

Research Status of Modern Timber Structures in China and Abroad

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Abstract

This paper focuses on the timber structures in the field of civil engineering. It begins by clarifying the research background and significance, emphasizing its crucial role in the sustainable development of the industry, the enrichment of architectural forms, etc. Meanwhile, it sorts out the current research status at home and abroad, clarifying the advantages and disadvantages of existing achievements, laying a foundation for subsequent discussions. Subsequently, it deeply analyzes the basic characteristics of timber structures, including the physical and mechanical properties of wood, connection methods and joint details. It also introduces the innovative breakthroughs in systems and technologies of modern timber structures, such as new structural systems and the progress of fireproof and anti-corrosion technologies. Through practical examples in multiple fields, it presents its application in residential buildings, public buildings, and bridge engineering. In addition, it analyzes the technical and market promotion difficulties faced by the development of timber structures and gives corresponding countermeasures. In general, while summarizing the research results, it looks forward to the future development trend of timber structures, facilitating their continuous application expansion in civil engineering.

Keywords

Timber Structures; Wood Properties; Glued Laminated Timber Structures; Fireproof Technology; Anti-Corrosion Technology

1. Introduction

1.1. Research Background and Significance

Throughout the development of civil engineering, timber structures have occupied an important position [1]. From ancient traditional dwellings to magnificent palaces and temples, wood, with its unique advantages, became one of the major building materials, as exemplified by the Forbidden City in China and the Ise Grand Shrine in Japan [2]. These classic timber buildings are not only places for human habitation and activities, but also crystallizations of culture and art, witnessing the social

features and the development of architectural craftsmanship of various historical periods [3].

However, with the rise of modern industry and the acceleration of urbanization, new building materials such as concrete and steel have gradually become the mainstream in the field of civil engineering, and the application scope of timber structures has been restricted to a certain extent. In recent years, however, with a deeper understanding of the concept of sustainable development and ever-increasing requirements for building quality, timber structures have once again received widespread attention.

Compared with other building materials, wood possesses many remarkable advantages. First, wood is a renewable resource; during its growth it absorbs carbon dioxide and releases oxygen, exerting a positive impact on the environment and conforming to the low-carbon and environmentally friendly concept currently advocated worldwide [4]. Second, wood has good thermal insulation performance, which can effectively reduce the energy consumption of buildings during service and provide strong support for achieving building energy-efficiency goals. Third, wood is relatively light in weight and convenient to process and transport; during construction it can reduce reliance on large mechanical equipment, lower construction cost and difficulty, and help shorten the construction period. In addition, timber buildings also have unique aesthetic value; their warm texture and natural grain can create comfortable and cozy living and working environments for people, satisfying the pursuit of high-quality living spaces [5].

This study aims to deeply explore the application and development of timber structures in civil engineering. Through systematic research on their material properties, structural forms, connection techniques, fireproof and anti-corrosion measures, and durability, it reveals the advantages and potential of timber structures, providing a theoretical basis and technical support for promoting their wide application in modern civil engineering. This is of important practical significance for enriching architectural forms, promoting the sustainable development of the construction industry, and meeting people's increasingly diverse building needs.

1.2. Review of Research Status at Home and Abroad

Scholars at home and abroad have carried out extensive and in-depth research on timber structures [6] and have achieved fruitful results in many aspects, providing a solid theoretical foundation and technical support for the development of timber structures [7].

In terms of material performance optimization, foreign scholars have revealed the relationship between the composition of wood cell walls and their mechanical properties through research on the microstructure of wood [8], thereby developing high-performance engineered wood products such as laminated veneer lumber (LVL) and glued laminated timber (Glulam). These materials have higher strength and

stability, broadening the application scope of timber structures [9]. Domestic scholars have also carried out a large number of studies in this regard, such as testing and analyzing the material properties of domestic timber to improve its applicability in building structures [10].

In the field of structural system innovation, foreign researchers have designed a variety of new timber structural systems [11], such as the cross-laminated timber (CLT) structural system, which has good fire-resistant and seismic performance and has been applied in some multi-storey and high-rise buildings [12]. In addition, there are hybrid structural systems combining timber with other materials, such as timber-steel and timber-concrete hybrid structures, which give full play to the advantages of different materials and improve the overall performance of the structures [13]. Domestic universities and research institutions are also actively exploring timber structural systems suitable for China's national conditions, and have carried out relevant theoretical analyses and experimental studies [14].

As for fireproof and anti-corrosion technologies, foreign research is relatively advanced. A variety of new fireproof coatings and preservatives have been developed [15]; by improving their chemical compositions and formulations, the fireproof and anti-corrosion effects have been enhanced and the impact on the environment has been reduced. At the same time, the behavior of timber structures in fire has been studied, and performance-based fire design methods have been proposed, providing a more scientific design basis for the fire safety of timber buildings [16]. Domestic research, on the basis of introducing advanced foreign technologies, is also carrying out localized development and improvement to meet the needs of domestic timber buildings [17].

In terms of application research, foreign countries have widely applied timber structures in residential, commercial, public buildings, bridges and other fields, accumulating rich design and construction experience [18]. For example, in some low- and multi-storey dwellings, timber structures are favored for their rapid construction and good living performance [19]; in public buildings such as gymnasiums and exhibition halls, the unique aesthetic value of timber structures is fully displayed. In China, with the renewed understanding of timber structures and policy support, the application of timber structures in tourist buildings, characteristic town construction and other areas has gradually increased [20], but their application in high-rise and large-span timber buildings is still in the exploratory stage [21].

Nevertheless, the existing research still has some shortcomings. In terms of material performance optimization, although the performance of engineered wood products has been improved, research on the development and application of some new wood species is still relatively limited. In terms of structural system innovation, the construction techniques of some new structural systems are relatively complex and costly, which restricts their large-scale promotion. In terms of fireproof and anti-corrosion technologies, the durability and stability of some environmentally

friendly fireproof and anti-corrosion products still need to be further improved. In application research, the long-term performance monitoring and evaluation of timber structures under different regional climatic conditions are not yet complete [22]. These shortcomings provide directions for further exploration and improvement in this study.

2. Innovative Systems and Technological Breakthroughs of Modern Timber Structures

2.1. Development and Application of New Timber Structural Systems

2.1.1. Optimization and Upgrading of Light-Frame Timber Structures

Light-frame timber structures have broad application prospects in modern residential buildings [23], and their optimization and upgrading are mainly reflected in material selection, structural layout, and member design.

In material selection, more and more high-performance engineered wood products are being applied to light-frame timber structures. For example, specially treated laminated veneer lumber (LVL) is used as floor and roof joists. Compared with traditional solid wood joists, LVL has higher strength and stability; its material is uniform, which can effectively reduce the strength differences caused by natural defects of wood. At the same time, new structural composite wood products such as oriented strand board (OSB) are widely used as sheathing panels for walls and floors [24]. OSB has good dimensional stability and load-bearing capacity, can enhance the integrity of timber structures, and its production process is relatively environmentally friendly, conforming to the requirements of sustainable development.

In structural layout, in order to improve space utilization and seismic performance, the floor and roof systems of light-frame timber structures have been improved. By adopting a ribbed floor structural form, reasonably arranging joist spacing and adding rib beams, the floor bears loads more uniformly and can withstand larger loads, while the floor thickness is reduced and the indoor clear height is increased. In roof design, a spatial truss structure is introduced; by utilizing the principle of triangular stability, the overall stiffness of the roof is improved and its resistance to wind and snow loads is enhanced. For example, in residential construction in some earthquake-prone areas, the optimized light-frame timber roof can effectively transfer seismic actions to the foundation, reducing the risk of roof damage during earthquakes and ensuring the safety of residents' lives and property.

Taking modern residential building cases as an example, a residential community in a certain region of the United States adopted an optimized light-frame timber structural system. During construction, due to the high degree of standardized production and prefabrication of members, the construction speed was significantly accelerated [25]; compared with traditional brick-concrete residential buildings, the construction period was shortened by about one-third. At the same time, the good

thermal insulation performance of wood reduced the heating energy consumption of the dwellings in winter by about 20%, and the cooling energy consumption in summer also decreased, achieving remarkable energy-saving effects. In addition, the natural texture and warm tones of wood created a comfortable and cozy living environment for residents, improving living comfort and satisfaction.

However, light-frame timber structures also face some challenges in market promotion. On the one hand, consumers' awareness and acceptance of timber dwellings are still limited, and some consumers worry about the durability, fire performance and later maintenance cost of timber structures. On the other hand, compared with traditional building materials, the construction cost of light-frame timber buildings may be relatively high in some regions, mainly due to the high cost of wood processing and prefabricated member production, as well as the lack of professional construction teams [26]. Therefore, it is necessary to strengthen the publicity and promotion of the advantages of light-frame timber structures and improve consumers' awareness; at the same time, construction cost should be reduced through technological innovation and large-scale production, so as to promote the wider application of light-frame timber structures in residential construction.

2.1.2. Innovative Development of Glued Laminated Timber Structures

The innovative development of glued laminated timber (Glulam) structures is mainly reflected in the research and development of adhesives, the improvement of gluing processes, and the standardization of member manufacturing[27]. These innovations enable glulam structures to show unique advantages in large-span buildings and spatial structures of public buildings.

In the research and development of adhesives, important progress has been made in the development of new environmentally friendly adhesives. These adhesives not only have higher bonding strength, ensuring the stability of glulam members during long-term service, but also have better weather resistance and durability, reducing problems such as cracking of gluing surfaces caused by adhesive aging. For example, some bio-based adhesives have been developed; they have better compatibility with wood and can effectively resist the influence of environmental factors such as moisture and temperature changes, improving the overall performance and service life of glulam structures.

The improvement of gluing processes is also the key to the innovation of glulam structures. By adopting CNC processing technology and advanced gluing equipment[28], high-precision manufacturing and automated production of glulam members have been realized. By precisely controlling parameters such as wood moisture content, gluing pressure and temperature, the stability and consistency of gluing quality have been improved. For example, in the manufacturing process of glulam beams, CNC equipment can precisely cut wood according to design requirements and ensure the flatness of gluing surfaces and the uniformity of gluing

thickness, so that the mechanical properties of glulam beams are fully exerted, enabling them to withstand larger bending moments and shear forces and meet the needs of large-span buildings.

Taking a large-span glulam bridge as an example, it adopted an innovative glulam structural system [29]. The main span of the bridge reaches 80 m; by adopting a structural form combining prefabricated glulam arch ribs and the bridge deck system, the design goal of lightness and robustness was achieved. The curved shape of the glulam arch ribs was perfectly presented through digital design and precise manufacturing, not only satisfying the structural requirements of the bridge but also adding a unique landscape to the surrounding environment. In the spatial structures of public buildings, for example, a large exhibition hall adopted a glulam roof system; by utilizing the machinability of glulam members, a complex spatial grid structure was constructed, realizing the design concept of column-free large space[30] and providing spacious and flexible exhibition space for exhibition activities.

However, glulam structures also face some technical difficulties in large building projects. For example, glulam members are large in size and require special transport equipment and route planning during transportation to ensure that the members are not damaged. In on-site installation, due to the large weight of members, large hoisting equipment and professional installation teams are required, and the installation accuracy requirements are high; otherwise, the overall performance of the structure will be affected. To solve these problems, a construction method of sectional prefabrication and on-site splicing can be adopted to reduce the difficulty of member transportation; at the same time, advanced surveying and positioning technologies can be used to improve the accuracy and efficiency of on-site installation, ensuring the smooth application and promotion of glulam structures in large building projects.

2.2. Advances in Fireproof and Anti-Corrosion Technologies for Timber Structures

2.2.1. Advanced Fireproof Technical Measures

With the increasing application of timber structures in modern buildings, fireproof technology has become a key link in ensuring their safety. In recent years, a series of advanced fireproof technical measures have emerged, providing strong guarantees for the fire safety of timber buildings.

New fireproof coatings are one of the important means of fire protection for timber structures. Compared with traditional fireproof coatings, new fireproof coatings have higher fireproof performance and durability. For example, intumescent fireproof coatings can expand rapidly when subjected to high temperature, forming a thick thermal insulation layer that effectively prevents flame and heat from being transmitted to the interior of the wood [16], thereby delaying the combustion rate of the wood and gaining precious time for personnel evacuation and fire rescue. Some

new fireproof coatings also have good weather resistance; they can maintain their fireproof performance in the natural environment for a long time, are not easy to peel, crack or age, and greatly improve the fireproof reliability of timber buildings.

Fireproof boards also play an important role in the fire protection of timber structures. For example, fireproof boards such as gypsum boards and fiber cement boards have good thermal insulation performance and non-combustibility, and can be used as sheathing panels for timber walls, floors and roofs to form effective fire barriers. These fireproof boards can not only prevent the spread of flame, but also block the transfer of heat to a certain extent, reducing the damage of fire to the main body of timber structures. In practical application, the installation methods and structural details of fireproof boards are continuously optimized; through reasonable jointing and fixing methods, their fireproof performance is fully exerted while taking into account the aesthetics and practicability of the building.

Fireproof structural design is an important part of timber structure fire protection. Reasonable fire compartment division can effectively limit the spread range of fire and avoid the spread of fire in the whole building [31]. In timber buildings, by setting up fire walls, fire shutters and other fire separation facilities, the building space is divided into several relatively independent fire compartments. When a fire occurs in one compartment, the spread of fire to other compartments can be prevented, reducing fire losses. The provision of evacuation routes is also crucial, ensuring that personnel can evacuate quickly and safely to safe areas in the event of a fire. For example, a sufficient number and width of evacuation staircases and corridors should be provided, and evacuation routes should be kept unobstructed without obstacles; at the same time, conspicuous evacuation indication signs and emergency lighting equipment should be equipped to provide clear guidance for personnel evacuation.

Taking a timber public building as an example, it adopted an advanced fire protection system design. In terms of fire compartment division, according to the functional layout and usage requirements of the building, the building was divided into several fire compartments, and fire walls were used to separate adjacent compartments. The fire resistance rating of the fire walls met the requirements of relevant national standards, ensuring that fire would not easily break through the compartment boundaries and spread. The design of evacuation routes was also reasonable: multiple evacuation staircases and spacious evacuation corridors were provided; the width of the staircases and the dimensions of the steps conformed to ergonomic principles, facilitating rapid passage of personnel. The walls of the evacuation corridors were decorated with non-combustible materials, and evacuation indication signs and emergency lighting fixtures were installed, so that even in the case of power failure during a fire, sufficient lighting and clear indication could be provided for personnel evacuation. In the selection of fireproof materials, the surface of the structural timber of the building was coated with new intumescent fireproof coating, whose fireproof performance passed strict testing and certification, effectively

protecting the wood from being quickly ignited and burned in the event of a fire. At the same time, fireproof boards were used as the roof sheathing, further enhancing the fireproof performance of the roof and preventing fire from spreading from the roof to other parts. Through the comprehensive application of these fireproof measures, the timber public building could effectively control the spread of fire in the event of a fire, ensuring the safety of personnel's lives and the structural safety of the building.

From the perspective of development trends, performance-based fire design methods have broad application prospects in timber buildings. This design method no longer relies solely on traditional fire codes and standards; instead, according to the specific functional use, fire risk, personnel density and other factors of timber buildings, it formulates more scientific and reasonable fire design schemes through computer simulation and analysis [15]. For example, fire dynamics models are used to simulate the development process of fire and analyze the influence of different fireproof measures on fire spread, personnel evacuation and structural safety, thereby optimizing fire design so that fireproof measures can meet the actual needs of buildings more precisely and improve the fire safety and economy of timber buildings. With the continuous progress of science and technology and the ever-increasing requirements for fire safety of timber buildings, performance-based fire design methods will gradually become the mainstream direction of timber structure fireproof technology development, promoting the development of timber building fireproof technology toward a more intelligent and precise direction.

2.2.2. Efficient Anti-Corrosion Treatment Methods

The anti-corrosion treatment of wood is the key to improving the durability of timber structures [32]. In recent years, a variety of efficient methods have emerged in the field of wood anti-corrosion treatment, covering chemical methods and physical methods [33], and these methods have their own characteristics in terms of principles, operation processes and effects on wood performance.

Preservative impregnation in chemical methods is a commonly used anti-corrosion means. Its principle is to penetrate preservatives into the interior of wood through pressure impregnation, vacuum impregnation and other methods, so that the preservatives form stable compounds with the moisture in the wood, thereby inhibiting the erosion of wood by decay fungi, insects and termites. In the operation process, the wood should first be dried so that its moisture content reaches a certain standard; then the wood is placed in an impregnation tank containing preservatives, and a certain pressure or vacuum degree is applied so that the preservatives fully penetrate into the cell lumens and cell walls of the wood. Commonly used preservatives include chromated copper arsenate (CCA) preservative, ammoniacal copper quaternary (ACQ) preservative, etc. However, because CCA preservative contains heavy metal components, it has certain potential harm to the environment, and its use has been restricted to a certain extent. ACQ preservative is relatively

environmentally friendly and has good anti-corrosion effect, but it may have a certain impact on the mechanical properties of wood, such as slightly reducing the strength of wood; therefore, reasonable design and treatment should be carried out according to specific conditions in use.

Drying treatment and heat treatment in physical methods are also important anti-corrosion measures. Drying treatment achieves the anti-corrosion purpose by reducing the moisture content of wood and reducing the moisture conditions inside the wood that can support the growth of decay fungi. Common drying methods include natural drying and artificial drying. Natural drying has low cost, but the drying time is long and it is greatly affected by climatic conditions. Artificial drying, such as kiln drying, can reduce the moisture content of wood to an appropriate range in a relatively short time, but the drying temperature and humidity must be strictly controlled; otherwise, problems such as cracking and deformation of wood are likely to occur. Heat treatment processes wood at high temperature, causing partial pyrolysis and carbonization of some components in the wood, changing the chemical composition and physical structure of the wood, thereby improving the anti-corrosion performance and dimensional stability of the wood. During heat treatment, the cell wall structure of the wood changes, the hygroscopicity of the wood decreases, and decay fungi are difficult to survive and reproduce in such an environment. However, heat treatment will also darken the color of the wood, which may affect the appearance and processing performance of the wood; careful consideration should be given when it is applied in occasions with special requirements for the appearance of wood.

Taking outdoor timber facilities as an example, for the anti-corrosion treatment of timber boardwalks, the method of preservative impregnation combined with regular maintenance is usually adopted. Because timber boardwalks are exposed to the outdoor environment for a long time and are greatly affected by rain, sunlight, microorganisms and other factors [34], ACQ preservative with good weather resistance is first selected for impregnation treatment of the wood, so that the wood has certain anti-corrosion ability. During service, the boardwalk is inspected and maintained regularly, such as replacing timber boards with signs of decay in time and recoating the wood surface with preservatives or protective paint, so as to extend the service life of the boardwalk. For structures such as timber pavilions, in addition to preservative impregnation, drying treatment and appropriate structural design are combined to improve their anti-corrosion performance. Before constructing a timber pavilion, the wood is fully dried so that its moisture content is controlled within an appropriate range, reducing the risk of deformation and cracking of the wood during service. At the same time, in the design of timber pavilions, attention is paid to drainage and ventilation design to avoid long-term accumulation of rainwater on the wood surface, creating a good environmental condition for the anti-corrosion of wood.

In the innovative direction of anti-corrosion treatment technology, the development of green, environmentally friendly, long-acting and low-toxicity preservatives is one of the current research hotspots. Researchers are committed to finding natural plant extracts, biological fungicides and other components as substitute components of preservatives. These new preservatives are not only environmentally friendly, but also can effectively inhibit the growth of wood decay fungi [35] and have good anti-corrosion effects. For example, tannin, essential oil and other components extracted from plants have antibacterial and anti-corrosion effects; applying them to wood anti-corrosion treatment is expected to reduce the environmental pollution caused by traditional preservatives. In addition, the research and development of new anti-corrosion treatment processes is also advancing, such as supercritical fluid impregnation technology, which utilizes the special properties of supercritical fluids to make preservatives penetrate into the interior of wood more uniformly and deeply, improving the durability and stability of anti-corrosion effects. At the same time, combining multiple anti-corrosion methods, such as heat treatment first and then preservative impregnation, can give full play to the advantages of different anti-corrosion methods and further improve the anti-corrosion performance of wood, providing technical support for the safe use of timber structures in a wider range of fields and for a longer period. With the continuous development and improvement of these innovative technologies, the anti-corrosion treatment of timber structures will become more efficient and environmentally friendly, laying a solid foundation for the sustainable development of timber buildings.

4. Challenges and Countermeasures in the Development of Timber Structures

4.1. Technical Bottlenecks and Solutions

In the process of high-rise and large-span development, timber structures face many technical bottlenecks in structural performance [36]. With the increase of building height, the influence of wind loads and seismic actions on high-rise timber buildings becomes more significant, and their structural stability becomes a key issue [37]. For example, under strong wind, high-rise timber buildings may experience large lateral displacement, leading to a decline in occupant comfort [38] and even endangering structural safety. In the event of an earthquake, how to ensure that timber structures can effectively absorb and dissipate seismic energy and avoid collapse is an urgent technical problem to be solved [39].

The optimization of the mechanical performance of joints in large-span timber spatial structures is also an important challenge. Joints in large-span structures need to bear large axial forces, shear forces and bending moments. Traditional joint connection methods may suffer from local failure, stress concentration and other problems under such complex loading conditions [40], affecting the overall performance and reliability of the structures. For example, in the roof structures of some large timber

gymnasiums, the reliability of joints is directly related to the stability and safety of the roofs [41]; once a joint fails, it may lead to partial or even overall collapse of the roof, causing serious consequences.

Research institutions and enterprises at home and abroad have carried out active exploration and attempts in this regard [42]. Some foreign research teams have developed new timber structural systems, such as hybrid structural systems combining cross-laminated timber (CLT) with steel or concrete. Through reasonable structural layout and member design, the advantages of different materials are fully utilized to improve the overall stability and seismic performance of the structures [43]. In numerical simulation and analysis technology, advanced finite element software is used to simulate and analyze the mechanical performance of timber structures under various load conditions; through parametric research, structural design schemes are optimized, providing a theoretical basis for practical engineering [44]. For example, by simulating the wind-induced response of high-rise timber buildings under different wind speeds, the building shape and structural layout are adjusted to reduce the influence of wind loads on the building.

Experimental research is also an important means to solve technical problems [45]. A large number of timber structure tests, including full-scale model tests and scaled model tests, have been carried out at home and abroad [46]. Through experimental research, the mechanical performance data of timber structures under different loads are obtained, the accuracy of numerical simulation results is verified, and new problems are discovered and improvement measures are proposed. For example, full-scale tests are conducted on joints of large-span timber structures to study the failure modes and load-bearing capacities of the joints under different stress states [47], providing a basis for the optimal design of joints.

However, there are still some technical bottlenecks that need to be further broken through [48]. In interdisciplinary research, although certain progress has been made, the deep integration of timber structures with other disciplines (such as materials science, mechanics and architecture) is still insufficient; interdisciplinary cooperation and exchange need to be strengthened to jointly tackle technical problems. In large-scale full-scale test verification, due to high test cost, great technical difficulty and other reasons, related experimental research is still relatively limited; further investment and support are needed to carry out more large-scale full-scale tests with practical engineering guidance significance, so as to promote the development of timber structure technology to a higher level.

5. Conclusions and Prospects

5.1. Summary of Research Findings

This study conducted a comprehensive and in-depth exploration of the application of timber structures in civil engineering, covering multiple key fields such as material properties, structural systems, fireproof and anti-corrosion technologies, application

cases, and development challenges and countermeasures, and achieved a series of research findings of important value.

In terms of material properties, through detailed analysis of the physical and mechanical properties of wood, the significant influence of physical properties such as wood density, moisture content, dry shrinkage and wet swelling, as well as mechanical performance indicators such as compressive, tensile, bending and shear strengths, on the performance of timber buildings was clarified. This provides a key theoretical basis for the design and construction of timber structures, enabling us to select wood more scientifically and reasonably and give full play to its mechanical performance advantages, ensuring the safety and stability of timber structures. For example, in light-frame timber dwellings, reasonably designing member dimensions and connection methods according to the mechanical properties of wood can not only meet structural load-bearing requirements, but also effectively control cost and construction difficulty.

In the field of structural systems, the optimization, upgrading and innovative development of new timber structural systems such as light-frame timber structures and glulam structures have achieved remarkable results. The improvements of light-frame timber structures in material selection and structural layout have significantly improved space utilization and seismic performance; at the same time, application cases in residential buildings fully demonstrate their advantages such as fast construction speed, energy saving and comfort. Relying on breakthroughs in adhesive research and development, gluing process improvement and member manufacturing standardization, glulam structures have successfully met the needs of large-span buildings and spatial structures of public buildings. The successful implementation of projects such as large-span glulam bridges and exhibition hall roofs highlights their unique advantages and application potential in large buildings. The progress of fireproof and anti-corrosion technologies provides a solid guarantee for the safety and durability of timber structures. Advanced fireproof technical measures, including the application of new fireproof coatings and fireproof boards and the optimization of fireproof structural design, combined with the development trend of performance-based fire design methods, have greatly improved the fire safety of timber buildings. Efficient anti-corrosion treatment methods, such as the application of chemical preservative impregnation, physical drying and heat treatment technologies, as well as the research direction of green and environmentally friendly preservatives and new anti-corrosion processes, have effectively enhanced the anti-corrosion performance of wood, extended the service life of timber structures, and ensured that they can function stably and reliably under various environmental conditions.

In response to the technical bottlenecks and challenges faced in the development of timber structures, corresponding solutions and strategies were proposed. In overcoming technical difficulties, through the joint efforts of research institutions

and enterprises at home and abroad, certain progress has been made in improving the structural performance of high-rise and large-span structures and in construction technology and quality control, including the development of new structural systems, the application of numerical simulation analysis technology and experimental research, and the adoption of strict construction quality management systems, construction personnel training and advanced construction monitoring technology. These measures have effectively solved some key problems and laid a foundation for the further development of timber structures. However, sustained efforts are still needed in interdisciplinary research and large-scale full-scale test verification to break through the remaining technical bottlenecks and promote timber structure technology to a higher level.

In summary, this study reveals the broad application prospects and development potential of timber structures in the field of civil engineering. Their achievements in technological innovation and application practice provide strong support for promoting the sustainable development of the construction industry, and they are expected to play a more important role in future civil engineering construction, meeting people's needs for high-quality and green buildings. At the same time, they also provide useful reference and experience for research and practice in related fields, promoting the continuous improvement and development of timber structure technology.

5.2. Outlook on Future Development Trends

Looking to the future, timber structures show broad development prospects and potential in the field of civil engineering and will continue to evolve and innovate in multiple aspects to cope with changing building demands and global challenges.

In the research and development of new building materials, high-performance wood-based composite materials are expected to achieve further breakthroughs. With the continuous progress of materials science and technology, researchers will be committed to developing wood-based composite materials with higher strength, better durability and fireproof performance, such as nano-modified wood and fiber-reinforced wood composite materials. These new materials will not only retain the natural advantages of wood, but also overcome its inherent defects, providing more possibilities for the application of timber structures in high-rise, large-span buildings and special environments. For example, the application of nanotechnology may optimize the microstructure of wood, significantly improving its mechanical properties and dimensional stability, thereby expanding the application scope of timber structures and enabling them to play a role in more complex construction projects.

Digital design and manufacturing technologies will be applied more widely and deeply in the field of timber structures. With the help of advanced technologies such as computer-aided design (CAD), building information modeling (BIM) and computer

numerical control (CNC) machining, the design of timber structures will become more precise and efficient, and the manufacturing process will become more automated and intelligent. Through BIM technology, designers can carry out comprehensive virtual modeling and analysis of timber buildings, predict and solve problems in structural performance, construction technology and other aspects in advance, optimize design schemes, and improve building quality and construction efficiency. CNC machining technology can realize high-precision batch production of timber structure members, ensure the dimensional accuracy and quality consistency of members, reduce the workload and errors of on-site construction, lower costs, and promote the development of timber buildings toward industrialization and standardization.

The concept of green and sustainable development will be more fully reflected and deepened in timber buildings. With the increasing global attention to climate change and resource shortage, timber structures, as a renewable, low-carbon and environmentally friendly building material, will become an important choice for achieving the goal of sustainable building development. In the future, timber buildings will pay more attention to the improvement of energy efficiency; through the organic combination with renewable energy systems (such as solar energy and geothermal energy), zero-energy or low-energy operation of buildings can be realized. At the same time, the life-cycle management of wood will be more complete; every link from the planting, harvesting and processing of wood to the design, construction, use and demolition of buildings will follow the principles of sustainable development, minimizing the impact on the environment and realizing the recycling of resources and ecological balance.

Timber structures have potentially important roles and value in responding to challenges such as global climate change and resource shortage. As a carbon storage material, wood absorbs a large amount of carbon dioxide during its growth and continues to fix carbon during the service period of buildings, helping to reduce greenhouse gas emissions and alleviate the global warming trend. Compared with traditional building materials, the energy consumption of timber buildings in the production process is lower, which can effectively reduce the dependence on non-renewable energy and promote the optimization and transformation of the energy structure. In addition, with the sustainable management of forest resources and the development of planted forests, the supply of wood will be more stable and reliable, providing a solid material foundation for the long-term development of timber buildings.

However, to achieve the sustainable development of timber structures, future research still needs to focus on some key areas and key technical issues. In the development of high-performance wood-based composite materials, the relationship between the microstructure and macroscopic properties of the materials needs to be studied in depth, the preparation processes need to be optimized, the performance

stability and reliability of the materials need to be improved, and the problems of large-scale production and cost control need to be solved. In the intelligent operation and maintenance technology of timber buildings, the research and application of structural health monitoring technology, intelligent control systems and big data analysis technology should be strengthened [49], so as to realize real-time monitoring, fault diagnosis and intelligent regulation of timber buildings during service, discover and deal with hidden structural safety hazards in time, extend the service life of buildings, and improve the safety and comfort of buildings.

In addition, the standardization system of timber buildings should be strengthened, and the relevant design codes, construction standards and quality acceptance standards should be improved [50], so as to promote the standardized and orderly development of the timber building market [51]. Interdisciplinary cooperation and exchange should be strengthened to integrate the knowledge and technologies of materials science, structural engineering, architectural design, environmental science and other disciplines, promoting the innovative development of timber structure technology. Investment in timber structure technology research and development and talent cultivation should be increased, a sound talent training system should be established, and a group of timber structure professionals with innovation ability and practical experience should be cultivated, providing talent guarantee for the sustainable development of timber structures in the field of civil engineering.

In short, with the continuous progress of technology, the constant renewal of concepts and the in-depth development of research, timber structures will usher in more brilliant development opportunities in the field of civil engineering, creating greener, more comfortable and smarter building environments for humanity, playing an important role in the global sustainable development process, and becoming one of the important directions of future building development.

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