Timber Design Guide 2019-14

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Title:	Mass Timber Floor Systems – vibration serviceability considerations		

Introduction

Consideration of structural vibrations is critical in the design of many buildings and structures. Occupants have increased expectations of the quality of their environment, and modern equipment has stringent vibration requirements to ensure optimal performance. Combined with an increasing desire to create more economical, lighter, and longer-spanning structures, these factors have caused vibration criteria to become a significant consideration in design.

Mass timber floor systems tend to be susceptible to vibration problems, as they are often lightweight and flexible. Vibration performance can often control the structural design of a mass timber floor.

Measuring Vibration

In the past, floor vibration was often addressed by limiting the fundamental frequency of the floor structure to a value above 8Hz, which is an attempt to prevent resonance by keeping the natural frequency well above typical walking pace. However, floors can be excited at higher harmonics (multiples) of a pedestrian's footstep frequency, and shorter spans with higher frequencies also have lower mass, making them easier to excite. Natural frequency alone is not a good measure of vibration performance; the accelerations or velocity being felt provide a better measure.

More advanced analysis methods can be used to calculate the response of a floor to pedestrian footfall. Modal response analysis determines the accelerations or velocities across the floorplate during pedestrian excitation, providing a more precise (although not necessarily more accurate) way of designing and assessing structures.

Vibration Acceptance Criteria

Human acceptance criteria for vibration is highly subjective; a level of vibration that causes one individual to complain might go unnoticed by another. Similarly, vibration that causes concern or distraction for an individual sitting in a quiet office could be acceptable to the same person walking around a common area.

Current vibration acceptance criteria are based on perception studies and attempt to take this subjectivity into account by specifying different targets for different environments. ISO, British, and American standards have converged, and the currently accepted base level of acceleration perceptible by humans is defined by ISO 2631-2 / ISO 10137, as shown in Figure 1.

Human tolerance of vibration varies with the direction, regularity, and duration of vibration. Depending on the frequency of vibration, humans sense vibrations differently –- humans are most sensitive to acceleration in the 4-8Hz range. Posture is also a factor – people have different sensitivities while sitting, standing, or lying down. Intermittent vibrations are more acceptable than frequent occurrences.

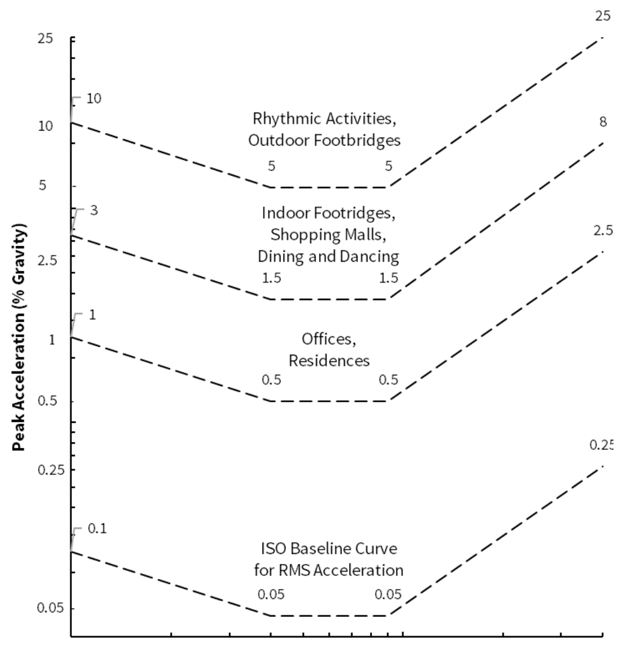

Figure 1: Recommended peak acceleration tolerance limits for human comfort, after Allen and Murray (1993), Design Criterion for Vibrations Due to Walking

Various guidance documents suggest acceleration limits below which there is a low likelihood that occupants will complain of feeling uncomfortable ("low probability of adverse comment"). Recommended limits for various spaces and structure types vary significantly among guidance documents. These discrepancies highlight the difficulty of assigning specific limits in the grey area of vibration perceptibility.

Current accepted acceleration limits in the US expressed as a percentage of gravity can be found for various occupancies in Figure 1. Selection of vibration criteria should be discussed with the client early in schematic design.

Calculated vibration performance levels should be treated only as estimates and can be significantly different from the actual performance of a floor measured in service. The accuracy of vibration performance predictions is low for several reasons:

- Many factors used in the calculation of accelerations are estimates with a high degree of uncertainty and variability.
- There are significant differences in suggested acceleration limits.
- Small variations in predicted acceleration (10% to 20%) are not noticeable; a significant change in terms of perceptibility would generally require a change in vibration level by a factor of two.

For the above reasons, binary pass/fail decisions based on small deviations in calculated performance from guidance limits should be avoided.

Vibration Response of Floors

The vibration response of floor structures to footfall is typically governed by either resonant or transient vibrations, depending on the natural frequency of the floor and its inherent damping (refer Figure 2). Floors with a lower frequency (<10Hz) and low damping (<3.5%) tend to respond in a steady-state (resonant) manner, excited by a continuous series of steps. Higher frequency or heavily damped floors tend to be dominated by a transient 'heel-drop' response.

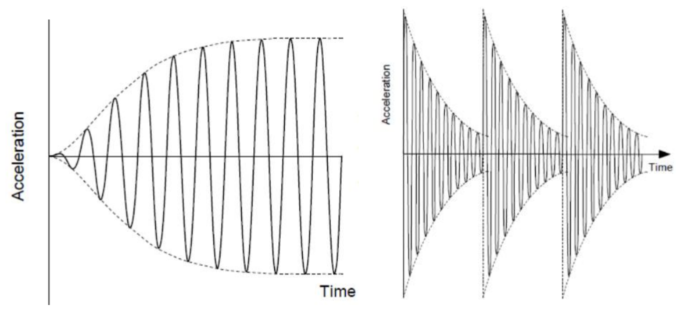

Figure 2: Steady State (Resonant) and Transient (Impulsive) Vibrations

Analysis Methods

Three analysis methods are commonly used to predict footfall vibration performance, generally with increasing level of precision:

- Simplified formulas such as that presented in the ***CLT Handbook***
- Modal response analysis
- Time history analysis

However, as with any analysis, the accuracy of the analysis method is only as good as the accuracy of the input assumptions. It is important not to conflate the increasing *precision* of the above three analysis types with an increase in *accuracy*. Due to the small amplitude of floor vibrations and the significant effect of in-situ effects such as the presence of partitions, damping, or the loading on the floor, predicting accelerations due to human footfall with a high degree of accuracy is difficult.

For evaluating floor vibration, there are various guidelines in North America and Europe which have been developed to determine accelerations. Guides such as the ***American Institute of Steel Construction (AISC) Design Guide 11***, the ***Steel Construction Institute (SCI) P354***, and the ***Concrete Centre CCIP-016*** all provide methods for conducting the three aforementioned types of analyses.

Simplified Formula Approaches

The ***CLT Handbook*** (FPInnovations, 2013) presents a formula which limits the span of a simply supported, bare CLT panel based on the more restrictive of two criteria: deflection under a unit point load and natural frequency. This formula, however, ignores the contribution of different damping levels, the weight of any superimposed mass (such as concrete topping), and any added flexibility of supporting structure, which are all significant factors in vibration performance. The ***CLT Handbook*** formula results in the following maximum spans for typical mass timber panel thicknesses:

4 1/8" thick, 3-ply CLT or 3 1/2" thick NLT/DLT/GLT – 11'-12' *

6 7/8" thick, 5-ply CLT or 5 1/2" thick NLT/DLT/GLT – 15'-17' *

9 5/8" thick, 7-ply CLT or 7 1/4" thick NLT/DLT/GLT – 19'-21' *

**Panels simply supported on rigid supports (e.g. walls), no concrete topping*

Mass timber floor systems commonly have a non-composite concrete or gypsum topping for acoustic isolation. The presence of a topping has a significant impact on the vibration characteristics of a mass timber floor. The increased floor mass tends to reduce the natural frequency, but it also increases the modal mass of the floor system and thus can make it harder to excite with footfall. Depending on topping thickness, it can also add some stiffness to the floor assembly. The ***CLT Handbook*** recommends that the calculated maximum floor span be reduced by 10% for floors with topping. That recommendation is overly conservative and often inappropriate.

For early-stage design with mass timber panels supported on bearing walls, the ***CLT Handbook*** formula can be used only as an initial estimate of the maximum vibration-controlled span. For panels supported on beams, this formula is unconservative, because the beams contribute greatly to the flexibility of the system. A more detailed acceleration analysis may be appropriate in this case.

Other simplified formulas for assessing performance are presented in the ***SCI***, ***CCIP***, and ***AISC*** design guides. These formulas calculate the theoretical steady-state acceleration based on a series of underlying simplifications and assumptions which are baked into the formulas. There are significant differences in the assumptions between the three guides.

Utilizing these simplified formulas to evaluate mass timber floor systems should be done with caution, as they have often been calibrated to in-situ testing performed on the material system the guide was written for (e.g. composite steel or concrete floors).

Modal Response / Time History Analysis

The most precise assessment of floor response is a time history analysis incorporating an estimation of walking paths, forcing function, and response points on the floor at which vibration should be measured. This level of analysis is rarely performed and usually not required for floor structures.

A simplified modal response analysis assessment method is based on a 'response-spectrum' type approach, using a square root sum of squares (SRSS) method to sum the response contribution to the acceleration from each mode. This method is more precise than a simple hand calculation. It assumes that the excitation force is applied continuously (resonance achieved), and that a full steady state response occurs at the most responsive location on the floor – even though any walking path is of finite length and would only cross this point briefly.

Performing a modal analysis and calculating resulting accelerations requires an accurate finite element (FE) model to predict the dynamic response of the structure.

The accuracy of FE model results can be illusory, as they are highly dependent on the modelling assumptions made, and engineering judgement plays a large part in the review of the output. Predictions can be heavily influenced by parameters such as the number of bays modelled or the value of damping assumed.

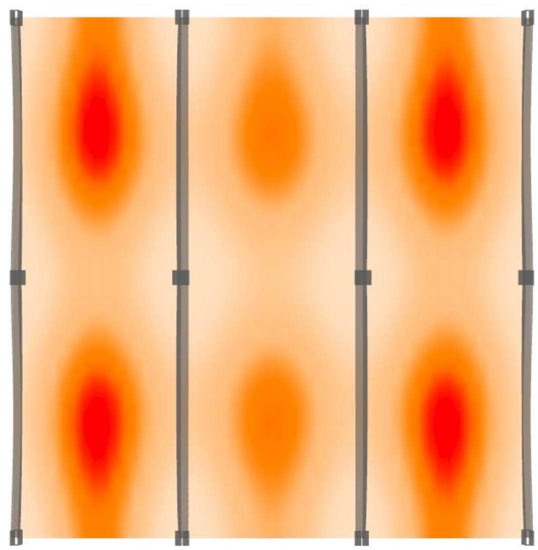

Figure 3: Acceleration Output across a floorplate from an FE Model

Mass Timber Floors

Mass timber floors tend to have low mass and stiffness, leading to potential problems with vibration performance at relatively short spans.

When performing analysis to assess accelerations on a floor plate, modal damping in the range of 2.5% - 3.5% can be assumed. The stiffening effect of composite action between the mass timber panel and the concrete topping should be ignored unless the assembly is explicitly designed and detailed as composite. The effect of panels which are continuous over multiple spans does not improve the vibration performance much if there is a concrete topping, as the natural frequency does not change between single- and double-span, and the topping will typically engage the modal mass of adjacent bays in any case.

Mass timber suppliers often provide vibration-limited span tables, but these are typically based on the ***CLT Handbook*** formula and may be unconservative if the floor is supported on flexible beams rather than rigid bearing walls.

Conclusion

Vibration design of mass timber floor systems often controls the floor panel selection and thickness.

For floor systems other than simple wall-supported spans, the use of the latest ***CCIP/SCI/AISC*** guidance using a simplified modal response analysis along with FE modelling is generally recommended. Acceleration limits recommended are themselves relatively coarse indicators of acceptability and should be used with appropriate engineering judgement along with the review of results from the FE models. Vibration performance should be discussed early with clients to select a performance level.

- There is no black and white analysis method or criteria.
- Vibration performance and human perception are on a continuum.
- Acceptable level of vibration performance must be discussed early with clients.

It is important to note that more detailed analysis can only give an idea of the range in which any floor system will perform.

A more detailed ***Mass Timber Floor Vibration Guide*** is expected to be released in 2020 with more specific recommendations on analysis methods.

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Bibliography / Useful References

Floor vibrations due to Human Activity, AISC Design Guide 11 – Murray, Allen and Ungar, 2017

Design of Floors for Vibration: A new Approach, *SCI P354* – Smith, Hicks & Devine, 2009

A design guide for footfall induced vibration of structures, CCIP-016 – Willford & Young – The Concrete Centre – 2006

SETRA – Footbridges: Assessment of vibrational behaviour of footbridges under pedestrian loading – 2006

ISO 2631, Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1 (1997): General requirements, Part 2 (2003): Vibration in buildings

ISO 10137: 2007 – Bases for the design of structures – Serviceability of structures and walkways against vibrations

BS 6472-1: 2008, Guide to evaluation of human exposure to vibration in buildings

Bachmann, H et al., 'Vibration Problems in Structures', Birkhauser Verlag, Berlin 1995

Dynamics of Structures – Clough and Penzien