Article no. 33

THE CIVIL ENGINEERING JOURNAL 3-2019

CONSTRUCTION PROCESS ANALYSIS FOR A MULTI-STORY BUILDING STRUCTURE WITH FLOORS SLAB OF LONG-SPAN

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ABSTRACT

To shorten the duration of construction and reduce the costs, identifying the number of floors supported by scaffolds is necessary to construct a multi-story building with the floors plate of long-span open-web sandwich slab, composed of the upper and lower ribs, shear key, and surface sheet. This study proposes a favorable method of two-stage construction support floors, namely the construction stages I and II, by establishing their finite element models that consider the effect of the horizontal tube constraining the upright tube in scaffolds. Furthermore, to ensure accuracy of the model in construction stage II, the full-hall supports of the first floor in construction stage I are equalized to uniform surface loads, and then the two construction processes are simulated by considering the upright tubes of the scaffolds and the structure. Comparison of the two modeling results with field-measured data shows that the equivalent methods of the upright tube and the full-hall supports are feasible. In addition, for an open-web sandwich floor slab whose span is ≤24.00m, only the full-hall supports of the floor can be retained if its lower floor is the basement roof; otherwise, the full-hall supports should be retained both on this floor and its lower one. When the span of the floor slab is 39.00m and if the span of the lower two floors slab is ≤24.00m, reaching the concrete design strength, then the full-hall supports should be retained on this floor and the lower floor, and partial re-supports should be applied to the second lower floor.

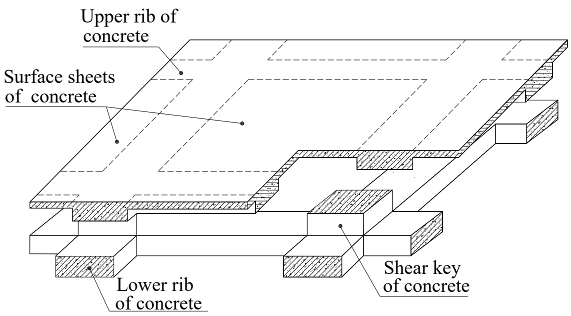
KEYWORDS

Open-web sandwich slab, Multi-story building structure with long-span floors slab, Construction process, Number of floors supported by scaffolds, Equivalent of upright tube

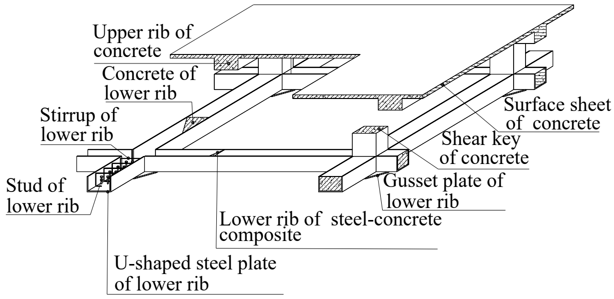
INTRODUCTION

A single-story structure with a long-span floor slab is widely used in industrial and public buildings, which occupy a large number of land resources. Thereby, considering the construction of buildings with multiple functions, fewer land occupancy and larger land utilization rate, as promoted by Ministry of Housing and Urban-Rural Development of the People's Republic of China, single-story long-span industrial and public buildings must be developed into multi-story long-span ones [1].

At present, the types of the slab structure with long-span are as follows: the steel-concrete composite grid slab with a higher structural height [2], the prestressed concrete slab and prestressed concrete hollow-core plate having a huge average concrete thickness and a large amount of steel used [3], the reinforced concrete multi-ribbed slab and prestressed reinforced concrete multi-ribbed plate with a heavy structural weight and hard-controlled crack [4], and the reinforced concrete vierendeel grid slab having a high structural height and low shear stiffness [5].



(a) Reinforced concrete open-web sandwich slab



(b) Composite open-web sandwich slab

Fig. 1 – Members and details of open-web sandwich slabs structure

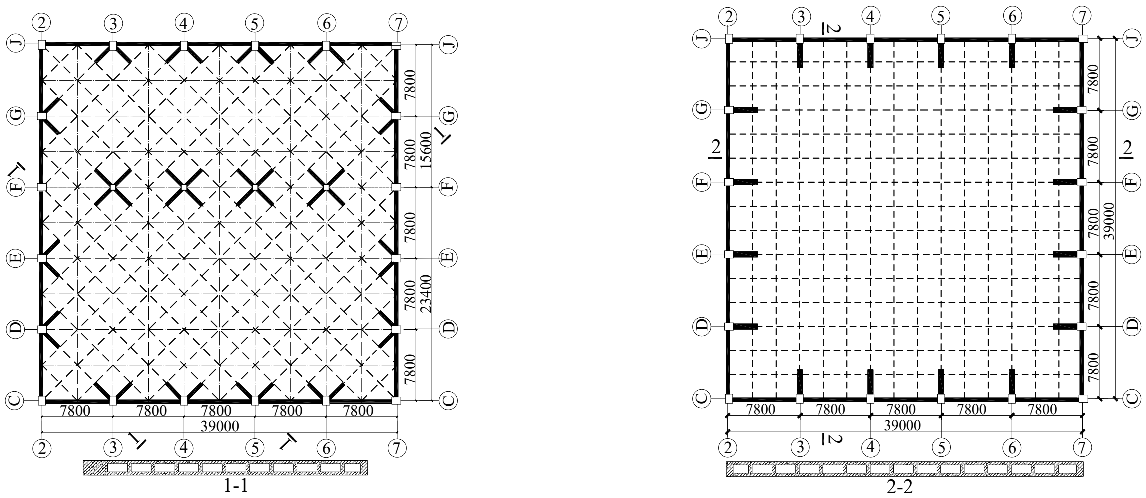
To deal with these problems, Ma et al. [6] proposed the reinforced concrete open-web sandwich slab structure, widely applied in multi-story long-span buildings with the floor span of 16m to 21m, which hollows out the belly concrete of the solid rib in the multi-ribbed slab to form the upper and lower ribs [7-8]. The remaining concrete at the crossing point of the ribs acts as a shear key to transmit the shearing force, thus making the upper and lower ribs deform together, as shown in Figure 1(a). The slab has a relatively lower structural height compared with the ones of the aforementioned structures. However, an increase of cross-sectional width of the shear key can result in ≤1 of the ratio of the height of the shear key to the width of its section, which conquers the poor shear stiffness of the reinforced concrete vierendeel grid structure. Furthermore, the increase of the shearing stiffness of the shear key can compensate for the decrease of the bending stiffness of the slab caused by the reduction of its height [9]. Featured by its light weight, low steel-used, and low structural height, this structure has several functions, such as load-bearing, necessitated decoration, and pipeline-stent support. To meet the needs of constructing buildings with larger span, a U-shaped steel-concrete composite open-web sandwich slab floor system was presented in [10-12], as shown in Figure 1(b). The U-shaped steel plate wraps three sides of lower rib, which dramatically improves its crack resistance. In addition, it erases the limitations of an enormous need of cast-in-situ concrete formworks for reinforced concrete open-web sandwich slab floor.

José and Lobato [13] proposed a method of a floor slab constructed by steel beams and waffled slabs, and Li and Yang [14] put forward a constructing method of support system of a single-story plant building with long-span beam-slabs. Furthermore, for beam-slabs structure with a long-span and a larger height between ground and first floor, Zong et al. [15] and Li et al. [16] recommended with steel beams and scaffolds and with Bailey trusses, H steel braces, and scaffolds to hold up formworks of the concrete of beam-slabs, respectively. However, these methods are mainly focused on construction of a single floor slab of traditional buildings. In contrast, Fang et al. [17], Zhao et al. [18] and Puente et al. [19] studied the axial stiffness of falseworks and the number of floors supported by it during the construction of traditional reinforced concrete buildings. Furthermore, Fang et al. [17] showed that the axial stiffness of construction supports considerably affects the deformation of the floor. Meanwhile, Fang et al. [17] and Zhao et al. [18] argued that the number of support floors has a significant impact on buildings construction safety. Puente et al. [15] explored how the layout position of the construction support influences its load. However, studies on open-web sandwich slab, including reinforced concrete and U-shaped steel-concrete composite open-web sandwich slabs, mainly focus on the design-calculation method and static-force performance at the application stage [20], and the number of support floors, required for the structure construction, is not specified in the current technical code [9, 12].

During the construction of multi-story long-span building structures with open-web sandwich slab floors, full-hall scaffolds are set up from the first floor to the top in succession. And, the scaffolds can only be removed from top to bottom on the condition that the top structure concrete reaches the design strength. Under this condition, scaffolds and formworks cannot be reused during the construction, thus increasing costs. If the full-hall scaffolds and formworks of the lower floor cannot be removed in time, then the following decoration is delayed, thereby prolonging construction. Hence, analyzing the whole construction process of the multi-story long-span building with open-web sandwich slab floors is necessary to obtain the suitable number of support floors, aiming to shorten construction duration, and reduce construction costs. In addition, finite element models for simulating construction support systems focused on upright tubes and ignore the effect of horizontal tubes constraining the upright tubes [21], which will make upright tubes incorrect loading, then causing some errors. Thereby, to obtain a more accurate finite element model of constructing an open-web sandwich slabs building, an equivalence of on-site scaffold systems is necessary.

For these reasons, this study proposes a more accurate finite element model of the upright tubes considering the constraint of the horizontal tubes, as well as two-stage construction support layers to reduce construction costs and duration. In addition, the finite element analysis results and field-measured datum are compared to offer suggestions for the support floors during the construction of a multi-story long-span open-web sandwich slabs building and to provide some references for future engineering practices.

CASE STUDY



(a) Reinforced concrete open-web sandwich Slabs of the first and second floors *(b) U-shaped steel-concrete composite open-web sandwich slab of the fourth floor*

Fig. 2 – Open-web sandwich slab structures applied in the Project (unit: mm)

The structure of the project, renovation, and expansion project for Guizhou Provincial Old Cadres Activity Facilities, is a multi-story long-span open-web sandwich slab construction with two basements and five floors on the ground. The total height of the building is 28.90m, and each basement is 3.90m tall, the first floor on the ground is 7.00m, the second to the fourth are 5.10m, and the fifth 6.60m. The floors of the basements are an ordinary beam-supported slab, whereas the long-span floors on the ground are open-web sandwich slab. The roof is a square pyramid

DOI 10.14311/CEJ.2019.03.0033

steel reticulated shell.

The project is composed of parts A and B. This paper only deals with the open-web sandwich slab structure in part A. Given that the length-to-width ratio of the first and second floors of this part is more than 1.50, the reinforced concrete open-web sandwich slab structures of orthogonal-diagonal lattice [Figure 2(a)], with a largest span of 23.4m, are favorable for its structural spatial load subjected. The range between axis 2 to 7 and between axis C to J on the third floor is of none-floor ceiling. The fourth floor is an orthogonal positive-position composite open-web sandwich slab, as shown in Figure 2(b), with a span of 39.00m, and the U-shaped steel plate of its lower rib is Q345B steel with a thickness of 6.00mm. Generally, an open-web sandwich slab structure would exert a large shear force to its border supports, so solid web girders are better to be adopted near the supports. The blackened areas, as shown in Figure 2, represent the solid web girders, and the dotted lines represent the upper and lower ribs of the open-web sandwich slab. The open-web sandwich slab adopts the construction method of cast-in-situ concrete twice. The first time involves casting the concrete C40 of the lower ribs and shear keys (casting to the bottom of the upper ribs), and the second time involves casting the concrete C45 of the upper ribs and surface sheets. The main cross-sectional dimensions of each floor member are shown in Table 1.

Tab. 1 - Cross-sectional sizes of each floor member (mm)

Storey / Member	-2	-1	1	2	4
Largest beam (or upper rib)	450×800	400×1600	350×250	350×250	400×300
Minimum beam(or lower rib)	250×500	200×500	350×250	350×250	400×300
Thickness of surface sheet	100	160	100	100	100
Shear key	—	—	350×350	350×350	400×400

Note: The structural heights of open-web sandwich slab of the first and second floors are 950mm, and that of the fourth floor is 1600mm.

SUPPORT FLOORS IN CONSTRUCTION

Open-web sandwich slab with a span of ≤24.00 m

The loads during the construction of a reinforced concrete open-web sandwich slab with a span of ≤24.00m are shown in Table 2. If the design strength is reached, then the basement roof of a structure can generally bear a dead load of ≥2.00kN/m^2 and a live load of 4.00kN/m^2, furthermore, a floor structure on the ground can withstand at least a dead load of 2.40kN/m^2 and a live load of 2.80kN/m^2, respectively.

When the lower floor of the newly-casting open-web sandwich slab is the basement roof, the total load that the roof can withstand is 8.00kN/m^2>7.10kN/m^2 according to the load data. Thus, retaining the full-hall supports of this floor can meet the demands for sustaining the newly-casting slab. When the lower floor is not the basement roof, the total load that the structure can withstand is 5.20kN/m^2<7.10kN/m^2. Then, the full-hall supports of this floor cannot meet the needs. If the full-hall supports of this floor and its lower floor are retained, then the total load is 5.20×2=10.40kN/m^2>7.10kN/m^2, which can hold up the newly-casting slab.

Thus, for an open-web sandwich slab with a span of ≤24.00m, if the lower floor is the basement roof, then only the full-hall supports of this floor should be retained. Otherwise, the full-hall supports of this floor and the lower floor should be retained.

Tab. 2 - Loads during the construction of a reinforced concrete open-web sandwich slab

Load	Load data (kN/m^2)	Load	Load data (kN/m^2)
Newly-casted concrete weight	5.60	Construction live load	1.00
Formwork weight	0.50	Sum	7.10

Composite open-web sandwich slab with a span of 39.00 m

The loads during the construction of a composite open-web sandwich slab with a span of 39.00m are shown in Table 3. Similarly, a single-floor structure can withstand a total load of 5.20kN/m^2<11.80kN/m^2. If only retaining the full-hall supports of this floor, then it does not sustain the newly-casting concrete of a composite open-web sandwich slab. If the full-hall supports of this floor and its lower floor are retained, then the load sustained is 5.20×2=10.40kN/m^2<11.80kN/m^2, which is not satisfactory but would not be much different.

Therefore, for a composite open-web sandwich slab with a span of 39.00m, the full-hall supports of this floor and its lower floor should be retained and some partial re-supports should be set up on its second lower floor to reduce construction costs and duration.

Tab. 3 - Loads during the construction of a composite open-web sandwich slab

Load	Load data (kN/m^2)	Load	Load data (kN/m^2)
Newly-casted concrete weight	10.30	Construction live load	1.00
Formwork weight	0.50	Sum	11.80

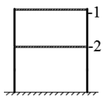
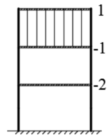
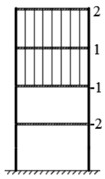
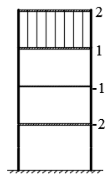
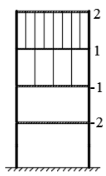
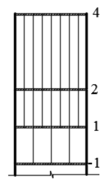
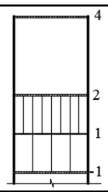
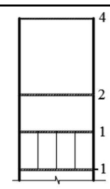
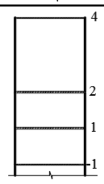
Two-stage construction support floors

This paper mainly studies the support floors required for constructing a multi-story building with open-web sandwich slabs. In addition, the frame structure of the two floors underground has satisfied the design strength of the concrete while constructing an open-web sandwich slab on the first floor, and has little influence on the construction of an open-web sandwich slab on the ground. Therefore, to simplify the finite element models, the construction of the two basements is not discussed further.

Considering the construction duration of the open-web sandwich slab, a brief introduction of the two-stage construction support floors is shown in Table 4. If the supports arranged in Table 4 are adopted, then the total construction duration of the building is 169 days, the following decoration of the first floor can be carried out on the 87th day, and the scaffolds and the formworks can be reused. If the traditional way of successively setting up scaffolds from the first floor to the top is adopted, then the total construction duration is 143 days, but the following decoration of the first floor can be only carried out on the 144th day, and the scaffolds and the formworks cannot be reused. Therefore, the support floors proposed in this paper can reduce construction costs and carry out earlier follow-up decoration of the lower floor.

As shown in Table 4, Step 2 shows that a layer of basement roof supports a layer of open-web sandwich slab with a span of ≤24.00m. Step 3 shows that the basement roof and a layer of open-web sandwich slab, with a span of ≤24.00m, support a layer of open-web sandwich slab with a span of ≤24.00m. Step 6 shows that two layers of open-web sandwich slab, with a span of ≤24.00m, and one-layer roof, with partial re-setup steel tubes, support an open-web sandwich slab with a span of 39.00m.

Tab. 4- Support floors in two-stage construction

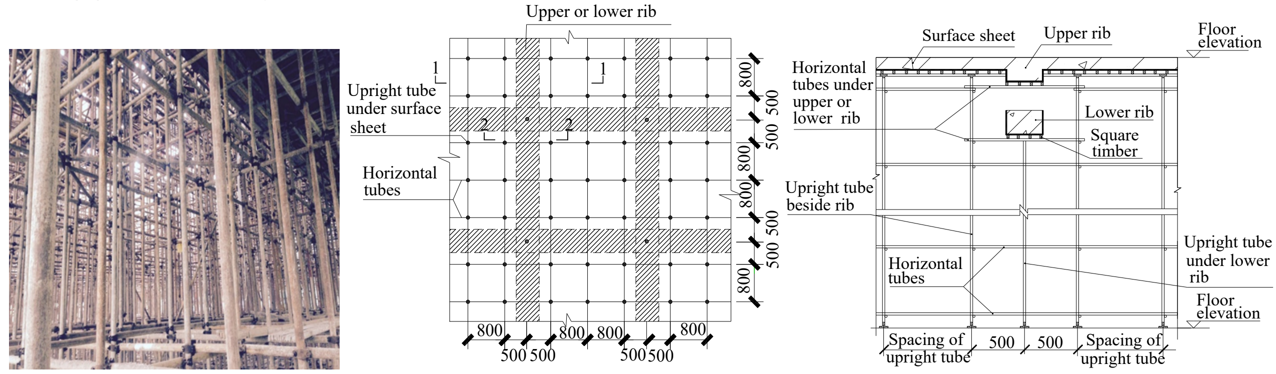
Step	Construction description	Diagram	Step	Construction description	Diagram
1 (I)	Construction structure of B1and B2 (concrete strength of both reaches 100%).		2 (I)	①Build the scaffolds on the first floor (10d); ② Set up the formworks of lower ribs and shear keys on the floor, tie up steel bars (7d), and cast concrete (1d); ③ Set up the formworks of upper ribs and surface sheets on the floor, tie up steel bars (7d), and cast concrete (1d).	
3 (I)	① Four days after the concrete of upper ribs and surface sheets on the first floor is casted, scaffolds are set up on the second floor (10d); ② Set up the formworks of lower ribs and shear keys on the floor, tie up steel bars (7d), and cast concrete (1d); ③ Set up the formworks of upper ribs and surface sheets on the floor, tie up steel bars (7d), and cast concrete (1d).		4 (I)	28 days after the concrete of upper ribs and surface sheets on the second floor is casted, remove the scaffolds on the first floor (2d).	
5 (II)	Re-set up partial re-supports on the first floor (1d).		6 (II)	① Build the scaffolds on the fourth floor with high headroom (15d); ② Set up U-shaped steel plate of the lower ribs and shear keys formworks for the fourth floor, tie up steel bars (20d), and cast concrete (1d); ③ Set up the formworks of upper ribs and surface sheets on the floor, tie up steel bars (7d), and cast concrete (1d).	
7 (II)	28 days after the concrete of upper ribs and surface sheets on the fourth floor is casted, remove its scaffolds (2d).		8 (II)	Remove the scaffolds on the second floor (2d).	
9 (II)	Remove the re-supports on the first floor (1d).				

Note: -2, -1, 1, 2, and 4 in the structural diagrams represent the top plate of the B2, B1, first, second, and fourth floor, respectively (There is no the third-floor ceiling). Then, I and II represent the first and second stage construction process, respectively. When casting upper ribs and surface sheets concrete on the second floor, the concrete age of the first floor has reached 28d.

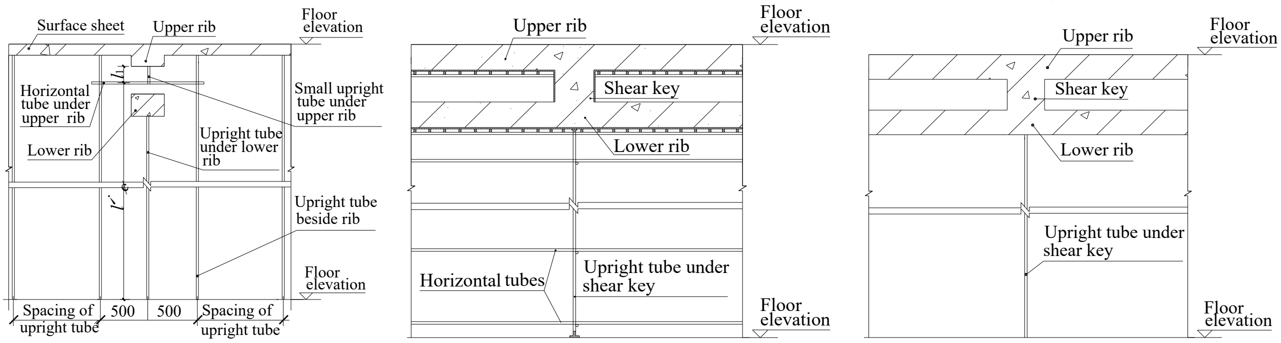
THE SETUP OF FINITE ELEMENT MODEL

Equivalent method of support system at construction site

This construction project adopts the support system of steel tubes full-hall scaffolds with couplers, whose layout in the construction site is shown as Figure 3(a). Q235 steel tubes are adopted whose specification is $\phi 48 \times 3$mm. The lift height of the horizontal tubes of each floor is 1500mm. The spacing of upright tubes underneath the surface sheets of the open-web sandwich slab on the fourth floor is 800×800 mm, as shown in Figure 3(b), and that on the first and second floors is 900×900mm. The layouts of tubes underneath upper and lower ribs as well as the shear key of open-web sandwich slab at 1 - 1 and 2 - 2 profiles of Figure 3(b) are shown as Figsures 3(c) and 3(e), respectively.



(a) High-formwork on the fourth floor (b) Upright tubes below surface sheets (c) Supports under ribs at 1 - 1 profile



(d) Supports under ribs in finite element model (e) Supports under shear key at 2 - 2 profile (f) Support under shear key in finite element model

Fig. 3 – Supports of open-web sandwich slab (unit: mm)

(1) Establishing method of small upright tubes under upper rib in the model

To set up the finite element model and ensure the accuracy of the load transfer path, the square timbers under the upper rib to the small upright tube are equalized, according to the equivalence of the load bearing capacity of the horizontal tube under the upper rib, as shown in Figures 3(c) and 3(d). In this way, the load from the upper rib can be transmitted from the small upright tube to the horizontals, and then to the upright ones beside the rib.

The maximum deflection of the horizontal tube under the upper rib with the on-site construction is $[v]$=min (l/150, 10) [22]. Considering the horizontal tube as a simply supported beam, as shown in Fig. 4, the maximum deflection under its mid-span is $f_{max}=F_{cr}l^3/(48EI)$. Supposing $f_{max}=[v]$, the load bearing capacity $F_{cr}=48EI[v]/l^3$ can be obtained.

Taking this project as an example, as shown in Figure 3(d), a detailed explanation is presented. According to the above formula, the load bearing capacity of the horizontal tube can be obtained as F_{cr}=9752.71N. A suitable slenderness ratio λ_1 is specified for the small upright tube to ensure that it will only experience yield failure but not buckling failure, which requires that λ_1 is smaller than λ_s in Figure 5, based on the critical buckling stress of compression bar. For Q235 steel, λ_s=61.61, λ_p=100.82, a=304MPa, and b=1.12MPa. Taking the small upright tube λ_1=20 and l_1=400mm, its radius of gyration is i_1=20mm. According to the formulas $N_{cr}=\sigma_s \cdot A_1=F_{cr}$=9752.71N, its cross-sectional area is A_1=41.50mm^2. With the formula of the area and radius of gyration, the size

DOI 10.14311/CEJ.2019.03.0033

of the small upright tube can be obtained as ϕ56.80×0.24mm.

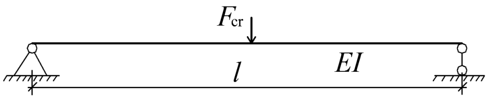


Fig.4 – Simply supported beam

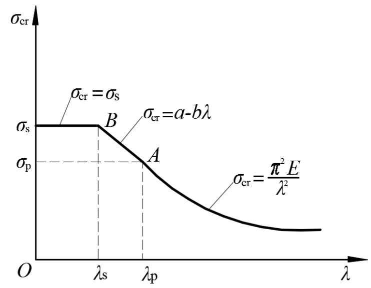


Fig.5 – Critical buckling stress of the compression bar

(2) Establishing method of other upright tubes

The equivalent principle of the upright tubes beside the rib or below the surface sheet, the lower rib, and the shear key, is equal to the axial stiffness and the load bearing capacity. In other words, A' and λ' of upright tubes after equivalence are equal to A and λ of the on-site upright tubes, so that the effect of the horizontal rod constraining upright tube is considered. The upright tubes beside rib of the fourth floor are taken as an example, as shown in Figures 3(c) and 3(d), for further explanation. In the on-site support structure, the effective length of upright tube beside rib l is the spacing of horizontal rods, namely, l=1500mm. In the finite element model, its length l'=10200-400=9800mm (the length of the upright tube is 10200 mm, the one of the small upright tube l_1=400mm). As $\lambda=\lambda'$ and $A=A'$, then A'=424mm^2 and i'=103.93 mm. According to the formula of the area and the radius of gyration, the size of upright tubes beside rib of the fourth floor in the model is ϕ 294.28×0.46mm. This equivalent method is also applied to the upright tubes under the surface sheet, the lower rib, and the shear key. These on-site upright tubes and their simplified supports in the finite element model are shown in Figures 3(c, e) and 3(d, f), respectively.

According to the above calculations, the equivalent cross-sectional dimensions of each floor's upright tubes beside rib or under surface sheet, lower rib, and shear key are shown in Table 5.

Tab. 5 - Equivalent cross-sectional dimensions of upright tubes (mm)

Floor	Upright tube beside rib	Upright tube under surface sheet	Upright tube under lower rib	Upright tube under shear key
1	ϕ198.56×0.68	ϕ210.51×0.64	ϕ189.60×0.72	ϕ189.60×0.72
2	ϕ141.87×0.96	ϕ153.78×0.88	ϕ132.94×1.02	ϕ132.94×1.02
4	ϕ294.28×0.46	ϕ306.25×0.44	ϕ268.84×0.50	ϕ268.84×0.50

Selection and setting of elements in finite element model

Using SAP2000 to build the model, the surface sheet is simulated by a thick-shell element and all others are by frame element. The surface sheets are designated to be automatically constrained by the upper ribs. The upright tubes in the support system are set to be pressure-receiving-only elements, and the bending moment and torque at the junction with the concrete are released to simulate the actual stress of the upright tube. The coupling process is performed at the junction between the upper or lower rib and the frame beam at the borders of the open-web sandwich slab to designate node bounding and select body bounding, respectively.

DOI 10.14311/CEJ.2019.03.0033

Setting of influencing factors and calculation conditions

In view of the time variation of material properties, geometric models, and loads during the construction period, if only an integral model is built and loaded for once, then it cannot accurately reflect the stress change of the open-web sandwich slab and the support system during construction. Therefore, this paper analyzes the entire construction process with the stage construction module of SAP2000. Table 4 shows that when casting concrete of the upper floors, the age of concrete of this floor has reached 28 days, so the construction duration in the models is 28 days. The authors set the CEB-FIP parameters based on time according to the relevant formulas in the CEB-FIP90 series model [23].

ANALYSIS AND RESULTS

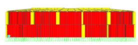
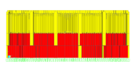
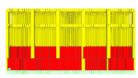
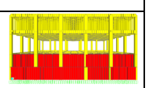
Analysis model

To shorten construction duration and reduce costs, the project needs to remove the full-hall supports of the first floor after the concrete strength of the second floor reaches 100%. Some partial re-supports on the first floor can be re-set up before the full-hall supports of the fourth floor are set up. Therefore, in the finite element analysis, construction stage I in Table 4 is built firstly, which is the analysis model corresponding to the construction Steps 1 – 4, and it is also called Model 1. Then, Model 2 of construction stage II is established, which includes the construction Steps 5 to 9 in Table 4. The effect of the full-hall supports of the first floor in Steps 2 to 4 on the Model 2 is equalized to uniform surface loads.

Model 1

The construction conditions of each step and analysis steps of this model are shown in Table 6.

Tab. 6 - Step–construction conditions and analysis steps in Model 1

Step	Implementation and removal of member	Load	3D model
1	Implement structures of B1 and B2	Self-weight of B1 and B2 structures; Add construction live load to B1 and B2.	
2	Implement the open-web sandwich slab structures and their supports on the first floor	Self-weight of the first floor structure; Add construction live load of the first floor; Remove the construction live load of B1.	
3	Implement the open-web sandwich slab structures and their supports on the second floor	Self-weight of the second floor structure; Add construction live load of the second floor; Remove the construction live load of the first floor.	
4	Remove the supports of the first floor	Add construction live load to B1.	

(1) Axial forces of steel upright tubes and stresses of the surface sheets at each floor

In Model 1, the axial forces of the steel upright tubes are 0.84kN to −30.64kN (at the following contents, tensile force or stress is positive, and compressive force or stress negative). Thus, the tension is so small that the upright tube can be considered as a pressure-receiving rod, which is consistent with the actual force. The load-bearing capacity of the steel tube is F_{cr}=84.10 kN>30.64kN, which indicates that its strength is sufficient. In addition, the stresses at the lower surface and the upper surface of the each floor's surface sheets are analyzed, which indicates that the surface sheets can meet the requirement subjected load.

(2) Deflection of the surface sheets at each floor

The cracking of the floor slab should be strictly controlled during the construction. Whereas, excessive deflection of the slab is a key factor that causes the formation of cracks. Therefore, the deflection of the slab is needed to pay attention during the construction.

Tab. 7 - Maximum deflection of floor–slabs in each step (mm)

Step \ Floor	-1	1	2	Step \ Floor	-1	1	2
1	4.51	—	—	3	8.04	6.69	3.02
2	5.95	4.09	—	4	4.50	47.12	43.13

The maximum deflection of the surface sheets at each construction step are shown in Table 7. The maximum deflections at both ordinary beam-supported slab and open-web sandwich slab are less than code limit, so that the deflection of the floor-slabs is satisfied.

In summary, during the floor construction of an open-web sandwich slab with a span of ≤24.00m, if the lower floor is the basement roof, then the full-hall supports of the floor can be retained, otherwise, the full-hall supports of this floor and its lower floor should be kept.

Model 2

(1) Equivalent uniform surface loads

To ensure the accuracy of the analysis in the construction stage II, Model 1´ is established by the effect of the full-hall supports of the first floor to be equalized to uniform surface loads in Steps 2 to 4 of Table 4. The equivalent diagram is shown in Figure 6, where L_1 refers to construction live load, while L_2–L_7 are equivalent uniform surface loads (L_1=1.0kN/m^2, L_2=L_3=L_5=2.5kN/m^2, L_4=3.5kN/m^2, L_6=6.0kN/m^2, and L_7=5.0kN/m^2). The construction conditions and analysis steps of Model 1´ are shown in Table 8.

A comparison of the maximum deformations of the floor-slabs in Model 1 and Model 1´ is shown in Table 9. For the slab of the first and second floors, a small differential of deflections is presented. Thus, this equivalence is accurate for open-web sandwich slabs of the two floors. For the slab of B1, there is a big difference between the two models in Step 2 and Step 3, but a small difference in Step 4. Given that the equivalent uniform surface loads are mainly applied to the analysis of construction stage II, including Steps 5 to 9, so the accuracy of its initial-state Step 4 can provide an accurate simulation of stage II.

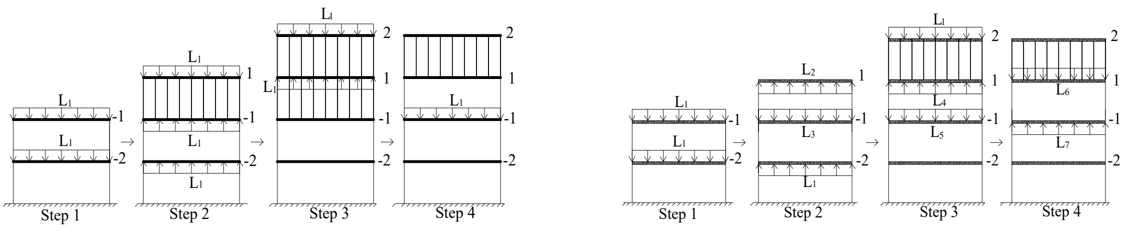
DOI 10.14311/CEJ.2019.03.0033

Tab. 8 - Step–construction conditions and analysis steps in Model 1´

Step	Implementation and removal of member	Load
1	Implement structures of the B1 and B2	Self-weight of the B1and B2 structures; Add construction live load L_1 to the B1 and B2.
2	Implement open-web sandwich slab structures of the first floor	Self-weight of the first floor structure; Add live load of the first floor L_2; Add live load of B1 L_3; Remove construction live load of B2 L_1.
3	Implement open-web sandwich slab structures and its supports of the second floor	Self-weight of the second floor structure; Add construction live load of the second floor L_1; Add live load of the first floor L_4; Add live load of B1 L_5.
4	——	Add live load of the first floor L_6; Add live load of B1 L_7.

Tab. 9 - Comparison of maximum deflections of floor–slabs between Model 1 & Model 1´

Step	1	2		3			4		
Floor / Model	B1	B1	1	B1	1	2	B1	1	2
Model 1 (mm)	4.51	5.95	5.64	8.04	7.73	2.57	4.50	46.60	43.49
Model 1´ (mm)	4.51	8.91	4.10	13.38	6.70	3.03	4.49	47.14	43.15



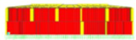
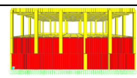
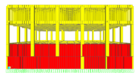
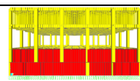
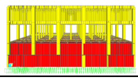
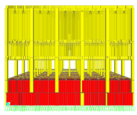
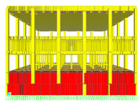
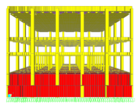
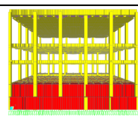
(a) Construction steps of Model 1 *(b) Construction steps of Model 1´ equalized to Model 1*

Fig. 6– Construction steps of Models 1 and 1´

(2) Steps of Analysis

The construction conditions and analysis steps of Model 2 are shown in Table 10.

Tab. 10 - Step-construction conditions and analysis steps in Model 2

Step	Implementation and removal of member	Load	3D diagram
1	Implement structures of B2 and B1	Same as Model 1´	
2	Implement open-web sandwich slab structures of the first floor	Same as Model 1´	
3	Implement open-web sandwich slab structures and its supports of the second floor	Same as Model 1´	
4	——	Same as Model 1´	
5	Re-set up the partial re-supports of the first floor	——	
6	Implement open-web sandwich slab structure and its supports of the fourth floor	Self-weight of the fourth floor structure; Add construction live load of the fourth floor; Remove the construction live load of the second floor.	
7	Remove the supports of the fourth floor	Add construction live load of the second floor.	
8	Remove the supports of the second floor	Add construction live load of the first floor.	
9	Remove partial re-supports of the first floor	——	

(3) Arrangement of partial re-supports in first floor

To avoid punching failure of the lower and upper slabs of the first floor, the two ends of the re-support should be placed directly above the beam of the lower slab and under the shear key of the upper slab. Given the rigidity of the girders and the columns of the basement roof, at those positions, the re-supports composed of eight steel tubes can be subjected to strong load, as shown in Figure 7(a), and the other re-supports at the rest of positions are constitutive of four steel tubes. To ensure the stability of the re-support and prevent it from buckling failure, a horizontal rod and an X-brace are arranged at 3 m above the ground, as shown in Figure 7(b). In addition, the single diagonal brace at the borders of the re-supports system is set fastened to the ground by expansion bolts, as shown in Figure 7(c).

(a) Re-support (b) Overall view of re-supports (c) Surrounding single diagonal braces

Fig.7–On-site partial re-supports of the first floor

(4) Load-bearing capacity of the re-supports

According to the model results, the maximum axial force of a re-support with eight steel tubes is 230.36kN and that of a re-support with four steel tubes is 78.27kN. The basic parameters of the first re-support are A=3.39×10^{3}mm^2, I=1.26×10^{7}mm^4, l=3000mm, i=60.90mm, and λ=49.26<61.61. As shown in Figure 5, its bearing capacity is F_{cr}=797.12kN>230.36kN. Similarly, the bearing capacity of the second re-support is F_{cr}=317.77kN>78.27kN. Thereby the bearing capacity of these re-supports is satisfactory.

(5) Stress and deflection of the surface sheets at each floor

Similar to Model 1, analysis on the stresses of the surface sheets at each floor in the Steps 5 to 9 shows that the stresses of the reinforcement bars and surface sheets are less than their designed strength, respectively. The maximum deflection of the surface sheets at each step of stage II is shown in Table 11. The deflection of each surface sheet is less than the code limit defining the maximum deflection, thus, the surface sheets are safe.

Tab. 11 - Maximum deflection of floors' surface sheets in each step (mm)

Step \ Floor	-1	1	2	4	Step \ Floor	-1	1	2	4
5	4.50	47.15	43.16	—	8	4.53	47.52	52.09	42.78
6	5.92	51.09	47.49	4.84	9	4.51	51.02	52.10	42.81
7	4.51	47.11	43.12	42.78					

ON-SITE MEASUREMENTS

During construction, the open-web sandwich slab is pre-arched with a pre-arch value of its short-span length multiplied 1/500. The first and second floors of the project are divided into two parts at the F axis, and the pre-arch of the floors is built from the slab's long sides to its central line. The maximum pre-arch height of the slab with a span of 23.40 m is 46.80mm. The plan size of the fourth floor is 39.00m×39.00m, and thus a pre-arch height of 78.00mm is built from the slab's four sides to its middle. To simplify the establishment of the models, the influence of pre-arching is neglected in the finite element analysis.

DOI 10.14311/CEJ.2019.03.0033

Measured data and comparative analysis

In the construction stage II, the deflection of the first floor's slab is monitored by the Laser Level at the construction site, as shown in Figure 8. The measured location is at the middle of the open-web sandwich slab with a span of 23.40m, where the maximum deflection measured is shown in Table 12.

Tab. 12 - Field-measured deflection for the first-floor slab with a span of 23.40 m

After Step	4	6	8	9
Deflection (mm)	35.00	61.00	54.00	56.00

Fig. 8 – Pictures of on-site measurement of the first-floor slab

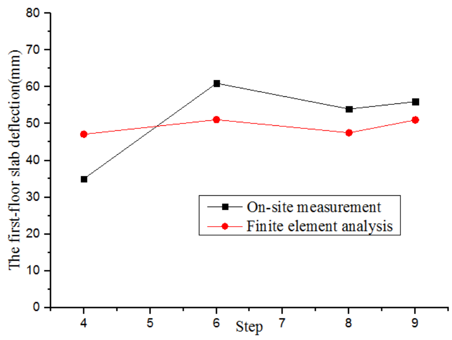


Fig.9 – Comparison between the models results and the on-site measured datum

As shown in Table 12, after the removal of the full-hall supports of the first floor and before the concrete casting of the fourth floor (Step 4), there is an 11.80mm of pre-arching value that remained in the open-web sandwich slab with a span of 23.40m. Furthermore, after the structure of the fourth floor is completed (Step 6), the slab of the first floor has been deflexed by 14.20mm. Then, after the full-hall supports of the second and fourth floors are removed (Step 8), the deflection of the first-floor slab has an obvious rebound of 7.00mm, indicating that the slab is in elastic stage and the deflexed deflection remained at 7.20mm. Finally, after the removal of partial re-supports of the first floor (Step 9), its deflection is slightly increased to 9.20 mm. However, the deflection deducted from the pre-arching value of the slab is less than the code limit defined the maximum deformation, indicating that the structure is safe. And, during measurement, the first-floor slab is checked and no cracking of concrete is observed, which confirms the safety of the structure.

A comparison between the maximum deflections of the finite element analysis and the on-site measurement at the first-floor slab is shown in Figure 9. The trend of finite element results is consistent with that of field measured datum. However, differences still exist between the results, especially after the removal of full-hall supports of the first floor (Step 4) and the completion of the fourth-floor structure (Step 6).

Difference analysis

Taking various factors into consideration, the difference between finite element results and field measured datum mainly arises from the following aspects. Firstly, it is about construction load. In the finite element model, the self-weight of the structure and construction live load have been

DOI 10.14311/CEJ.2019.03.0033

considered, but the random dynamic load or concentrated load caused by material accumulation are neglected in the model.

Secondly, that one is on-site measurement. Given that the height of the first floor is relatively high, the length of the Level Rod is insufficient, and ensuring the accuracy of the level elevation measured is difficult, which results in some errors in the measured data.

Thirdly, it is the shrinkage and creep models of concrete. Previous research showed that the concrete shrinkage value and creep value of CEB-FIP90 model are much smaller than the measured values during the early age of concrete [24, 25].

Lastly, during construction, gaps exist at the coupler of the steel tubes and the interface between the steel tubes and the concrete. Under load, these gaps will cause cumulative vertical deformation of the support system.

CONCLUSIONS

The conclusions from the study are following:

(1) Considering the effect of the horizontal rod constraining the upright steel tube in scaffolds, an equivalent upright rod, with its axial stiffness and load bearing capacity equalized to that of the upright steel tube, would result in a more accurate finite element results.

(2) For the two-stage construction, the effect of the full-hall supports of the first floor in the stage I can be considered equivalent to the uniform surface loads to ensure the accuracy of the whole process analysis in stage II.

(3) When the newly cast-in-situ floor-slab is an open-web sandwich slab with a span of ≤24.00m, the full-hall supports of the floor can be retained if the lower floor is the basement roof; otherwise, the full-hall supports of this floor and its lower floor should be retained.

(4) When the newly cast-in-situ floor-slab is an open-web sandwich slab with a span of ≤39.00m, and when the span of the lower two floors' slab is ≤24.00m and both reach the design strength of concrete, the full-hall supports of this floor and its lower floor should be retained. In addition, the partial re-supports of its lower second floor should be arranged directly under the shear key of the floor slab and directly above its ground girder.

ACKNOWLEDGEMENTS

The work described in this paper was fully supported by three grants from the First Class Subject Foundation of Civil Engineering of Guizhou Province under contract no. QYNYL [2017] 0013, the Natural Science Research Project of Guizhou Province Department of Education under contract no. [2015] 364, and the Science and Technology Support Plan Project (Social Development Breakthrough) of Guizhou Province under contract no. QianKe He SY [2012] 3067.

REFERENCES

[1] Ma K. J., 2014. Proceedings of Spatial Grid Cassette Structure, Vol. 1. Research Center of Spaces Structure, Guizhou University, Guiyang, China.

[2] Soare M. V., Crainicescu M., Tarog D., 1985. Double-Layer Grids with Steel Members and Reinforced Concrete Slabs. International Journal of Space Structures, vol. 1(1): 27-32. doi: 10.1177/026635118500100104.

[3] Yu R. B., Zhang Q., Mao X. C., 1983. Design and Research of Long Span Partially Prestressed Concrete Multistory Frame. Journal of Building Structures, vol. 4(6):18-31. doi: 10.14006 /j.zj gxb.1983. 06. 002. (in Chinese)

[4] Ajdukiewicz A. D., Kliszczewicz A. T., 1986. Experimental Analysis of Limit States in a Six-panel Waffle Flat-plate Structure. Aci Structural Journal, vol. 83(6): 909-915.

[5] Shanmuganathan S., Kubik L. A., 1993. “Optimization of CUBIC Space Frame Structures.” Proc. 4th Int. Conf. on Space Structures: Thomas Telford, London, England.
[6] Ma K. J., Huang Y., Xiao J. C., Luo. Z., 1995. A Review of RC Open-web Sandwich Plate Structure and Grid Space Structure Study and Application. Spatial Structures, vol. 1(3): 28-36+41. doi: 10.13849 /j.issn.1006 -6578. 1995. 03. 005. (in Chinese)
[7] Huang Y., Ma K. J., Zhang H. G., Xiao J. C., Jiang S. F., 1997. Study and Application of Reinforced Concrete Open-web Sandwich Slab Structure. Journal of Building Structure, vol. 8(1): 55-64. doi: 10.14006 /j.jz.jgxb.1997.06.008. (in Chinese)
[8] DB22/48-2005, Technical Code for Reinforced Concrete Open-web Sandwich Slab Structure. Local Standard of Guizhou Province of P. R. China, Construction Department of Guizhou Province, Guiyang, China, 2005.
[9] Wei C. X., 2007. Study the Mechanics in Beings of Open-web Grids and Open-web Sandwich Plates from the Stiffness Variety (Zhejiang University, Hangzhou, China, in Chinese), Master Thesis.
[10] Hu L., Ma K. J., 2012. Research and Application of U-shaped Steel-plate Concrete Composite Open-web Sandwich Slab Structure with High Strength Bolts. Journal of Building Structure, vol. 33(7): 61-69. doi:10.14006/j.jzjgxb.2012.07.007. (in Chinese)
[11] Wang Q. M., Li C., Chen Z. H., Ma K. J., Duan X. K., 2015. Design of Steel-concrete Composite Open-web Sandwich Plate Roof of Meditation Hall in Suzhou Chongyuan Temple. Building Structure, vol. 45(2): 25-28. doi: 10.19701/j.jzjg.2015.02.006. (in Chinese)
[12] DB23/1539-2014, Technical Specification for Reinforced Concrete Space Griding Structure with Open-web Sandwich Plate. Local Standard of Heilongjiang Province of P. R. China, Department of Housing and Urban-Rural Development of Heilongjiang Province, Haerbing, China, 2014.
[13] José E., Lobato L. Flat Slab System Formed by Steel Beams in a Composite Construction Combined with Waffled Slabs, Mexico, MX 2013000404A, 2014-06-20.
[14] Li B. P., Yang H. Construction Method for Large-span Cast-in-situ Beam Slab Support System of Plant, China, CN 101929244A, 2010-12-29.
[15] Zong K. F., Jia H. Y., Li Y. F., Xu K. Construction Method of High-altitude Large-span Beam-slab Template Steel Support System, China, CN 102094524A, 2011-06-15.
[16] Li P. F., Chen H., Guo X. K. Load-bearing Supporting Structure of High-altitude Large-span Beam-slab Concrete Formwork, China, CN 109750830A, 2019-05-14.
[17] Fang D. P., Geng C. D., Zhu H. Y., Liu X. L., 2002. Safety Analysis of Reinforced Concrete Structures during Construction. China Civil Engineering Journal, vol. 35(2): 1-7. doi: 10.15951/ j. tmgcxb. 2002.02.001. (in Chinese)
[18] Zhao T. S., Fang D. P.,Gu X. L., Zhang Y., 2004. Performance of Casting In-site Concrete Buildings during Construction. Engineering Mechanics, vol. 21(2): 62-68. (in Chinese)
[19] Puente I., Azkune M., Insausti A., 2007. Shore–slab Interaction in Multistory Reinforced Concrete Buildings during Construction: An Experimental Approach. Engineering Structures, vol. 29(5):731-741. doi: 10.1016/j.engstruct.2006.06.018.
[20] Zhang H. G., Hu L., Ma K. J., Zheng T., 2006. Analysis on Static Behavior of Open-web Sandwich Plate and a Practical Method. Journal of Guizhou University of technology (Natural Science Edition), vol. 35(03): 82-87. (in Chinese)
[21] Lin Z. Z., Zhang Y., Yang J. J., 2013. Analysis of Multi-story Formwork Supporting System by Detection and FEM. Industrial Construction, vol. 43(2): 94-98. (in Chinese)
[22] JGJ130-2011, Technical Code for Safety of Steel Tubular Scaffold with Couplers in Construction. National Standard of P. R. China, China Architecture & Building Press, Beijing, China, 2011.
[23] Thomas T., 1993. CEB-FIP Mode Code 1990. Committee Euro-International Du Beton.
[24] Song K., 2002. Research on Difference of Time Depended Vertical Deformation of SRC High-rise Buildings (College of Civil Engineering, Tongji University, Shanghai, China, in Chinese), Master Thesis.
[25] Hua J. M., 2008. Study on Early Shrinkage Deformation Performance and Crack Comprehensive Control Technology of Ready Mixed Concrete (College of Civil Engineering, Chongqing University, Chongqing, China, in Chinese), Master Thesis.