

Exploration of steel structure modular building technology system based on rapid assembly—take X-house for example

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Abstract: Through modular design and modular assembly technology measures, taking function, space and structural system as structural units; Three-dimensional building information technology is applied in design, manufacturing, on-site assembly and other links. The modular technology system of steel structure for rapid assembly such as modular structural system of building space, beam-column nodes, node design optimization, on-site hoisting and assembling of modular building structural system, modular mechanical and electrical equipment unit design and other applications is comprehensively and systematically discussed. Taking X-house project participating in the Dubai International Solar Energy Competition as an example, the research and practice of residential technical system for rapid assembly are systematically introduced.

Keywords: modularization, steel structure, building information model, rapid assembly

1. Research background

The International Solar Decathlon, launched by the U.S. Department of Energy in 2002, is a biennial competition to design and build a single-story or double-story house of 120-200 square meters with a full set of daily household appliances and furniture and other living facilities, and aims to build a solar home within twenty days and using solar energy as the only energy source. The International Solar Decathlon is the world's most important green building competition and is known internationally as the Sustainable Building Olympics.

In order to improve the global impact of buildings, especially in the application of renewable energy in zero energy buildings and the challenge of building within 20 days, a modular building structure system with rapid design assembly is needed.

Due to the advantages of higher building quality, faster construction speed, smaller construction cost and more flexible design space, and the fact that steel modular building technology is highly regarded for its low-carbon, efficient and sustainable features, it is important to demonstrate the advantages of steel modular building technology to the world and promote its promotion and application. [1]

In order to cope with the international solar decathlon competition, and in view of the characteristics of steel structure buildings, this study systematically discusses the technical characteristics, design principles, construction processes, and sustainability of the steel structure modular building technology system by taking an entry as an example. This study summarizes the advantages, limitations, and development prospects of this technology system, hoping to provide a reference for the promotion and application of steel structure modular building technology.

2. Research Object

X-house is a third-generation assembled modular building product jointly built by CSCI and South China University of Technology. Participated in the 2021 International Solar Decathlon held in Dubai [2], X-house took part in all 13 competitions, won 9 of them, and finally won the overall championship in the Middle East region, which is the most awarded competition in China since its participation.

In order to respond to the requirements of the competition, this entry X-house is used as the basis for a detailed study and comparative analysis of the design, production, manufacturing and on-site

assembly of the steel modular building, combining the characteristics of the steel modular building, so as to gain an in-depth understanding of the characteristics and advantages of the steel modular building technology system through a comparative analysis of the problems faced in the construction process and the solutions. In addition, the modular assembly building technology at home and abroad is also introduced, analyzed and studied in order to draw more comprehensive and accurate conclusions.

3. Rapid construction based steel modular building

In order to meet the indicators of the competition, the entries need to meet not only green low carbon sustainability, but also specific indicators such as clean energy, future, innovation, mobility, smart solutions and happiness, and most importantly, rapid construction, commissioning, installation and operation need to be completed within 20 days. Focusing on the advantages of modular steel buildings, the program design characteristics of modular steel buildings, the characteristics of manufacturing and current assembly, this paper intends to study the characteristics of modular buildings from the perspective of rapid construction and assembly, and to present the project completion results

3.1 Modular design to cope with rapid construction

As a high-level form of construction, modular building can realize standardization of more than 90% components, which can make assembly simpler and more convenient, with fewer lifting times, shorter on-site construction periods, and lower cost. Connecting with high-strength bolts ensuring quality and making the building safer and more reliable. No wet work on site making it more environmentally friendly. Factory prefabrication helps save materials and prevent waste.

Modular buildings can be transported in finished containers, which have the characteristics of high loading and unloading efficiency, low labor costs, small safety risks and short cargo transit time. It is conducive to multimodal transport such as land and sea transport, and is also suitable for cross-border transportation, etc [3]. Taking into account the advantages of modular construction and the possibility of prefabrication, long-distance sea transport and multiple transshipment, rapid disassembly and recovery construction, a variety of factors are considered in the design planning to avoid the influence of adverse factors as much as possible. Mainly follows.

(1) Standardization of design and component parts

X-house, as a new generation of steel structure modular building with zero energy consumption, keeps exploring the needs of modular building in terms of zero energy consumption technology solution, application and marketing. The standardization of component parts and units has become one of the necessary conditions. The standardization of component parts is considered in the planning and design of X-house, and the whole building is considered to be composed of four highly integrated modular units of bedroom, living room, dining and kitchen, and equipment. The four unit modules are factory-made and adopt standardized module, which can realize the spatial scale, function and application combinations of the building, and finally to achieve functional diversity. At the same time, different modules can be combined to form different forms of functional spaces with different styles. Each standardized module can also be combined with roofing, shading, ventilation and decoration modules to form a complete system of standardized module units. The arrangement and combination of dining module, equipment system module, roof solar module, water treatment system, and etc. can also realize the standardized application of overall appearance, structural system, interior decoration and other parts and components, laying a foundation for exploring the industrialized application of modular parts and components.

(2) Reinforcement design to deal with long-distance sea and land transportation and lifting

In order to meet the short construction time limit of the competition site, it is necessary to do a lot of work in the design, processing and manufacturing process in advance, to design and manufacture standardized parts and components, and at the same time to carry out pre-build and pre-assembly in China to ensure the efficiency and accuracy of on-site construction.

The main structural units were transported from Guangzhou to Dubai by land and sea, and the whole modular units were reinforced to meet the demanding requirements of sea transportation and lifting.

(3) To carry out research and practical exploration of industrialization and industrialization of

construction

The climax of residential industrialization was set off in Europe and the United States in the 1950s, and modular buildings became popular in post-war Japan in the 1960s [4]. At the beginning of the 21st century, China began to promote the application of modular buildings, such as the Xiongan Citizen Service Center office and hotel-style apartments, with a construction area of about 30,000 m² and about 600 steel structure modules, which were built in 2017. The height of modular buildings continues to climb, from the initial low-rise, gradually expanding to multi-story, high-rise and super high-rise. For example, The Clement Canopy condominium in Singapore, built in 2019, has about 40 floors, 140m, and 1899 modules, is the tallest concrete modular building in the world.

In October 2021, the State Council's "Notice on the Issuance of the Action Plan to Reach the Carbon Peak by 2030" clarified: promote green low-carbon building materials and green construction methods, accelerate the industrialization of new buildings, vigorously develop assembly-type buildings, promote steel structure housing, promote the recycling of building materials, and strengthen green design and green construction management [5]. In January 2022, "The 14th Five-Year" Construction Industry Development Plan " issued by Ministry of Housing and Construction proposed that by 2025, the proportion of prefabricated buildings in new buildings will reach more than 30%. As a new generation of zero-energy steel structure modular housing system, X-house integrates architecture, structure, electromechanics, and decoration, which is conducive to the realization of green and low-carbon intelligent construction concepts, the promotion of recycling of building materials, and the exploration and practice of modularization, industrialization and industrialization research of steel structure buildings.

(4) Diversified combination of unit modules

Green and low-carbon life under the background of carbon neutrality, the future residence will not only be a zero-energy building, but also a low-carbon way of life. The X-house is a single-story freestanding house inspired by the wind catcher tower of traditional Middle Eastern dwellings, and innovatively adopts the structural form of steel modular units assembled into an atrium, which makes the house extremely scalable.

Through the modular design strategy, the four functional modular units can be assembled in different combinations to form a single-story house in the form of an atrium for a family of two, or a multi-story house for a multi-person nuclear family to meet the individual needs of the nuclear family, which can better adapt to the future market trend and individual needs of modular buildings. Through the organic combination and layout of functional modular units, it can form a residential layout form with distinctive characteristics as the traditional concrete residential form, and also form a rich settlement colony space, thus avoiding the formation of a single style, monotonous form, and no identification problems. Therefore, the steel structure modular building also has great expandability and adaptability, as shown in Figure 1.

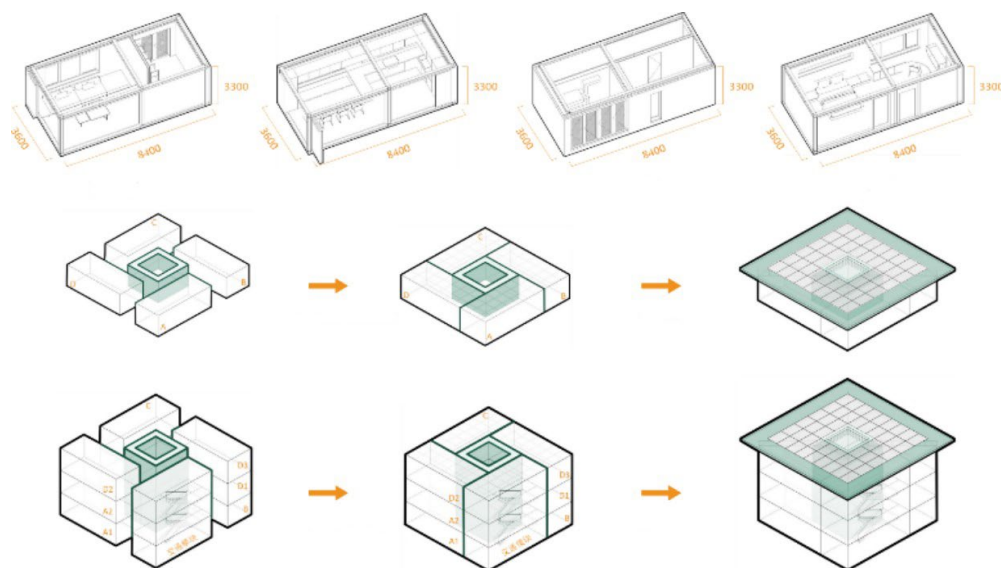


Figure 1: Module unit splicing method

3.2 Modular design and on-site assembly technical measures

This project adopts SketchUp, archiCAD and other 3D software for architecture, from scheme planning, to construction drawing design and factory production. The design planning analysis and simulation calculation are carried out through the 3D information model of the building, so as to ensure the modular design concept to be put into practice and make the modular design concept take root from drawings to reality. The application of three-dimensional information technology for architecture realizes multi-faceted and multi-angle applications from the organization of spatial structure components, the arrangement of mechanical and electrical equipment pipelines and the reconstruction of the organization analysis of construction process procedures.

(1) Modular structure system of building space

In order to participate in the competition and explore the zero energy modular building, , considering the characteristics of container shipping, during the design planning process, each functional modular unit is conformed to the size of shipping container for shipping. Each box module unit is factory-made with independent structure and functional space.

Through the orderly combination on site, it becomes a building with completed functional space. Each building modular unit has an independent envelope, interior system, building equipment, etc., combined into individual space units, and all are manufactured and assembled in the factory. In the factory manufacturing, all equipment, piping, decoration and decoration can be designed and installed in advance, as shown in Figure 2 and Figure 3.

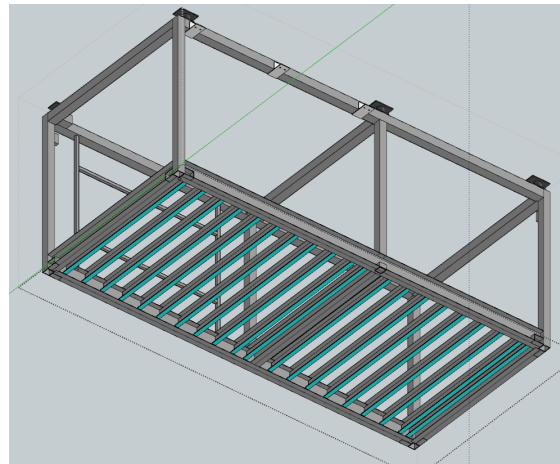


Figure 2: Modular box construction

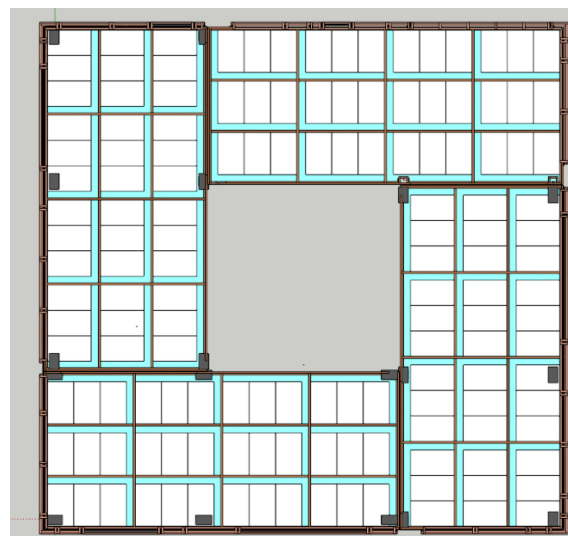


Figure 3: Building plan of the modular box

(2) Beam-column node processing and assembly node design optimization

Each modular unit of a modular building is a complete structural system consisting of top beam, bottom beam and corner column. Welded connections, high-strength bolts, prestressed connections and combined connections are usually used between modular units. The connection nodes between modules play a very important role in ensuring the integrity, stability and applicability of the final structure, therefore reliable connection nodes are required, otherwise the structure formed by multiple modules will be deformed, damaged or even collapsed [6]. Due to the high reliability of using bolted connections, this connection method is especially suitable for low- and medium-story buildings, which can effectively avoid its sensitivity problems. This project is a one-story building without complex shaped structures, which is relatively simple, so bolted connections are used in this project. In the modular unit, the connection parts of each modular unit mainly consist of connection box, limit box, fastener, foot column, bottom side beam/end side beam, etc. In order to prevent transportation and collision, the structural system is reinforced, as shown in Figure 4 and Figure 5.



Figure 4: Production diagram of modular structure system



Figure 5: Factory site production diagram

(3) On-site assembly of modular building structure system

The on-site assembly of modular building adopts the way of "building blocks", and the nodes of modular units are connected with high-strength bolts to connect the modules reliably into the whole building. The modular steel building is simple, time-saving, fast, high quality, time-saving and economical, and can be installed by lifting the whole unit.

The maximum weight of the modular unit in this project is 20 tons, and the lifting radius is about 23 meters, and a 100-ton truck crane is used on site for lifting. The four boxes were lifted in counterclockwise direction to reduce installation errors. The roof steel structure was assembled into 6 pieces on the ground and then lifted and installed as a whole. The roof photovoltaic panels and solar thermal panels will be lifted to the corresponding positions after the lifting is completed, as shown in Figure 6.



Figure 6: Module Unit Lifting, Roof Unit Lifting

(4) Modular mechanical and electrical equipment unit design

In HVAC and intelligent control design, X-house adopts modular unit system design scheme, with the whole functional design as a whole, each model unit as a functional unit, and "connectors" such as interface, bayonet or splicing joints between modules to realize the connection between equipment and units. The internal water supply and drainage piping, HVAC piping, electrical lighting design, intelligent control design and integrated wiring of each unit are independently controllable and combinable.

The modular unit has integrated most of the electromechanical piping and water supply and drainage piping. On-site installation needs to connect the pipelines and pipes between the boxes. The lines between the roof photovoltaic panels need to be connected sequentially before connecting to the battery and inverter.

(5) Application of building information model

The project adopts SketchUp, archiCAD and other 3D software for architecture. In the 3D design software, the building envelope, decoration and decoration contents, strong and weak electric pipelines, HVAC pipelines and water supply and drainage pipelines are designed in a unified way, and finally the construction drawings are issued based on the 3D building information model, which is used to guide the design, production and processing of parts and components and assembly. The building information model improves the accuracy of design and construction and accelerates the construction period , as shown in Figure 7.

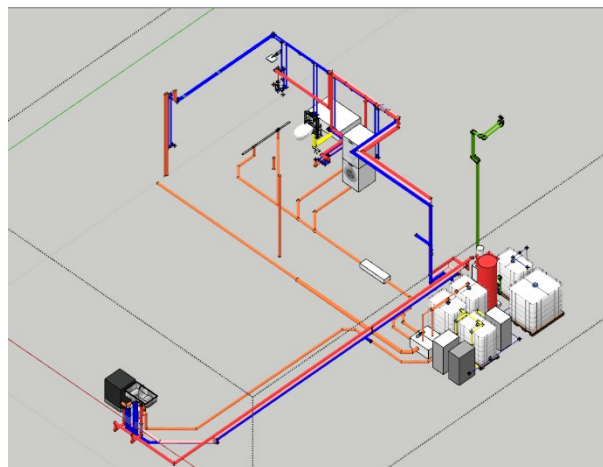


Figure 7: 3D model display of electromechanics

(6) Other modular designs

In order to achieve energy self-sufficiency, solar photovoltaic and solar thermal systems are installed on the roof. The roof photovoltaic bracket steel structure adopts traditional steel structure, the profile adopts H section steel, which involves overhanging structure with 2 meters overhang, and due to the limitation of shipping transportation conditions, the 200 square support structure is divided into 14 small units for assembling, and the assembling between each unit adopts bolted connection, using steel plate reinforcement to strengthen the connection nodes to ensure the flatness and stiffness requirements of the bracket plane. The outdoor deck steel structure adopts the traditional steel structure with square steel profile, and the outdoor deck structure is divided into several small units for assembling, and the assembling between each unit adopts bolt connection to ensure the flatness and strength requirements of the structure, as shown in Figure 8.



Figure 8: Installation of roofing elements

3.3. Implementation results

Combining the local climate characteristics, this project chooses the atrium-style house as the prototype of the house. The atrium is the core of the whole, which is composed of bedroom, living room, dining kitchen and equipment, and four functional steel modular units. Special materials and ingenious design of four partition walls make the atrium a carbon-negative residence that can meet the needs of a variety of scenarios such as watching movies, gatherings, fitness, and office.

Combined with other competition strategies, X-house won the first place in the overall score of the International Solar Decathlon Middle East (SMDE2021) and won 9 individual titles. This is the best result of Chinese contestants in previous competitions, and the first entry to win both the China and the Middle East editions of the International Solar Energy Competition, as shown in Figure 9.



Figure 9: Project realistic view - panoramic view

4. Research conclusion and significance

Steel modular building technology system is a new type of construction technology, which has the characteristics of fast construction speed, high construction quality, high resource utilization and

sustainability, and therefore has a wide range of applications in modern architecture. This paper discusses the application of steel modular building technology system in practice, taking the X-house, an entry in the Dubai International Solar Energy Competition Middle East 2021 (SDME 2021), as an example, and draws the following conclusions.

(1) The steel modular building technology system has advantages in terms of rapid construction, construction speed, building quality, resource utilization, and sustainability.

(2) The design principles of this technology system include modularization, industrialization, standardization and personalization, and the diversified combination of unit modules can meet the needs of different customers.

(3) In terms of manufacturing and on-site assembly, refined management is required in terms of program design, manufacturing and construction to ensure construction quality and progress.

(4) Through the project itself, the modular building structure system of rapidly assembled steel structure is studied in depth and systematically, and the possible path of industrialization of steel structure building is actively explored to provide theoretical and practical support for the rapidly disassembled steel structure modular building.

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