Predicting Vibration Behaviour of Cross Laminated Timber Floors

Ebenezer USSHER
PhD Student
Univ. New Brunswick
Fredericton, Canada
eussher@unb.ca

Ebenezer has extensive experience in design and construction of large structures, and is currently researching dynamics of lightweight systems.

Ian SMITH
Professor Emeritus
Univ. New Brunswick
Fredericton, Canada
ismith@unb.ca

Ian holds PhD and DSc degrees from London South Bank Univ., and is author of over 250 structural mechanics publications.

Summary

Ultra-lightweight products like Cross-Laminated-Timber (CLT) have entered the marketplace as alternatives to cast in-situ or precast reinforced concrete (RC) for construction of floor slabs. The primary advantage of using lightweight materials is that they reduce structural demands on supporting elements. However, lightweight slabs tend to exhibit higher levels of acceleration than RC slabs when subjected to dynamic loads, making it prudent to pay close attention to vibration serviceability when designing CLT slabs. Discussion here addresses a detailed finite element (FE) analysis approach as the reference point for defining accuracy capabilities of simple dynamic analysis formulas. It is concluded CLT floor slabs embody complexities in their modal responses that are beyond abilities of simple engineering formulas to predict.

Keywords: cross-laminated-timber; design; finite element analysis; modal frequencies; mode shapes; peak acceleration; vibration serviceability.

1. Introduction

Cross-Laminated-Timber (CLT, also known as X-LAM) is a class of ultra-lightweight slab products that resemble massive plywood and have three or more bonded layers of lumber boards. CLT has been used in Europe for more than 20 years to construct various types of low-rise building superstructures. In North America its use is still at an early stage but growing steadily with two high capacity manufacturing plants now existing in Canada to serve the continental market. Product thicknesses range from less than 100 mm to over 500 mm depending on the manufacturer. Most often CLT is seen as an alternative to cast in-situ or cast in place reinforced concrete (RC) in a range of slab construction situations.

Employing CLT floor and roof slabs has clear benefits in terms of global structural responses of building superstructure systems, especially those that are tall and slender where control of lateral drift under wind or seismic design load scenarios controls sizes of structural elements. However, it is also important to pay close attention to the serviceability performance of the lightweight floor slab substructures. Like any other type of plate elements that have high stiffness to mass characteristics, CLT floors tend to exhibit relatively high levels of vertical acceleration when subjected to dynamic forces. Consequentially there exists greater potential than has existed with RC slabs that vibration serviceability performance will be the crucial design factor in determining slab thicknesses. Discussion below addresses whether similarly simple design analysis practices are adequate for vibration serviceability design of CLT floor slabs. Intent is not to direct engineers toward choice of particular floor vibration serviceability performance criteria. It is to advise whether simple methods of modal analysis are sufficiently accurate to useful applied in conjunction with various performance criteria.

2. Finite Element versus Analytical Models

Prefabricated CLT slab segments can be regarded as orthotropic plates. For thin slabs consisting of one or more prefabricated slab segments the most important analysis parameters are geometry, (characteristic plan dimension, plan shape), and flexural rigidities for axis of material symmetry directions. As is generally the case, modal frequencies of CLT slabs are eigenvalues that satisfy equation (1):

$$\det([K] - \omega^2[M]) = 0 \quad (1)$$

where [K] and [M] are stiffness and mass matrices for the slab, and ω is the circular modal frequency vector. As is outlined in the full manuscript, FE modal analyses are used to accurately determine modal frequencies and mode shapes; with those solutions then being yardsticks for measuring capabilities of simple design level formulas to predict parameters like the fundamental modal frequency (f_1) and the number of first order modal frequencies not exceeding 40 Hz (n_{40}). Analytical formulas such as those proposed by Leissa and the Eurocode 5 were also employed to estimate f_1, other modal frequencies and n_{40}.

3. Findings

Comparisons of FE modal analysis results with estimates of modal frequencies obtained using simple engineering formulas makes it clear that the latter cannot adequately represent effects that material characteristics of CLT and common floor construction features have on higher order modal frequencies. Although simple formulas do often yield reasonably accurate estimates of f_1, that is normally insufficient because commonly adopted generalised vibration serviceability design criteria also require accurate estimation of other modal response parameters (e.g. n_{40}). It follows therefore that, except in limited cases where knowledge of f_1 alone suffices, simple dynamic analysis formulas are unsuitable for vibration serviceability design of CLT floor slabs. This should not be construed as applying to other types of floor slabs (e.g cast in-situ RC slabs).

The authors recommend that design analyses intended to predict modal response characteristics of CLT slabs should have the following minimum features:
- realistic representation of the layout geometry and support conditions,
- realistic representation of the orthotropic elastic properties, and density of CLT slab elements; and
- realistic representation of any discontinuities and semi-rigid construction joints within slabs.

In instances where slabs support structural elements that do not align with the supports of the slabs themselves, and/or slabs support fixed imposed masses, it is also important to incorporate effects of those permanent features in a realistic manner. This militates toward need to employ numerical modal analysis methods, which in the contemporary context is achievable using structural analysis tools like commercial FE software products. Commonly employed design criteria assume that either, only fundamental modal frequencies, or sometimes the first few low order modal frequencies (e.g. $\leq$ 40 Hz) can be excited in ways that negatively influence vibration serviceability of floors. However, that is not always correct, especially when harmonics of excitation frequencies correspond to harmonics or frequency separations of floor modal frequencies. Studies by the authors and their co-investigators suggest that modes with frequencies up to 100 Hz can be dynamically excited in ways that negatively influence vibration serviceability of CLT floor slabs. This is because harmonic frequencies of excitations and responses can match, and/or there is coincidence of excitation frequencies with modal response frequency separations. Such considerations strongly suggest empirically based design criteria calibrated against building occupant assessments of floor performances (as have been suggested for CLT and other floor slab systems) cannot be generally reliable substitutes for design criteria related to physical phenomena.

4. Conclusions

Analyses presented here clearly demonstrate that successful application of vibration serviceability design criteria to floor slabs constructed from ultra-lightweight slab materials like Cross-Laminated-Timber requires more than usual attention to choice of dynamic analysis techniques. Most importantly a basic requirement is that models correctly represent material features like in-plane orthotropicity of CLT slab segments, and presence of construction features like semi-rigid joints between CLT slab segments. Simple analysis formulas can predict fundamental modal frequencies of CLT slabs accurately, but cannot reliably predict other parameters that characterise dynamic responses of such systems. If excessively simplified and inaccurate methods are used to predict dynamic response characteristics of CLT floor slabs that has potential to result in oversizing of slabs and / or poor vibration serviceability performance of occupied buildings.