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Research Article

Tests and Analysis on Vertical Vibration of Long-Span Prestressed Concrete Floor System

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Abstract: As the long-span prestressed concrete floors are widely used in stadiums, buildings with large open space and high buildings, the vertical vibration serviceability is becoming increasingly important. So the research of long-span prestressed concrete floor vertical vibration under pedestrian loads has great significance. According to practical engineering, the study presented the vibration measurement scheme and the vibration signal was detected by high sensitivity piezoelectric accelerometer, we got the first two order frequencies of the floor vertical vibration and the corresponding damping ratios by mode-superposition method. Also, finite element models were established to simulate the floor vertical vibration. Based on the comparison between the numerical results and the corresponding measurements, the most appropriate model was determined for studying the dynamic behavior of long-span prestressed floors.

Keywords: Finite element analysis, long-span prestressed concrete floor, serviceability, vibration tests

INTRODUCTION

With the application of new lightweight, high strength materials and the improvement of structural analysis and construction technology, prestressed concrete floors are widely used in stadiums, long-span space structures to meet the requirements of large open space (Pavic *et al*., 2001). As small damping and low fundamental frequency, long-span prestressed concrete floors are sensitive to floor vibration induced by mechanical and human activity. It may cause the users' anxiety and psychological panic when floor vibration is excessive. Vibration serviceability for long-span floors has been a considerable problem after the reduction of the floor thickness and the decline of damping properties (She and Chen, 2009).

Long-span floor vertical vibration serviceability involves vibration source (stimulation loads), transmission route (floors) and vibration receivers (residents) (Steffens, 1965). These three aspects should be considered these three aspects at the same time in reasonable evaluation and design standards of long-span floor vertical vibration serviceability (Baehmann *et al*., 1995). The acceleration of the structure seems to be the most appropriate response quantity to use as a limitation of the motion parameters and it (and its derivative) is directly related to the whole-body forces that are sensed kinesthetically. Annoyance threshold accelerations are shown in Fig. 1 (Allen and Rainer, 1976; Ellingwood, 1989). Whole-body vibrations within the range of 3-10 Hz are especially critical because large body organs within the rib cage and abdomen resonate within this frequency range (Grether, 1971). Vibratory movement at frequencies less than 1 Hz can also be associated with more motion sickness

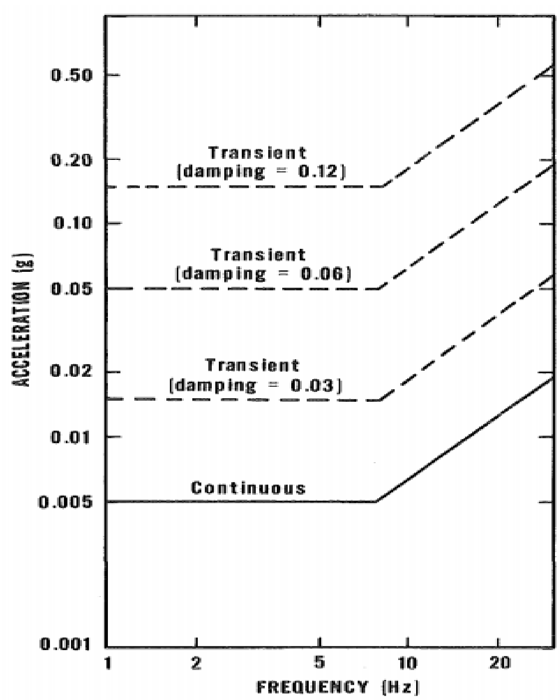

Fig. 1: Annoyance threshold vibrations

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and systemic response to the dynamic force (Brace *et al*., 1984). Motion in this frequency range is a special consideration to minimize the effect of wind excitation on very tall buildings. The tolerance of a person to vibration also depends on his activity at the time motion occurs and it is recommended that the limit should be occupied with the construction of the building.

The discussion of long-span floor vertical vibration serviceability has already begun in the 19th century. Tomas Tredgold once wrote that beams should be done deep enough in order to avoid inconvenience caused by floor vibration, who was one of the founders of British Civil Engineering Association in 1828 (Allen and Pernica, 1998). Reiher and Meister conducted a study about the problem of large-span floor vertical vibration in the laboratory and put forward the related standard in 1931(Murray *et al*., 1997).

With the increasingly impacts on human activity, the design standards gradually need to be refined. At present, there are two methods to solve the large-span floor vertical vibration serviceability. One is the frequency adjustment method, set floor frequency higher than a limit value; the other is dynamic response value methods, which limit the value of the dynamic response of the floor loads. The first method is relatively simple and easy to achieve in the design phase, but does not directly contains the pedestrian load factors; the second method includes the motivation, structure and the reaction, but calculation complexity. Due to the complexity of the floor structure system, field measurement is the best way to determine the dynamic characteristics (Pavic *et al*., 2007). Therefore, taking the Shenyang Olympic Center as an example, field measurements and analysis of its dynamic properties were carried out and the results were compared with those obtained by numerical simulation analysis. Shenyang Olympic Center is the largest concrete floor system in stadiums, with strong representation in China. The most appropriate model can be determined and it also meets the vibration serviceability. So the research of long-span prestressed concrete floor vertical vibration under pedestrian loads has great significance and it can give suggestions for other practical engineering. Finally, combined with other similar structure dynamic test results, this study put forward some suggestions on vibration design and control standards of the long-span floor, such as design parameters, design model, the overall vibration frequency and floor vertical vibration frequency limit etc.

MEASUREMENT SCHEME

The long-span pre-stressed concrete frame beam structure is used in Shenyang Olympic Sports Center whose span is 39.9 m and 32.4 m. The testing floors are the hexagonal area (Fig. 2). The vertical vibration signal was detected by high sensitivity piezoelectric accelerometer (LC0132T) and it can analyze the frequency and damping of the main structure (Lin *et al*.,

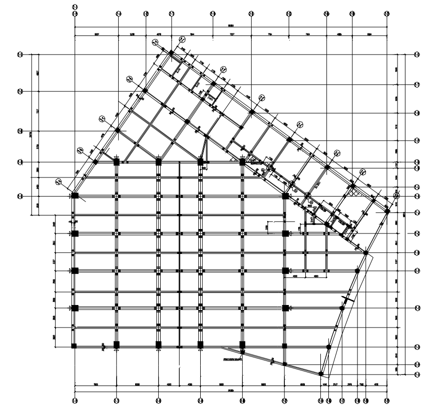

Fig. 2: Sketch map of testing floors

2010; Chi *et al*., 2010). Due to the intensive vibration frequency and local vibration mode, the test grid should be equally intensive.

The test was carried out in four phases, namely:

- Measuring points are arranged in accordance with the vertical and horizontal vibration dynamic testing.
- Fixed reference point will be arranged in central as far as possible and other regions are mobile measuring points.
- Connect the sensor connect to the acquisition instrument and record the position of the corresponding channel and collection point
- Check and debug the signal acquisition instrument and computer.

Measuring torsional mode, the mobile points are arranged symmetrically. Total vertical vibration measurement points are 80, the horizontal are 20. The recording time for each testing condition should be maintained for at least 30 min and the sampling frequency of the measuring points should be set at 256 Hz or more.

STRUTURAL DYNAMIC ANALYSIS

In the dynamic analysis, the balance equations structure of the finite element structure system generally can be expressed as:

$$MX''(t) + CX'(t) + KX(t) = -MZ''(t) \qquad (1)$$

where,

M, C, K	=	The mass, damping and stiffness matrix of the structure
$X''(t)$, $X'(t)$, $X(t)$	=	Acceleration, velocity and displacement
$Z''(t)$	=	The ground motion acceleration

In mathematics, the equation represents a second order linear differential equation which includes a group of constant coefficients. There are many methods to solve the equation. Due to the complexity of the structural analysis and the practical needs of design, the modal superposition method and the direct integral method are commonly used. This study analyzes the overall stiffness based on the modal superposition method. Modal superposition method is that making a coordinate change before solving the original structure dynamic balance Eq. (1):

$$X(t) = \phi U(t) \tag{2}$$

where, ϕ is the matrix, $\phi_i(i = 1,2.......n)$ is determined by the eigenvectors of the equation:

$$K\phi = \omega^2 M\phi$$

Also,

$$\phi^T M\phi = I$$

$$\phi^T M\phi\omega^2 = \begin{bmatrix} \omega_1^2 & & \\ & \omega_2^2 & \\ & & \omega_3^2 \end{bmatrix}$$

where,

ϕ = The mode vectors
ω = Its corresponding circular frequency

The corresponding the cycle expressed as:

$$T_i = \frac{2\pi}{\sqrt{\omega_i}}$$

$U(t)$ = Displacement vector
$U_i(t)$ = Called modal coordinates
$U_i(t)$ = The project of $X_i(t)$ based on the mode vectors

Through the formula (2), the finite element node displacement is transformed into generalized displacement. And the original finite element node coordinates base is replaced by the modal coordinate's base. The coordinate transformation has two purposes: one is for a better approximate solution with reducing the number of coordinates and the other is to simplify the calculation of the equations of motion.

The key to the modal superposition method is to solve the generalized eigenvalue problem:

Table 1: Results of vertical frequencies of floor (Hz)

Number	Primary	Second
1	4.915	8.556
2	4.799	8.138
3	5.083	9.227
4	4.956	8.262
5	4.844	8.353
Average	4.919	8.507

Table 2: Results of damping ratios（%）

Number	1	2	3	4	5	Average
Primary	1.27	1.17	1.57	1.21	1.38	1.32
Second	0.92	0.81	1.15	0.89	1.07	0.97

$$\left([K] - \omega^2[M]\right)\{\phi\} = 0 \tag{3}$$

The more degrees of freedom in large-span structure system, the more troublesome of solving Eq. (3), with comprehensive consideration of structure and the actual conditions, we use the total stiffness Analysis method to get generalized eigenvalue.

As to understand the dynamic characteristics of long-span floor structure, the study has presented the first two order natural cycle and vibration mode. By the analysis of dynamic characteristics we can understand the size of the overall structural rigidity, stiffness distribution and determine the relative weak parts of the structure. Then provide reference for the further optimization and adjustment of the design in the long-span floor structure.

SURVEYING FREQUENCY

The second floor is tested for 5 times, not less than 30 min every time and the acceleration signals are recorded by the signal acquisition software. Then eliminate the initial term, the DC and the trend of error from acceleration signals. We can get the power spectrum by the spectrum analysis of random signals with period gram algorithm and frequency is identified by peak value method. The half-power method determines the damping ratio. Table 1 and 2 display the first two order frequencies of the floor vertical vibration and the corresponding damping ratios.

According to the Table 1, the first two order frequencies of the floor vertical vibration are 4.919 Hz and 8.507 Hz. For general sports, the lower limit value of the natural frequency is 3~3.5 Hz. When the natural frequency of vibration is greater than 6 Hz, it can neglect evaluation analysis of vibration serviceability. The testing floors meet the lower limit of the natural frequency, but it still needs evaluation analysis of vibration serviceability. Table 2 shows that the first two order damping ratios of the floor structure are between 0.8% and 1.6% and the average damping ratios are 1.32% and 0.97%, they are closed to the values of the concrete structure.

Table 3: Frequency comparison between FEM Analysis and measurements in model 1

Number		1	2	3	4	5	Average
Measurement	Primary	4.915	4.799	5.083	4.956	4.844	4.919
	Second	8.556	8.138	9.227	8.262	8.353	8.507
Finite element analysis	Primary	3.645	3.645	3.645	3.645	3.645	3.645
	Second	7.720	7.720	7.720	7.720	7.720	7.720
Error (%)	Primary	25.8	24.0	28.3	26.5	24.8	25.9
	Second	9.8	5.1	16.3	6.6	7.6	9.3

Table 4: Frequency comparison between FEM Analysis and measurements in model 2

Number		1	2	3	4	5	Average
Measurement	Primary	4.915	4.799	5.083	4.956	4.844	4.919
	Second	8.556	8.138	9.227	8.262	8.353	8.507
Finite Element Analysis	Primary	6.127	6.127	6.127	6.127	6.127	6.127
	Second	10.75	10.75	10.75	10.75	10.75	10.753
Error (%)	Primary	24.7	27.7	20.5	23.6	26.5	24.6
	Second	25.7	32.1	16.5	30.2	28.7	26.4

Table 5: Frequency comparison between FEM Analysis and measurements in model 3

Number		1	2	3	4	5	Average
Measurement	Primary	4.915	4.799	5.083	4.956	4.844	4.919
	Second	8.556	8.138	9.227	8.262	8.353	8.507
Finite Element Analysis	Primary	4.822	4.822	4.822	4.822	4.822	4.822
	Second	9.195	9.195	9.195	9.195	9.195	9.195
Error (%)	Primary	1.9	0.5	5.1	2.7	0.5	2.0
	Second	7.5	13.0	0.3	11.3	10.1	8.1

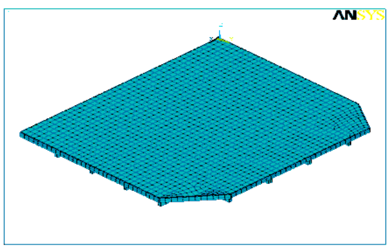

Fig. 3: Simply supported and clamped floor model

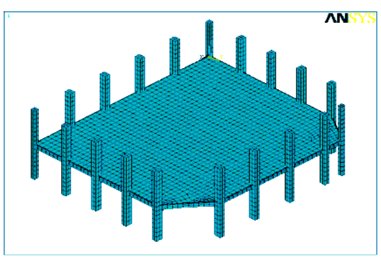

Fig. 4: Slab-column model

FINITE ELEMENT ANALYSIS

Analysis method: According to the practical situation, the modeling and simulation of the boundary conditions were carried out by the software ANSYS and there were three different component models. The natural frequency of vibration was calculated by the mode decomposition method. Compared with measurement frequency, it can determine the most appropriate model. Three finite element models:

- Simply supported floors model
- Clamped floors model
- Slab-column model

These three models didn't consider the impact of non-load bearing element on the floor, but considered the influence of the secondary beam. In this study, the mesh size about the dynamic behavior of floors was studied. Through the establishment of three different mesh sizes model, the mesh size about the impact of natural frequency could be neglected, mode has certain influence on the appearance of the vibration. Shell63 element simulates concrete floor slab and beam189 element simulates beam and column. Figure 3 and 4 show the model grids.

Results and comparison: The analysis shows that, although the natural frequencies of the three models have some differences, vibration shape diagrams change very small. The fourth order vibration shape diagrams are shown in Fig. 5, 6 and 7. By the results of Table 1, it can be seen that the first two order frequencies are smaller than the measurement. The reason is that the rigidity of the plate reduced without considering rotating restriction. Based on the comparison between the first two order natural frequency and the corresponding measurements, the use of slab-column model to simulate the floors proved to be satisfactory for studying the dynamic behavior of long-span prestressed floors. The analysis shows that the first order frequency and the measured results are closer, the second order frequency error is larger and it may be caused by frequency intensive characteristics of long-span floor system. Compared with previously published work, the result is similar and reliable, it has great reference value. Table 3, 4 and 5 display

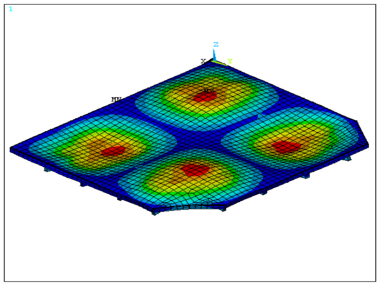

Fig. 5: The fourth order vibration shape diagram (model 1)

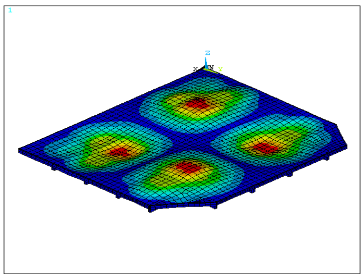

Fig. 6: The fourth order vibration shape diagram (model 2)

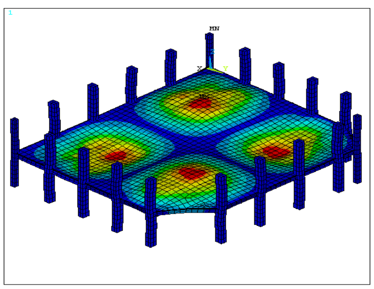

Fig. 7: The fourth order vibration shape diagram (model 3)

frequency comparison between FEM Analysis and measurements.

CONCLUSION

Based on the field measurements, the following conclusions can be obtained. The primary frequency of vertical vibration is 4.919 Hz, the corresponding damping ratio is 1.32% and the second is 8.507 Hz and 0.97%. Compared with the numerical results, we can see that the fundamental frequency of the floor meets the requirements of vertical vibration serviceability. On the whole, the problem of vibration serviceability for large-span prestressed floor is still in research. Due to the uncertainty of pedestrian load and floor structures, the control standard is too conservative abroad, but there is a lack of the relevant codes and standards in China. Therefore it still needs further research.

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