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Timber structures — Vibration performance criteria for timber floors

Structures en bois — Critères de performance vibratoire pour les planchers en bois

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Foreword

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This document was prepared by Technical Committee ISO/TC 165, *Timber structures.*

Introduction

Timber floors are known to be prone to producing high level of vibration caused by human activities due to the light-weight nature of these systems. Given that human tolerance to floor vibration is rather subjective and could be influenced by a number of vibration response parameters, such as frequency content, peak vibration level (e.g. displacement, velocity and acceleration), mean vibration level and damping, there has not been any general agreement among researchers and code writers on the human acceptability criteria for design against objectionable floor vibration. With the advent of engineered timber floor products, it is necessary to provide generic guidelines on the establishment of human acceptability criteria for specific floor construction product. With the appropriate calculation procedures for response parameters, such human acceptability criteria can then be used by designers to predict floor vibration performance at the design stage. Such human acceptability criteria can also be used to evaluate floor vibration performance in the field or laboratory testing according to the test procedures given in ISO 18324.[1] To differentiate between these two types of human acceptability criteria, in this report, the criterion uses the measured parameters is called "Performance criterion", and that uses the calculated parameters is called "Design criterion".

Given that human tolerance levels to floor vibration may vary between countries due to cultural differences, floor construction products, and construction practices, it is felt that floor vibration performance criterion developed in one region may not be directly applicable to the others. Consequently it is the view of the ISO/TC 165 that a more fruitful approach is to provide guideline methods to individual countries and regions to develop their own human acceptability criterion. This is the main purpose of this document.

The methods reviewed in this document are intended to be used for establishing human acceptability criteria using the parameters that have been found to correlate well with human acceptability of timber floor systems. Generally a study is required that includes measurement or calculation of these parameters and a human subjective evaluation rating of the vibration performance of a number of floor systems in the field or in the laboratory, and subsequent statistical analyses to determine the best human acceptability criterion function. The proposed methods have been published in numerous research reports and peer-reviewed papers based on significant research efforts over the last four decades. They also have been validated by measurements and feedbacks on numerous field timber floors.

The potential floor vibration response parameters include fundamental natural frequency, static deflection under a concentrated load, peak-velocity, peak-acceleration, and root-mean-square acceleration. These parameters can be measured in the laboratory or in the field, and also can be calculated.

A comprehensive procedure is provided to establish human acceptability criteria using the measured or calculated response parameters and the subjective evaluation rating through advanced statistical analysis of a large database of timber floors. If the categorical variables of the subjective rating have more than two performance levels, a "Discriminant analysis" shall be used, while a "Logistic regression" can be used for the case of two performance levels. A simplified procedure is also provided for establishing human acceptability criteria using a relatively small database.

Annex A provides an example of questionnaire that was used in laboratory studies in Canada. Annex B demonstrates the application of the comprehensive procedure to establish a performance criterion for timber floors used in Canada (human acceptability criterion using measured criterion parameters). Annex C shows the application of the simplified procedure to establish a design criterion (human acceptability criterion using calculated parameters,) and the calculation formulae for the criterion parameters for cross laminated timber (CLT) floors used in Canada. Annex D presents the design criteria and the calculation formulae for the criterion parameters in EuroCode 5 (EC5).[5] Annex E presents the design criteria and the calculation formulae for the criterion parameters proposed by Hamm et al[8].

Timber structures — Vibration performance criteria for timber floors

1 Scope

This document provides a review of key floor vibration design criteria (human acceptability criterion using calculated parameters) developed in research studies on timber floor around the world over the last 30 years. Associated design methods are provided in the Annexes. The methods proposed in this report are intended to be used for establishing human acceptability criteria for timber floor vibrations induced by walking activities.

The proposed methods are applicable to the following timber floors: lightweight floors made of timber joists and thin wood panel subfloor, heavy timber floors made of heavy timber beams with a thick timber deck, and mass timber slab floors such as cross laminated timber (CLT), nail laminated timber (NLT) and glued laminated timber.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

4 Background

A substantial amount of research efforts has been undertaken to develop human acceptability criterion for timber floor vibration control. Table 1 summarizes the most influential human acceptability criteria using calculated parameters, which is simply called “Design criteria”. Table 1 also summarizes the method used to develop the criterion, and the pros and cons of the criterion.

The Canadian National Building Code (NBC) presents provisions to control lumber joist floor vibration through limiting the floor deflection under a 1 kN load, see Table 1.[2] The NBC design criterion was developed based on research efforts by FPInnovations scientists between 1970s and 1990s.[3] Across Canada survey was conducted in 1970s. The survey included field testing and interview of the occupants using a comprehensive questionnaire. The questionnaire was developed in conjunction with statisticians and psychologist. A conversational approach was used so that the interview did not alert the occupants to the suspicion that the floor performance was likely to be of interest in the survey. The questionnaire included the following factors:

— previous experience of the evaluator on performance of floor,

— mechanical vibration of the floor by his/her own sensing and caused by others’ walking action,

— noise generated by the floor movement,

— visual effect caused by floor vibration.

A prompted approach was used by providing the occupant with a list of clues, as given in the questionnaire for three floor motion effects – hearing, feeling and seeing, and their potential causes. For each response, the interviewee can choose up to three causes. This approach ensures that the evaluator's response is not influenced by his/her awareness that the performance of his/her property is being assessed, and that there is consistency across all units. The detailed questionnaire consisting of 57 questions can be found in[3].

The interview information obtained in each house included:

a) country of adult life of those born outside North America,

b) ethnic origin of ancestor,

c) place of birth,

d) size of childhood community,

e) number of adults living in the home,

f) respondent has children in certain age groups,

g) distribution of male respondents by age group and cities surveyed,

h) ownership status,

i) original owner,

j) total family income,

k) monthly rent,

l) cost of house,

m) age of property,

n) year that property was bought or built,

o) type of housing lived in most of life,

p) last previous housing type lived in,

q) present housing type,

r) satisfaction with neighbourhood,

s) satisfaction with house,

t) satisfaction (parts of the house),

u) summary of number of dislikes about components of house,

v) when floor motion, squeak, slope, cold, and noise was first noticed,

w) occupant's acceptability ratings of floors for which squeaking, slope, coldness, or noisiness was noted (unprompted responses),

x) estimated weight of respondent

y) respondent's gait

z) condition of property.

More than 600 field single-family floors were studied. The floors were built with lumber joists with finish and subfloor, with or without lateral elements and with or without gypsum board ceiling. The finish materials included hardwood flooring, carpet and tile. The subfloor materials included lumber plank and plywood. The lateral elements included bridging, blocking and strapping. The nails or nail and glue connections were used to attach the subfloor to joists. The ceilings were made of gypsum boards attached to the bottom of the lumber without use of resilient channels.

Field tests were also conducted on the selected houses to measure the point-load static deflections and the peak dynamic displacement responses to an impulse. The objective of the field tests was to verify the computational models to predict the floor static deflection and the peak displacement response of the floor. Finally the calculated 1 kN static deflection was selected as the parameter for the design criterion. "Discriminant analysis" software was used to derive the design criterion. The design criterion along with the calculation formula to estimate the floor deflection has been adapted in NBC since 1990[2].

This NBC 1 kN static deflection design criterion is simple and reliable for the types of floor systems studied. Besides the joist and subfloor stiffness, it also accounts for the contributions of stiffening features, including use of glue, bridging, blocking, strapping, and gypsum board ceiling. However, floor construction products and practices have changed in Canada since the 1980s. For example multi-family construction and floors with heavy concrete topping are now more common.

In the USA Dolan at al[4] proposed a design criterion of floor fundamental natural frequency of 15 Hz for unoccupied floors, and 14 Hz for occupied floors to control floor vibration. The design criterion was developed through testing of 86 laboratory and field timber floors. The study included measurement of the fundamental natural frequencies of the floors, and subjective evaluation. The floor vibration performance was judged by several researchers while standing on the floor during a heel-drop test. The evaluator would then feel the response and indicate whether he/she felt that the vibration was annoying (unacceptable), marginal, or acceptable. The floors were made of lumber or engineered wood joists and a subfloor of plywood or oriented strandboard (OSB). A formula was provided to calculate the fundamental natural frequencies of these floors. The formula accounts for only the mass and stiffness of the joists and the subfloor. Parameter of "Relative power" was used along with the measured fundamental natural frequency to separate the unaccepted floors from accepted floors. Relative power was defined as a measure of how much energy is in the system, e.g. fundamental frequency times displacement. The 14/15 Hz criterion is simple, and works for certain span-range floors, but it may be conservative for long span floors and floors with a heavy topping.

EuroCode-5 (EC5) requires the checking of three design criteria for timber floor vibration control.[5] The three criteria set limits on the minimum fundamental natural frequency of 8 Hz, the maximum deflection to 1 kN concentrated load, and the peak velocity to 1 Ns impulse. The criteria are provided in Table 1. Annex D provides the criteria and the formulae to calculate the frequency and peak velocity in details. EC5 does not specify how to calculate the 1 kN static deflection, and the stiffness of the floor along floor span and across floor width directions. Therefore, it is unknown whether the topping, ceiling, and the vibration enhancements are included in the criteria. It was understood that the EC5 design criteria were evolved from the original work by Ohlsson [6] and [7]. Limited information was found on the approach of the development of the design criterion. It was briefly mentioned in[6] that the poor vibration performance of timber floors reported by the designers and owners of houses were investigated. The feedback was used to set up the criterion limits. It is known that subsequently European and New Zealand researchers conducted laboratory and field tests to evaluate Ohlsson's work, in an attempt to modify the EC5 criteria. It should be noted that calculation of the peak velocity requires assumptions of floor width and damping ratio. Assumptions also are needed to decide the 1 kN concentrated load and the peak velocity limits.

Recently Hamm et al[8] proposed a design method to control vibration for a broad range of timber floors. The design criteria were set for two-level performance: 1) higher demand performance floors and 2) lower demand performance floors. The design criteria consist of three single variable criterion:

1) deflection under a 2 kN concentrated load less than 0.5 mm for higher demand and 1.0 mm for lower demand;

2) fundamental natural frequency larger than 8 Hz for higher demand, and 6 Hz for lower demand; and

3) for frequency less than 8 Hz floors, the maximum acceleration less than 0.05 m/s^2 for higher demand and 0.1 m/s^2 for lower demand.

Formulae were provided to calculate the static deflection, fundamental natural frequency and maximum acceleration. Table 1 b briefly summarizes the criteria. Annex E presents the design criteria and the calculation formulae. The criteria were developed using floors in existing buildings, including 57 timber beam floors, 42 with heavy screed, 8 with light screed and 7 without any floor finish, 16 timber-concrete composite floors and 38 massive timber floors, 20 of them with heavy screed and 7 with light screed and 11 without any finish. The formulae to calculate the floor stiffness along and across span directions for the broad range of timber floors studied are not given. The limit for each criterion was identified by plotting the data on an x-y plane where x-axis is the calculated deflection, or frequency, or maximum acceleration, and the y-axis is the subjective rating (categorical variable). The performance limits were manually identified. The calculation of the maximum acceleration and deflection requires knowledge of damping ratio, and is iterative.

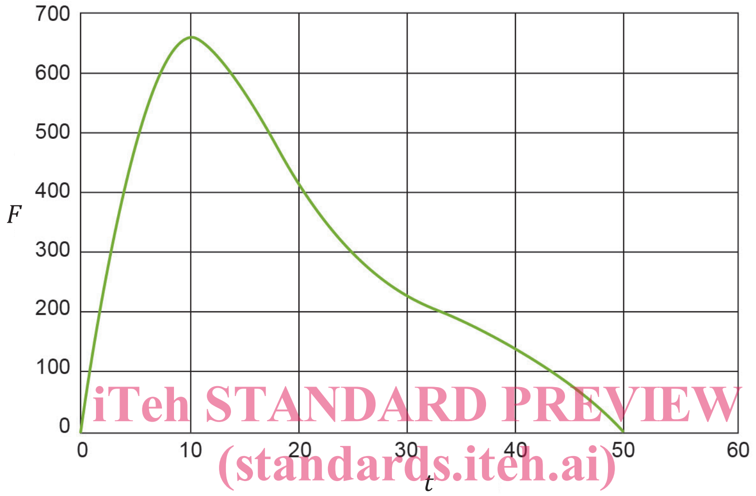
Table 1 — A summary of floor vibration design criteria for timber floors

Criterion parameters	Design criterion	Method of development of the criterion and database	Pros and cons	Reference
d_{1kN} where d_{1kN} = deflection under a 1 kN load in mm	for span < 3 m: $d_{1kN} \le 2$ mm, for span ≥ 3 m: $d_{1kN} \le 8/span^{1.3}$	— Field survey and subjective evaluation — More than 600 lumber joisted single-family floors in Canada — Approximate formula to calculate the 1 kN static deflection — Use commercial advanced statistical software “Discriminant analysis” to derive the design criterion	For timber joisted floors without topping: — simple — reliable For timber joisted floors with topping: — may be liberal	National Building Code of Canada (NBC)[1]
f_1 where f_1 = fundamental natural frequency in Hz	for unoccupied floors: $f_1 \ge 15$ Hz for occupied floors: $f_1 \ge 14$ Hz	— Testing and subjective evaluation of 86 lumber and engineered wood joist floors — Approximate formula to calculate the fundamental natural frequency	For timber joisted floors without topping: — simple — for certain span range For timber joisted floors with topping: — may be conservative	Dolan et al[4]
f_1, d_{1kN} and V_{peak} where V_{peak}=peak velocity due to unit impulse in m/(Ns^2)	1) $d_{1kN} \le a$ 2) $f_1 \ge 8$ Hz 3) $V_{peak} \le b^{(f_1 \xi -1)}$ where a =0.5-4mm, b=50-150, “a” and ”b” need to be determined by user based on the decision of performance level	— Limited poor performance field floors — Theoretical reasoning — Approximate formulae to calculate the fundamental natural frequency and peak-velocity	— Require judgement by users to select certain parameters — Complicated — Involve iteration — Formulae not provided to calculate deflection and floor stiffness in span and width direction	EC5[5]
f_1, d_{2kN} and a_{max} where d_{2kN} = deflection under a 2 kN load in mm where a_{max}= Maximum acceleration in m/s^2	For higher demand: 1) $d_{2kN} \le 0.5$ mm 2) $f_1 \ge 8$ Hz 3) $a_{max} \le 0.05$ m/s^2 if $f_1 \le 8$ Hz For lower demand: 1) $d_{2kN} \le 1.0$ mm 2) $f_1 \ge 8$ Hz 3) $a_{max} \le 0.1$ m/s^2 if $f_1 \le 8$ Hz	— Field study of 95 timber floors — Formulae provided to calculate static deflection, fundamental natural frequency and maximum acceleration	— Require judgement by users to select certain parameters — Complicated — Involve iteration — Formulae not provided to calculate floor stiffness in span and width direction	Hamm et al[8]

5 Mechanism of timber floor vibration response to human normal walking actions

5.1 Characteristics of footstep force

Researchers[6,7,9-12] have found that the footstep force generated by walking comprises two components. One component is a short duration impact force induced by the heel of each footstep on the floor surface, as illustrated in Figure 1. The duration of the heel impact varies from about 30 ms to 100 ms depending on the conditions and the materials of the two contact surfaces (the floor and the shoes worn by the person walking), and on the weight and gait of the person. The second component is the walking rate, a continuous series of footsteps consisting of a wave train of harmonics, at multiples of about 2 Hz, Figure 2.



Key

t time (milliseconds)

F force (pounds)

Figure 1 — Forcing function based on an average of five heel drop forces on a concrete surface[9]