CONSTRUCTION TECHNIQUES OF INNOVATIVE HOUSING SYSTEMS IN CHINESE MAINLAND

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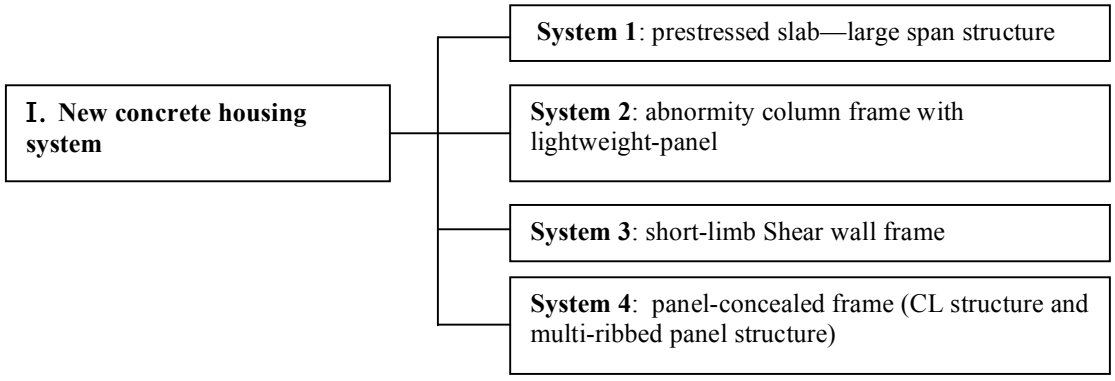
Abstract: There are advanced experiences to be learned from developed countries in terms of housing construction techniques. However, both in the region of Chongqing and throughout China, the lack of incorporation of modular housing component production hinders housing standardization and the advancement of housing component system. This paper aims to analyse the construction techniques of the innovative housing systems of the Chinese Mainland. Six innovative housing systems have been successfully adopted in main cities of the Chinese Mainland in recent years, by using prefabrication of standardized components. The six innovative housing systems are divided into two categories: I) New concrete housing system and II) Steel structure housing system. The main technological characteristics of the housing systems, including their advantages and disadvantages, suitability in contrast to the traditional housing systems are examined. The innovative housing systems could be used as models for promoting industrialized housing in western city of China.
Keywords: Industrialized housing; Innovative housing systems; Construction techniques; China

1 Introduction

There are good lessons to be learned from developed countries over the past decades in terms of the development of industrialized housing. But, there are some problems regarding directly imported industrialized housing systems. The imported industrialized housing systems are too expensive and therefore impractical for developing countries. Moreover, there are certain industrialized housing systems such as volumetric and tunnel-form systems, which are not suitable for application in developing countries, either because of environmental issues or because of economic and social benefits directly relating to the present conditions in the region of China. While these approaches to industrialized housing production resulted in expensive and inappropriate dwellings, the thrust of technology development is geared towards two streams, i.e., prefabrication of small components and partial prefabrication. Hence, the innovative housing construction techniques that use local resources for feasible application of industrialized housing have been developed in China. The housing systems should be an open system, i.e., compatible with conventional and other building methods. The production process should involve minimal capital, use of local materials, require small and affordable equipment or machinery, and demand simple skill specialization.

Six innovative housing systems have been successfully adopted in main cities of Chinese Mainland in recent years, by using prefabrication of standardized components. The housing systems are divided into two categories: I) New concrete housing system and II) Steel structure housing system. The new concrete housing system has four sub-systems, and the steel structure system has two sub-systems. Figure 4.1 shows the innovative housing systems of classification.



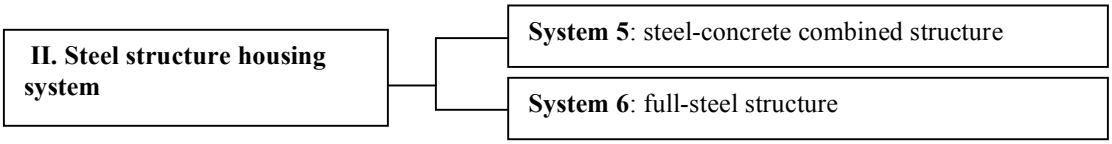


Figure 1: Innovative Housing Systems of Classification

2 Technological Characteristics of the New Concrete Housing System

New structural styles and materials have been combined to form an optimal housing system, which is called a new concrete housing system in the context of the dissertation. Some improvements on the traditional structural system have been made in terms of singleness of shape, high consumptions of resource, lower industrialized level and inflexibility of architectural layout. This system is divided into four representative sub-systems which are described as follows.

2.1 System 1—Prestressed Slab—Large Span Structure (PSLS)

System 1, a large span structure (PSLS), is composed of components of lateral force-resistance around unit and prestressed large span slab. The system has some characteristics such as large span, non-beam and non-column indoor, flexibility partition, strong bearing capacity, anti-crack, anti-shake, reasonable cost, simple construction techniques and short construction period, etc. PSLS has also increased the usable floor area and head room of housing; additional storeys (up to 3) can be built under the limitation of the total height of the middle-high storey residential building. The system can be classified into three shapes according to various components of lateral force-resistance: (1) shear wall-large slab structure (this structure is applicable to middle-high-rise residential building); (2) core tube-large slab structure (this structure is applicable to high-rise residential building); (3) multi-storeys frame-large slab structure (this structure is applicable to 9 or under 9 storeys residential building).

The main matching floor shapes of PSLS are described as follows:

(1) Prestressed slab of pouring on site
It aims to overcome the limitation of the traditional concrete slab through prestressing; slab span is 6 to 12 metres, the bearing capacity is 10KN/M², non-beam, slab thickness is 200-250mm, and grade of concrete strength is above C30.
(2) High efficient prestressed slab of prefabrication
It aims to overcome the limitation of slab of pouring on site, such as complex techniques, long construction period and uneven quality.
(3) Prestressed two-way (reversible) composite slab
Precast soleplate is used as a permanent moulding board and is placed in bottom, prestressed steel bars are placed in the precast soleplate, and steel bars of negative moment are placed around sides of the pouring layer. Precast soleplate is combined with pouring layer tightly in order to form two-way slab.

The characteristics of PSLS are:

（1）Meeting the requirements of large span housing; the span is 10 metres and loading is above 10KN/M².
（2）Good structural performance and good performances of anti-crack and anti-shake.
（3）Improving flexibility of layout.
（4）Light deadweight, thin slab, less consumption of steel bars and materials.
（5）Even quality due to industrialized production.

（6）Less work quantity on site, and improving condition of construction site.
（7）Help to environment protection and energy-saving.

The disadvantages of PSLS are：

(1) Prefabricated slab is limited due to the high requirement of structure integrality in highly seismic region.
(2) Fireproof time of prestressed slab is lower than reinforced concrete structure.
(3) Supporting structure of below-part needs to be improved

2.2 System 2--Abnormal Column Frame with Lightweight-Panel (ACLP)

The system, abnormal column frame with lightweight-panel (ACLP), was developed in Tianjian of China in order to solve the problem of edge-angle of frame column in indoor. Namely, based on the characteristic of residential plane layout, the abnormal column of font style of "T", "L", "Z" and "+" (see Fig.4.2) are combined with beams and floors to form the concealed frame bearing structure. The system is applicable to middle-high rise residential building. According to the requirement of industrialized housing development, wall materials adopted should be high-efficient, more function, lightweight, heat insulation and energy-saving. Local materials and industry waste should be first considered as the wall materials, such as coal gangue, pumice and perlite; flyash and slag, etc. Wall panels should be produced based on overall plans, systematic design, uniform standard, mass production and standardized panel shapes.

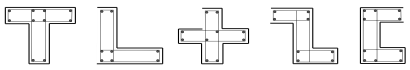


Figure 2: Cross-section shapes of abnormal columns

The characteristics of ACLP are presented as follows:

(1) Improving architectural function (aesthetically pleasing)
- "Concealed frame", i.e., a frame column, is concealed in wall, so as to improve sight and function indoor.
- Flexibility of inner architectural design is improved; usable area is increased 8%-10% more than the traditional housing system (Chen, 2000).

(2) Reduction of structural deadweight
- The deadweight reduction is from 15kn/m² to 9-10kn/m², reduction of deadweight is about ½-1/3 more than the traditional housing system (Chen, 2000).
- Reduction of earthquake reaction benefits with foundation design.

(3) Materials of lightweight and heat preservation can be adopted in the system of abnormal column frame
- Materials of filler wall are made of slag, flyash and industry waste, reducing environment pollution.

(4) Saving consumption of energy sources
- Consumption of production and maintenance costs are saved, meeting the nation standard of residential building energy-saving, i.e. index of heat consumption at <20.5w/m² (Chen, 2000).

The disadvantages of ACLP include:

The joint technique of abnormal columns and filling walls is a key problem; meantime, crack appears easily.
Wet method of construction is not yet eliminated fully.
Transportation of precast units could also be a problem for construction sites located in congested urban areas.

2.3 System 3—Short-Limb Shear Wall Structure (SLSW)

System 3, i.e., short-limb shear wall structure (SLSW), belongs to a system of shear wall structure; it is applicable to tower-type building of pouring reinforced concrete on site. According to the characteristics of middle-high-rise residential building, setting of reinforced concrete shear wall is based on the partition of vertical traffic center (staircase and lift), and thus sequentially form an entire core tube structure as main body to bear vertical load and lateral force. The characteristics of SLSW are as follows: (1) Thin wall and improvement of architectural function because the common length of wall limb is about 5-8 times than limb width, which is laid at crossing point of partition wall; (2) Reduction of dead load of building due to reduction of quantity of shear wall with lightweight wall; (3) Reduction of construction time; and (4) No applicability to high seismic region.

2.4 System 4—Panel Concealed-Frame Structure (PCF)

System 4, i.e., panel concealed-frame structure (PCF), is one of the results of wall innovation for industrialized housing development. This system is a new system of panel-column bearing structure, which is formed from composite wall panel and concealed frame. The CL structure and multi-ribbed panel structure are two representative types of this system.

2.4.1 CL Structure System

The CL structure system is a composite system of reinforced concrete (see Fig.4.3), which is formed from abnormal column frame and composite shear wall. The core of this system is composite wall panel, which is a new shear wall of bearing and heat insulating. This wall panel is formed from concrete wall panels of inside and outside, and sandwich materials of heat insulation and sound insulation. Reinforced concrete wall panel and insulation interlayer are made of integrative systems of heat insulation.

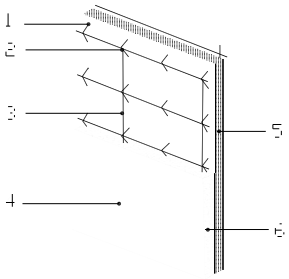


Figure 3: Structural drawing of CL panel

Notes: 1. oblique cutting bar;
2. Bearing bar;
3. Pouring concrete in site
4. Welding framework
5. Polystyrene board
6. Fine aggregate concrete

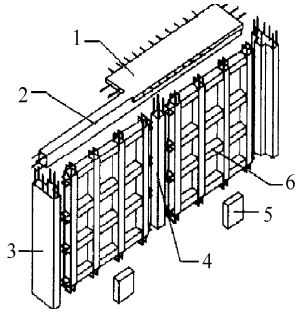


Figure 4: Structural drawing of multi-ribbed panel (Yao *et al*. 2003)

Notes: 1. Floor;
2. Frame beam (connecting);
3. Frame column in the end;
4. Frame column in the middle;
5. Filling block;
6. Concrete gridiron

The CL system is applicable to multi-storey residential building whose height limited less than 25 metres (Li, 2004). It has many advantages as a substituted structure of blocks, which are described as follows:

- Light deadweight and good aseismatic capacity.

- Good performance of heat insulation and sound insulation: heat insulation of CL wall is twice than traditional wall; and five times than concrete wall.
- Usable area of CL system could be increased 5%-10% more than that of traditional structure (Li, 2004).
- Push industrialized housing development due to industrialized production: the CL's components can be mostly carried out industrialized production, so there is less work on site and high industrialized level in construction progress.
- Environmentally friendly: green environmental materials of Non-radiations and non-pollutions are adopted in the CL system; construction waste of the CL system can be reduced 50% more than the traditional system (Li, 2004).
- Superior strength and durability: the CL system's main body is reinforced concrete structure which has high safety; its exterior wall has good corrosion resistance and carbonization resistance; its lifetime is 50%-100% longer than the traditional systems (Li, 2004).
- Reasonable cost and high competitive capacity: cost of the CL system is increased 10%-15% more than the traditional system, but building sale cost can be increased by 30%-50%; according to usable area, its cost equal to one of traditional system, the same cost but different structures (Li, 2004).

2.4.2 Multi-Ribbed Panel Structure (MRP)

The research on the multi-ribbed panel structure (MRP) was begun in 1990 by the research institute of building engineering of new technology and Xian Building Science Technology University. The research result has obtained the identification of national Construction Ministry in Dec 2000, and got two national patents (ZL97242185.8, ZL991125715.X). In 2002, the result has been listed in the main popularity plan of nationality by Construction Ministry (Number: 2002004).

The MRP system is formed from multi-ribbed composite panel and frame-concealed (see Fig.6.4). It is applicable to 8 and under 8 degree seismic region; the building height should not exceed 15 storeys, i.e. 45 metres. The MRP's frame is prefabricated from reinforced concrete sash and aerated silicate blocks filled inside sash. The filling materials are made of industry wastes such as slag, flyash and lightweight aggregates. In this system, composite wall panel has the functions of partitioned space and heat insulation, and also can be used as a bearing component. As a result, the MRP can reduce the size of frame sections and the consumption of reinforcing bars, and also reduce structural economic index. Its characteristics are as follows:

- Good aseismatic capacity: the maximum bearing capacity of the MRP increases 1.6-1.8 times than the traditional system, and the deformability increases 2 times more than the traditional one (Yao *et al*, 2003).
- Good structural flexibility: the MRP is applicable to residential building of multi-storey and middle-high-rise; it can be combined with other systems for use and can increase usable area due to reduction of wall thickness.
- Good effect of energy-saving: the MRP has good heat-insulating property; heat engineering test shows that total heat resisting coefficient of 250mm exterior wall is high than that of 615mm solid brick wall, close to that of 490mm hollow brick wall, thus meeting the nation standard of energy-saving wall.
- High industrialized degree and rapid construction speed: the MRP's production adopts prefabrication in factory as well as making on site; at the same time, construction process is expedited due to improving of mechanization and can reduce construction period 1/3 shorter than traditional system.
- Remarkable community benefit; the MRP protects land resource and environment due to large consumption of industry waste; it is reported that the building per 10,000 m² just consumes 2,000-3,000 m³ industry waste, and avoids 800 m² of the damaged land (Yao *et al* , 2003).
- Remarkable economic benefit: light deadweight, rapid construction speed and less man-day; construction cost per square metre is reduced 4%-6% and 10%-12% more than the traditional system and frame one respectively (Yao *et al*, 2003).

On the other hand, the disadvantages of the PCF system have also been reported. For example, the PCF system has the follow disadvantages when applied in the housing industry of Chongqing, the largest western city of China:

- Higher production cost due to employment of professional techniques and equipment - a particular concern for the city due to its abundant supply of cheap imported labour.
- Higher capital investment risk because of new manufacturing facilities and automated equipment when compared with conventional labour-intensive methods.
- Higher cost of transportation for prefabricated elements from plant to their construction site.

3 Technological Characteristics of Steel Structure Housing System

It is reported that the building height of the steel structure housing systems is suitable to multi-storey (about 6 storeys) and small high-rise building (about 12 storeys), commonly, non-exceed 18 storeys. The steel structure housing is generally divided into full-steel structure and steel-concrete combined structure in terms of components materials.

System 5: Steel-Concrete combined Structure (SCCS)

System 5, i.e., steel-concrete combined structure (SCCS), is a composite type based on steels and concrete. The supporting system of SCCS is composed of combined steel tube and concrete columns, combined steel skeletons and concrete beams, support of resistance-lateral forces and composite concrete floors. The systematic techniques of multinomial patents of SCCS focus on the components including exterior wall panel of energy-saving and prefabricated interior partition panel. Tianjin University cooperated with Tianjin Construction Engineering Group to develop a set of technology of the SCCS system. It had been adopted in Tianjin to build housing of 300,000 square metres (Wang and Zhang, 2004; Chen, 2003). Based on the tentative project in Tianjin (see Fig.4.5), a series of technological systems regarding research development, technological design, components manufacture and assembly on site have been formed. Due to successful application in high-rise residential building, the SCCS system possesses credible technological support, and also accords with nation industrialized policy. Consequentially the SCCS system has a great development potential.

Figure 5 Tentative Project in Tianjin (Wong and Zhang, 2004)

The characteristics of the SCCS system are described as follows:

- Compared with reinforced concrete system, it characteristics include light deadweight, small size of components cross-section, moulding board saving and short construction period.
- Compared with steel structure, it characteristics include steel consumption reduction, improved structural stability, fire-resisting and durability, and remarkable economic benefit.
- The construction cost of SCCS equals to the current reinforced concrete system, and it has highly industrialized degree, and advanced and integrated economic-technological level.
- Safety and protection
- Consistent quality

- Ease of installation
- Reduced weather dependency
- Aesthetically pleasing

The limitations of SCCS system when applied in the housing industry of Chongqing have also been reported:

- Non-formed chain of construction industry
- Poor manufacture capability of local manufacturers
- Increased cost due to transportation of components

System 6: Full-Steel Structure (FSS)

System 6, i.e., full-steel structure (FSS) is applicable to multi-storey residential building. Two structural styles of beam-column framing and frame-support are usually adopted by the FSS system (Chen et al, 2004; Chen, 2002; Huang and Li, 2003; Wang and Zhang, 2004; Wang, 2004; Yang, 2004).

Light steel structure (LSS) is a main style of FSS; LSS is suitable for low-storey and multi-storey residential building (Chang, 2004; Peng and Shi, 2003; Shu *et al*, 2001; Xu and Zhu, 2004). LSS is known for bearing low load, adopting small size of components and light deadweight. Economically formed steels of LSS include cold-rolled formed steels, hot-rolled formed steels, welding formed steel of H and T, or seamless steel tube. These components are made of supporting frame of building, while lightweight wall materials are composed of enclosure structure. The lightweight wall materials include extruded steel board and composite board, PC panel, autoclave lightweight concrete panel (ALC) and strawboard. These lightweight wall materials have good physical performance of heat-insulating, fireproofing and waterproofing. The light steel structure has a lot of characteristics or natures when compared with the traditional housing structure. These characteristics are described in detail as follows:

- All steel construction components are manufactured off-site and delivered to site cut to length, drilled and fabricated to facilitate fast and easy assembly and erection. Consequently there is very little steel waste on the construction site.
- Flexibility of architectural space layout meets various requirements of different customers.
- LSS has big span between columns; the whole walls in LSS system are non-bearing wall; the walls can optionally layout; it could make architectural space rich and it is favorite of customers.

Health and safety

- Compared with working on-site, off-site, factory production is much safer. Many processes are fully or semi-automated and factory conditions are generally suitable, dry and well-lit when compared with working on-site, which is less safe for workers and may be delayed due to inclement weather.

Low waste

- Steel construction products are efficiently manufactured using hi-tech, computerized equipment that minimizes materials waste. Computer aided design (CAD) systems are efficiently integrated with manufacturing software to produce quality products efficiently, accurately and quickly. Any steel waste produced during manufacturing such as off-cuts or turnings are 100% recycled into new steel.

Strength

- Consistent manufacturer-controlled properties of material, thus eliminating grading or site quality checks.
- Stable strength that does not normally degrade with time.
- Geometry is precision-formed, thus section properties are very accurate.

Economy

- Steel is light weight. LSS has light deadweight due to adopting lightweight materials of wall and floor, thus saving foundation costs. Light steel residential building under 18 storeys could save foundation cost by 20%-30%. Its dead load is 30% and 20% of the traditional system and concrete shear wall one respectively.
- LSS has small section components. Usable area of housing is increased. It is also easy to handle and minimize site plant requirements.
- Members are cut to size with pre-punched assembly and service holes which increases accuracy and reduces site work.
- Design life is long and maintenance is rarely required.

Sustainability and energy conservation

- Steel is 100% recyclable and can be recycled repeatedly without compromise to strength. Moreover, magnetic separation provides an inexpensive method for steel removal from solid waste.

Factory manufacture and quality

- Factory production facilitates accurate, quality workmanship which results in high quality, reliable products with fewer defects than work conducted on-site. Optimized use of off-site manufacture could decrease construction time by 10% and reduce defects by 20% while increase predictability on project completion by 20% and productivity by 20%.
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Factory applied coatings

- Corrosion and fire protection coatings for steelwork have been applied increasingly in factory instead of on-site. This enables greater quality control, i.e. more uniform coverage, reduces waste through overspray and reduces the time taken on-site to apply coatings to the steelwork.

Predictability

- Surveys of construction clients have confirmed that predictability is a key issue on large projects. Because steel construction products are manufactured off-site, delivered to site on a 'just-in-time' basis, suffer few defects and are erected quickly on-site, steel construction is more predictable than many other forms of construction. A predictable construction programme means that clients can plan and finance more accurately by using steel construction with lower risk due to unforeseen delays.

Modular construction

- Steel-based, modular construction systems afford maximum off-site manufacturing opportunity. Modules can be fitted out with floor finishes and sanitary (and other) fittings in the factory and simply and quickly craned into position on site.

Rapid construction

- Building cost and construction programme have been key drivers in traditional construction. Fast, reliable and predictable construction programmes save money and reduce local impacts associated with construction work. Off-site manufacture provides higher quality products that require less 'snagging' on site, leading to savings in both time and cost. Unlike on-site construction, off-site manufacture is not

delayed by inclement weather. Therefore, by reducing the duration of site work, the risk of weather-related delays is minimized. Compared with traditional housing systems, the construction period can be lessened by 1/3.

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Major limitations of applying the system in Chongqing

- Professional and advanced workmanship causes the need for high level of supporting equipment and techniques as well as management skills.
- Higher capital investment in a new manufacturing facility and automated equipment.
- Professional techniques and equipment lead to increase in cost of production. Fireproof limit of steel is only 10 min-20min, cost of fireproof measure is high. High cost of steel structure is the key problem for non-popularity.
- Little control over the volume and stability of market demand, the nature of orders, i.e. their size, diversity, and complexity and the distance between the plant and site locations
- Light steel structure system particularly needs skilled erectors on-site to insure all work is exact and professional.
- Their considerable weight and bulkness make transportation and erection a rather complicated and costly process.
- Lack of integrated design and manufacture technology to ensure a high quality, integrated process.
- Supporting components in terms of wall panel, interior wall partition and floor need to be developed; integrated technology regarding integral kitchen and toilet is also needed to be developed.
- Today the technology of corrosion and fire protection coatings is not perfect, and needs continuous improvement.

4 Conclusion

This paper provides comprehensive knowledge on selecting the innovative housing systems for application in the Chinese Mainland. The paper reviews the technological characteristics of innovative housing systems successfully operated in recent years in main cities of Chinese Mainland, including new concrete housing system and steel structure housing systems. The main technological characteristics of the housing systems, including their advantages and disadvantages, suitability in contrast to the traditional housing systems are examined. These existing advanced housing systems have been successfully used in main cities of the Chinese Mainland and could be used as models for promoting industrialized housing in Chongqing, a western city of China.

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