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The Development of Steel Construction with the Innovation Brought by High-Tech Architecture

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Abstract: Steel is arguably one of the most popular materials in the world today, with a strong, reliable, flexible and sustainable structure that is used as the primary structural material in most of the world's infrastructure and buildings today. As a highly malleable and growing structure, the way architects and structural engineers have used steel has evolved over the centuries and, as technology evolves, the use of steel in the architectural world is likely to evolve in the future. The article wants to take the famous cases of steel buildings as an entry point to develop the impact of steel application on modern architectural design and innovation. Three case studies are used to illustrate how steel structures can meet the needs of modern architecture and achieve creative breakthroughs in architectural and structural design. The three cases are the Chicago Home Insurance Building, the HSBC Building in Hong Kong and the Centre Pompidou in France. This paper deeply elucidates and systematically summarizes how structural designers break through tradition and seek innovation when existing structural technology cannot meet the demands of architectural design. How designers break through traditions, seek, and create new techniques that help turn architects' imaginations into reality. It also provides an important basis for future cooperation and innovation in architectural and structural design.

Keywords: steel structure, high technology school, Chicago Home Insurance Building, Hong Kong HSBC Building, the Centre Pompidou

1. Introduction

In the 19th century, steel was gradually introduced as a material for building construction, and its unique characteristics opened up new doors and unprecedented possibilities for architectural design. As one of the most widely used materials in modern times, steel has its own unique characteristics. For example, it is light in weight, but very strong in material strength. Because steel is less dense than concrete and wood and has a higher yield strength ratio, it is suitable for large spans, high heights, and heavy load-bearing structural grid processing under the same stress conditions of small cross-section, light weight, and ease of transport and installation. For example, the material plasticity and seismic performance of steel are very good, it can develop a large deformation without fracture. Moreover, for building construction, steel structure has the characteristics of high industrialization, reasonable cost, and short construction period [1]. A lot of research has been done on steel structure, especially on the material properties of steel and the structural framework of steel structure. However,

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there is a lack of specific research on the innovation of architectural design to drive the breakthrough in the use of steel structure. In this article, we would like to take the famous case of steel structure architecture as the starting point to study the phenomenon that steel structure and modern architecture design influence each other and drive each other to innovation. From the 19th century to today, about 200 years have been marked by booming and innovative architectural design. The development of science and technology and the collision of the humanities have made architects search for higher skies and stronger structures. This paper explores the excellent architectural cases of this period to enrich the research results of the combination of modern architecture and structural design. Based on this, the author selects three representative steel buildings in the history of modern architecture and uses the case study method to sort out how architectural design and steel structure development drive each other and summarize how this collision influences the development of modern steel buildings. To draw architects' attention to the technical and artistic characteristics of modern building structures. The potential and value of steel structures in modern architecture is fully explored, providing an important reference for future collaboration and innovation in architectural structural design.

2. The Starting Point of Steel Construction: Home Insurance Building

On October 8, 1871, on a calm Sunday night, an unintentional accident sparked the shocking and world-shaking Chicago Fire. The fire lasted for days and nights, took a heavy toll, displaced 100,000 people, and nearly destroyed the entire city. In both the United States and other countries, early houses built 150 years ago were made of wood and were highly combustible, and the chain reaction caused by a fire was enormous. After the disaster, some avant-garde architects began to look for stronger and more reliable building materials to conceive a new generation of buildings, and steel, which had been used in bridge construction and industrial facilities, came to their attention of architects. Moreover, the post-disaster reconstruction work encountered social and economic problems such as increasing population and rising land prices [2]. So, architects began to increase the number of floors to increase the usable area and started to let the building develop into the sky.

In 1884, William Le Baron Jenney designed a headquarters building for the Home Insurance Company in New York, which is considered the world's first skyscraper and the first high-rise structure supported internally and externally by metal and structural steel (including reinforced concrete) that is fireproof. The entire building is 42 meters high and stands 10 stories tall [3]. The building is divided into two main sections, with a cooked iron beam frame on the bottom six floors and a steel frame on the top four floors, allowing for a large number of interior walls that do not have to bear the pressure of the entire building, thus reducing the thickness of the walls and providing more space inside. At the same time, the use of steel framing frees the building's facade from the need for load-bearing and provides maximum natural light to the building. Because of the steel structure, the building weighs only one-third as much as a masonry building of the same size, allowing the Home Insurance Building to be built with more floors than any other building of its time [4]. This advantage greatly satisfied the New York Home Insurance Company's need for a large office space for its headquarters, and the building was later expanded by two additional floors, reaching a height of 55 meters. In addition to being a landmark in the use of skyscrapers and steel structures, lifts, wind bracing, and plumbing were only a few of the technologies that the building pioneered. The Home Insurance Building and subsequent supertall buildings built during the same period pioneered a novel method of construction replaces the conventional stone load-bearing walls with a lightweight cast-iron framework and a stone or terra cotta brick facade, with the skeleton being separate from the fa çade. [5]. William Le Baron Jenney and his contemporaries, such as Louis Henry Sullivan, formed the influential "Chicago School" of architecture.

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3. Revolutionary Evolution in Steel Construction: HSBC Headquarters

The High-Tech style of architecture emerged in the late 1950s. Its type of architecture highlights the achievements of contemporary industrial technology and flaunts them in the design of the building form and interior environment, advocating "mechanical beauty." Their signature feature is often to highlight the most advanced industrial construction technology of the current era, displaying structural components including beams, grids, and other pieces of machinery and pipes such as cables and air ducts, highlighting technology and the spirit of the era. The building shape and style pay attention to the design tendency of expressing high industrial technology [6].

Traditional high-rise buildings are usually erected with a core tube that serves as the main structural support for the surrounding structure, while Norman Foster uses a similar treatment to the Centre Pompidou, moving the structure from the center to the outside, making the entire building supported by a structural system similar to the exoskeleton, it gives the interior a spacious and open space. The eight sets of stout structural columns as the main supporting structure are combined with the main truss to be exposed on the outside of the building, forming a tough and powerful facade effect. Due to there is no inner column, Foster boldly designed the entire office area into an open-plan office area, which was the first in the world [7]. Due to the freedom brought by the external structure, Foster's property is completely open to the air, forming a public square where pedestrians can stop at will, leaving only two escalators to rise to the office area. Foster used the advanced global production methods that are “produced around the world – unified transport to Hong Kong for assembly” on less structures and room components saves a lot of money [8]. With a large area of glass curtain walls on the side of the building with reference to Hong Kong's local climate, the huge atrium provides comfortable lighting for the office area.

Despite the incredible steel consumption required for the surrounding steel structure, the cost of the entire building reached a record $1 billion, HSBC insisted on investing in construction. It is said that this is because the bank’s executives appreciate Foster’s design and believe that this is a well-deserved "artwork", and it is worthwhile to spend a lot of money for a work of art [9].

Although this is Foster's early famous work, it can be seen that many of the design styles accompanying his life, the prototype of the concept, and repeated in later works. The greatest highlight of the whole design is the interior space without any supporting structure, all the architectural structures are designed outside the building, thus greatly increasing the use space of the floor, and the design of the glass curtain wall makes the whole building lighted with natural light in a large area, which sets an excellent example for the design of future buildings. Technology's fascination with creative structural design and bold exposed structures are typical of the high-tech style, reflecting the technological beauty of modern architecture from the inside out.

4. The Perfect Interplay of Architecture and Structure: Georges Pompidou National Centre for Arts and Culture

Another representative work of the High-Tech school of architecture is the Georges Pompidou National Centre for Arts and Culture, in the 4th arrondissement of Paris, in the Beaubourg neighborhood. The center was proposed by the French president in 1969 and designed by Richard Rodgers and Renzo Piano. At the outset, Rogers and Piano proposed to design "a truly flexible container": all interior spaces could be rearranged at will. The concept of flexibility extends to every component of the building; the center will serve as "an ever-changing framework, a Meccano suite, a climbing frame for the elderly and the young," in Rogers' words [10].

The building is envisioned as a well-serviced shed containing a series of unified spaces, supported externally by a separate structural framework, capable of changing plan, section, and elevation as a whole, and able to absorb unforeseen future requirements. To enable the realization of such a design

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vision, the two architects designed the art center as a whole as a rectangular block 60 meters wide, 166 meters in length, and six floors high. The building's floors are enormous, measuring 44.8 meters wide, 166 meters in length, and 7 meters high. 28 circular steel columns support the whole structure. Except for a fireproof partition wall, there are no solid walls and not even a single interior column. It is flexible and simple to use since different usage locations are temporarily divided approximately by moveable walls, screens, furniture, or railings, as well as the interior organization may be modified at any moment. In Rogers' original design, indeed the floor slab might have been shifted up and down to change the floor height, however this notion was too fantastical to be implemented. [11].

Influenced by the liberal artistic atmosphere of Paris, the two architects painted the steel beams, columns, trusses, ties, and various other piping in colors, exposing them unobtrusively on the façade. The ones in red are used for vehicles, the ones in blue are used for air conditioners, the ones in green are used for drainage and water supply pipes, and the ones in yellow are used for electrical facilities and pipelines [12]. From the street, people can observe the intricate interior machinery of the structure. The main way of accessing the floors is an escalator, which is built inside a sizable glass circular tube dangling from the building's façade towards the square. One of the architects' purposes in placing it outside the building is to keep the interior space of the floors unobstructed.

The creation of this imaginative work was made possible thanks to two architects and their structural team, Peter Rice of Arup and his team. While the architectural design of the Pompidou Centre was a great success, the cross-genre idea became a problem for the structural engineers: how to define the framing form for the giant open steel frame structure and the connection nodes to support the floor slabs [13]. When Rice traveled to Japan to view some of the 1970 Osaka World's Fair exhibition, the ultimate solution was started. From a massive space frame created by Professor Yoshikatsu Tsuboi and Kenzo Tange at the exhibition site, he observed the startling shape of massive cast steel nodes. From this exposition, Rice chose cast steel as the material for the giant open steel frame structure of the Pompidou Art Centre, and Rice himself explained the reason in the interview: Standard sections, I-beams, angles, steel tubes, etc. are often used to construct steel buildings. The continuous manufacturing line assures consistent aesthetic appearance and quality, but it also severely restricts room for unique expression. Additionally, because conventional steel is impersonal, lacks surprise for the general public, and has preconceived assumptions of many different sorts, it is challenging to encourage an emotional connection between the visitor and the designer or builder. On the other side, the use of cast steel may defy convention by utilizing an uncommon mix of cast and conventional steel components to provide an image of architecture that is both approachable and surprising [14].

After solving the structural material problem, another problem that followed was that the traffic area and services were outside the main span façade, so a natural break point was needed to place the façade on the whole span. The standard cast-steel construction was not intended for this, and it resembled a prison window in form. Lennart Grut, another team member, is credited by Rice with finding the solution by suggesting a short-supported cantilever beam to support the main truss beam and thereby elegantly resolving all the conflicts between structure, space, and architecture. This cantilevered structural shape, developed by German engineer Heinrich Gottfried Gerber (1832–1912) for the building of bridges, was successfully adapted into the most significant structural innovation of the Centre Pompidou: the Gerberette. The Gerberette, which resembles a seesaw pivoting on columns, has a short end that supports the truss beams for the main span and a long, thin end that is driven up and held firmly by tie rods linked to the bottom of the building. The goal of a translucent façade is accomplished as the visual disturbance is reduced and the exterior columns are replaced with tie rods [15]. The case of the Pompidou Centre fully demonstrates the innovation brought by architectural and structural design, where the architect's demand for space is realized by the structural engineer's creativity, and the structural engineer is able to incubate new technologies with the

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architect's continuous exploration of space. Although the Pompidou Centre is a mixed blessing, the building is a perfect testimony of the collaboration between architecture and structural design.

5. Conclusion

Structural design is the cornerstone of architectural design and an essential part of it. Since the 19th century, steel structure has become one of the most popular structures in modern society. With the development of society's needs and science and technology, steel structures are bound to undergo disruptive innovations in the future, and will be combined with architectural design to bring better quality, reliable and flexible buildings to society. By studying its origins and analyzing innovative steel construction projects in history, we can better face problems in the future when we encounter technical innovation bottlenecks, be inspired by historical precedents, and insist on the motivation of innovation

This paper analyzes the relationship between steel structure technology and architectural design from three architectural cases. However, due to space constraints, it is impossible to describe how steel structure and other types of buildings, such as housing, promote each other's development. Future studies will focus on broadening the category of architectural cases and increasing the analysis of how other types of buildings combine with steel structures to develop and innovate.

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