Field Testing and Investigation of the Dynamic Performance and Comfort of Timber Floors

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Abstract

Field tests were conducted on timber floors in three wood-framed buildings in order to obtain their dynamic characteristics and evaluate the vibration comfort. The measured fundamental vibration frequency, damping ratio and root-mean-square acceleration, were used to evaluate human comfort caused by timber floor vibration. The results show that the fundamental vibration period of the thirteen tested timber floors was between 9.96Hz and 18.70Hz, which is sufficiently outside the frequency range of human activities excitation to preclude the resonance of timber floors. The thirteen timber floors in the test program satisfied the vibration control standards when the vibration environments and duration were taken into consideration. The damping ratios of the timber floors show a strong amplitude dependence, with high damping ratios correlated with large vibration amplitude. The average value of the damping ratio obtained from the impulse load tests was 5.05%, which was suitable for timber floors under normal human activities. In practice, vibration should be considered during the design of large-span timber floors.

Keywords: timber floor; fundamental frequency; damping ratio; comfort; field test

1. Introduction

Floors in buildings are typically designed using strength and deflection criteria under static uniform loads. This approach results in static deflection limitation and span-to-depth ratio limits of a beam or joist under uniform loads. These two methods used in practice are adequate for short-span floors constructed with traditional materials, such as reinforced concrete. On the contrary however, deflection criteria are sometimes insufficient to guarantee the acceptable vibration characteristics of long-span lightweight floors (i.e. timber or steel floors) under normal human activities (walking). The footstep force generated by human activities comprises two components: one is the short duration heel impact force of each footstep; and the other is the continuous series of footsteps generating a wave train of harmonics. Based on the nature of the footstep force, there are two types of vibration in floors subjected to human activities (Ohlsson, 1991), the transient vibration and resonance, depending on the inherent dynamic properties of the floor. If the fundamental natural vibration frequency of a floor is above 8–10Hz, which is far above the footstep frequency and its harmonics, then the vibration induced by footstep forces is dominated by the transient response caused by the individual heel impact force from each footstep. The transient vibration takes place at the natural frequencies of the floor and dissipates quickly. The peak value of a transient vibration of a floor system is governed by its stiffness and mass. Conversely, if the fundamental natural frequency of a floor is below 8Hz, the floor will resonate with one of the harmonics. The magnitude of this resonance is significantly affected by the damping ratio of the floor system. So the most common design approach to prevent disturbing floor vibration is to limit the fundamental natural frequency of the floor. For example the Chinese Technical Specification for the Steel Structure of Tall Buildings (1998) provides an equation to calculate limiting composite beam fundamental natural frequency to avoid resonance.

Light weight and flexibility are two obvious characteristics of timber flooring compared with the traditional reinforced concrete flooring. In North America, wood-framed construction is common for residential housings, making timber floor vibration control an interesting research area. Many approaches to preventing timber floor vibration have been developed by researchers, which has been summarized by Hu and Chui, 2001. There are six approaches, namely, limit on uniform distributed

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live-load deflection, limit on point-load deflection, limit on point-load deflection and peak-velocity due to unit impulse, limit on fundamental frequency and frequency-weighted root-mean-square acceleration, limit on fundamental natural frequency, and limit on a combination of the parameters mentioned above. Unfortunately few, if any, of these approaches have been widely used in practical design.

2. Background

At present, the North American type of wood-framed construction is accepted in a few regions in China. The Xiang E Elementary School (Fig.1. - Fig.4.), Chengdu, Sichuan, China may be the first school in China built after the Wenchuan earthquake (12/05/2008) using wood-frame construction. The Chinese Code for Design of Timber Structures (2003) has no provisions for timber floor vibration design and control. There have been few studies conducted on timber floor vibration (Zhou, 2008a and 2008b) in China. Field tests on thirteen timber floors were conducted to measure their dynamic characteristics, followed by an evaluation of timber floor human comfort levels using applicable criteria developed for other similar structures. The results presented in this paper are directly applicable in design practice.

3. Timber Floor Configuration

The basic structural configuration of a typical wood-joist floor in the Xiang E Elementary School buildings, such as the one shown in Fig.5., comprises a number of wood joists with blocking spaced 406 mm at the center built into the floor plan and supported on fixed perimeter wood beams, called header joist and edge joist which are framed into the building walls. The wood sub-floors (15.5 mm thickness OSB) are connected to the joists using common nails. In addition, the sub-floor has an overlay of a thin layer of normal reinforced concrete topping (40 mm thick). Gypsum boards are connected to the bottom of the joists for fire protection. Fig.6. shows a timber floor under construction. The timber floors, with different weights, dimensions, joist types, thicknesses, spans, and uses, investigated in the field tests are summarized in Table 1.

4. Field Test Description

The field test included three parts. The first is the ambient vibration test that is used to obtain the fundamental period of the timber floor. The second is the vibration test under human activities (Fig.7.). In this part the random excitation is produced by
one, two, three or four people walking a designated route. The purpose of this part was to acquire the peak acceleration value of the floor under normal human activities. The purpose of the last part of the test was to acquire the vibration under an impulsive load. The data obtained in this part can be used to calculate the damping ratio of the timber floor using the half-power bandwidth method. For the test, an acceleration transducer was located in the middle of the floor. Fig.8. shows the location of the acceleration transducer and the walking route. Data collection and analysis was accomplished by the SVAS system (Fig.9.).

5. Test Results
The typical recorded vertical acceleration responses
of the timber floor to ambient vibration, human activities and impulse load are shown in Figs.10. - 12., respectively.

Fig.13. shows the power spectrum of the vertical acceleration response of the timber floor under ambient vibration obtained directly by the SVSA system. The fundamental vibration frequency of the timber floor can be obtained based on Fig.13.

Table 2. lists all the fundamental vibration frequencies of the tested floors. Also listed are the floor damping ratios calculated using the half-power bandwidth method using the impulse load and ambient vibration response data. Table 3. summarizes the peak vertical accelerations of the tested timber floors under human activities.

The test results show that the fundamental frequencies of the thirteen tested timber floors range from 9.96 Hz to 18.70 Hz. This indicates that the vibration of the timber floors is dominated by the transient response caused by the individual heel impact force from each footstep and the peak values of a transient vibration of the floor systems will be governed by the stiffness and mass according to Olhsson's conclusion (Olhsson, 1991). The average damping ratio of the timber floors obtained from the
Table 3. Maximum Vertical Accelerations of Timber Floors Under Human Activities

| Floor No. | Peak acceleration value under human activities in the middle floor span (gal) |
|-----------|--------------------------------------------------------------------------------|
|           | One person | Two persons | Three persons | Four persons | More than four persons |
| No.1      | 4.319      | 3.365      | 4.016        | 3.049        | 3.169                 |
| No.2      | 7.337      | 5.399      | 5.429        | 5.255        | 8.888                 |
| No.3      | 10.58      | 10.94      | 9.922        | 8.151        | 6.854                 |
| No.4      | 11.45      | 13.54      | 18.39        | 14.12        |                       |
| No.5      | 1.386      | 1.434      | 1.360        | 1.181        |                       |
| No.6      | 15.95      | 13.07      | 13.12        | —            | 19.20                 |
| No.7      | 4.502      | 8.012      | 9.264        | 9.729        |                       |
| No.8      | 10.08      | 15.67      | 12.15        | 13.95        | 34.86                 |
| No.9      | 9.249      | 6.284      | 10.29        | 10.23        | 19.06                 |
| No.10     | 3.930      | 6.531      | 6.498        | 5.176        | —                     |
| No.11     | 7.365      | 6.784      | 7.669        | 6.832        | —                     |
| No.12     | 5.963      | 12.58      | 8.831        | 10.08        | 11.10                 |
| No.13     | 7.840      | 7.096      | 12.24        | —            | 11.08                 |

ambient vibration is 0.95%, which is very close to the conservative value of 1% recommended by Ohlsson (Olhsson, 1991). The average value of the damping ratio calculated using the half-power bandwidth method based on vibration data of the timber floor under the impulse load is 5.05%. This shows that a high damping ratio can be obtained from a large-amplitude vibration. The vibration amplitude of the timber floors under impulse load and normal human activities is larger than that of ambient vibration, and therefore, 5.05% is the reasonable maximum damping value for timber floors examined in this test. Many other studies (Erik, 2008, Smith and Chiu, 1988, Onysko, 1985, Hu, 2000) have focused on the damping ratio of the timber floors: the values recommended in these studies range from 2% to 3.6%.

6. Vibration Comfort Evaluation

In this section, a Chinese code (2006) is used to evaluate the vibration comfort of the timber floor based on the vibration accelerations recorded under human activities. The objective of the code is to prevent whole-body vibration in people caused by indoor vibration sources such as human activities, based on consideration for human health and comfort. The vibration acceleration level \(L_a\) (unit: dB) was adopted to evaluate the comfort of the timber floor according to the Chinese code. \(L_a\) is calculated by equation (1):

\[
L_a = 20 \log (a/a_0)
\]

where \(a\) (unit: m/s²) is the frequency-weighted root-mean-square acceleration that can be calculated by the SVSA system directly in different frequency ranges and the duration of each measurement is around 300 seconds; \(a_0\) is the base acceleration equal to 10⁻² m/s². The calculated results of the vibration acceleration level are listed in Table 4.

It can be found that the maximum value of \(L_a\) for each floor occurred near their fundamental frequencies, which means that resonance happened under the combined action of the human activities and the dynamic characteristics of the timber floor. The \(L_a\) values for the No. 1 - No. 6 and No. 10 - No. 11 timber floors satisfy the Level I vibration limit according to the Chinese code. The remaining timber floors do not satisfy either Level I or Level II vibration limits from the center frequency of 6.3 to 16 Hz. Actually, in the test process some of the participants felt that the vibration of the No. 8 and No. 13 timber floors was disturbing for them, while in the other timber floor tests no one felt the disturbing vibration. The span of the timber floors that satisfy the Level I vibration limit is less than 4 m. The timber floors with a large span-width ratio (No. 7 - No. 8) and large span (No. 9/No. 12 - No. 13) are prone to produce disturbing vibration under human activities according to the Chinese code (2006). Random human activities excite higher vibration modes of the timber floors, such that resonance may occur even if the fundamental vibration frequency of a timber floor is far above the value that can avoid resonance. Fortunately, in practice, the duration of the resonance-causing human activities is relatively short (less than 10 - 20 minutes) and damping of the floors increases with increasing vibration amplitudes. This means that the relatively large and durable vibration amplitude is not likely to occur in these timber floors.

Table 4. Vibration Acceleration Level of a Timber Floor (Unit: dB)

| Center frequency of one third sound level | Floor No. | Limit value on level I | Limit value on level II |
|------------------------------------------|-----------|------------------------|------------------------|
| 4 Hz                                     | 1         | 46                     | 70                     |
| 5 Hz                                     | 2         | 53                     | 70                     |
| 6.3 Hz                                   | 3         | 54                     | 70                     |
| 8 Hz                                     | 4         | 53                     | 70                     |
| 10 Hz                                    | 5         | 53                     | 70                     |
| 12.5 Hz                                  | 6         | 53                     | 70                     |
| 16 Hz                                    | 7         | 53                     | 70                     |
| 20 Hz                                    | 8         | 53                     | 70                     |
| 25 Hz                                    | 9         | 53                     | 70                     |

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7. Conclusions

Field tests and vibration comfort evaluations were conducted on thirteen timber floors of three buildings in the Xiang E Elementary School, the first school in China to utilize modern timber construction in a high-seismic zone. The following conclusions are made:

1) The fundamental vibration frequencies of the thirteen timber floors range between 9.96 and 18.70 Hz, which is high enough to prevent larger resonance vibration of the timber floors under human activities.

2) The thirteen timber floors in the test program all satisfy the vibration control standards when the vibration environments and duration are taken into consideration.

3) The damping ratio of the timber floor showed strong amplitude dependence, (a high damping ratio could be obtained that depended on large-amplitude vibration). The value obtained from the impulse load was 5.05%.

4) In practice, vibration control design should be taken into consideration for timber floors with large span-width ratio and large span.

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