

Vibration Serviceability Design and Field Tests of Long-Span Ultra-Slim Composite Floor System for Super Tall Residential Buildings

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ABSTRACT

The application of long-span ultra-slim composite floor system with no secondary beams can increase the floor clearances, broaden the exterior visions and avoid exposed beams after the repositioning of partition walls during the layout alterations in the whole life cycles of super tall residential buildings. Because of its large flexibility and low damping, the structural design of long-span ultra-slim composite floor system tends to be controlled by vibration serviceability issue rather than safety issue. This paper presents a case study of such a floor system used in a super tall residential building project located in Xiamen city of southeast China. Focuses are placed on design measures to improve the floor vibration serviceability performance, floor responses analysis methods, floor responses field test method and floor vibration serviceability assessment criteria. Two design methods, namely increasing the rebar ratios in floor slabs and using additional steel plates to form composite slab sections, were considered to improve performance of the floor vibration serviceability. Three-dimensional finite element method was applied for the analysis of floor vibration responses, and field tests were conducted to update the structural model and verify the structural responses. The current code-based vibration assessment method was evaluated and some suggestions were put forward for the vibration assessment of long-span ultra-slim composite floor system in super tall residential buildings.

1. INTRODUCTION

The application of long-span ultra-slim composite floor systems with no secondary beams to super tall residential buildings can not only increase the floor clearances for broaden the exterior visions but also avoid the exposure of beams when users want to change the locations of some partition wall, thus improving the living quality and

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functionality of the residential buildings. However, because of the application of light-weight high-strength materials and its longer spans, such kind of ultra-slim composite floor tends to be more flexible with lower damping and natural frequency if the floor thickness is small. Vibration serviceability problems due to occupants' activities, 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).

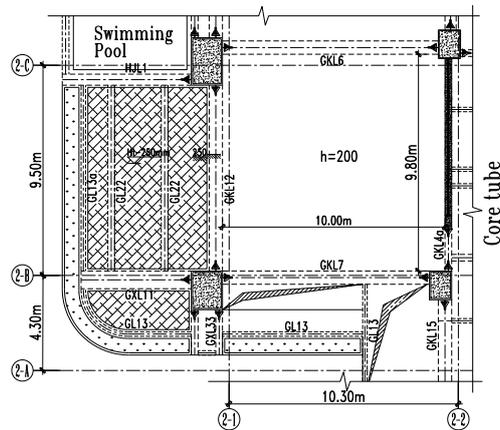
When designing a long-span composite floor, vibration serviceability requirements involves two aspects, stiffness and vibrations. The stiffness requirement can be met by controlling the displacements and widths of cracks of the floor under static load. But these controlling measures cannot guarantee the vibration serviceability under human activities since the inertial force is ignored. As a result, even the safety criteria are satisfied, the vibration serviceability of the floor can be very poor. The vibration serviceability performance of long-span composite floors has attracted the attentions of engineers. Some guidelines such as the American AISC standard, the British CCIP-016 standard and the Chinese technical guide JGJ3-2010 have explicit requirements concerning vibration serviceability. The long-span ultra-slim composite floor, however, are not covered by these design guidelines.

Based on a super tall residential building which has a long-span ultra-slim composite floor, the following efforts are made in this paper. Measures to improve vibration serviceability performance of structures are proposed. Floor vibrations under human activities are predicted and also measured during field tests. Current guidelines on vibration serviceability are assessed.

2. Design of the long-span ultra-slim composite floor

A super tall residential building project named Dijingyuan located in the west of Xiamen, which is a city at southeast of China. The total coverage area of this project is 54286.697 square meters in which 15200.3 square meters are covered by 7 buildings. 5 out of the 7 buildings are super-high-rise steel residential buildings with a structural height of 245.75 m. This project will become a new landmark of Xiamen. As a landmark, its structural design has very high expectations for both safety and serviceability.

In order to increase the floor clearance which is a requirement of high-end 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.1. This long-span ultra-slim composite floor was designed according to the latest design guidelines in China and the vibration serviceability issue of this long-span ultra-slim composite floor was analyzed in this paper.



Boundary conditions of the floor: Up-continuous, down-simply-supported, left-simply-supported, right-continuous

Fig. 1 Plan view of the long-span ultra-slim composite floor

2.1 Design against loading 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. 2. 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.

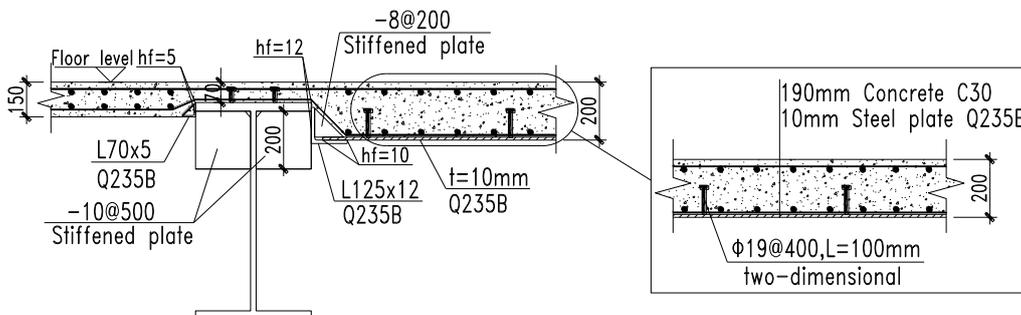


Fig. 2 Section of the composite floor

The stiffness contributions of steel plates of different thicknesses to a same floor were analyzed and the results are shown in Fig. 3. It shows that as the thickness of the floor increases, the stiffness of the composite floor increases. When the thickness of the steel plate lies within the range $<0.08H_{\text{slab}}$, the steel plates effectively increase the stiffness of the composite floor.

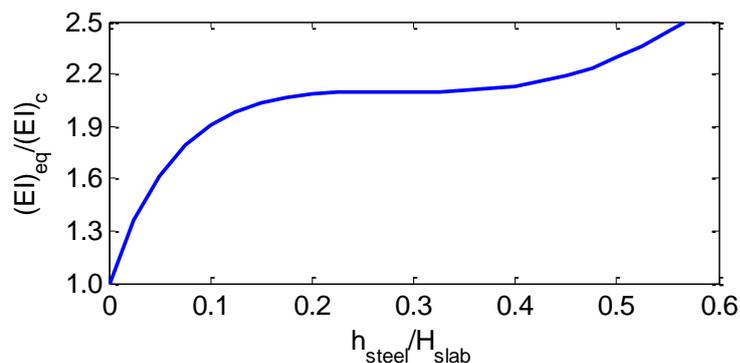


Fig. 3 Stiffness contributions of steel plates with different thicknesses

Based on the above analysis and the design method of structural members resisting moments in the design guideline for concrete structures GB 50010-2010 (the guideline for short, hereafter), 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

Both loading capacity design and serviceability check of the designed floor with the two designed sections under static load have been done based on the methods of structural members resisting moments in the guideline, respectively. 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 plate. And the steel rebar arrangement of the composite floor is 16@100 in two lays and two directions.

2.2 Design against Vibration serviceability

As a high-end residential building, according to the technical guide GJG 3-2010 in China, the vertical modes of a floor 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 also provided in Appendix A of the technical guide GJG 3-2010.

(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).

$$E_{eq} = \frac{E_c I_c + E_s I_s}{I_c} = \left(1 + \frac{E_s I_s}{E_c I_c}\right) E_c \quad (1)$$

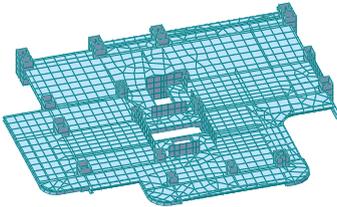
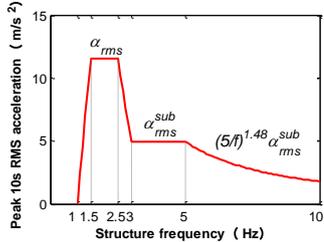
The thickness of the protective layer *c* is equal to 15 mm and therefore the equivalent elastic modulus of the above-designed section is 1.85*E_c*.

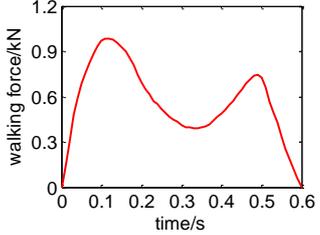
Through a modal analysis, the fundamental vertical mode of the designed long-span composite floor is 7.48Hz, which is larger than the threshold 3.0Hz. It means that the designed long-span composite floor can meet the requirements of vertical frequency.

(2) Peak acceleration prediction

In order to guarantee the vibration serviceability of the designed floor, the simplified method in the guideline, finite element method and the response spectrum method proposed by Chen et al. (2014), which has been adopted by the Chinese standard “Technical Code for Human Comfort of the Floor Vibration”, were used to predict the peak of the accelerations of the designed floor. The parameters for each of the three methods are listed in Table 2.

Table 2 Parameters for the prediction of peak accelerations

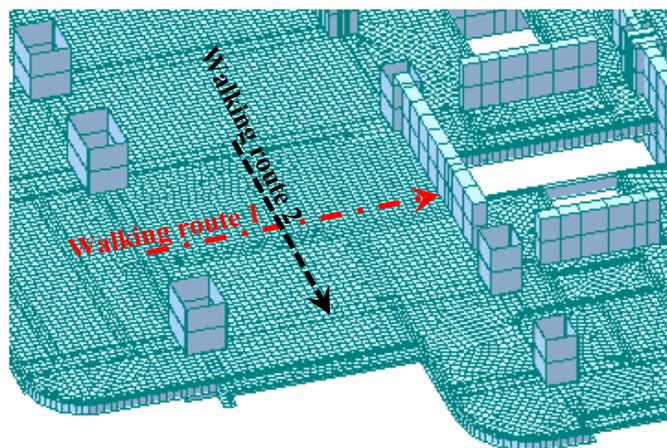
Name	Simplified method in the guideline	Finite element method	Response spectrum method
Model	$a_p = \frac{F_p}{\beta \omega} g$ <p>In which, a_p is the peak acceleration of the floor (m/s²); F_p is the walking load when the pedestrian is walking at a frequency close to the floor’s natural frequency (kN); β is the damping ratio of the floor; ω is the effective weight of the floor (kN).</p>	 <p>FEM model</p>	 <p>10s RMS acceleration response spectrum</p>

<p>Walking load</p>	$F_p = p_0 e^{-0.35f_n}$ <p>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).</p>	 <p>Bauman's single step loading, weight 75 kg, walking frequency 2.0Hz</p>	<p>Measured walking load of two consecutive steps based on Chinese samples</p>
<p>Structural parameters</p>	<p>The vertical natural frequency f_n Payload weight (ω) of the impedance Damping ratio β</p>	<p>Structure arrangements Component parts size Material properties Damping ratio</p>	<p>Vertical natural frequency Modal mass of the floor Damping ratio</p>

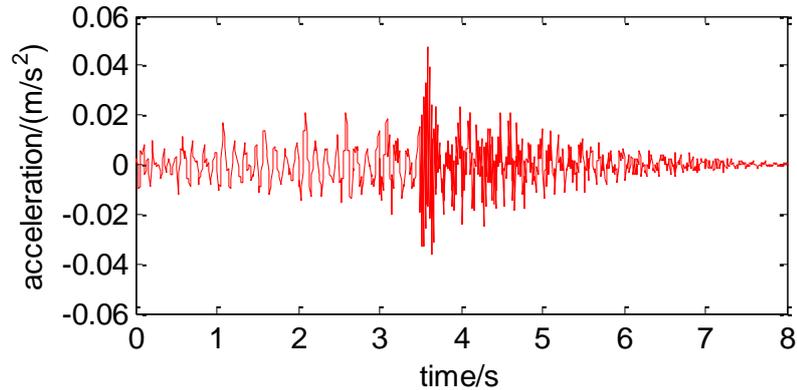
The peak accelerations predicted by these three methods are shown in Table 3. Two walking routes were considered in the finite element method and they are shown in Fig.4(a). The floor accelerations with route 1 predicted by finite element method are shown in Fig.4(b).

Table 3 Calculated peak acceleration

Name	Simplified method in the guideline	Finite element method	Response spectrum method
Peak acceleration m/s^2	0.016	0.048	0.062



(a) Walking routes



(b) Acceleration response at the mid-span of the floor

Fig.4 Acceleration response of the floor

It is shown that peak accelerations predicted by the three methods differ to a great degree. Peak accelerations predicted by the first two methods can meet the guideline's requirement, but that of the response spectrum method is larger than the threshold 0.05 m/s^2 .

3. Field tests of the floor

Given that the case floor is a typical long-span ultra-slim composite floor, investigation on the vibration serviceability of such kind of floors are rare. In order to verify the correctness of the structural design against vibration serviceability, field test was conducted on the constructed floor to get its dynamic properties and vibrations.

Field test of the floor was conducted on two separate days. The first attempt of field test was done when the floor had been constructed while the cement mortar flooring layer had not been paved. The aim of the first attempt is to measure the stiffness and dynamic parameters (natural frequency and damping ratio) of the long-span composite floor. These measured parameters can be used to verify and update the model built in the vibration serviceability design. The second attempt took place when a 60mm's thick cement mortar flooring layer had been paved and aimed to get the final stiffness, dynamic parameters and vibration amplitudes of the floor under human activities. The measurements can be used to assess the three vibration serviceability assessment methods.

During the field tests, ambient vibration tests were done to get the floor's modal properties and various kinds of human activities were organized on the floor to get the floor's vibrations under human activities (She 2010). Details relating the two kinds of tests are shown in Table 4.

