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Prediction of motion responses of cross-laminated-timber slabs

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ABSTRACT

Cross-laminated-timber (CLT) floor slabs have clustered modal frequencies, with higher order modes significantly influencing motions caused by dynamic footfall forces. Presented analyses address dependence of predicted slab motions on construction details and modal frequency filtering decisions. Based on the results, ideas are presented for creating robust vibration serviceability design methods applicable to CLT floor slabs. Those ideas are consistent with ISO limits on human toleration of motions under defined conditions, and design code classifications of building occupancy conditions. Ongoing research is implementing them.

1. Introduction

Cross-laminated-timber (CLT) is a generic term for prefabricated engineered wood products that roughly equate to thick plywood. CLT products have three or more bonded layers of lumber that are arranged to cross-reinforce each other [1]. They are commonly available in thicknesses up to about 300 mm, [2–4]. CLT has been used in Europe for about two decades and latterly elsewhere in the construction of low- to medium-rise buildings. More recently use of CLT has expanded to encompass a wide variety of architectures including ones creating longer span elevated floors supported by various types of superstructure system (e.g. open plan office buildings, buildings with structural steel or RC primary frameworks) [3,5–7]. It is being regarded as alternative to reinforced concrete (RC) and composite concrete-steel (C-S) for slab construction. Greater variety of floor construction methods leads to more complicated situations where floor motions created directly (e.g. footfall impacts), or indirectly (e.g. operating equipment) by building occupants, affect functionality of buildings [8,9]. For instance, composite floor construction practices where layers of CLT and other materials are interconnected may decrease static deflections, but can create observable motions resulting from dynamic forces [10].

Industry led guidance documents have been created in Europe and Canada that aim to ensure satisfactory vibration serviceability performance of CLT floors [11–13]. Such guidance draws on empirical approaches previously suggested for lightweight floors having closely-spaced parallel joists of limited span [8,14–16]. The supporting premise is building occupant satisfaction with performances of floors correlates with rule-of-thumb solutions or relatively simple estimation of engineering characteristics of floors (e.g. static deflection (d_1) of floor under 1 kN load, fundamental natural frequency(f_1)) [14–20]. Unfortunately, such approaches [e.g. 14,18,19] only work well for calibrated situations.

A number of methods have been developed for predicting out-of-plane responses of floors and other substructure systems to defined dynamic excitation [21–28]. Such approaches relate peak or root-mean-square motions that occur at floor surfaces as the result of defined excitations. The responses are therefore ones that directly correlate with motions that building occupants will sense. Excitations are dynamic forces judged representative of those created by human occupying buildings. Such approaches are the only ones that can be applied in a neutral manner to alternative engineering design situations.

Subsequent sections of this paper discuss dynamic analysis methods and apply them to analytical assessment of slabs constructed from CLT plates. The effects of higher order vibration modes on the vibration performance are also studied. This gives a foundation for commenting on suitability of already proposed vibration serviceability performance assessment methods, and definition of requirements for reliable engineering analysis of such systems.

2. Technical background

2.1. Standards practices for evaluation of human sensitivity to motion

Humans are sensitive to and sometimes disturbed by building motion intensities well below those required to cause damage.

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Nomenclature

List of Symbols

a	measured acceleration response of the floor
a_0	acceleration limit
a_p	estimated peak acceleration
b	floor width
d_1	static deflection of the floor under 1 kN load
E_1, E_2, E_3	elastic moduli in the global directions 1, 2, 3
F	vertical concentrated static force applied at any point on the floor
f_1	fundamental natural frequency
f_p	step frequency of human footfall (activity rate)
G_{xy}	shear modulus in the x–y plane
g	acceleration due to gravity
h	slab thickness
k_1, k_2, k_3	fastener stiffnesses in the global directions 1, 2, 3
l	floor length
m	mass per unit floor area (Kg/m^2)
n_{40}	number of first order frequencies up to 40 Hz
P	weight of a person supported by the floor
P_0	constant force
R	reduction factor accounting for spatial variation of human footfall force
t	time
u_{peak}	peak dynamic displacement
u'_{peak}	peak velocity
u''_{peak}	peak acceleration
W	floor weight
w	maximum instantaneous vertical deflection caused by F
α_i	dynamic coefficient for the ith harmonic force component
β	limit of unit impulse velocity
γ	limit of maximum instantaneous vertical deflection
ϕ	phase angle
ν	unit impulse velocity response
ν_{xy}	Poisson's ratio in the x–y plane
ζ	modal damping ratio

Reportedly they can sense motion amplitudes as small as 2.5×10^{-3} mm [29]. Generally accepted scientific opinion is their toleration of vibrations relates to frequency and type of activity (e.g. walking, sitting, sleeping) [23,30].

ISO Standard 2631-2 recommends peak acceleration levels humans can tolerate as a function of the frequencies of cyclic motions and the function of a building/structure, [31]. The reference (baseline) relationship is given in terms of root-mean-square (RMS) acceleration, which recognizes curves related to type of building occupancy are given in terms of peak acceleration levels. British Standards BS6472 [32] and the American Institute of Steel Construction (AISC) DG-11 [33], use modified forms of ISO 2631-2 relationships between tolerable peak acceleration levels and cyclic forcing frequency for various building occupancies [33].

Provisions like those of ISO 2631-2, BS 6472 and AISC employ discrete abstractions of types of motions building occupants will actually experience. This reflects that they are created in manners intended to balance true complexity of human-structure interactions with need for tractable engineering design calculation practices. Tractability of design practices depends on excitation sources being consistent and easily definable, and structural motions excitations cause being uncomplicated. Proximity of design situations to those dual requirements varies between building occupancy classifications, and will reflect construction method and material choices. Striking acceptable tradeoffs was part and parcel of creating design guidelines like BS 6472 and AISC recommendations, and will be for future guidelines.

2.2. Dynamic methods for evaluating floor motions

Eurocode 5 recommendations use dynamic response of floors to a defined excitations as a general way of assessing serviceability performance [34]. At present, provisions only apply to rectangular plan lightweight timber joisted floors simply supported along all four edges (denoted here SSSS floors). The provisions also only apply to floors where f_1 is > 8 Hz. The Austrian version of the Eurocode 5 [35] provides an acceleration-based assessment criteria for floors with f1 < 8 Hz based on the work of Mohr and Hamm et al. [36,37]. For floors of other types subject to continuous (i.e. forced) vibrations there is cross refenence to peak acceleration limits specified in ISO 2631-2 [31].

Eurocode 5 addresses the serviceability requirements of floors by limiting both maximum static deflection and impulse velocity response. Eqs. (1) and (2) show primary design relationships of the Eurocode 5 methods:

$$w/F \le \gamma \quad \text{(mm/kN)} \tag{1}$$

$$\nu \le \beta^{(f_1\zeta-1)} \quad \text{(m/Ns}^2\text{)} \tag{2}$$

where the limitations γ and β on responses w/F and ν are not defined in the Eurocode 5 but the prerogative of national application documents (i.e. local design codes based on Eurocode 5). Nevertheless, it is suggested human toleration limits on ν should depend on β a parameter, f_1 and ζ the modal damping ratio. Suggested choices of γ (Eq. (1)) and β (Eq. (2)) are not independent. In applications, engineers have discretion over vibration serviceability performance through choices of γ and β combinations. Calculations of f_1 and ν assume floor mass corresponds to self-weight of the floor and other permanent actions, i.e. excludes occupancy live loads.

Within above equations w/F is the maximum instantaneous vertical deflection caused by a vertical concentrated static force F applied at any point on the floor, taking account of the load distribution. Unit impulse velocity ν is the maximum vertical floor vibration velocity caused by a unit impulse, (1 Ns) applied at the point of the floor giving a maximum response. It is calculated taking account of components of motion associated with first order natural frequencies < 40 Hz. First order motions are ones having a single half-sinewave mode shape parallel to joists direction, n_{40} is the number of such modes for a particular floor. The practice of considering modes other than the fundamental mode contribute significantly to aggregated floor surface motions experienced by building occupants is a major departure from other practices. Other approaches applicable to timber joisted floors presume responses are dominated by the fundamental mode. [e.g. 17,18]. The Eurocode 5 approach follows research findings of Ohlsson [23].

Commentary D of the National Building Code of Canada [38] reinforces advice that vibration control methods based on simpler methods (e.g. deflection limits) can lead to unsatisfactory design solutions. Vibration serviceability performance measures implemented by the Canadian National Building Code [39] employ criteria based on direct control of motions with limits on them matching provisions of ISO 2631-2 [31]. Commentary D advises that above mentioned AISC and parallel Canadian Institute of Steel Construction guidelines may be applied for controlling floor vibration due to occupant induced disturbances for steel construction. For all other structural materials, including light-frame timber construction following guidelines provided by the Applied Technology Council (ATC) is suggested [40].

The ATC guideline is based on research by Allen and Murray [25] with Eq. (3) predicting acceleration levels created by resonant footfall excitations as ratios of acceleration due to gravity (a/g):