Research on Design of Vibration Comfort of Large Span Roof Based on structural scheme

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Abstract. This article focuses on the layout of three types of large-span floor slabs with ordinary concrete ribbed beams, restressed beams, and box-shaped slabs combined with specific engineering projects. By using finite element software, the vibration comfort of the three kinds of structural schemes was evaluated from the aspects of structural dynamic characteristics, jump load response and so on. The analysis results show that the common ribbed beam system can meet the vibration comfort requirement of the slab under reasonable plane layout. Restressed beam system has little effect on the frequency of natural vibration of the floor slab. The box beam system can increase the natural vibration frequency of the vertical vibration of the floor and improve the vertical vibration performance of the floor.

1. Introduction
At present, the complexity of building use requirements and the continuous improvement of structural design content make the design and research of large-span concrete roof structure increasingly comprehensive. Relevant codes [1] [2] give dual-control indicators, including natural frequency and peak acceleration limits, and relevant literatures [3]-[5] give a relatively comprehensive evaluation method of floor vibration comfort based on domestic and foreign standards. However, there are few studies on the reasonable selection of roof structure, considering the comfort level of floor vibration. In this paper, the floor vibration comfort of three kinds of roof structures, ordinary concrete ribbed beam, restressed beam and box-shaped slabs, is analyzed, and the suggestions for the use of various schemes under different conditions are put forward from the perspective of scheme comparison.
The comprehensive building of Jintong primary school in Chongqing is established in the steep slope area, as the typical slope structure with one side of the steep slope and the other side facing the sky, as shown in the figure 1. The building is a frame structure with five stories and a total height of 22.7m. The roof is the school basketball and badminton playground, and there are two large-span roofs. The column network arrangement of the structure is shown in Fig. 2. The sizes are 28.7mx21m for plate A and 34.2mx21.6m for plate B, respectively. In this project, the roof is a stadium and the next floor is a room for equipment. There is no strict requirement for indoor net height.

2. Design of long-span roof

2.1. Ribbed beam roof

According to the dimension condition of floor slabs in zone A and B, one-way secondary beams are arranged in the direction of smaller side lengths (zone A: 21m, zone B: 21.6m). Two secondary beams are arranged between columns of each span. The cross sections of primary and secondary beams are 300mmX1600mm. The layout scheme of roof is shown in Fig 3. Meanwhile, two simply supported beams are set up in the direction of vertical secondary beams. The cross section of the simply supported beams is 200 mm X400 mm. On the one hand, it is considered that the span of the long-span beam is longer, the vertical deflection is larger, and the short-span simply supported beam system can reduce the calculated length of the long-span beam. On the other hand, the short simply supported beam system at the large-span roof can improve the lateral stiffness of the whole roof structure and transfer the internal force between the transverse large-span columns.
2.2. Restressed beam roof

The basic layout of the restressing beam system is basically the same as that of the rib beam system, except that the restressing force is applied to the large span primary and secondary beams (section 300X1600). The restressed steel strand is made of 10X7 type, the total area is 1400mm², and the tension control stress is 1395Mpa. The linear arrangement of the restressed tendons is shown in Fig 4. The prestress in the model is simulated by steel cable, considering the contribution of prestress to the structural stiffness.

2.3. Box girder roof

On the basis of the structural arrangement of the rib beam roof, an 80mm thick concrete floor with a single layer of bidirectional steel is provided for the entire structural beam bottom of the large span area. The bottom of the plate is flush with the bottom of the large span beam of 1600mm high, forming a box form with a large span. Its cross-section is shown in Fig 5.
3. Comfort evaluation of roof structure

The analysis model is established by finite element software. In combination with the relevant specifications [2], consider the use of the sports field of the roof, so that the vertical vibration comfort of the roof meets the requirements of the moving jump load. The evaluation indexes of roof comfort include the vertical natural frequency of roof and the peak acceleration of vertical vibration under jumping load. Reference [3] [6] defines the mass source, including own weight, standard value from dead load and effective standard value of live load distribution. Considering the use of this floor as a sports field, the dead load is approximately 5 kN/m² and the live load is 4 KN/m².

3.1. Structural modal analysis

The first six natural frequencies and vibration directions of the roof structures are shown in Table 1. In all kinds of forms, the first three modes are plane integral vibration (X-direction and Y-direction vibration) of the structure. From the fourth mode, the vertical (Z-directional) vibration of the long-span roof is the main mode. The fourth-order natural vibration frequency of each structural form is greater than 3 Hz, which satisfies the requirements of the specification [2]. Compared with the rib beam structure, the fourth-order natural vibration frequency of the prestressed beam type only increased by 2.2%, while the box beam type increased by 68.6%. This shows that the box with double-deck plates greatly increases the vertical stiffness of the structure, and the contribution of restressing force to the overall stiffness of the structure is small.

The first two modes of the vertical (Z-direction) self-vibration of the roof structure are shown in Fig 6. The first-order mode shape of the vertical (Z-direction) vibration appears in the large-span B-plate area, and the second-order vertical (Z-direction) mode shape appears in the A-plate area. Meanwhile, the most unfavourable vertical (Z-direction) vibration point is at the near-center-of-gravity position of the A and B zones. That is to say that the closer to the center of the large-span plate, the more pronounced the vibration of the center of gravity, and the greater the vibration displacement. The vertical vibration displacement of the box-beam plate is the smallest, the restressed beam roof is the second, and the vertical vibration displacement of the box girder roof is the largest.

| Order number | Ribbed beam | Prestressed beam | Box girder |
|-------------|-------------|-----------------|-----------|
|             | Frequency   | Vibration form  | Frequency | Vibration form | Frequency | Vibration form |
| 1           | 3.4763      | Translation-Y  | 3.4769    | Translation-Y | 4.0170    | Translation-X |
| 2           | 3.4919      | Translation-X  | 3.4905    | Translation-X | 4.3073    | Translation-Y |
| 3           | 3.8788      | Torsion        | 3.8782    | Torsion       | 4.7173    | Torsion       |
| 4           | 4.1624      | B Vertical     | 4.2554    | B Vertical    | 7.0170    | B Vertical    |
| 5           | 4.3887      | A Vertical     | 4.5183    | A Vertical    | 7.3534    | A Vertical    |
| 6           | 4.7124      | B Vertical     | 4.9394    | B Vertical    | 7.3915    | B Vertical    |
3.2. The steady-state analysis of long-span roof

The vibration, considering that the plane of the large-span slab in the A and B areas is an approximate regular rectangle, of the center of gravity of the large-span slab is larger according to the actual vibration deformation and modal analysis results. The most unfavorable vibration point can be selected in the center of gravity of the large-span slab. The position of the vibration point where the vertical displacement is the largest is as shown in Fig. 6. The elastic modulus of concrete is enlarged by 1.3 times, considering that the elastic modulus of concrete under load excitation is larger than that under dead load [4]. When the structure is analyzed in steady state, the frequency range can be 0~20Hz.

Figure 6. Vertical vibration mode of structure
Comparing the frequency-displacement spectrum of the most unfavourable vibration point in Fig. 7, it can be seen that the spectral characteristics of the concrete rib beam type and the restressed beam type are basically similar. The difference of the first natural frequencies is very small, which indicates that restressing cannot effectively improve the vertical natural frequencies of long-span slabs. The first natural frequencies of box-girder slab are 8.2 Hz in zone A and 7.8 Hz in zone B, which increase greatly. At the vibration points of A and B plates, the first vertical natural frequencies of the ribbed beam structure are the smallest, with the area A being 5.0Hz and the area B being 4.7Hz. All three types of roof structures meet the requirements of more than 3Hz [2]. At the same time, the peak displacement of the box girder-slab structure is about twice as much as that of the other two roof forms. This shows that the overall vertical stiffness of box girder is large, and the anti-deformation ability is obviously enhanced.

| Form      | Ribbed-beam | Prestressed | Box-girder |
|-----------|-------------|-------------|------------|
| Zone A    | 5.0         | 5.1         | 8.2        |
| Zone B    | 4.7         | 4.8         | 7.8        |

### 3.3. Peak Vibration Acceleration of Jumping Load

According to the results of steady-state analysis, the most disadvantageous vibration points of plate A and B are selected as the excitation points of human-induced vibration to analyze the vibration response under jumping loads. The function used in reference [7] on jump load is expressed as follows:

\[
P(t) = G + \sum \alpha_i G \sin(2\pi f_i t)
\]

(1)

Where \(G\) is a single person weight, taking 70kg/person; \(\alpha_i\) is the vertical i-th order excitation factor; \(f_i\) is the i-th vertical vibration frequency of the roof excitation point; the time interval is 0.001 s. The excitation effect of the jump load on the roof can be expressed by a sinusoid. Therefore, only the first order of the formula is used for calculation. Single person continuously jumps 6S to form load function curve. A load function curve is formed by jumping 6S continuously by a single person, as shown in Fig. 8.
The acceleration time history curves of single jumping load at excitation point under three roof structures are shown in Fig. 9. Combined with the peak accelerations of the A and B plates in Table 3, it can be seen that:

(1) Under the same roof structure, the roof area of Zone B is 22.6% larger than that of Zone A, and the acceleration of Zone A is 0.7~0.9cm/s-2 larger than the acceleration of Zone B. It shows that the larger the area of the large span, the larger the weight, and the larger the span, the smaller the stiffness. The whole roof is flexible in the vertical direction, and the peak acceleration generated by the vertical vibration becomes smaller.

(2) In the same large-span area, the peak acceleration of the restressed structure is the smallest, the box-girder roof is the second, and the peak acceleration of the rib beam type is the largest. It is indicated that the vertical vibration peak acceleration of the entire large span roof can be reduced by applying restressing to the long-span roof or using the box-girder roof, but the degree of reduction is limited. The peak acceleration of the pre-stressed slab is slightly less than that of the box girder slab. The main reason is that the overall stiffness of the box structure increases while the mass also increases greatly, which makes the peak acceleration of the vertical vibration of the structure under the excitation of resonance load larger than that of the restressed floor.

(3) According to the requirements of the relevant literature [4]-[6] for the acceleration limit, when the natural vibration frequency of the structure exceeds 4 Hz, the limit on the peak acceleration under the jump load of the playground can be 5 cm/s². Obviously, the three types of long-span roof structures all meet the requirements of peak acceleration of vertical vibration.

Table 3. Peak acceleration under single person jumping load (cm/s²)

| Form          | Ribbed-beam | Prestressed | Box-girder |
|---------------|-------------|-------------|------------|
| Zone A        | 3.665       | 3.202       | 3.354      |
| Zone B        | 2.769       | 2.521       | 2.619      |
Figure 9. Acceleration time history curve of excitation point under single jump load

4. Conclusion
This paper, combined with specific projects, conducts overall modal analysis, steady-state analysis of vertical vibration points and calculation of peak acceleration of vertical vibration for three kinds of long-
span roof from the perspective of scheme comparison. The results show that the three types of roof structures can meet the requirements of floor vertical vibration comfort.

The effect of restressing on the vertical natural frequency of large-span roof is slight. The box-girder slab works as a space box in the whole large-span slab, which effectively increases the stiffness of the whole slab area and improves the vertical vibration characteristics of the large-span structure. The structure on the box-girder slab can be used in the main optimization scheme when the vertical self-vibration of the large-span roof is not satisfied.

The peak acceleration of vibration can be reduced by applying prestress to the structure or adopting box-girder and plate structure.

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