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The Research of Time-History Response Analysis of Floor Vibration Based on Simulation of Group Walking

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Abstract. Occupant comfort when large-span floor systems are subjected to crowd-induced vibrations has become an important index to evaluate serviceability of structures. Control of deflections stipulated in current code requirements cannot sufficiently represent the serviceability requirements of floor systems. Harmonic vibration analysis procedure is introduced by foreign code requirements to deal with floor vibrations, with the restriction to those with regular shapes and simple boundary conditions. This paper proposes a time-history analysis program for the generation of load induced by human activities based on the stimulation of group walking, analyzing the floor systems with special boundary condition, span and damping by time-history method. Compared with the results of crowd-induced load experiment, the analytical results confirmed the accuracy of this analysis procedure in representing the characteristic of crowd-induced floor vibrations, which is applicable for evaluation of floor systems with arbitrary shape and boundary condition.

Keywords: floor vibrations; time-history analysis; crowd-induced load; group walking stimulation

1. Introduction

Materials with large stiffness and light weight are widely used with the development of architectural design, construction technology and material properties improvement. Because of occupants' various requirement for living space, in order to gain a maximum limit of free space, layout with less partition wall and large-span is more and more popular. This tendency makes floor system become much more sensitive to small loads such as load induced by human activities. Therefore, establishment of evaluation method and standard of floor vibration for residential performance, which is concerned during design stage, could help to gain a building more economical and comfortable.

2. Background

As a cross task of ergonomics and structure engineering, there is few study of floor vibration in our country. A few research were studied in U.S., JAPAN and some European countries, and some related guidelines for design were published such as Critical review of guidelines for checking vibration serviceability of post-tensioned concrete floors by British Concrete Institute(BCI), Design Guide on the Vibration of Floors by British Construction Steel Institute(BCSI) and Construction Industry Research and Information Association(BCIRIA), Design Guide on the Vibration of Floors in Hospitals by BCSI, Floor Vibration due to Human Activity by American Institute of Steel Construction(AISC) and National Building Code of Canada. There are no such guidelines in our country. Harmonic vibration analysis procedure is introduced by foreign code requirements to deal with floor vibrations, floor system is simplified as a single degree of freedom system and boundary condition is simplified as simply supported. This method is too simplistic to describe practical situation. According to the research by CHEN and PAVIC, an ideal result could be gained by finite element time-history analyses. But it is difficult to apply practically because of the complicated load processing.

In this paper, based on the basic rules of group walking, time-history data of the load induced by human activities is generated by a program which is programmed to stimulate group walking. This program also has an auto-interface for finite element software with which avoids complicated data processing. And time-history analysis of floor vibration can be realized.

3. Dynamic model of crowd-induced load

In this paper, different dynamic model of crowd-induced load is introduced before the research of floor vibration induced by human activities. According to the frequency of human walking, it can be classified as follows: walking slowly, walking normally, walking fast and run. The walking frequency is in range of 1.7Hz～3.2Hz. The frequency and load time-history of different walking mode determined by Buchman and Ammann are shown in Fig.1.

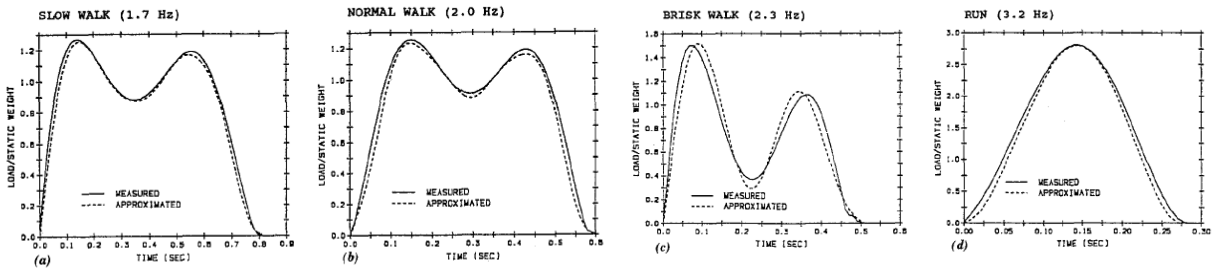


Fig. 1. Approximated versus Measured Footfall Forces

The velocity, frequency and step length of the four walking model is listed in reference [8], as shown in Table 1.

Table 1 The velocity, frequency and step length of the four walking model

Walking model	Velocity (m/s)	Frequency (m)	Step length (Hz)
Walking slowly	1.10	0.60	1.70
Walking normally	1.50	0.75	2.00
Walking fast	2.20	1.00	2.30
Run	3.30	1.30	2.50

During the process of walking, time-history of impact load induced by foot trampling on floor could be simplified as a half sine wave function and when foot raise off floor, the load value is 0. The mathematical model of the load could express by：

$$\begin{cases} F(t) = k_p P \sin(\pi f_p t) & t < t_p \\ F(t) = 0 & t_p < t < T_p \end{cases} \quad (1)$$

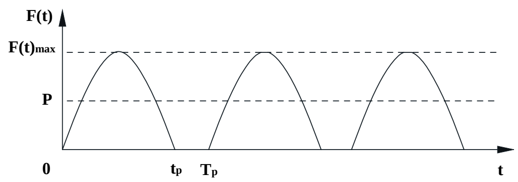


Fig.2 Simplified time-history curve of crowd-induced load

Where Tp is load cycle, fp is walking frequency, tp is the trampling time during the load cycle, kp whose value is F(t)max/P is magnification factor of impact load , P is deadweight of human. The load time-history curve is shown in Fig.2.

4. Simulation of group walking and procedure of program FVAP for the generation of load induced by human activities

Floor vibration is mainly caused by dynamic load induced by group walking. The process of group walking could be described by properties as follows: amount of the group, each person's deadweight, starting point, walking direction and walking model (step length, frequency, magnification factor is included). In order to gain load time-history of each point of the floor system, simulation of group walking is needed. Taking account of the random human activities, the simulation model is simplified with assumptions as follows: (1) human deadweight, walking model, starting time, walking path are random; (2) walking process is a uniform rectilinear motion; (3) human deadweight is 700±145N, a random variable of normal distribution. Based on the above theory, a program FVAP (Floor Vibration Analysis Program) for the generation of load induced by human activities is programmed in this paper with an object-oriented language. Introduction of element information, demarcation of active boundary, definition of the crowd amount and walking model can be carried out in the program. Simulation of group walking of the floor systems with special boundary condition could be realized and time-history data of crowd-induced load could be gained through this program. The program interface is shown in Fig.3.

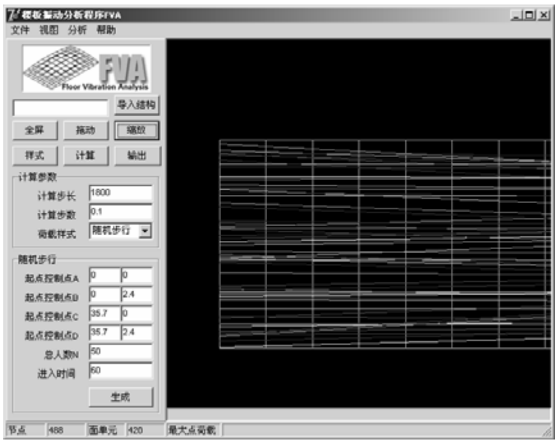


Fig.3 Interface of FVAP

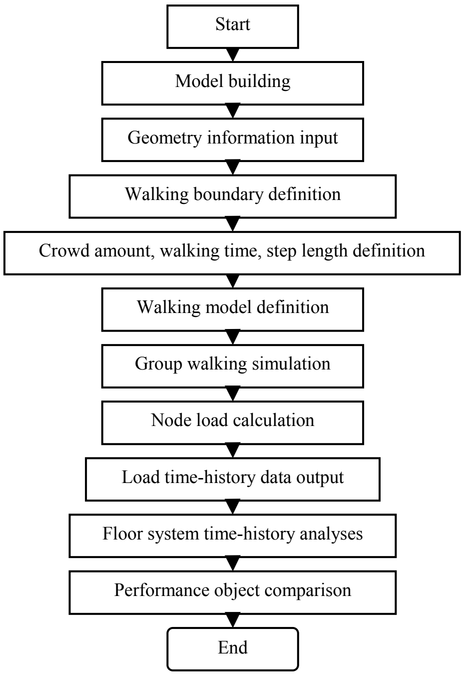


Fig.4 Time-history analyses procedure of floor system

The calculate procedure of time-history analyses for floor system is shown in Fig.4.

Along with mass data quantity generated by this program, in order to apply in practical engineering, an auto-interface for finite element software such as SAP2000, Etabs and Midas is used for data input. Therefore, dynamic time-history analysis of floor system could realized by finite element software.

5. dynamic time-history analysis of floor system and example

In this paper, a structure of pedestrian bridge is taken as an example to introduce the procedure of dynamic time-history analysis of floor vibration.

5.1. finite element model building

A crowd-induced load test of a pedestrian bridge was introduced by Wheeler. The pedestrian bridge is a two-span steel structure with section shown in Fig.5. The two span is 16.32m and 19.83m respectively. The 16mm steel plate is used for the floor. And 460UB section steel is used for main girder whose upper flange is welded with the floor. Under live load 3.5kN/m2, the static deflection is L/503, where L is the length of main span.

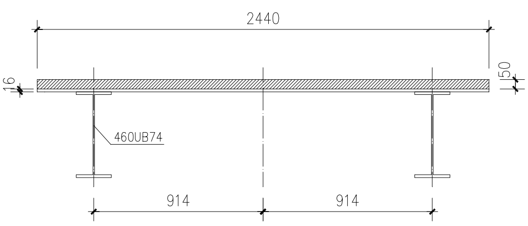


Fig.5 Section

The finite element software of SAP2000 is used for structural analysis in this paper.

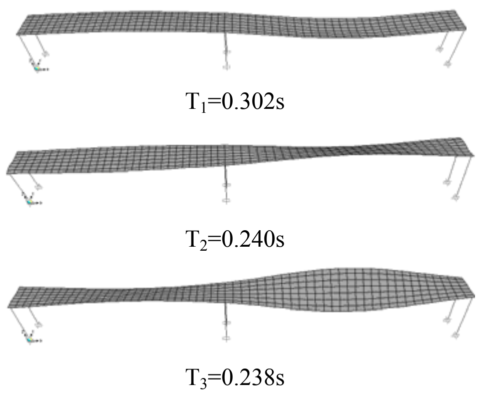


Fig.6 Finite element model and results of modal analysis

The integrated model composed of bar and shell unites is applied to the analysis model as shown in Fig.6. In order to input the node load time-history conveniently, the size of mesh generation would be smaller than the step length (about 750mm). The modes gained from modal analysis are shown in Fig.6. the first frequency tested in the experiment f1,exp and calculated from finite element analysis f1,calu is 3.2Hz and 3.3Hz respectively, which indicate that the dynamic characteristics of the real structure can be basically reflected in the model. The nature frequency of this pedestrian bridge is close to the walking frequency, so the deflection is a little bigger. In order to ensure the degree of comfort acceptability, floor vibration checking is needed.

5.2. Simulation of group walking and generation of load time-history

Floor system information of finite element model is input to FVAP in which walking boundary could be definite. In order to compare finite element analysis to the results of experiment, walking mode is taken as normal walking whose parameters are shown in Table.1. The enter time of group is set to 60s, the statistical time is set to 120s and time step is set to 0.1s. The amount of walking group is taken as 1, 15, 30, 60 respectively for the 4 work conditions. Fig.8 shows the nephogram of floor maximum moment value(M_{max}) when there is a single person walking on the pedestrian bridge.

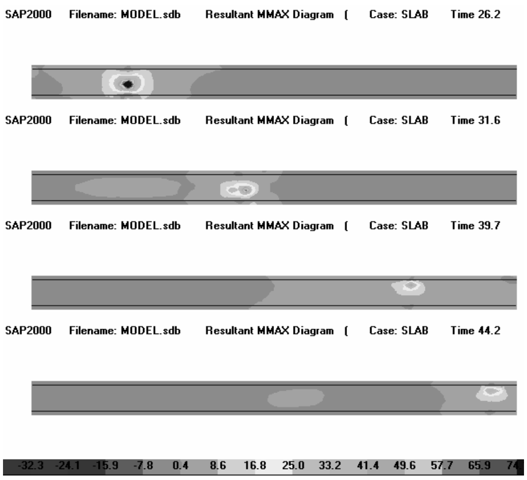


Fig.7 Moment response of floor system (N=1)

The load time-history file generated in FVAP can be input to SAP2000 automatically. The load time-history curve of a certain node gained when the amount of the group is 60 is shown in Fig.9.

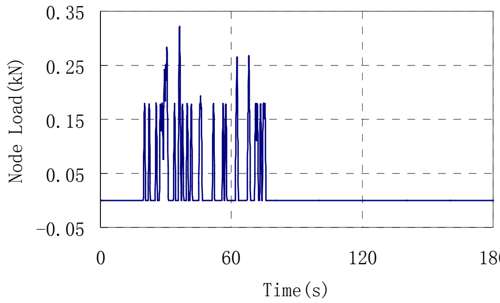


Fig.8 Vertical load time history of Node No.430 (N=60)

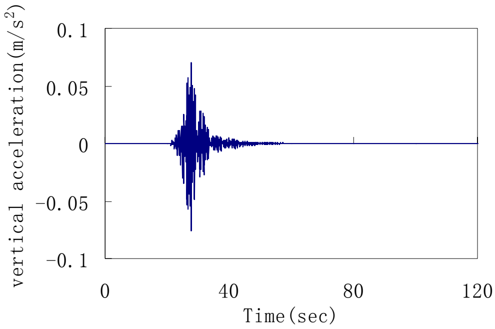
5.3. Time-history analysis of floor vibration

The Newmark direct integration method is adopt for time-history analysis, where the parameters could be α=0.5 and β=0.25. Rayleigh damping is proposed, and the damping ratio of the first and second mode is taken as the value of 0.02. The step length in analysis is 0.1s and the number of step is 1200.

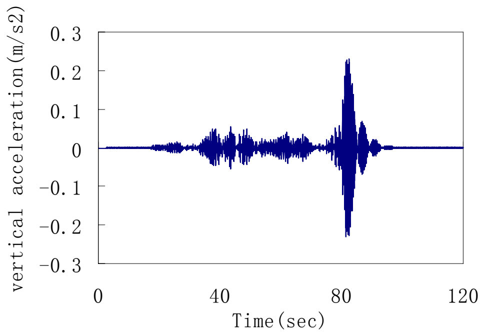
The description of calculation: finite element model with 448 nodes, 10 bar elements, 420 shell elements; computer with Inter(R) Pentium(R)1.50GHz CPU, 760MB memory. Single time-history analysis project costs 82s, so the calculation amount of this floor vibration time-history analysis method is accessible in practical engineering application.

5.4. Comparison of Analysis Structure

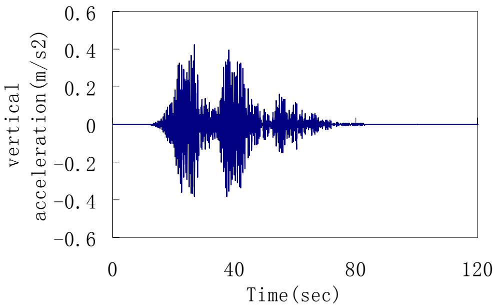
As an example, analyze the floor vibration in four conditions whose number of the crowd is 1,15,30 and 60 respectively. The time-history of vertical acceleration of floor in the four conditions are shown in Fig.9.



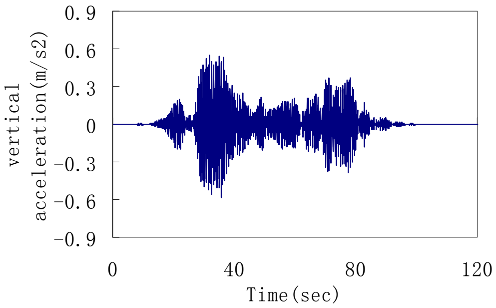
(a) The time-history of vertical acceleration (N=1)



(b) The time-history of vertical acceleration (N=15)



(c) The time-history of vertical acceleration (N=30)



(d) The time-history of vertical acceleration (N=60)

Fig.9 time-history curve of vertical acceleration

Comparing the maximum value of vertical acceleration in four conditions with the test performed by Wheeler, the result shown in Fig.10 indicate that the result of time-history analysis is bigger than the result measured, mainly due to the difference induced by the support of periphery structure, the increase of damping and the influence of high order mode. Thus we can consider that the result of time-history analysis is partially safe.

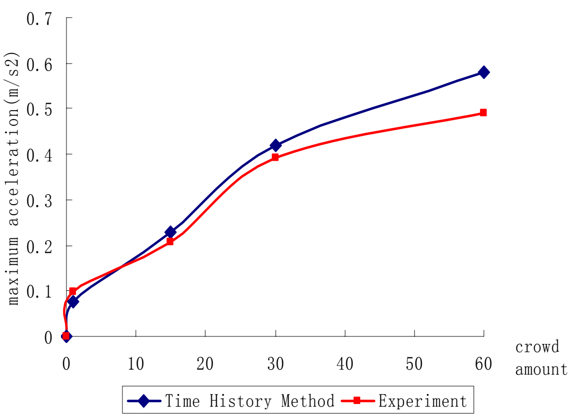


Fig.10 The relationship between maximum acceleration and the crowd amount

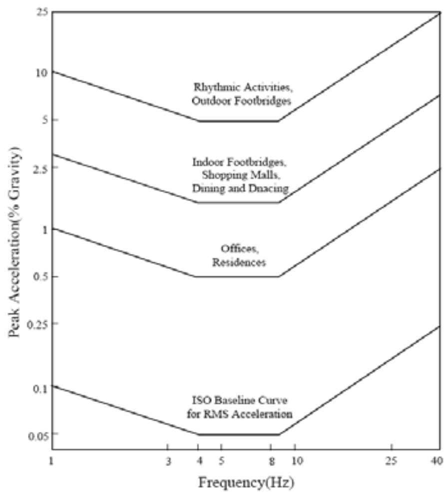


Fig.11 ISO 2631-2:1989 performance evaluation curve

5.5. Evaluation of Floor Vibration

The International Standard Organization (ISO) presented a baseline by measuring the human's apperceiving degree of heel-drop load. That is defining the vibration resistance index of the buildings with different application to heel-drop load by limiting the maximum acceleration. For instance, the coefficient of office and house building, emporium and bridge is 10, 30 and 100 respectively, the specified value of maximum acceleration calculated by using the coefficient above is shown in Fig.11.

From Fig.10, the floor vibration is relevant to the number of the crowd, and the number must be defined before the floor time-history analysis. According to Load Code[10], for pedestrian bridge , the live load is 3.5kN/m^2, frequent coefficient is 0.5, the effective live load is 3.5×0.5=1.75kN/m^2 which is equal to crowd density of 1.75÷0.7=2.333 person/m^2, the area of floor is 87.11m^2, the total number of people is N=87.11×2.333=203. When in normal walking model, the frequency and distance of walking are 2Hz and 0.75m, the whole length of the pedestrian bridge is 35.7m with the time that is about 35.7÷0.75÷2=23.8s to pass it. Thus suppose the number of the crowd N is 210,the time for entering the floor is 25s. Result obtained from time-history analysis by 10 random samples are shown in Fig.12. The average value of floor maximum vertical accelerations is 1.406m/s^2 which is stable according to Fig.12. Compared to the index curve of performance of ISO 2631-2 (Fig.11), for the performance point of acceleration of floor is above the index curve, the acceleration of the pedestrian bridge is unsatisfied and the structure stiffness should be enhanced.

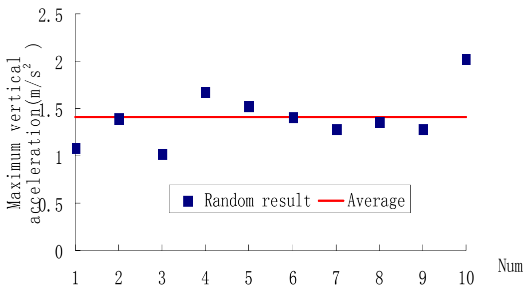


Fig.12 Maximum vertical acceleration under random crowd induced load

6. Conclusion

By limiting the displacement or self-vibration frequency of crowd-induced floor vibrations, the amplitude can be limited while the control effect of the acceleration is not ideal. However, it is acceleration maybe velocity in high frequency region that discomforts the user.

With the development of the computer technology, the transition from simplified calculation to computer analysis for the floor vibration should be realized. This paper simulates group walking by proposing a program and calculates the time-history of group walking load for floor vibration time-history analysis. The input and output of data flow avoid the trouble of data processing so as to facilitate engineering application. This method, a reflection of the dynamic characteristic of floor and time-history property of walking load, can simulate the respond of crowd-induced floor vibration relatively accurately.

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