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Experimental Study on Use of Sound Absorption Treatment for Reduction of Environmental Sound Propagation and Reverberation in Staircases: A Case Study in Housing

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Academic Editor: Ambrose Dodoo

Received: 15 December 2016; Accepted: 14 February 2017; Published: 18 February 2017

Abstract: In recent years, many open-plan houses have been proposed not only for comfort reasons, but also as a place to engage in family life. However, in contrast to the fact that this kind of plan makes it easy for people to interact, the daily life household sounds that occur inside the home may be perceived as noise. It is especially difficult to suppress the propagation of sound and reverberation in staircase and stairwell areas due to the absence of sound-absorbing furniture. In this study, we focused on addressing sound management within the staircase area in open-plan housing where sound absorption is particularly difficult. In order to suppress sound propagation on the upper and lower floors and the reverberation of sound, we placed a thin sound absorption panel on the wall, ceiling, and riser of the staircase. As a result, we were able to confirm that the propagation of sound on upper and lower floors can be suppressed by carrying out the sound absorption treatment on the staircase. Furthermore, we found that in stairway landing areas, the suppression effect of the propagation of sound varies depending on the position of the sound source and the positioning of the sound absorption panel, and that there is a position for placing the sound absorption panel where the sound-absorbing effect is effective.

Keywords: sound absorption treatment; stairwell; sound pressure level; average sound absorption coefficient; open-plan

1. Introduction

In recent years, housing plans aimed at restoring connections between families, which have become distant due to the formation of nuclear families, have been proposed. What is sought is something that not only provides comfort but also functions as a place to engage in family life. However, in contrast to the fact that this kind of plan makes it easy to connect people, the daily life household sounds that occur inside the house may be perceived as noise. Even though these sounds are generated by the families with whom one lives, these become the factors that lower the degree of mutual satisfaction of living together. In particular, when three generations live together, the lifestyle differs for each generation, so even if there are the sounds caused by relatives, they are treated as noise.

These situations can be handled by taking measures to increase the sound insulation efficiency of openings such as doors inside the room and partition walls. However, in open-plan houses, the propagation path of sound is diverse. Furthermore, since large spaces are used as living rooms, the condition is such that among the various daily life household sounds, sounds from the television and of children playing reverberate easily and propagate easily to other rooms. In normal living rooms, it is thought that the sound is absorbed due to the arrangement of the furniture, carpet, and curtains, and hence the feeling of excessive reverberation and sound propagation are suppressed. However, in spaces such as staircases and stairwells that connect the upper and lower floors, it is difficult to place materials with such a sound-absorbing effect. In particular, the staircase does not have as much of a spatial margin as the living room and almost matches the line of movement of a person; therefore, the available space for placing sound absorption material is very limited.

In educational institutions such as schools—from an educational perspective—it is necessary to have moderate silence and voice communication without any hindrance. Therefore, in each country, standards and regulations for indoor noise and the soundproofing efficiency between rooms, and inside or outside of rooms [1–7], have been established, and these educational facilities, such as schools, are actively being studied. Tang et al. measured the reverberation times and noise levels in the classrooms of primary and middle schools of Hong Kong, and derived the relationship between the reverberation times and speech transmission indices for speech transmission design [8,9]. Zannin et al. measured the reverberation times and indoor-outdoor sound insulation efficiency in the public school facilities of Brazil and studied the actual conditions of the acoustic environment quality [10]. Chiang et al. conducted noise measurements and a questionnaire survey in open-plan primary schools of Taiwan and they also studied the action conditions of the acoustic environment quality [11]. Both cases have reported that the target acoustic environment for study is inadequate. Ruggiero et al. determined the distribution of the sound pressure level in school music rooms from a simulation that used general-purpose software, and studied the installation position of the sound absorption panel and verified the effect on the reverberation time [12]. Nocera et al. investigated the acoustic environment quality of a lecture venue where a tensile membrane structure was used and proposed an improvement method by simulation [13]. Shih et al. obtained room acoustic characteristics of various design conditions by simulation using general purpose software for a container house with a low acoustic environment quality [14]. However, these studies did not mention the residential space. Additionally, there are few reports on the acoustic environment for residential spaces and useful methods to improve it.

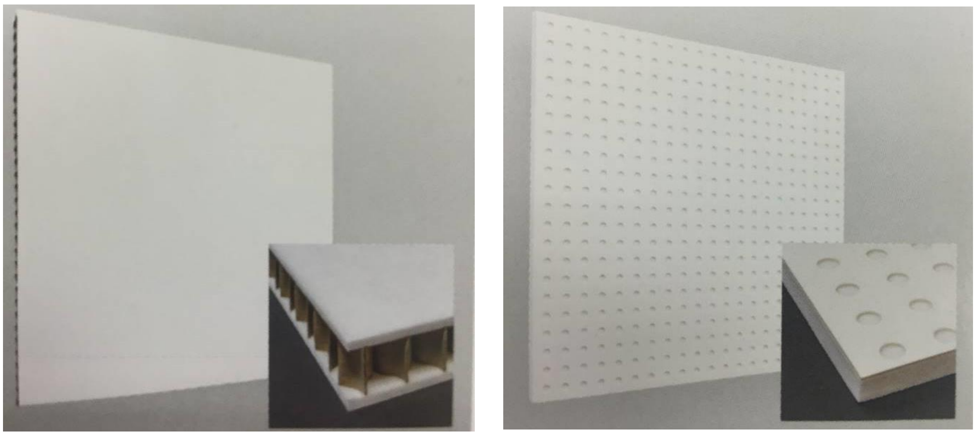
Studies on residential buildings have been reported by Díaz et al. They measured the reverberation times of 11,687 rooms targeting closed-space bedrooms, and living rooms [15]. Watanabe et al. and Hanyu et al. conducted auditory experiments on living room spaces and studied the impact of change in the average sound absorption coefficient on things such as "sense of luxury" and "preferences" [16,17]. However, in all the studies, the reports are targeted on the living room space and there are very few reports on spaces such as staircase and stairwells.

Therefore, in this study, we focused on addressing the staircase area in open-plan housing, where sound absorption is particularly difficult. We placed a thin sound absorption panel on the wall, ceiling, and riser of the staircase in an attempt to suppress the propagation of sound on the upper and lower floors and the reverberation. In the actual measurements, we used pink noise as the sound source and measured the sound pressure level, the A-weighted sound pressure level and the reverberation times of the upper and lower floors and the staircase landing for various placement conditions and evaluated the transmission loss. As a result, we were able to confirm that the propagation of sound on the upper and lower floors can be suppressed by carrying out the sound absorption treatment in the staircase. Furthermore, we found that in the stairway landing areas, the transmission loss of propagated sound differs depending on the sound source position and the position of the sound absorption panel, and there is a position for placing the sound absorption panel where the sound-absorbing effect is effective.

2. Experimental Method

2.1. Characteristics of the Sound Absorption Panel

The sound absorption panel used in the experiment was made of two types of polyester nonwoven fabrics, Type A and Type B, which are shown in Figure 1. The sound absorption coefficient was measured by JIS A 1409 [18] and has the characteristics shown in Figure 2. However, this sound absorption coefficient is measured with a 1.08 m square of test specimen. Therefore, the sound absorption coefficients are above 1.0 by area effect. Both types have peaks in the 1600 Hz band. Type A is a paper with a honeycomb structure that is sandwiched between polyester nonwoven fabrics on both sides and Type B is a paper with perforated cardboard on the surfaces. The sizes of the sound absorption panels used in the experiment are shown in Table 1.



(a) (b)

Figure 1. Sound absorption panels used in the experiment; (**a**) Type A paper with honeycomb structure; (**b**) Type B paper with perforated cardboard on the surfaces.

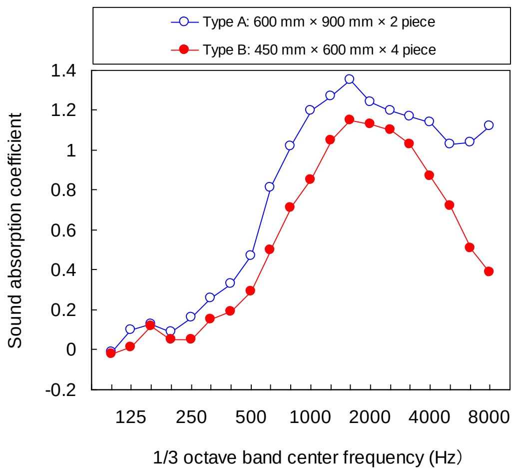


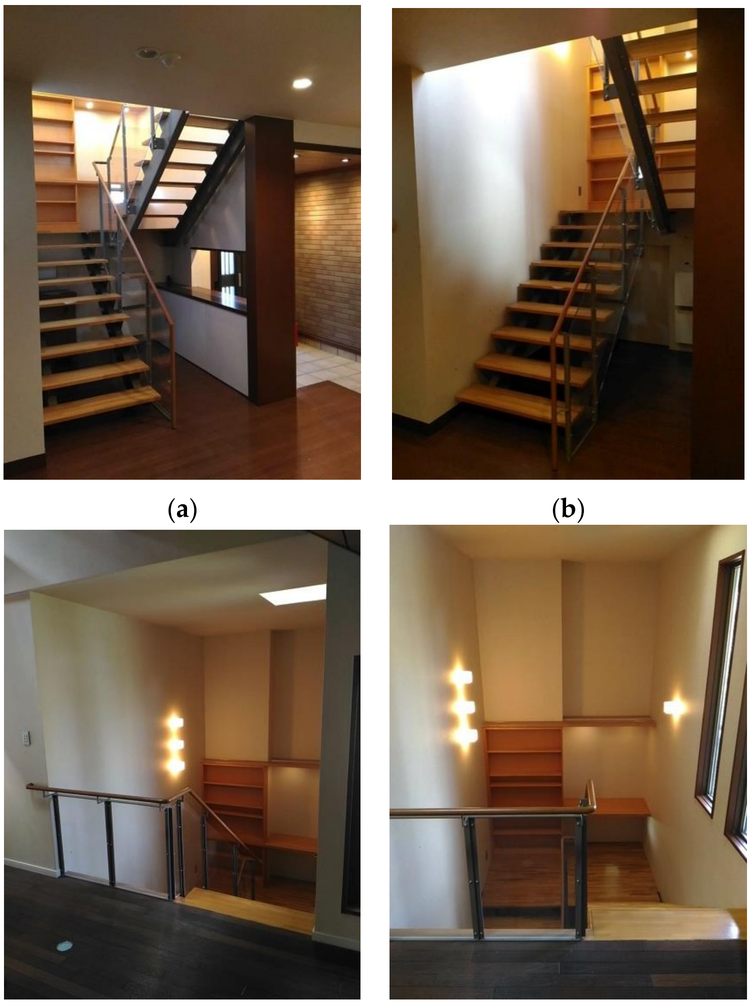
Figure 2. Sound absorption coefficient measurement results by JIS A 1409.

Table 1. Type and size of the sound absorption panels used in the experiment.

Type	Size (mm)
A	W: 700 × H: 900 × T: 29
B	W: 1000 × H: 175 × T: 10

2.2. Overview of Stairwell and Experiment

As shown in Figure 3, the experimental environment was an open type staircase where the riser is not covered. Figure 4 shows the drawing of the staircase. Measurement points were set at three places namely the first floor, the stair landing area, and the second floor, and the height of the microphone at each point was set to be 1200 mm above the floor. Because the ceiling height of the house verified in this study is 2400 mm, therefore, the microphone was set on the half of 2400 mm (1200 mm in height). The sound source was positioned at two places namely the first floor and the second floor. In this study, a directional loud speaker (Bose made: 802) and pink noise were used because it is assumed that the human voice and generated sound by TV are directional as same as directional loud speaker. The ceiling height is 2600 mm for the first floor, 2400 mm for the second floor, and 3800 mm from the stairway landing to the ceiling on the second floor. The sound volume played was such that the sound pressure level was about 90 dB at the measurement point on the sound source side.



(**a**) (**b**) (**c**) (**d**)

Figure 3. Stairwell used in the experiment. (**a**) As seen from the first floor, side 1; (**b**) As seen from the first floor, side 2; (**c**) As seen from the second floor, side 1; (**d**) As seen from the second floor, side 2.

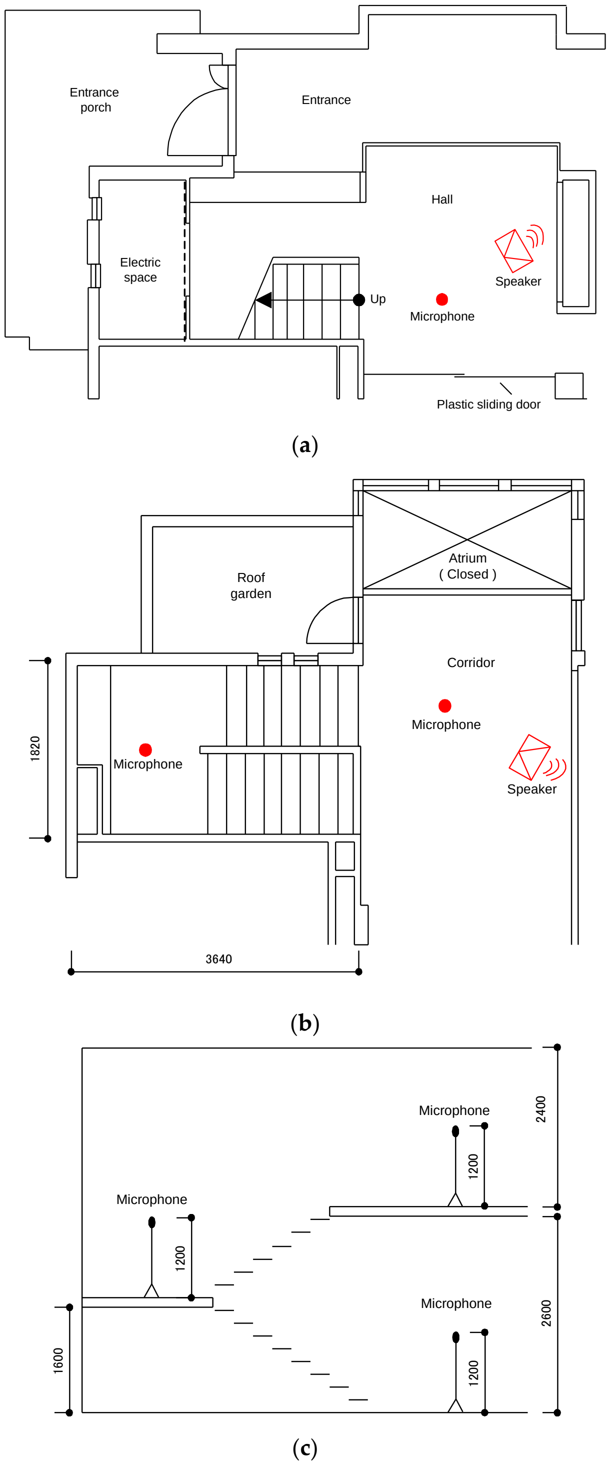


Figure 4. Plan of the stairwell used in the experiment. (**a**) First floor plan, sound source position and measurement position; (**b**) Second floor plan, sound source position and measurement position. (**c**) Sectional view of stairwell and microphone height.

As shown in Table 2, the experiment was carried out through ten experimental configurations with different sound source positions, sound absorption panel types, sound absorption panel positions, and number of panels. Type A is installed on the walls and ceiling, while Type B is installed on the riser. The sound pressure level and reverberation times were measured in the configurations shown in Table 3. Measurement of sound pressure level was carried out through ten configurations of different sound source position, sound absorption panel type, sound panel installation position, and the number of panels installed. The measurement of the reverberation times was carried out for each sound source position before and after placement of the sound absorption panel(s) on the wall of the stairway landing in four configurations. Figure 5 shows a condition where the sound absorption panel is placed in the riser. Figure 6 shows the condition where the sound absorption panel is placed on the wall of the landing area, and Figure 7 shows the condition where the sound absorption panel is placed on the second floor walls and ceiling. Before placing the sound absorption panel, the walls and the ceiling had wallpaper stuck on gypsum boards.

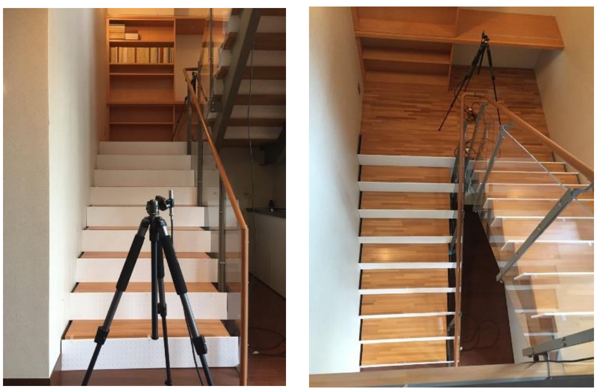
Table 2. Sound source position, sound absorption panel type, installation position, number of panels and panel area.

Specimen No.	Sound Source Position	Sound Absorption Panel Installation Position and Number of Panels				Panel Area (m^2)
		Riser	Wall of the Landing	Wall of the Second Floor	Ceiling of the Second Floor	
1	First floor	-	-	-	-	-
2		Type B × 18	-	-	-	3.15
3		-	Type A × 10	-	-	6.30
4		Type B × 18	Type A × 10	-	-	9.45
5		Type B × 18	Type A × 12	Type A × 6	Type A × 2	15.75
6	Second floor	-	-	-	-	-
7		Type B × 18	-	-	-	3.15
8		-	Type A × 10	-	-	6.30
9		Type B × 18	Type A × 12	-	-	9.45
10		Type B × 18	Type A × 12	Type A × 6	Type A × 2	15.75

Table 3. Measurement pattern of sound pressure level and reverberation time.

Specimen No.	Sound Pressure Level	Reverberation Time
1	○	○
2	○	-
3	○	○
4	○	-
5	○	-
6	○	○
7	○	-
8	○	○
9	○	-
10	○	-

Note: ○: Carried out; -: Not carried out.



(a) (b)

Figure 5. Sound absorption panel installation status in the riser. (**a**) Setup as seen from the first floor. (**b**) Setup as seen from the second floor.

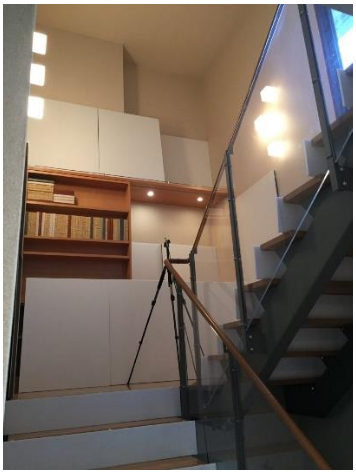


Figure 6. Sound absorption panel installation setup in the wall of landing.

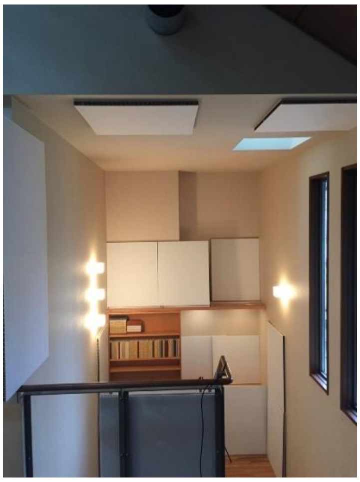


Figure 7. Sound absorption panel installation setup in the wall and ceiling of second floor.

3. Reduction Effect of Sound Pressure Level

Figure 8 shows the difference in sound pressure levels due to variations in the sound source position, installation area, and installation position, given in Table 2, which uses "no sound-absorbing panel being installed" as the standard reference. Figure 8a,c,e on the left show the case where the sound source is on the first floor, while Figure 8b,d,f on the right show the case where the sound source is on the second floor. In addition, Figure 8a,b show the case where the sound source position and the measurement points are the same, while Figure 8c,d show the case where the measurement point is the landing area, and Figure 8e,f show the case where the sound source position and the measurement points are different on the upper and lower floors.

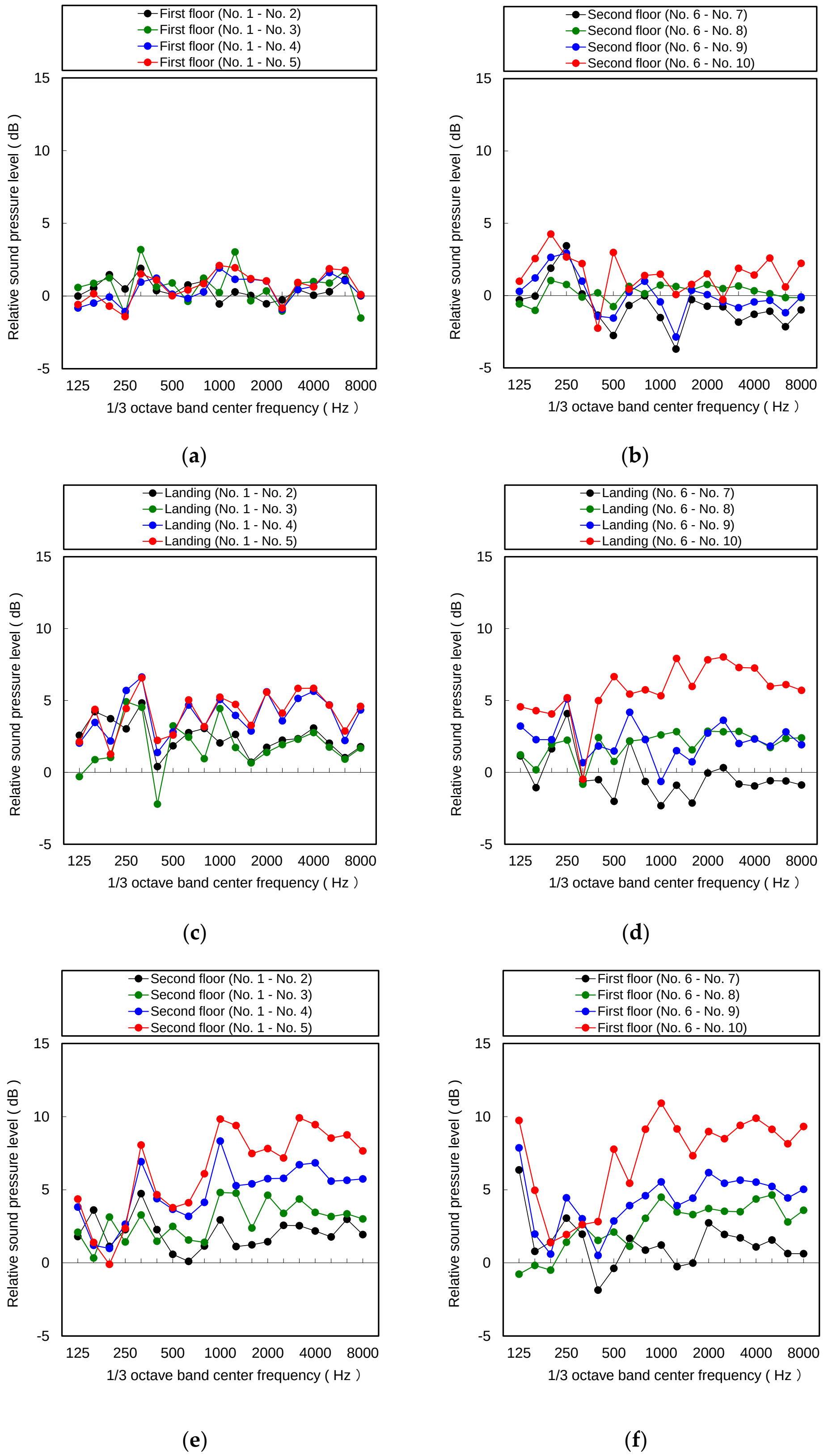


Figure 8. Effect on sound pressure level of the sound absorption panel installation. (**a**) Sound source position: first floor; Measurement position: first floor; (**b**) Sound source position: second floor; Measurement position: second floor; (**c**) Sound source position: first floor; Measurement position: landing; (**d**) Sound source position: second floor; Measurement position: landing; (**e**) Sound source position: first floor; Measurement position: second floor; (**f**) Sound source position: second floor; Measurement position: first floor.

In the case of Figure 8a,b, since the measurement point and the sound source position were located nearby, the direct sound became dominant, and in either case, at all the frequencies, there was almost no sound pressure level difference due to the effect of the difference in installation area and installation positions. In the case of Figure 8c,d—the intermediate floor, that is the landing—where the sound source was located, in Figure 8c, on the first floor, though there were variations based on the frequency band, there was almost no difference due to the panel placement position, namely on the landing walls and riser, given by No. 2 and No. 3. From this, it can be seen that it is more effective to install the sound absorption panel on the riser with a smaller installation area than installing the sound absorption panel on the landing walls. Furthermore, the sound pressure level difference did not change substantially regardless of the presence or absence of the sound absorption panel on the staircase space of the walls of the second floor and ceiling, given by No. 4 and No. 5. From this, it can be seen that there is little effect even if the sound absorption panel is installed on the wall and the ceiling of the second floor. When the sound source was located on the second floor, as given by Figure 8d, the sound pressure level difference between No. 8 and No. 9 was almost the same in most frequency bands, and there was almost no change in No. 7. From these results, it can be said that the effect is small in the landing area when the sound source is located on the second floor, or when the sound-absorbing panel is installed on the riser. In addition, in the case of No. 10, since the sound pressure level difference increased in comparison with No. 8 and No. 9, it can be said that by installing the sound absorption panel on the staircase wall of the second floor and ceiling, there was some effect on the sound pressure level reduction. In the case of Figure 8e,f in which the sound source position and the measuring points were different on the upper and lower floors, the trend differed from that of Figure 8c,d, where regardless of the installation position of the sound absorption panel in both cases, the sound pressure level difference also increased with the increase in the sound-absorbing effect.

From the results above, in the staircase of the open-plan house focused on in this study, it was found that the reduction in the sound pressure level varied with the installation area and installation position of the sound absorption panel, depending on the sound source position when the measurement point was in the landing area. When the sound source was located on the first floor, the efficiency was improved by installing the sound absorption panel on the riser rather than the landing wall. When the panel was installed on the staircase wall of the second floor and the ceiling, the sound absorption was less effective. When the sound source was located on the second floor, unlike the case where the sound source was located on the first floor, the effect was small even if the sound-absorbing panel was installed on the riser. The effect increased when the panel was installed on the staircase wall of the second floor and ceiling. Therefore, it was found that there is an installation position for the sound absorption panel where the sound absorption effect is effective, depending on the sound source position in the landing area. Furthermore, when the sound source position and the measurement points are different on the upper and lower floors, there is a difference in effect, depending on the installation position of the sound absorption panel and the number of panels. However, it was confirmed that the sound pressure level difference increases as the sound-absorbing effect increases, regardless of the sound source position.

Next, in order to grasp the sound-absorption effect quantitatively, Figure 9 shows the A-weighted sound pressure level reduction for each measurement point. The target frequency was in the 125 Hz to 8000 Hz band. Although there were some differences depending on the installation position of the panel, it was confirmed that the A-weighted sound pressure level reduction increased with the increase in the sound-absorbing effect in the staircase, except for the landing area of Figure 9a. In Figure 9a, the sound source was set on the first floor, and the improvements were confirmed. The amount of improvements was about 2 dB and 1.5 dB in the case of No. 2 and No. 3, and about 3.5 dB for No. 4 and No. 5, respectively, at the landing areas. Furthermore, in the case where the sound source was set on the second floor, there were improvements of about 1 dB, 2 dB, 4.5 dB, and 5.5 dB in the case of No. 2, No. 3, No. 4 and No. 5, respectively. Although there was a difference in the improvement due to the difference in the installation position, the improvements due to sound absorption were confirmed on the A-weighted sound pressure level. Additionally, even in Figure 9b, the sound source was set on the second floor, and a maximum improvement of about 5 dB was confirmed in both the landing area and the first floor.

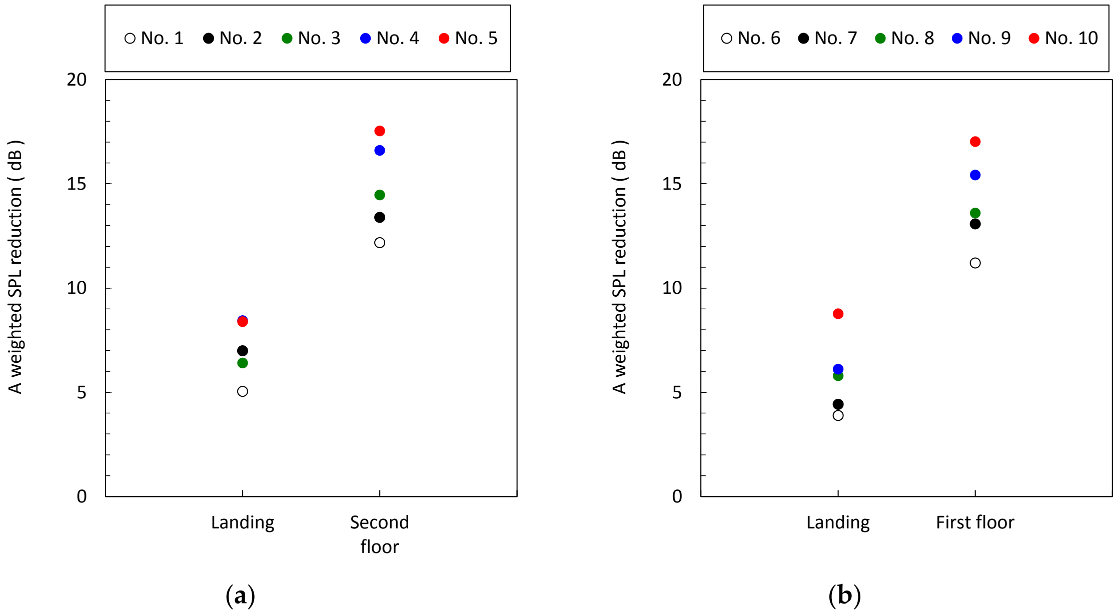


Figure 9. A-weighted SPL reduction at each measurement point. (**a**) Sound source position: first floor; (**b**) Sound source position: second floor.

From the above results, in the staircase studied in this study, though the effectiveness of the sound absorption panel varied with the sound source position, installation position, and number of panels installed, it was confirmed that it is generally effective in improving the A-weighted sound pressure level.

4. Calculation of Average Sound Absorption Coefficient

We calculated the average sound absorption coefficient using Equation (1) [19]. Figure 10 shows the reverberation times measured at each measurement point before installing the sound-absorbing panel (No. 1, No. 6),

$$\overline{\alpha} = -e^{-0.161\ V/TS} + 1, \tag{1}$$

where $\overline{\alpha}$ refers to the average sound absorption coefficient, T refers to the reverberation time (s), V is the room volume (m^3), and S is the summation of the surface area of the "ceiling", "wall", "landing", "riser" and "tread" of the staircase (m^2). From the sound pressure level of Figure 8, we calculated the improvement in the average sound absorption coefficient using the following equations [19].

$$L_D = SPL - SPL_2 = 10\log\frac{4}{R} - 10\log\frac{4}{R_2} = 10\log\frac{R_2}{R} \tag{2}$$

Therefore,

$$10^{(L_D/10)} = \frac{R_2}{R} \tag{3}$$

On one hand,

$$R = \frac{S\overline{\alpha}}{1-\overline{\alpha}} \tag{4}$$

and

$$R_2 = \frac{S(\overline{\alpha}+\overline{\alpha_I})}{1-(\overline{\alpha}+\overline{\alpha_I})} \tag{5}$$

where R is the room constant for specimen No. 1 or No. 6, R_2 means the room constant for specimens No. 2–5 and No. 7–10, L_D is the relative sound pressure level shown in Figure 8, $\overline{\alpha_I}$ is the improvement in the average sound absorption coefficient. By substituting Equations (4) and (5) into Equation (3), the effective average sound absorption coefficient $\overline{\alpha} + \overline{\alpha_I}$ is obtained.

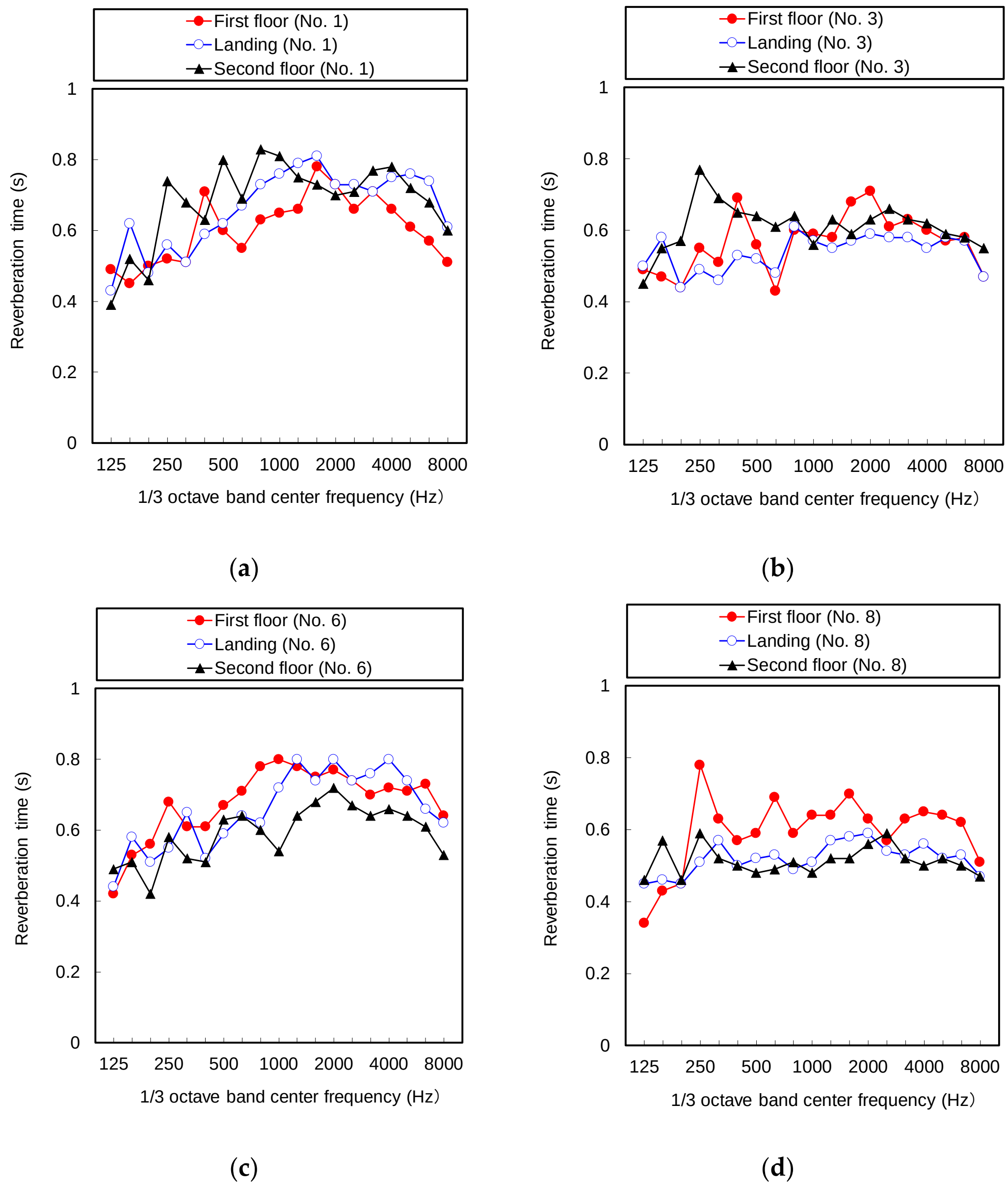


Figure 10. Measurement results on reverberation time of the sound absorption panel installation. (**a**,**c**) Sound source position: first floor; (**b**,**d**) Sound source position: second floor.

Figure 11 shows the average sound absorption coefficient obtained by adding the improvement calculated from the sound pressure level difference to the average sound absorption coefficient before installing the sound absorption panel. (Hereinafter, this is referred to as the effective average sound-absorbing power.)

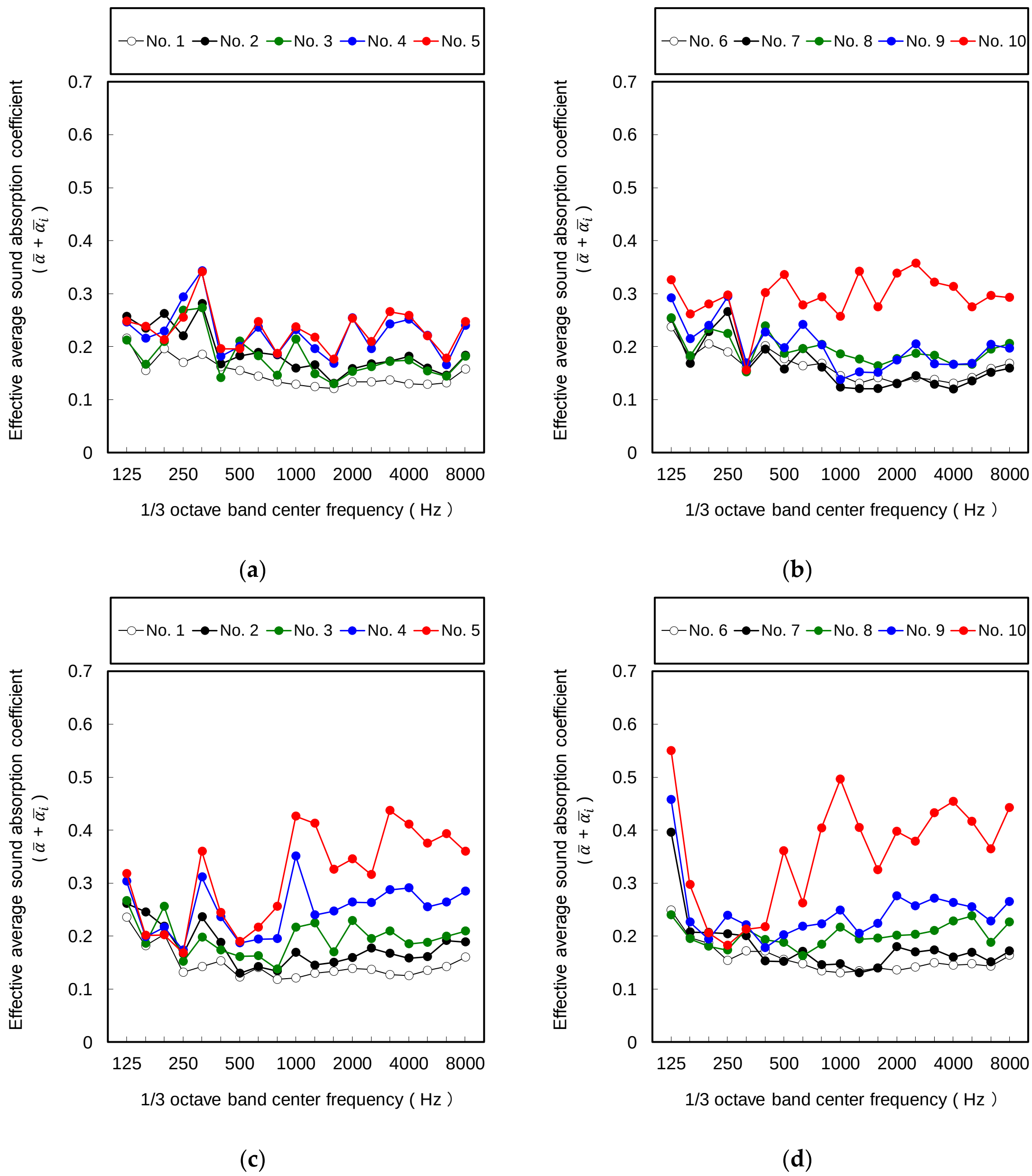


Figure 11. Effect on sound absorption coefficient of the sound absorption panel installation. (**a**) Sound source position: first floor; Measurement position: landing; (**b**) Sound source position: second floor; Measurement position: landing; (**c**) Sound source position: first floor; Measurement position: second floor; (**d**) Sound source position: second floor; Measurement position: first floor.

Similar to the sound pressure level difference, the calculated average sound absorption coefficient in Figure 11 shows a difference in effect depending on the sound source position, installation position and installation area. When the measurement points of Figure 11a,b are at the landing area, there is an installation position that has an effect on the calculated average sound absorption coefficient depending on the sound source position, and when the sound source of Figure 11a is on the first floor, from the calculated average sound absorption coefficients of No. 2 and No. 3 it can be seen that there is an effect on the improvement of the calculated average sound absorption coefficient by installing the sound-absorbing panel on the riser that has a smaller installation area than the wall of the landing area. From the calculated average sound absorption coefficients of No. 4 and No. 5, it can be seen that installation on the second floor wall and the ceiling is less effective in improving the calculated average sound absorption coefficient. When the sound source of Figure 11b is on the second floor, from the calculated average sound absorption coefficient of No. 2, it can be seen that unlike the case of the first floor being the sound source, the effect is small even when the sound absorption panel is installed on the riser, and from the calculated average sound absorption coefficient of No. 10, it was found that installing the panels on the second floor wall and ceiling in the staircase improves the calculated average sound absorption coefficient more efficiently. In addition, when the sound source position and the measurement points are different on upper and lower floors, there is a difference in effect depending on the installation position and the number of sound absorption panels. However, we could confirm that regardless of the sound source position, the calculated average sound absorption coefficient increases with the increase in the sound-absorbing effect.

5. Conclusions

In this study, in order to improve the acoustic environment inside a house through a sound absorption treatment, we focused on the open-plan staircase, and placed thin sound absorption panels on the wall, ceiling, and riser of the staircase, and experimentally studied the suppression effect on the propagation of the sound on the upper and lower floors when the installation position, the number of panels and the sound source position were changed.

As a result, in the open-plan staircase studied in this study, it was found that the effect of the sound absorption treatment on the sound pressure level, the A-weighted sound pressure level, and the average sound absorption coefficient varied depending on the sound source position. When the measurement point was the landing area, then there was a position for placing the sound absorption panel where the sound-absorbing effect was effective. To be specific, when the sound source was located on the first floor, a more effective sound absorption effect could be obtained by installing the sound absorption panel at the riser rather than the wall of the landing area, and it was found that installing the sound absorption panel on the second floor wall of the staircase and ceiling proved to be less effective. In addition, when the sound source was located on the second floor, it was found that unlike the case of the sound source being located on the first floor, the sound absorption effect was small even if the sound-absorbing panel was installed on the riser. However, there was an efficient sound absorption effect when the panels were installed on the second floor wall of the staircase and ceiling. When the sound source position and the measuring points were different on the upper and lower floors, the effects differed depending on the installation position of the sound absorption panel and the number of panels installed. However, the sound absorption effect increased with the increase in the sound-absorbing effect regardless of the sound source position. However, only a single case study on the open plan staircase room was conducted in this paper. In the future, we will propose a practical prediction method for sound-absorbing treatment by measuring many different cases such as a closed plan. Furthermore, it is also interesting to analyze the reduction effect of the sound pressure level in the case of using a directional speaker, especially in the high-frequency region as reported by Scrosati et al. [20]. Therefore, we will consider this point in future work.

Author Contributions: Takafumi Shimizu conceived and designed the experiments; Toru Matsuda, Hikaru Suminaga and performed the experiments; The measured sound pressure levels and reverberation times were analyzed by Toru Matsuda and Kimie Yoshitani; Masaru Koike and Yasutomi Matsushima contributed on the measurements of sound absorption coefficients of the panels; Toru Matsuda and Takafumi Shimizu wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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