Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 7562656, 12 pages
https://doi.org/10.1155/2022/7562656

Research Article

The Effect of the Environment on the Serviceability of the Cross-Laminated Timber (CLT) Floor: Virtual Reality as a Research Tool

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Received 17 March 2022; Revised 14 June 2022; Accepted 11 July 2022; Published 30 August 2022

Academic Editor: Jorge Branco

The environment is one of the factors that may influence occupants' perception of floor vibration and the assessment of floor serviceability. In this study, laboratory tests were conducted on a 3-ply CLT floor. Occupants' assessment of the floor serviceability under human-induced vibration was investigated. Virtual reality (VR) technique was used as a research method, simulating two common environments in life. First, the correlation between the occupants' annoyance rating and serviceability indicators (response factor and vibration dose value (VDV)) was compared with existing standards. The results show that the response factor method in ISO 10137:2007 is conservative for timber floors in both bedroom and gym environments. The VDV method in BS 6472-1:2008 can generally reflect the vibration acceptability of timber floor vibration. Then, the effect of acceleration and environment on the floor serviceability assessment was investigated through statistical methods, respectively. A weak positive correlation between the annoyance rating and the acceleration was found. The effect of the environment on floor vibration assessment was found to be significant.

1. Introduction

The construction industry sector contributes a huge proportion of greenhouse gas emissions globally [1]. Building with timber is a competitive solution because timber is genuinely a renewable material that can sequester carbon in the atmosphere. Timber floor is a common structural element with the advantage of prefabrication, and there are more than 300,000 timber floors built each year in the UK [2]. The density of the timber is about 20% of concrete. According to Newton's Law, the same foot force excites larger acceleration in timber floors compared with concrete floors due to the lightweight nature of timber. Furthermore, due to the development of engineered wood products like cross laminated timber (CLT), timber structures are tending to be larger and taller. The large-span requirement makes the floor systems of modern timber structures prone to vibration problems [3]. Thus, a careful design of timber floors with small vibration and high serviceability is of great importance.

1.1. Floor Vibration. Among all the building components, the floor is the one that interacts with occupants most. Human activities such as walking, running, and jumping can induce floors to vibrate. For humans, each body member and organ has distinct natural frequencies within 0–80 Hz [4]. Thus, exposure to human-induced vibrations has an impact on human's comfort and health. It is said that more than 50 million Europeans are suffering from structural vibration [5]. The discomfort from floor vibration is a universal issue.

Research related to the serviceability of the floor is of great necessity.

Studies have been conducted to investigate the properties of joist timber floors. It was found that timber floors with a higher mass density showed a smaller vibration response [6]. Reducing the joist spacing of joist timber floors can increase the stiffness of the floor and improve the floor performance [7].

Studies have been conducted on CLT floors. As for floor dimension, it was found that the natural frequency of the CLT floor reduced as the aspect ratio of the floor increased [8]. With regard to boundary conditions, Uí Chúláin and Harte [4] found that the natural frequency of the two-way supported CLT floor was 90% higher than that of the one-way supported CLT floor. Huang et al. [9] carried out research on the dynamic behaviors of CLT floors, concerning the spacing and size of the beam, and other supporting conditions. Casagrande et al. [10] assessed the vibration performance of the CLT floor by analytical, numerical, and experimental methods and found that internal partitions and nonstructural elements are important factors that influenced the dynamic response of the floor. To predict the human-induced vibration, Chang et al. [2] proposed the peak acceleration method to predict VDV of CLT floors. The method was further developed by Wang et al. [8], concerning factors such as the aspect ratio of the floor, the number, and the walking speed of the occupants. To control the vibration of the CLT floor, Huang et al. applied a multituned mass damper to reduce the floor vibration response [11, 12]. In summary, the previous research on CLT floors have focused on the characteristics of the floors and vibration control measures.

1.2. Acceptability Criteria. The evolution of design approaches to prevent annoying vibrations in timber floor was reviewed chronologically by Hu et al. [13]; which made important contributions to the development of standards in floor serviceability. Weckendorf et al. [14] provided background knowledge for the serviceability of the timber floor, including floors made of novel engineered wood products, such as CLT. With respect to current standards, Eurocode 5 [15] is widely used by engineers to design the timber floor. In terms of the serviceability limit of vibration, Eurocode 5 employs the criteria based on fundamental frequency. Residential floors with fundamental frequency greater than 8 Hz need to meet the requirements of vertical deflection and a unit impulse velocity response, while those with fundamental frequency less than 8 Hz need a special investigation. Despite the requirements specified in Eurocode 5, indicators to assess the floor vibration also include root-mean-square acceleration (RMS acceleration, a_{RMS}), response factor, and VDV.

1.2.1. RMS Acceleration. Peak acceleration sometimes cannot reflect the vibration over a period. Instead, RMS acceleration puts the vibration over a period into consideration. Chui [16, 17] proposed the limit of frequency-weighted RMS acceleration of the timber floor to be $a_{RMS} < 0.45 m/s^2$ for domestic structures, but this proposal has not been adopted into the standard. In ISO 2631-2:2003 [18], the standard for the evaluation of human exposure to vibration in buildings, it is clearly stated that guidance values in acceptance criteria are not provided because the possible range of a_{RMS} is too wide to be included in an International Standard.

1.2.2. VDV. VDV method was developed by Michael Griffin in 1980s. This method is suitable for evaluating intermittent vibration and can be applied in a range of different environments including road or off-road vehicles, aircraft, sea vessels, and building vibration [19–21]. Comprehensive introduction about VDV is accessible in a book named "Handbook of Human Vibration" [22]. BS 6472-1:2008 [23] proposed VDV to assess building vibration. VDV is calculated using the weighted acceleration which is filtered using the frequency weighting curve specified in BS 6841 [24]. VDV in day time is calculated by equations (1) to (3):

$$VDV = \left(\int_0^T a_w^4(t)\mathrm{d}t \right)^{0.25}, \tag{1}$$

where VDV is the vibration dose value (in $m \cdot s^{-1.75}$), $a_w^4(t)$ is the frequency-weighted acceleration (in m/s^2), and T is the total period of the day (in s) during which vibration may occur.

For constant or regularly repeated vibrations, we get

$$VDV = \left(\frac{t_{\mathrm{day}}}{t_\tau} \right)^{0.25} \times VDV_\tau, \tag{2}$$

where VDV_τ is the representative sample of τ seconds and t_{day} is the duration of exposure per day (s).

For conditions when there are N vibration episodes of different durations t_n during the assessment period, each with a vibration dose value of VDV_{t_n},

$$VDV = \left(\sum_{n=1}^{n=N} VDV_{t_n}^4 \right)^{0.25}. \tag{3}$$

Probabilities of adverse comment are classified into three categories according to VDV values. Table 1 [23] shows the referable VDV values for each adverse comment category.

1.2.3. Response Factor. In ISO 10137:2007 [25], a series of frequency-weighted base curves and multiplying factors are applied to realize satisfactory vibration of the floors. Base curves derived from base values and frequency weighting curves which are specified in BS 6841 [24], and the z-axis base curve is shown in Figure 1. Multiplying factors are the limiting values of response factors, which are defined as the ratio of the calculated weighted RMS acceleration to the frequency-related RMS acceleration $a_{RMS,\mathrm{frequency}}$ exhibited in Figure 1, [26]. The response factor is calculated by the following:

Table 1: VDV ranges which might result in various probabilities of adverse comment within residential buildings (BS 6472-1:2008) [23].

Time	Low probability of adverse comment ($m/s^{1.75}$)	Adverse comment possible ($m/s^{1.75}$)	Adverse comment probable ($m/s^{1.75}$)
16 h day	0.2~0.4	0.4~0.8	0.8~1.6
8 h night	0.1~0.2	0.2~0.4	0.4~0.8

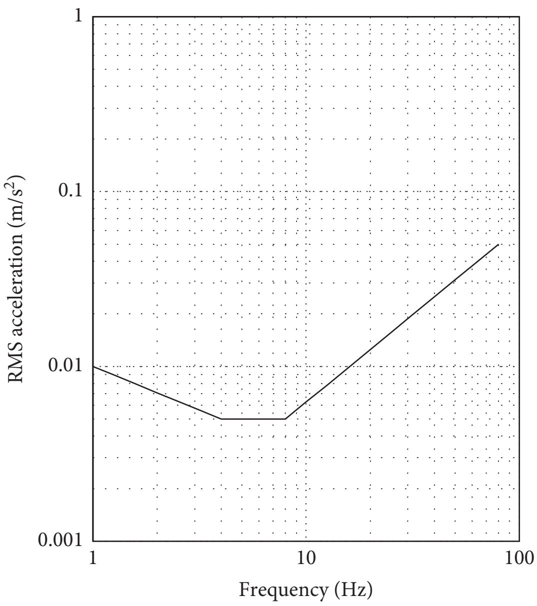


Figure 1: z-axis base curve [24].

$$Response\ factor = \frac{a_{w,RMS}\ (m/s^2)}{a_{RMS,frequency}\ (m/s^2)}, \tag{4}$$

(for z-axis vibration).

Table 2 exhibits the multiplying factors used in several countries to specify satisfactory magnitudes of building vibration with respect to the human response listed in ISO 10137 [25]. The multiplying factors for continuous vibration and intermittent vibration in residential buildings are 2 to 4. The reason that the limit is a range rather than a specific value is that occupants exhibit wide variations of vibration tolerance in residential areas.

Notably, the reference VDV values in BS 6472-1:2008 (as shown in Table 1) were available in the 1992 version of the standard. Some of the multiplying factors in ISO 10137:2007 (as shown in Table 2) also appeared in BS 6472:1984 [27] and only slight changes have been made. In other words, the values specified in the current standard have not been fully updated for more than 30 years, so it is essential to evaluate whether they are still applicable now. Besides, the VDV and the response factor do not fully harmonize with the current Eurocode 5. In the next generation of Eurocode 5, which will be published in 2025-2026, the response factor will be introduced as an indicator to assess the residential timber floor serviceability. Due to this complexity, for industry, it is difficult for engineers to understand how the serviceability of the timber floor links with the response factor, which may confuse engineers in the design stage. There are few relevant studies regarding this issue. Thus, it is of importance to test the timber floor and conduct a survey, thereby linking the serviceability of the floor and the response factor.

1.3. Factors Affecting Comfort Assessment. The acceptable vibration levels for each individual are influenced by many factors. Intrinsic factors include population type (age, sex, size, fitness, etc.), experience, expectation, arousal, motivation, financial involvement, body posture, and activities [24, 25, 28]. Extrinsic factors include the magnitude, frequency, axis, input position, duration of vibration, and other environmental influences [24, 29, 30].

The surrounding environment or "atmosphere" affects human perception. Many studies have shown that the environment affects the occupants' mood and performance, and even their physical and mental health [31–36]. Factors that influence occupants' perception of the environment include light, color, temperature, noise, or smells [24, 37, 38]. For example, in the field of thermal comfort, the "hue-hypothesis" claims that the color of light influences people's temperature sensation [39–41]. Light of long wavelengths makes people feel warmer, while light of short wavelengths makes people feel cooler. Similarly, occupants may feel differently in different environments even if they are experiencing the same level of floor vibration.

However, sometimes it is not realistic to create an authentic room for experimental tests. Zhou et al. [42] placed furniture and other symbolic items on a testing floor to make the test subjects feel like they were staying in a real living environment. However, this method does not give the test subjects a completely immersive feeling. With the development of computer technology, VR has become an effective research tool in industries including architecture, engineering, and construction. Studies have proved that VR could provide people with an adequate sense of presence and arouse affective and emotional states similar to those in a real environment [43–48]. Thus, it is an ideal research tool to simulate environments that are not easily accessible in the laboratory so as to obtain human perception and response to the environment.

The objective of this paper is to examine if people have different feelings on a level of vibration in different environments. More importantly, in the draft of the new Eurocode 5 (currently in revision), only two environmental categories (residential and office) are selected. However, it is impossible to classify all the environments into these two categories. For example, the school can be classified as neither residential nor office. Therefore, it is significant to know the effect of the environment on the occupants' evaluations to the floor vibration. Comprehensive floor design should put this into consideration, so as to prevent the timber floor from being designed conservatively and to

Table 2: Multiplying factors used in several countries to specify satisfactory magnitudes of building vibration with respect to a human response [25].

Place	Time	Multiplying factors to a base curve: Continuous vibration and intermittent vibration	Multiplying factors to a base curve: Impulsive vibration excitation with several occurrences per day
Critical working areas	Day	1	1
	Night	1	1
Residential	Day	2 to 4	30 to 90
	Night	1, 4	1, 4 to 20
Quiet office, open plan	Day	2	60 to 128
	Night	2	60 to 128
General office	Day	4	60 to 128
	Night	4	60 to 128
Workshop	Day	8	90 to 128
	Night	8	90 to 128

save more materials. For places where occupants hold high tolerance to vibration, the requirements of the floor design could be lowered appropriately.

In this study, an experiment on a full-scale 3-ply CLT floor is carried out, and 30 test subjects are employed to experience the human-induced vibration on the CLT floor. During the tests, VR equipment is adopted to simulate the different environments for the subjects. By giving a human-induced vibration, test subjects should feedback their comfort levels subjectively through questionnaires. The vibration acceleration of the floor in each test is recorded by sensors simultaneously. It is aiming to build and understand the relationship between the acceleration and the comfort level of the CLT floor vibration. In addition, the effect of the environments on the comfort level during the human-induced vibration on the CLT floor is investigated, and this can lay a foundation for the future accurate design. Notably, “environments” in this study denote room environments.

2. Methods

2.1. CLT Floor and Its Dynamic Properties. Figure 2 presents the CLT floor employed in this study. This CLT floor is a 3-ply CLT with a total thickness of 105 mm (layout: 35L-35 T-35L). The span of the floor in longitudinal direction is 4.20 m and the width is 2.35 m. The raw material for the CLT floor was SPF (spruce-pine-fir) provided by Ningbo Sino-Canada Low-Carbon Technology Research Institute Co. Ltd. The density of the timber material is 0.458g/cm^3, the modulus of elasticity is 9200 MPa, and the bending strength is 31.3 MPa. The moisture content of the timber was 13% tested in a storage condition of 40% R. H. 10℃. As shown in Figure 2, the CLT floor was supported by CLT walls with a thickness of 105 mm in four sides. The CLT floor was connected to CLT walls by drilling self-tapping screws (M7 in diameter and 140 mm in length) from the top.

Three accelerometers were installed on the CLT floor, and the sampling rate was 1,000 Hz, which complied with the minimum sampling rate specified in BS EN 16929:2018 [49]. The first accelerometer was located on the central point of the floor, the second accelerometer was located in the middle between the central point and the edge in the longitudinal direction, and the third accelerometer was located in the middle between the second accelerometer and the edge in the transverse direction.

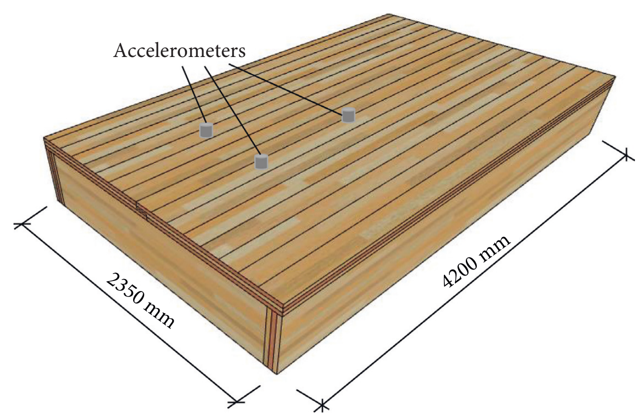


Figure 2: Schematic diagram of the floor tested.

The technologies to excite a floor for modal testing include shaker, impact hammer, heel-drop, and human excitation [7, 49–51]. This study followed the heel-drop method suggested in BS EN 16929:2018 for the timber floor and the procedure in this study has fulfilled the requirements. In this study, a person weighing 60 kg stood on his toes and then dropped his heels rapidly through a distance of about 65 mm. The free vibration response of the CLT floor was recorded by the abovementioned accelerometers. The dynamic parameters were obtained by a linear-prediction singular-value decomposition-based matrix pencil (SVD-MP) method, which is based on time-domain curve-fitting analysis. This method can be used to estimate the frequency and damping of structures from measured data and is efficient in computation [52–54]. After analysis, the natural frequency of the CLT floor can be determined to be 15.05 Hz, and the damping ratio is 12.07%. Figure 3 shows the time-domain response of the CLT floor in the heel-drop test.

2.2. Assessment Environment Setup. The study of Chamilothori et al. [44] showed that there was a high level of perceptual

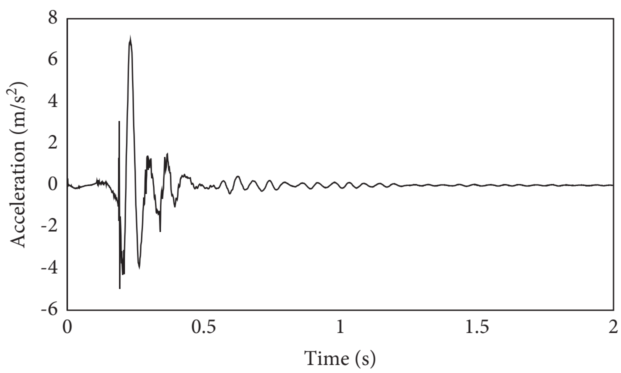


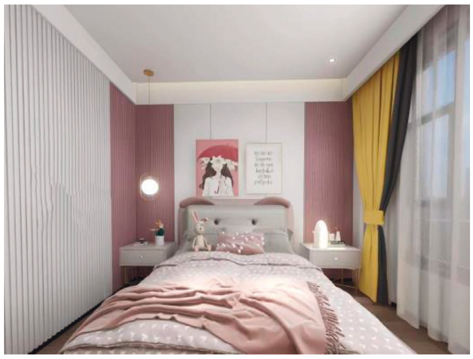
Figure 3: Acceleration-time response of the floor to the heel-drop test.

accuracy between the real and virtual environments from the aspects of subjective evaluations in virtual scenes, users' physiological reactions, and their perceived presence in the virtual environment. Bhagavathula et al. [43] found there was no statistical significant differences in human behavior in a virtual and real environment. Xu et al. [55] drew similar conclusions and provided robust evidence for the validity of VR as a tool for data acquisition. The feasibility to use VR as a research tool has also been proved in many research [45–48, 56]. In this study, two VR environments were set up to simulate different places in real life. As shown in Figure 4, the first environment was a bedroom, representing places where occupants relax and enjoy their private time. The second environment was a rest area in a gym, representing places where occupants may have interactions with others. These models were visualized for use in the VR glasses using KoolVR software developed by Hangzhou Qunhe Information Technology Co. Ltd. What people saw after wearing VR glasses was a 3D scene. When the test subjects turned their head, the scene in their field of vision changed synchronously. In other words, test subjects could look around the room, which could provide them with a sense of presence. The eye level was adjusted to about 1.2 m to assume a scenario in which the test subject sat in the virtual environment.

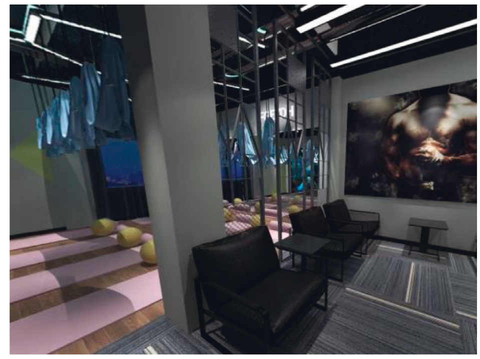
2.3. Test Subjects. A total of 30 Chinese test subjects (17 males and 13 females) participated in the tests. Power analysis suggested this sample size was sufficient to detect a medium effect in terms of the difference in annoyance ratings between the two different environments, assuming an alpha of 0.05 and a power of 80%. There were no specific criteria for sample selection, but it was ensured that all test subjects had a basic knowledge of the chosen scenarios. In other words, they knew what the rooms look like and how they are used in real life. The age distribution is shown in Table 3. All of the test subjects have no disability, and they do not have diseases related to bones or muscles, assuring all of them can sense the vibration normally. In terms of living conditions, 16 of the test subjects come from the city and 14 of them are from the suburbs. All of them are currently living on concrete floors, and only one of them reported vibration concerns in their own house. It is notable that all test subjects claimed that they had not experienced the vibration of timber floors, and this may have an influence on their perception and assessment of the vibration of timber floor because the perception on a timber floor is totally different from that on a concrete floor.

2.4. Test Procedures. In this study, the effect of the acceleration and the environments on the serviceability of the CLT floor was investigated. The test subject sat in a chair on the central point of the CLT floor, as shown in Figure 5. To eliminate the potential influences of sitting postures on vibration perception and evaluation in the tests, a chair of common height was chosen so that all the test subjects could have their feet touching the floor. The chair was stiff enough to ensure it could transmit the floor vibration to the test subject, while it could stay still when the floor was not induced by any vibration source. Besides, test subjects were asked to sit in a posture that was the same with others. The test subjects wore the VR glasses and adapted to the first virtual environment (bedroom) for 5 minutes. The test did not commence until the test subjects confirmed that they had adapted to the VR scene without nausea or other symptoms. They wore the earplugs for the whole test so as to isolate external noise. During the test, a tester weighted 60 kg and walked or ran randomly around the test subject for 15 seconds, and the test subject was asked to experience the floor vibration carefully. After having a rest of 5 minutes, the second virtual environment (rest area in a gym) was displayed in the VR glasses and the random walking or running was conducted again on the CLT floor by the same tester. After the vibration experience, the test subject was asked to have a rest of 5 minutes and then answered a questionnaire. The CLT floor vibration behavior in each test was recorded by the accelerometers aforementioned.

The questionnaire contains three parts. The first part is basic information concerning their demographic, home circumstances, and experience of building vibration, as presented in Section 2.3. The second part is regarding the test subject's engagement in the experiment. Test subjects evaluated the reality of the VR environment using a 5-point Likert questionnaire. Likert scale is a subjective evaluation method. Due to its simplicity, it is commonly used at present and has been applied in previous studies to assess the annoyance to the environments [57–59]. The third part is the



(a)



(b)

Figure 4: View from VR glasses: (a) the bedroom; (b) the rest area in a gym.

Table 3: Age distribution of test subjects.

Age (years old)	Number of test subjects
0–20	4
21–30	7
31–50	11
50+	8
Averaged age	38.83 years old
Standard deviation	14.81

Figure 5: The test subject and the walking/running tester.

assessment of the annoyance rating of CLT floor vibration in different virtual environments. All the test subjects were asked to assess the serviceability of the floor in each virtual environment using the 7-scale Likert scale (1: extremely comfortable; 2: very comfortable; 3: comfortable; 4: moderate; 5: uncomfortable; 6: very uncomfortable; 7: extremely uncomfortable), and this assessment feedback was regarded as "annoyance rating" in this paper. Notably, the questionnaire used in this study was not referred to the questionnaire template given in ISO/TR 21136:2017 [60]. The major reason is that the main variable of this study is the room environment, and several variables (sound, rattling, price of the floor, posture, and objects' moving) in ISO/TR 21136:2017 could complicate the analysis and deflect from the main theme. Thirty people participated in the tests. All of them experienced the floor vibration under relatively gentle excitation, and 14 of them agreed to experience the floor vibration under relatively intense excitation. So, totally 44 questionnaires were collected.

3. Results and Discussion

3.1. Research against the Current Standard. The fundamental natural frequency of this floor is 15.05 Hz. According to the base curve shown in Figure 1, the frequency-related RMS acceleration obtained by linear interpolation is $9.4 \times 10^{-3} m/s^2$. Figure 6(a) and 6(b) exhibit the response factor of the bedroom as well as the rest area in a gym against the annoyance rating, respectively. The range of the acceptable response factors is boxed in red in Figure 6. It is to be noted that the annoyance rating result of both the bedroom and the gym environment in this test are inconsistent with the standard. According to ISO 10137:2007 [25], the vibration is acceptable when the response factor is lower than 4 (for residential) or 8 (for workshops), as shown in Table 2.

As seen in Figure 6(a), for the bedroom environment, occupants feel discomfort even when the response factor is small, and it proves that people could have a low vibration tolerance when they are in a private environment. In following discussion, annoyance ratings of 6 and 7 are collectively called extra uncomfortable. From the results of this test, response factor = 20 can be a limit value for the bedroom environment. When the response factor is less than 20, only 3% of the questionnaires reported extra uncomfortable. When the response factor is equal to or higher than 20, the percentage of extra uncomfortable raised drastically to 62%. As seen in Figure 6(b), for the gym environment, the limit value could be response factor = 22. When the response factor is less than 22, 9% of the questionnaires gave an annoyance rating of 5 or higher. When response factor is equal to or higher than 22, the counterpart is 58%. For timber floors in the bedroom area, the limit value of the response factor can be appropriately increased to 20 instead of 4 in ISO 10137:2007 because the comfort acceptability actually remains the same in the range between 0 and 20, in which it can avoid conservative designs and achieve the cost-effectivity. The limit value for gym can also be raised according to the same findings. One thing to be noted is that this study drew a preliminary conclusion for revising the standard of timber floor vibration, and further study

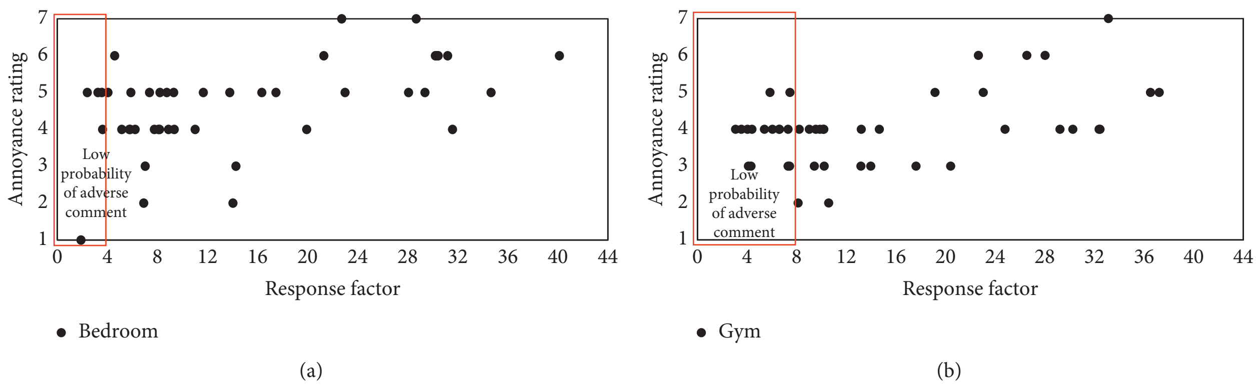


Figure 6: Relationship between the annoyance rating and the response factor of (a) the bedroom and (b) the rest area in a gym.

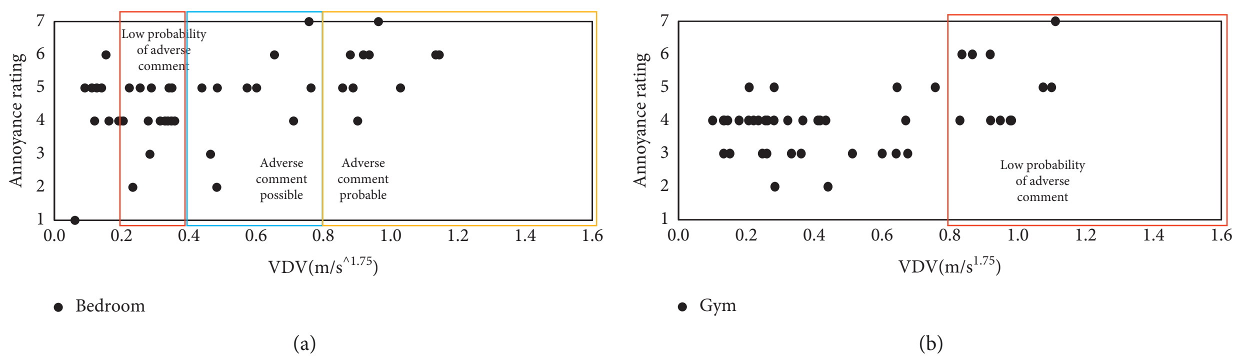


Figure 7: The relationship between the annoyance rating and VDV of (a) the bedroom and (b) the rest area in a gym.

involving a larger sample size should be conducted to obtain a more accurate limit value.

Figure 7 shows the relationship between the annoyance rating and VDV. VDV in Figure 7 is calculated according to (1) [23]. The VDV ranges, which might result in various probabilities of adverse comment during daytime specified in BS 6472-1:2008, are highlighted with boxes of different colors in Figure 7. In following analysis in this paper, the gym environment is categorized as the workshop. As seen in Figure 7(a), for the bedroom environment, when VDV is equal to or less than 0.6, only 3% of the questionnaires reported extra uncomfortable. When VDV is higher than 0.6, the percentage of extra uncomfortable raised drastically to 53%. For timber floors in the bedroom area, the current standard is a little bit conservative. The maximum limit value of VDV of low probability of adverse comment can be appropriately extended to 0.6, as the acceptability level actually remains the same in the VDV range between 0 and 0.6. As seen in Figure 7(b), for the gym environment in this test, when VDV is below 0.8, no one reported extra uncomfortable. When VDV is higher than 0.8, the percentage of extra uncomfortable is 36%. This is consistent with the limit values of VDV in the current standard. In summary, the VDV method can generally reflect the vibration acceptability of timber floor vibration.

Another thing to be noted is that presently only residential buildings, office, and workshops are distinguished in the VDV method in the standard. In reality, there are far more kinds of environments. Hence, a more detailed classification of the environment should be considered so that different VDV ranges can be applied for different conditions.

Table 4: Result of partial correlation analysis between the annoyance rating and acceleration (in terms of response factor and VDV).

	Correlation coefficient	2-tailed significance (p value)
Response factor	0.493	<0.001
VDV	0.498	<0.001

3.2. Effect of Acceleration. This section is to obtain the relationship between response acceleration and serviceability of the floor. In statistics, partial correlation analysis is used to study the linear relationship between two variables after excluding the effect of one or more independent factors. In this section of the study, partial correlation analysis was carried out to investigate the correlation between the annoyance rating and the response acceleration of the floor (in terms of response factor and VDV), excluding the effect of the environment. The result is exhibited in Table 4, indicating that there is a weak positive correlation between the annoyance rating and the acceleration both in terms of the response factor and VDV.

Table 5: Median value of the annoyance rating in each response factor range.

Annoyance rating	Response factor 0.00–10.00		10.01–20.00		20.01–30.00		30.01–40.00	
	$E1$	$E2$	$E1$	$E2$	$E1$	$E2$	$E1$	$E2$
Median	4	4	4.5	3.5	5.5	5	6	4.5
IQR	1	1	1.25	1	1.75	2	0.5	1

There is one thing to note that all of the test subjects had not ever lived on timber floors, and their assessment and judgment of CLT floor vibration is based on the comparison with concrete floors of their own house. Literature reviews have revealed that former living conditions, racial, country, and other factors may affect the perception of floor vibration [29, 42]. In future, test subjects from different countries and with experience of living on timber floors should be involved.

3.3. Effect of the Environment. Apart from acceleration, the effect of the environment on the annoyance rating was also considered. In this study, two environments were chosen as variables: the bedroom and the rest area in a gym, representing private and public places, respectively. It can be observed that occupants feel more uncomfortable in the bedroom environment compared with in the gym environment.

To verify the difference between different environments, further statistical analysis was carried out. Firstly, a test of normality was conducted on the annoyance ratings of the test subjects in the two environments. A Shapiro–Wilk test suggested that the data in this study were not normally distributed. The paired-samples Wilcoxon Signed Ranks Test was therefore used, as this is a nonparametric test to compare results between two conditions (the two different environments) for the same set of participants. The test suggested a significant difference in annoyance ratings between the two environments ($Z = -4.287$ and $p < .001$). The bedroom environment produced a greater annoyance rating ($\text{median} = 5$ and $\text{IQR} = 1$) than the gym environment ($\text{median} = 4$ and $\text{IQR} = 1$).

In order to show the influence of the environment on the CLT floor serviceability more directly, the median and the interquartile range of the annoyance rating for each response factor range are shown in Table 5. In Table 5, $E1$ represents the "bedroom" environment and $E2$ represents the "rest area in a gym" environment. The median of annoyance rating of the bedroom in almost each response factor range is higher than that of the rest area in a gym.

In this paper, only two environments were simulated. In future studies, more environments including more human activities could be considered. As for VR technique, the virtual environment in this study only consisted of static images. For further study, sound and virtual characters may be involved to make the virtual environment more realistic. In terms of test subjects, studies have shown that vibration perception and assessment vary across countries due to differences in living styles and floor systems [29, 42]. In future, occupants from different countries and occupants with experience of living on timber floors could be invited so that the vibration assessment could be more inclusive and convincing.

4. Discussion

In practical application of CLT floors, some functional layers are adopted for requirements such as sound insulation and pipeline installation. There are variable functional layers, including concrete screed, cement screed, dry screed, fine sand/gravel screed, and rubber layer, and there are many choices of thickness of these layers. As a pilot study, to eliminate the influences of variables caused by the functional layers, this study did not consider the influence of nonstructural components but focused on the vibration serviceability of the bare CLT floor itself, to see the effect of the room environment on the occupants' evaluation of vibration. In future studies, functional layers will be considered to furnish the relationship between the human annoyance rating and the vibration level.

Occupants' response and evaluation to the environment involves both a psychological and a physiological aspect. In this study, the Likert scale method is adopted to obtain the effect of the environment on occupants' perception. Likert scale can quantify people's subjective evaluation, and its simplicity and feasibility makes it commonly used in studies to assess the annoyance to the environments [57–59]. Measurement of physiological responses of test subjects can provide a supplement to the subjective evaluation. Literature [31, 45] measured the physiological responses, such as skin reaction, heart rate, and blood pressure, to assess the impact of the environment on occupants. For instance, electromyography (EMG) can be used to investigate the pattern of the facial muscle to detect different emotions. Blood volume pulse (BVP) can show the tension condition. Electroencephalography (EEG) can be used to record bioelectrical responses which denote the state of quietness or alertness. Measuring occupants' physiological responses can make up for the subjectivity of the Likert scale method and can achieve a more accurate assessment. In future studies, occupants' physiological responses can be included in the scope of experimental records.

CLT is a lightweight material and CLT floors can be excited to larger vibration compared with reinforced concrete floors. The peak acceleration obtained in this test is around 0.69 m/s^2. All of the test subjects in this study live on reinforced concrete floors in China where vibration in daily life is negligible (as per the Chinese standard JGJ/T 441-2019 [61], the limit value of vertical acceleration for reinforced concrete floors is around 0.05 to 0.2 m/s^2, which is far less than the peak acceleration of this study). So, even a tiny vibration on the timber floor could lead to a negative comment from these subjects. These series of tests in this paper are essential to replicated in countries where most people have the experiences of living on timber floors. The upcoming research outcomes will expand a new scope to discuss whether the living experience will influence occupants' evaluation of vibration.

5. Conclusion

In this study, laboratory tests were conducted on a CLT floor, and occupants' assessment of the floor serviceability under human-induced vibration was investigated. Virtual reality was used as a research method, simulating two common environments in life. First, the correlation between the occupants' annoyance rating and serviceability indicators (response factor and VDV) was compared with existing standards. Then, the effect of acceleration and the environment on floor serviceability assessment was investigated through statistical methods, respectively. The following can be drawn as follows:

(1) Occupants have lower vibration tolerance in the bedroom than in the gym. This indicates that the room environment has an effect on occupants' evaluation of floor vibration.

(2) The current limit values of the response factor in ISO 10137:2007 are conservative for timber floors in both the bedroom and gym environments. The limit values can be appropriately increased to avoid conservative designs and achieve the cost-effectivity.

(3) VDV method can generally reflect the vibration acceptability of timber floor vibration. The results of the gym environment are consistent with BS 6472-1: 2008. However, for the bedroom environment, values in the current standard are a little bit conservative. A slight adjustment is needed. Besides, more detailed classification of the environment should be considered in BS 6472-1:2008.

(4) The annoyance rating of floor vibration increases as the response acceleration gets larger, but in a weak manner.

Factors such as the environment and the type of floors may influence the floor serviceability. Due to the complexity, it is recommended that a database for timber floor vibration could be created so as to provide reference and guidance to the revision of standards concerning the serviceability of the timber floor in.

Appendix

Questionnaire for CLT Floor Serviceability

Part One: Basic Information

Name:

Gender:

Age:

Telephone:

(1) Your weight kg

(2) Do you have any bone or muscle related diseases? (.)

A. No B. Yes

(3) The house you are living in is (.)

A. New residential district B. Old neighbourhood

C. Self-built one-storey house D. Self-built multi-storey house

(4) The floor in your house is made of (.)

A. Concrete B. Timber C. Other

(5) Are you troubled by floor vibration problems in your life? (.)

A. Yes B. No

(6) Can you accept the floor vibration of your house?

Part Two: Engagement in the Experiment

(1) When you wear the VR glasses, do you feel like you fit in the setting?

Part Three: Assessment of CLT Floor Vibration

(1) How would you rate the serviceability of the floor (annoyance rating)?

Table 6:

Perfectly acceptable	Acceptable	Moderate	Unacceptable	Very unacceptable

Table 7:

Test	Very real	Real	Moderate	Unreal	Very unreal
1					
2					

Table 8:

Test	Extremely comfortable	Very comfortable	Comfortable	Moderate	Uncomfortable	Very uncomfortable	Extremely uncomfortable
1							
2							

Data Availability

The data used to support the findings of the study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank the financial support from the start-up funding at Newcastle University and the National Natural Science Foundation of China (51908007). In addition, the authors would like to thank Mr. Xinrui Wang, an undergraduate student at Beijing University of Technology, for his assistance during the tests.

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