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VIBRATION SERVICEABILITY DESIGN ANALYSIS OF CROSS-LAMINATED-TIMBER FLOOR SYSTEMS

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ABSTRACT: Despite much R&D in recent decades, definition of robustly reliable engineering design approaches for avoiding vibration serviceability problems with timber and other lightweight flooring systems has remained elusive. Success depends on having appropriate vibration serviceability performance assessment criteria, and ability to predict floor response parameters used by those criteria. This paper addresses prediction of dynamic response characteristics of cross-laminated-timber (CLT) floor systems using finite element methods. Attention is focussed on systems that contain realistic construction features like intra-slab CLT panel to-panel joints, and variations in floor slab edge supports. Modelling assumptions are verified by comparing analytical predictions with laboratory test measurements.

KEYWORDS: Cross-laminated-timber, Design, Dynamic response, Joints, Support conditions, Vibration serviceability

1 INTRODUCTION

Vibration serviceability of lightweight floors constructed from wood-based or other materials receives most R&D attention. This is because such systems are prone to high amplitude motions in the frequency range that is annoying to humans. Several calculation methods have been suggested for screening out poor constructions at the design stage, based mostly on study of floors having parallel arranged joists overlaid with wood-based subflooring. Unfortunately many floors having poor dynamic performance continue to be built, and suggested design practices have been found unreliable except in contextually limited circumstances.

Successful engineering vibration serviceability design depends on having appropriate performance assessment criteria, and ability to predict response parameters used by those criteria. Currently suggested performance assessment criteria require that engineers be able to predict one or more of: out-of-plane response natural frequencies; peak velocity or peak acceleration caused by a defined dynamic excitation; and static deflection due to a defined gravity force. This paper addresses prediction of dynamic responses parameters by analytical methods in the context of cross-laminated-timber (CLT) floor systems. The focus on CLT reflects that it is a class of shallow profile engineered wood product that has become popular for construction of large floor systems in applications formerly beyond the capabilities of timber solutions. As in many instances CLT is used as a substitute for reinforced concrete (RC) slabs, there is an expectation of building owners and occupiers that CLT floors will have performance characteristics equal to or better than those of equivalent RC floors. Discussion here supports enablement of that objective.

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2 FINITE ELEMENT FLOOR SYSTEM MODELS

Finite element (FE) approximation models were constructed to replicate full-scale laboratory-built floors tested at the University of New Brunswick UNB). The arrangements considered incorporate single and double CLT panels having two or four edges supported. In double panel tests intra-slab (panel edge-to-edge) connections have half-lapped joints. What is presented here is intended as a basis for understanding what modelling features are essential for reliable application of vibration serviceability design criteria. It is also a benchmark for credibility of proposed simplified design analogies. Models were built using thick plate bending elements. Intra-slab joints plate connections were represented as hinge connections, matching actual behavior of half-lapped joints made using self-tapping screws. Various slab boundary conditions were considered ranging from hinged to fixed, as can occur in actual practice.

The FE analyses correctly predict the number, types and sequences of modes for each experimental situation. In absolute terms all differences between predicted and observed modal frequencies are quite small, or in most cases negligible. Discrepancies between predicted and observed behaviours are direct consequences of the simplifications in representation of end and edge support conditions and intra-slab connections. Supplemental FE analyses showed that discrepancies can be rendered negligible through model refinement. Table 1 shows the effect of doubling the width of a floor built using 175mm thick CLT panels of lengths of 5.5m and widths of 2.28m. In that table case *S-2end* corresponds to a single panel with end hinge supports; and case *D-2end* corresponds to double panels edge-to-edge connected with a hinge and ends of panels hinge supported.

Table 1*: Comparison of modes and modal frequencies for single and double CLT panel floors*

S-2end		***D-2end***	
Mode	*Frequency (Hz)*	*Mode*	*Frequency (Hz)*
1,1	12.2	1,1	11.9
1,2	18.5	1,2	14.1
2,1	38.6	1,3	21.4
2,2	45.2	2,1	38.6
3,1	70.8	2,2	40.5
3,2	76.6	2,3	57.5
1,3	95.6	1,4	69.3
4,1	104	3,1	71.2
4,2	110	2,4	72.6
3,3	124	3,2	82.5
5,1	138	3,3	85.0

A number of important influences can be observed in the tabulated results, First, increasing floor slab width lowers the fundamental modal frequency (mode 1,1). In terms of practical design this illustrates that suggested simplified methods of predicting fundamental natural frequencies of CLT slab systems cannot be generally valid. Second, the number of mode shapes that need to be considered increases when the floor width is increased. This impacts for example, application of the vibration serviceability design practice recommended by Eurocode 5. Other influence that Table 1 illustrates include that when width is increased there is tendency toward clustering of modal frequencies and that non-trivial far-field motion transmissions are possible.

All the analyses presented in the full manuscript support the contention that simplified vibration serviceability analyses cannot be reliable unless applied to relatively trivial problems.

3 GENERAL OBSERVATIONS

Creation of floor systems having poor out-of-plane dynamic response characteristics can be the consequence poor solution definition. Sometimes no amount of analytical complexity, or increasing the amount of material employed, will be able to overcome consequences poor solution definition. Therefore although it is important to have reliable vibration serviceability design criteria and reliable methods of estimating parameters used by those criteria; it is equally important to properly select solutions. Many examples of poorly performing timber floors are the consequence of introducing high levels of disparity between the flexural rigidities of floors in parallel and perpendicular to span directions. This is why for example many efforts have been directed toward creation of methods that increase the across-width flexural rigidities of floors. Except when their plan geometries are complex or highly elongated, isotropic slabs exhibit good separation of their modal frequencies. That greatly decreases proneness to amplification of motions under forced or free vibration conditions, and means that relatively simple vibration serviceability design criteria can be applied successfully. It is also essentially the reason why it is simpler to design and construct satisfactory RC floor slabs than to design and construct satisfactory timber or some other types of lightweight floor systems.

There is no possibility of a universal simple vibration serviceability design method ever being found for all timber floor systems. However such a Holy Grail may be possible for timber floor construction methods that result in approximately isotropic plate dynamic responses. Studies at UNB beyond the scope of the present discussion are developing practical ways of creating CLT slabs that behave as close approximations to isotropic slabs.

4 CONCLUSIONS

It is quite feasible to model the vibration response of CLT floor slab systems with construction details typical of actual practice. However, accurate and complete calculations are only possible if models are realistic. Discussion here helps define what realistic means. Conversely this discussed does not support propositions that have been made for application of simplified design criteria and analysis methods.