Sustainable Future: Development and Potential of Modern Timber Structures

Qilin Chen *

School of Civil Engineering, Southeast University, Jiangsu, China

* Corresponding Author Email: 213193274@aa.seu.edu.cn

Abstract. The increasingly prominent issues of high energy consumption and carbon emissions brought about by traditional construction materials have led to the rapid emergence of modern timber structures as a sustainable alternative. This paper comprehensively analyzes the multiple advantages of timber construction, emphasizing its characteristics such as environmental friendliness, thermal insulation, seismic resistance, flexibility, and durability. The eco-friendliness of timber structures stems from wood being a renewable resource, and the construction process significantly reduces carbon footprint. Wood possesses certain flexibility and shock-absorbing capabilities, enabling it to dissipate energy during earthquakes and enhance the building's seismic resistance. Additionally, the design flexibility of modern timber structures allows their application in diverse complex scenarios to meet various demands. In timber structure design, optimization of mechanical performance remains crucial to ensure stability and safety. Implementing appropriate protective measures can prolong the service life of timber structures and ensure their safety in fire incidents. Numerous successful domestic and international cases demonstrate the feasibility of timber structures in various architectural contexts, highlighting their broad prospects for development. Particularly in China, the abundant potential of timber resources provides substantial opportunities for timber structure development. With advancing technology and accumulated experience, China's timber structure construction is poised to achieve significant breakthroughs. In summary, with its unique advantages, modern timber construction will continue to demonstrate its sustainable development value in areas including environmental friendliness, seismic resilience, and durability. It will play a crucial role in contributing to the sustainable development of future architecture.

Keywords: Timber; Timber structural system; Modern timber structure.

1. Introduction

Timber structures in China have a history that dates back thousands of years, with the earliest evidence tracing back to around six to seven thousand years ago. The popularity of timber construction began during the Qin and Han dynasties, and its technological advancements matured during the Tang and Song dynasties, reaching its zenith during the Ming and Qing dynasties. Elements like "mortise and tenon" joints and "Sunmao" bracket sets have long been recognized as symbolic representations of Chinese culture. Architectural marvels such as Yingxian Timber Pagoda and Foguang Temple exemplify the extraordinary craftsmanship of ancient Chinese timber structures. China held a significant position in global timber construction technology for a significant duration.

However, over the past century, due to excessive deforestation in modern times, the development of timber construction techniques faced a prolonged stagnation period. In the present-day Chinese construction industry, concrete and steel are commonly associated with modernization and industrialization, supplanting timber as the primary building materials. Yet, as China underwent rapid development following the era of reform and opening-up, the predominantly concrete and steel-based construction industry raised growing concerns. As of 2020, the construction sector accounted for approximately 45.5% of China's energy consumption and contributed to 50.9% of the nation's carbon dioxide emissions. This underscores the pivotal role the construction industry plays in energy consumption and carbon emissions [1]. Moreover, concrete, as the primary construction material, generates significant non-degradable waste without effective means of disposal upon reaching the end of its service life.

To address the issues of high-energy consumption and pollution within the construction industry, timber-an ancient and historically significant construction material re-emerged as a viable alternative, showcasing numerous advantages in terms of environmental sustainability. With the rapid rise of engineered wood products, notably cross-laminated timber, since the latter part of the previous century, a distinctive timber structural system has emerged. Numerous cases in Europe and North America have already demonstrated the immense potential of timber structures. In China, abundant forest resources coupled with an increasing awareness of environmental protection are expected to drive substantial growth in timber structures.

This article will focus on the characteristics and main forms of timber structures, provide a comparative analysis of current developments in timber structures both domestically and internationally, and offer a glimpse into the future of timber structure development in China.

2. The Characteristics of Timber Structures

2.1. Advantages of Timber Structures

In contrast to concrete and steel, modern timber structures possess numerous advantages, including the renewability of timber, low energy consumption, low pollution, excellent thermal insulation, lightweight structural properties, aesthetic appeal, and ease of assembly, seismic resistance, and durability.

2.1.1. Environmental friendliness

Timber resources possess a stronger regenerative capability. Timber can naturally grow cyclically through solar energy, as long as there's a balance between accumulation and consumption and rational harvesting. In comparison to other materials like brick, concrete, and steel, timber can be regenerated over cycles of approximately 50 to 100 years. Currently, with the development of forestry and timber processing industries, an increasing number of fast-growing species can also be used in building structures, significantly shortening the regeneration cycle of forestry resources. Predictions estimate that around 2029, China's timber supply source will shift from foreign markets to the domestic market, and forest resources will also be positioned to meet the market's timber demand, providing favorable conditions for the future development of timber structures in China [2].

Timber is an environmentally friendly construction material that, compared to concrete and steel, demonstrates lower environmental impacts across various aspects. In terms of energy consumption during construction, timber structure buildings consume only 45% of the energy of concrete buildings and 66% of the energy of steel structures. Additionally, timber structure buildings exhibit lower carbon dioxide emissions, accounting for only 66% of those from concrete buildings and 81% of those from steel structures [3]. Furthermore, a comparative study indicates that replacing concrete wall panels with Cross-Laminated Timber (CLT) panels can effectively reduce greenhouse gas emissions by 44.6% and energy consumption by 49.3% [4]. Timber structure buildings also outperform in terms of air pollution, with levels ranging from 4.3% to 15% of concrete buildings and 3.5% to 66% of steel structures [5]. Additionally, timber structure buildings exhibit lower water pollution indices, accounting for only 47% of those from concrete buildings and 29% of those from steel structures. In terms of ecological resource consumption, the indices for timber structure buildings are also lower, with 52% of concrete buildings and 88% of steel structures [6]. Unlike the past assumption that timber structures may harm the environment, trees indeed absorb a significant amount of carbon dioxide and release oxygen during their growth and maturation process. Although the carbon sequestration capacity of mature timber diminishes, the amount of carbon dioxide released during natural decay is relatively minimal. Considering that, unlike concrete, the construction waste generated by timber structures after demolition is biodegradable, timber structures are an environmentally friendly choice among major building materials today.

2.1.2. Thermal insulation

Timber boasts exceptional thermal insulation properties. This is due to the inherent structural characteristics of wood, where the cells contain voids, forming a natural hollow material structure. This structure slows down the rate of heat conduction, thus imparting timber with commendable thermal insulation performance. Consequently, timber structures are praised for their ability to provide warmth in winter and coolness in summer. Data reveals that when comparing the thermal conductivity coefficients of Cross-Laminated Timber (CLT) and cement mortar, the former is merely 32% of the latter [3]. Moreover, lightweight timber structures incorporate ample space for insulation materials within their structural framework and wall panels, further enhancing their thermal insulation capabilities. Such structures are considered an ideal form for residential housing.

2.1.3. Seismic resistance

Timber structures are characterized by their lightweight nature. Common timber typically ranges from 300 to 900 kg/m³, while Cross-Laminated Timber (CLT) falls around 400 to 700 kg/m³, making it at least 64% lighter than concrete and possessing lower density compared to traditional building materials. The strength of wood is influenced by factors such as load type, load direction, and wood grain. Nevertheless, with proper design, the compressive and bending strength of wood in the grain direction remains quite high. Thus, in the context of reasonable design, timber structures tend to have lighter overall weight.

Furthermore, timber structures benefit from excellent seismic performance due to their relatively light mass. The impact of earthquakes on structures is closely related to their mass, and the lightweight nature of timber structures means they experience lower seismic forces. Additionally, the lighter mass of timber structures results in reduced harm to occupants during collapse caused by earthquakes, making them comparatively safer than other building materials.

Moreover, timber structures often exhibit favorable ductility and toughness in their overall structural systems. Therefore, in various strong earthquakes both domestically and internationally, timber structures have demonstrated outstanding seismic performance. It is particularly noteworthy that lightweight timber structures, widely used in residential construction, hold a significant share. These structures not only possess a lightweight self-weight but also feature well-distributed connections between panels and dimensional lumber, providing high structural redundancy and excellent lateral stiffness for wall systems. This exceptional lateral stiffness contributes to the remarkable seismic performance of lightweight timber structures.

2.1.4. Flexibility

Timber structures exhibit the characteristic of easy assembly and construction. Wood possesses excellent malleability during processing, allowing it to be cut into various required shapes and achieving a high degree of prefabrication. As timber structural components are relatively lightweight, they are more convenient for transportation and installation, thereby enhancing the feasibility of assembly-based construction. In the field of lightweight timber structures, even standalone villas can be constructed without the need for large equipment. For high-rise timber structures, such as the 18-story tall wood hybrid structure student residence "Brock Commons" construction was completed within 18 months, whereas an equivalently sized concrete building would take around 22 months to complete. Brock Commons saw the installation of two large-scale timber structure floors and prefabricated facades each week. Importantly, timber floors are immediately available for construction after installation. In contrast, concrete forms need to be removed after the concrete reaches a certain strength post-initial setting, whereas timber structural prefabrications can be produced in factories. This not only accelerates construction speed but also reduces noise and disturbance to neighboring properties compared to concrete forms [7].

2.1.5. Durability

Timber structures possess a certain level of durability. When subjected to proper design, effective moisture-resistant constructions, and appropriate fire prevention measures, the durability of timber

structures can be effectively ensured. Examples like the Yingxian Timber Pagoda built in 1056 and the Foguang Temple Grand Hall with over 1200 years of history showcase ancient Chinese timber structures. Globally, structures such as Japan's Horyu-ji Temple and Norway's Stave Church boast histories approaching or even surpassing a thousand years, while Europe also preserves numerous 19th-century timber structures. These ancient buildings testify to the enduring nature of timber structures. In modern times, taking Japan as an example with its widespread use of timber structures, the lifespan of lightweight timber residential buildings reached 50 years or more in the 2000s, aligning with the regeneration cycle of specification materials used in such structures [8]. Furthermore, timber structures offer aesthetic qualities that other materials cannot match: wood possesses natural textures and warm colors, which, under the play of light, create a distinct texture, providing a close-to-nature feeling for those inhabiting these spaces.

2.2. Disadvantages of Timber Structures

Wood structures also have some disadvantages, which can sometimes impact their applications. Therefore, when designing, it's important to consider appropriate measures to mitigate these drawbacks and avoid adverse effects on usage.

Wood exhibits distinct characteristics in both longitudinal and transverse directions, making it an anisotropic material in terms of mechanical performance. The strength of wood is closely related to factors such as the nature of applied forces, direction, and wood grain orientation. There are significant differences in strength between tension and compression along and across the grain, with compression along the grain having relatively higher strength. Therefore, in design, it's preferable to have components bear compressive forces whenever possible and to avoid tensile forces, especially in the transverse grain direction. Additionally, simple and direct load-bearing connection designs should be used to minimize stress concentration and the occurrence of complex stress states.

Wood is susceptible to corrosion. Experimental evidence shows that the strength of wood decreases by approximately 30% after undergoing several months of decay [9]. Wood decay is primarily caused by the growth of wood-rotting fungi, which thrive at temperatures around 20℃. To prevent wood decay, several effective measures can be taken: using dry wood, ensuring adequate ventilation and moisture prevention in the building, choosing naturally resistant woods, or applying wood preservation treatments.

Wood is prone to damage from various organisms such as termites and beetles. When wood moisture content is above 50% to 60%, a large number of wood-destroying insects can be found in the wood. However, these insects struggle to survive when the moisture content is below 10%. Therefore, controlling wood humidity effectively is a key measure to reduce or prevent pest infestations. Clearing construction sites and their surroundings of roots and decayed materials, and setting up chemical barriers, can prevent pest occurrence [10]. Heat treatment of wood can also be applied to kill insect eggs. After wood structures are attacked by pests, chemical treatments can be used.

The flammability of wood is a real concern. For wood structures, setting reasonable fire separation distances, safe evacuation routes, and installing smoke detection devices are critical measures to prevent fires. Moreover, modern large-sized components used in wood structures are relatively less prone to combustion. Wood ignites at around 250℃and chars at a rate of 0.6 to 0.7 mm/min. The charring layer on the wood surface delays the speed of combustion, providing some protection to the interior wood. Design typically takes into account the minimum size of structural components, allowing for structural function after charring and meeting the building's fire resistance design requirements. For CLT structures, consideration should be given to adhesive failure causing detachment after a fire. Experiments show that CLT with more layers has a higher fire endurance limit [11]. Overall, fire prevention requires comprehensive consideration from multiple aspects, including residents' awareness, choice of interior decoration materials, and sound fire-resistant design.

3. Forms of Wood Structures

The forms of wood structures are diverse and cannot be exhaustively listed here. However, contemporary wood structures can generally be categorized into light wood frame systems and heavy wood frame systems.

Light wood frame systems consist of closely spaced small-sized dimensional lumber connected together, forming light wood walls with structural sheathing covering. These parts are fastened with nails. The lateral resistance system of light wood frame structures mainly includes shear walls and floor systems. These walls, composed of skeletal frames and sheathing, resist horizontal forces such as those generated by earthquakes and wind loads. Meanwhile, the roof system transfers the vertical forces from the roof to the two perpendicular walls, thus allowing the wall to function in shear and distribute the forces parallel to the wall.

The small dimensions of the members used in light wood frame structures allow for efficient utilization of the wood and make sustainable forestry practices viable. Additionally, the lightweight nature, dense and uniform connections, and high structural redundancy of light wood frame structures contribute to excellent seismic performance. Moreover, these structures are characterized by modular design, convenient construction, concealed utility lines, and excellent thermal insulation properties.

In North America, light wood frame structures are extensively used in residential buildings, with approximately 85% of multi-story homes and 95% of low-rise homes employing this system. Furthermore, around 50% of low-rise commercial and public buildings, such as restaurants, schools, churches, stores, and office buildings, adopt light wood frame structures [12].

Heavy wood frame structures encompass systems like post-and-beam and beam-and-column structures. Differing from light wood frame structures, heavy wood frame systems employ larger-sized wood members and use joinery or metal fasteners for connections. Structurally, heavy wood frame systems often do not rely on walls to carry loads, allowing for open and diverse spatial configurations. Moreover, the larger dimensions of the wood members enhance fire resistance, eliminating the need for fire-rated gypsum board protection and showcasing the inherent beauty of wood and its textures.

Notably, emerging is the system of Cross-Laminated Timber (CLT), which capitalizes on the anisotropic nature of wood. It involves stacking odd layers of sawn timber or structural composite panels perpendicular to each other and bonding them with adhesive, fully exploiting the mechanical properties of wood. CLT is used in shear walls to resist lateral forces in buildings, such as those generated by earthquakes.

Apart from post-and-beam and CLT systems, there are also wood spatial structures. This includes wood gridshell structures, wood cable-net structures, and wood shell structures. These structures are characterized by exposed wood and are often used in large-scale public buildings like exhibition halls and airports to highlight the structural and aesthetic qualities of wood.

The fundamental distinction between light and heavy wood frame systems lies in the size of the wood members. Light wood frame systems use small-sized dimensional lumber, while heavy wood frame systems employ large-sized solid wood or glulam members, resulting in differences in spatial structures and fire protection measures. Beyond light and heavy wood frame systems, hybrid systems are emerging. For instance, concrete-wood hybrid structures use concrete for the lower stories and heavy wood for the upper ones or combine concrete core walls with external wood structures. Similarly, steel-wood hybrid structures use steel for framing or support. Hybrid structures combine different materials to maximize their mechanical properties.

4. Current International Status and Case Studies of Wood Structures

In North America, lightweight wood construction is the preferred building material. Taking the United States as an example, out of the 1.5 million new residential buildings constructed annually, 90% utilize wood structures [13]. Additionally, the wood industry is a cornerstone national industry in Canada, with a highly developed wood residential construction industry and standards. In Northern

Europe and Japan, a significant proportion of newly built low-rise residential buildings also employ wood structures.

In cities with scarce land resources and higher population density, tall buildings with heavy timber construction mainly using CLT are also rapidly developing.

The 25 King office complex located in Brisbane, Australia, was completed in 2018 and was the tallest timber structure building in Australia at the time. The building stands at 45 meters tall with 10 stories. The architectural design showcases the timber structure through transparent exterior walls, providing a warm and bright appearance. The use of glued laminated timber (glulam) and CLT is a distinctive feature of the building. The structure incorporates large V-shaped columns and a network of timber columns, while the interior features CLT floor panels for a warm and soft surface effect [14].

Situated in the heart of Sweden, Sara Kulturhus combines a theater, art gallery, public library, conference center, and hotel. The building rises approximately 80 meters with 20 stories. Sara Kulturhus includes 6 theater stages, a city library, 2 galleries, a 205-room hotel, a conference center, restaurants, a rooftop terrace bar, and spa facilities. The hotel building utilizes CLT modules around a CLT core, while the lower levels feature a combination of CLT beam-column systems and CLT shear walls. By replacing concrete with timber, the project significantly reduces carbon emissions, and the prefabrication of timber components greatly accelerates the construction speed [15].

International House Sydney, completed in 2017, features six above-ground levels constructed entirely with timber and glued laminated timber (glulam), even incorporating timber elements for staircases. The Y-shaped support structure at the base of the building visually highlights the load transfer path, giving the building a strong presence. The project also employs prefabricated timber components and precise construction planning, leading to a considerable reduction in construction time and improved quality control during construction [16].

The All-Wood Swimming Pool at Freemen's School in the UK, completed in 2017, uses a roof structure composed of glulam beams encased with CLT panels. The timber material provides thermal insulation properties and, with corrosion-resistant treatment, perfectly meets the pool's requirements. Continuous wooden beams are painted white, creating a vibrant and engaging indoor space [17].
From the examples above, it's evident that even in scenarios with high building density requirements or large-span public spaces like sports arenas, timber construction can excel. Moreover, in these projects, timber showcases impressive achievements compared to concrete in terms of construction time reduction and pollution reduction.

5. Current Domestic Status and Case Studies of Wood Structures

The Taiyuan Botanical Garden's three greenhouses employ a wooden grid shell structure without internal column supports. With a span of nearly 90 meters, it is one of the largest such timber structures in the world, creating a naturally open indoor greenhouse space. The shell is constructed using glued laminated timber (glulam) arranged in a two to three-layer intersecting pattern. Additionally, the park's tea house and restaurant utilize a construction method reminiscent of ancient Chinese wooden structures, where wooden beams are stacked and interlocked to support the roof structure [18].

Located in Nanjing, the Jiangsu Rehabilitation Hospital was completed in 2022. Glulam materials were employed for the roof on the 5th floor and the 7th to 8th floors, marking the first instance in the nation of using a wood-concrete hybrid structure in a multi-story building. The wood structure of the building incorporates CLT materials and innovative combinations of vertical and horizontal connections involving steel components embedded in wood columns, significantly enhancing the stability of the timber structure [19].

In terms of regulations, China has established standards and specifications for timber structures, including the "General Specifications for Timber Structures," "Design Standards for Timber Structures," "Technical Standards for Multi-Story Timber Structures," "Technical Standards for

Prefabricated Timber Structures," and "Technical Specifications for Glued Laminated Timber Structures." Comparatively, China's timber structure standards and regulations have absorbed and transformed advanced technologies from other developed regions like Europe and North America, achieving an advanced level. In terms of construction acceptance, operation maintenance, and seismic design, China has certain advantages [20].

The above content illustrates that China currently possesses the technology to construct and develop timber structures. However, there are still some limiting factors in China's timber structure development. According to the "China Forest Resource Report (2014-2018)," although China's forest area is approximately 220 million hectares with a forest coverage rate of 22.96%, the per capita forest resources are relatively scarce, forest quality is low, resource distribution is uneven, and available resources are limited. Currently, engineering wood materials still heavily rely on imported timber supply. Presently, China is the world's largest importer of timber.

Fortunately, according to the "China Forest Resource Report (2014-2018)," the ninth national forest resource inventory has shown an improvement compared to the eighth inventory, with a forest coverage rate of 21.63%, an increase of 1.33%. The national forest area has net increased by 12.66 million hectares. Compared to a 12% forest coverage rate 30 years ago, China's forest area and stock volume have consistently grown over the past 30 years. Currently, China's forest resources are growing the most and the fastest globally, with evident ecological improvements [21]. The future development of China's forest resources is foreseeable, especially with the promotion of low-carbon development and rural revitalization policies, along with recent improvements in regulatory standards. This indicates that the engineering wood industry related to forest resources can further develop in the future, reducing the proportion of imported timber and forming an independent and complete industry chain.

6. Conclusion

Summing up the above analysis, it is evident that modern timber structures, as representatives of sustainable development, are rapidly emerging on the global stage. Their multiple advantages in terms of environmental-friendliness, insulation, seismic resistance, versatility, and durability make them a viable alternative to traditional building materials. However, in the process of timber structure design and application, optimizing mechanical performance remains crucial to ensure stability and safety. Issues such as preservation against decay, insect infestations, and fire protection also need to be gradually addressed to extend the lifespan of timber structures and ensure their safety.

Whether on a domestic or international scale, numerous successful cases have demonstrated the feasibility of timber structures in various architectural scenarios. Especially in China, abundant timber resources provide unique advantages and enormous potential for the development of timber structures. With continuous technological advancements and accumulated experience, China's timber structure construction is bound to experience even greater breakthroughs and developments.

In conclusion, modern timber structures will undoubtedly continue to demonstrate their sustainable development value in areas such as environmental protection, seismic resistance, and durability. As a significant force in the future of the construction industry, timber structures will actively contribute to driving sustainable development in the architectural field and promoting more ecologically friendly urban construction. From a long-term perspective, timber structures are not just a choice of building material; they symbolize ecological balance and innovative development, leading the path toward a more sustainable and green future for architecture.

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