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The Development and Evolution of Building Structural Systems

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Abstract. Building structures are fundamental to the construction industry. The continuous improvement of building structures will not be the effect of the progress in one certain technology. It is the consequence of the interaction of several factors such as building materials, mechanical theory, construction technique and social needs. Adopting time as the main line, this article analyzes the developmental features of building structures in an orderly manner; studies the influence of the key structural system of buildings on their safety, durability and form; presents the practical cases of empirical structural systems, scientific structural systems and innovative diversified structural systems; summarizes the four basic elements that determine the iterative progress of structural systems; and on the basis of the newest research results at home and abroad, discusses the developmental trends of building structures under the condition of low-carbonization, industrialization and intelligentization. This study is of great significance in the study of the underlying principles that dictate the evolution of building structures and in designing current structures.

Keywords: building structures, structural systems, development trends, green buildings, intelligent buildings

1. Introduction

In light of the ongoing urbanization process in China and the "dual carbon" plan, the trend of building construction has been moving towards super-high-rise buildings, wide span buildings, unconventional geometry, and green low-carbon buildings. In turn, the existing structure system has become more and more incapable of coping with the requirements of modern architecture. Throughout the development of architecture, any innovation of the structure system has brought about an overall renewal of the architectural form and construction technique.

For better clarification of the forces that operate to determine how materials, concepts, techniques, and social requirements affect structural evolution, it is required to examine the evolutionary history of structural systems and have a thorough knowledge of the benefits, drawbacks, and application opportunities of different structural systems. Moreover, it will help develop a theoretical basis for the application of new structural systems like low-carbon structures, prefabricated structures, and intelligent structures in engineering applications by making use of the latest findings from home and abroad combined with future development prospects.

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Studies relating to the construction of buildings overseas started quite early and have led to the development of a more developed theory. Ascione F. et al. analyzed the evolution of structural systems of high-rise buildings and concluded that structures with various heights and functions show various patterns of selection and thus provide the necessary theoretical basis for the design of modern super-tall buildings [1]. Zamora-Castro S. A. analyzed new high-performance and low-carbon construction materials over a long period and showed that novel cementitious materials and recycling of building materials constitute the key strategy to reduce the high amount of carbon emitted during the process of building construction [2]. The group led by El Masry A. studied the BIM technology thoroughly and developed an intelligent building management and control system [3]. On the other hand, overseas researchers focused their investigations on the seismic performance of jointed traditional wooden structures of East Asia and further developed the theory of mechanical behavior of traditional structures [4].

Domestic research enjoys abundant resources, profound history, and many strengths in both historical accumulation and modern development. Yang Qingshan has studied the structure mechanism and earthquake resistance of ancient wooden structures in China, drawing lessons from the mechanical wisdom of traditional mortise and tenon structure [5]; Yang Dixiong systematically summarized the century-long development process of structural mechanics, pointing out the critical importance of advanced mechanical theory in the development of structure system [6]; Miao Ruyun and others have done research on the multi-objective optimization design of modern architectural structures, forming a structural design philosophy emphasizing safety, economy, and durability [7]; Wu Gang and Xiao Xuwen devoted themselves to the development of prefabricated construction, studying the driving role of industrial construction technology in structure system [8, 9]; Zhao Yuxi and others, combined with the "dual carbon" policy, have set forth a development route for low-carbon innovation of building structures [10].

2. Stages of evolution and core characteristics of building structural systems

2.1. Traditional empirical structural systems of ancient times

In olden days, before the time when productive forces and science had developed, the erection of building structure depended solely on experience and lacked theories for structural design; the building structure can roughly be classified into two types: the wood structure system and the masonry structure system.

Chinese traditional ancient architecture features mortise and tenon wooden structures, whereby there is flexibility in the loading capacity brought about by interlocking and overlaying of the materials. The mortise and tenon structure lacks a rigid fixing constraint, meaning that there is high flexibility and energy dissipation; therefore, they are able to resist both earthquakes and strong winds due to small frictional deformations and hence having seismic resilience [5]. Wood structural materials are easily accessible, highly flexible and light in weight, hence applicable for most architectural structures, including ancient homes, temples, and palaces. Nonetheless, weaknesses associated with wood cannot be ignored since it is flammable, susceptible to decay, and fragile, and hence not suitable for building skyscrapers.

The structural system in stone masonry is a commonly seen structural system in both Chinese architecture and ancient foreign architecture; it depends on the weight of the stone masonry and the bonding between stone masonry and mortar to resist loads. It can ensure great rigidity, high fire resistance, and high corrosion resistance. Ancient Western architecture utilizes arches and domes to change the route of loading; thus, it can create very magnificent architectural spaces, while stone

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masonry structure is widely used in Chinese architecture to construct ancient towers, city walls, and houses. However, the stone masonry structure has very poor tensile strength and shear strength, and it is a very brittle structure without great seismic capability. Moreover, these structures have very great self-weight and long construction period.

2.2. The modern scientific structural system of the industrial age

Through the advancements that were achieved in the area of materials science and theories of mechanics because of the Industrial Revolution, it became possible for the construction of buildings to be taken out of the realm of empiricism completely, and hence introduced into a more modern phase of development. The creation of steel and reinforced concrete revolutionized the whole idea of traditional building structures.

These materials possess such qualities as high strength, good toughness, and even distribution of stresses. Moreover, steel structures are relatively lighter than masonry constructions, and therefore, it is ideal for the construction of large span industrial and civic buildings. This is because of the tendency to build increasingly tall and large span structures and thus serves as the foundation for such developments. Reinforced concrete buildings have the benefits of concrete and steel materials. They overcome the limitations of any individual building material and have great constructional properties. They can be used in making different irregularly shaped parts.

Yang Dixiong in his investigation indicates that the perfection of the theoretical basis of the discipline of structural mechanics and material mechanics is one of the fundamental markers of the evolution of modern structural engineering science [6]. The engineering industry of today does not depend on the empirical evaluation of the situation anymore; thanks to the use of mechanical formulas, loading, internal forces, deformation and structural stability are estimated with precision, thus making it possible to develop a structure quantitatively. Nevertheless, structural systems in the modern environment are rather homogeneous and include mostly brick-concrete constructions and classical frame systems; construction still depends on manual casting, thus failing to meet the demands of modern structures.

2.3. A contemporary framework for diversified innovation

Under the swift development of urbanization, the demand for building functions has been diversified; under the emergence of tall buildings, big span buildings, and strangely-shaped buildings, the development of the structure system is undergoing a new phase of innovation with high efficiency, diversity, and accuracy. And in this research the sample of these kind of buildings are shown in Figure 1, Figure 2 and Figure 3.

In the case of very tall super high-rise buildings, lateral force resisting systems like frame-shear wall systems and tube-type structures have been extensively used; through load dispersion in both vertical and lateral directions, this system can greatly improve the lateral stiffness of the building. In public buildings like sports stadiums, airports, and convention centers, space frames or spatial structures including space frames, space shells, and cable stayed systems have increasingly been used. This structure facilitates spatial load distribution, is mechanically efficient, has long span capability, and can form beautiful shapes; thus, it meets the needs of architectural requirement of large span columnless buildings.

On the other hand, prefabricated buildings have come to be favored as well. Through the application of factory fabrication and field assembly, prefabricated buildings have managed to replace conventional building techniques, shorten the building cycle, decrease pollution, and

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enhance construction accuracy [9]. Moreover, the development of seismic isolation and vibration reduction buildings, light composite buildings, and intelligent monitoring buildings keeps on advancing; they are able to fulfill many engineering demands, including those concerning special conditions of the sites, low carbon development, and safety as well as disaster prevention.



(a) (b) (c) (d)

Figure 1. (a) Stonehenge (UK), (b) residential architecture (China), (c) the Giza Pyramids (Egypt), and (d) the Parthenon (Acropolis of Athens) (picture credit: original)



(a) (b) (c) (d)

Figure 2. (a) Stonehenge (UK), (b) residential architecture (China), (c) the Giza Pyramids (Egypt), and (d) the Parthenon (Acropolis of Athens) (picture credit: original)



(a) (b) (c) (d)

Figure 3. (a) Stonehenge (UK), (b) architectural structures (China), (c) the Giza Pyramids (Egypt), and (d) the Parthenon (Acropolis of Athens) (picture credit: original)

3. Core driving factors for iterative structural systems

3.1. Innovation and iteration in building materials

The material basis for the development of structural systems is the materials, and every new property developed by the material leads to the development of the structural systems. In the ancient times, the weaker properties of the natural stone material limited building height, span, and load-bearing capacity. It is through the invention of the steel and concrete material during the industrial age that the limitations of the natural materials have been overcome.

The materials used for modern construction are continually being improved with respect to their strength, lightweight nature, emission reductions, and durability. Studies show that through the creation and use of composites of materials made from solid wastes, low carbon cement materials, and high performance composite materials there will be a reduction in carbon emissions within the construction sector as well as improvement of structural mechanical properties [2]. The use of new

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materials such as ultra low carbon clinker free cement, recycled aggregate concrete, and carbon fiber composites will facilitate structural lightweighting and low carbon upgrades while ensuring structural load bearing performance.

3.2. Further development of mechanical theory and design techniques

Scientific theories make up the base of any structure system. In the olden days, there was no scientific theory related to mechanics; everything was based on experience only, hence making it unsafe. The development of a scientific theory for mechanics made it possible to quantify the design process, thus giving rise to structural engineering.

Modern analysis of finite-element simulation, seismic design based on performance, and life-cycle design theory keep on developing. By combining BIM digital simulation techniques with intelligent simulation techniques, advanced stress analysis and structural optimization of complicated building models with irregular shapes, huge span dimensions, and super-high-rise have been achieved; meanwhile, unnecessary structural components have been simplified by considering safety and economic performance indicators.

3.3. Upgrade of building technologies and equipment

Modern construction techniques and technology helped in making the use of new structural systems feasible and successful. During ancient times, construction purely through manual labor could only give simple and small-scale structures and was not capable of making complex structures. Modern construction equipment made possible the construction process to be mechanized; hence the quick adoption of traditional steel-concrete structures.

With the advancement in the assembly technology of prefabrication and the prestressed structure technology and the high altitude construction technology, the construction of the ultra-high-rise structure, large span space structure, and special shape structure has been achieved with high precision [3]. The above technologies have turned innovative structural systems into practical engineering structures and have made possible the diversification of structural systems.

3.4. Social needs and functional upgrading in architecture

The progress of social development and the improvements in architectural functions have been responsible for structural development. In ancient architecture, there was no need for buildings to serve any purpose other than housing and ceremonial purposes, so basic structures could satisfy such requirements. The progress of modern industrialization has made it necessary to have factories and big public buildings, resulting in high-strength large span structures.

In ancient societies, where productive forces were limited, architectural requirements were confined to basic residential, ritual, and defensive functions. With limited space, simple load-bearing requirements, and low floor heights, rudimentary earth-and-wood or masonry structures were entirely adequate to meet these needs, rendering complex structural innovations unnecessary.

In modern industrialized societies, the surge in demand for industrial plants, urban residential buildings, and public structures has created a societal need for buildings featuring greater spatial extent, larger volumes, and higher load-bearing capacities—factors that have driven the emergence of high-strength, large-span, and large-scale modern structural systems.

In todays highly advanced urbanization landscape, urban land resources are becoming increasingly scarce, driving construction toward high-rise, intensive development. The growth of

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cultural and sports sectors, transportation infrastructure, and cultural tourism industries has given rise to a multitude of large-span, irregularly shaped, and landmark buildings. Simultaneously, the comprehensive implementation of national "dual carbon" policies and building industrialization initiatives has established green, low-carbon, energy-efficient, and industrialized construction as mandatory requirements. This diverse, high-end, and eco-friendly demand for modern buildings continues to compel the ongoing optimization, innovation, and upgrading of structural systems, thereby shaping the future direction of architectural construction.

4. Future development trends in modern building structural systems

4.1. Deep development of low-carbon lightweight materials and green structures

On the premise of the dual-carbon policy, the low-carbon lightweighting of buildings has been regarded as an important trend in building structures. Traditional building structures made up of concrete and steel have the characteristics of large self-weight and large use of building material as well as carbon emissions.

In terms of material, low-carbon building materials derived from industrial solid waste, building material recycling, and recyclable steel structures will gradually be used to replace conventional building materials. In this way, carbon emissions can be cut down during the entire life cycle of the building material, including its manufacturing, construction, and even demolition stages [10, 2]. At the same time, low-carbon management will be implemented in the building life cycle as a whole, and energy conservation and carbon emissions reduction will be well coordinated.

4.2. Integrated development of industrialization and digital intelligence

The process of modernization and renovation of building structure needs the development of an integrated industry, digitization, and intelligence construction approach. The traditional construction approach involves long cycle time for construction, considerable environmental pollution, and inconsistent construction quality; on the other hand, the prefabricated industry construction method allows pre-fabrication of construction components and their installation, which makes the process much more efficient [9].

In the meantime, BIM technology, IoT-based monitoring technology, and finite element simulation technology will be fully incorporated into the construction industry [3]. With the help of digital modeling and simulation, the structure will be designed optimally to minimize construction mistakes; with the assistance of intelligent sensors, the stress, settlement, and vibration changes in the structure can be monitored in real-time, thus allowing dynamic early warnings on the safety of the structure. In the future, an integrated industrial system of intelligent design, prefabrication at factories, assembly construction, and digital operation will be created, facilitating the intelligentization of building structures.

5. Conclusion

This paper systematically reviews the three-phase evolutionary trajectory of building structural systems from ancient times to the present day. It sequentially examines the construction characteristics, load-bearing advantages, and application limitations of ancient empirical structures, modern scientific structures, and contemporary diversified innovative structures, respectively. Furthermore, from four dimensions—building materials, mechanical theory, construction

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techniques, and societal demands—the paper provides a systematic analysis of the core driving mechanisms behind the iterative upgrading of structural systems.

Research indicates that the evolution of building structural systems is a dynamic process characterized by the synergistic drive of multiple factors, continuous iteration, and ongoing optimization. Innovation in building materials provides the material foundation for structural upgrades; advancements in mechanical theory and design technologies offer scientific theoretical support; upgrades in construction equipment and building technologies ensure the practical implementation of these systems; and evolving societal demands for building functionality guide the overall direction of structural system innovation. These four factors work in concert to propel building structures from rudimentary and simplistic forms toward modern, efficient, safe, diverse, and green systems.

Against the backdrop of the new era—characterized by the "dual carbon" strategy and the rapid advancement of digital construction—modern building structural systems will continue to evolve toward low-carbon and lightweight design, green and ecological development, industrialized construction practices, and intelligent design, operation, and maintenance capabilities. Driven by ongoing innovations in new building materials, mechanical theory, and intelligent construction technologies, future building structures will achieve a multidimensional integration of safety performance, functional performance, economic performance, environmental performance, and intelligent performance, thereby continuously fostering high-quality, sustainable, and modernized development within Chinas construction industry.

Studies have shown that the development of buildings is influenced by various elements, including the development of materials, which form the material basis for their development; mechanical theory, which forms the theoretical basis for development; building techniques, which ensure engineering support for buildings; and demand from society, which directs the direction of development. As for the new era, the development of building structures will develop towards green and low-carbon construction, lightweight structures, industrialized construction, and smart operations and maintenance.

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