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METODE PRORAČUNA VIBRACIJA MEĐUSPRATNIH KONSTRUKCIJA OD UNAKRSNO LAMELIRANOG DRVETA

Rezime:

Unakrsno lamelirano drvo (CLT) je inovativni pločasti proizvod na bazi drveta koji se dobija lepljenjem slojeva ortogonalno postavljenih drvenih lamela (dasaka). CLT paneli predstavljaju efikasno rešenje za međuspratne konstrukcije u jednoetažnim i višeetažnim zgradama. Zbog male težine i velikih raspona, dimenzionisanje ovih međuspratnih konstrukcija najčešće je uslovljeno kriterijumima graničnih stanja upotrebljivosti, tj. ograničenjima za deformacije i vibracije. Vibracije međuspratnih konstrukcija prouzrokovane ljudskim aktivnostima, kao što je hodanje, neće dovesti do loma konstrukcije, ali mogu uticati na komfor korisnika ukoliko nisu adekvatno kontrolisane. U radu je dat pregled nekoliko metoda za proračun vibracija pri proveri graničnih stanja upotrebljivosti CLT međuspratnih konstrukcija stambenih zgrada. Razmatrane su razlike u obuhvaćenim parametrima i graničnim vrednostima ovih metoda.

Ključne reči: CLT međuspratna konstrukcija, vibracije, pobuda hodanjem, proračunska metoda

VIBRATION SERVICEABILITY DESIGN METHODS FOR CROSS LAMINATED TIMBER (CLT) FLOORS

Summary:

Cross laminated timber (CLT) is an innovative engineering wood product made by gluing layers of solid timber boards placed in orthogonally alternating orientation to the neighbouring layers. CLT panels provide an efficient solution for floors in single- and multi- storey buildings. Due to the light-weight and often long-span, design of these floors is generally governed by serviceability limit state criteria, that is deflection or vibration limits. Floor vibrations induced by dynamic actions, such as people walking, do not result in structural failure but may cause discomfort of occupants if the vibrations are not properly controlled. This paper gives an overview of some available methods for vibration serviceability design of residential CLT floors. Differences in considered parameters and limit values of these methods are discussed.

Key words: CLT floor, vibrations, walking excitation, design method

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1. INTRODUCTION

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

For CLT panels used as floor elements serviceability limit state (deformation, vibration) generally controls 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. Human-induced vibrations do not collapse the floors, but can annoy occupants or cause malfunction of vibration sensitive equipment. Consequently, requirement for the design against disturbing vibrational performance is particularly important for light-weight floors built from materials such as timber. In addition, vibration serviceability of timber floors is becoming more relevant due to increased demand for building new floor systems with larger spans.

Vibrational serviceability of timber floor systems has received much attention in recent decades, with different design guidelines being suggested. Proposed design methods range from simple limitations of static deflection to the ones intended to limit fundamental frequency and vibration velocity or acceleration levels at floor surfaces caused by defined excitations [1]. However, vibration serviceability design criterions applied to traditional timber floors are probably not appropriate for CLT floor design.

This paper focuses on the basic principles for 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 divers results.

2. FLOOR DYNAMICS

Annoying vibration of timber floors is commonly associated with walking excitation. Walking frequency (common range 1.5-2.5 Hz) has a direct impact on dynamic load applied. The dynamic force from walking has been found to excite frequencies up to the third or fourth harmonic of walking frequency.

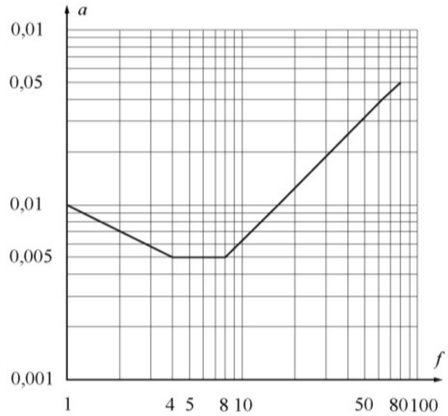
Vibration response of a floor when subjected to dynamic loading depends on its stiffness, mass and damping. Stiffness and mass determine floor's natural frequencies, while damping affects the time it takes for an induced vibration to decay. Depending on the value of fundamental frequency, vibration response of floor due to people walking may differ [2]. So called low-frequency floors have 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 fundamental frequency above 8-10 Hz show a transient vibration response to individual heel strike from each footstep. Depending on the intervals between successive impacts and damping of vibration, adjacent transient vibration responses may interact with each other.

Response of floors to an impact can be represented by the time history of displacement, velocity or acceleration. 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 initial forced and free vibration parts of the response.

3. HUMAN PERCEPTION OF FLOOR VIBRATION

Human body is an incredibly complex and sensitive receiver which 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 [3]. Acceptable vibration levels for human occupancies vary with individual, person's activity, body posture, life environment and expectation of felt vibrations. Presence of visual or audio effects may significantly reduce the acceptable vibration magnitude. Therefore, it is difficult to set the threshold of human perception of vibrations.

Characterization of building vibration with respect to human response is given in ISO 10137 Annex C [4], which includes "base curves" expressed as a function of r.m.s acceleration and frequency. At vibration acceleration magnitudes below values corresponding to the base curves, in general adverse comments, sensations or complaints are very rare. Since the magnitude, which is considered to be satisfactory, depends on the circumstances, multiplying factors are used to increase the acceleration level of these base curves according to intended use of the building. These multiplying factors are referred to as "response factors".



Key:
a – r.m.s. acceleration, m/s^2
f – frequency, Hz

Figure 1 – Building vibration z-axis base curve for acceleration (vertical direction) [4]

The base curve for vertical vibration is presented in Figure 1. The graph shows that the perception threshold for vibrations is lowest for frequency range between 4 to 8 Hz, with constant value of $a_{\mathrm{rms,base}} = 0.005$ 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 minimum perception level is not constant in terms of acceleration but it increases as the frequency increases. However, when this part of curve is integrated, it can be shown that it is constant in terms of velocity with a value of $v_{\mathrm{rms,base}} = 0.0001$ m/s. Therefore, below floor frequency of 8 Hz acceleration criterion for vibration perception threshold can be applied and above 8 Hz velocity criterion can be applied.

4. DESIGN METHODS FOR CLT FLOOR VIBRATIONS

Vibration serviceability design method in current Eurocode 5 essentially refers to design of timber-joisted floors, where annoying vibration is attributed to isolated floor structure. As CLT floors are solid slabs, their dynamic properties differ from that of traditional timber floors. 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. For floor elements supported at four sides, the transverse load-carrying effect should be taken into account. Due to the orthotropic nature of CLT, floor stiffness is not equal in perpendicular directions, but continuous support can be provided to all edges. For multi-span systems, continuous slab effect should be considered.

Multi-storey CLT buildings are generally 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. Thus, another highly important aspect of vibrations is seen in the influence of support conditions (e.g. hinged, partly clamped, clamped) and in the influence of upper storey loads transmitted through the walls on the degree of clamping.

4.1. DESIGN METHOD ACCORDING TO HAMM ET AL.

Vibration serviceability design method proposed by Hamm et al. [5] is a result of research project at Technical University of Munich which involved experimental and theoretical investigations of different types of timber floors (timber joisted floors, timber-concrete floors, massive timber floors). Austrian National annex ÖNORM B 1995-1-1 is based on this study. It should be mentioned that this is the only National annex to Eurocode 5 which deals with vibrations of CLT floors.

Rules for design and construction applicable to timber floors are divided in three different classes according to Table 1. First step is to decide whether floors should be with higher or lower demands or without any demands in terms of vibration performance.

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

- For floors supported on two sides:

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

- For floors supported on all four sides:

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

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.

Table 1 – Floor classes, constructive requirements and limiting values of criterions [5]

	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	$f_{\text{limit}} = 8$ Hz	$f_{\text{limit}} = 6$ Hz	-
Stiffness criterion	$w_{\text{limit}} = 0.5$ mm	$w_{\text{limit}} = 1.0$ mm	-
Acceleration criterion	$a_{\text{limit}} = 0.05$ m/s^2	$a_{\text{limit}} = 0.1$ m/s^2	-

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

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

with

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

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 choosing the load of 2 kN instead of usual 1 kN was good correlation between the values of deflection and subjective evaluation of vibration behaviour.

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

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

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.bau forschungs gmbh Austria, Thiel et al. [6] expanded and modified design method suggested by Hamm et al.

As mentioned before, in addition to frequency and stiffness criterion, vibration acceleration if fundamental frequency is below critical value needs to be checked. Without detailed explanation as following equations refer to the previous design method, the focus is on additional parameters that are taken into account.

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

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

Furthermore, shear flexibility in CLT element should be taken into account by using the effective apparent bending stiffness $(EI)_L$ (based on bending and shear deformations). Additionally, different support conditions and continuous floor effect for multi-span floors can be considered through modification factors k_{m} and $k_{\text{f},2}$ that multiply the frequency.

In examination of 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:

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

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 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 excitatory person F_0 = 700 N and on modal damping ratio ζ. For single-span floors, it may be determined as:

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

with effective floor mass:

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

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

Table 2 – Fourier coefficients and excitation frequencies based on fundamental frequency [6]

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

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.

4.3. DESIGN METHOD ACCORDING TO HU AND GAGNON

Hu and Gagnon [7] developed design criterion based on understanding the fundamentals of CLT floor vibrations as well as laboratory tests and subjective evaluation 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.

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 the longitudinal stiffness and mass, expressed by the fundamental frequency f_1 and 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/m^2):

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

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

Fundamental frequency of a simply supported CLT panel may be calculated as:

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

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 $\mathrm{kg/m}^3$;

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

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

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

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. [8] presented new design rules for 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 best floor performance level, VI for worst, but still acceptable, and VII for unacceptable floor performance level. Recommendation for selection of floor performance level for residential categories is shown in Table 4. Nevertheless, these floor performance levels should be specified in National annexes of each member country, as it is necessary to consider culture variations between countries, or they should be specified by investors or designers.

Table 3 – Floor performance levels and corresponding criterions [8]

<table>
<tr><td rowspan="2">Criterion</td><td colspan="7">Floor performance levels</td></tr>
<tr><td>I</td><td>II</td><td>III</td><td>IV</td><td>V</td><td>VI</td><td>VII</td></tr>
<tr><td>Frequency criterion f_1 [Hz] $\geq$</td><td colspan="7">4.5</td></tr>
<tr><td>Stiffness criterion w [mm] $\leq$</td><td colspan="2">0.25</td><td>0.5</td><td>0.8</td><td>1.2</td><td>1.6</td><td rowspan="4">no criterion</td></tr>
<tr><td>Response factor $R \leq$</td><td>4</td><td>8</td><td>12</td><td>16</td><td>20</td><td>24</td></tr>
<tr><td>Acceleration criterion (when $f_1 < 8$ Hz) a_{rms} [m/s^2] $\leq$</td><td colspan="6">$R \times 0.005$</td></tr>
<tr><td>Velocity criterion (when $f_1 \geq 8$ Hz) v_{rms} [m/s^2] $\leq$</td><td colspan="6">$R \times 0.0001$</td></tr>
</table>

Table 4 – Recommended selection of floor performance levels for residential use category [8]

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

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

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

with

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

where:

$k_{e,1}$ is frequency multiplier in case of a double-span floor on rigid supports;
$k_{e,2}$ is frequency multiplier in 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 $\mathrm{kg/m}^2$.

When calculating vibrations, floor mass should be a unique value including at least the sum of mass caused by permanent loads (self-weight of the floor as well as all supported or suspended horizontal layers). The floor mass may also include mass caused by 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.

If all factors affecting deflection are considered, for instance when floors are spanning partially or totally on non-rigid supports or when floors are not only subjected to uniform loading, eq. (14) may be replaced with:

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

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

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

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

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

with

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

$$I = \frac{42 f_{\text{w}}^{1.43}}{f_1^{1.3}} \tag{20}$$

where:

β $= (0.65 - 0.01 \cdot f_1) \cdot (1.33 - 11.0 \cdot \zeta) \cdot \eta$;
η $= 1.52 - 0.55 \cdot k_{\text{imp}}$ when $1.0 \leq k_{\text{imp}} \leq 1.5$, else $\eta = 0.69$;
$v_{\text{tot,peak}}$ is total peak velocity response, in m/s;
k_{imp} is impulse multiplier factor;
$v_{1,\text{peak}}$ 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, modal damping ratio for CLT floors may be assumed between 2.5-6% depending on floor construction, support conditions, presence of non-load bearing partitions and 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 neglecting the floor mass, it allows an approximate comparison of proposed performance levels with existing requirements. Maximum deflection in mid-span of a single span floor may be calculated as:

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

where all of the parameters are as previously defined.

5. DISCUSSION

Overall criterions that should be checked through different design methods are presented in Table 5. All methods have in common verification of frequency and stiffness criterion. Some of them also prove vibration velocity and acceleration.

Table 5 – Overview of considered criterions in different design methods

Method	Frequency	Stiffness criterion	Velocity criterion	Acceleration criterion
Hamm [5]	yes	yes	no	yes
Thiel [6]	yes	yes	no	yes
Hu [7]	yes	yes	no	no
Abeysekera [8]	yes	yes	yes	yes

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

Table 6 – Overview of considered parameters in different design methods

Method	Support conditions	Shear flexibility	Transverse load-carrying effect	Effective width B_{eff}	Mass
Hamm [5]	no	no	yes	yes	$g_0 + \Delta g$
Thiel [6]	yes	yes	yes	yes	$g_0 + \Delta g$
Hu [7]	no	yes	no	no	g_0
Abeysekera [8]	yes	no	yes	yes	$g_0 + \Delta g + \psi_2 \cdot \text{p}$

Support conditions significantly affect the values of natural frequencies in a way that frequencies are increasing as floor is clamped or partly clamped. Clamping of floor can be achieved when load from upper floor is transferred through walls. This will also have a positive impact on deflections of floor. 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 vibration. Consideration of shear flexibility leads to decrease in fundamental frequency and increase in deflection. Transverse load-carrying effect should be considered when floor is supported on all four sides. This parameter raises floor fundamental frequency depending mostly from the ratio of bending stiffness in longitudinal and transverse direction as well as on the ratio of floor width to span. Effective floor width B_{eff} has an impact on floor deflection in a way that taking into account the effective width reduces floor deflection. As previous parameter, this influence greatly depends on the ratio of bending stiffnesses. Floor mass affects floor natural frequencies and vibration acceleration. Increase of 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 part of imposed loads.

When speaking of limit values, it is evident that the limit values for proposed criterions are based on highly subjective opinion of the test person. In order to get a better description of actual behavior of floor structure, a floor classification system based on vibration serviceability performance was developed.

6. CONCLUSION

Vibrational serviceability often governs design of timber floors. Due to its specific dynamic behaviour, the existing design methods for low- and high-frequency floors may not be applicable to CLT floors. For verification of CLT floor vibrations a several methods exist. However, it is currently impossible to define which guidelines would be best suited for prediction of unacceptable vibrations. This is due to differences in consideration of some parameters and limit values. Any reliable design approach should be derived from predictable and measurable parameters and should reflect the type of occupancy for which is it intended. Although simplicity of the procedure in practice is required, it must not be achieved to the detriment of accuracy.

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