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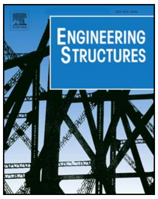

Vibration responses of glulam beam-and-deck floors

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ABSTRACT

Floor vibration serviceability problems can exist for floors constructed from low mass-to-stiffness engineered-wood products. This paper addresses responses of beam-and-deck floors constructed using glued-laminated-timber (glulam) products. Such floors have widely spaced parallel beams supporting flat wise oriented deck elements and are a relatively new construction option for floors having spans up to about 10 m. The primary focus of discussion here is the experimental investigation of how design variables like span, support arrangement, beam spacing and the addition of non-structural topping materials alter vibration responses of floors. Focus group opinions of acceptability of motions of floors resulting from walking footfall impacts were collected as an indication of the practicality of using engineering design decisions to control vibration of beam-and-deck floors. Collected opinions support the premise that dynamic motions of floors can be controlled in desired ways using practical engineering design methods. However, it was also apparent from the data that suitable methods need to be ones specifically calibrated to suit beam-and-deck floors rather than those applied to other types of low mass-to-stiffness engineered-wood products. No attempt is made to propose new vibration serviceability performances criteria or design methods. This is because it would conflict with ongoing international efforts to create criteria and methods that apply across a wider range of floor construction technologies.

1. Introduction

Well established ways of constructing lightweight timber floors exist for various types of building designs and occupancy situations. In some instances design is prescriptive, but that is confined to the situations like the construction of lumber joisted floors in houses and some other small buildings [1]. Nearly always design of timber floors with spans greater than about 4 m is controlled by static or dynamic engineering serviceability performance related criteria [1–8]. This reflects that all types of lightweight floors can be prone to amplifying motions to levels unacceptable to humans or which inhibit proper operation of equipment located on them [1,2,6,8–11].

Since 1970s architecture and construction methods for timber building superstructures have departed substantially from traditional methods [12]. For domestic dwellings and other relatively small buildings, major changes included substitutions like replacing sawn timber joists with open-web joist products or wood I-joists; substituting panelized deck products for the sawn timber boards; and the introduction of completely new construction methods like voided prefabricated panels. In some instances, this resulted in performance problems like motions disturbing to humans during every day activities like walking. In reaction researchers began to study the phenomena. Latterly attention has expanded to encompass use of new engineered-wood products like Cross-Laminated-Timber (CLT) capable of being substitutes for non-timber slabs in residential and commercial buildings [13,14]. However, the R&D literature is dominated by studies on performances of rectangular plan floors with relatively closely spaced joists (circa ≤ 400 mm), reflecting commonness of such systems [1–4,9,15–18].

Some research delved into the fundamental issues, but mostly the goal was to find practical ways of minimizing chances of creation floors with behaviours acceptable to building occupants. There has been in essence a split in approaches to developing engineering practice design methods applicable to lightweight floor constructed from timber products. Europeans have tended toward approaches where engineers use mechanics-based equations to predict dynamic motions caused by defined impact or impulsive forces, with responses judged acceptable if they do not exceed threshold levels deemed appropriate to particular building occupancy situations [2,3,6]. The prime manifestation is provisions for vibration serviceability performance of floors contained in the pan European Eurocode 5 [7]. That and similar approaches are classical engineering methods. However, it is important to recognize they involve use of disturbance functions (e.g. impact force, unit impulsive force) and acceptable motion levels (e.g. peak velocity, root-

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mean-square acceleration) calibration to achieve consistent design outcomes for particular situations [1]. This limits practical utility of classical engineering methods, e.g. the Eurocode 5 provisions only apply to rectangular shaped floors that are simply supported along all four edges and have closely spaced parallel arranged joists spanning parallel to on axis of plan symmetry. The particular scope limitation is not fundamental, but is because the supporting research was restricted to such cases [19]. Appendix A summarizes the Eurocode 5 approach.

Beginning with the work by Onysko [20] an alternative vibration serviceability design approach has been developed which sidesteps need for defined disturbance functions and acceptable motion levels associated with particular building occupancy situations [4–6,8,17,18,21,22]. Instead the taken approach is to conduct surveys that canvas how building occupants asses relative suitability of floors having specific architectural and construction features. Correlations are then inferred between such opinions and measurements of parameters like the fundamental natural frequencies (f_1 values) and static displacement characteristics (d values) of floors building occupants assessed. Employing discriminative analysis techniques correlation studies yield empirical equation intended to separate floors into acceptable and unacceptable performance classes. Intent is that engineers use such equation on a pass-or-fail basis to screen from consideration floor design solutions likely to result in performance unsatisfactory to building occupants e.g. [13,15,17,18]. The downside of empirical correlation approaches is they rely on correctness of choices of parameters like f_1 and d values as predictors of acceptable or unacceptable performance, and lack of generality of equation fitted by discriminative correlation methods. It has been demonstrated empirical design equations can lead to one third of floor designs being wrongly classified as acceptable or unacceptable performances [1]. The reason is even simple departures from calibration conditions like altering plan aspect ratio or the number of support edges for rectangular plan floors can alter parameters modal frequencies (f_i values) and d values considerably [1,3,14]. Eq. (1), which applies to rectangular plan floors with closely spaced joists and residential building occupancies, is illustrative of proposed empirical design relationships [21]. Intent is input parameters fundamental natural frequency (f_1) and static displacement caused by a 1 kN gravitational force located at the center of plan position (d_1) be estimated using closed form engineering formulas. Constants 0.44 and 18.7 were derived through correlation studies intended to bias pass-fail errors toward rejection of floors having performances marginally acceptable to building occupants. Mentioned 1 in 3 design decision errors applies to application of Eq. (1), and is a minimum estimate made using its original calibration data.

$$\frac{f_1}{d_1^{0.44}} > 18.7 \tag{1}$$

The current state-of-the-art is neither classical engineering nor empirical correlation approaches to vibration serviceability design of lightweight floors constructed from woodproducts are sufficiently developed for applications to cases beyond their calibration scenarios. This leaves the conundrums of how to avoid possible construction of floors with unacceptable performance when new building architectures or construction materials and methods are employed. The remainder of this paper addresses one such conundrum related to vibration performance of so-called beam-and-deck floors constructed from glued-laminated-timber (commonly referred to as glulam) elements. Glulam beam-and-deck floors have widely spaced parallel beams supporting flat wise oriented deck elements, Fig. 1. To date examples of such systems are limited, but they are gaining popularity for non-residential buildings [23]. Goals of research reported here is to examine which construction variables influence their static and dynamic response characteristics, and to examine ability of standard engineering analysis methods to predict those characteristics. Information presented will have utility irrespective of whether it is applied in conjunction with classical engineering or empirical correlation design methods.

2. Test and data analysis methods

2.1. Test schedule

Nine floor configurations were tested representing effects of construction variables on vibration responses of glulam beam-and-deck floors, Table 1. Reference Floor 0 was designed to satisfy Ultimate Limiting States (ULS), but not Serviceability Limiting States (SLS) criterion applicable in Canada [8,24], Fig. 1. Eight modified floors (Floors 1 to 8) were created to elucidate effects of decreasing beam span, increasing the number of beams (i.e. decreasing the beam spacing), and adding an intermediate line beam support, and construction detail changes like addition of non-structural toppings. Sequential modifications improved SLS performance. The adopted un-factored live load used was 2.4 kPa, which matches office floors and some commercial building occupancy classifications in Canada [8]. Fig. 2 shows examples of modified systems.

Floor 0 was constructed using three 130 mm × 304 mm × 5 m long 20f-E Spruce-Lodge pole Pine-Jack Pine glulam beams, and eight 600 mm × 80 mm × 5 m long No. 2 grade Spruce-Pine-Fir glulam deck elements [24]. Metal angle brackets and 6 mm diameter 60 mm long proprietary HECO-TOPIX® Flange head screws were used to attach beams to 130 mm thick support walls constructed from additional 304 mm deep beams. Support walls were themselves supported on glulam deck elements anchored to reinforced concrete laboratory floor (Fig. 1b and c). Deck elements were attached to beams using four 6 mm diameter 160 mm long HECO-TOPIX® Flange head screws per connection. Adopted support conditions simulated simple bearing supports found in practice. The screws are partly threaded and plated with bright zinc. Substitution of similar proprietary screws would not alter floor response characteristics in measurable ways. In Floor 4 adjacent deck elements were interconnected using twenty pairs of 100 mm long HECO-TOPIX®-CC screws having a shank diameter of 6.5 mm installed from opposing directions at an angle of 45°, Fig. 3(a).

The Oriented Strand-Board (OSB) overlay in Floor 7 consisted of 2R40/2F20 rated 15.5 mm thick 1.2 m by 2.4 m sheets [24]. Strong axes oriented in the across-beam direction. Joints between sheets were staggered leaving 3 mm expansion gaps. OSB was fixed to deck elements using 3.66 mm diameter by 65 mm long common wire nails. Nailing was at 150 mm intervals around sheetperimeters and 300 mm elsewhere, Fig. 3(b). The additional non-structural overlay added to create Floor 8 was 38 mm self-compacting concrete poured directly onto the OSB layer of Floor 7. The concrete topping had a compressive strength of 30 MPa, density of 2300 kg/m^3, maximum aggregate size 10 mm, and a slump of 500 mm. The type of high workability concrete is typical of that used in practice, and was poured by an experienced crew.

2.2. Vibration tests and data analysis

Prior to construction Forced Vibration Tests (FVT) were conducted to determine the average flexural rigidities beam and deck elements [25]. Extracted modulus of elasticity values are reported in Table 2. Ambient Vibration Tests (AVT) were conducted to measure modal frequencies and mode shapes of each test floor [26]. Static deflection caused by a 1 kN vertical load (d_1 values) were measured at the center-span position of each floor, using a dial gage with 0.01 mm precision referenced from the laboratory floor.

In FVT a beam or deck element was suspended on two flexible rubber ropes, at free-free nodal points located at 0.22 and 0.78 of the length [26]. This was done because other support methods would influence definition of span and damping characteristics. Elements were dynamically excited using an instrumented hammer, with acceleration responses measured using a piezoelectric accelerometer. The excitation