition, the advancement of industrial production technology has brought about changes in material properties and advancement in structural technology, which has played a role in promoting the development of modern large-span timber structures. Under the proposition of large-span timber structures, five important elements constitute the main part of the research, namely, material properties, typology of large-span timber structures, production and construction, joint construction and sustainability, which helps to find the efficient way to create large-span architecture space by using timber structure.

KEYWORDS: *Lightweight, Typology, Timber Structure, Sustainability, Large-span*

I. INTRODUCTION

Wood is a renewable building material with relatively low environmental load. Its scientific use can reduce the burden on the natural environment due to human construction activities. Over millennia, the knowledge about construction with wood and the associated architectural language spread throughout the world. The first methods of construction evolved and the necessary knowledge and skills for dealing with wood as a building material were gradually amassed. At first this was in connection with simple housing, but later came to be used for more complex internal layouts. (Thomas Herzog, 2004) Wood can now be used by architects in large-span structures. The prefabrication of the wooden structure also makes it suitable for use in renovation projects and large-scale public building projects, which can reduce the construction period, costs, and production pollution. Therefore, the research question is - How to use timber structures to create large-span architecture space? The purpose of this research is to find ways to quickly and efficiently construct large-scale public buildings, and to provide new ideas for the reconstruction and addition of many concrete buildings.

Therefore, in the context of contemporary culture and technology, it is of great practical significance to study the architectural design of the modern large-span timber structure. This research takes modern large-span timber structures as the research object, and focuses on the most important points - structure, joint construction and energy-saving performance, to explore the performance of this structure type in contemporary architectural design and related design methods.

II. METHODOLOGY

Under the topic of large-span timber structures, five important elements constitute the main part of the research, namely, material properties, typology, production and construction of timber structures, joint construction and sustainable performance. The structure selection part involves morphology, and the sustainable performance involves the relevant knowledge of ecology. These five key factors have different sub-theories, and they together form the main framework of the entire research. In addition, these five elements influence and restrict each other in the selection of the final structure type and the determination of the structure form.

In general, this is a qualitative research. The entire research tries to understand the two concepts of timber and large-span building structures more clearly, and uses case analysis, classification methods and other methods to explain the scope of application, various properties, and construction processes of large-span timber structures more clearly. At the same time, in some more specific research and problems, quantitative analysis methods are also used, and for quantifiable aspects such as wood strength and energy performance, graphs and data analysis and research are conducted as well.

III. ELEMENTS

3.1. Material

As an important building material, wood is nowadays widely used in large-span timber structure systems. Therefore, some specific properties are worthy of in-depth study.

Wood is a porous material. The ducts, wood fibers and other cells that make up wood all have cell cavities. The porosity of wood has a great influence on its performance and direction of use: low thermal conductivity, mechanical elasticity, wood can absorb a considerable part of energy when impacted by heavy loads. (Liu Kang, 2012)

Wood is an anisotropic material. The structure and properties of wood have distinct characteristics in three directions. For example, the tensile strength of wood along the grain is 40 times that of the horizontal grain; the compressive strength of the wood along the grain is 5-10 times that of the horizontal grain. These two characteristics can be inferred from the cross-sectional view of the wood under the microscope.

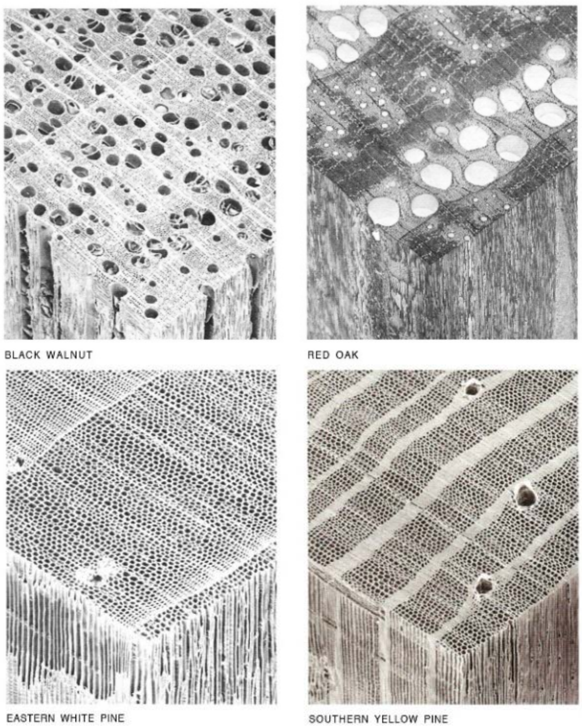

Figure 1. Cross-section of the wood under the microscope

Reference from: https://careforwood.wordpress.com/wood-anatomy/

Another very important feature is that wood, as a building material, is lighter in quality than other materials and is more suitable for large-span structural systems. The Material Property Chart made by Professor Mike Ashby can clearly show the characteristics of the material. It can be drawn from the chart that, under the condition of the same density, the elastic modulus and physical strength of wood have better properties than most other materials that can be used as building structures.

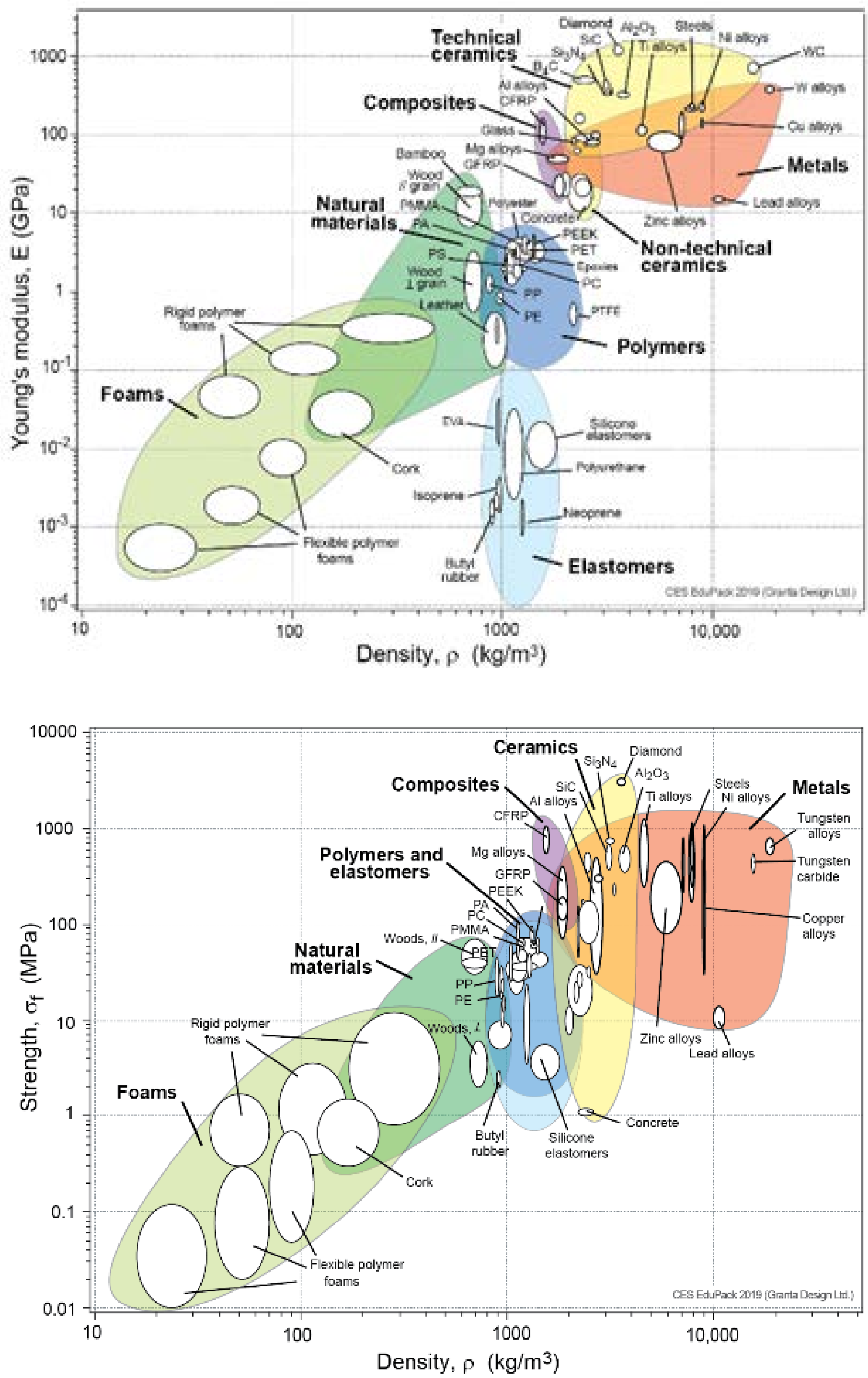

Figure 2. The Material Property Chart

Reference from: https://www.grantadesign.com/education/students/charts/

Natural wood has the advantages of light weight and easy processing, but it also has defects such as uneven texture and easy deformation. Due to the limited mechanical properties of the material itself, natural wood is mostly used in small and medium-span buildings, or parts of modern large-span wooden structures.

3.2. Typology

First of all, it's important to define what is large-span timber structure. Augus J. Macdonald mentioned in *Structure and Architecture*: A long-span structure is defined here as one in which the size of the span forces technical considerations to be placed so high on the list of architectural priorities that they significantly affect the aesthetic treatment of the building. (Augus J. Macdonald, 2019) Nowadays, buildings with wooden components as the main structure and spanning more than 30 meters horizontally are generally regarded as large-span timber structure buildings.

For a large-span timber structure building, its structural form can truly reflect the force of the structure, thereby expressing the internal logic of the structure. Therefore, for the classification of large-span timber structure buildings, analysis should be conducted on the basis of structural mechanics. In the entire structural system, the loading state of one single component can be analyzed separately, and under the action of different forces, the structural components show different morphological changes, and this morphological change is precisely the embodiment of mechanics logic. Under normal circumstances, the loading state of structural components can be divided into five categories: tension, compression, bending, shearing and twist. Therefore, the loading state of the internal components of the timber structural system has become the most important basis for classification.

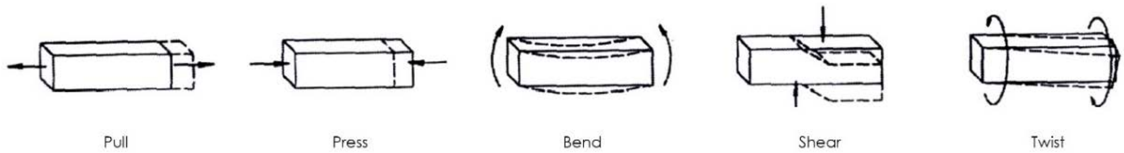

Figure 3. Categories of loading states.

3.2.1 Tension effect structure system

Wooden suspension structure

In the traditional large-span structural system, the roof's own weight and external load are transmitted to the foundation through the bearing and transmission of the lower supporting structure, forming a complete force transmission path. The advantage of the wooden suspended structure system is to reduce the consumption of structure materials and increase the span of the building space through the reorganization of the force mechanism. And because the wood itself has better tensile strength, the structural members with better tensile strength can be formed through the connection of steel joints.

Wood suspension cable composite structure

Suspended cable structure refers to a structural system that mainly uses cables to span a large space. These tensioned cables are used as the main load-bearing components and are suspended on the corresponding supporting structure. The suspension cable in the structure generally uses high-strength steel wire ropes, and the main structure is generally composed of wooden components.

3.2.2 Compression effect structure system

Arch structure

When arch structure facing the action of external force, internal bending moment of it is reduced to a minimum, the main internal force becomes axial pressure, the stress is uniformly distributed. At the same time, the vertical component of the axial pressure is used to resist the shear force of the structure, so that the internal shear stress of the structure is extremely small. Therefore, the arch structure is very suitable for compressive materials to build large-span structures.

3.2.3 Tension & Compression effect structure system

Truss structure

The truss is composed of upper and lower chords and web members, and its nodes are generally hinge points. When force acts on the node, all the rods have only axial force, and the material strength can be fully utilized at this time. From the overall point of view of the structure, the truss is a bending member, but for each member in the truss, it is a member in tension or compression. The truss structure can also be generally divided into two types: plane truss and three-dimensional truss.

Space truss structure

"The space truss structure refers to trusses unfolded in space. If the truss is a deformation of the beam, then the grid can be regarded as a deformation of the plate. The components of the space truss structure are all standard components. It is a homogeneous structure composed of rods of the same specification that can be mass-produced." (Peng Xiangguo, 2007) In the large-span timber space truss structure, most of the individual rods are made of glulam components. Most of the connections are made of rigid materials such as metal balls or bolts to form a stable structure system in a mass production method. The space truss structure can be divided into two types: three-dimensional truss system and pyramid space truss system.

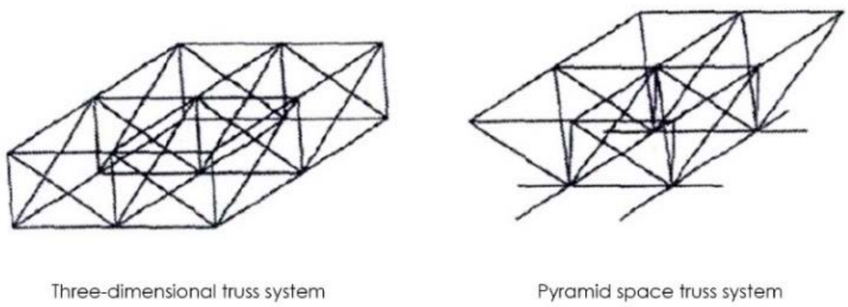

Figure 4. Three-dimensional truss system & pyramid space truss system.

Grid structure

The grid structure improves the structural defect that the linear arch structure departs from the plane and loses stability by crossing the linear arches. This structure is relatively simple and clear, and at the intersection of the structure, due to the simplicity of the design and construction of the wood joints, the structure is widely used.

3.2.3 Bending-shearing effect structure system

Portal frame structure

The main structure of the portal frame structure is arranged in the form of units. The units are combined into a portal shape by columns and beams. The portal frames are connected by lateral supports and standard bars. This structural form connects beams and columns through rigid nodes, changes the structural stress distribution, improves structural strength and span, and forms a very stable and simple structural system.

3.3. Production & Construction

3.3.1 Production

With the improvement and advancement of technology, the composite improvement of wood is more suitable for the contemporary construction industry system.

The first type is Glued-Laminated Timber. Boards or small squares with parallel wood grains are firstly terminated or side-joined in the length or width direction to form a laminate, and then laminated and glued in the thickness direction. Glued-laminated timber is not restricted by the natural size of the wood; it can be made into components with reasonable and variable cross-sections or curved components according to the characteristics of the force and the requirements of use. Glued-laminated timber can be configured with different grades of wood in the construction according to the different stresses that each part of the component bears, and the defects of the wood are layered evenly. The length and cross-sectional dimensions of the component are not restricted by the natural wood size, and can be made into various curved components according to the requirements of architects.

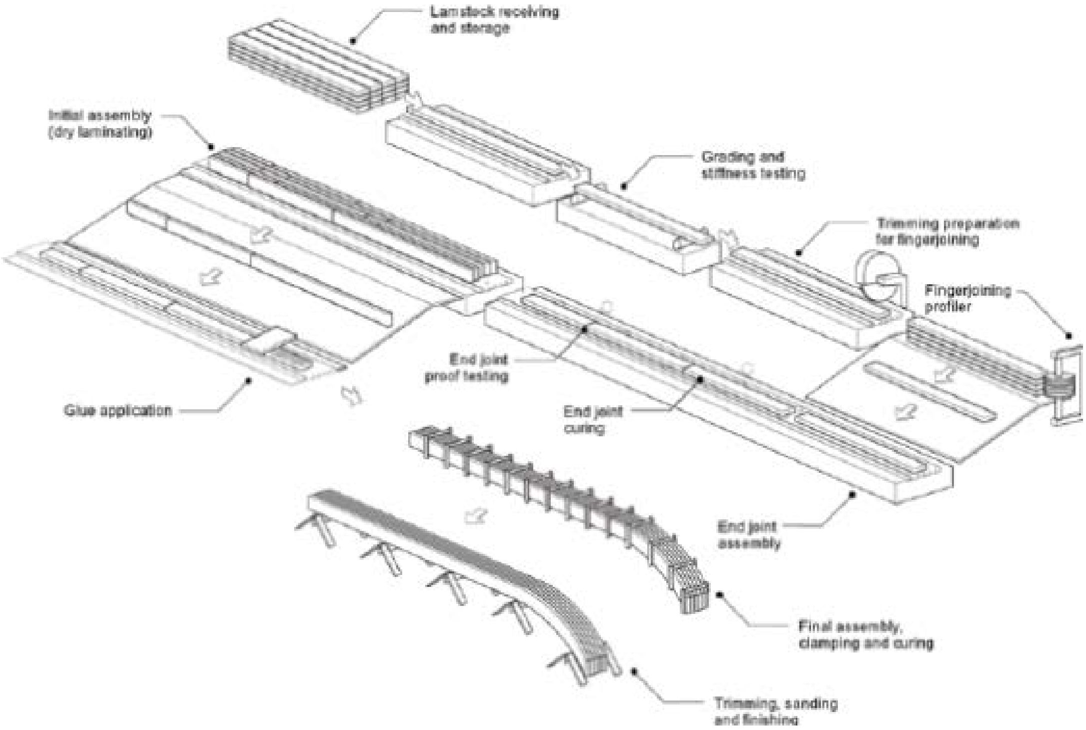

Figure 5. Production flow of Glued-Laminated Timber.

Reference from: https://www.researchgate.net/figure/Manufacturing-steps-of-glued-laminated-timbers-Canadian-Wood-Council-2005_fig8_251494186

The second type is wood-based structural panel. Wood-based structural panels refer to wood-based panels used for load-bearing structures, which are suitable for light wood structure floor cladding panels, roof panels and wall panels. This kind of board has the same size, and uses waterproof adhesive, through high temperature and high pressure and structural glue, to bond very small material particles or fragments to make products.

The third type is the wooden component. It is mainly produced based on new materials, and the characteristics of different materials are used to form a new wood component combination. The general wooden component refers to the component of the wood-based structural panel and the laminated wood glued with water-resistant glue, including laminated glulam thin web beams, prefabricated wood I-Joist beams and stress-skin ribbed panels.

3.3.2 Construction

For large-span timber structures, reasonable construction techniques and methods are beneficial to shorten construction time, improve construction accuracy, and reduce energy consumption. In most of the current large-span timber structure engineering cases, most of the main parts of the timber structure are prefabricated in the factory, and then loaded and transported to the construction site. It can also reduce the difficulty of construction, reduce a lot of high-altitude construction, which can improve the efficiency of construction. For the construction methods of prefabricated timber components on site, the following classifications can also be made.

Hoisting construction

Hoisting construction is to use lifting equipment such as tower cranes to move and fix the timber components that make up the main body of the building structure with relatively large volume and mass to a specific design position. After the main structural components have been installed and connected stably, the high-altitude installation and construction of the auxiliary structure will be carried out on this basis. (Li Yan, 2007) For example, in the Nine Bridges Country Club project designed by Shigeru Ban, dozens of structural support columns and the timber grid roof were transported to the construction site after the prefabrication in factory. After the main structure was fixed, then the tower crane was used to move the timber structure roof that has been evenly divided into multiple curved surfaces to its corresponding position and connected to the column.

Figure 6. Hoisting construction process of Nine Bridges Country Club.

Reference from: Nine Bridges Country Club / Shigeru Ban Architects" 03 Apr 2014. ArchDaily. Accessed 3 Jan 2021. <https://www.archdaily.com/490241/nine-bridges-country-club-shigeru-ban-architects> ISSN 0719-8884

Jacking construction

Jacking construction refers to a vertical transportation method in which the roof structure is assembled on the ground and then lifted to the design elevation by the action of a jack. The equipment used in this method are efficient and simple. The jack is supported upside down on the gasket under the timber roof structure. In the jacking method, the jack has a constant lifting weight and good stability. This construction method belongs to high-altitude operations. Measures should be taken during the jacking process to prevent the roof structure from shifting and pay attention to the synchronization of jacking. The common feature of jacking construction and hoisting construction is that the main structure is assembled on the ground and then installed vertically to the specified height with lifting equipment, but the difference is that the jack of the jacking method is under the structure, and the lifting equipment of the hoisting method is above the structure.

On-site gluing construction

On-site gluing construction refers to the assembly of the timber components that make up the main structure after being transported to the construction site. This construction method requires high accuracy of on-site gluing and splicing, and it also requires that most of the spliced timber components be the same components of the same specification, reducing the difficulty of on-site assembly. At the same time, on-site splicing has relatively high environmental requirements, such as temperature and humidity must meet certain standards before construction.

3.4. Joint construction

The technological progress of connecting joints between the components is also one of the main reasons for the continuous development of large-span timber structures. In the past, the connection between timber structures components was very simple. Especially in the oriental architecture world, the use of brackets, mortise and tenon joints and other forms that do not require joint components can also be used to construct large-span timber buildings, but this method is difficult to meet the demand of modern construction projects, the appearance of more and more new joints and connection methods have improved the shape, span and stability of timber structures.

3.4.1 Pin connection

Pin connection is a commonly used connection method in large-span timber structure systems. It uses steel plates, bolts or other connectors to connect timber components. The connectors are generally made of metal, which bear resistance of bending, shear, or tension between the connectors under load. This method is common in the connection between beams and columns and in some simple and homogeneous structures.

3.4.2 Hinged connection

Hinged connection is a joint that connects two wooden components together with metal components that can rotate at both ends. This kind of joint only transmits pressure and tension but not bending moment, allowing relative changes in the positional relationship between the components on both sides to meet the requirements of structural design. (Liu Kang, 2012) In actual engineering cases, hinged connection nodes are often used at the support of modern large-span timber structures or the connection position between columns and the horizontal structure of the roof.

3.4.3 Embedded connection

Embedded connection refers to crossing and stacking several layers of wood components in vertical direction, and then use bolts, gaskets and steel plates to fix the junction. This method is suitable for timber grid structures, because the wooden components are usually crossed and then embedded connection can ensure the local stability. In this method, the joints are small but effective.

3.5. Sustainability

Nowadays, timber structure buildings are becoming more and more important to people because of the excellent green ecological performance and sustainability of timber structure buildings, especially for large-span timber structure buildings due to its large amount of building materials and the huge building space. As a renewable material, wood has inherent advantages over other materials. Moreover, the performance of the whole life cycle of wood can not only regulate the natural environment during the growth process, but also requires very low energy consumption during the processing, production, and construction stages. Only one square meter of floor space supported by a steel beam emits 40 kg of $CO2$ and requires 516 megajoules of energy. Concrete is not much better, clocking in at 27 kg of $CO2$ and 290 megajoules of energy. In contrast, a square meter of floor space supported by a wooden beam only emits 4 kg of $CO2$ and requires only 80 megajoules of energy. In other words, constructing that square meter of space with wood instead of steel would reduce carbon emissions to one-tenth of its original output. (Lilly Cao, 2019) An Italian environmental assessment company named ATHENA compares the ecological performance of wood with the two main building materials, steel and concrete, to get the results in the following table:

Table 1. Comparison of the environmental impact of major building materials during the life cycle. (Nie Jinpin, 2016)

Material	Water pollution	Energy consumption	Greenhouse effect	Air pollution index	Solid waste	Ecological resource utilization
Wood	1	1	1	1	1	1
Steel	1.2	2.4	1.81	1.42	1.36	1.16
Concrete	1.9	3.7	1.25	1.67	1.96	1.97

In addition to the production and construction stages, compared with other structures, large-span timber structures also have excellent thermal insulation properties. Under the same circumstances, when the same thermal insulation effect is achieved, the thermal insulation performance of the timber structure is 15%-70% better than that of the steel structure. In the case of the same thickness, the thermal conductivity of wood is $0.17w/m^2 \cdot k$, which is slightly lower than the thermal conductivity of foamed concrete of $0.19w/m^2 \cdot k$, which is 1/10 of standard reinforced concrete and 1/150 of steel. The good thermal insulation performance of wood will save a lot of energy consumption in the use stage of large-span timber structure buildings, especially for large spaces, it can reduce the energy consumption of building ventilation, air conditioning, heating systems, etc.

IV. CONCLUSIONS

There is no doubt that large-span timber structure buildings will be more and more used in the future because of their unique advantages and characteristics. The five key points analyzed above, materials, typology, production and construction, joint construction, and sustainability, are the basic elements for studying large-span timber structure buildings. They are independent of each other, while they influence and restrict each other. These five elements have vital impacts that cannot be ignored to determine the structural form and generation of the plan.

How to create a large-span timber structure space? First, it is necessary to analyze the relationship between the site and the building, and also to combine the functional requirements of the building to determine the space, volume, scale and so on of the building. After a preliminary analysis on this basis, the main elements such as the approximate span, spatial pattern, and architectural form are determined. Then according to the mechanical characteristics and material properties of the wood structure, that is, its light-weight, tensile strength, and good compressive strength, the appropriate structure form is selected. Besides it, the selected structure must be able to truly and fully reflect the force of the structure, express the internal logic of the internal wooden components of the structure, and ensure the mechanical rationality of the entire structural system.

According to the characteristics of the force, the different large-span timber structure systems are divided into several categories. At the same time, according to the characteristics of large public buildings, the span and rise-span ratio of different structural systems are classified and compared according to the volume, as shown in the following table:

Table 2. Comparison of the various structure system's span and rise-span ratio.

Characteristics of the force received	Structure system	Geometric form	Applicable span	Rise-span ratio (S/L)
Tensile & Compressive stress	Truss structure	Plane	10m — 50m	1/14 — 1/10
	Grid structure	Space	15m — 120m	1/20 — 1/10
Compressive stress	Arch structure	Plane	18m — 200m	1/8 — 2
Bending-shear stress	Portal frame structure	Plane	20m — 90m	1/7 — 1/2
Tensile stress	Suspension structure	Plane	50m — 200m	1/20 — 1/10

On the basis of the selected structural system, it is necessary to go deep into the joint construction design, and use efficient and clear construction logic to solve the problem of the connection and ensure the stability of the overall structure. Finally, combined with the specific functional layout, streamline and other issues, combined with the structure itself, the enclosure system of large-span timber structures should be considered, and at the same time make good use of the characteristics of wooden buildings to ensure the environmental protection and sustainability issue.

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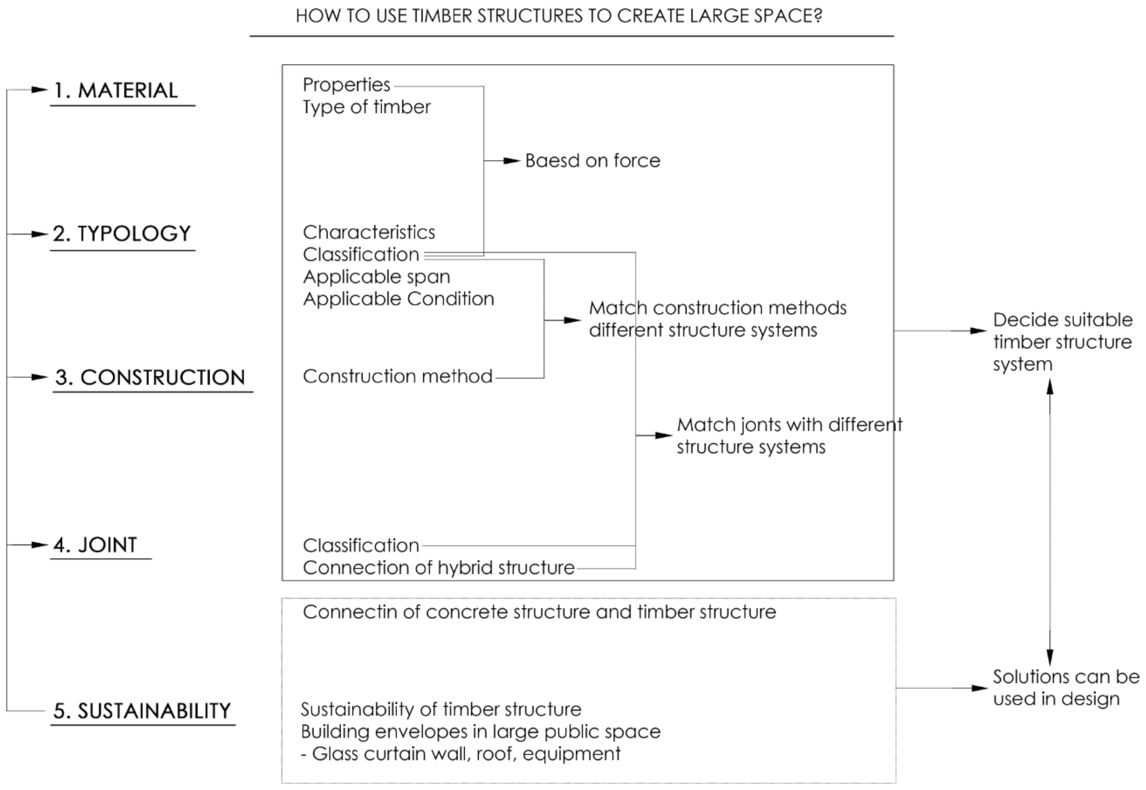
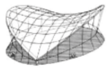
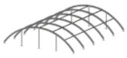
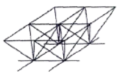
APPENDIX

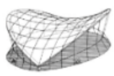
1.1



Appendix 1.1 Research structure, own image

1.2

	Schematic Diagram	Load Condition	Structure Member	Construction Method	Applicable Joints
Wooden Suspension Structure		Tensile stress	Wooden diagonal brace, Steel-wood hybrid roof/Steel cable	Lifting construction	Hinged connection
Cable Composite Structure		Tensile stress	Wooden column and arch, Steel cable	Lifting construction	Hinged connection
Arch Structure		Compressive stress	Wooden column, Wooden arch, Sec-ondary connecting member	Jacking construction	Pin connection
Portal Frame Structure		Bending-shear-ing stress	Wooden column, Wooden beam and secondary member	Jacking construction	Pin connection
Truss Structure		Tensile & Compressive stress	Wooden column, Wooden truss and secondary member	Lifting construction	Pin connection
Space Truss Structure		Tensile & Compressive stress	Wooden supporting column, Wooden members	Lifting construction	Metal ball connection
Grid Structure		Tensile & Compressive stress	Wooden roof, Support-ing system	Hoisting construction	Embedded connection

	Schematic Diagram	Applicable Span	Rise-Span Ratio	Main Features	Pros and Cons
Wooden Suspension Structure		50 - 200m	1/20 - 1/10	Steel-wood com-bination, Hybrid	-Large span -Single form
Cable Composite Structure		30 - 150m	1/20 - 1/8	Thin roof, Mem-brane, Hybrid	-Light-weight -Few connected joints
Arch Structure		18 - 200m	1/8 - 2	Small bending moment, Good compressive perfor-mance	-Small span -Single form
Portal Frame Structure		18 - 60m	1/10-1/2	Large internal space, Heavy weight	-Small span -Single form
Truss Structure		10 - 75m	1/10-1/5	Plane geometric form, Weak stiff-ness	-Good stability -Single form -Simple construction
Space Truss Structure		20 - 80m	1/14 - 1/10	Component stan-dardization, Strong stiffness	-Heavy weight -More consumables
Grid Structure		15 - 120m	1/20 - 1/10	Various forms, Integration	-Rich in form -Light-weight -Difficult construction

Appendix 1.2 Structure system properties, own image