Floor impact sound insulation of timber three-story school building for final full-scale fire test

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ABSTRACT

There is a tendency that school buildings are constructed with timber construction, because the timber school buildings effectively improve the educational environment. However, the floor impact sound insulation of timber buildings often presents a problem. This paper reports the floor impact sound insulation of the timber three-story school building for final full-scale fire test. The results showed that the heavy-weight floor impact sound insulation using a car-tire source was L_r-65 or 66.2 dBA and the light-weight floor impact sound insulation was L_r-75 or 77.4 dBA. This three-story timber school building was of one-hour quasi-fire-resistive construction with "a reduced section design". Therefore, the building had large-sized girders and beams. Furthermore, the classrooms were arranged in "an open-plan type" with a large volume of sound-receiving room. From the results of the floor impact sound insulation, the effects of reduced section design and open-plan type are considered.

Keywords: Floor impact sound insulation, Timber school building, Reduced section design
I-INCE Classification of Subjects Number(s): 51.1.4, 51.5

1. INTRODUCTION

Efforts toward the construction of timber public buildings have been made since the enforcement of the Act for Promotion of Use of Wood in Public Buildings (Law No. 36 of 2010 of Japan). There is a tendency that schools as public buildings are constructed with timber construction, because timber school buildings effectively improve the educational environment, including stress reduction. However, a three-story school building needs to be of fireproof construction to satisfy the Building Standard Law of Japan. In this connection, the timber three-story school buildings with one-hour quasi-fire-resistive construction were constructed as specimen, and full-scale fire tests were conducted three times (i.e., preliminary test, preparatory test and final test) in order to review the technical criteria regarding quasi-fire-resistive performance.

The floor impact sound insulation of the test specimen used for the preliminary fire test conducted in February 2012 has been already reported in reference (1). This paper reports the measurement results of the floor impact sound insulation of the timber three-story school building as a test specimen, where the final full-scale fire test was conducted in October 2013. These three-story timber school buildings for preliminary and final fire test, which were of one-hour quasi-fire-resistive construction with a reduced section design, had large-sized girders and beams. However, the specification such as floor topping, base floor material, ceiling and area of sound-receiving room were different. In reference (1), the three-story school building for preliminary fire test had two constructions, wood-frame construction and framework construction, and the increase of the floor impact sound insulation was investigated for six floor specifications. In this paper, the floor cross-section of the three-story school building for final fire test was designed with specifications with no special consideration of the floor impact sound insulation. Thus, the floor impact sound insulations were

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measured mainly for the purpose of collecting data on medium-rise timber buildings. Moreover, the effects of reduced section design on the floor impact sound insulation was considered.

2. BUILDING OVERVIEW

Figure 1 shows a plan view of the timber three-story school building specimen for the final fire test. Each floor had an area of 16 m x 12 m (excluding the staircase) with two classrooms (8 m × 8 m in area) of open-plan type connected through open space. A single classroom area was chosen for the measurement of the floor impact sound insulation of the timber three-story school building.

Figure 2 shows the cross-sectional view of the separation floor of the classroom. The school building was of one-hour quasi-fire-resistive construction with a reduced section design. According to the Building Standard Law of Japan, the structural strength of a building provided with a reduced section design is to be obtained from an allowable stress calculation of the effective cross-section excluding the reduced sections in order to confirm that the burning of the surface portion will have an adverse effect on the structural strength. Therefore, the columns, girders and beams need to be thicker than usual. The columns, girders and beams were of structure with a 45-mm-wide reduced section each added to the four sides of them. Each KOU-OTSU beam (smaller beam) used in conjunction with a larger one is placed at 1,000-mm intervals between beams, and the base floor materials were made of structural plywood (t=28 mm) and plywood (t=12 mm). The independent ceiling, the ceiling of which boards were attached to beams, consisted of double layer fire-resistant gypsum boards (t=12.5 mm each) for the base and was covered with a gypsum board (t=9.5 mm) for a finish.

Table 1 shows the comparison of floor specification between preliminary and final fire test. These final fire test specimens were almost the same in girder and beam specification. However, there were other specification differences. For example, the base floor material of the test specimen used for the final fire test was not made of autoclaved lightweight concrete panel (ALC panel), the ceiling that did not expose any beams consists of triple layer ceiling boards, and the classrooms were in open-plan style with a large volume of sound-receiving room.

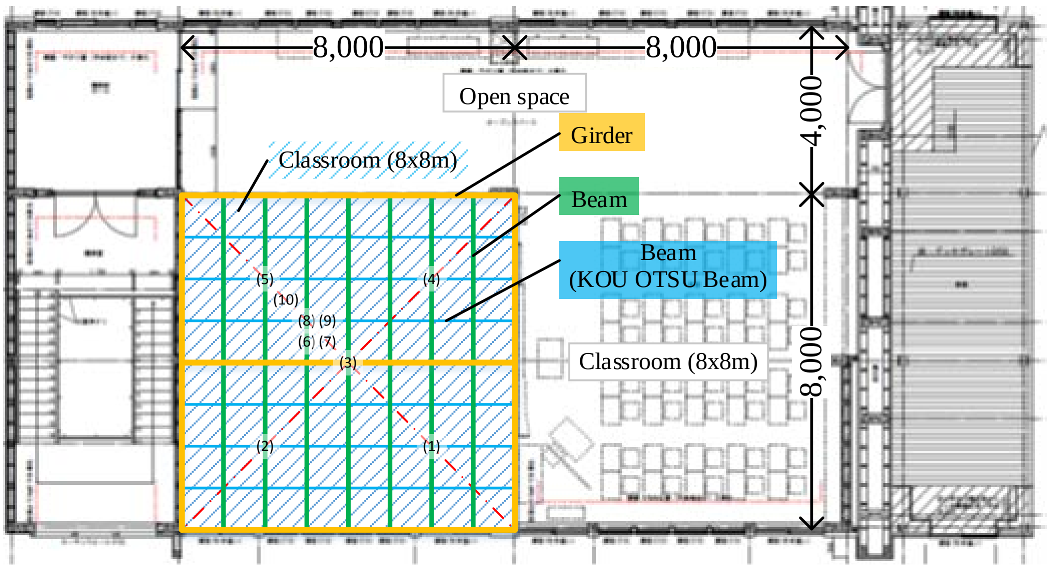

Figure 1 – Plan view of the timber three-story school building specimen

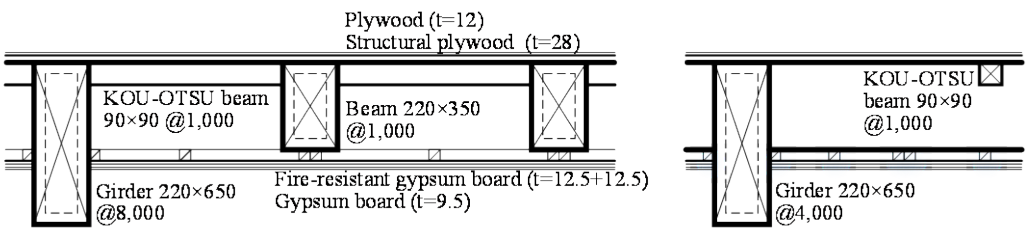

Figure 2 – Cross-sectional view of the separation floor of the class room

Table 1 – Comparison of floor specification between preliminary and final fire test

	Framework construction of preliminary fire test in reference (1)			Final fire test
Floor topping	Floating floor	Floating floor	None	None
Base floor material	Autoclaved lightweight concrete, t=75 mm Structural plywood, t=28 mm			Plywood, t=75 mm Structural plywood, t=28 mm
Girder	**Larch, Structural laminated wood, 220 x 650 mm, @4,000, @8,000**			
Beam	**Japanese Cedar, Structural laminated wood, 220 x 350 mm, @1,000**			
Ceiling	Triple layer ceiling board provided between beams; Gypsum board, t=12.5 mm, Rock wool decorative acoustic board, t=9 mm	None	None	Double layer ceiling board; Fire-resistant gypsum board, t=12.5 mm, Fire-resistant gypsum board, t=12.5 mm, Gypsum board, t=12.5 mm
Sound source room	8 x 16 m, 128 m^2			8 x 8 m, 64 m^2
Sound receiving room	8 x 16 m, 128 m^2			16 x 12 m, 192 m^2

3. MEASUREMENTS

3.1 Measurement Overview

The floor impact sound insulations were measured in conformity with JIS A 1418-2 and JIS A 1418-1 by references (2, 3). The impact sources for measurement of the heavy-weight floor impact sound insulation were a car-tire source and a rubber ball source, and of the light-weight floor impact sound insulation was a tapping machine.

For the measurement of the floor impact sound insulation, the excitation positions were five positions and the sound-receiving positions were five positions, i.e., (1) through (5) in Figure 1. In addition, another set of five excitation positions, i.e., (6) through (10) in Figure 1, was selected with consideration of the locations of the girders, beams and KOU-OTSU beams.

The floor impact sound insulations were evaluated with JIS A 1419-2 by reference (4).

3.2 Floor Impact Sound Insulation

Figure 3 shows the measurement results of the floor impact sound insulation at five excitation positions, i.e., (1) through (5) in Figure 1. The composited calculation results of A-weighted floor impact sound pressure levels are shown as well; with the heavy-weight floor impact sound insulation of 31.5 to 500 Hz octave band and the light-weight floor impact sound insulation of 125 to 2000 Hz octave band.

The heavy-weight floor impact sound insulation using the car-tire source was L_r-65 or 66.2 dBA and the light-weight floor impact sound insulation was L_r-75 or 74.4 dBA.

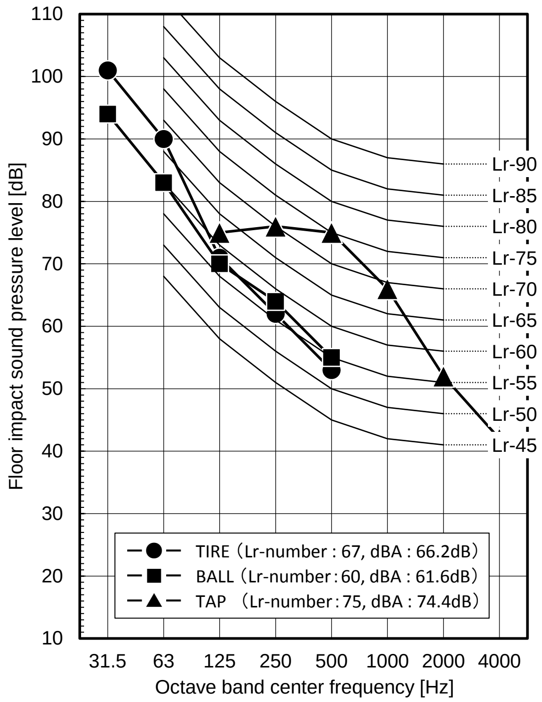

Figure 3 – Measurement results of the floor impact sound insulation of the timber three-story school building for final full-scale fire test

The floor impact sound insulation obtained was evaluated in accordance with the applicable grading specified of the Architectural Institute of Japan in reference (5). Table 2 shows the applicable grades of the floor impact sound insulation for classroom specified by the Architectural Institute of Japan. Only the car-tire source is used to evaluate the heavy-weight floor impact sound insulation. As the results of Figure 3, the heavy-weight floor impact sound insulation was evaluated as Third grade and the light-weight floor impact sound insulation was outside the grade range of applicable grade by Architectural of Japan. In view of use of the general classrooms, countermeasures are considered necessary against the light-weight floor impact insulation such as the dragging of chairs etc.

Table 2 – Applicable grades of floor impact sound insulation of classroom by Architectural Institute of Japan in reference (5)

Impact source	Grade			
	Special grade	First grade	Second grade	Third grade
Car-tire source Tapping machine	*L*-50	*L*-55	*L*-60	*L*-65

3.3 Floor Impact Sound Insulation Changes Caused by Differences in Excitation Positions

Figure 4 shows the floor impact sound pressure level classified by excitation positions. The heavy-weight floor impact sound pressure level at excitation positions (7) and (10) between beams and between KOU-OTSU beams were almost same at any other excitation positions at the 63 Hz octave band, but have peaks in 125 Hz and 500 Hz octave bands. Therefore, the frequency characteristics of the heavy-weight floor impact sound insulation at excitation positions (7) and (10) were different from those of the other excitation positions.

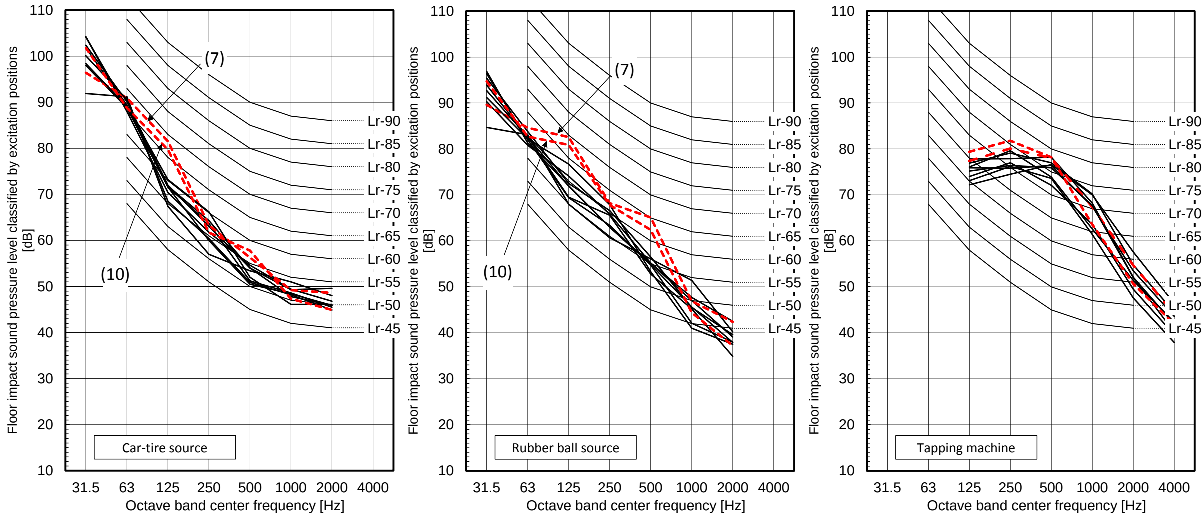

Figure 4 – Measurement results of the floor impact sound pressure level classified by excitation positions

Figure 5 shows the A-weighted floor impact sound pressure level classified by excitation positions changes caused by the differences in excitation positions (1) through (10). The A-weighted floor impact sound pressure levels show that there was a difference of approximately 4 dB between excitation positions in the case of the car-tire source, and approximately 3 dB in the case of the tapping machine between excitation positions. However, the A-weighted floor impact sound pressure levels using the rubber ball source were in a fluctuation range of approximately 9 dB. Furthermore, the A-weighted floor impact sound pressure levels at excitation positions (7) and (10) showed the high values. It is thought that the impedance level of excitation positions (7) and (10) had lower than other excitation positions, because the floor rigidity of excitation positions (7) or (10) were lower than that of other excitation positions. From the viewpoint of the measurement method, it is considered necessary to take excitation positions into consideration of measuring the floor impact sound insulation to be imposed on timber buildings.

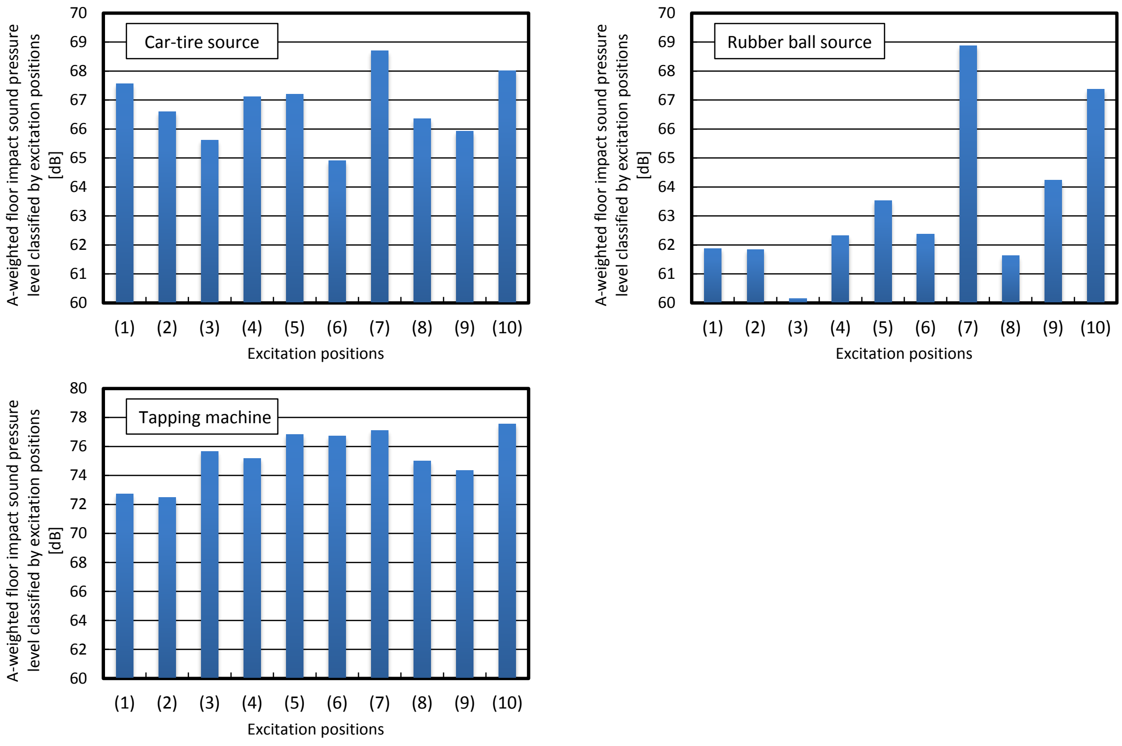

Figure 5 – A-weighted floor impact sound pressure level classified by the difference excitation positions

4. DISCUSSIONS

4.1 Effect of Reduced Section Design

The girders and beams of the timber three-story school buildings for the full-scale preliminary and final fire tests were of structure with a 45-mm-wide reduced section each added to the four sides of them. It is considered that this design increased the weight and rigidity of the floor cross-sectional structure and improved the floor impact sound insulation. In order to confirm the effect of the reduced section design on the floor impact sound insulation, the driving-point impedance of the floor cross-section with reduced sections and that without reduced sections were calculated and compared.

Figure 6 shows the cross-sectional views for consideration of influence of reduced section design. (a) on the left in Figure 6 shows the separation floor with reduced section design, (b) on the right in Figure 6 shows the separation floor without reduced section design. If the charring rate was assumed to 0.75 mm/s, the beam burns by 45 mm an hour. When a building becomes the fire at the worst, the section of beams (b) decreases from (a). However, the building is not destroyed structurally by reduced section design.

As the impedance method that is estimated the floor impact sound insulation, the floor impact sound insulation changes by the driving-point impedance of slab by reference (5, 6 and 7). Each basic driving-point impedance value was calculated from Equation (1) and basic driving-point impedance level was calculated from Equation (2). Equation (1) is defined in the driving-point impedance in reference (5, 6 and 8). In this paper, the equations were extended to a timber floor, and the floor impact sound insulation difference was examined from the driving-point impedance level difference.

A value of wood's density of 600 kg/m^3, Young's modulus of plywood of 6.0×10^9 N/m^2 and Young's modulus of beam of 1.0×10^{10} N/m^2 were substituted and the respective driving-point impedance levels with and without the reduced section design were calculated. The calculated results showed a driving-point impedance level of 105.5 dB with the reduced section design and a driving-point impedance level of 97.3 dB without the reduced section design, and an effect of approximately 8 dB was confirmed by the reduced section design.

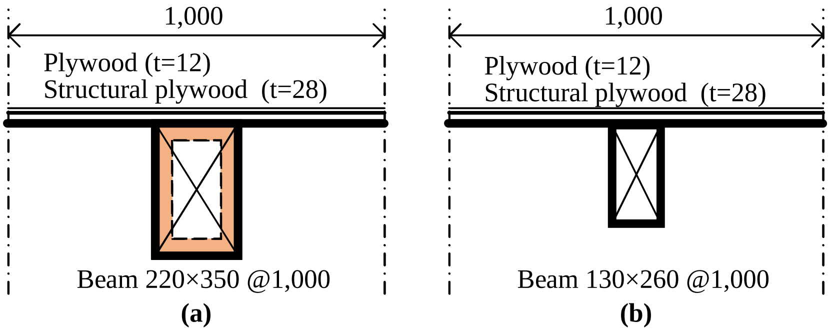

Figure 6 – Cross-sectional view for consideration of influence of reduced section design (left: Reduced section design, right: without Reduced section design)

$$Z_b = 8\sqrt{Bm} = 8\sqrt{\sum(EI)\cdot m} \quad (1)$$

$$L_{Z_b} = 10\cdot \lg\left(Z_b^2 / Z_0^2\right) \quad (2)$$

where
- Z_b is the basic impedance of the floor slab;
- B is the bending rigidity of the floor slab;
- m is the surface density;
- E is the Young's modulus;
- I is the second area moment;
- L_{Zb} is the basic impedance level;
- Z_o is the reference impedance (=1 kg/s).

4.2 Effect of Volume of Sound-Receiving Room

With regard to the measurement of heavy-weight floor impact sound insulation, Schoenwald et al. reported that a change in the volume of sound-receiving room involves a level change in the heavy-weight floor impact sound insulation by reference (8). According to the plan view of the timber three-story school building in Figure 1, each floor had two classrooms of open-plan type connected through open space, which resulted in a large volume of sound-receiving room. Therefore, the heavy-weight floor impact sound insulation in the case of the classrooms separated by 8 × 8 m was calculated from equation (3, 4) as already specified.

The calculated results shows that the classrooms of open-plan type made improvements in the heavy-weight floor impact sound insulation by approximately 5 dB because of an increase in the volume of sound-receiving room. The classrooms of open-plan type, however, have negative aspects, such as a decrease in the airborne sound insulation between classrooms and a longer reverberation time.

$$L_{S_2} = L_{S_1} + 10 \cdot \lg(V_1/V_2) \tag{3}$$

$$L_{S_2} - L_{S_1} = 10 \cdot \lg(V_1/V_2) \tag{4}$$

where L_{S1}, L_{S1} are the heavy-weight floor impact sound pressure level;
V_1, V_2 are the volume of the sound-receiving room.

4.3 Consideration of Improvements in Floor Impact Sound Insulation

The floor cross-sectional specifications shown in Figure 2 may be considered to have a problem in floor impact sound insulation. Therefore, the floor impact sound pressure levels were calculated as a method for floor impact sound insulation improvements in the case of using a floating floor (a dry double floor). The floating floor was assumed the same as that adopted for the preliminary full-scale fire test in reference (1). Figure 7 shows a cross-sectional view of the floating floor and Figure 8 shows the measurement results of reduction of transmitted floor impact sound level of the floating floor.

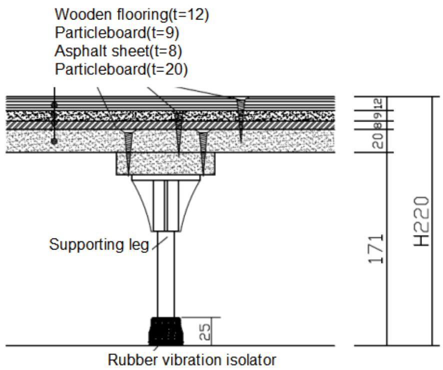

Figure 7 – Cross-sectional view of floating floor for consideration of improvement in floor impact sound insulation

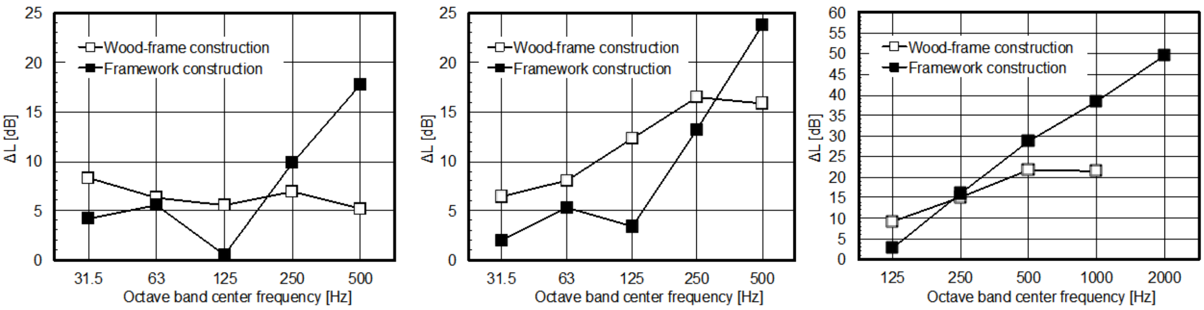

Figure 8 – Measurement results of reduction of transmitted floor impact sound level of the floating floor in reference (1) (left: Car-tire source, center: Rubber ball source, right: Tapping machine)

Figure 9 shows the estimated results of the calculated floor impact sound pressure level with the reduction of transmitted floor impact sound level of the framework construction in Figure 8. From these results, it has been assumed that the installation of the floating floor would improve the heavy-weight floor impact sound insulation using the car-tire source to L_r-60 or 61.8 dBA and the light-weight floor impact sound insulation of L_r-60 or 57.6 dBA.

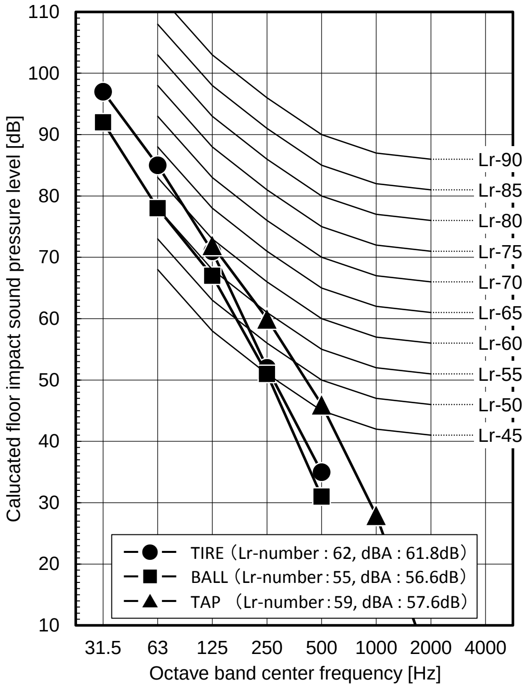

Figure 9 – Estimated results of the calculated floor impact sound insulation

5. CONCLUSIONS

This paper has reported the measurement results of the floor impact sound insulation of the timber three-story school building for the final full-scale fire test. As the results, the following findings have been obtained.

- This school building is provided with cross-sectional specifications with no countermeasures, in particular, against floor impact sound insulation. The heavy-weight floor impact sound insulation using the car-tire source was L_r-65 or 66.2 dBA and the light-weight floor impact sound insulation was L_r-75 or 74.4 dBA.
- In the case of the rubber ball source, the experiment showed greater level differences of the A-weighted floor impact sound pressure level due to the differences in excitation positions. Therefore, from the viewpoint of the measurement method, the excitation positions of floor impact sound insulation imposed on the timber building need to be taken into consideration.
- The estimated floor impact sound insulation showed an improvement of approximately 8 dB because of a beam size increase resulting from the 45-mm-wide by reduced section deign.
- An increase in the volume of sound-receiving room resulting from the classrooms of open-plan type showed an improvement of approximately 5 dB in the heavy-weight floor impact sound insulation.
- The floating floor showed possible improvements in the heavy-weight floor impact sound insulation and the light-weight floor impact sound insulation.

ACKNOWLEDGEMENTS

This research was conducted as a part of the joint research of the Building Research Institute (BRI) and the National Institute for Land and Infrastructure Management (NILIM) under the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) conducted for the advanced promotion project of MLIT for timber building standards (represented by Yuji Hasemi as Principal Researcher).

A part of this research was supported by JSPS KAKENHI Grant Number 26420594.

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