Engineering Structures 82 (2015) 44–54

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Vibration properties of a timber floor assessed in laboratory and during construction

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ARTICLE INFO

Article history:
Received 13 December 2013
Revised 6 October 2014
Accepted 9 October 2014

Keywords:
Timber floor
Wooden floor
Vibration
Damping
Frequency
Mode shape
Modal analysis

ABSTRACT

Natural frequencies, damping ratios and mode shapes of a prefabricated timber floor element have been assessed experimentally in laboratory with different boundary conditions and *in situ* (in field) at different stages of construction. In laboratory the change in modal parameters was studied with free-free boundary conditions and simply supported on two sides. Three different simply supported tests with changes in boundary conditions were carried out; the floor placed on the support without any fastening or interlayer between support and floor, the floor screwed to the supports and the floor placed on an elastic interlayer between support and floor. The *in situ* tests were carried out first on the single floor element and then on the entire floor of the room into which the floor element was built in. The damping ratio of the floor increased from 1% to 3% when simply supported in laboratory to approximately 5% when placed upon a polyurethane interlayer (Sylodyn®) *in situ*, and to approximately 6% when fully integrated in the building. Thus the *in situ* conditions have considerable influence on the damping and the values assessed are very high in comparison with damping values suggested in design codes. Regarding natural frequencies it was concluded that the major change in these occur as the floor element is coupled to the adjacent elements and when partitions are built in the studied room, the largest effect is on those modes of vibration that are largely constrained in their movement.

1. Introduction

Wood is the only renewable and, in a 50–100-year perspective, CO_2-neutral structural material available and therefore increased construction with timber, rather than other materials, is desirable with respect to sustainability perspectives. It is, however, necessary that timber construction meets requirements and expectations regarding structural performance, safety and serviceability in all respects. One area that must be considered carefully is how people experience vibrations and springiness in timber floors as open plan solutions with long spans are challenging for such floors. Due to the light weight, timber floors are more prone to annoying vibrations induced by human activities than heavy concrete floors.

It has been shown by Lenzen [1] that damping is a key factor for the human response to transient vibrations. The vibration performance of the floor structure itself is determined by the floor stiffness, mass and damping. The stiffness and mass properties of the floor determine the floor natural frequencies. The damping affects the time it takes for an induced vibration to decay. The mass and stiffness are parameters that are relatively easy to predict and calculate with established methods. The values used for damping of timber floors, however, are mostly rough estimates and there are no established prediction models for damping of timber floors, although there are some proposals for analysis methods. Yeh et al. [2,3] have proposed a method to predict damping in glued and nailed joints and Labonnote [4] a model to predict material damping in timber floors in which each component contributes to the total material damping of the floor structure.

Measurements of dynamic properties of timber floors have been carried out in laboratory by many researchers. Many have made parametric studies on floors and studied the effects caused on

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Abbreviations: CLT, cross-laminated timber; EC5, Eurocode 5; PUR, polyurethane; EMA, experimental modal analysis; CMIF, Complex Mode Indicator Function; LSFD, least-squares frequency-domain; FRF, frequency response function; FFT, fast Fourier transform; MPC, modal phase colinearity; MPD, mean phase deviation; MC, moisture content; MOE, modulus of elasticity; COV, coefficient of variation.

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http://dx.doi.org/10.1016/j.engstruct.2014.10.019
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natural frequencies, mode shape and damping ratio by changing e.g. type of floor joist, joist spacing, type of board for flooring, the type of connection between joists and board, blocking between beams and boundary conditions. The reported range for damping ratios from laboratory tests lies between 1% and 5% depending of type of floor. Chui [5] has reported damping ratios of about 1.5% for solid timber joist floors with chipboard or plywood flooring. The damping ratios for the fundamental mode assessed in laboratory by Bernard [6] were approximately 2% for I-joist and glulam joist floors with particleboard or plywood flooring. Weckendorf [7] reported average damping ratios of 2.8% for the fundamental mode of an I-joist floor and values between 1.1% and 1.2% for higher modes. Ljunggren [8–10] performed tests on lightweight floors with steel joist and found damping ratios between 1% and 2% depending on support conditions and floor covering. Zhang et al. [11] studied the effect from joist spacing, strongback bracing and ceiling on vibration performance of floors with metal web joists and found an average damping ratio of 0.9% and that the damping ratio of the fundamental mode was not largely influenced, but that there was an increase by strongback bracing for vibration modes higher than four. Hamm and Richter [12] have found damping ratios between 2.15% and 4.57% for the fundamental mode of solid timber joist floors with and without different top floor solutions and different boundary conditions. The damping of cross laminated timber floor plates (CLT) with or without light or heavy top flooring was found by Fitz [13] to vary between 2% and 4% depending on boundary conditions, i.e. supports on two or four sides. Floors supported on two sides yielded values near 2% independently of the type of top flooring. Bolmsvik and Brandt [14] have investigated the effect of damping elastomers on the vibration levels in lightweight timber framework mock-ups consisting of timber walls and floors and found average damping levels of 1.2% for a structure with no damping elastomer and 2.1% for a structure with damping elastomer included in the joint between wall and floor. Recently Hu and Gagnon [15] conducted measurements and a subjective evaluation of floor vibration performance of CLT floors in laboratory. The work resulted in design criteria and methodology for vibration control of CLT floors. It was found that the damping ratio was about 1% and did not vary much with varied CLT element thickness, floor span, support conditions and joint configuration. The work by Homb [16] includes both laboratory and *in situ* tests. Traditional timber joist floors tested in laboratory with or without transverse stiffeners, simply supported on two or continuous over three supports showed damping ratio values between 2% and 5%. The floors with lightweight steel joists showed lower damping ratio, below 2% and the floors with joists comprising timber in flanges in and different configurations of thin metal plates in web, had damping ratios between 2% and 3%.

Damping ratios for timber floors from *in situ* tests have not been reported in the same extent as from laboratory tests. The damping ratios of the *in situ* tested floors by Homb [16] were much higher than for the floors measured in laboratory. The damping ratio extracted from laboratory and *in situ* measurements, for two similar types of joist floors with same span length, increased from 4% to 10%. Homb assumed that the very high values *in situ* were caused by changed excitation and measurement method and no further comparison between obtained damping values from *in situ* and laboratory measurements was therefore made due to the uncertainty of results. Zimmer [17] have performed *in situ* tests on CLT floors with different support conditions and during different construction phases, when the CLT plates were screwed together, after finished timber frame construction and when the heavy topping had been installed on the floors. The results show that the damping ratio of the floors did not change on average between the two first construction phases where it was 3.1%, but increased to 6.4% when the heavy topping was installed in the last phase. The effect on damping ratio from support conditions and clamping at supports by loading from walls and storeys above was possible to assess in the two first construction phases, while the heavy topping prevented it in the last phase. From *in situ* tests on traditional solid timber joist floors by Ohlsson [18] damping ratios between 2.5% and 4.9% have been reported.

Hu et al. [19–21] have carried out *in situ* tests on hundreds of floors in Canada during extensive research programs, first in the 1980s and then in the late 1990s, to develop serviceability design criteria for timber floors. The average damping ratio found for joist floors with a concrete topping was 3.6%. However, the damping was not included in the criteria suggested on basis of their results as it was considered too uncertain both to measure and to predict. The lack of knowledge about the damping mechanisms was a further argument not to include the damping in the criteria. Talja and Toratti [22] have proposed a design method and classification of floors in vibration classes based on laboratory and *in situ* tests on steel-, concrete and timber floors. The damping ratio was not taken into account here either. The work by Hamm and Richter [12] also included *in situ* tests on a large number of timber floors, both bare and finished ones, together with subjective assessment of floor vibration performance to develop design guidelines for vibration serviceability. According to their proposed guidelines damping should be considered only when the frequency limit is not met and additional examination of floor acceleration has to be performed.

In the building code used in Sweden and in EU, Eurocode 5 (EC5) [23], the influence of damping is considered and has a fixed value in the design calculations of floor performance due to vibrations, if not another value is proven to be more accurate. The recommended damping ratio to use in design guides for a timber floor is 1% in the national application document for Sweden [24]. This is a conservative value that should produce results on the safe side. In UK the corresponding value is 2% [25]. For the interested reader a summary and comparison of the different national applications of EC5 among European countries have been made by Zhang et al. [26]. The floor structures considered in EC5 are traditional types of floors in residential buildings with joists in the load bearing direction and sheathing on top of the joists that may be considered contributing to the load bearing capacity if properly attached to the joists. For some types of floors, without discrete joists, the stiffness may be more evenly distributed along the width of the floor and the stiffness in the direction perpendicular to the load bearing direction may be comparatively high. Such floors are not fully covered by the code and consequently the design guidelines should then be used with caution. In the guideline assessed in the project *Human Induced Vibrations of Steel Structures* (Hivoss) [27] the recommended value of structural damping for a timber floor is 6% and if also damping from furniture and finishes are added the total damping ratio for a traditional solid timber joist floor, without ceiling on the underside would end at a total of 7%. Thus the difference between recommendations regarding values for damping is rather large. In the informative annex B of the standard ISO 10137:2007 [28] there are recommendations on damping values for the fundamental mode of different types of floors within a given range of span. Damping values for typical and extreme values, respectively, are given and also a value for preliminary design of a bare floor. For wood joist floors the given typical range is 1.5–4.0%, the extreme range is 1.0–5.5% and the value for design of bare floors is 2.0%.

The vibration performance of a floor changes as it is integrated in the structural system adding parts like supplementary surface layers, partitions, fittings and fixtures. These added parts affect both floor mass and stiffness and consequently also the natural frequencies and the corresponding modes of vibration determining the vibration performance of the floor. The interaction with the surrounding parts has an effect on the damping properties. The