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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.

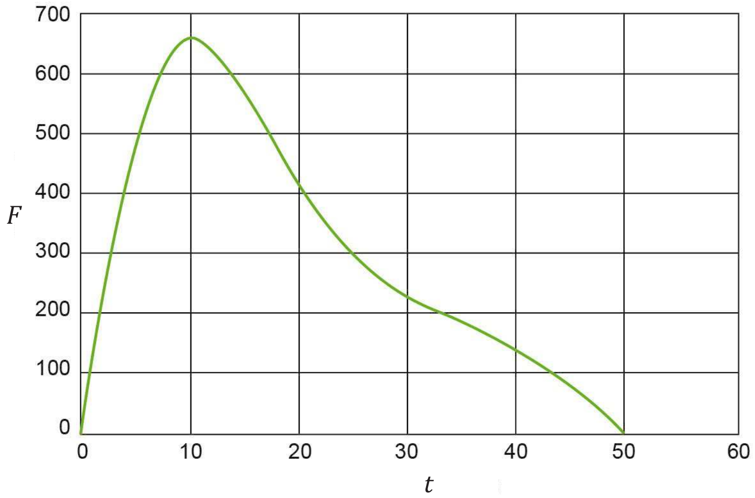
**Table 1 — A summary of floor vibration design criteria for timber floors**

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

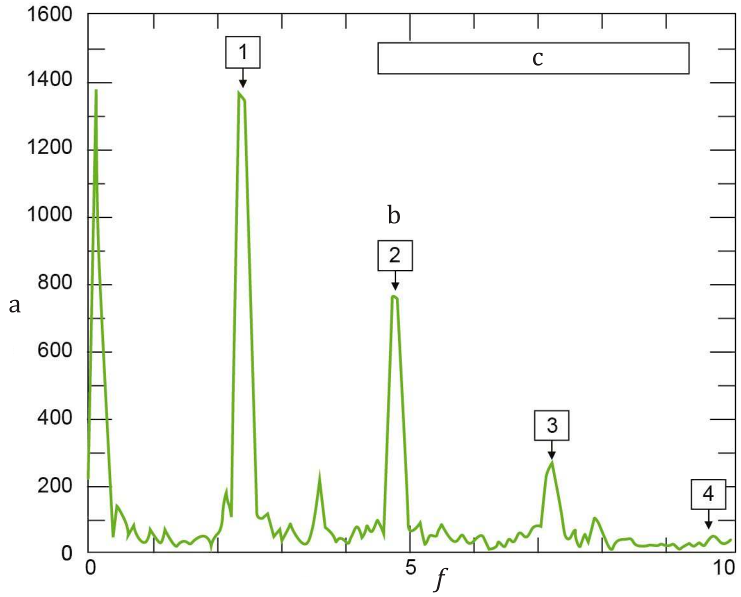



**Key**

*t* time (milliseconds)

*F* force (pounds)

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




**Key**

*f* frequency (Hz)

a magnitude

b harmonic

c Fourier amplitude spectrum

**Figure 2 — Fourier transform spectrum of the loading time history of normal walking action by one person[10]**

## 5.2 Responses of timber floors to the footstep force

How a floor responds to the footstep excitation described above depends on the floor's inherent properties such as mass, stiffness, and capacity to dissipate the excitation energy (i.e. damping of the floor system.) The two components in the walking excitation can initiate two types of vibrations, depending on the inherent properties of the floor and walking rate. The two types of vibrations are transient vibration and resonance.

If the fundamental natural frequency of a floor is above 8 Hz and is far above the footstep frequency (walking rate) and its predominate harmonics, then the vibration induced by the footstep forces is most likely dominated by a transient response caused by the individual heel impact force from each footstep. The transient vibration decays quickly, and takes place at multiples of the footstep frequency. The peak values of a transient vibration are mainly governed by the stiffness and mass of the floor system.

On the other hand, if the floor fundamental natural frequency is below 8 Hz, and is in the range of the footstep frequency and its predominate harmonics, then the floor most likely will resonate with one of the harmonics, and the vibration will be constantly maintained by the action of the walking excitation. The magnitude of the resonance is largely dependent on the damping ratio of the floor system. Furthermore, if the floor fundamental natural frequency is around 2 Hz, which is close to the footstep frequency, the magnitude of the resonance will be high because, as shown in Figure 2, most of the energy in the walking excitation is concentrated at the walking frequency.

The fundamental natural frequency of a floor is largely governed by the system stiffness in the major stiffness direction and its mass. It has been found that for the majority of the satisfied timber floors, their fundamental natural frequency is above 8 Hz. Therefore, the responses of most of timber floors to normal walking activities are of a transient nature.

### 5.3 Parameters correlated to human acceptability of timber floor vibration

In general, humans are more tolerant to short duration vibration (e.g. transient vibration) than the longer lasting resonance. Researchers[3,4,6-8,13-17] have found that the vibration performance parameters of timber floors such as floor static deflection, natural frequency, peak-velocity, peak – or root-mean-square (rms) – acceleration correlated to human perception of timber floor vibration. Furthermore, it has been found that the combination of fundamental natural frequency and static point load deflection correlated well with human perception of walking vibrations for a broad range of timber floors.[16,17] Other combinations of fundamental natural frequency with vibration magnitude parameters such as peak velocity, peak acceleration, and root-mean-square (rms) acceleration also yielded good correlation with human acceptability[16].

### 5.4 General forms of human acceptability criterion of timber floor vibration

ISO 2631-2[18] and BS 6472[19] established a general human acceptability criterion of vertical vibration by limiting the rms-acceleration at various frequencies for human comfort. The criterion was expressed in terms of rms-acceleration as a function of the 1/3 octave frequency. Converting the 1/3 octave frequency scale into linear frequency scale in a range of 8 Hz to 20 Hz, the ISO (BS) criterion becomes

$$rms - a \leq Cf^{2,95} \tag{1}$$

where

$rms\text{-}a$ is rms-acceleration, m/s$^2$;

$C$ is a constant;

$f$ is frequency, Hz.

Similar forms of the timber floor acceptability criterion to the ISO human acceptability criterion were independently identified through a Canada-wide survey and testing on hundreds of field timber floors.[16] They can be generalized as shown in Formula (2).

$$y \leq C_1 f^x \tag{2}$$

where

$y$ is the timber floor vibration parameter (e.g. point-load deflection, peak-velocity, peak-acceleration, or rms-acceleration);

$C_1$ is the first constant to be determined;

$x$ is the second constant to be determined.

## 6 Comprehensive procedure using a large database

### 6.1 General

Human acceptability to vibration is subjective, and significantly affected by the culture of an individual country. Therefore, the constants in Formula (2) may vary from country to country. Clause 6 provides a comprehensive procedure to determine the two constants in Formula (2) for establishing the human acceptability criterion.

The comprehensive procedure to establish a specific human acceptability criterion includes the following steps:

1) Identify at least 30 floors that contain some with poor performance, covering the various construction details commonly used in field. The floors can be the field floors or laboratory floors.

2) Conduct subjective evaluation of the floor vibration performance. See 6.1 or 6.2 for the detailed procedure of the subjective evaluation.

3) Measure at least two of the floor vibration parameters. One should be the fundamental natural frequency. The other can be the 1-kN static deflection, peak-velocity, peak-acceleration, or rms-acceleration. ISO 18324[1] provides the procedure to measure natural frequencies and 1-kN static deflection of timber floors. The response parameters also can be calculated. An appropriate statistical analysis procedure is used to analyse the database to establish the criterion as expressed in Formula (2). See 6.3 for appropriate statistical analysis tools.

4) Verify the criterion using a separate database having sufficient poor performance floors.

## 6.2 Subjective evaluation procedure and questionnaire for laboratory floors

For subjective evaluation in the laboratory, it often involves building a test floor and conducting a subjective evaluation of the floor performance. It is recommended that response is collected from a minimum of 20 participants. They should reasonably cover the range of age, gender, gait and weight. It should record the essential information about the evaluator and the test floor.

Evaluator

— age

— gender

— gait

— degree of subjectivity

Test floor

— structural members and construction details;

— with or without furnish and furniture.

The structural and construction details should be recorded to enable the floor stiffness properties in the two orthogonal directions and the mass density to be calculated. As practical as possible, the test floor should mimic an occupied floor with furnish and furniture that is typical of the life style of the local people.

The evaluation procedure includes two steps:

1) Self-observation by the evaluator:

   The evaluator walks over the floor several times in a normal manner to feel the floor movement and hear any movement of furniture and furnish.

2) Observation of the evaluator when another person is walking on the floor:

   The evaluator is asked to sit on a chair located at the centre of the floor to feel the floor movement, while another person is walking on the floor. This step is performed three times to ask three participants with different gaits to walk on the floor.

At the end of the procedure, the evaluator will complete a questionnaire immediately. The questionnaire shall consider 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.

An example questionnaire that has been used in Canada is given in Annex A. The questionnaire can be developed according to each country's situations and culture. The Canadian version shown in Annex A can be used as an initial template.

### 6.3 Subjective evaluation procedure and questionnaire for field timber floors

For the field timber floors, each house or unit in apartment or condominium buildings, only one occupant is chosen to be the subjective rating evaluator. Information about the evaluator and the floor details as specified in 6.1 is recorded.

The design of the interview questionnaire may consider the following factors:

— previous experience of the evaluator on performance of floor;

— cost of the property relative to the average property prices in the region;

— mechanical vibration of the floor by his/her own sensing and caused by others' walking motion;

— noise generated by the floor movement;

— visual effect caused by floor vibration.

Although the questionnaire for field floors is similar to that for laboratory floors, it is recommended that the survey be in the form of a casual conversation. A prompted approach can be taken by providing the evaluator 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, he/she 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. Reference[20] provides an example of the field floor survey questionnaire used in Canada since 1970s, which was subsequently modified in 1990s.

### 6.4 Statistical analysis to derive human acceptability criterion from timber floor vibration database

Statistical analysis tools are necessary in order to derive the human acceptability criterion of timber floor vibration using the database comprising the subjective ratings and measured or computed vibration response indicators of the tested floors. The conventional linear regression cannot be used because the database contains more than one type of variable. One is the conventional quantitative predictor variable such as frequency, deflection, velocity, acceleration, etc. The other is the categorical predictor variable in the form the occupant's rating of floor vibration performance such as "acceptable", "marginal" or "unacceptable" that is coded with integers. Such type of database does not meet the criterion for conventional linear regression analysis. Any recognized commercial advanced statistical analysis software can be used.

There are two methods provided in most commercial statistical analysis software. One is called discriminant analysis. This tool is for the database containing categorical predictor variables of more than two categories such as "acceptable floor", "marginal floor", and "unacceptable floor". Reference[3] gives an example for using discriminant analysis to derive the human acceptability criterion for lumber joisted floors from a database containing three categorical predictor variables. If the database contains only two categorical predictor variables, such as "acceptable floor" and "unacceptable floor", then logistic regression tool can be used. Reference[16] provides an example of using logistic analysis to derive the human acceptability criterion for engineered wood joisted floors from a database containing two categorical predictor variables.

It is recommended to transform the variables of the measured or calculated vibration indicators into natural logarithm basis before the discriminate analysis or logistic regression so that the derived criterion will have the same form as Formula (2). It is a pre-requirement to have knowledge of discriminant analysis or logistic regression. It is also recommended to use the commercial software that has been recognized by the statistical analysis community.

Annex B provides an example of using the comprehensive procedure to derive a human acceptability criterion for light frame timber floors in Canada using measured 1 kN static deflection and fundamental natural frequency of field floors.

### 6.5 Verification of the criterion derived using a new database

The criterion function derived through the discriminant analysis or the logistical regression needs to be verified using a new database about 1/3 size of the database that was used to derive the criterion to check if the criterion can discriminant the poor performance floors from the good performance floors with the similar degree of accuracy to the original criterion.

## 7 Simplified procedure using a small database

The comprehensive procedure presented in Clause 6 requires a large database. Besides, for the innovative timber floors that have not been built in the field, the subjective evaluation and measurements only can be conducted on full-scale laboratory-built floors. Building more than 30 floors in laboratory and testing these floors is costly. Therefore, a simplified procedure can be used. The simplified procedure contains the following steps:

1) Accept the general form of human acceptability criterion shown in Formula (2).

2) Build at least two full-scale floors in the laboratory. These floors shall be designed to have poor vibration performance. As a guide they can be designed based on a deflection limit of span/180.

3) Each floor configuration is evaluated by at least 20 evaluators. The average of the 20 ratings is used to assign the floor vibration performance.

4) Measure at least two of the floor vibration indicators. One is the fundamental natural frequency. The other can be the 1-kN static deflection, peak-velocity, peak-acceleration or the rms-acceleration. ISO 18324[1] provides the procedure to measure natural frequencies and 1- kN static deflection of timber floors. These indicators also can be calculated.

5) Repeat steps 3 and 4 after the floor span is reduced by a regular decrement until the floor performance is considered marginal or acceptable.

6) Use the measured or calculated vibration indictors, e.g. the fundamental natural frequency and one of other indicators on the two floors with marginal performance to derive two constants, e.g. “$C_1$“ and “$x$“ in Formula (2).

It is recommended that an additional floor, with a different configuration and product size to the ones used in developing the performance criterion, be built and tested following steps 2 to 5. This will provide further confidence in the validity of the developed performance criterion.

Annex C provides an example of using the simplified procedure to derive a Canadian acceptability criterion for CLT floors based on calculated 1 kN load static deflection and fundamental natural frequency.

# Annex A
(informative)

# Subjective evaluation questionnaire for laboratory floors used by FPInnovations, Canada

| | |
|---|---|
| **Evaluator's name** | |
| **Evaluator's ID** | |
| **Age:** | |
| Below 45 | |
| 45 or over | |
| **Sex:** | |
| Female | |
| Male | |
| **Type of dwelling:** | |
| I live in a single family dwelling that I own | |
| I live in a single family dwelling that I rent | |
| I live in a condominium that I own | |
| I live in a condominium that I rent | |
| I live in an apartment | |
| **The floor in my most recent or current dwelling are:** | |
| Concrete floors | |
| Wood floors | |
| **The floors where I currently live are:** | |
| Very solid | |
| Solid | |
| Marginal or undecided | |
| Bouncy or springy | |
| Very bouncy | |
| **I consider myself:** | |
| Selective or "picky" | |
| Somewhat selective | |
| Not too selective | |
| Not selective at all | |
| **Post-interview questionnaire filled by interviewer** | |
| **Evaluator's weight:** | |
| Heavy | |
| Medium | |
| Light | |
| **Evaluator's gait:** | |

| | |
|---|---|
| Heavy | |
| Normal | |
| Light | |

| Questions | Score (1–5)[a] |
|---|---|
| The floor in the home I currently live is better than this floor | |
| This is a not satisfactory floor for a low price house[b] | |
| This is a not satisfactory floor for a medium price house[b] | |
| This is a not satisfactory floor for an expensive custom house[b] | |
| I could feel the floor move or bounce while I was walking | |
| I could feel the floor move or bounce while others walked | |
| I was annoyed by the floor movement or bounce | |
| I could hear objects rattling while I was walking | |
| I could hear objects rattling while other walked | |
| I was annoyed by the rattle | |
| I could see objects moving while I was walking | |
| I could see objects moving while others walked | |
| I was annoyed by the objects movement | |
| | |
| Rate the overall floor vibration performance (1–5)[c] | |

[a] 1=Agree; 2=Agree somewhat; 3=No opinion; 4=Disagree somewhat; 5=Disagree

[b] Price: Low: <150K; Medium:180-250K; Expensive: >350K

[c] 1 = Definitely unacceptable; 2 = Unacceptable; 3 = Marginal; 4 = Acceptable; 5 = Definitely acceptable

NOTE House price changes from time to time and vary from region to region and country to country.

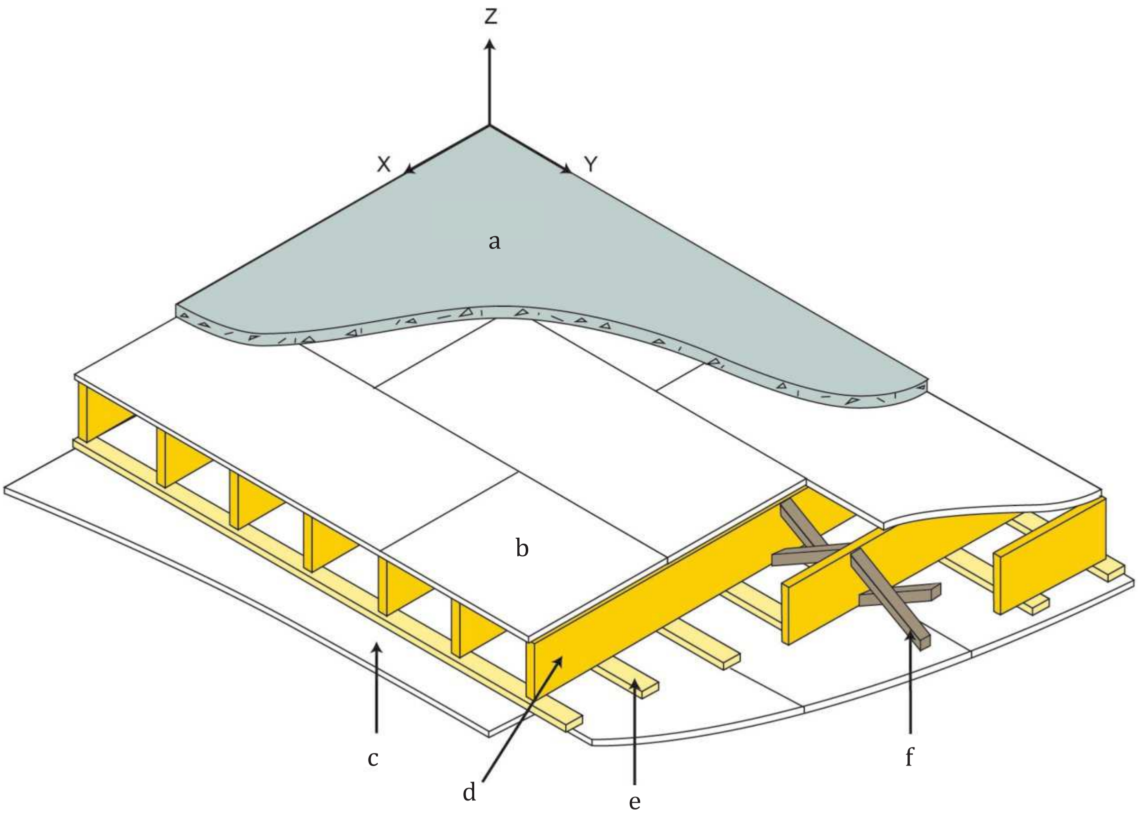
# Annex B
(informative)

# An example of the application of the comprehensive procedure to establish acceptability criterion for light frame timber floors in Canada

## B.1 Scope of Annex B

Annex B presents the development of acceptability criterion (performance criterion) for light frame timber floors in Canada as an example to demonstrate the application of the comprehensive procedure described in Clause 6. The vibration indicators were measured according to ISO 18324.[1] This acceptability criterion (performance criterion) was developed to control the vibration induced by normal walking in Canadian light frame timer floors built with joists and subfloor as basic components. Figure B.1 illustrates a typical North American light frame timber floor system. The figure does not include the finish and the resilient layer under the topping (screed).




**Key**

a topping

b subfloor

c ceiling board

d joist

e ceiling support

f bridging

**Figure B.1 — Typical North American light frame timber floor system**

## B.2 Field survey and performance testing

An across-Canada field survey was conducted on more than 100 field light frame timer floors in the houses and a few of multi-family buildings. The buildings were occupied and with furniture. Performance testing was conducted to measure the static deflections under a concentrated load of 1 kN applied at floor centre, fundamental natural frequencies, velocities and accelerations. The house owners or the occupants were interviewed using the comprehensive subjective evaluation procedure described in 6.2 and the long survey questionnaire provided in[20].

## B.3 Selection of the vibration indicators

After a preliminary analysis of the measured data, it was decided to use the measured fundamental natural frequency and 1 kN static deflection as the criterion parameters.

## B.4 Derivation of acceptability criterion (performance criterion) through logistic regression

It was decided to develop the minimum requirement for Canadian acceptability of floor vibrations, therefore two categorical predictor variables of human acceptability, e.g. "acceptable" and "unacceptable" were used. Logistic regression was conducted on the field light frame timber floor database. For each floor three parameters were measured: 1. the subjective rating, either "acceptable", or "unacceptable"; 2. the measured fundamental natural frequency; 3. the measured 1-kN point load deflection. The measured fundamental natural frequencies and the 1-kN point load deflections of more than 100 field floors were transformed into natural logarithm scale for the analysis. Using a commercial statistical analysis program, the human acceptability criterion (performance criterion) was derived as below:

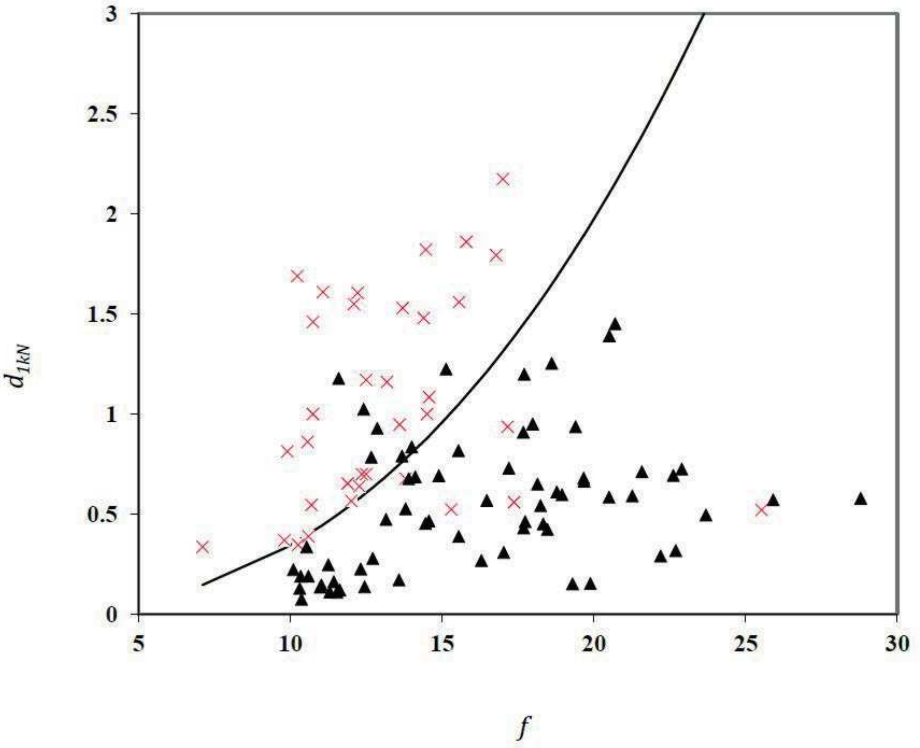
$$d_{1kN} \leq \frac{f^{2,56}}{1090,31} \tag{B.1}$$

where

$d_{1kN}$ is the measured 1 kN point load deflection in mm;

$f$ is the measured floor fundamental natural frequency in Hz.

Figure B.2 illustrates how the logistic regression analysis is able to discriminate the unacceptable group from the acceptable group, and arrive at the human acceptability criterion based on the measured fundamental natural frequencies and 1 kN point load deflections of the field light frame timber floors. It can be noted that from Figure B.2 that there are a few floors that were misclassified. This is generally unavoidable especially for a large database due to the subjective nature of the topic.




**Key**

*f* measured fundamental natural frequency (Hz)

$d_{1kN}$ measured 1 kN static deflection (mm)

— d < = f ^ 2,56 / 1090,31 criterion

× unacceptable floor

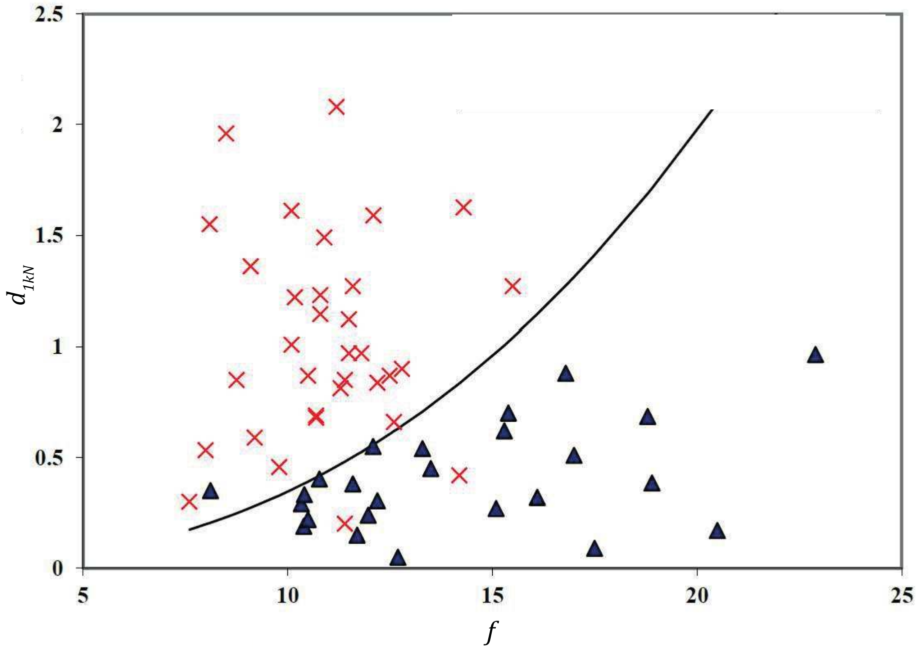
▲ acceptable floor

**Figure B.2 — Logistic regression on the database of field light frame timber floors in across Canada occupants' survey and testing**

## B.5 Verification of the acceptability criterion (performance criterion)

The performance criterion was verified by a new database. The new database and the criterion are plotted in Figure B.3. The new database consisted of field test data on 21 additional Canadian wood-based floors, and 37 floors tested and subjectively evaluated at various laboratories. The data on the 21 field floors were collected after the formulation of the criterion. The laboratory-tested floors included: 10 engineered wood floors studied at FPInnovations; four light-weight steel joist floors tested at the laboratory of the Swedish Institute of Steel Construction[23]; nine light-weight steel joisted floors tested at Lappeenranta University of Technology in Finland,[24,25] and 14 wood joisted floor tested in other laboratories. All the laboratory floors did not have occupants and furniture.

As shown in Figure B.3, the criterion performed on the new database even better than the original criterion on the original database in terms of the rate of the number of the misclassified floors to number of the entire floors.




**Key**

| | |
|---|---|
| *f* | measured fundamental natural frequency (Hz) |
| $d_{1kN}$ | measured 1 kN static deflection (mm) |
| — | d < = f ^ 2,56 / 1090,31 criterion |
| × | unacceptable floor |
| ▲ | acceptable floor |

**Figure B.3 — Verification of the performance criterion of light frame timber floors in Canada**

# Annex C
(informative)

# Example of application of the simplified procedure to establish acceptability criterion (design criterion) for cross laminated timber (CLT) floors in Canada

## C.1 Scope of Annex C

The example in Annex C demonstrates the use of the simplified procedure to establish a Canadian acceptability criterion for CLT floors. There was no CLT floor in Canada in 2010, but a CLT floor vibration design criterion was considered necessary for the product to be used in Canada. There was a need to develop a Canadian acceptability criterion (design criterion) for CLT floors. To use the comprehensive procedure to establish the criterion, at least 30 CLT floors plus additional at least 10 CLT floor for the validation would be required, which would be costly. Therefore the simplified procedure was adopted.

The vibration indicators, e.g. 1 kN load static deflection and fundamental natural frequency were calculated. Therefore, the acceptability criterion is called design criterion as opposed to performance criterion. In other words, the developed criterion would have accounted for potential inaccuracy in the calculation procedure and the deviation of actual CLT properties from the published design properties.

The assumptions underlying the calculation method are:

— CLT slab floors without ribs;

— bare CLT floors and ignoring the stiffening effects from finish, partition, continuity of multi-span, and ceiling;

— support conditions are considered to be simple.

## C.2 Full scale laboratory CLT floor study

A total of 20 configurations of full-scale CLT floors of three thicknesses of (140 mm, 185 mm and 230 mm) CLT panels were tested in FPInnovations laboratory. The spans ranged from 4.5 m to 8 m with variable joint details, support condition, topping and ceiling.[21] For each size of CLT, the first floor system was over-spanned to ensure poor vibration performance. Then the floor span was reduced in steps. For each span, the floor performance was subjectively evaluated by 20 evaluators using the procedure described in 6.1 and the questionnaire included in Annex A. As the span was reduced, the floor performance was gradually improved from unacceptable, marginal and finally to acceptable.

## C.3 Selection of vibration indicators

It was decided to use fundamental natural frequency and 1 kN load static deflection of a 1 m wide CLT panel as the criterion parameters.

## C.4 Development of formulas to calculate fundamental natural frequency and 1 kN static deflection of CLT floors

Simple beam formulae were used to calculate the fundamental natural frequency, $f$ and 1 kN static deflection, $d_{1\ kN}$ of the 1 m wide CLT panel, Formulae (C.1) and (C.2), respectively.

$$f = \frac{\pi}{2l^2}\sqrt{\frac{EI_{app}}{\rho A}} \qquad \text{(C.1)}$$

where

$l$ is CLT floor span (m)

$EI_{app}$ is CLT apparent stiffness in the span direction for 1 m wide CLT panel in N-m$^2$/m

$$EI_{app} = \frac{1}{\frac{1}{(EI)_{eff}} + \frac{11.52}{(GA)_{eff}\, l^2}}$$

where

$EI_{eff}$ is CLT effective stiffness of 1 m CLT panel without shear effect in N-m$^2$;

$GA_{eff}$ is CLT shear stiffness of 1 m CLT panel in N;

$\rho$ is CLT density in kg/m$^3$;

$A$ is CLT cross-section area of the 1 m wide CLT panel, in m$^2$.

$$d_{1kN} = \frac{1000 P l^3}{48 EI_{app}} \qquad \text{(C.2)}$$

where

$P$ is 1 kN point load, equal to 1000 N.

## C.5 Derivation of acceptability criterion for CLT floors

Recall that the general form of the human acceptability criterion, Formula (2) in 5.4 is as follows:

$$y \le C_1 f^x$$

The Canadian acceptability criterion for CLT floors was derived by using the calculated 1 kN static deflections and fundamental natural frequencies of two CLT floors with marginal performance. These two CLT floors were rated by 20 evaluators with an average rating of 3.4. According to the 1—5 rating scale, below:

1 = Definitely unacceptable

2 = Unacceptable

3 = Marginal

4 = Acceptable

5 = Definitely acceptable

The 3.4 rating indicates the floor performance was close to marginal, rating scale of 3.

For these two marginal floors, the acceptability is on the borderline of human acceptability. Therefore Formula (2) becomes Formula (C.3).

$$y = C_1 f^x \quad \text{(C.3)}$$

where

$y$ is the calculated 1 kN static deflection of the marginal CLT floor in mm;

$f$ is the calculated fundamental natural frequency of the marginal CLT floor in Hz;

$C_1$ and x are the two constants to be determined.

For each marginal CLT floor, there is one formula with the two unknown constants. So there are two formulae with these two unknown constants, Formulae (C.4) and (C.5).

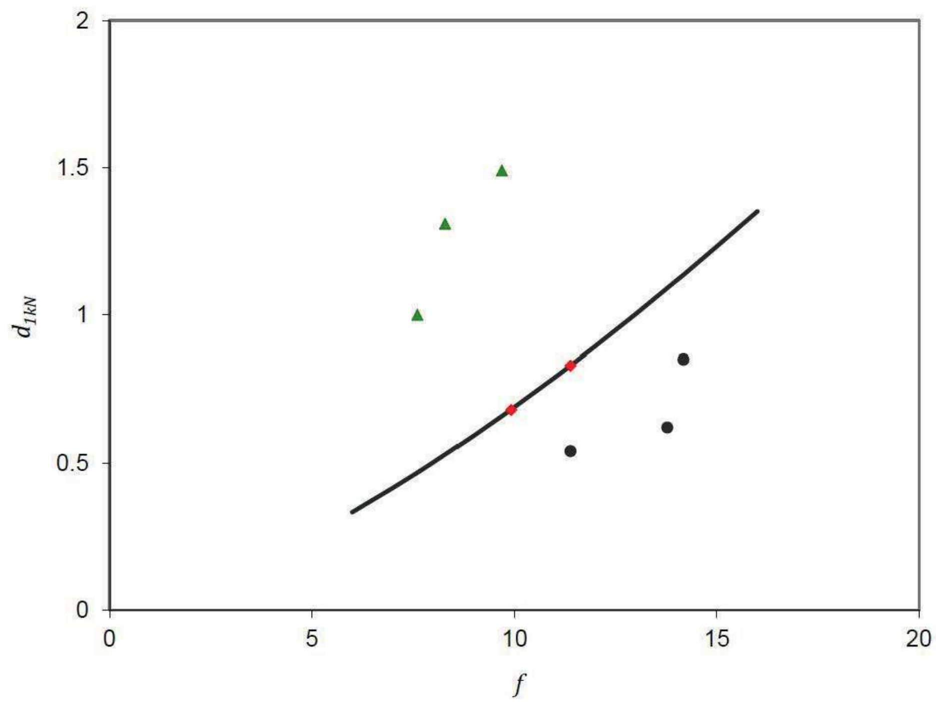
$$0{,}68 = C_1 \, 9{,}91^x \quad \text{(C.4)}$$

$$0{,}83 = C_1 \, 11{,}38^x \quad \text{(C.5)}$$

$C_1$ and x were determined by solving these two formulae simultaneously. $C_1$ was obtained as 1/39 and x was obtained as 1,43. Therefore the Canadian acceptability criterion of CLT floors was obtained as below:

$$d_{1kN} \leq \frac{f^{1,43}}{39} \quad \text{(C.6)}$$

Figure C.1 illustrates the derivation of the Canadian acceptability criterion of CLT floors using the two marginal laboratory CLT floor data and other data to verify the criterion.




**Key**

$f$ calculated fundamental natural frequency (Hz)

$d_{1kN}$ calculated 1 kN static deflection (mm)

— d ≤ f ^ 1,43 / 39,00 criterion

▲ unacceptable floor

● acceptable floor

♦ marginal floor

**Figure C.1 — Derivation of the Canadian acceptability criterion of CLT floors using two marginal floor data and the verifications using other CLT floor data**

## C.6 Further verification

The criterion along with the calculation formulae was verified by comparing the calculated spans for some CLT products using the Canadian design criterion with the spans calculated using the software “CLTDesigner”[22]. Table C.1 shows the comparison.

**Table C.1 — Verification of the Canadian acceptability criterion for CLT floors**

| CLT thickness (mm) | Span calculated using Canadian design criterion (m) | Span calculated using “CLTDesigner” for 1% damping[16] (m) |
|---|---|---|
| 100 | 3,58 | 3,53 |
| 120 | 3,76 | 3,75 |
| 140 | 4,50 | 4,43 |
| 160 | 4,80 | 4,76 |
| 180 | 5,16 | 5,14 |

**Table C.1** *(continued)*

| CLT thickness (mm) | Span calculated using Canadian design criterion (m) | Span calculated using "CLTDesigner" for 1% damping[16] (m) |
|---|---|---|
| 200 | 5,68 | 5,67 |
| 220 | 5,84 | 5,89 |
| 240 | 6,09 | 6,17 |

Since 2010 when the CLT design method was published in Canada, several CLT buildings have been built. It was found that the CLT floors with the spans meeting this criterion are satisfactory to the occupants or the owners. The original design method including this criterion and the calculation method was expanded to account for the effect of multi-span CLT panel continuity, and stiffening effects of wood flooring, tile, partitions, and ceiling on floor vibration performance. The expanded design method was adopted by the Canadian timber design standard, CSA O86 [26].

# Annex D
(informative)

# EC5 design criteria and calculation methods for criterion parameters

## D.1 Scope of Annex D

Annex D presents the design criteria and the calculation formulae for the criterion parameters in Eurocode 5 (EC5)[5].

## D.2 Design criteria

EC5 specifies three criteria for controlling vibration in residential floors.

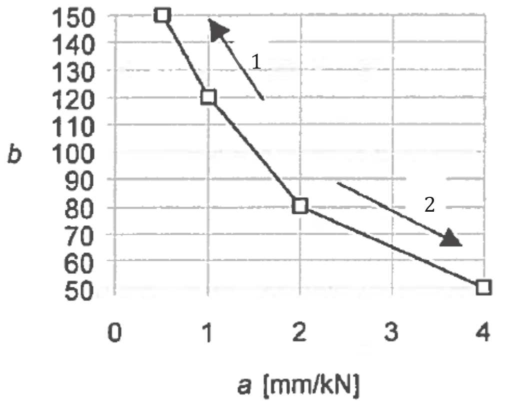
1) Fundamental natural frequency, $f_1$ greater than 8 Hz

2) $w/F \leq a$ in mm/kN

   where w is the maximum instantaneous vertical deflection caused by a vertical concentrated static force, F applied at any point on the floor, taking account of load distribution. a is determined according to Figure D.1.

3) $v \leq b^{(f_1 \zeta - 1)}$ in m/(Ns$^2$)

   where v is the unit impulse velocity response, i.e. the maximum initial values of the vertical floor vibration velocity (in m/s) caused by an ideal unit impulse (1 N-s) applied at the point of the floor giving maximum response. Frequency components above 40 Hz may be disregarded. $\zeta$ is the modal damping ratio. b is determined according to Figure D.1.




**Key**

1 better performance

2 poorer performance

**Figure D.1 — Recommended range of and relationship between a and b[21]**

## D.3 Formulae to calculate the design criterion parameters

EC5 provides the formulae to calculate the criterion parameters, e.g. $f_1$, and $v$. EC5 specifies that the calculation should be made under the assumption that the floor is unloaded, i.e. only the mass corresponding to the self-weight of the floor and other permanent actions shall be included.

For a rectangular floor with overall dimensions $l$ x B, simply supported along all four edges and with floor joist span $l$, EC5 recommends that the fundamental natural frequency $f_1$ may approximately be calculated as

$$f_1 \cong \frac{\pi}{2l^2}\sqrt{\frac{(EI)_l}{m}} \tag{D.1}$$

where

$m$ is the mass per unit area in kg/m$^2$;

$l$ is the floor span, in m;

$(EI)_l$ is the equivalent plate of bending stiffness of the floor along the span direction, in Nm$^2$/m;

EC5 does not specify the formula or guidance to calculate the $(EI)_l$.

EC5 does not provide the formula to calculate the static deflection $w$.

EC5 recommends that for a rectangular floor with overall dimensions $l$ x B, simply supported along all four edges, the value $v$ may, as an approximation, be taken as:

$$v = \frac{4(0.4 + 0.6n_{40})}{mBl + 200} \tag{D.2}$$

where

$B$ is the floor width in m;

$n_{40}$ is the number of first-order modes with natural frequencies up to 40 Hz. It may be calculated from Formula (D.3).

$$n_{40} = \left\{\left[\left(\frac{40}{f_1}\right)^2 - 1\right]\left(\frac{B}{l}\right)^4 \frac{(EI)_l}{(EI)_B}\right\}^{0,25} \tag{D.3}$$

where

$(EI)_B$ is the equivalent plate bending stiffness, in Nm$^2$/m, of the floor in the direction perpendicular to the span, where $(EI)_B < (EI)_l$. EC5 does not specify the formula or guidance to calculate the $(EI)_B$.

# Annex E
(informative)

# Hamm et al. design criteria and calculation methods for criterion parameters

## E.1 General

Annex E presents the design criteria and the calculation formulae for the criterion parameters proposed by Hamm et al[22].

## E.2 Design criteria

Hamm et al propose to use three criteria for timber floor vibration control as summarized in Table E.1

**Table E.1 — Hamm et al. criteria for timber floor vibration control**

| | Higher performance demand | Lower performance demand |
|---|---|---|
| **Frequency** | ≥ 8 Hz | ≥ 6 Hz |
| **2 kN static deflection** | ≤ 0.5 mm | ≤ 1.0 mm |
| If 4.5 Hz ≤ f < 8 Hz, then check the acceleration limit | | |
| **Maximum acceleration** | ≤ 0.05 m/s² | ≤ 0.10 m/s² |

## E.3 Formulae to calculate the design criterion parameters

The frequency can be calculated using Formula (E.1).

$$f_1 \cong \frac{\pi}{2l^2}\sqrt{\frac{(EI)_l}{m}} \quad \text{(E.1)}$$

where

$m$ is the mass per unit area, in kg/m$^2$;

$l$ is the floor span, in m;

$(EI)_l$ is the equivalent plate bending stiffness of the floor along the span direction, in Nm$^2$/m.

Hamm et al do not specify the formula or guidance to calculate the $(EI)_l$.

The deflection of the floor under a single static load of *2 kN* is given in Formula (E.2).

$$w(2kN)=\frac{2l^3}{48EI_l b_{w(2kN)}} \tag{E.2}$$

where:

$$b_{w(2kN)}=min\begin{cases} b_{ef} \\ b \end{cases} \tag{E.3}$$

Where *b* is the floor width in m;

$$b_{ef}=\frac{l}{1,1}\sqrt{\frac{(EI)_b}{(EI)_l}} \tag{E.4}$$

where

$(EI)_b$ is the effective stiffness in transverse direction in $Nm^2/m$.

Hamm et did not specify the formula or guidance to calculate the $(EI)_b$.

The maximum acceleration, a, can be calculated by Formula (E. 5).

$$a=\frac{0,4*F(t)}{m*0,5l*0,5b*2D} \tag{E.5}$$

where

$D$ is the floor damping;

$F(t)$ is the harmonics of the dynamic force, (N), Hamm et al recommended the following[22]:
For floors with fundamental natural frequency in the range of 1,5 – 2,5 Hz, F (t) = 280 N;
For floors with fundamental natural frequency in the range of 3 – 5 Hz, F(t) = 140 N;
For floors with fundamental natural frequency in the range of 4,5 – 7,5 Hz, F(t) = 70 N.

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