Research on design method and production process of the fully dry-connected prefabricated slab

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Abstract. The design method and production process are presented in this paper for the fully dry-connected prefabricated slab, which consists of lower base slab units, upper cover slab units and connection systems. The cover slab units, the base slab units, and the connection systems form a whole slab that has good continuity and integrity through a dislocated installation method. The shear bolts are pre-buried on the edge of the slabs, and holes are set on the steel beams connected with the slabs, and the dry connection is realized by passing the pre-buried bolts through the holes on the steel beams. Based on the structural characteristics of the fully dry-connected prefabricated slab, this paper proposes a design method for the slab and carries out component design according to the need of a given project. Through the research on the production process of the designed slab, a set of production process suitable for the fully dry-connected prefabricated slab, including "double nut fixing method" and "pre-embedded threaded cylinder method", was established, so as to make a contribution to the design and application of the slab.

Keywords: fully dry connection; prefabricated slab; design method; production process

1 Introduction

The existing slabs can be divided into cast-in-place slabs and prefabricated slabs according to the construction method. Cast-in-place slabs have a wide range of applications [1-5] and have good integrity and continuity, but require a lot of on-site wet work; the construction period is long and the components cannot be disassembled and reused, which does not conform to the concept of green and environmental protection. In order to improve the degree of prefabrication of buildings, prefabricated slabs have been widely used in prefabricated structures [6-10]. Various prefabricated slabs have reduced the amount of concrete poured to a certain extent, but they still cannot completely avoid onsite casting on the basis of ensuring the integrity and continuity, and

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the demolition is difficult, which leads to the inability to give full play to the advantages of short construction period and strong environmental protection of prefabricated steel structures.

In order to solve the above problems, Lan Tao, et al. proposed a fully dry-connected prefabricated slab [11]. The slab completely avoids wet work on the construction site under the condition of ensuring good continuity and integrity, and solves the problem of long construction period and inability to disassemble of the traditional cast-in-place slab, which meets the needs of construction industrialization and green development.

In view of the special structural form of the fully dry-connected prefabricated slab, a detailed design of the slab is conducted in this paper, and the design method and production process of the slab are presented.

2 Structural system

2.1 System introduction

The fully dry-connected prefabricated slab is composed of base slab units, cover slab units (displaced cover fastening base slab unit) and a connection system (including concrete shear keys with pre-embedded bolts, steel sleeves, nuts, gaskets), as shown in Figure 1.

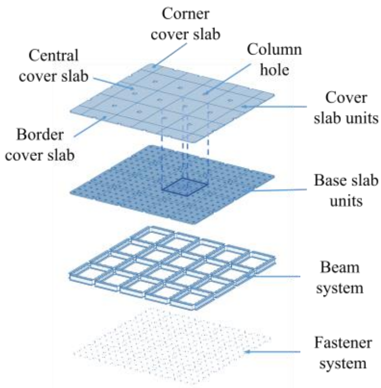


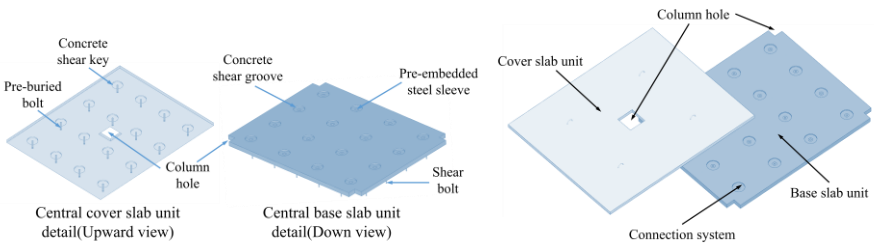
Fig. 1. This is a figure of fully dry-connected prefabricated slab system. The cover and base slab units are stacked, dislocated and connected by connection systems to form a continuous slab system.

The fully dry-connected prefabricated slab and the steel beam are connected by the connection system through inserting the pre-buried shear bolts into the reserved holes on the steel beam. Finally, the cover and base slab units and the steel frame beams form a structural system with integrity and continuity. At this time, the center of the base slab mainly bears the positive bending moment, and the center of the cover slab mainly bears the negative bending moment.

2.2 Structural features

2.2.1 Slab units

As shown in Figure 2(a), the cover slab unit is a reinforced concrete slab with concrete shear keys at the bottom and pre-buried bolts, and the base slab unit is a reinforced concrete slab with concrete shear grooves at the top and pre-embedded steel sleeves (pre-buried bolts and pre-embedded sleeves are respectively connected with steel bars by spot welding). After the fully dry-connected prefabricated slab is assembled in a dislocation arrangement, the relative positions of the cover and base slab units are shown in Figure 2(b).



(a) Structural diagram of cover and base slab units (b) Dislocation installation of the slab units

Fig. 2. Structural features of the fully dry-connected prefabricated slab

2.2.2 Connection system

As shown in Figure 3, the connection system of the fully dry-connected prefabricated slab consists of concrete shear keys, shear key pre-buried bolts, pre-embedded steel sleeves, nuts and gaskets, which can guarantee the effective connection between the cover and base slab unit.

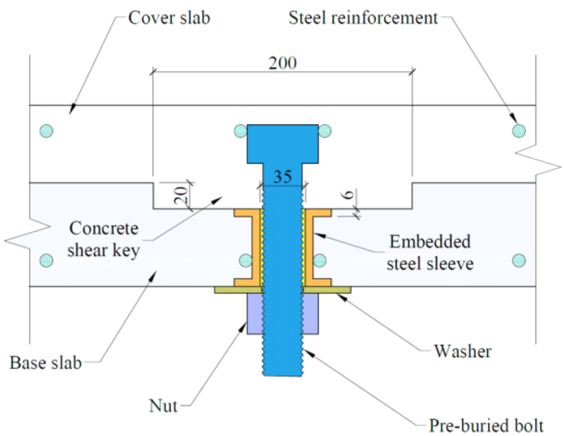


Fig. 3. This is a detailed diagram of the connection system of the fully dry-connected prefabricated slab.

2.3 Assembly process

The installation process of the fully dry-connected prefabricated slab can be carried out according to the following steps (as shown in Figure 4):

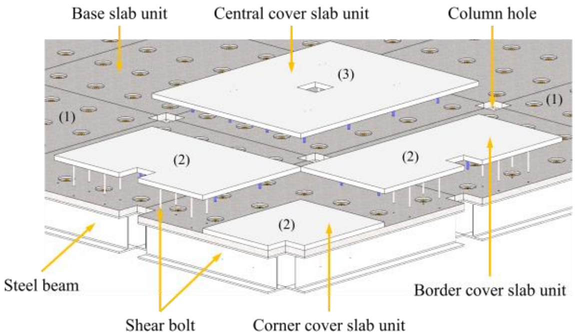


Fig. 4. Assembly diagram of the fully dry-connected prefabricated slab

(1) Install the base slab units (specimen (1) shown in Figure 4) one by one by passing the edge pre-buried shear bolts through the reserved holes of the steel beams, and tighten the nuts;

(2) Install the side and corner cover slab units (specimen (2) shown in Figure 4) one by one by passing the pre-buried shear bolts through the reserved holes of the base slabs and the steel beams, and tighten the nuts;

(3) Install the cover slab units at other positions (specimen (3) shown in Figure 4) one by one by passing the bolts pre-buried in concrete shear keys through the pre-embedded steel sleeves of the base slab units, and tighten the nuts.

3 Design method

3.1 Two-stage loading effect

According to the structural characteristics and assembly process of the fully dry-connected prefabricated slab, the internal force can be calculated according to the following two stages:

(1) In the first stage, there is no connection between the prefabricated cover and base slab units, the load is borne by the base slab units, and the base slab is calculated as a four-sided simply supported bending member; the load includes the self-weight of the prefabricated cover and base slab units and the construction live load at this stage.

(2) In the second stage, the connection between the prefabricated cover and base slab units is completed. The slabs are calculated according to the overall slab, and the load includes the self-weight of prefabricated cover and base slab units, the self-weight of surface layers and suspended ceilings, and the service load during the normal using stage.

3.2 Design value of internal force

3.2.1 Bending moment

The design values of bending moment in the two stages are taken according to the following provisions:

The first stage

$$M_1=M_{1G}+M_{1Q}$$

Positive bending moment section of the second stage

$$M=M_{1G}+M_{2G}+M_{2Q}$$

Negative bending moment section of the second stage

$$M=M_{1G}+M_{2G}+M_{2Q}$$

where M_{1G} represents the design value of the bending moment generated by the self-weight of the prefabricated cover and base slab units at the calculation section; M_{2G} represents the design value of the bending moment generated by the self-weight of the surface layer and the suspended ceiling at the calculation section in the second stage; M_{1Q} represents the design value of the bending moment generated by the construction live load at the calculation section in the first stage; M_{2Q} represents the design value of the bending moment generated by the variable load at the calculation section in the second stage, generated mainly by the variable load during the normal service stage.

3.2.2 Shear force

The design values of shear force in the two stages are taken according to the following provisions:

The first stage

$$V_1=V_{1G}+V_{1Q}$$

The second stage

$$V=V_{1G}+V_{2G}+V_{2Q}$$

where V_{1G} represents the design value of the shear force generated by the self-weight of the prefabricated cover and base slab units at the calculation section; V_{2G} represents the design value of the shear force generated by the self-weight of the surface layer and the suspended ceiling at the calculation section in the second stage; V_{1Q} represents the design value of the shear force generated by the construction live load at the calculation section in the first stage; V_{2Q} represents the design value of the shear force generated by the variable load at the calculation section in the second stage, generated mainly by the variable load during the normal service stage.

3.3 Component design

Applying the fully dry-connected prefabricated slabs to ordinary residential buildings, taking a 2.4m×3m steel frame grid as an example, according to the two-stage force characteristics of the slab and the selecting principle of internal force design values, reinforcement details of the fully dry-connected prefabricated slab are shown in Table 1 (slightly adjusted according to structural features).

The diameter of the concrete shear key is 200mm, and the thickness is 20mm; the pre-buried bolt of the shear key is M30; the inner diameter of the embedded steel sleeve is 35mm, and the thickness is 6mm. As shown in Figure 5, the base diameter of the pre-embedded hoisting threaded cylinder of the base slab is 50 mm, and other geometric parameters are shown in Figure 6 and Figure 7.

Table 1. Summary of reinforcement results of the fully dry-connected prefabricated slab

Rebar type	Reinforcement	Reinforcement area A_s (mm^2/m)
Longitudinal reinforcement of cover slab	9A10@100	707
Transverse reinforcement of cover slab	9A10@100	707
Longitudinal reinforcement of base slab	9A10@100	707
Transverse reinforcement of base slab	9A10@100	707
Ring reinforcement of cover slab	4A10	314
Base diameter of threaded cylinder	d_s=50mm	——

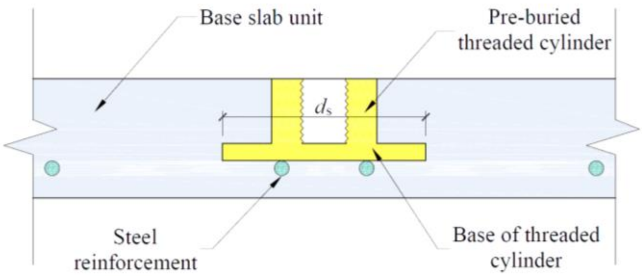
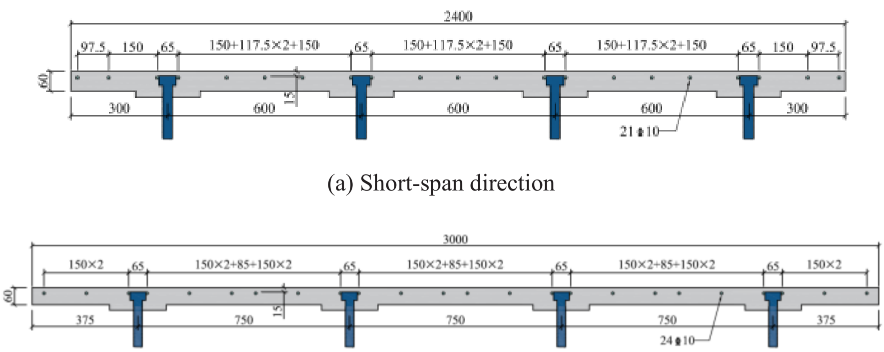


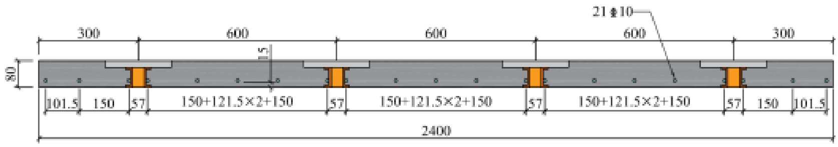
Fig. 5. Schematic diagram of pre-embedded hoisting threaded cylinder in the base slab unit



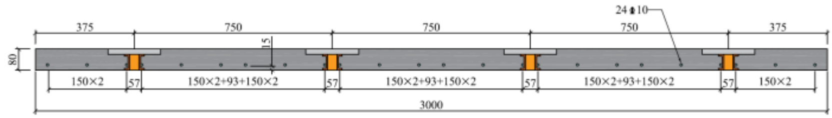
(a) Short-span direction

(b) Long-span direction

Fig. 6. Reinforcement diagram of cover slab unit



(a) Short-span direction



(b) Long-span direction

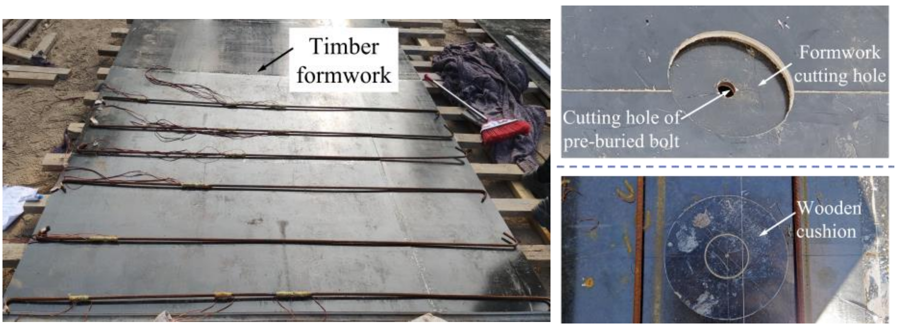
Fig. 7. Reinforcement diagram of base slab unit

4 Production process

For the processing and production of the fully dry-connected prefabricated slab designed in the previous section, a set of mass production process of this new slab is established.

4.1 Formwork preparation

Customized glulam formworks were adopted to produce and process the fully dry-connected prefabricated slabs, as shown in Figure 8(a). The concave and convex structure of the connection system of the fully dry-connected prefabricated slab was achieved by arranging the cushion layer and bottom die cutting method, as shown in Figure 8(b).



(a) Bottom form support (b) Concave-convex structure

Fig. 8. Formwork preparation

4.2 Layout of embedded parts

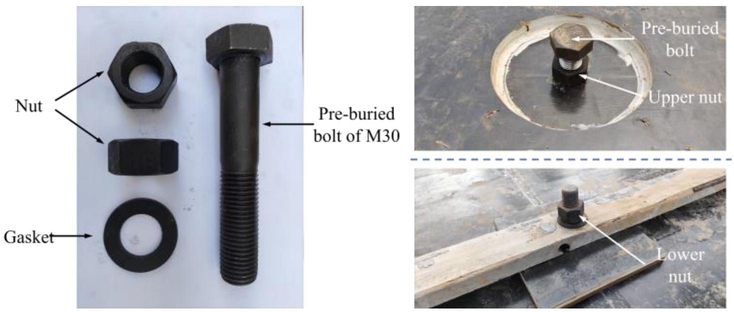
In addition to steel reinforcements, the fully dry-connected prefabricated slab contains four types of pre-embedded parts, including pre-buried bolts, pre-embedded steel sleeves, steel rings, and hoisting threaded cylinders. Their positions and numbers are summarized in Table 2.

Table 2. Summary of embedded parts

Types of embedded parts	Slab unit	Number
Pre-buried bolt	Cover slab unit	16
Pre-embedded steel sleeve	Base slab unit	16
Steel ring	Cover slab unit	4
Hoisting threaded cylinder	Base slab unit	4

4.2.1 Bolts pre-buried in concrete shear keys

The shear key pre-buried bolt model of the cover slab unit is M30, as shown in Figure 9(a). According to the structural characteristics of the fully dry-connected prefabricated slab, the pre-buried bolts need to be inserted into the center of the bottom die cutting hole of the cover slab unit. In order to ensure the production accuracy, the pre-buried bolts should be safely and reliably fixed on the formwork to avoid the deviation of bolts during the binding of steel bars or the vibration process of concrete pouring. The use of adhesives cannot meet the requirements of reliable connection between pre-buried bolts and formwork, so a “double nut fixing method” is proposed through field practice verification. As shown in Figure 9(b), the pe-buried bolts are fixed on the bottom form, in which the upper nut is poured into the concrete, and the lower nut is removed after the concrete curing is completed. The method is not only safe and reliable, but also can conveniently adjust the pre-buried depth of the bolts during the production process.



(a) M30 pre-buried bolt (b) “Double nut fixing method”

Fig. 9. Pre-buried bolt and the fixing method

4.2.2 Pre-embedded steel sleeves

The physical picture of the pre-embedded steel sleeve of base slab unit is shown in Figure 10.

(a) Pre-embedded steel sleeve (b) Fixing method of pre-embedded steel sleeve

Fig. 10. Pre-embedded steel sleeve and the fixing method

According to the structural characteristics of the fully dry-connected prefabricated slab, the pre-embedded steel sleeves were placed at the center of the wooden cushion of the bottom formwork of the base slab unit, and the stability of the steel sleeve is better than that of the pre-buried bolt, which can be fixed by "bonding + steel nails inside the sleeve". The strength of the adhesive is negligible compared with the strength of the concrete, so it does not affect the later demolition work. Foam filling material should be placed inside the pre-embedded sleeves to prevent them from being blocked by concrete during pouring.

4.2.3 Pre-embedded hoisting threaded cylinder of base slab unit

The physical picture of the pre-embedded threaded cylinder of base slab unit is shown in Figure 11(a). According to the processing drawing, the pre-embedded threaded cylinders were placed upside down at the lifting points of base slab unit, and bonded and fixed with the bottom mold. After the steel mesh is tied, the bases of the pre-embedded threaded cylinders were welded to the steel mesh, as shown in Figure 11(b). The method can not only fix the position of the pre-embedded threaded cylinders, but also improve the hoisting carrying capacity of the base slab unit. Foam filling materials should be placed inside the pre-embedded threaded cylinders to prevent them from being blocked by debris during production, processing and transportation.

(a) Pre-embedded threaded cylinder (b) Fixing method of pre-embedded threaded cylinder

Fig. 11. Pre-embedded threaded cylinder and the fixing method

4.2.4 Pre-embedded reinforcement ring of cover slab unit

The physical picture of the pre-embedded reinforcement lifting ring of the cover slab unit is shown in Figure 12. According to the processing drawing, the positions of hanging points on the bottom mold of the cover slab unit was determined. After the reinforcement meshes were bound, the pre-embedded reinforcement hanging rings were inserted into the corresponding lifting points under the steel meshes, and the pre-embedded reinforcement rings were bound with the steel meshes.

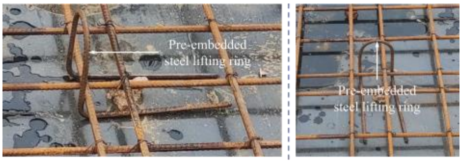


Fig. 12. Pre-embedded reinforcement rings

4.3 Reinforcement binding

According to the processing drawings, the steel meshes of slab specimens were bound. Since the fully dry-connected prefabricated slab designed in the previous section is a two-way slab, it needs to meet the requirements that the short-span direction reinforcements are on the bottom and the long-span direction reinforcements are on the top, as shown in Figure 13.

After the reinforcement mesh binding was completed, the pre-buried bolts of the cover slab unit and the pre-embedded steel sleeves of the base slab unit were respectively welded with the reinforcement meshes, as shown in Figure 14. This measure can not only fix the position of the embedded parts, ensuring the accuracy of production and processing, but also improve the shear bearing capacity of the shear connection key.

(a) Cover slab unit (b) Base slab unit

Fig. 13. Binding diagrams of steel meshes

(a) Pre-buried bolt (b) Pre-embedded sleeve

Fig. 14. Connection method between embedded parts and reinforcement mesh

4.4 Concrete pouring and curing

Commercial concrete (C30) was used to pour the slab specimens, full vibration should be carried out and attention should be paid not to damage the embedded parts during the pouring process, so as to strictly ensure the quality of the slab specimens, as shown in Figure 15(a). After the concrete was poured, the thickness of the slab specimen was strictly controlled by leveling the upper surface of the specimen, as shown in Figure 15(b). All slab specimens were cured under standard curing conditions.

(a) Vibration of concrete (b) Leveling of upper surface

Fig. 15. Concrete pouring of slab specimen

The physical pictures of the cover and base slabs after the molds were removed are shown in Figure 16.

(a) Cover slab unit (b) Base slab unit

Fig. 16. The physical pictures of the slab specimens after removing molds

The on-site pre-assembly of the finished cover and base slab units showed that the production accuracy of each slab unit meets the requirements. Therefore, the production process proposed in this section can be used for the mass production of the fully dry-connected prefabricated slab.

5 Conclusion

The fully dry-connected prefabricated slab system researched in this paper completely avoids on-site concrete pouring and curing while ensuring the continuity and integrity of the slab, greatly shortens the construction period, and enables to achieve repetition at the component level during the accommodation stage, which enables the full potential of steel structure in terms of green and efficient construction, making it a truly holistic industrialized green building over the entire lifecycle.

A "two-stage" design method is proposed based on the structural characteristics and assembly method of the fully dry-connected prefabricated slab. The elastic calculation method is used to solve the two-stage internal forces, and the reinforcement calculation and bearing capacity verification are carried out. The design of the fully dry-connected prefabricated slab is shown, which can be used as a reference for subsequent technology promotion and application.

Based on the fully dry-connected prefabricated slab, the research on the production process is carried out, and a set of production process, including the "double nut fixing method" and "pre-embedded threaded cylinder method", is established in combination with the structural characteristics of the slab, which can be used in the follow-up mass production of the slab.

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