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A Practice in China for Computer Aided Design and Construction of Prefabricated Enclosure Walls

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Abstract

This article combines the author's past software development and other work practices related to computer-aided design and construction of building enclosure walls, discussing how computer technology can assist in various methods and directions during the design and construction of building enclosure walls. It mainly involves structural design of load-bearing enclosure walls, structural design of non-load-bearing enclosure walls, thermal insulation design of building enclosure walls, waterproof design of building enclosure walls, planning for enclosure wall hoisting, calculation verification for enclosure wall hoisting, and construction of enclosure walls. Whether in the design of the main structure of the building or in the planning and decoration of the building space, designers need to put in a lot of effort for enclosure walls. It is worth studying how to fully utilize the capabilities of computer technology to free up more time for designers. This article has certain reference value for research and application in related fields.

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1 Introduction

The building enclosure walls is an important component of the building system (not necessarily part of the main structural system), playing a pivotal role in building structure and architectural space design. Generally speaking, building enclosure walls can be constructed using brick walls, concrete walls, stone walls, timber walls, glass curtain walls, metal walls, etc. as well as inorganic materials (such as glass fiber-reinforced inorganic materials). Based on their load-bearing characteristics, the enclosure walls of a building can be categorized into load-bearing walls and non-load-bearing walls.

However, there are pain points and problems to be solved for traditional enclosure wall design and construction process. The poor fire resistance, insufficient waterproof and anti-seepage, moisture-proof performance, lousy insulation effect, and low strength are flaws. And the construction process is complex and time-consuming, which increases construction costs and time. The development of prefabricated buildings and building industrialization can solve many problems. Meanwhile prefabricated engineering design and construction process bring new issues that need attention.

For example, prefabricated components require strict dimensional planning, and prefabricated components with incorrect dimensions will become waste; The demand for multi-disciplinary collaborative design is more evident, and precise hole reservation is required; There are added requirements for short-term working condition verification of individual components, such as lifting, delamination, etc.; The number of drawings has greatly increased, and non-structural professional information is also required to be supplemented in the drawings; The problem of data silos in design is becoming increasingly prominent, and the demand for integrated design, production, and construction data is becoming stronger. So new engineering design and construction process requires new computer-aided technology. There is no much systematic and targeted research to this series of multi-disciplinary issues targeted towards prefabricated walls.

The article discusses the trying of one computer software scheme that integrates prefabricated component design and traditional structural engineering design into one big process, called “YJK's built-in prefabricated building design software”, which may adapt to the need to support the prefabricated walls design and construction processes of selection, planning, and installation. Involving several targeted aspects, such as structural design, insulation design, waterproof design, and installation engineering of prefabricated enclosure walls.

2 Cad for Prefabricated Load-Bearing Enclosure Walls

2.1 Technical Scheme

Believe in the law that if the solution process is clear, rule-based expert systems or similar systems can be used, else if the solution process is unclear, machine learning is needed to obtain rules.

Because the design, calculation and detailing process can be planned as deterministic programs and user interactive programs in computers, so the final scheme was as two aspects, one as a rule-based systems, the other as an interaction system. All data was embedded within the structural analysis software.

In short, it was based on structural design models, rule-based, and integrated into the main process of structural analysis.

2.2 Wall Type

Currently, in the practice of prefabricated building structures in China, the common-used prefabricated walls are based on the "Prefabricated Concrete Shear Wall Exterior Panels" (15G365-1) and "Prefabricated Concrete Shear Wall Interior Panels" (15G365-2).

In addition, there are numerous prefabricated wall systems in China, each with its own advantages. In the YJK's built-in prefabricated building design software, besides supporting the above two reference manuals, it also supports various forms such as single-row sleeve prefabricated walls, double-row full-sleeve prefabricated walls, double-sided composite shear walls, and vertically unconnected prefabricated walls, etc.

2.3 Design Process

In the YJK's built-in prefabricated building design software, the general design process of prefabricated walls includes: establishing structural models, designing prefabricated wall subdivision schemes, performing overall structural calculations, editing planar reinforcement, carrying out detailed design of prefabricated walls, making detailed drawings of prefabricated walls, and exporting the inventory list of prefabricated walls.

According to the current design logic of YJK's built-in prefabricated building design software, the prefabricated wall subdivision scheme is a specialized task based on the existing building structure model. Of course, with the rapid development and maturity of the national building industrialization level, the software may gradually evolve into another systematic workflow following the progress of the industry. Figure 1 shows the subdivision scheme for prefabricated wall in the software (filling parts are prefabricated walls).

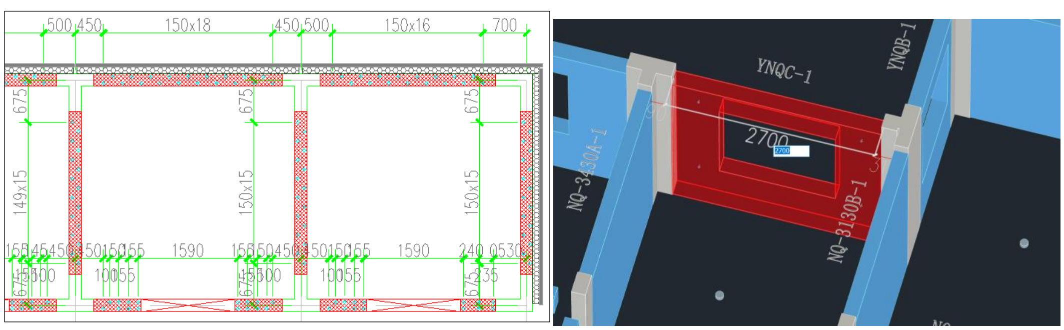


Figure 1: Subdivision scheme for prefabricated walls of 15G365-1 and 15G365-2

in YJK's built-in prefabricated building design software

Based on current practice and understanding, in the proposed amendments to the "Technical Standard for Sawtooth-Shaped Prefabricated Concrete Shear Wall Structures" (T/HNKCSJ011-2024), it is suggested that the original provision 3.0.1, which reads "Design of prefabricated subdivision scheme, including structural selection, structural layout, force transfer path, and production and assembly of prefabricated units of structural components," be revised to read: "Overall scheme design, including structural selection, structural layout, design of prefabricated subdivision scheme, force transfer path, and production and assembly of prefabricated units of structural components." This is because, based on the reading and understanding of this standard, provision 3.0.1 mentions a total of five structural design processes of the building's structural system. It is believed that the first process does not solely encompass the "design of prefabricated subdivision scheme".

2.4 Calculation

In the integrated prefabricated shear wall structure system, other than overall calculations (Figure 2), node connections performance is also important. the Technical Specification for Prefabricated Concrete Structures (JGJ1-2014) stipulates that the shear bearing capacity of the horizontal joints at the bottom of prefabricated shear walls should be checked.

In the YJK's built-in prefabricated building design software, there are corresponding functions (Figure 3).

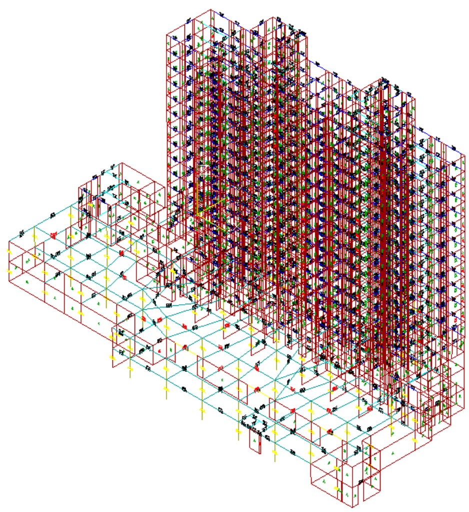
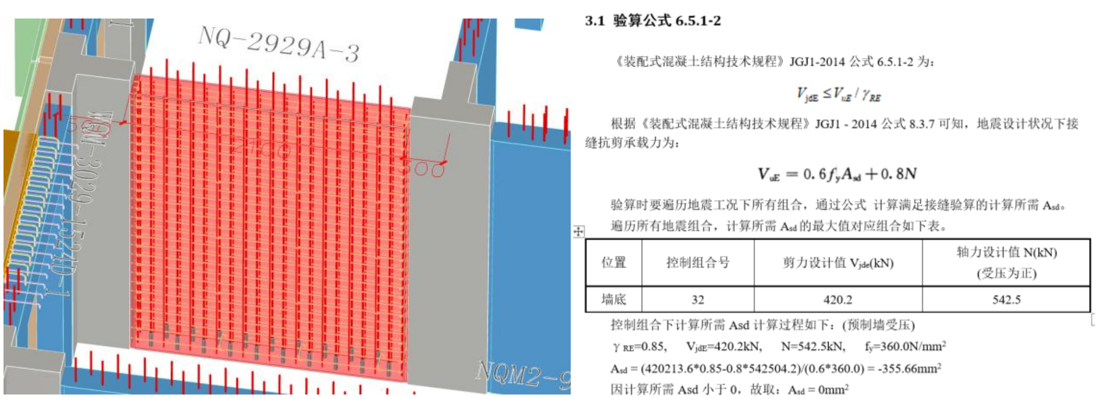


Figure 2: Shear wall building model for structural calculation



3.1 验算公式 6.5.1-2

《装配式混凝土结构技术规程》JGJ1-2014 公式 6.5.1-2 为：

$$V_{jdE} \leq V_{uE} / \gamma_{RE}$$

根据《装配式混凝土结构技术规程》JGJ1 - 2014 公式 8.3.7 可知，地震设计状况下接缝抗剪承载力为：

$$V_{uE} = 0.6 f_y A_{sd} + 0.8N$$

验算时要遍历地震工况下所有组合，通过公式 计算满足接缝验算的计算所需 A_{sd}。遍历所有地震组合，计算所需 A_{sd} 的最大值对应组合如下表。

位置	控制组合号	剪力设计值 V_{jde}(kN)	轴力设计值 N(kN) (受压为正)
墙底	32	420.2	542.5

控制组合下计算所需 Asd 计算过程如下：(预制墙受压)

γ_{RE}=0.85, V_{jdE}=420.2kN, N=542.5kN, f_y=360.0N/mm^2

A_{sd} = (420213.6*0.85-0.8*542504.2)/(0.6*360.0) = -355.66mm^2

因计算所需 Asd 小于 0，故取：A_{sd} = 0mm^2

Figure 3: Some result content of the prefabricated wall horizontal joints calculation

in YJK's built-in prefabricated building design software

2.5 Component Reinforcement and Detailed Drawings

In the YJK's built-in prefabricated building design software, the principle of "normal structure drawing first" is followed. The design process involves the construction drawing by plane integral representation method and the detailed reinforcement drawing for prefabricated walls. The process of obtaining reinforcement for prefabricated walls is shown in the figure.

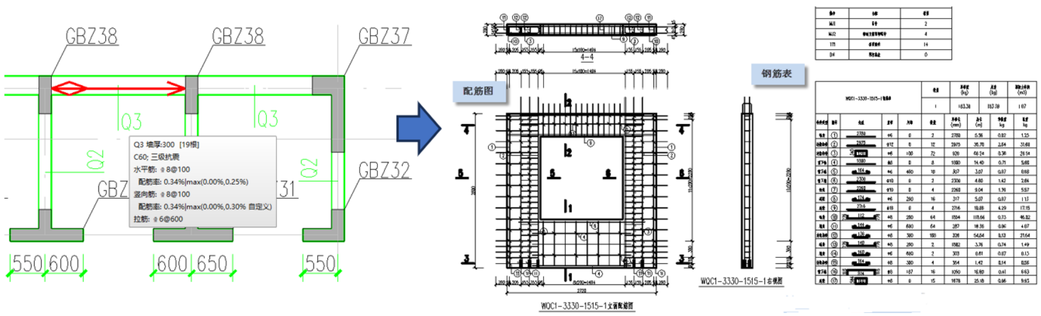


Figure 4: Prefabricated wall reinforcement obtaining process in

YJK's built-in prefabricated building design software

After obtaining detailed reinforcement information, you can proceed to review the reinforcement diagram for prefabricated walls.

3 Cad for Prefabricated Non-Load-Bearing Enclosure Walls

3.1 Technical Scheme

Generally speaking, non-load-bearing walls are not parts of structural analysis model. Because current structural analysis only focuses on the load and rough stiffness contributions it causes, without the strong need for precise non-load-bearing wall model data. But some experts do strongly suggest accurately stiffness considering.

Actually in YJK structural software, non-load-bearing walls can be modeled. Simultaneously, prefabricated non-load-bearing walls can be modeled based on the ordinary non-load-bearing wall data.

In short, prefabricated non-load-bearing walls was based on ordinary non-load-bearing wall data in the structural design software, and is rule-based, and integrated into the main process of structural analysis.

3.2 Wall Type Of Ordinary Non-Load-Bearing Wall

Non-load-bearing enclosure walls can be categorized based on their stress characteristics as self-supporting walls and partition walls.

And partition walls are classified according to their construction methods as follows:

(1) Block partition wall:

Block partition walls are constructed by block units made of some kind of material such as ordinary bricks, hollow bricks, aerated concrete, etc. The degree of prefabrication is relatively low, and nowadays they are less commonly used in prefabricated buildings.

(2) Lightweight frame partition wall

The lightweight frame partition wall consists of two parts: the frame and the surface panel layer. The frame can be made of wood or metal, and the surface panel layer can be made of wood, plywood, fiberboard, gypsum board, etc.

(3) Plate partition wall

Plate partition wall refers to the direct installation of lightweight sheets with large dimensions in length and width. The lightweight sheets can be made of autoclaved lightweight concrete strip panels (ALC), composite slab walls, etc. It is easy to assemble and is widely used in prefabricated buildings nowadays.

In special, for frame structure buildings, non-load-bearing enclosure walls can be categorized into infilled walls and curtain walls. And the infilled walls (including internal partition walls and external partition walls) can be prefabricated.

3.3 Prefabricated Concrete Non-Load-Bearing Enclosure Wall

The prefabricated concrete non-load-bearing enclosure wall can be either a single piece of wall or an assembled wall made of slats.

For the kind of single piece, the YJK's built-in prefabricated building design software can support various types of prefabricated concrete partition walls such as prefabricated infilled walls, prefabricated beams with partition walls, and prefabricated external wall panels.

For the kind of assembled with slats, software can support prefabricated partition walls in the form of strip panels, primarily made of ALC (autoclaved lightweight concrete strip panels).

3.4 Design Process

The design process of prefabricated non-load-bearing enclosure walls in YJK's built-in prefabricated building design software are: establishing a structural model with partition walls, specifying prefabricated partition walls, checking and calculating prefabricated partition walls, editing the detail of prefabricated partition walls, making detailed drawings of prefabricated partition walls, and exporting the inventory list of prefabricated partition walls.

The screenshot shown in the figure depicts a portion of the designated and editable features for prefabricated partition walls in YJK's built-in prefabricated building design software.

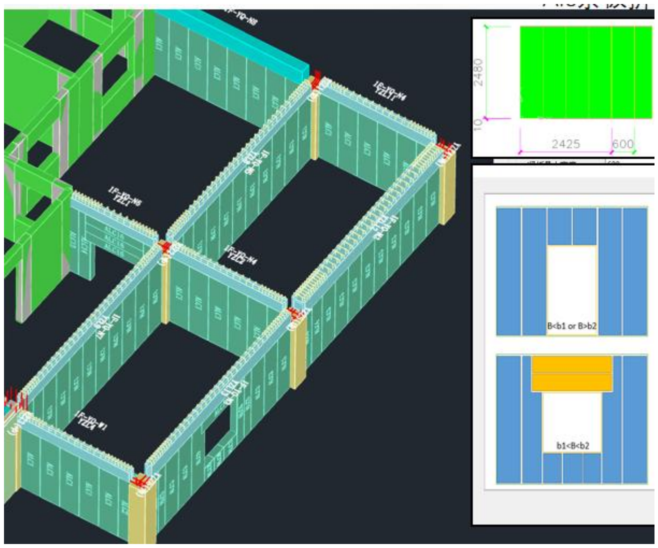
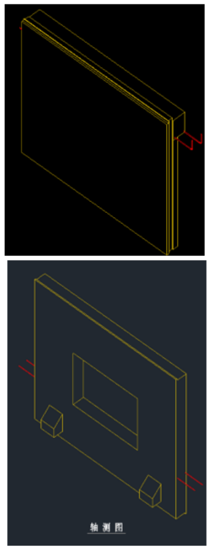


Figure 5: The designation and subdivision functions for prefabricated partition walls (ALC, assembled with slats) in YJK's built-in prefabricated building design software

3.5 Computer-Aided Calculation Related to Structural Safety

The bearing capacity of the external enclosure wall should be calculated under the effects of wind load and seismic load.

In the YJK's built-in prefabricated building design software, the action effect value of the prefabricated external enclosure wall refers to 10.2 of the Technical Specification for Prefabricated Concrete Structures (JGJ1-2014). The calculation is carried out separately for the two cases of "upper end fixed and lower end hinged", as well as "upper and lower end hinged", and the envelope is taken. The bending bearing capacity of the wall body is checked with reference to 6.2.10-1 of the Code for Design of Concrete Structures (GB 50010-2010) and the Technical Specification for Prefabricated Concrete Structures (JGJ1-2014). The shear bearing capacity of the wall body is checked with reference to 6.3.1-1, 6.3.3-1, 6.3.3-2 of the Code for Design of Concrete Structures (GB 50010-2010) and the Technical Specification for Prefabricated Concrete Structures (JGJ1-2014). The node bearing capacity is checked separately for in-plane shear and out-of-plane tensile resistance. The figure shows part of the results.



（2）抗弯承载力计算：

参 (GB 50010-2010　6.2.10-1 JGJ 1-2014)

截面有效高度：$h_0=87.00mm$

由 $M \le \partial_1 f_c bx(h_0-x/2)$ 求得 $x=27.91mm \le \xi_b h0$

由 $\alpha_1 f_c bx=f_y A_s$ 得：

$A_s=\alpha_1 f_c bx/f_y=221mm^2$

实际配筋 $904.78mm^2$,满足抗弯承载力。

（3）抗剪承载力计算：

参 (GB 50010-2010　6.3.1-1、6.3.3-1、6.3.3-2)

$h_w/b=0.58<4$

所以 $V=0.25\beta_c f_c bh=46.65KN>10.12/2$

斜截面承载力 $V=0.7\beta_h f_t bh=13.06KN>10.12/2$，满足抗剪承载力。

Figure 6: Some part of calculation for prefabricated external non-load-baring enclosure wall in YJK's built-in prefabricated building design software

4 The Enclosure Wall In The Automatic Assembly Rate Calculation

4.1 Technical Scheme

Assembly rate is currently a reference indicator in China for evaluating the industrialization level of prefabricated buildings. This indicator roughly represents the proportional between prefabricated and non- prefabricated parts. In fact, the calculation methods vary greatly, and there are different calculation regulations in different regions of China.

The calculation process is not completely clear even according to specific regulation. But it is not very suitable for using machine learning methods because the answer to question is essentially a contractual relationship and the rules are still in development and discussion. So the software system was planned as rule-based expert system, permitting different regions switching to different rules.

4.2 Software Implementation

The screenshot shown in the figure depicts the UI of load-bearing and non-load-bearing enclosure walls when automatically calculating the assembly rate in YJK's built-in prefabricated building design software, based on the national standard "Evaluation Standard for Prefabricated Buildings" (BG/T51129-2017). Additionally, it supports over twenty other local evaluation standards.

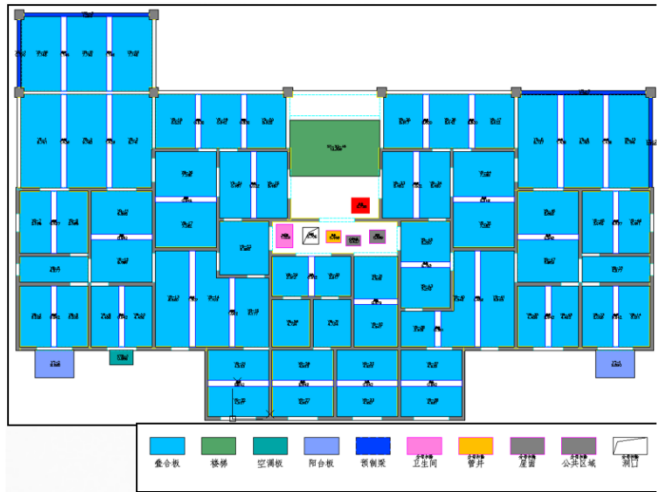


Figure 7: The assembly rate calculation view in YJK's built-in prefabricated building design software

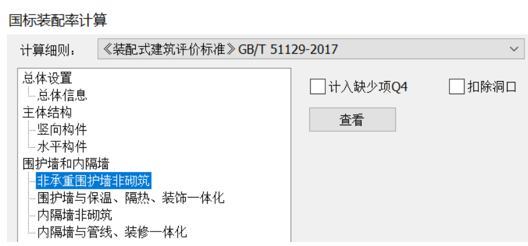


Figure 8: Part of the UI related to non-load-bearing enclosure walls in the calculation of assembly rate using YJK's built-in prefabricated building design software (GB part)

5 Thermal Insulation Design and Cad Technology for Prefabricated Exterior Enclosure Walls

5.1 Technical Scheme

Heat preservation in winter and thermal insulation in summer are crucial considerations that cannot be overlooked in exterior enclosure wall architectural design.

This issue is solely about the prefabricated enclosure wall itself, and have nothing to do with the underlying structural design or structural models.

Current technical solution categorizes this issue as a deepening design of components. For example, the placement of insulation layers for walls of different types and shapes, the definition method of local insulation components, etc.

5.2 Heat Preservation And Thermal Insulation Design For Different Kind Of Wall

In YJK's built-in prefabricated building design software, the types of insulation supported include: sandwich prefabricated exterior walls with insulation layer (GB standard load-bearing prefabricated walls, Figure 9), double-sided laminated walls (including load-bearing walls and non-load-bearing walls) with internal insulation layers, and embedding boards.

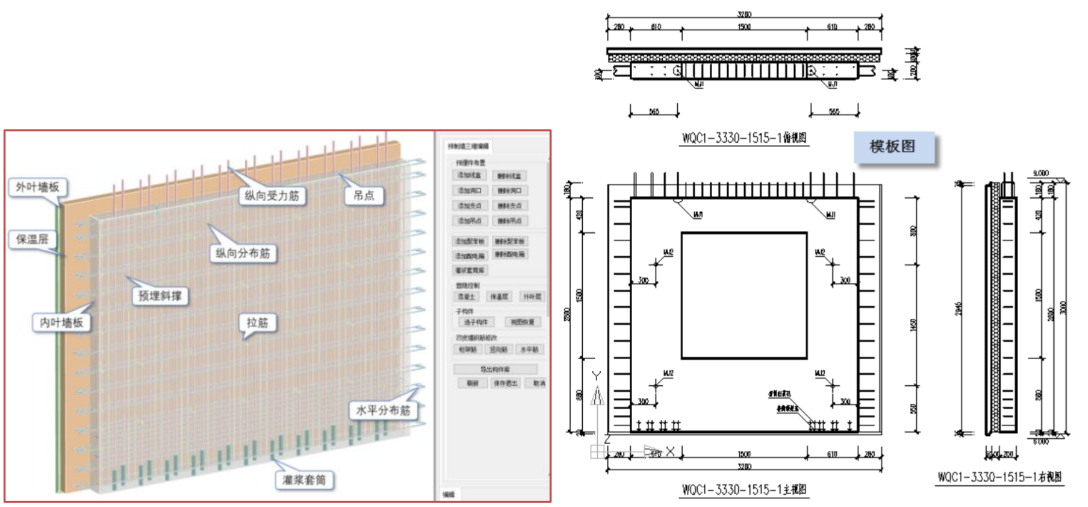


Figure 9: a sandwich prefabricated exterior wall (with an insulation layer which is larger than wall itself)

In YJK's built-in prefabricated building design software (GB part)

5.3 Insulation Material

The insulation layer material for the exterior enclosure wall can be spray-on insulation materials such as polyurethane insulation materials; insulation boards made from inorganic fiber materials, such as glass wool and rock wool; and insulation boards made from polystyrene resin, including expanded polystyrene (EPS) boards and extruded polystyrene (XPS) boards.

YJK's built-in prefabricated building design software supports embedding polystyrene boards for prefabricated walls to reduce self-weight (weight-reducing boards), at the same time, it can guarantee insulation functionality.

5.4 Fire Protection For Insulation Layer

The "Technical Specification for Prefabricated Concrete Structures" (JGJ1-2014) 4.3.2 stipulates that the combustion performance of insulation materials in sandwich exterior wall panels should meet the requirements of Class B_2 in the "Classification for Burning Behavior of Building Materials and Products" (GB8624-2012). According to Chapter 4 of the "Classification for Burning Behavior of Building Materials and Products" (GB8624-2012), Class B3 refers to flammable materials.

To comply with the Technical Specification for Prefabricated Concrete Structures, according to the provisions of JGJ1-2014, the amendment suggestion for the "Technical Standard for Sawtooth-Shaped Prefabricated Concrete Shear Wall Structures" (T/HNKCSJ011-2024) is to adjust the original provision "The insulation layer should be made of materials with a combustion performance not lower than Class B. The thickness should be determined by calculation" to "The insulation layer should be made of materials with a combustion performance not lower than Class B_2. The thickness should be determined by calculation".

The fire protection standards for the insulation layer of the external enclosure wall should be improved in accordance with regulations, in order to prevent the spread of fire from one part of the building to another along the external wall as much as possible.

Although YJK has the function of fire resistance calculation for structural components, the fire resistance for insulation layer is suggested to be confirmed through the definition method in the previous two sections.

6 Waterproof Design and Cad Technology for Prefabricated Exterior Enclosure Walls

6.1 Technical Scheme

Waterproof performance is another important design considerations for the exterior enclosure walls.

This issue is solely about the prefabricated enclosure wall itself, and have nothing to do with the underlying structural design or structural models.

Current technical solution also categorizes this issue as a deepening design of components. For example, waterproof details of vertical connection nodes for prefabricated wall outer leaf panels, and treatment for horizontal connection nodes between prefabricated walls.

6.2 Waterproof Material

In article 4.3.1-2 of the Technical Specification for Prefabricated Concrete Structures, it is stipulated that silicone, polyurethane, and polysulfide building sealants should comply with the provisions of Silicone Building Sealants (GB/T14683), Polyurethane Building Sealants (JC/T482), and Polysulfide Building Sealants (JC/T483), respectively.

The Technical Specification for Prefabricated Concrete Structures (JGJ1-2014) does not specify any restrictions on the use of sealants, so proposing amendments to "Technical Standard for Sawtooth-Shaped Prefabricated Concrete Shear Wall Structures" (T/HNKCSJ011-2024) that it is recommended to lift the restrictions on the use of sealants. Specifically, the original provision "The joints of the external protective layer should be sealed with structural sealants. The durability and performance indicators of the structural sealants should meet the relevant provisions of the current national standard 'Silicone Structural Sealants for Building' GB16776" is suggested to be adjusted to "The joints of the external protective layer should be sealed with structural sealants. The durability and performance indicators of the structural sealants should comply with the relevant provisions of the current national standard.".

If there are no other considerations, designers should be able to independently weigh and select the appropriate sealant based on project needs.

6.3 Design related to Waterproof

The YJK's built-in prefabricated building design software has been enhanced with the ability to automatically set tongue-and-groove joints, following the criterion method for the national standard of prefabricated shear walls. As shown in the figure.

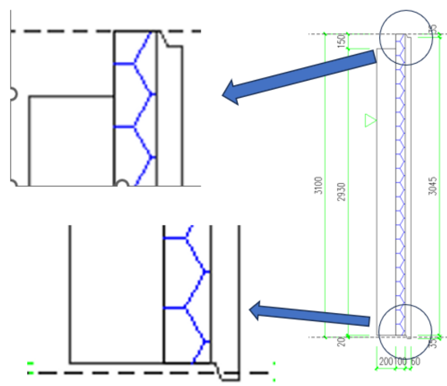


Figure 10: YJK's built-in prefabricated building design software automatically sets up tongue-and-groove joints for prefabricated exterior walls

People also can use YJK's built-in prefabricated building design software to design horizontal nodes of the external enclosure walls mutually, as shown in the figure.

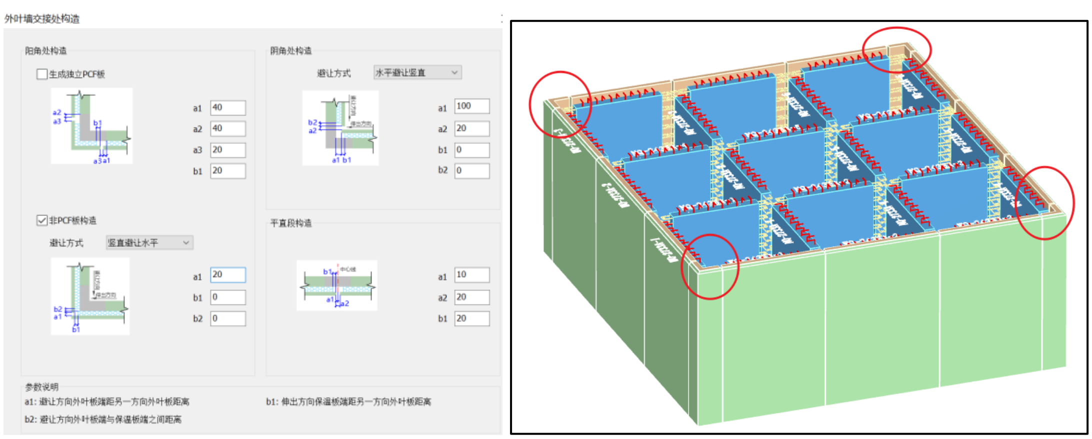


Figure 11: Wall horizontal connection node design

in YJK's built-in prefabricated building design software

7 Computer Technology for The Construction of Prefabricated

Enclosure Walls

7.1 Technical Scheme

Regarding construction, if we focus on the issue of prefabricated components, it can be assumed that this issue is solely about prefabricated enclosure wall itself, and have nothing to do with the underlying structural design or structural models.

However, there are various issues with different aspects to be solved. Firstly, 3D Model based visualization is required for installation planning function, and the core technology is about Computer Graphics. Secondly, independent lifting safety calculation is needed in the lifting validation, and Material Mechanic is the core related knowledge. Thirdly, to achieve automatic installation, it is required that the design data can match the on-site environment, so the core is about data transmission and sharing, coordinate alignment between computer data and the real world.

7.2 Installation Planning

To achieve the goal of facilitating users in planning and simulating the construction installing of wall panels, efforts in two aspects were made.

The hoisting scheme function in YJK's built-in prefabricated building design software is implemented by the way of dynamic display of the model.

On the other hand, reinforcement collision is always a troublesome thing for prefabricated components. Steel collision detection program provides prompts. In some cases, also providing a certain degree of automatic avoidance solutions (Figure 12).

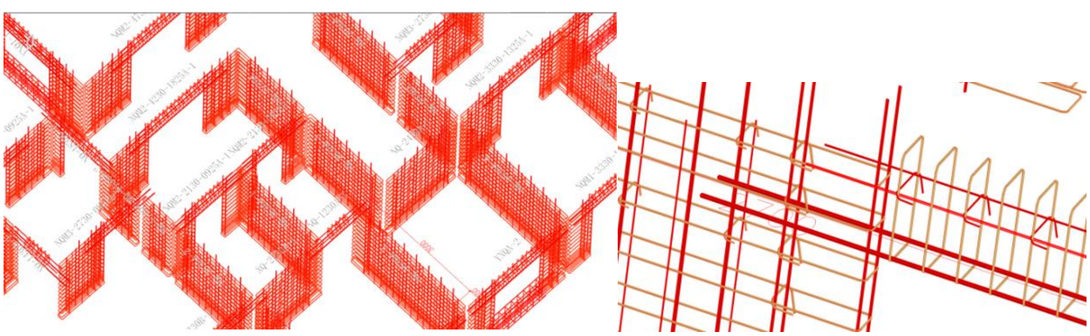
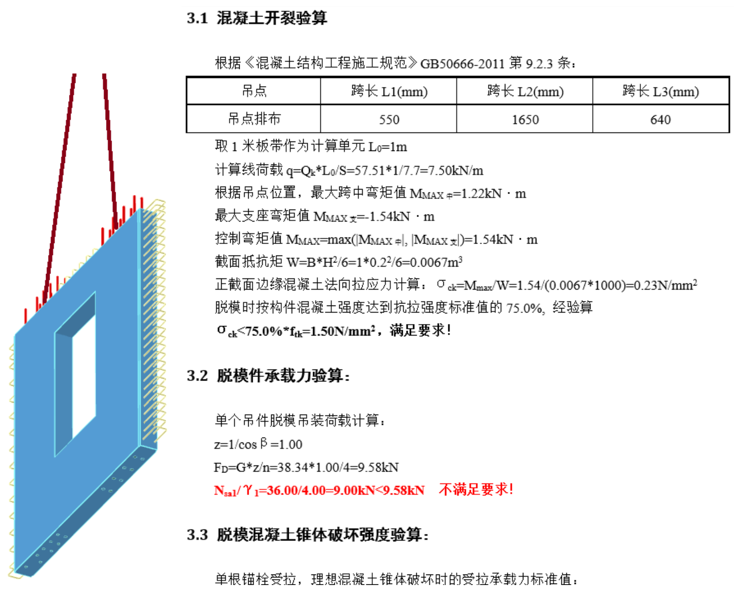


Figure 12: Reinforcement collision detect program in YJK's built-in prefabricated building design software

7.3 Lifting Verification

Some part of the calculation content for the hoisting calculation function in the YJK's built-in prefabricated building design software is shown in the figure below. It can automatically perform hoisting calculation verification for wall panels and output a complete hoisting calculation sheet.



3.1 混凝土开裂验算

根据《混凝土结构工程施工规范》GB50666-2011 第 9.2.3 条：

吊点	跨长 L1(mm)	跨长 L2(mm)	跨长 L3(mm)
吊点排布	550	1650	640

取 1 米板带作为计算单元 L_0=1m

计算线荷载 $q=Q_k*L_0/S$=57.51*1/7.7=7.50kN/m

根据吊点位置，最大跨中弯矩值 $M_{MAX中}$=1.22kN · m

最大支座弯矩值 $M_{MAX支}$=-1.54kN · m

控制弯矩值 $M_{MAX}=\max(|M_{MAX中}|, |M_{MAX支}|)$=1.54kN · m

截面抵抗矩 $W=B*H^2/6=1*0.2^2/6=0.0067m^3$

正截面边缘混凝土法向拉应力计算：$\sigma_{ck}=M_{max}/W$=1.54/(0.0067*1000)=0.23N/mm^2

脱模时按构件混凝土强度达到抗拉强度标准值的 75.0%, 经验算

$\sigma_{ck}<75.0\%*f_{tk}$=1.50N/mm^2，满足要求!

3.2 脱模件承载力验算：

单个吊件脱模吊装荷载计算：

$z=1/\cos\beta$=1.00

$F_D=G*z/n$=38.34*1.00/4=9.58kN

N_{sa1}/γ_1=36.00/4.00=9.00kN<9.58kN 不满足要求!

3.3 脱模混凝土锥体破坏强度验算：

单根锚栓受拉，理想混凝土锥体破坏时的受拉承载力标准值：

Figure 13: Some part of the calculation content for wall hoisting in

YJK's built-in prefabricated building design software

7.4 For Wall Installing Robot

The key technologies for wall installing robots are perception (sensors) coordinate positioning, navigation,

decision-making, etc.

The integration of wall installation robots with BIM enclosure wall data can be achieved by the alignment of virtual and real spatial coordinates. This enables accurately placing the enclosure wall to the correct position and angle at the construction site. The robots should do specific tasks such as carrying, setting out, etc.

ALC wall data of YJK's built-in prefabricated building design software can be imported into REVIT for subsequent robotic operations (Figure 14), while other wall data can be imported into AUTOCAD for subsequent robotic operations.

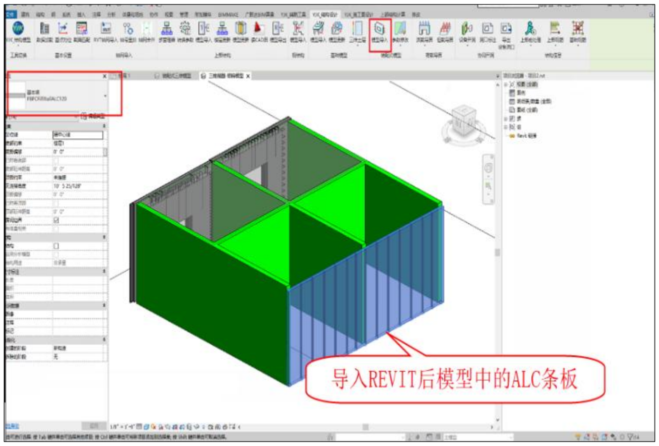


Figure 14: Output ALC data into revit

7.5 Roughly Estimating Carbon Emissions

The entire process of carbon emission calculation can be divided into three stages: the production stage of prefabricated components, the transportation stage of prefabricated components, and the construction stage.

Factors influencing calculation during transportation phase mainly include transportation distance, fuel consumption, etc. and issue of empty load should be considered. At the construction phase, calculation results show that carbon emission of prefabricated buildings is significantly less than that of cast-in-place buildings.

Speaking of carbon emission calculation during the production phase, the accuracy depends on the precision of the steel reinforcement data, and further improvement is needed for software.

8 Summary

During the entire process of building enclosure walls, from design to installation and construction, computer-aided technology can be leveraged to enhance productivity in many areas.

This article discusses several computer technology solutions. It primarily covers the structural design of load-bearing and non-load-bearing enclosure walls, insulation design for exterior enclosure walls, waterproofing design for exterior enclosure walls, as well as hoisting and construction. It should be noted that not all implemented content has been listed here.

There are both successful experiences and lessons that need to be learned. One of the successful experiences is the benefits brought by close integration. Lessons learned include that detailed design should be based on a more powerful 3d platform, which is currently on the way to implementation. In addition, the refinement of functions is also underway, for example, targeted functional improvements and new multi-disciplinary collaboration solutions.

The next generation of implementation plans is also under consideration, one of which is more scalability and definability of rules, and the other is a feasible solution to reduce user interaction and interference.

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