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FILTERING FREQUENCY REQUIREMENT FOR VIBRATION SERVICEABILITY ANALYSIS OF CLT FLOORS

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Abstract: Transient floor vibrations building occupants sense are acceleration/velocity surface motions caused by dynamic forces such as footfall impacts. Eurocode 5 serviceability design provisions recognize this by limiting peak velocity caused by a unit impulsive, based on accounting for sub-motions of modes having natural frequencies less than 40 Hz. At present that approach has only been developed for rectangular plan floors having closely spaced parallel arranged lumber joists. Comparable North American code provisions for lightweight timber floors account for only the fundamental modal frequency, or parameters like floor mass and flexural rigidity which relate indirectly to motion frequencies and amplitudes. Unfortunately, such approaches lead to high proportions of floors being under or over designed in terms of vibration serviceability. Need exists to extend Eurocode 5 method to floors other than joisted timber systems. The investigation reported here addresses how various vibration modes contribute to transient motions of floors constructed from Cross-Laminated-Timber (CLT) plates. It is shown CLT floors will experience accelerations which are strongly influenced by a wide range of modes with a wide range of natural frequencies. By implication current Canadian timber design code and North American industry recommendations are not reliable approaches for avoiding unacceptable motions of CLT, and possibly other types of lightweight, floors under normal building use conditions. It is concluded improved design approaches for CLT floors should be based on the Eurocode 5 approach, but the appropriate design analysis filtering frequency would be substantially higher than the 40 Hz value for lumber joisted floors.

1 INTRODUCTION

Timber is widely used to construct elevated floors in buildings. Traditionally light-frame lumber joisted floors were synonymous with timber construction in North America and elsewhere, but now a wide range of options exist. Newer options suit constructing of taller (circa > 4 storey) all timber- and hybrid-buildings for residential and mercantile occupation, and meeting needs of architects and contractors who prefer prefabricated systems (Weckendorf et al. 2015). Cross-Laminated-Timber (CLT) is the generic name for a class of prefabricated thick timber-plate products well suited to construction of slab floors (Smith and Frangi 2008). The broad characteristic of CLT products are they have bonded layers that cross-reinforce it in orthogonal plate directions, making it well suited as an alternative to reinforced concrete (RC) slabs.

Attractiveness of CLT products is they have low mass to stiffness and mass to strength ratios (ANSI). 2012). This provides transportation and construction site handling advantages, and can lead to substantial cost savings for superstructure and foundation systems proportional to aggregated reductions in total gravitational weights. Also, to note are scheduling and cost benefits related to absence of wet construction processes, and avoidance of superstructure element curing periods. On the other hand, using CLT is simply not a matter of substituting one material for another of equal strength or stiffness. Like other relatively lightweight slabs, CLT slabs potentially increases proneness of floors to vibration serviceability performance problems (Weckendorf et al. 2016; Ussher et al. 2017). CLT floors may be designed for quite long or multiple spans, with or without structural sub-beam supports and it is therefore necessary to explicitly consider the levels of motion responses that will occur at floor surfaces under normal building use conditions.

Contemporary ways of predicting vibration serviceability performances of lightweight timber floors can be classed as indirect empirical rule methods (*empirical methods*) or classical engineering methods based on vibration response analyses (*engineering methods*). Empirical methods do not directly account for complexities of how floors respond to excitation sources. Instead they relate satisfaction of building occupant with floor motions to easily estimated parameters like floor fundamental natural frequency (f_1), maximum deflection under a 1 kN concentrated gravity force (d_1), or floor mass and flexural rigidity in the span direction (Onysko 1985; Hu and Gagnon 2011; CSA *in press*). Such methods correspond to simplified notions of how humans sense and respond to vibratory motions. Unfortunately, the simplified approaches lead to high proportions of floors being under or over designed in terms of vibration serviceability (Weckendorf et al. 2015). Engineering methods predict how floors respond to defined excitations and assess acceptability of resulting motions (AISC 1997; IRC/NBC 2015). Estimated response parameters such as dynamic displacement (u) and its derivatives; velocity and acceleration (u' and u'') are often compared to acceptable limits related to human toleration of vibration motions. Human toleration of motions depends on building occupancy conditions and aggregated effects of floor surface sub-motions of mode of vibration excited by impacts or other dynamic disturbances (ISO 2003). Eurocode 5 (CEN 2004) contains engineering vibration serviceability assessment provisions for rectangular plan floors supported along all edges which have closely spaced lumber joists, based on work by Ohlsson (1988). Those provisions require estimation of the peak floor surface velocity resulting from a unit impulsive force applied at the centre-floor position, taking account of contributions from first order modes having frequencies less than 40 Hz (n_{40}). In this context, first order mode shapes are only those with a single half-sine wave shape in the floor span direction. For rectangular lumber joisted floors having all edges simply supported the several lowest order modes usually are first order mode. In other cases analysis filtering frequencies other than 40 Hz might apply and other than first order modes might need to be considered (Weckendorf et al. 2016; Ussher et al. 2017).

(a) physical setup (b) FE representation

Figure 1: Example 2-segment 7-ply CLT floor

Recent experimental and analytical research at the University of New Brunswick (UNB) on floors constructed from CLT slab elements showed dynamic responses of such systems do not mirror behaviour of lumber joisted floors, and vibration modes with natural frequencies much higher than 40 Hz contribute significantly to surface motions human sense (Weckendorf et al. 2016; Ussher et al. 2017). The investigation reported here addresses how vibration modes contribute to transient motions of CLT floors based on Finite Element (FE) time-history analyses (Usher et al. 2017). Figure 1(a) shows an example of a rectangular CLT floor having CLT plate elements interconnected by a half-lap construction joint secured with self-tapping screws. Figure 1(b) shows the corresponding FE mesh used to predict time history responses to dynamic forces representative of impacts occurring under normal building use conditions.

This and other analysed situations discussed below highlight the need to accurately represent real construction features, like presence of intra-slab joints that can articulate modes and support conditions, when predicting motions which represent vibration serviceability performance by engineering methods.

2 TECHNICAL BACKGROUND

Occupants of buildings can be disturbed or annoyed by motions on floor surfaces due to their own, or other, activities such as walking, running, jumping and rhythmic exercising. This reflects that humans can perceive motions as small as 2.5 μm (Polensek 1970). Generally, it has been established human perception of vibrations relates to frequency content, dynamic displacement levels, and acceleration levels of motions. Empirical design criteria formulated to discriminate the vibration performance of floors assume motions are dominated by the fundamental frequency (f_1). In early work on vibration of lightweight timber floors it was envisaged designing floors so f_1 was high-tuned above resonant frequencies of internal human sensory organs (circa f_1 > 8 Hz) would eliminate or mitigate occurrence of unacceptable motions (Weckendorf et al. 2016). Simple methods have been used for estimation of allowable spans of lumber floor joists and some proprietary floor construction products used in non-engineered buildings (e.g. Onysko 1985; Dolan et al. 1999; Hu and Gagnon 2011). Such approaches are not state-of-the-art, because humans simultaneously sense multiple modal components of motions. Acceptable vibration motion levels are therefore best assessed in terms of floor surface velocities or accelerations which are summed effects of modal motions within human sensory range (Ohlsson 1988; Smith and Chui 1988).

Human footfall impacts are important dynamic actions representative of common building occupancy situations, and Parts 1 and 2 of ISO Standard 2631 (ISO 1987, 2003) gives guidance on their definition for study vibration serviceability issues. Part of the ISO guidance recognizes that human exposure to vibrations be assessed with reference to the appropriate axis of body motion (e.g. standing versus lying), and need to account for summed weighted effects for vibration at different frequencies. Appropriate weighting of motions depends on the direction of exposure and frequency component under consideration, using unfiltered time-history responses preferably determined as acceleration. Root-mean-square (rms) values of weighted accelerations should be calculated as recommended in Part 1 of ISO 2631 (ISO 1987). Calculated weighted rms accelerations (a_{rms}) can be compared to 'base curves' to evaluate acceptability of human exposure to vibrations in terms of acceleration, or velocity as a function of frequency. The American Institute for Steel Construction Design Guide 11 (AISC, 1997) is formulated based on Part 2 of ISO 2631 and gives human tolerance to vibration expressed as relationships between peak or rms acceleration and cyclic forcing frequency, for various building occupancy situations. An alternative Vibration Dose Value (*VDV*) method is recommended in standards such as ISO 10137 (ISO 2007) and Part 1 of BS 6472 (BSI 2008) for assessing human responses to intermittent vibrations. *VDV* is defined by Equation [1] where, $a(t)$ is frequency-weighted acceleration (m/s^2), and T is the total time-period during which vibration occurs (seconds). Both ISO 10137 and BS 6472 provide acceptable limits of the *VDV*. Use of frequency-dependent weighting factors is intended to reduce influences higher-order frequencies have in recognition of observed human sensitivity to low frequency components of oscillatory motions (e.g. resonant frequencies of internal body organs). As already mentioned, Eurocode 5 (CEN 2004) provisions recommend assessing vibration serviceability of lumber joisted floors by limiting the peak velocity response due to unit impulsive force (1 Ns). It is the closest approach to date to ISO 2631 recommendations.

[1] $$VDV = \left[\int_0^T a^4(t)dt\right]^{0.25}$$

For purposes of further discussion peak aggregated velocity ($v_{peak} = u'_{peak}$), peak aggregated acceleration ($a_{peak} = u''_{peak}$), cumulative weighted root-mean-square acceleration (a_{rms}), and *VDV* are taken to be motion characteristics most suitable for vibration serviceability performances of CLT or other types of lightweight floors. The associated core research question is what are appropriate filtering frequencies for analytical determination of such motion characteristics for CLT floors.

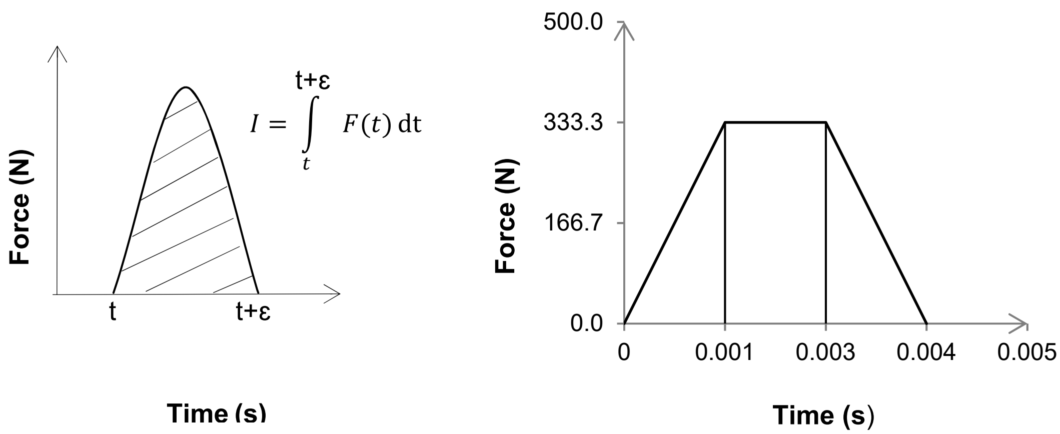
3 DYNAMIC ACTION FROM HUMAN MOTION

Various models have been formulated to mimic human footfall impacts, Figure 2. A so-called heel-drop impact resulting from humans raising themselves on their toes and then suddenly releasing their gravitational weight onto a floor was adopted by Smith and Chui (1988) as the forcing function setting lumber joisted floors into motion. They developed a closed form expression for calculating resulting a_{rms} values as a function of floor geometry and physical characteristics. However, to achieve this they only considered the fundamental mode motion, throwing into question validity of resulting vibration serviceability assessments. Rainer and Pernica (1986) proposed a representation of walking and running footfall impact in the frequency domain as Fourier series:

$$P(t) = W^*\left[1 + \sum_{n=1}^{N} \alpha_n \sin\left(2\pi n f_q t + \theta\right)\right] \quad [2]$$

where W^* denotes a person's weight, α_n is the Fourier coefficient of the n^{th} harmonic (also called the dynamic load factor), f_q is the activity rate, Θ is the phase angle, and N is the number of terms in the series expansion for a particular $P(t)$. The common range of walking frequencies is between 1.2 and 3 Hz, with frequencies > 3.2 Hz representing jogging or running. Rainer and Pernica (1986) reported dynamic walking forces excite floor vibration modes with frequencies up to the third or fourth harmonic of the walking frequency. It should not however be presumed this is a general rule, because many variables influence such observation. The authors do however regard Rainer and Pernica as having demonstrated validity of Equation [2].

Based on Ohlsson (1988), Eurocode 5 (CEN 2004) implements an ideal impulsive force of 1 Ns, instead of actual footfall impacts, to initiate floor motions. In consequence, tolerance levels for unit impulse velocity (v_{peak}) are calibrated to account for differences between footfall and a unit impulsive forces. As Figure 2(b) illustrates, a loading function having high intensity, very short duration and area 1Ns can be employed in lieu of an idealized impulsive force. That technique facilitates time-history response computations and was implemented in FE analyses that follow.



(a) Heel-drop impact (b) Pseudo unit impulsive force

Figure 2: Example dynamic force functions

4 FINITE ELEMENT ANALYSES

4.1 FE Modal Analyses

The well known commercial FE software package *Abaqus/CAE* was employed to develop numerical models for predicting the modal characteristics of CLT floors. Modal parameters such as natural frequencies and mode shapes from experimental work conducted at the University of New Brunswick were used in calibrating the FE models. Floors analyzed involved systems with one or two CLT element segment(s) of different thicknesses and ply orientation configuration, as well as various boundary conditions. Analyses of two floors with 245 mm thick 7-ply (4X3 layup: ∥⊥∥⊥∥⊥∥) are discussed here. Notation symbols meaning: ∥ = parallel to grain of lumber surface laminates and ⊥ = perpendicular to grain of lumber surface laminates. *Floor-1* has a single CLT element, plan dimensions of span *L* = 6.285 m and width *W* = 2m, with simply supported at span ends and edges free to vibrate (SFSF supports). The surface laminates are oriented parallel to the span. *Floor-2* has two CLT elements connected at mid-width by a 64 mm half-lap joint (Figure 1(a)), *L* = 6.285 m, and *W* = 3.94 m. Self-tapping screws (6mm diameter by 160mm long) spaced at 300 mm were used as interconnect the CLT elements at the joint. Other features of *Floor-2* matched those of *Floor-1*.

The analysed cases exhibit both symmetrical and unsymmetrical mode shapes in the floor width direction, which happens because of the SFSF condition. It demonstrates combined influences of altering the *L/W* ratio and introducing intra-slab construction joints. *Floor-2* exhibits more pronounced clustering of modal frequencies than *Floor-1* due to its lower *L/W* ratio and presence of the half-lap joint.

In the FE models ABAQUS orthotropic S4 elements, which are 4-node doubly curved general-purpose shell elements, were used to model the CLT elements assuming uniform physical and mechanical properties. Elements had plan dimensions of about 100 mm, based on subsidiary analyses proving convergent eigenvalue extractions and mode shapes were obtained. Table 1 summarizes material properties of the CLT (ANSI 2012). Floor edge supports were simulated as hinge line supports. The half-lap joints in *Floor-2* was modelled using fastener elements that created a semi-rigid line connection, Figure 1(b). Translational stiffness characteristics of screws in joints based on laboratory measurements were taken as 900 N/mm in floor span, width and through slab coordinate directions (Ussher et al. 2017).

Table 1: Apparent properties of CLT employed for dynamic FE modelling*

Property		Elastic moduli			Shear moduli			Poisson's ratios	
	E1	E2	E3	G12	G13	G23	v12	v13	v23
(units)	GPa	GPa	GPa	GPa	GPa	GPa	--	--	--
Value	10.00	4.50	2.00	1.00	0.10	0.10	0.44	0.30	0.30

*Density, ρ = 520 Kg/m3, Damping ratio, ζ = 1%, Direction 1 = parallel to span, direction 2 = perpendicular to span, direction 3 = perpendicular to slab

4.2 Verification of FE Modal Model

Table 2 compares extracted FE modal frequencies with matched test values taken from Weckendorf et al. (2015). Small discrepancies are attributable to FE models not accounting for minor geometric imperfection and material variability within CLT. Other comparisons of FE and test derived modal frequencies and mode shapes also confirm accuracy and robust of adopted analytical modelling techniques (Ussher et al, 2017).

Table 2: Comparison of experimental and FEM modal frequencies (Hz)

Mode* (*m,n*)	*Floor -1:* single-segment slab				*Floor-2:* two-segment slab			
	Mode #	Test	FE	% Error	Mode #	Test	FE	% Error
1,1	1	11.3	11.5	+0.2	1	11.0	11.5	+0.5
1,2	2	22.2	23.2	+1.0	2	14.8	15.4	+0.6
1,3	-	--	--	--	3	22.3	23.2	+0.9
2,1	3	39.6	39.1	-0.5	4	37.9	39.1	+1.2
2,2	4	53.9	52.5	-1.4	5	43.7	43.2	-0.5
2,3	-	--	--	--	6	53.4	52.5	-0.9
3,1	5	75.3	72.6	-2.7	8	68.0	72.6	+4.6
3,2	6	95.3	88.6	-6.7	10	78.2	76.4	-1.8
3,3	-	--	--	--	11	94.4	88.6	-5.8

**m,n* denotes the degree of curvature in plan and width directions respectively

4.3 FE Time-History Analyses

Time history analyses were conducted for floors the same as *Floor-1* and *Floor-2,* or differing from those systems in respect of boundary condition. Considered boundary conditions are SFSF, span ends and one edge simply supported (SSSF condition), and span ends and both edges simply supported (SSSS condition). Tabulated motion characteristics are shown in Tables 3 and 4.

Table 3: CLT floor: L = 6.29 m, W = 2.00 m, single 7-Ply CLT element, t = 245mm

Analysis filtering frequency (Hz)	No. of modes	Peak velocity, v_{peak} (10^{-3} m/s)	Peak acceleration, a_{peak} (m/s^2)	Weighted rms acceleration a_{rms} (m/s^2)	Vibration dose value, VDV (m/s$^{1.75}$)
		SFSF SUPPORT CONDITION			
f_1	1	1.061	0.431	0.037	0.043
40	4	3.267	1.368	0.086	0.111
60	5	3.267	1.368	0.086	0.111
80	6	3.703	1.747	0.088	0.112
100	7	4.807	2.458	0.092	0.125
150	12	5.554	3.171	0.093	0.127
180	17	5.646	4.599	0.093	0.127
200	19	5.646	4.599	0.093	0.127
250	25	6.582	5.133	0.093	0.127
300	34	7.221	6.180	0.093	0.128
		SSSS SUPPORT CONDITION			
f_1	1	1.799	0.732	0.032	0.050
40	1	1.799	0.732	0.032	0.050
60	1	1.799	0.732	0.032	0.050
80	2	2.493	1.546	0.035	0.061
100	2	2.493	1.546	0.035	0.061
150	4	2.755	1.789	0.036	0.061
180	6	2.755	1.789	0.036	0.061
200	9	2.963	2.390	0.036	0.061
250	12	2.963	2.390	0.036	0.062
300	20	3.021	2.501	0.036	0.062

All investigated cases determined time-history responses of floors resulting from a pseudo unit impulsive force (1 Ns), Figure 2(b). The SSSF case is considered because it facilitates generalization of findings, due to its creation of complex mode shapes having clustered modal frequencies. Extracted response characteristics reported here are v_{peak}, a_{peak}, a_{rms}, and *VDV* as functions of various analysis filtering frequencies up to 300 Hz. In principle using an analysis filtering frequency of 40 Hz matches the basis of the Eurocode 5 (CEN 2004) approach for lumber joisted floors, except in the present cases effects of all rather than just first-order modes are included. For SFSF and SSSF floors (i.e. one or two edges free to vibrate, the impulsive force was applied, and the dynamic motion characteristics extracted at mid-span 100 mm from the/a free edge. For SSSS floors the impulsive force was applied and the dynamic motion characteristics extracted at the centre-floor position. Chosen locations maximised the number of energetically excited modes in each case. Modal damping ratios were assumed to be 1 %, based on the Canadian CLT Handbook (Hu and Gagnon 2011).

Table 4: CLT floor: *L* = 6.29 m, *W* = 3.94 m, two 7-Ply CLT elements interconnected by a half-lap joint, *t* = 245 mm

Analysis filtering frequency (Hz)	No. of modes	Peak velocity, v_{peak} (10^{-3} m/s)	Peak acceleration, a_{peak} (m/s^2)	Weighted rms acceleration a_{rms} (m/s^2)	Vibration dose value, VDV (m/s$^{1.75}$)
		SFSF SUPPORT CONDITION			
f_1	1	0.530	0.215	0.019	0.022
40	4	2.981	1.238	0.065	0.085
60	7	2.981	1.238	0.065	0.085
80	9	3.639	1.863	0.069	0.090
100	11	3.844	2.499	0.070	0.093
150	20	4.761	3.856	0.070	0.094
180	27	5.391	4.570	0.071	0.094
200	30	5.631	4.690	0.071	0.094
250	44	6.695	4.795	0.072	0.095
300	58	7.820	4.819	0.076	0.101
		SSSF SUPPORT CONDITION			
f_1	1	1.124	0.458	0.040	0.047
40	3	2.929	1.213	0.076	0.099
60	5	2.929	1.213	0.076	0.099
80	7	3.439	1.684	0.079	0.103
100	9	3.952	2.316	0.083	0.112
150	18	4.795	3.889	0.083	0.114
180	23	5.419	4.602	0.083	0.114
200	26	5.540	4.644	0.083	0.114
250	39	7.408	4.767	0.090	0.123
300	53	7.437	4.768	0.090	0.123

Tables 3 and 4 summarize effects of altering the analysis filtering frequency on the selected motion characteristics. All motion characteristics correspond to a one second averaging time, as recommended by IS0 10137 (ISO 2007). Weighting function for vertical direction accelerations are applied in accordance with Part 2 of ISO 2631 (ISO 2003) and BS 6742 (BSI 2008), to mitigate influences of high-order modes on values of a_{peak}, a_{rms}, and *VDV.* As can be seen in Tables 2 and 3, irrespective of the type of floor involved and the motion characteristic involved, there is clear need to consider contributions both low- and higher-order modes of vibration make to motions that occur at floor surfaces. Although only responses of CLT floors to unit impulsive force excitation is reported here, other analyses by the authors using footfall impacts based on equation [2] yield the same essential conclusion. Something to note relative to the Eurocode 5 focus on the SSSS support condition and consideration of only first order modes in determination of n_{40} is those support conditions only create symmetric mode for rectangular plan floors. It is to be noted the underpinning research focussed on lumber joisted floors suitable for domestic dwellings (Ohlsson 1988). In such circumstances occurrence of modes that are no first ones is rare for natural frequencies less than

40 Hz. This is because *L* is usually less than *W* and the nature of the construction ensuring flexural rigidities perpendicular to span are significantly less than those parallel to span. Any vibration serviceability design approach based on engineering methods should therefore consider contributions all types of modes make to calculated motion characteristics.

5 GENERAL DISCUSSIONS

FE time-history analyses based motion characteristics reported here highlight sensitivity of CLT floor, and undoubtedly most other types of lightweight floor, surface motions to the effects of relatively high-order modes excited by impact type forces. It can be validly assumed that empirical or otherwise simplistic vibration serviceability design methods (Hu and Gagnon 2011; CSA *in press*) are inherently unreliable. Development of generalized, or only CLT applicable, engineering design practices can on the other hand be expected to be reliable because they can realistically address motion responses of floors and the characteristics of dynamic forces which excite transient motions. As already indicated, there are logical reasons why appropriate choices of analysis filtering frequencies will differ depending on characteristics of floor systems. Results in Tables 3 and 4, and other results not included here, suggest choice of an analysis filtering frequency greater than 100 Hz is appropriate for CLT floors. This matches deductions by Weckendorf et al. (2016) who carried out experimental investigations of CLT floors typical of North American residential and mercantile buildings.

The main practical challenge to implementation of robustly reliable engineering design methods for vibration serviceability performance of CLT and other types of lightweight floors is reducing the methods to a level of practicality without excessive loss of accuracy or generality. The authors envisage this can be achieve by separating definition of design principle from structural analysis aspects of design. The former would be specified in a design code(s) and the latter dealt with by design aids or computer based tools. A highly desirable aspect of this approach is it leaves responsibility for choice of analytical methods firmly in the hands of engineers. The existing Eurocode 5 provisions (CEN 2004) demonstrate that for an exactly defined simple situation (i.e. rectangular plan joisted floor simply supported along all edges) it is possible to implement a reliable engineering method in the form of a few quite simple formulas. Under Eurocode 5 engineers have discriminative control of the applicable tolerance limit of v_{peak} for specific design situations. Similar practical methods are feasible for other types of floors, plan shapes and support conditions. This contrasts with current empirical design methods prevalent in North America (Hu and Gagnon 2011; CSA *in press*), because their application cannot be broken down into an underlying principle, do not separately define an assessment criterion or analytical concept. For complex design situations, engineering methods can be implemented using FE or other suitable analysis methods. Unfortunately, there is no reliable way of applying empirical design methods to complex design situations

6 CONCLUSIONS

Analyses and discussion in this paper draw attention to the need to account for how higher order modes of vibration contribute to CLT floor surface motions which might infringe vibration serviceability performance requirements. It is concluded the best available option is creation of new design practices which extend concepts underpinning current Eurocode 5 practices applicable to simple lumber joisted floors. Such new approaches should be consistent with International Standards Organization procedures for calculation of motion characteristic and for determination of motion levels humans will tolerate under particular building use conditions. Unfortunately, it is also concluded current Canadian timber design code and North American industry recommendations are not reliable approaches for avoiding unacceptable motions of CLT, and possibly other types of lightweight, floors under normal building use conditions. This is because empirical practices lack ability to reliably discriminate between floors having acceptable dynamic performance and those which do not.

Acknowledgements

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