WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

ACCEPTABILITY CRITERIA OF TIMBER FLOOR VIBRATION: A SUBJECTIVE EVALUATION

Haoyu Huang[1], Wen-Shao Chang[2]

ABSTRACT: There is a pressing concern due to timber floors' susceptibility to vibration issues exacerbated by trends towards larger, open spaces. This study aims to investigate criteria for acceptable timber floor vibration by establishing a correlation between human response and floor vibration levels across different environments. By utilising Virtual Reality (VR) technology to simulate environments and recruiting participants from the UK and China, the research evaluates subjective vibration perceptions in private (bedrooms) and public (gyms) use, highlighting the influence of building function and cultural background on comfort levels. Findings examined existing standards, highlighted the need for criteria that covers a broader range of building functions, and demonstrated significant cultural differences in vibration tolerance. The study laid foundations in terms of refining criteria for facilitating the use of timber floors.

KEYWORDS: Timber floor vibration; Acceptability criteria; Serviceability ; Vibration perception

1 – INTRODUCTION

The study of structural vibration comfort has gained increasing attention in recent years, particularly in the field of timber construction [1]. As timber structures become more widely adopted in modern construction due to their sustainability, efficiency, and aesthetic appeal, it is crucial to understand their vibrational characteristics and the impact of these vibrations on occupant comfort. Unlike traditional concrete and steel structures, timber exhibits different mechanical properties, such as lower mass and damping ratios, which can lead to noticeable vibrations under everyday human activities, such as walking, running, or jumping.

Studies have been conducted on cross laminated timber (CLT) floors' vibration. As for floor dimension, it was found that the natural frequency of the CLT floor reduced as the aspect ratio of floor increased [2]. With regard to boundary conditions, Uí Chúláin and Harte [3] found that the natural frequency of two-way supported CLT floor was 90% higher than that of one-way supported CLT floor. Huang et al. [4] carried out research on the dynamic behaviours of CLT floors, concerning the spacing and size of beam and other supporting conditions. Casagrande et al. [5] assessed the vibration performance of CLT floor by analytical, numerical and experimental methods, and found that internal partitions and non-structural elements are important factors that influenced the dynamic response of the floor. To predict the human-induced vibration, Chang et al. [1] proposed the peak acceleration method to predict the vibration dose value (VDV) of CLT floors. The method was further developed by Wang et al. [2], concerning factors such as the aspect ratio of the floor, and the number and the walking speed of the occupants. To control the vibration of the CLT floor, Huang et al. applied multi-tuned mass damper to reduce the floor vibration response [6, 7]. In summary, the previous research on CLT floors have focused on the characteristic of the floors and vibration control measures.

The level of vibration discomfort can vary significantly depending on structural properties, environmental conditions, and personal experiences of the users. While engineering standards such as BS 6472-1:2008 [8] and ISO 10137:2007 [9] provide guidelines for acceptable vibration limits in buildings, these standards may not fully consider the influence of psychological and environmental factors on human perception. Therefore, a more holistic approach is needed to assess how different indoor environments affect vibration comfort perception.

Current standards, such as SCI Publication P354, ISO 10137:2007, and BS 6472-1:2008, have not been updated for three decades and limited in the variety of function categories (e.g., residential, office) in vibration

[1] Haoyu Huang, School of Engineering, Newcastle University, Newcastle upon Tyne, UK, haoyu.huang@newcastle.ac.uk

[2] Wen-Shao Chang, Lincoln School of Architecture and the Built Environment, University of Lincoln, Lincoln, UK, WChang@lincoln.ac.uk

https://doi.org/10.52202/080513-0172

evaluation. This overlooked categorisation leads to conservative design applications, posing challenges to efficient material use in timber floors. Bearing these considerations in mind, this study seeks to establish a correlation between human responses and various levels of floor vibration by subjective evaluations using human perceptions, with the goal of refining the existing criteria for acceptable timber floor vibration. In this study, vibration tests were conducted on a full-scale timber floor, where participants experienced vibrations in different indoor settings and provided comfort evaluations through questionnaires. The study analyzed acceleration data and questionnaire responses to assess how different indoor environments affect floor vibration comfort perception. Additionally, similar experiments were performed in China and the UK to investigate how experience and expectations influence vibration comfort perception.

2 – TIMBER FLOOR HUMAN PERCEPTION TESTS IN CHINA

2.1 CLT FLOOR AND ITS DYNAMIC PROPERTIES

Figure 1 presents the CLT floor employed in the China test. This CLT floor is a 3-ply CLT with a total thickness of 105mm (layout: 35L-35T-35L). The span of the floor in longitudinal direction is 4.20m and the width is 2.35m. 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 0.458 g/cm^3, the modulus of elasticity is 9200MPa, and the bending strength is 31.3MPa. The moisture content of the timber was 13% tested in a storage condition of 40% R.H. 10℃. As shown in Figure 1, the CLT floor was supported by CLT walls with a thickness of 105mm in four sides. The CLT floor was connected to the CLT walls by drilling self-tapping screws (M7 in diameter and 140mm in length) from the top.

Three accelerometers were installed on the CLT floor, and the sampling rate was 1,000Hz, which complied with the minimum sampling rate specified in BS EN 16929:2018 [10]. 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 between the second accelerometer and the edge in the transverse direction.

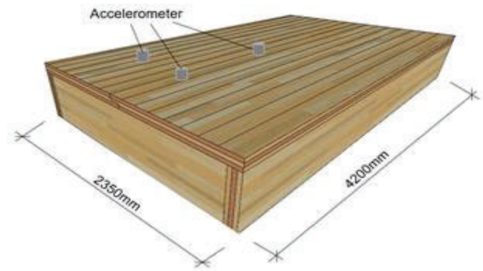


Figure 1 Schematic diagram of the CLT floor tested

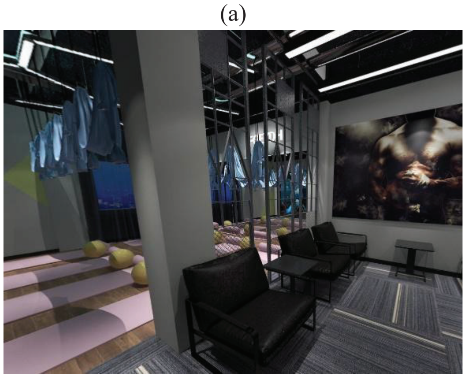
The technologies to excite a floor for modal testing include shaker, impact hammer, heel-drop and human excitation [10-13]. This study followed the heel-drop method suggested in BS EN 16929:2018 for the timber floor and the procedures in this study has fulfilled the requirements. In this study, a person weighing 60kg stood on his toes and then dropped his heels rapidly through a distance of about 65mm. The free vibration response of the CLT floor was recorded by the accelerometers mentioned above. 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 [14-16]. After analysis, the natural frequency of the CLT floor can be determined to be 15.05Hz, and the damping ratio is 12.07%.

2.2 ASSESSMENT ENVIRONMENT SETUP

In this study, two VR environments were set up to simulate different places in real life. As shown in Figure 2, 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 visualised 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 1.2m to assume a scenario in which the test subject sat in the virtual environment.

https://doi.org/10.52202/080513-0172

(a)



(b)

Figure 2 View from VR glasses (a) the bedroom; (b) the rest area in a gym

2.3 TEST PROCEDURES

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%. 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 3. 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 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 60kg 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 experiences, the test subject was asked to have a rest of 5 minutes and then answered a questionnaire. The CLT floor vibration behaviour in each test was recorded by the accelerometers aforementioned.

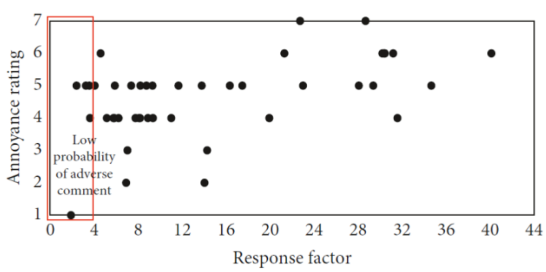
Figure 3 A test subject and the walking/running tester

The questionnaire contains three parts. The first part is basic information concerning their demographic, home circumstances, and experience of building vibration. 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. The third part is the assessment of the annoyance rating of CLT floor vibration in different virtual environments. All the test subjects were asked to assess the serviceability of 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.

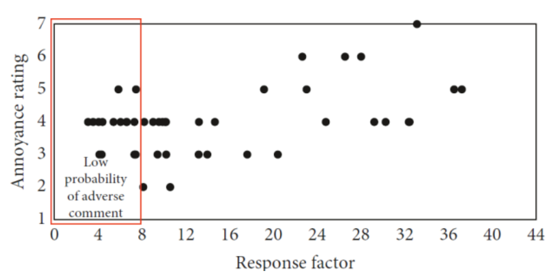
2.3 RESULTS AND DISCUSSION

The fundamental natural frequency of this floor is 15.05 Hz. The frequency-related RMS acceleration obtained by linear interpolation is $9.4 \times 10^{-3} \mathrm{m/s^2}$. Figure 4 (a) and (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 4. It is noteworthy 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, the vibration is acceptable when RF is lower than 4 (for residential) or 8 (for workshops).

As seen in Figure 4 (a), for 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 for bedroom environment, 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 bedroom environment. When response factor is less than 20, only 3% of the questionnaires reported extra uncomfortable. When response factor is equal to or higher than 20, the percentage of extra uncomfortable raised drastically to 62%. As seen in Figure 4 (b), for gym environment, the limit value could be response factor=22. When 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 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 note is that this study drew a preliminary conclusion for revising the standard of timber floor vibration, and further study involving larger sample size should be conducted to obtain a more accurate limit value.



(a)

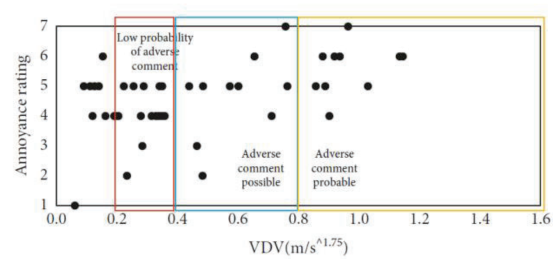


(b)

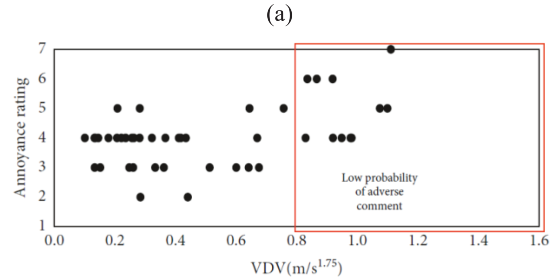
Figure 4 Relationship between annoyance rating and response factor of (a) the bedroom and (b) the rest area in a gym

Figure 5 shows the relationship between annoyance rating and VDV. 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 colours in Figure 5. In following analysis in this paper, the gym environment is categorised as workshop. As seen in Figure 5 (a), for 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, 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 5 (b), for 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 summary, VDV method can generally reflect the vibration acceptability of timber floor vibration.

Another thing to note is that presently only residential buildings, office and workshops are distinguished in 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.



(a)



(b)

Figure 5 The relationship between the annoyance rating and VDV of (a) the bedroom and (b) the rest area in a gym

Apart from acceleration, the effect of environment on annoyance rating was also considered. In this study, two environments were chosen as variables: the bedroom and

https://doi.org/10.52202/080513-0172

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.

In this study, 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 [17, 18].

3 – TIMBER FLOOR HUMAN PERCEPTION TESTS IN THE UK

It should be noted that the participants in China had no prior experience living or working on timber floors. When evaluating the comfort of timber floor vibrations, they might have compared their experience to that of living on concrete floors. It is widely known that factors such as life experience, ethnicity, and nationality can influence people's perception of floor vibrations. Therefore, it is necessary to invite participants from different countries who have experience living on timber floors to take part in the study. Consequently, a same test was conducted in the UK (Figure 6).

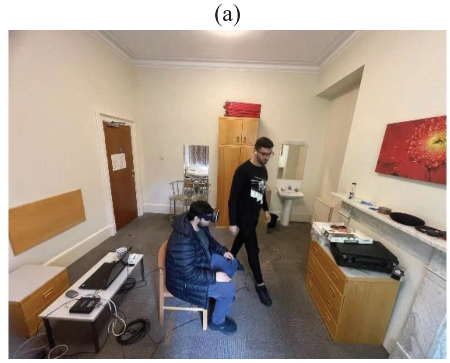
3.1 TEST SET-UP

The test was conducted at Newcastle University as show in Figure 6. The timber floor is a wood joist floor, measured 10.5 m in length and 8 m in width. A CT1500L accelerometer was used to record the acceleration at the floor's central point, with a sampling rate of 2048 Hz and a sensitivity of 5.4 V/g. A heel-drop test was performed to record the floor's acceleration response, and the analysis determined that the floor's natural frequency was 14.24 Hz, with a damping ratio of 14.25%. The VR environments used in this test (bedroom, gym) were the same as those in the Section 2.2.

A total of 22 participants (16 males and 6 females) took part in the test. All participants were in good health and capable of perceiving vibrations normally. Regarding their residential experience, 77% of the participants lived in houses with timber floors, and 86% had previously experienced timber floor vibrations.

The experimental methods and analysis procedures were the same as in the Section 2. A total of 22 participants experienced floor vibrations under mild excitation, and 8 of them agreed to experience the vibrations again under stronger excitation. As a result, a total of 30 questionnaires were collected.

(a)



(b)

Figure 6 Test set-up in the UK (a) accelerometors set-up and (b) human-induced vibration and perception test

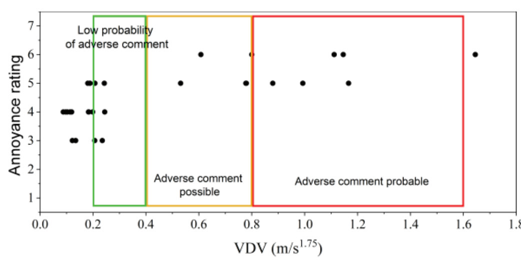
3.2 EXPERIMENTAL RESULTS AND COMPARISON WITH EXISTING STANDARDS

The natural frequency of this floor was found to be 14.24 Hz. Based on the baseline, linear interpolation yielded an RMS acceleration of 8.899×10^{-3} m/s² for this frequency. The corresponding vibration annoyance ratings are presented in Figures 7 and 8, where the coloured boxes indicate the criteria defined by BS 6472-1:2008 and ISO 10137:2007.

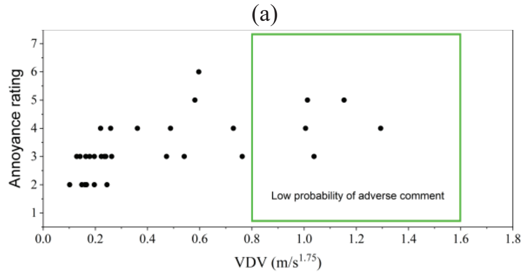
Observing Figure 7 (a) for the bedroom environment, when the VDV was below 0.6, no participants reported significant discomfort. When the VDV was 0.6 or above, 50% of participants reported significant discomfort. The boundary of 0.6 as the VDV criteria aligns with the results from both the UK and China tests. Thus, it can be concluded that the BS 6472-1:2008 standard for timber floors in bedrooms is somewhat conservative. The upper limit of the VDV range for "low probability of adverse comment" could be expanded from 0.4 to 0.6 based on the findings from both countries.

Observing Figure 8 (a), if the response factor of 20, as suggested by the previous China test, is used as the comfort criteria for the bedroom environment, when the response factor was below 20, only 4% of participants reported significant discomfort. When the response factor was 20 or above, 57% of participants reported significant discomfort. This confirms that a response factor of 20 as the comfort criteria for residential environments is supported by both the UK and China tests. However, the existing ISO 10137:2007 standard defines a comfort criteria for residential environments at only 2-4, which appears overly conservative.

Observing Figure 7 (b) and Figure 8 (b) for the gym environment, only one participant reported significant discomfort of rating 6. The vibration that this participant experienced was not among the most intense cases in the dataset, suggesting that this result may be an outlier. Overall, UK participants demonstrated a higher tolerance for timber floor vibrations in gym environments. In the China test, a response factor of 22 was suggested as the comfort criteria for gym environments. However, the UK test results showed significant variability, and no clear comfort criteria could be identified. To establish a comprehensive comfort classification in floor vibration standards, more experimental data is needed.

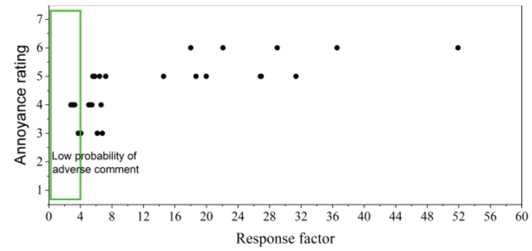


(a)

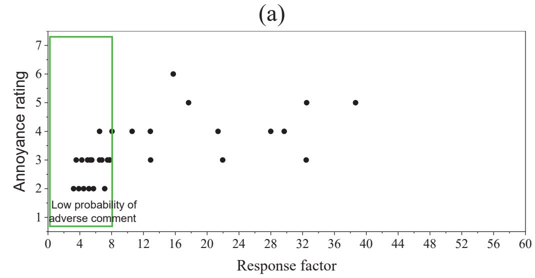


(b)

Figure 7 Relationship between the annoyance rating and VDV of (a) bedroom and (b) gym



(a)

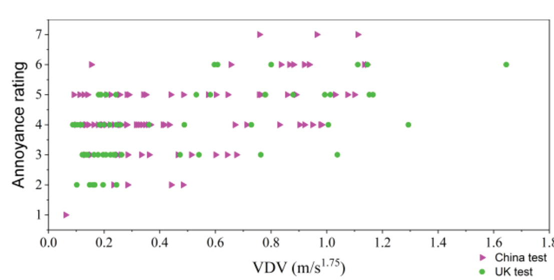


(b)

Figure 8 Relationship between annoyance rating and response factor of (a) bedroom and (b) gym

4 – COMPARISON OF THE TIMBER FLOOR HUMAN PERCEPTIONS BETWEEN UK AND CHINA

A comparison of the experimental results from China and the UK reveals that, for similar floor vibration responses, UK participants generally reported lower vibration annoyance ratings, indicating a higher tolerance for vibrations (Figure 9). Overall, a greater proportion of Chinese participants gave higher annoyance ratings, whereas a greater proportion of UK participants gave lower annoyance ratings (Table 1). This difference may be attributed to the fact that timber structures are more common in the UK. At least based on the randomly selected test samples, most UK participants had prior experience working or living on timber floors. As people become accustomed to timber floor vibrations in daily life, they develop an expectation of such vibrations during experiments, leading to a higher tolerance. When establishing serviceability-related standards for timber floor vibrations, the requirements in China should be stricter than those in the UK to ensure a more comfortable experience for floor users.



https://doi.org/10.52202/080513-0172

Figure 9 Comparison of experimental results between China and the UK

Table 1 Proportion of people with different annoyance ratings in tests in China and the UK

Annoyance rating	UK test		China test	
	Number of people	Proportion (%)	Number of people	Proportion (%)
7	0	0.00%	3	3.41%
6	6	10.00%	10	11.36%
5	14	23.33%	23	26.14%
4	17	28.33%	35	39.77%
3	17	28.33%	12	13.64%
2	6	10.00%	4	4.55%
1	0	0.00%	1	1.14%

5 – CONCLUSIONS

This paper examines the impact of different indoor environments on the perception of timber floor vibration comfort from the perspective of human subjective experience. Full-scale timber floor tests were conducted in both China and the UK. VR glasses were used to simulate different indoor environments, allowing participants to experience floor vibrations under various conditions and provide comfort evaluations. Based on the measured floor acceleration responses and questionnaire survey results, the study assesses the perceived comfort of timber floor vibrations in different indoor environments and compares how indoor settings influence human comfort perception. Additionally, the experimental data from China and the UK were compared with existing floor vibration standards, BS 6472-1:2008 and ISO 10137:2007, to provide recommendations for future revisions. Furthermore, by analyzing data from both countries, the study explores the influence of prior residential experience on the perception of timber floor vibration comfort. The main conclusions are as follows:

(1) For bedroom environments, the VDV criteria for residential comfort in BS 6472-1:2008 appears to be conservative for timber floors. The upper limit of the VDV range for "low probability of adverse comment" could be appropriately expanded. Based on the experimental results of this study, this upper limit could be increased from the current 0.4 to 0.6. The response factor criteria for residential comfort in ISO 10137:2007 is overly conservative, set at only 2-4, and could be increased to 20. Relaxing these criteria in the standards could prevent overly conservative designs and improve cost-effectiveness.

(2) The existing standards lack a comprehensive classification of environmental categories, failing to cover some common real-life scenarios. For gym environments, there is no directly applicable category in the standards, with the closest existing category being workshops. Based on the China experimental results, a response factor of 22 could be set as the comfort criteria. However, the UK data showed significant variability, with no clear comfort criteria, and overall, UK participants exhibited a higher tolerance for timber floor vibrations in gym environments.

(3) Significant differences were observed in annoyance ratings between bedroom and gym environments. Participants generally found timber floor vibrations in bedroom environments more uncomfortable than in gym environments, indicating lower vibration tolerance in private spaces. However, when vibrations were weak, the impact of the environment on comfort perception was minimal.

(4) Compared to Chinese participants, UK participants demonstrated a higher tolerance for timber floor vibrations. This may be attributed to the greater prevalence of timber structures in the UK, where people are more accustomed to timber floor vibrations. When developing comfort standards for timber floor vibrations, different countries should consider their specific contexts, ensuring a comfortable experience while controlling costs and avoiding overly conservative designs. For international standards, it is recommended to include participants from different countries, both with and without prior experience living on timber floors, to create a more inclusive vibration evaluation framework.

6 – REFERENCES

[1] W. S. Chang, R. Harris, and T. Goldsmith. “A New Design Method for Timber Floors – Peak Acceleration Approach.” In: International Network for Timber Engineering Research Meeting 2018. 2018.
[2] C. Wang et al. “Predicting the human-induced vibration of cross laminated timber floor under multi-person loadings.” In: Structures 29 (2021), pp. 65–78.
[3] C. Uí Chúláin and A. M. Harte. “Experimental investigation of the serviceability behaviour of a cross laminated timber floor.” In: Civil Engineering Research in Ireland CERI-ITRN 2018. NUI Galway, 2018.
[4] H. Huang, Y. Gao, and W.-S. Chang. “Human-induced vibration of cross-laminated timber (CLT) floor under different boundary conditions.” In: Engineering Structures 204 (2020), pp. 1–11.
[5] D. Casagrande et al. “Analytical, numerical and experimental assessment of vibration performance in timber floors.” In: Engineering Structures 168.AUG.1 (2018), pp. 748–758.

[6] H. Huang, C. Wang, and W. S. Chang. "Reducing human - induced vibration of cross - laminated timber floor – Application of multi - tuned mass damper system." In: Structural Control and Health Monitoring 28.2 (2020), pp. 1 – 20.
[7] H. Huang and W.-S. Chang. "Application of pre-stressed SMA-based tuned mass damper to a timber floor system." In: Engineering Structures 167 (2018), pp. 143–150.
[8] BSI. BS 6472-1:2008 Guide to evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz) Part 1: vibration sources other than blasting. London, UK, 2008.
[9] ISO. ISO 10137. Bases for design of structures – Serviceability of buildings and walkways against vibrations. Geneva, Italy, 2007.
[10] BSI. BS EN 16929:2018. Test methods - Timber floors - Determination of vibration properties. 2018.
[11] Z. Han, J. M. W. Brownjohn, and J. Chen. "Structural modal testing using a human actuator." In: Engineering Structures 221 (2020), p. 111113.
[12] I. Glisovic and B. Stevanovic. "Vibration behaviours of timber floor." In: World Conference on Timber Engineering. Riva del Garda, Italy, 2010.
[13] P. Hamm, A. Richter, and S. Winter. "Floor vibrations–new results." In: World Conference on Timber Engineering. 2010.
[14] Y. Hua and T. K. Sarkar. "Matrix pencil method for estimating parameters of exponentially damped/undamped sinusoids in noise." In: IEEE Transactions on Acoustics, Speech, and Signal Processing 38.5 (1990), pp. 814–824.
[15] T. K. Sarkar and O. Pereira. "Using the matrix pencil method to estimate the parameters of a sum of complex exponentials." In: IEEE Antennas and Propagation Magazine 37.1 (1995), pp. 48–55.
[16] T. Zieliński and K. Duda. "Frequency and Damping Estimation Methods - An Overview." In: Metrology and Measurement Systems 18.4 (2011), pp. 505–528.
[17] S. W. Han, M.-J. Lee, and K.-H. Moon. "Acceleration Thresholds of Vertical Floor Vibrations According to Human Perception Levels in Korea." In: Advances in Structural Engineering 12.4 (2009), pp. 595–607.
[18] H. Zhou et al. "Design methods to control vibration of solid lumber joist floors." In: Journal of Chongqing Jianzhu University 30.03 (2008), pp. 49–52.

https://doi.org/10.52202/080513-0172