A Novel Design of Energy-Saving and Prefabricated House System for Rural Area of Northwest China

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Abstract. This research proposes a novel type of rural house design that combines a prefabricated steel frame and EPS cavity blocks as exterior envelop. It has the advantages of low energy consumption, moderate cost, and low assembly difficulty, so as to meet the sustainable development goals of rural areas of China, where status quo of industrialization and economic development is at relatively low level. The article introduces the prefabricated structural features of the system, a semi-industrial construction process, features of refined room modules design based on the size of furniture and residents need at different level, and an automated combination of room modules to house mode with the aid of computer programs to save design time and better meet residents needs. It satisfies China's goal of improving the liveability of rural areas and vigorously developing new prefabricated building systems. Finally, the article looks forward to the future research and development direction.

1. Design backgrounds

The EPS cavity block is made of expandable polystyrene beads after heating and moulding process. It has closed cell structure and different dimensions. ICF (Insulated Concrete Form) system is a building system with integrated insulation and structure. Firstly, the EPS cavity blocks are inserted through staggered tongue-and-groove seams, and quickly assembled as the inner and outer templates of the cast-in-place concrete load-bearing wall; then vertical and horizontal steel bars are erected at specific positions inside the block. After their verticality is corrected, concrete is poured into it. Finally, a low-rise building composed of cast-in-situ concrete walls integrated with thermal insulation materials as templates is formed.

Compared with traditional rural houses in China, the safety performance of ICF houses, especially the seismic performance, is significantly improved. The experiment of Solomon et al. [1] showed that the plastic deformation of ICF blocks is 78 times that of ordinary concrete blocks. The existence of EPS blocks helps to change the destructive properties of sandwich concrete from brittleness to ductility. In ICF system, the main structure of the building and the thermal insulation materials are constructed simultaneously, insulation materials have the same life span as the main structure, which solves many structural problems caused by the post-added insulation of buildings. In terms of building industrialization, the construction ICF house has realize the transformation of wet work on the project site to partially pre-made in factory, which greatly improves efficiency [2].
The popularization of ICF system benefits also from its excellent energy-saving performance. The measured value of the heat transfer coefficient is very close to theoretical value, while the measured value of the heat transfer coefficient of exterior wall of light wood frame and light gauge steel house is 18-26% lower than theoretical one. And thanks to the continuous insulation construction detail, the effective R-value of the walls of the ICF system has been increased by 25% [3]. Although the detailed structure and environmental conditions are different, many researches showed that compared with rural houses without insulation, energy consumption of ICF house can be saved by 65-80% [4,5].

Beginning in 2018, the author’s research team has carried out a tracking study on the develop status of ICF house in Guanzhong rural area (a cold climate zone in Northwest China, including the city of Xi’an, Baoji, Xianyang, Weinan, Tongchuan, and Yangling). According to related research, 98.6% of traditional houses in Northwest China rural areas are constructed of clay bricks without insulation; the average heating energy consumption of those houses is 150 W/m², and the average annual coal consumption is about 97.4 kg/m² [6]. Rural houses without insulation cause huge energy waste, and the emerge of ICF system in Guanzhong area in recent years can change this unfavourable situation. Through on-site investigations, many residents have reported that ICF house has a considerable improvement in terms of living comfort and energy saving compared with their previous traditional house (masonry and concrete frame), and the cost is only increased by 10%, while the construction period is shortened. So, this system is welcomed by more and more rural residents. Meanwhile, it is found that the following problems have yet to be resolved: the low level of standardization of the design of new rural houses, which is not conducive to the integration of whole building industry; the low degree of refinement of house layout design, especially the insufficient consideration of spatial scale and applicability to meet the needs residents’ standards for modern life; due to the drastic changes in social conditions of rural area, the long-term sustainable use of the house is not fully considered.

The top ten tasks of the Ministry of Housing and Urban-Rural Development of China in 2019 include improving rural housing conditions and living environment to promote rural liveability; focusing on the development of new construction methods; in-depth promoting of the supply-side structural reform of the construction industry; and vigorous developing of prefabricated buildings such as steel structures. Combining the above development status and opportunities of the industry, the research team proposed a new type of rural house system that combines prefabricated steel structures and EPS cavity blocks.

2. General introduction

2.1. Main character
This novel system uses a steel frame as the main structure, and the outer envelope (wall and roof) uses EPS cavity blocks, with steel columns and beams inserted inside the blocks. The internal wall system can choose light-weight wall products such as lightweight concrete blocks, gypsum bricks, ALC panel
or light gauge steel composite walls as dividing and non-structural components. Therefore, the walls of the interior space can be flexibly arranged according to different requirements of residents or changes in usage, realizing variable residence and full life cycle residence. Since the steel frame is used as main structure, in addition to concrete as filler in the cavity, thermal insulation mortar can also be the filler in the EPS cavity blocks, which further reduces the heat transfer coefficient of the wall. The connecting detail of the inner and outer leaves of the EPS cavity block are specially designed to better combined with structural components (figure 1).

2.2. Structural features
The main structural system includes steel frame system and floor system, and a full bolt connection method is adopted to better adapt to the rural construction conditions. The beam-column joints are rigidly connected, and the primary and secondary beams are hinged connected. In the design process, it is recommended to ignore the contribution of the ICF shear wall to the lateral force. The system still mainly relies on the steel frame to resist horizontal force. The main force transmission path of the structure is the same as the traditional low-rise steel frame structure.

In order to meet industrialized manufacturing requirements, the structural components should adopt standardized parts and components, generally not exceeding 3 specifications. In this system, beam can be hot-rolled H-shaped steel or lightweight high-frequency welded H-shaped steel, and column is welded square steel pipe. According to different architectural design, in accordance with the development idea of "less specifications, more combinations", a variety of structural layout could be formed by the combination of different parts and components through standardized design. The beam-column, beam-beam, and column-column connections are connected by pressure-bearing high-strength bolts to save the number of bolts and the amount of on-site installation. Compared with the friction-type high-strength bolt connection, on the one hand, according to the "Steel Structure Design Standard" (GB50017-2017), the bearing capacity of the pressure-bearing bolt connection depends on the minimum value of the bolt shear capacity and the pressure-bearing capacity of the member. The performance of pressure-bearing is better than friction type; On the other hand, it also simplifies the construction process. There are no special requirements for the friction surface treatment, only oil stains and floating rust need to be removed, and no friction surface anti-slip coefficient test is required. However, when designing joints, it is necessary to ensure that the high-strength bolts are always elastic to avoid the reduction of joint bearing capacity caused by the plastic deformation of the screw [7].

As the node connection is the key to the structural system, the research team is also developing new type of bolted connection node. In order to meet the poor construction conditions in rural areas, the construction method system requires relatively simple method. Series of new beam-column connection nodes, including layered prefabricated steel structure beam-column nodes (figure 2), square-steel-tube end-plate butt-through steel-bar connection nodes (figure 3), rectangular steel-pipe-column steel-beam end-plate bolt connection nodes (figure 4) are developed, and have applied for related patents. The foundation can be precast or cast-in-place concrete foundation, and the typical foundation form is independent foundation or strip foundation. The connection between the bottom column and the foundation can be either buried or exposed. The connection between them adopts rigidly connected column feet. When considering the seismic design, the embedded column feet is preferred. The floor system can either adopt traditional cast-in-place reinforced concrete floor or light-weight prefabricated laminated slabs, ALC boards, reinforced truss laminated slabs and other lightweight fabricated floors. Because rural houses are different from urban residences, they are generally two-story buildings with independent stair. The sound insulation requirements can be relatively low, so some lightweight, highly-integrated, and relatively low-cost floor system can be choosing.
2.3. Construction process (figure 5)
After the foundation and ground floor are constructed, steel structural columns are installed on the first floor; most of the fireproof and anti-rust treatment of the column is completed in the factory, bolt nodes and other nodes are installed on site; after the structural columns are installed, EPS cavity blocks are assembled; while block position are corrected, concrete or thermal insulation mortar are poured layer by layer in the cavity; after that, is the construction of the floor slab; then it’s the proceed of the installation of the second story steel structure, the insertion of the cavity blocks and the pouring of the infill; Finally is the roof floor EPS block and roof construction (light steel frame sloping roof and resin tile). The whole process does not require large lifting equipment.

3. Serialized house design

3.1. Overall design idea
Entering modern society, the detached houses or townhouses in Guanzhong area have developed from the traditional courtyard layout to an integrated combination, and the inner courtyard gradually evolved in to the front and rear courtyards of the residence. Traditional Guanzhong rural house usually has three-bay with an entire width about 10 meters. Although three-bay layout is symmetrical per traditional Chinese architectural idea, the room in the middle, which is usually guest hall, cannot be used as a living room in modern society as the width is too small. The house design in this research all have one large and one small bay facing the south orientation, with the large bay as living room and entrance hall, and the small bay as bedroom. At the same time, in order to save land, it is recommended that the width of house design meets the basic requirements, but its depth can be relatively increased to fulfil life demands.

There is an obvious trend of miniaturization of rural families in Guanzhong area. According to the survey, the current rural family population is 3-4 people on average. While the children are employed or go to school, the permanent household population is only the couples. The design of the house mode should advocate a compact living style under the reduced family population size, so about 3 bedrooms per household is a suitable scale. However, this design also retains the common two-story house with at least five bedrooms for multi generation family.

This research proposes several house design modes, focusing on compact space layout and convenient internal traffic organization. In order to facilitate easy-construction and energy conservation, all modes have simple style with local characteristics, and can be independent or connected as townhouses, either be single-storey or double-storey. All modes can be combined with front and rear courtyards to meet different needs for parking, landscape, and breeding.

In the process of research, one found is that houses in Guanzhong rural area rarely have the same size (width and depth), it depends on the various dimension of the plot and residents’ need. In order to adapt this phenomenon, the research introduces various room modules and room combination rules to generate different house modes. Pivotal ideas of each room module design are briefly described as following:

3.2. Refined room module design
For every room type, there are various modules with different combination of width and depth, and the smallest one meets the most basic needs. With the increase of room width and depth, there are

![Figure 5. Construction process](image-url)
different furniture settings to meet increased life demands. Thus, the living space of family members can be further satisfied.

Bedroom (figure 6): Land saving is an important consideration for rural development in China, so the width of the bedroom should be relatively compact, including 3000mm, 3300mm, and 3600mm. When the bedroom is 3 meters wide, only one bed can be accommodated horizontally. When it is raised to 3.3 meters, thin furniture such as TV cabinets and bookcases can be arranged opposite the bed. When it is raised to 3.6 meters, the depth of the furniture can be further increased. For example, a wardrobe could be arranged to increase storage space. While limiting the width of the bedroom, the depth of the room can be lengthening appropriately, such as increasing the distance between the bed and the outer wall, to accommodate a space of different functions, including writing desks, dressing table, tea table, and even baby crib.

Living room (figure 7): It is recommended that the width of economical level is 3.9 meters, which can at least meet the needs of the common "1+2+3 seat" combination sofa and a comfortable TV viewing space. The width of comfortable level is 4.2 meters and the width of luxurious level is 4.5 meter. The improvement of the comfort of the living room can also be also reflected in the increase in the depth of the room. For example, a casual tea area can be added by the outer window to the south, and furniture such as storage cabinets or pianos and other facilities can be arranged on the outer wall of other rooms to the north.

Dining Room (figure 8): The dining room of the standard family has a rectangular dining table for 6 people (850mmx1500mm), and the dining room of a large family has a round dining table (diameter of 1500mm) for 8-10 people. Considering the convenience of people passing through the table when full seats, the minimum width of the dining room should be 2.7m.

Kitchen (figure 8): According to the different combination of house modes, the work surface of the kitchen has three types: linear, L-shaped, and U-shaped. The minimum linear length of all types is 3 meters, meeting the needs of allocating five working areas including water basin, stove, refrigerator, chopping board, and temporary placement. As the size of the kitchen increases, the length of the working surface increases, various kitchen utensils can be arranged more conveniently. In all the house modes, the dining room and the kitchen are arranged adjacent to each other to facilitate the
expansion of the operating space and the development of pastry making with Guanzhong characteristics.

Toilets and other service rooms (figure 9): The toilets are arranged in separated dry and wet zones. Smaller house will be equipped with a washing machine in the bathroom, and larger house with two floors can be equipped with a dedicated laundry room or housekeeping room under the stairwell. Bathrooms with different widths are mainly reflected in the width of the washbasin area. The difference in depth is reflected in whether a bathtub can be arranged.

Entrance hall: The entrance of a typical Chinese urban apartment is usually between the living room and the dining room. It is convenient to enter the kitchen when entering the house. However, the entrance of the rural house in Guanzhong area is generally set in the south, and the living room and bedroom are also arranged in the south, so the kitchen needs to be arranged in the north direction. Therefore, the flow line from the entrance to the kitchen must pass through the living room or even the bedroom. This caused certain interference to the functional zoning of the house. This research proposes to use a sunspace as the entrance porch, setting up shoe cabinet and temporary storage space to enhance conveniences. Sunspace also has an important energy-saving function [8].

Storage space and others: If the homestead is deep enough, special rooms for storage, audio-visual entertainment, learning and reading, makeup and dressing, leisure, etc. can be added. It is recommended to use non-insulated sloping roofs, because EPS floor blocks have already been used. Sloped roof is also beneficial to drainage, at the same time acting as a buffer zone for climate, but it needs to be treated with pests while be used as additional storage space.

4. Customized design process

4.1. Room module combination
This research did not introduce standardized house types with fixed size, but based on the above-mentioned room modules of different dimension, four types of house combination modes were formulated. Residents can choose different room module combinations and dimension according to the limit of the homestead or the total area (cost).

**House combination mode A**: mode A (figure 10) is a single-story, three-bedroom unit, with a minimum width of 9.3 meters and a minimum depth of 9.3 meters. With a regular layout, function partition is quite clear. A loggia or sunspace can be set outside the south-facing living room.

**Unit combination mode B**: mode B (figure 11) is also a single-story, three-bedroom unit. The recommended minimum width is 9.9 meters and minimum depth is 9.3 meters. Compared with mode A, the bathroom of this type is set to the north, which can ensure that the bathroom have natural lighting and ventilation when single unit are combined into townhouses. The figure shows that a dedicated housekeeping room is added between the south-facing bedroom and the north-facing bedroom.

**House combination mode C**: mode C (figure 12 and 13) is a double-storey, five-bedroom unit, with a minimum width of 9 meters and a minimum depth of 11.7 meters. The living room adopts a one-and-a-half-story full-height design. Along a half-story staircase from the second floor, residents can reach the roof of the living room, which is the south-facing terrace. The high ceiling design makes the space more open, and the large terrace also meets the needs of drying cloth or cereals.

**House combination mode D**: mode D (figure 14 and 15) is also a double-storey, five-room unit. The recommended minimum width is 8.7 meters and minimum depth is 11.1 meters. Compared with mode C, the bathroom of this unit type is set to the north, which can ensure that the bathroom has natural lighting and ventilation when house units are combined. The second floor can be equipped with a south-facing terrace, or a double-height area in the living room. Sunspace can be set outside the south living room on ground floor.

4.2. Automatic generation of house layout based on computer program

![Figure 18. mode A combination logic illustration](image)

![Figure 19. Prolog interface for mode A](image)

![Figure 20. various room layout outcome under certain restraints for mode A](image)

Numerous room modules of different width and depth can be finally combined into the above-mentioned house modes of different sizes (figure 16 and 17). In order to quickly generate house layouts under the constraints of site width and house area (cost), and house builders can quickly display suitable house layouts to customers and make choices, the research successfully uses the computer program Prolog to assist in this process. Prolog is a logical programming language oriented to deductive reasoning. It is based on the processing of first-order predicate calculus. Due to its simple grammar, rich expressive power and unique characteristics of non-procedural language, it is very...
suitable for expressing human rules of thinking and reasoning. Because room modules in this study are rural residences and their formation are relatively regular, the combination logic is relatively easy to formulate (figure 18). First, the room module size is constructed in the program, and combination logic and limiting factors are set (figure 19). As long as the limiting condition value is typed, a certain number of qualified apartment combination results can be quickly generated (figure 20), and then the homebuilder can quickly draw the plan based on the result for residents to choose.

4.3. **Style selection**
For Guanzhong rural houses, facade materials are usually constrained by cost, so simple treatments are preferred. Stone-like painting and partial stone tiles combination are suitable for EPS cavity blocks as finishes. At present, the appearance of rural houses in Guanzhong area is greatly affected by the so-called "Western style", and residents should be actively guided to choose modern Chinese or simple country style with mass production of industrialized decorative components (figure 21).

4.4. **Environmental response**

If there is a large demand for new houses at the same time, a linear layout with pleasant street space should be formed to encourage neighbour communications (figure 22). When there are existed farm houses on both sides, residents should be actively guided to pay attention to the coordination between new building and the neighbours in terms of orientation and setback.

4.5. **Furniture and equipment**
Since the rooms have adopted a modular design based on 300mm module, the furniture in all rooms can be customized and assembled in large quantities. This will facilitate the contractors to integrate the industrial chain, improve the degree of industrialization and customization, and reduce the cost at the same time.

The EPS cavity block enclosure has low heat transfer coefficient and high air tightness. It is recommended to use a multifunctional environmental unit that integrates fresh air, purification, refrigeration, dehumidification, and heating functions. It can further reduce energy consumption and purify air.

5. **Conclusions**
In the context of China’s sustainable development strategies for large number of rural areas such as energy saving and land saving, and the opportunity of China’s vigorous development of new prefabricated building systems, this research proposes a way to give full play to the advantages of steel structure frame and the EPS cavity block enclosure system. The characteristics of this rural house system mainly include:
1. Prefabricated steel structural components with convenient transportation and easy installation;
2. Building envelope with outstanding energy saving effect, moderate cost and industrialized level due to combination of prefabrication and on-site cast;
3. House design based on furniture layout with high plot-size adaptability, and computer program-based generation for high customizable combination.
Following research will mainly focus on: house type generation based on BIM software for direct visual result, integration of the entire industry for full house decoration and equipment delivery, and urban design guidelines for rural self-built houses. It is hoped that such a multi-discipline integration approach will promote the sustainable and liveable development of the rural settlement environment of China in the future, especially the northwest area.

6. Reference

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