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Dynamic response of CLT plate systems in the context of timber and hybrid construction

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ABSTRACT

An experimental investigation of low amplitude dynamic responses of cross-laminated-timber (CLT) floors is presented to illuminate effects of variables like plan aspect ratio, support conditions and CLT type. Data extraction and analysis focus on determination of modal frequencies and damping. Practical implications of results are discussed in the context of vibration serviceability.

1. Introduction

Vibration serviceability is a key performance issue for building substructures within heavy superstructures that are compliant. This paper addresses vibration serviceability in the context of floors subjected to surface impacts like footfalls that cause out-of-plane low amplitude motions that can annoy humans [1]. Typically vibration serviceability design practices presume motions building occupants experience are dominated by flexibility and masses of floors themselves and effects of imposed masses associated with particular building occupancies. Consequentially design criteria address limiting static deflection under concentrated load, or empirically relating both fundamental frequency and static deflection under a concentrated load to building user satisfaction with particular floor systems [1]. Current approaches are therefore simplified extractions of actual complexities of specific design situations and can fail to properly address dynamic responses observed by people who occupy buildings constructed in nontraditional ways [1].

Use of the engineered wood composites known as cross-laminated-timber (CLT) has been fairly widespread in Europe for more than a decade, but commercial production in North America only started in 2011. CLT products are like massive plywood plates having three or more plies of lumber boards, with some having thicknesses over 500 mm making them suitable for long-span construction situations [2]. The range of possibilities has not been fully developed but engineers seek to employ CLT in applications previously suited to only reinforced concrete (RC) [2,3]. Although it is not specifically clear what future vibration serviceability problems associated with using CLT will be, engineers require data on how CLT floor slabs vibrate to objectively assess associated issues. Work discussed here aims to provide such data.

Technical differences between low amplitude dynamic responses of floor slabs with CLT spines and responses of traditional timber floors will include that the former do not necessarily exhibit flexible behaviour of all structural parts and are supported on superstructure systems of various types and materials. For example, CLT spine slabs can be incorporated into large structural systems manufactured from structural steel or RC. A premise of the study reported is assessments of CLT floor vibration serviceability need to be based on complete engineering analyses of particular construction situations. Prior investigations have yielded preliminary understanding of vibration characteristics of CLT materials, but contradict one another in important aspects [4–6]. One study [4] involved single plate multi-span and two-plate single span systems having 155 mm thick 5-ply plates, with focus on damping values for the fundamental mode. That showed damping values to increase for systems supported along all edges instead of two ends, and when two plates were interconnected in a way that only transferred shear forces. Higher damping was also observed for CLT

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without topping than with non-structural screed topping. That study underpins the European CLT design handbook [5], which also suggests when a person stands on a floor viscous damping ratios range from 2.5% to 4%. By contrast the Canadian CLT design handbook [6] suggests a viscous damping ratio of about 1% applies for all CLT floors. Such discrepancies underpin incompleteness of understanding surrounding the characteristics which determine whether impact induced vibrations will be long lasting or of short durations.

Other gaps in knowledge that require to be filled include damping for modes other than the fundamental one, and frequency separations that affect proneness to modal interaction that amplify motions [1]. The study reported addresses these factors and others like effects people standing on a floor have.

2. Testing program

Shallow floor slab systems with CLT spines were tested with emphasis on systems having high span to depth ratios expected to result in out-of-plane response fundamental natural frequencies approaching 8 Hz. This is because 8 Hz is traditionally considered the upper limit of the primary range of vibration frequencies causing human discomfort in normal building occupancy situations [7]. To note is that even when structural system responses can be 'high tuned' away from the human sensitivity range (i.e. $f > 8$ Hz) summed effects of various modal responses can be undesirable and need consideration.

Preliminary stage tests addressed 5-ply CLT plate systems in which the floor width and the degree of slab end fixity were varied, and effects of people standing on floors were measured [8]. Later tests studied 7-ply CLT plate systems where effects of the number of plates, plate orthotropy, and various support configurations were studied. Effects of alternative data analysis methods were investigated to determine likely robustness of practices underpinning literature estimates of modal parameters. All floor systems under investigation met the vibration design criteria set in the Canadian CLT handbook [6].

2.1. Testing 5-ply CLT plate systems

Table 1 and Figs. 1 and 2 summarise the scope of tests on 5-ply CLT plate systems for which the plate thickness $t = 175$ mm. The plate edge to edge dimensions were 5.5 m in the longitudinal direction, and 2.28 m in the width including a half-lap joint of 64 mm along one edge. Each ply of the CLT panel had the same thickness. The initial support system employed had steel I-beams (Type: S6 × 12.5) on which the CLT rested (Test 1), with I–beams fixed to a concrete laboratory floor. Gaps between CLT plates and supports occurring due to material/plate imperfections were filled with steel fillers/shims. In Test 3 a Spruce-Pine-Fir lumber element was inserted between the CLT plate edges and the top flange of the support beams to determine how rigidity of the support surface affects results. In Tests 1 and 3 self-weight of CLT was the only force preventing loss of contact at supports. In Tests 2 and 4 also representing steel beam and lumber bearing conditions additional hold-down forces were applied using three F-clamps per supported edge, with one at each end and one in the middle of an edge. F-clamps were also installed during Tests 5–8 where the person conducting vibration tests stood at locations shown in Fig. 1(a).

In Tests 9 to 12 a second CLT plate of the same size was added to the arrangement, with the two plates interconnected at adjoining half-lap edges using ASSY Ecofast screws of length 160 mm spaced at 300 mm. Test 9 was conducted to obtain modal characteristics of a bare floor, and Tests 10 to 12 were repetitions with a person standing on the floor at various locations (Fig. 1(b)). The F-clamps were installed for Test 9, with the number of clamps adjusted to the increased floor width (Fig. 2). The edge condition was kept unchanged for the remainder of the test series. Use of different support conditions in above mentioned tests was to determine if end fixity affects responses significantly.

2.2. Testing 7-ply CLT plates systems

Table 2 and Fig. 3 summarise the scope of tests on systems constructed from between one and three 7-ply CLT plates, with plates joined by 64 mm half-lap joints when there was more than one, using ASSY Ecofast screws of length 240 mm spaced at 300 mm.

Table 1
Summary of test parameters for 5-ply CLT plate systems.

Test	Plates	Support	Clamped	Person on floor
1	1	Steel	No	No
2	1	Steel	Yes	No
3	1	Lumber	No	No
4	1	Lumber	Yes	No
5	1	Lumber	Yes	Yes (Fig. 1a)
6	1	Lumber	Yes	Yes
7	1	Lumber	Yes	Yes
8	1	Lumber	Yes	Yes
9	2	Steel	Yes	No
10	2	Steel	Yes	Yes (Fig. 1b)
11	2	Steel	Yes	Yes
12	2	Steel	Yes	Yes

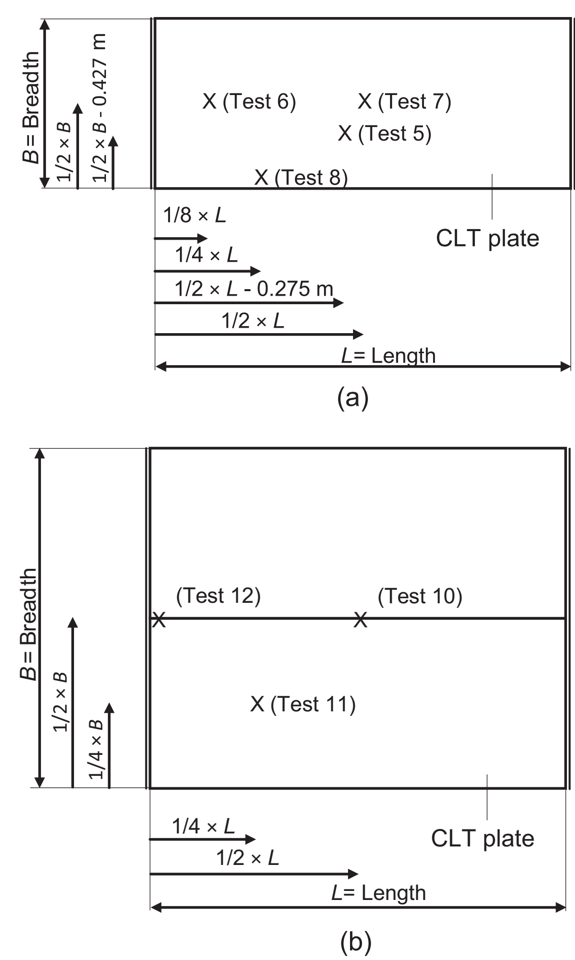

Fig. 1. Locations of person on the floors with 5-ply CLT plates. a) Tests 5–8. b) Tests 10–12.