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Technical paper

Design of cross-laminated timber (CLT) floors for human-induced vibrations

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ABSTRACT

Cross-laminated timber (CLT) is an innovative engineering wood product made by gluing layers of solid timber boards placed in an orthogonally alternating orientation to the neighbouring layers. CLT panels provide an efficient solution for floors in single- and multi-storey buildings. Due to their light weight and often long-span, the design of these floors is generally governed by serviceability limit state criteria, that is, deflection or vibration limits. Vibrations induced by dynamic actions, such as people walking and their everyday activities, cannot result in structural failure but may cause discomfort to occupants if vibrations are not properly controlled. This paper gives an overview of some available methods for the vibration serviceability design of residential CLT floors. Differences between these methods are discussed through the consideration of criteria and their limit values. Although some criteria are common to certain methods, it may happen that the same criteria take into account different factors. In order to get a better description of the actual behaviour of floor structure, certain classifications of floors based on vibration serviceability performance were introduced in design methods.

1 Introduction

Cross-laminated timber (CLT) is a massive engineering wood product made by gluing cross-wise layers of solid timber boards together to form large-scale panels. CLT products are usually fabricated with an odd number of layers (in general, three to seven layers). Due to their excellent in-plane and out-of-plane resistance, CLT panels have become very common for walls and floors. Advantages such as dimensional stability, good acoustic and thermal properties, and a high level of prefabrication make CLT a competitive structural material for many building types.

For CLT panels used as floor elements, serviceability limit states (deformations, vibrations) generally control the design. Although floor vibrations may result from many sources (e.g. use of machinery, external traffic, explosions), the most common and problematic ones are caused by the occupants themselves from their everyday activities. Such vibrations are particularly problematic because they cannot be easily isolated from the structure and they occur frequently [1]. Human-induced vibrations do not collapse floors, but they can annoy occupants or cause malfunctions of vibration-sensitive equipment.

When compared to heavy floors such as those made of concrete, the amplitudes of vibration responses found in timber floors are relatively high. This is because amplitudes of response are inversely proportional to the self-weight of the structure being vibrated. As human bodies are generally sensitive to vibrations, this high-level response can cause discomfort and disturbance to building occupants. As a result, design requirements for disturbing vibration performance are especially important for light-weight floors made of materials such as timber. New floor systems, such as CLT floors, differ in mechanical characteristics compared to traditional joist floors, as strength and stiffness are higher both in the load-bearing (longitudinal) and transverse directions. This also improves vibration performance, but the issue of floor vibrations induced by human activities is still very significant since new building designs allow buildings with larger spans.

Vibrational performance of wood floor systems has received a lot of attention in the last few decades, and different design rules have been suggested. Proposed design methods range from simple limitations of static deflection to those intended to limit fundamental frequency and vibration velocity or acceleration levels at floor surfaces caused by defined excitations [2]. However, the vibration serviceability design criteria applied to traditional timber floors are probably not appropriate for CLT floor design.

This paper focuses on the basic principles for the vibration design of residential floors made of cross-laminated timber. Some available design methods are presented and compared. Due to differences in considered parameters and limit values, application of these methods may lead to significantly different results.

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2 Floor dynamics

Acceleration and deceleration of the human body during various human activities cause dynamic forces. Forces depend upon many factors, including characteristics of the person(s) involved, activity being undertaken (e.g., walking, running, jumping), number of people, whether activities of different people are coordinated, and characteristics of the floor surface [3]. Walking excitation is commonly associated with the annoying vibration of timber floors. Walking frequency (common range 1.5-2.5 Hz) has a direct impact on the dynamic load applied. The dynamic force of walking has been found to excite frequencies up to the third or fourth harmonic of walking frequency [4].

The vibration response of a floor when subjected to dynamic loading depends on its stiffness, mass, and damping. For each floor mode of vibration, stiffness and mass determine the floor's natural frequencies, while damping affects the time it takes for an induced vibration to decay. Depending on the value of the fundamental frequency, the vibration response of the floor due to people walking may differ [5]. So-called low-frequency floors have a fundamental frequency below 8-10 Hz and can respond to walking excitation with resonant vibrations. The resonance is constantly maintained by continuous walking. On the other hand, high-frequency floors with a fundamental frequency above 8-10 Hz show a transient vibration response to each individual heel strike from each footstep. Depending on the intervals between successive impacts and the damping of vibration, adjacent transient vibration responses may interact with each other.

The response of floors to an impact can be represented by the time history of displacement, velocity, or acceleration [6]. Quantities such as peak value or root-mean-square (r.m.s.) value have been used as a measure of human sensitivity to vibration. The peak value is extracted from the initial part of the response (forced vibration) due to an impact. The r.m.s. value is determined from the entire response, including the initial forced and free vibration parts of the response.

The use of CLT elements has altered the characteristics of the dynamic response of floors and complete buildings, resulting in more vibration serviceability problems. At least in part, this is because engineered wood products, such as CLT, increase the modal stiffness-to-mass ratio and the design live load-to-dead load ratio, both of which tend to result in increased vibration acceleration levels [2].

3 Human perception of floor vibrations

The human body is an incredibly complex and sensitive receiver that is self-adapting and more or less susceptible to almost any type and level of motion, such as periodic, random, or transient vibrations, which normally occur in nature [7]. Acceptable vibration levels for human occupancy vary with the individual's activity, body posture, life environment, and expectation of felt vibrations. The presence of visual or audio effects may significantly reduce the acceptable vibration magnitude. Therefore, it is difficult to set the threshold for human perception of vibrations.

The characterization of building vibration with respect to human response is given in ISO 10137 Annex C [8], which includes "base curves" expressed as a function of r.m.s. acceleration and frequency. At vibration acceleration magnitudes below the values corresponding to the base curves, in general, adverse comments, sensations, or complaints are very rare. Since the magnitude that is considered satisfactory, depends on the circumstances, multiplying factors are used to increase the acceleration level of these base curves according to the intended use of the building. These multiplying factors are referred to as "response factors."

The base curve for vertical vibration is presented in Figure 1. The graph shows that the perception threshold for vibrations is lowest for the frequency range between 4 and 8 Hz, with a constant value of $a_{\text{rms,base}} = 0.005$ m/s^2. Vibrations having a frequency between 4 and 8 Hz are particularly critical because large body organs within the rib cage and abdomen resonate within this frequency range. Above 8 Hz, the minimum perception level is not constant in terms of acceleration, but it increases as the frequency increases. However, when this part of the curve is integrated, it can be shown that it is constant in terms of velocity with a value of $v_{\text{rms,base}} = 0.0001$ m/s. Therefore, below the floor frequency of 8 Hz, the acceleration criterion for vibration perception threshold can be applied, and above the 8 Hz, velocity criterion can be applied.

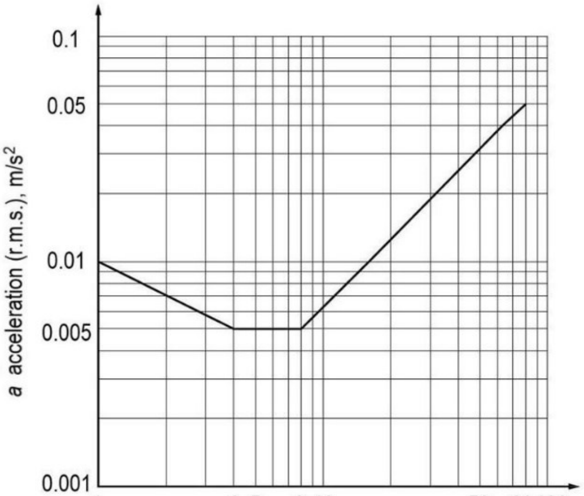

Figure 1. Building vibration z-axis base curve for acceleration (vertical direction) [8]

4 Design methods for CLT floor vibrations

The vibration serviceability design method in current Eurocode 5 [9] essentially refers to the design of joisted floors, where annoying vibration is attributed to isolated floor structure. As CLT floors are solid slabs, their vibration performance differs from that of traditional timber floors. Due to the fact that shear flexibility in CLT is of crucial importance and is already taken into account when calculating deflections, it is also mandatory to consider it in the context of vibrations. CLT slabs can have hinge-like joints between adjacent segments that enforce vertical translation continuity but not continuity of curvature at those locations, which makes their behaviour inconsistent with joisted floors [10]. Due to the orthotropic nature of CLT, floor stiffness is not equal in perpendicular directions, but appropriate support conditions can be provided at all edges. For floor elements supported on four sides, the transverse load-carrying effect should be taken into account. For multi-span systems, the continuous slab effect should be considered.

Multi-storey CLT buildings are generally of platform construction, where each successive storey is built from the floor below; hence, the floor is clamped in between walls of two storeys. A degree of semi-rigidity is therefore expected in all CLT floor-to-wall connections, which, combined with the stiffness of the walls above and below, will influence the dynamic response of the floor [11]. Thus, another highly important aspect of vibrations is seen in the influence of support conditions (e.g., hinged, partly clamped, fully clamped) and in the influence of upper-storey loads transmitted through the walls on the degree of clamping. In addition, the vibration behaviour of CLT floors is strongly influenced by non-load-bearing internal walls, flooring systems, and suspended ceilings [12].

4.1 Design method according to Hamm et al.

The vibration serviceability design method proposed by Hamm et al. [13] is the result of a research project at the Technical University of Munich that involved experimental and theoretical investigations of different types of timber floors (timber-joist floors, timber-concrete floors, and massive timber floors). Based on this research, the Austrian National Annex NORM B 1995-1-1 [14] was created. It should be noted that this is the only national annex to Eurocode 5 that addresses CLT floor vibrations.

Rules for design and construction applicable to timber floors are divided into three different classes according to Table 1. The first step is to decide whether floors should have higher or lower vibration performance demands, or no demands at all.

In general, the fundamental frequency f_1 of the floor is used for verification of the frequency criterion. The fundamental frequency of a simply supported rectangular floor can be calculated as:

- For floors supported on two sides:

$$f_1 = \frac{\pi}{2 \cdot L^2} \sqrt{\frac{(EI)_L}{m}} \quad [\text{Hz}] \tag{1}$$

- For floors supported on all four sides:

$$f_1 = \frac{\pi}{2 \cdot L^2} \sqrt{\frac{(EI)_L}{m}} \sqrt{1 + \left(\frac{L}{B}\right)^4 \frac{(EI)_B}{(EI)_L}} \quad [\text{Hz}] \tag{2}$$

where:

L	is floor span, in m;
B	is floor width, in m;
m	is mass per unit area of floor, in kg/m^2.
$(EI)_L$	is effective stiffness in longitudinal direction of the CLT element (with possible final screed, but without composite action, just adding its own moment of inertia), in Nm^2/m;
$(EI)_B$	is effective stiffness in transverse direction of the CLT element, where $(EI)_L > (EI)_B$, in Nm^2/m.

Since subjective evaluation of the vibration behaviour of floors is not correlated with frequency, it is equally important to check the stiffness criterion. Deflection of the floor due to a point load of 2 kN may be determined as follows:

$$w_{2\text{kN}} = \frac{2 \cdot L^3}{48 \cdot (EI)_L \cdot B_{\text{eff}}} \quad [\text{mm}] \tag{3}$$

Table 1. Floor classes, constructive requirements and limiting values of criterions [13]

	Floor class I	Floors class II	Floors class III
Vibration demands	Floors with higher demands	Floors with lower demands	Floors without demands
Description of perception of vibrations	- Vibrations are not perceptible or perceptible only when concentrating on them - Vibrations are not annoying	- Vibrations are perceptible - Vibrations are not annoying	- Vibrations are clearly perceptible - Vibrations are sometimes annoying
Type of use	- Corridors with short span - Floors with different occupancies - Floors in offices	- Floors inside occupancies - Floors in single-family houses under normal use	- Floors under non-residential rooms or roof spaces
Constructive requirements	Floating, heavy or light screed on grit fill or not	Floating, heavy or light screed on grit fill or not	-
Frequency criterion	f_{limit} = 8 Hz	f_{limit} = 6 Hz	-
Stiffness criterion	w_{limit} = 0.5 mm	w_{limit} = 1.0 mm	-
Acceleration criterion	a_{limit} = 0.05 m/s^2	a_{limit} = 0.1 m/s^2	-

with

$$B_{\mathrm{eff}} = \min\left\{\frac{L}{1.1}\cdot\sqrt[4]{\frac{(EI)_B}{(EI)_L}};B\right\} \tag{4}$$

where:

B_{eff} is effective floor width for calculating deflection, in m;

L, B, $(EI)_L$ and $(EI)_B$ are as previously defined.

The reason for using a load of 2 kN instead of the standard 1 kN was the good correlation between deflection values and subjective vibration behavior evaluation.

In the verification procedure, the vibration serviceability limit state for CLT floors is satisfied if the limiting values given in Table 1 are not exceeded. The fundamental frequency for floors classified as floor classes I and II must be at least $f_{1,\min} = 4.5$ Hz. In the case of floor structure with $f_{1,\min} \le f_1 \le f_{\mathrm{limit}}$, the limiting value of vibration acceleration should be satisfied in addition to the stiffness criterion. The value of vibration acceleration can be calculated as follows:

$$a = \frac{F_{\mathrm{dyn}}}{M^{*}\cdot 2\cdot\zeta} = \frac{0.4\cdot F(t)}{0.25\cdot m\cdot L\cdot B\cdot 2\cdot\zeta} \quad \left[\mathrm{m/s^2}\right] \tag{5}$$

where:

F_{dyn} is total dynamic force that includes factor of 0.4 considering that the force on the floor is acting during a limited time and not always in the middle of the span, in N;

$F(t)$ are harmonic parts of the force on the floor (for third harmonic part $F(t) = 70$ N);

M^{*} is modal mass of the floor, in kg;

ζ is modal damping ratio of floor construction (for bare CLT floors $\zeta = 0.01$; for CLT floors with floating screed $\zeta = 0.02$);

m, L and B are as previously defined, but for this criterion B should be less than $1.5\cdot L$.

4.2 Design method according to Thiel et al.

Based on in-situ measurements on CLT buildings at different construction phases conducted by the Competence Centre holz.bauforschungsgmbh Austria, Thiel et al. [15] expanded and modified design method from Hamm et al.

As previously stated, vibration acceleration must be checked if the fundamental frequency is less than the critical value, in addition to frequency and stiffness criteria. Without detailed explanation, as the following equations refer to the previous design method, the focus is on the additional parameters that are taken into account.

When a floor is supported on all four sides, the transverse load-carrying effect should be considered. That is, both torsional stiffness D_{xy} and effective bending stiffness in the transverse direction $(EI)_B$ should be included in the fundamental frequency calculation, as shown below:

$$f_1 = \frac{\pi}{2\cdot L^2}\sqrt{\frac{(EI)_L}{m}}\sqrt{1+\left(\frac{L}{B}\right)^2\cdot\frac{2\cdot D_{xy}}{(EI)_L}+\left(\frac{L}{B}\right)^4\frac{(EI)_B}{(EI)_L}} \quad [\mathrm{Hz}] \tag{6}$$

In addition, shear flexibility in CLT elements should be considered using the effective apparent bending stiffness $(EI)_L$ (based on bending and shear deformations). Additionally, different support conditions and a continuous floor effect for multi-span floors can be considered through modification factors k_m and $k_{f,2}$ that multiply the frequency.

In the examination of the stiffness criterion, the maximum instantaneous vertical deflection due to a concentrated static force F=1 kN should be determined and compared with the limit value. Load distribution and shear flexibility should be considered when calculating the deflection:

$$w_{1\mathrm{kN}} = \frac{F\cdot L^3}{48\cdot(EI)_L\cdot B_{\mathrm{eff}}}+\frac{F\cdot L}{4\cdot(GA)_L\cdot B_{\mathrm{eff}}} \quad [\mathrm{mm}] \tag{7}$$

where:

B_{eff} is floor effective width according to eq. (4);

$(GA)_L$ is effective shear stiffness in longitudinal direction of the CLT element.

Vibration acceleration depends on the effective (generalised) floor mass M_{gen}, floor fundamental frequency f_1, excitation frequency f_f (see Table 2), Fourier coefficient of the prevailing harmonic partial oscillation $\alpha_{i,f1}$ (see Table 2), self-weight of the excitatory person $F_0 = 700$ N and the modal damping ratio ζ. For single-span floors, it may be determined as follows:

$$a = \frac{0.4\cdot\left(\dfrac{F_0\cdot\alpha_{i,f_1}}{M_{\mathrm{gen}}}\right)}{\sqrt{\left(\left(\dfrac{f_1}{f_f}\right)^2-1\right)^2+\left(2\cdot\zeta\cdot\dfrac{f_1}{f_f}\right)^2}} \quad \left[\mathrm{m/s^2}\right] \tag{8}$$

with effective floor mass:

$$M_{\mathrm{gen}} = m\cdot\frac{L}{2}\cdot B_{\mathrm{eff}} \quad \left[\mathrm{kg/m^2}\right] \tag{9}$$

where B_{eff} is floor effective width according to eq. (4), but with $B_{\mathrm{eff}} \le$ half room width $B/2$.

The damping ratio ζ for CLT floors was found to be between 2% and 3.5%, depending on the type of floor construction and support conditions.

Table 2. Fourier coefficients and excitation frequencies based on fundamental frequency [15]

Fundamental frequency f_1 [Hz]	Fourier coefficient $\alpha_{i,f1}$	Excitation frequency f_f [Hz]
$4.5 < f_1 \le 5.1$	0.20	f_1
$5.1 < f_1 \le 6.9$	0.06	f_1
$6.9 < f_1 \le 8.0$	0.06	6.9

4.3 Design method according to Hu and Gagnon

Hu and Gagnon [16] developed design criteria based on understanding the fundamentals of CLT floor vibrations as well as laboratory tests and subjective evaluations of vibration floor performance conducted in Canada. The CSA O86 Technical Committee included this vibration-controlled design method in the CLT design guidance of CSA Standard [17].

Based on the laboratory study data analysis, it was found that vibrations induced by normal walking could be effectively controlled by designing a floor with a proper combination of longitudinal stiffness and mass, as expressed by the fundamental frequency f_1 and the 1 kN static deflection w of a 1 m wide CLT panel. The design criterion is expressed as:

- For bare CLT floors or CLT floors with light topping:

$$\frac{f_1}{w^{0.7}} \geq 13.0 \tag{10}$$

- For CLT floors with heavy topping (mass per unit area > 100 kg/m2):

$$\frac{f_1}{w^{0.7}} \geq 20.0 \tag{11}$$

Proposed limit values may be increased for multi-span floors and floors with semi-rigid or rigid support conditions, as these changes in parameters increase the natural frequency.

The fundamental frequency of a simply supported CLT panel may be calculated as follows:

$$f_1 = \frac{\pi}{2 \cdot L^2}\sqrt{\frac{(EI)_L}{\rho A}} \ \text{[Hz]} \tag{12}$$

where:

L is floor span, in m;

$(EI)_L$ is effective apparent bending stiffness in span direction for 1 m wide panel, which takes into account shear deformation, in Nm^2;

ρ is density of CLT panel, in kg/m^3;

A is cross section area of 1 m wide CLT panel, in m^2.

Static deflection at mid-span of a simply supported CLT panel under a 1 kN point load may be calculated as:

$$w = \frac{1000 \cdot F \cdot L^3}{48 \cdot (EI)_L} \ \text{[mm]} \tag{13}$$

where:

F is vertical concentrated static force of 1000 N applied at mid-span of the floor;

L and $(EI)_L$ are as previously defined.

,4.4 Design method according to Abeysekera et al.

Abeysekera et al. [18] presented new design rules for the vibration serviceability of timber floors, which are currently being drafted in CEN/TC250/SC5/WG3 Sub-group 4 “Vibrations”. The revision of the chapter on vibrations in Eurocode 5 is adapted for use in the design of floor structures made from CLT.

The new design method for human-induced floor vibrations introduces floor performance levels as given in Table 3. Level I stands for the best floor performance level, VI for the worst, but still acceptable, and VII for an unacceptable floor performance level. Table 4 shows the recommendation for selecting the floor performance level for residential categories. Nevertheless, these floor performance levels should be specified in the National annexes of each member country, as it is necessary to consider cultural variations between countries, or they should be specified by investors or designers.

For floor performance levels from I to VI, no further investigations are necessary if requirements in respect to fundamental frequency, acceleration or velocity, and stiffness from Table 3 are satisfied.

In the case of single- or multi-span rectangular floors supported on two or four sides directly onto rigid supports, primarily subjected to uniform loading, the fundamental frequency may be determined as:

$$f_1 = k_{e,1} \cdot k_{e,2} \cdot \frac{\pi}{2 \cdot L^2}\sqrt{\frac{(EI)_L}{m}} \ \text{[Hz]} \tag{14}$$

with

$$k_{e,2} = \sqrt{1 + \left(\frac{L}{B}\right)^4 \frac{(EI)_B}{(EI)_L}} \tag{15}$$

Table 3. Floor performance levels and corresponding criterions [18]

Criterion	Floor performance levels						
	I	II	III	IV	V	VI	VII
Frequency criterion f_1 [Hz] ≥	4.5						
Stiffness criterion w [mm] ≤	0.25		0.5	0.8	1.2	1.6	no criterion
Response factor R ≤	4	8	12	16	20	24	
Acceleration criterion (whenf_1< 8 Hz) a_{rms} [m/s^2] ≤	R × 0.005						
Velocity criterion (whenf_1 ≥ 8 Hz) v_{rms} [m/s^2] ≤	R × 0.0001						

Table 4. Recommended selection of floor performance levels for residential use category [18]

Use category	Quality choice	Base choice	Economy choice
Residential – multi-storey	Level I, II, III	Level IV	Level V
Residential – single house	Level I, II, III, IV	Level V	Level VI

where:

$k_{e,1}$ is frequency multiplier in the case of a double-span floor on rigid supports;
$k_{e,2}$ is frequency multiplier in the case of a two-way spanning floor;
L is floor span, in m;
B is floor width, in m;
$(EI)_L$ is apparent effective bending stiffness in longitudinal floor direction which should take into account shear deformation where applicable and may take into account bending stiffness of floating floor or screed (without composite action), in Nm^2/m;
$(EI)_B$ is effective bending stiffness in transverse floor direction, in Nm^2/m;
m is mass per unit area of the floor, in kg/m^2.

When calculating vibrations, floor mass should be a unique value, including at least the sum of mass caused by permanent loads (the self-weight of the floor as well as all supported or suspended horizontal layers). The floor mass may also include mass caused by the quasi-permanent value of uniformly distributed imposed loads. It is recommended to consider only additional mass induced by movable equipment (such as furniture) limited to 10% of total imposed loads.

When all factors affecting deflection are taken into account, such as when floors are partially or completely supported by non-rigid supports or when floors are not only subjected to uniform loading, eq. (14) can be replaced with:

$$f_1 = k_{e,1}\cdot k_{e,2}\cdot\frac{18}{\sqrt{\delta_{sys}}}\quad[\mathrm{Hz}] \tag{16}$$

where δ_{sys} is deflection of the floor under self-weight load applied on a single bay in a multi-span case, in mm.

When the fundamental frequency of the floor is below 8 Hz, floor vibration is assumed to be resonant. For resonant vibration design situations, root mean square acceleration a_{rms} may be approximated as:

$$a_{rms} = \frac{0.4\cdot\alpha\cdot F_0}{\sqrt{2}\cdot 2\cdot\zeta\cdot M^*}\quad\left[\mathrm{m/s^2}\right] \tag{17}$$

where:

α is Fourier coefficient according to the fundamental frequency as $\alpha = e^{-0,4\cdot f_1}$;
F_0 is vertical load of a walking person, usually taken as 700 N, in N;
ζ is modal damping ratio;
M^* is modal mass (taken as 50% of $m\cdot L\cdot B$ for floors supported on two sides, and as 25% of $m\cdot L\cdot B$ when floor is supported on all four sides), in kg.

When the fundamental frequency of the floor is equal to or above 8 Hz, floor vibration is assumed to be transient. For transient vibration design, root mean square velocity v_{rms} can be approximated as follows:

$$v_{rms} = \beta\cdot v_{tot,peak} = \beta\cdot k_{imp}\cdot v_{1,peak} = \beta\cdot k_{imp}\cdot k_{red}\cdot\frac{I}{M^*}\quad[\mathrm{m/s}] \tag{18}$$

with

$$k_{imp} = \max\left\{\begin{matrix} 0.48\cdot\left(\frac{B}{L}\right)\cdot\left(\frac{(EI)_L}{(EI)_B}\right)^{0.25} \\ 1.0 \end{matrix}\right\} \tag{19}$$

$$I = \frac{42 f_w^{1.43}}{f_1^{1.3}} \tag{20}$$

where:

β = $(0.65 - 0.01\cdot f_1)\cdot(1.33 - 11.0\cdot\zeta)\cdot\eta$;
η = $1.52 - 0.55\cdot k_{imp}$ when $1.0 \le k_{imp} \le 1.5$, else $\eta = 0.69$;
$v_{tot,peak}$ is total peak velocity response, in m/s;
k_{imp} is impulse multiplier factor;
$v_{1,peak}$ is peak velocity response for fundamental mode, in m/s;
k_{red} is reduction factor with a value of 0.7 considering that exciting source on floor and sensing person are at a distance from each other;
I is mean modal impulse, in Ns;
f_w is walking frequency and is assumed to be 1.5 Hz for residential floors, in Hz;
ζ is modal damping ratio;
M^*, L, B, $(EI)_L$, $(EI)_B$ and f_1 are as previously defined.

Realistic floor damping values are needed for the design procedure. Unless other values are proven to be more appropriate, the modal damping ratio for CLT floors may be assumed to be between 2.5 and 6% depending on floor construction, support conditions, the presence of non-load-bearing partitions, and the presence of people on the floor.

For all floors, there is a stiffness criterion that checks maximum deflection due to a single point load of 1 kN placed in the most unfavourable position of a single span floor strip having an effective width B_{eff} calculated according to eq. (4). Although this empirical criterion based on historical practice is not very relevant for CLT floors due to the neglect of floor mass, it allows an approximate comparison of proposed performance levels with existing requirements. The maximum deflection in mid-span of a single-span floor may be calculated as follows:

$$w = \frac{F\cdot L^3}{48\cdot(EI)_L\cdot B_{eff}}\quad[\mathrm{mm}] \tag{21}$$

where all of the parameters are as previously defined.

5 Calculation of the stiffness properties of CLT floors

As stiffness properties participate in each vibrational serviceability design method, it is important to specify how they can be calculated. Even though advanced plate theories were proposed, the current design of CLT elements, usually treated as one-meter-wide panel strips under transverse load, is based on beam theories. Traditional Euler-Bernoulli beam theory is the most commonly used approach for bending elements. However, as a result of shear deformations in CLT elements, it cannot be applied directly. There are basically three analytical methods for calculating the bending properties of CLT floors: the Gamma method, the K-method, and the Shear analogy method [19]. The main assumption when applying these methods is that floors are simply supported, loaded perpendicular to their plane, and carry load only in one longitudinal direction.

5.1 Gamma method

The Gamma method is based on the theory of a mechanically joined beams and is mostly used for beams with member sections flexibly connected by mechanical fasteners that are evenly spaced. Cross-sections and joint stiffness are constant in the direction of the beam axis. Shear deformation is accounted for by connection efficiency factors γ, which increase bending deformation, where γ= 1,0 represents a rigid connection and γ = 0 represents no connection at all. The Gamma method is shown in Annex B of Eurocode 5 [9], and current European Technical Approvals (ETA) have adopted this method for CLT bending elements.

Certain changes to the original theory were introduced so that it could be applied to CLT panels. Assuming that only boards in the longitudinal direction are carrying the load, only longitudinal layers are used for calculating the effective bending stiffness. The effect of cross layers is considered only through their rolling shear properties as the stiffness of imaginary fasteners connecting longitudinal layers. Shear deformations in longitudinal layers are ignored, so this method should be applied to CLT floors with span-to-depth ratios greater than 10.

Effective bending stiffness in the longitudinal direction, for cases with two or three longitudinal layers, is defined as follows:

$$(EI)_{L,\mathrm{eff}} = \sum_{i=1}^{n} (E_i \cdot I_i + \gamma_i \cdot E_i \cdot A_i \cdot z_i^2) \tag{22}$$

with

$$\gamma_i = \frac{1}{1 + \frac{\pi^2 \cdot E_i \cdot A_i}{L^2} \cdot \frac{t_{i,2}}{G_{R,i,2} \cdot b}} \quad \text{for } i = 1 \text{ and } i = 3 \tag{23}$$

and

$$\gamma_2 = 1 \tag{24}$$

where:

n is number of longitudinal layers;

E_i is modulus of elasticity parallel to the grain of the i-th longitudinal layer;

I_i is moment of inertia of the i-th longitudinal layer ($I_i = b \cdot t_i^3 / 12$);

A_i is cross-section area of the i-th longitudinal layer ($A_i = b \cdot t_i$);

b is width of CLT cross-section (usually taken as 1 m);

t_i is thickness of the i-th longitudinal layer;

z_i is distance between the center point of the i-th longitudinal layer and neutral axis of CLT cross-section, as presented in Figure 2;

$t_{i,2}$ is thickness of cross layer next to the i-th layer;

$G_{R,i,2}$ is shear modulus perpendicular to the grain (rolling shear modulus) of cross layer next to the i-th layer; it can be assumed to be 1/10 of shear modulus parallel to the grain G_0;

L is span of CLT panel.

Figure 2. Cross-section of symmetrical 5-layer CLT panel with relevant distances and thicknesses for the Gamma method

The Gamma method has an advantage over other methods for panels with asymmetrical cross-sections due to the different layer thicknesses or material properties of the layers. However, this method can be difficult to apply in multi-span floors and when a CLT panel has more than five layers. Furthermore, the Gamma method cannot provide precise effective stiffness in the transverse direction.

5.2 K-method

Blass and Fellmoser [20] established the K-method by applying the theory of composite materials to CLT panels. In this method, it is assumed that the stiffness of each layer adds to the effective bending stiffness of a CLT panel when it is bent. Since this method does not take into account how shear deformation affects each layer, it works best for CLT floors with a high span-to-depth ratio (greater than 30).

To obtain the value of effective bending stiffness $(EI)_{\mathrm{eff}}$, the modulus of elasticity parallel to the grain E_0 of each individual layer needs to be multiplied by a composition factor k_i depending on certain loading configurations, as well as on the panel orientation. For floors loaded perpendicular to their plane, it is relevant to use k_1 and k_2 composite factors for longitudinal and transverse floor directions. Hence, effective bending stiffnesses in longitudinal and transverse directions, respectively, are defined as follows:

$$(EI)_{L,\mathrm{eff}} = E_0 \cdot \frac{b \cdot a_m^3}{12} \cdot k_1 \tag{25}$$

and

$$(EI)_{B,\mathrm{eff}} = E_0 \cdot \frac{b \cdot a_m^3}{12} \cdot k_2 \tag{26}$$

with

$$k_1 = 1 - \left(1 - \frac{E_{90}}{E_0}\right) \cdot \frac{a_{m-2}^3 - a_{m-4}^3 + \ldots \pm a_1^3}{a_m^3} \tag{27}$$

$$k_2 = \frac{E_{90}}{E_0} + \left(1 - \frac{E_{90}}{E_0}\right) \cdot \frac{a_{m-2}^3 - a_{m-4}^3 + \ldots \pm a_1^3}{a_m^3} \tag{28}$$

where:

E_0 is modulus of elasticity parallel to the grain of individual layer;

E_{90} is modulus of elasticity perpendicular to the grain of individual layer;it can be assumed to be 1/30 of modulus of elasticity parallel to the grain E_0;

b is width of CLT cross-section (usually taken as 1 m);

m is total number of layers;

a_m, a_{m-2}, a_{m-4}…,$a_1$are relevant thicknesses of the panel.

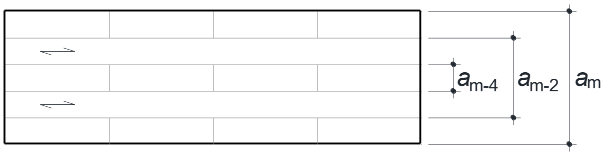

Figure 3. Cross-section of symmetrical 5-layer CLT panel with relevant thicknesses for K-method

For a 5-layer CLT panel, a_m is the thickness of the whole panel, a_{m-4} is the thickness of the middle layer, and a_{m-2} is the panel thickness minus the thickness of the outer layers (Figure 3).

5.3 Shear analogy method

The shear analogy method was developed by Kreuzinger [21] and shares many similarities with the Timoshenko beam theory. This method takes into account shear deformation of both longitudinal and cross layers and has been proven to be the best model for calculating the bending stiffness of CLT panels. This method has been implemented in Canadian and American standards for the design of timber structures [22].

The main principle of the shear analogy method is that the cross-section of a CLT panel is approximated with two rigidly coupled virtual beams that have equal deflection. One virtual beam has a bending stiffness equal to the sum of the inherent bending stiffnesses of each layer with infinite shear stiffness, while the bending stiffness of the second virtual beam is presented as the sum of the Steiner points of each layer (Steiner's theorem) with definite shear stiffness. Based on this, effective bending stiffness and effective shear stiffness in the longitudinal floor direction, respectively, can be calculated as follows:

$$(EI)_{L,\mathrm{eff}} = \sum_{i=1}^{n}\left(E_i \cdot b \cdot \frac{t_i^3}{12}\right) + \sum_{i=1}^{n}\left(E_i \cdot A_i \cdot z_i^2\right) \tag{29}$$

and

$$(GA)_{L,\mathrm{eff}} = \frac{\left(h - \frac{t_1}{2} - \frac{t_n}{2}\right)^2}{\left[\left(\frac{t_1}{2 \cdot G_1 \cdot b}\right) + \left(\sum_{i=2}^{n-1} \frac{t_i}{G_i \cdot b}\right) + \left(\frac{t_n}{2 \cdot G_n \cdot b}\right)\right]} \tag{30}$$

where:

n is total number of layers;

E_i is modulus of elasticity ofthe i-th individual layer (taken as E_0 for longitudinal layers and E_{90} for transverse layers);

A_i is cross-section area of the i-th individual layer ($A_i = b \cdot t_i$);

b is width of CLT cross-section (usually taken as 1 m);

t_i is thickness of the i-th individual layer;

z_i is distance between the center point of the i-th layer and neutral axis, as presented in Figure 4;

h is thickness of the panel;

G_i is shear modulus ofthe i-th individual layer (taken as G_0 for longitudinal layers and G_{90} for transverse layers).

In the case of floors supported on all four sides, effective bending stiffness in transverse direction should be obtained as follows:

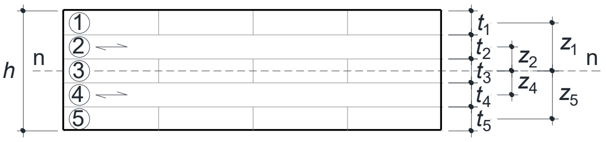

Figure 4. Cross-section of symmetrical 5-layer CLT panel with relevant distances and thicknesses for the Shear analogy method

$$(EI)_{B,\mathrm{eff}} = \sum_{i=2}^{n-1}\left(E_i \cdot b \cdot \frac{t_i^3}{12}\right) + \sum_{i=2}^{n-1}\left(E_i \cdot A_i \cdot z_i^2\right) \tag{31}$$

When calculating deflections and vibrations of a CLT floor, effective bending and shear stiffness are included through apparent bending stiffness, defined as:

$$(EI)_{L,\mathrm{app}} = \frac{(EI)_{L,\mathrm{eff}}}{1 + \frac{K_s \cdot (EI)_{L,\mathrm{eff}}}{(GA)_{L,\mathrm{eff}} \cdot L^2}} \tag{32}$$

where K_s is constant based on the influence of shear deformation, depending on loading configuration and boundary conditions (taken as 11.5 for uniformly distributed load and floors simply supported on two sides).

The Shear analogy method is accurate for various load configurations and multi-span systems and is not limited by the number of layers within a panel. It is best suited to floor structures with span-to-depth ratios greater than 8.

6 Discussion

Overall criteria that should be checked through different design methods are presented in Table 5. The verification of the frequency and stiffness criterion is shared by all methods. Some of them also prove vibration velocity and acceleration. The critical frequency of most design methods is 8 Hz.

Although some criteria are common to certain methods, it may happen that the same criteria take into account different factors. This may lead to noticeably different results. An overview of differences in consideration of some factors is given in Table 6.

Table 5. Overview of considered criteria in different design methods

Method	Frequency	Stiffness criterion	Velocity criterion	Acceleration criterion
Hamm [13]	yes	yes	no	yes
Thiel [15]	yes	yes	no	yes
Hu [16]	yes	yes	no	no
Abeysekera [18]	yes	yes	yes	yes

Table 6. Overview of considered factors in different design methods

Method	Support conditions	Shear flexibility	Transverse load-carrying effect	Effective width B_{eff}	Mass
Hamm [13]	no	no	yes	yes	$g_0 + \Delta g$
Thiel [15]	yes	yes	yes	yes	$g_0 + \Delta g$
Hu [16]	no	yes	no	no	g_0
Abeysekera [18]	yes	no	yes	yes	$g_0 + \Delta g + \psi_2 \cdot \mathrm{p}$

The support conditions have a large effect on the values of natural frequencies. When the floor is clamped or partially clamped, the frequencies increase. When loads from the upper floor are transferred through walls, the floor can be clamped. This will also have a positive effect on floor deflections. From the aspect of CLT as a material, shear flexibility is of crucial importance, and it is highly advised to take it into account in the context of vibrations. This implies that the Shear analogy method should be used when calculating the stiffness properties of CLT floors. Consideration of shear flexibility leads to a decrease in fundamental frequency and an increase in deflection. The transverse load-carrying effect should be considered when the floor is supported on all four sides. This parameter raises the floor´s fundamental frequency, which depends mostly on the ratio of bending stiffness in the longitudinal and transverse directions as well as on the ratio of floor width to span. Effective floor width B_{eff} has an impact on floor deflection in such a way that taking the effective width into account reduces floor deflection. As with the previous parameter, this influence greatly depends on the ratio of bending stiffnesses. Floor mass affects floor natural frequencies and vibration acceleration, so an increase in the mass leads to lower natural frequencies and also vibration acceleration. Taking into account more mass according to vibration sensitivity has more positive than negative effects. Permanent loads should always be considered, but in certain cases it is reasonable to include quasi-permanent parts of imposed loads.

When speaking of limit values, it is evident that limit values for proposed criteria are based on the highly subjective opinion of the test person. Hence, it is impossible to define which design method would be best suited for verifying vibrations. In order to get a better description of the actual behaviour of floor structure, a floor classification system based on vibration serviceability performance was developed. Floor classification based on dynamic characteristics (different limit values of criteria) allows designers and investors to be more aware of actual floor performance and to target desired floor performance.

7 Conclusion

Human-induced floor vibrations are regarded as a serviceability issue, primarily relating to occupant discomfort. Although vibration serviceability issues with timber floors are primarily associated with existing floors, they are also relevant to new floors. Taking contemporary trends into account, it is realistic to expect that in the future floor spans will be even larger, floors even lighter, and human expectations regarding the quality of living and working surroundings will be even greater. Therefore, it is necessary to define an adequate method (criteria) in current standards that would predict excessive vibrations, thus enabling the given problems to be eliminated or decreased during the design stage. Although the procedure must be simple in practice, it must not be at the expense of accuracy.

Due to the specific dynamic behaviour of CLT floors, the existing design methods for low- and high-frequency floors may not be applicable to CLT floors. There are several methods specifically for the verification of CLT floor vibrations. However, it is currently impossible to define which design guidelines would be best suited for the prediction of unacceptable vibrations. This is because the criteria and their limit values differ. Any reliable design approach should be derived from predictable and measurable parameters and should reflect the type of occupancy for which it is intended. It seems that the development of contemporary probabilistic methods can significantly change the approach to the problem of floor vibrations. Classification of floors based on the target response to vibration excitations (different limit values of criteria) has the advantage of providing a tool by which designers and investors can be more aware of actual floor performance.

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