The 2016 World Congress on
The 2016 Structures Congress (Structures16)
Jeju Island, Korea, August 28-September 1, 2016

Structural Design and Optimization of Long-Span Ultra-Slim Composite Floor for Super Tall Residence

*Rong He[1)], Guo Ding [2)], Yue Yang[3)] and Liwei Ye[4)]

[1), 2), 3)] Tongji Architectural Design (Group) Co., Ltd. Siping Road 1230, Shanghai, China
[4)] Xiamen Wansha tiancheng real estate development Co. Ltd. Haian Street 59, Xiamen, China
[1)] 52hr@tjadri.com

ABSTRACT

Super tall residential buildings are commonly developed as luxury properties with extraordinary building quality. The application of long-span ultra-slim composite floor system can increase the floor clearances, broaden the exterior visions and avoid exposed beams after the repositioning of partition walls. There are several challenges for the structural design of the floor system. On the one aspect, the vertical deflection and vibration serviceability will become the controlling design factors with the reduce of the overall structural thickness of the floor system; on the other aspect, the girders of the floor system contribute significantly to the overall stiffness of the lateral system, the reduction of the girder section height will increase the story drifts of the lateral system. To reach optimal long-span ultra-slim composite floor system design, one not only has to satisfy the safety, deflection and vibration serviceability requirements of gravity system, but also has to carefully compensate the significant stiffness reduction for the lateral system. A super tall residential building project located in Xiamen, China is employed in this study to illustrate the structural design and optimization of the special floor system.

1. INTRODUCTION

Due to the number of floors in super tall buildings is far greater than the general building, the design of the composite floor system has more influence on the weight of structures, net height of the floor, construction period and the cost of materials, etc. Currently the design of the composite floor system in super tall buildings generally emphasizes the weight of structures, construction period and the cost of materials, etc. But the floor clearances are seldom considered when the requirements of the minimum height are satisfied.

When the height of the floor in super tall residence is constant, the lower the total height of the floor beams and slab. The higher net floor height and broader exterior visions guarantee the better life.

[1),2) ,3)] Engineer
[4)] Deputy Manager

Exposed beams are required to be avioded in the residence. The smaller number of sub beams, the less impact on after the repositioning of partition walls. But at the same time, the calculation span of plate becomes larger. However Long-span ultra-slim composite floor for super tall residence would solve such problems perfectly, the research of the system in this area is basically blank at present.

A super tall residential building project located in Xiamen, China is employed in this study to illustrate the structural design and optimization of the special floor system.

2. Structural design and optimization

2.1 Structural design

The choice of floor system in super tall residences is related to the lateral system. In general, vertical structural members with smaller size are preferred, so as to get the higher room rate and better life experience. When the contact surface of the vertical members and the beam is steel structure, such as concrete filled steel tubes pole or steel-concrete composite shear wall with two-side connections, floor beams give priority to the use of steel beam in order to simplify joints connections. When the contact surface is concrete, concrete beams are preferred for the rigid joints.

To get better life and reduce the structural weight and size of members, the main priority is steel-concrete composite floor in super tall residence. Steel beams generally use the H shape or box. Floor slab can choose the composite floor slab or cast-in-place reinforced concrete floor slab. The stud shear connectors are adopted between the steel beam and floor.

Total height of the floor is determined by the height of steel beam and plate. Fig.1 shows the diagram of the height of composite floor. Their sum decreases to achieve the minimum thickness. Both issues are discussed later.

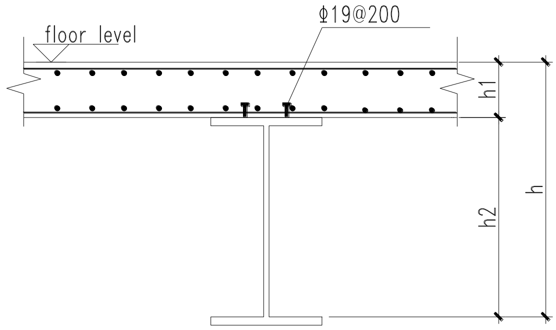

Fig.1 the diagram of the height of composite floor

Main beams design should meet the structural indicators of the whole system, such as the story drift ratio, ratio of rigidity-to-gravity and etc.. Also the design would meet the requirements of the deflection and strength under the vertical static floor load. Sometimes deflection problem can be solved through arch camber. The value of arch camber should be specified to ensure that the stud on the beam is under the level of the concrete slab during the construction.

Secondary beam design just need to meet the requirements of the deflection and strength under the vertical static floor load. Secondary beam can reduce the floor span calculation, effectively reduce the slab thickness, but at the same time beam will have a certain influence on the functional division of the residence. So it is necessary to choose a balance point between two methods. The secondary beam layout should be confirmed with architects and the owners together.

The thickness of slab needs to be calculated, considering the crack, deflection, construction feasibility and vertical vibration comfort. Crack and deflection limit values in the design guideline for concrete structures GB 50010-2010 (the guideline for short, hereafter), can directly be referenced.

The thinner the thickness of slabs, the bigger the calculated minimum steel. When the steel rebar is too close, it’s inconvenient to construct and hard to ensure the quality. The quality of construction has a great relationship with the construction level of construction units. So it’s necessary to confirm the maximum steel rebar arrangement with construction units and the owners.

Generally, such kind of ultra-slim composite floors tend to have less damping, be more flexible and with a lower natural frequency if the floor thickness is small. Vibration serviceability problems due to human occupants, rather than safety issues can become the controlling factor when designing a long-span ultra-slim composite floor (Pavic and Reynolds, 2002; She and Chen, 2009).

2.2 Structural optimization

Optimized design is divided into two parts, structural cost and architectural function optimization. In this paper, while achieving the optimization of building functions, we try to reduce the cost of structure as far as possible. Under the premise of satisfying the safety index of structure design, long-span ultra-slim composite floor is applied to maximize the mining floor clearances and avoid exposed beams after the repositioning of partition walls. While building function optimization may lead to the increase of the structural cost, it is required to inform the owner of the construction cost of superior quality of construction, for reference to the owners to confirm. Optimization design of process, that is to find the balance between the architectural function and structural cost, with the owners together. The whole design process is shown in Figure 2.

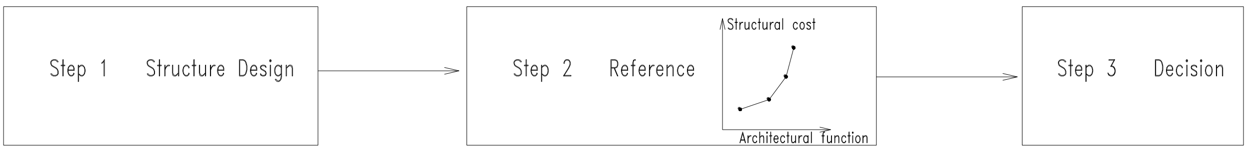

Fig.2 the process of Optimization design

When the beam has met the design requirements of interior height and structural requirements, the next step is to optimize. Different sizes of the beam sections with similar stiffness have little influence on the structural indicators. In the case of reducing the height of the different section, the flange area of the steel beam is increased firstly, and the thickness of the steel beam is increased at the same time. The method is so convenient as to assess the increased cost.

Electronic mechanical pipeline can go directly through the web plate with openings to lower total height of the floor. The web are strengthened according to the requirements of different specifications.

The steel beam can be embedded in the slab height, reducing the total height of the floor. It's shown in Fig.3. And both sides of the flange of the steel girder need to adopt certain structural measures to ensure the overall performance of the concrete.

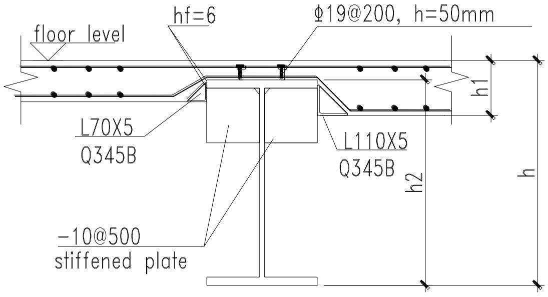

Fig.3 the diagram of the height of composite floor

3. CASE STUDY

The Dijingyuan project sitting on the first-line lake view of Yuandang Lake, is the first super tall and ecological housing group, which is of steel structure and with a height of 250 m in China. The project is composed of five 244.75 high residential buildings and two commercial buildings. The planning area is 54286.697 m2, and the building area is 550064.551 m2.

In order to increase the floor clearance which is a requirement of high-standard residential buildings, living rooms and dining rooms all adopted a long-span structural form. The largest floor has a dimension of 10.0m×9.8m and was designed to be a cast-in-site steel-concrete composite floor with a floor thickness of 200mm and a height-span ratio of 49, making itself a typical long-span ultra-slim composite floor as shown in Fig.4. The structural design of this long-span ultra-slim composite floor was conducted based on the current guidelines in China and the vibration serviceability issue of this long-span ultra-slim composite floor was analyzed in this paper.

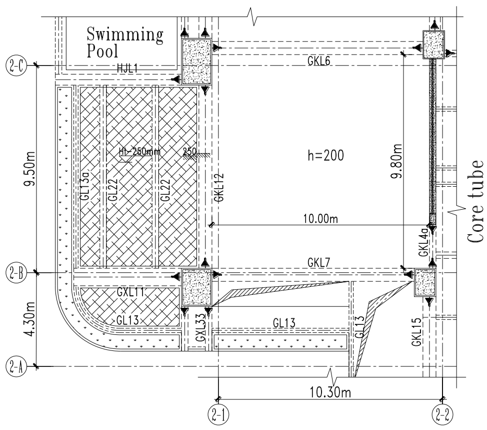

Fig.4 Plan view of the long-span ultra-slim composite floor

3.1 Design against bearing capacity

Preliminary analysis shows that the structural design of this floor is controlled by the vertical vibration serviceability during normal loading state which means the stiffness of the floor controls the design. By comparing different measures to improve stiffness, such as composite slab by steel bar truss and concrete and steel reinforced concrete floor, we decided to increase the rebar ratios in floor slabs and apply additional steel plates to make composite slab sections to increase the stiffness and therefore to improve the vibration serviceability performance of the floor. However, the following requirements should be met during the enhancement of stiffness:

(1) The designed steel beams are embedded in the floor and the concrete floor on top of the beams is 70mm's thick as shown in Fig.5. In order to secure the quality of construction, the maximum steel rebar arrangement is 16@100 in two lays and two directions.

(2) Steel plates thicker than 40mm should guarantee their performance in the Z direction. The cost of welding of thick plates is high and the welding quality is difficult to promise. Therefore, the steel plates used to enhance the stiffness should be less than 35mm in thickness.

(3) No fire retardant coating will be used for the added steel plates and thus we don't count their contribution to the loading capacity of the floor.

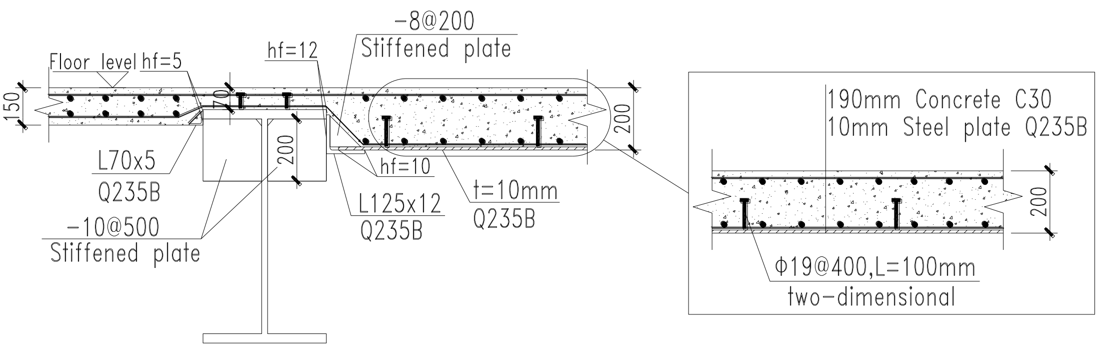

Fig. 5 Section of the composite floor

The stiffness contributions of steel plates of different thicknesses to a same floor were analyzed. When the thickness of the steel plate lies within the range <0.08H, the steel plates effectively increase the stiffness of the composite floor. Based on the above analysis, two candidate section designs are shown in Table 1.

Table 1 Designed sections

Designed section I		Designed section II	
Floor thickness	Steel plate thickness	Floor thickness	Steel plate thickness
200 mm	10 mm	180 mm	16 mm

For the two designed sections shown in Table 1, the calculated minimum steel and designed rebar for each section are shown in Table 2. Check of the floor displacement was done for section I and section II. The results are shown in Table 3.

Table 2 Reinforcement of designed sections

<table>
<tr><th rowspan="3">Designed floor thickness mm</th><th rowspan="3">Thickness of steel plates mm</th><th colspan="3">X direction</th><th colspan="3">Y direction</th><th rowspan="3">Check</th></tr>
<tr><th rowspan="2">Required area mm²</th><th colspan="2">Designed reiforcement</th><th rowspan="2">Required area mm²</th><th colspan="2">Designed reiforcement</th></tr>
<tr><th>Reinforce-ment</th><th>Reinforce-ment ratio %</th><th>Reinforce-ment</th><th>Reinforce-ment ratio %</th></tr>
<tr><td>200</td><td>10</td><td>1536</td><td>16@100</td><td>1.005</td><td>1336</td><td>16@100</td><td>1.005</td><td>√</td></tr>
<tr><td>180</td><td>16</td><td>1831</td><td>16@100</td><td>1.117</td><td>1586</td><td>16@100</td><td>1.117</td><td>√</td></tr>
</table>

Table 3 Check of the designed floor thickness

Designed floor thickness mm	Deflection/mm		
	Calculated	Threshold	Check
200	24.7	32.0	√
180	31.4	32.0	√

For safety and economy reasons, also the stiffness requirement by the vibration serviceability of long-span floors, section I was finally chosen. The composite floor was designed to have a floor thickness of 200mm with 10mm’s thick steel plates embedded.

2.2 design against Vibration serviceability

As a high-standard residential building, according to the technical guide GJG 3-2010, the vertical modes of a structure should be no smaller than 3Hz and the vertical accelerations should be smaller than the threshold listed in the technical guide. A simplified method to predict the peak vertical accelerations of floors is provided in Appendix A.

(1) Frequency of the vertical mode

People’s walking frequencies lie within 1.6Hz to 2.4Hz (Ding and Chen, 2016). Most long-span ultra-slim composite floors have a small damping and a low natural frequency. It is crucial to reasonably determine the natural frequencies of a floor. A delicate finite element model was built to predict the natural frequencies of the floor. To get an accurate modal mass, static load on the floor was added to the model. The effective live load on the floor was chosen as 0.3kN/m2 according to the related guideline (JGJ 3-2010).

In order to get an accurate modal stiffness, an equivalent elastic modulus was used to consider the stiffness contribution from steel rebar and embedded steel plates. The equivalent elastic modulus follows Eq. (1).

$$E_{eq} = \frac{E_c I_c + E_s I_s}{I_c} = (1 + \frac{E_s I_s}{E_c I_c}) E_c \qquad \text{Eq. (1)}$$

The thickness of the protective layer c is equal to 15 mm and therefore the equivalent elastic modulus of the above-designed section is 1.85Ec.

Through a modal analysis, the fundamental vertical mode of the designed long-span composite floor is 7.48Hz, which is larger than the threshold 3.0Hz. It means that the designed long-span composite floor can meet the requirements of vertical frequency.

(2) Peak acceleration prediction

In order to guarantee the vibration serviceability of the designed floor, the simplified method in the guideline, were used to predict the peak of the accelerations of the designed floor. The parameters for the method is listed in Table 4. Peak accelerations predicted by the method can meet the guideline's requirement.

Table 4 Parameters for the prediction of peak accelerations

Name	Simplified method in the guideline
Model	$$a_p = \frac{F_p}{\beta\omega} g$$ In which, a_p is the peak acceleration of the floor (m/s^2); F_p is the walking load when the pedestrian is walking at a frequency close to the floor's natural frequency (kN); β is the damping ratio of the floor; ω is the effective weight of the floor (kN).
Walking load	$$F_p = p_0 e^{-0.35 f_n}$$ In which, p_0 is the amplitude of the walking load, for residential buildings p_0 equals 0.30 kN; f_n is the vertical natural frequency of the floor (Hz).
Structural parameters	The vertical natural frequency f_n Payload weight (ω) of the impedance Damping ratio β
Peak acceleration m/s^2	0.016

4. CONCLUSION

Super tall residential buildings are commonly developed as luxury properties with extraordinary building quality. The application of long-span ultra-slim composite floor system can increase the floor clearances, broaden the exterior visions and avoid exposed beams after the repositioning of partition walls.

There are several challenges for the structural design of the floor system. On the one aspect, the vertical deflection and vibration serviceability will become the controlling design factors with the reduce of the overall structural thickness of the floor system; on the other aspect, the girders of the floor system contribute significantly to the overall stiffness of the lateral system, the reduction of the girder section height will increase the story drifts of the lateral system.

Optimized design is divided into two parts, structural cost and architectural function optimization. Optimization design of process, that is to find the balance between the architectural function and structural cost, with the owners together. Different sizes of the beam sections with similar stiffness have little influence on the structural indicators. The flange area of the steel beam is increased firstly. The method is so convenient as to assess the increased cost.

Electronic mechanical pipeline can go directly through the web plate with openings to lower total height of the floor. The steel beam can be embedded in the slab height, reducing the total height of the floor.

The thickness of slab needs to be calculated, considering the crack, deflection, construction feasibility and vertical vibration comfort.

REFERENCES

Ding, G., Chen, J. (2016) “Influences of Walking Load Randomness on Vibration Responses of Long-span Floors”, Journal of Vibration Engineering, 29(1), 123-131.

Ministry of Housing and Urban-Rural Development of the People’s Republic of China. (2010), Code for design of concrete structures (GB 50010-2010), Beijing: Architecture and Building Press.

Ministry of Housing and Urban-Rural Development of the People’s Republic of China. (2010), Technical specification for concrete structures of tall building (JGJ 3-2010), Beijing: China Architecture and Building Press.

Pavic, A., Reynolds, P. (2002), “Vibration Serviceability of Long-span Concrete Building Floors: Part 1 - Review of Background Information”, The Shock and Vibration Digest, 34(3), 191-211.

She, X.X., Chen, J. (2009), “A Review of Vibration Serviceability for Long-Span Floors”, Structural Engineers, 25(6), 144-149.