INTERNATIONAL STANDARD

ISO

24323

First edition
2023-12

Timber structures — Design method for vibrational serviceability of timber floors

Structures en bois – Méthode de dimensionnement aux états limites de service pour la vibration des planchers bois

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

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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. As a result, it is critical that the timber floor design process takes into account vibrational serviceability. In the past, static deflection check indirectly provided some degree of control, but it is not a complete solution to the vibration problem. Two ISO publications have been developed over the last few years under the auspices of ISO/TC 165. The first publication, ISO 18324[1], is intended for testing of floor response parameters for the purpose of evaluating vibrational serviceability of the floor. The second publication is ISO/TR 21136[2], which provides guidelines for developing floor vibration performance criterion.

Annexes A and B recommend limit values for coupled and decoupled criteria respectively. The calculation equations presented herein are based on the assumption that the floor system has a single span and simple support conditions.

This document provides flexibility for individual jurisdictions to develop their own performance levels within the same performance criterion framework using the procedure described in ISO/TR 21136[2], and for using other models to calculate the fundamental natural frequency and 1 kN static deflection if desired.

Timber structures — Design method for vibrational serviceability of timber floors

1 Scope

The design method provided in this document addresses vibration induced by walking action of occupants and covers the following timber floor systems:

a) Light frame floors built with timber joists spaced at a distance of no more than 610 mm with a layer of structural wood-based subfloor that is connected to the joists using mechanical fasteners or adhesive. The area density of a bare light frame floors without a screed (topping) and ceiling is not greater than 25 kg/m^2. Figure 1 shows such a light frame floor.

b) Mass timber floors built with mass timber panels such as cross laminated timber (CLT).

This document consists of three elements:

a) a baseline vibrational serviceability design criterion for timber floors using fundamental natural frequency and 1 kN static point load deflection as the design parameters including two types of design criteria, coupled and decoupled criteria;

b) equations for calculating the design parameters;

c) guidelines for the design values of the physical and mechanical properties of floor components.

The design method is based on the assumption that the floor system has a single span and simple support conditions.

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 terminology databases for use in standardization at the following addresses:

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

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

4 Baseline timber floor vibrational serviceability design criterion

Vibrational serviceability of a timber floor shall be evaluated by comparing its fundamental natural frequency and the static deflection at floor centre under a point load of 1 kN applied at the same location, with the criteria stated in either coupled criteria, see Formula (1), or decoupled criteria, see Formulae (2) to (4). It is the users' decision or preference to select the appropriate criteria that meet their needs.

a) Coupled criteria.

Using the coupled criteria, the vibration performance a floor is considered acceptable if the condition given by Formula (1) is satisfied:

$$\frac{f^X}{d_{1\,kN}^Y} \geq Z \tag{1}$$

where

    f is the fundamental natural frequency, Hz;

    $d_{1\,kN}$ is the 1 kN static point load deflection at floor centre, mm;

    X, Y and Z are constants determined from subjective evaluation study as per ISO/TR 21136[2].

It is recommended to perform a subjective evaluation study as per ISO/TR 21136[2] on at least two floors to define suitable values for X, Y, Z for individual country. In the absence of any relevant data for specific country or region, X = 1,56, Y = 1 and Z = 112,20 (see Annex A).

b) Decoupled criteria.

Using the decoupled criteria, Formulae (2) to (4), the vibration performance of a floor is considered acceptable if the fundamental natural frequency, static deflection under a 1 kN load at floor centre and the velocity meet the respective conditions shown below:

$$f \geq C_1 \tag{2}$$

$$d_{1kN} \leq C_2 \tag{3}$$

$$v \leq C_3 \tag{4}$$

where C_1, C_2 and C_3 are constants determined from a subjective evaluation study as per ISO/TR 21136[2]. In the absence of any relevant data for specific country or region, C_1 = 8 Hz may be used (see Annex B). Annex B provides Formulae (B1) and (B2) to calculate C_2 and C_3 for residential floors, respectively.

5 General models for calculating f and $d_{1\,kN}$

The static deflection under a 1 kN point load at floor centre, $d_{1\,kN}$, and the first natural frequency, f, of a timber floor simply supported on all four sides can be calculated using orthotropic plate models[3]. The

static deflection parameter in mm, $d_{1\text{ kN}}$, can be calculated using the series-type Formula (5) shown below[4]:

$$d_{1\text{ kN}} = \frac{4\times10^6}{ab\pi^4} \sum_{m=1,3,5} \sum_{n=1,3,5} \frac{1}{\left(\frac{m}{a}\right)^4 D_X + 4\left(\frac{mn}{ab}\right)^2 D_{XY} + \left(\frac{n}{b}\right)^4 D_Y}$$ (5)

where D_X is the equivalent system flexural rigidity in the span direction, in Nm as defined by Formula (6):

$$D_X = \frac{h^3 E_X}{12(1-v_{XY}v_{YX})}$$ (6)

D_Y is the equivalent system flexural rigidity in the across-span direction, in Nm as defined by Formula (7):

$$D_Y = \frac{h^3 E_Y}{12(1-v_{XY}v_{YX})}$$ (7)

D_{XY} is the equivalent system shear rigidity, in Nm as defined by Formula (8):

$$D_{XY} = \frac{h^3 G_{XY}}{12} + \frac{v_{YX} D_X}{2}$$ (8)

where

E_X is the modulus of elasticity of plate in x direction (span) in N/m^2;

E_Y is the modulus of elasticity of plate in y direction (across-span) in N/m^2;

G_{XY} is the in-plane shear modulus of plate in N/m^2

h is the plate thickness in m

v_{XY} is the Poisson's ratio with stress applied in x direction and strain measured in y direction

v_{YX} is the Poisson's ratio with stress applied in y direction and strain measured in x direction

a is the span of floor in m;

b is the width of floor in m.

The fundamental natural frequency, f, in Hz can be calculated from the following Formula (9):

$$f = \frac{\pi}{2\sqrt{\rho}} \sqrt{D_X\left(\frac{1}{a}\right)^4 + 4D_{XY}\left(\frac{1}{ab}\right)^2 + D_Y\left(\frac{1}{b}\right)^4}$$ (9)

where ρ is the mass per unit floor area, kg/m^2.

For light wood frame joisted floor systems, the simplified method presented in Clause 6 can be used. For mass timber panel floor systems, the simplified method presented in Clause 7 can be used.

NOTE   See Annex C for background on orthotropic plate models.

6 Simplified calculation procedures for light-frame timber joisted floors

6.1 Floor construction

Figure 1 shows the construction details of the type of light-frame timber floor system addressed by this simplified method.
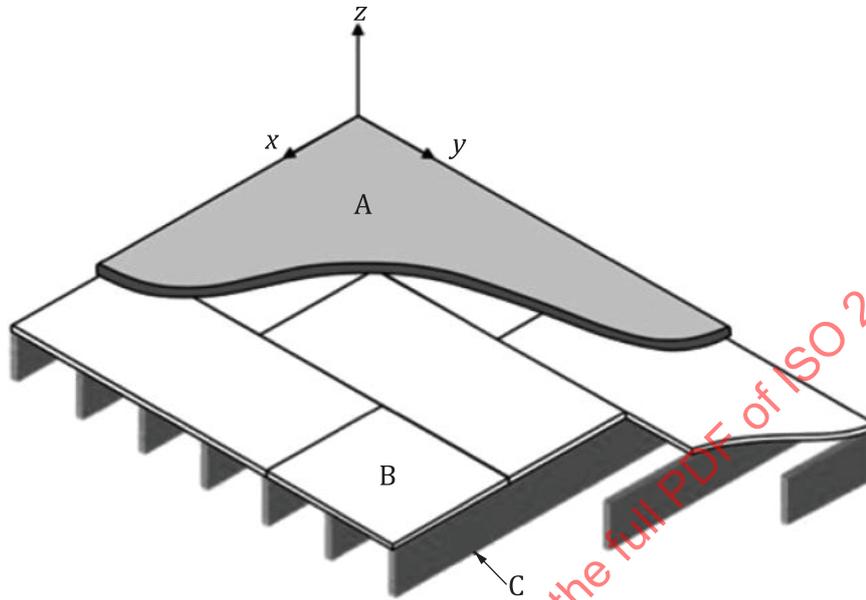
Key

A   topping layer

B   subfloor panel

C   floor joist

Figure 1 — Applicable light-frame timber floor system

6.2 Calculation of first natural frequency and static deflection under a 1 kN load at floor centre

The fundamental natural frequency, *f*, in Hz, of a floor shown in Figure 1 can be calculated using the following Formula (10)[5][6]:

$$f = \frac{\pi}{2l^2} \sqrt{\frac{D_{ef}}{m}} \tag{10}$$

The static deflection at floor centre under a concentrated load of 1 kN applied at the same location, d_{1kN}, in millimetres, can be calculated using the following Formula (11)[3][4]:

$$d_{1\,kN} = K_t \frac{1\,000 P l^3}{48 D_{ef}} \tag{11}$$

where

l is the floor span in m;

P is the point load of 1 000 N;

D_{ef} is the effective composite bending stiffness of the joists in the span direction in Nm^2 (in 6.3[7]);

K_t is the transverse system stiffness factor to account for the two-way action of a floor (in 6.4[7]);

m_l is the linear mass of the composite cross section of the floor that accounts for the joist, subfloor and topping in kg/m, calculated as follows:

$$m_l = m_J + \rho_s t_s b_1 + \rho_c t_c b_1 \tag{12}$$

where

m_J is the mass of joist per unit length in kg/m;

b_1 is the joist spacing in m;

ρ_c is the density of topping in kg/m^3;

ρ_s is the density of subfloor panel in kg/m^3;

t_c is the thickness of topping in m;

t_s is the thickness of subfloor panel in m.

6.3 Effective composite bending stiffness, D_{ef}

The effective composite bending stiffness, D_{ef}, in Nm^2 of the joist can be calculated using Formula (13), which accounts for the contribution of subfloor and, if present, the topping layer

$$D_{ef} = D_u + \bar{B}_1 h_1^2 - \bar{A}\bar{y}^2 \tag{13}$$

where

$$D_u = D_j + b_1 (D_{s\perp} + D_c) \tag{14}$$

where

D_j is the apparent bending stiffness of bare joist in Nm^2;

b_1 is the joist spacing in m;

$D_{s\perp}$ is the bending stiffness of 1 m wide subfloor panel in span direction in Nm;

D_c is the bending stiffness of a 1 m wide topping in Nm. D_c equal $E_c t_c^3 / 12$ where E_c is the modulus of elasticity of topping in N/m^2 and t_c is the topping thickness in m.

$$\bar{B}_1 = \frac{b_1 B_1}{1 + 10\dfrac{b_1 B_1}{s_1 L_1^2}} \tag{15}$$

where

B_1 is the sum of the axial stiffness of 1 m wide subfloor panel in minor strength axis;

$B_{s,\perp}$ in N/m and the axial stiffness of 1 m wide topping, B_c, which is equal to $E_c t_c$ in N/m, s_1 is the slip modulus per unit spacing for subfloor-to-joist connection and is equal to 5×10^6 N/m^2 for mechanical joint or when concrete topping is present and 10^8 N/m^2 for glued joint;

L_1 is the width of subfloor panels in the floor span direction for floor without topping or the floor span for floor with topping in m.

$$h_1 = \frac{d}{2} + \frac{0,5 t_s B_{s,\perp} + B_c \left(t_s + 0,5 t_c \right)}{B_{s,\perp} + B_c} \tag{16}$$

where

d is the joist depth in m;

t_s is the thickness of the subfloor in m.

$$\bar{A} = B_j + B_1 \ldots \tag{17}$$

where B_j is the axial stiffness of the joist in N.

$$\bar{y} = \frac{h_1 \bar{B}_1}{\bar{A}} \tag{18}$$

6.4   Transverse system stiffness factor, K_t

The transverse system stiffness factor, K_t, accounts for the contribution of subfloor and, if present, topping to the system stiffness in the across-span direction in reducing the static deflection of a timber floor, and can be calculated from the following Formula (19)[7][9]:

$$K_t = 0,029\,4 + 0,536 K_1^{0,25} + 0,516 K_1^{0,5} + 0,31 K_1^{0,75} \tag{19}$$

where

$$K_1 = \frac{K_j}{K_j + K_L} \tag{20}$$

where,

$$K_j = \frac{D_{ef}}{l^3} \tag{21}$$

$$K_L = \frac{0,585\,l\,D_{ef}}{b_1^3} \quad \text{N/m for floor with a subfloor only} \tag{22}$$

$$K_L = \frac{0,585\,l \left(D_{s,\parallel} + D_c + \frac{B_c B_{s,\parallel}}{B_c + B_{s,\parallel}} h_3^2 \right)}{b_1^3} \quad \text{N/m for floor with a subfloor and topping} \tag{23}$$

where

$D_{s,\parallel}$ is the bending stiffness of 1-m wide subfloor panel in major strength axis in Nm;

$B_{s,\parallel}$ is the axial stiffness of 1-m wide subfloor panel in major strength axis in Nm;

h_3 is a thickness, in m, calculated with <u>Formula (24)</u>:

$$h_3 = \frac{t_s + t_c}{2} \tag{24}$$

7 Simplified calculation procedures for mass timber floors

7.1 Floor construction

The equations provided in this clause are for calculation of the design parameters for floor systems built with mass timber panels, such as CLT. The floor systems shall be rectangular and simply supported along all four edges.

7.2 Calculation of first natural frequency and static deflection under a 1 kN load at floor centre

The fundamental natural frequency, f, of a mass timber panel floor can be calculated using the following <u>Formula (25)</u>[8]:

$$f = \frac{\pi}{2l^2}\sqrt{\frac{D_{ef}}{m}} \tag{25}$$

where

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

l is the floor span in m;

D_{ef} is the effective system bending stiffness for 1-m wide floor in the span direction, Nm^2/m.

The static deflection of a mass timber panel floor at floor centre under a 1 kN point load applied at the same location, $d_{1\,kN}$, can be calculated using the following <u>Formula (26)</u>[8][9][10],

$$d_{1\,kN} = \frac{1\,000 P l^3}{48 w_{ef} D_{ef}} \tag{26}$$

where

P is the centre point load of 1 000 N;

w_{ef} is the effective width of the floor in m, calculated as follows:

$$w_{ef} = \frac{l}{1,1}\sqrt[4]{\frac{D_\perp}{D_{ef}}} \leq w \tag{27}$$

where

w is the width of the floor in m;

$D_\perp$ is the effective bending stiffness for 1-m wide floor in the transverse direction in Nm^2/m.

NOTE   See Annex C.

8   Design values of floor components

The design values used in the calculation equations such as mass and stiffness of floor components shall be obtained from material specifications given in design standards or producer's technical literature.

Annex A
(informative)

Coupled criteria for timber floor vibrational serviceability design

A.1 General

This annex presents the development of the baseline timber floor vibrational serviceability design criterion for a broad range of timber floors using the comprehensive procedure provided in ISO/TR 21136[2] through the steps described in A.2 to A.4. Floor vibration perception is subjective, therefore, the three constants in the baseline design criterion can be adjusted according to the culture and construction practice of individual jurisdictions using the simplified procedure described in ISO/TR 21136[2].

A.2 Selection of design parameters

It has been recognized that for light-weight timber floors, the static deflection and fundamental natural frequency can be suitable design variables because they can be reliably measured and calculated, and are good predictors of human response to floor vibrations[1][7]. Therefore, it was decided to use the fundamental natural frequency and 1 kN static point load deflection as the design parameters for the timber floor vibrational serviceability design criterion.

A.3 Assembling an international database of timber floor vibration serviceability

So far, researchers from four countries have conducted extensive field testing, including occupant survey of timber floor vibrations. Dolan et al[11] in USA established the field floor database of about 100 light frame timber joisted floors. Canadian researchers also developed a similar database as Dolan's of about 100 light frame timber joisted floors including solid sawn lumber and engineered joist floors[12]. Some of them had concrete topping and ceiling. Toratti and Talja[13][14] in Finland conducted field studies on about 140 floors made of timber, steel or concrete, but most of these were timber floors. Hamm et al[9] reported the field studies in Germany on more than 130 floors with a broad range of timber floors, most of them are mass timber and timber-concrete composite floors. All of the timber floor databases contain the subjective ratings and field measured static deflections and fundamental natural frequencies. Among them, the Canadian and German databases contain the calculated 1 kN static deflections and fundamental natural frequencies of the field floors. Therefore, these two databases were merged and used to derive the baseline timber floor vibrational serviceability design criterion presented in this standard.

## A.4 Decision on the mathematical models for calculation of the design parameters

The Canadian study developed comprehensive equations to calculate the fundamental natural frequency and 1 kN static deflection of the tested floors[12]. The German study also developed parallel equations for timber floors, including the mass timber floors[9].The Canadian and German equations were used as the design equations to derive the baseline timber floor vibrational serviceability design criterion.

A.5 Derivation of the baseline timber floor vibrational serviceability design criterion through logistic regression

Logistic regressions were also performed on the German, Canadian, and the combined databases from Germany and Canada using the calculated parameters to derive the baseline design criteria.

Figure A.1 shows a comparison of three design criteria derived using the calculated floor deflections and frequencies of floors in German, Canadian, and combined German and Canadian databases. The efficiency of these design criteria in separating acceptable and unacceptable floors was around 80 %. This efficiency level is considered acceptable for design purposes. Comparing these three design criteria, it can be clearly observed that Canadians are more tolerant to floor vibration than the Germans.

Figure A.2 illustrates the verification of the baseline timber floor vibrational serviceability design criterion derived from the combined Canadian and German databases against the subjective ratings.
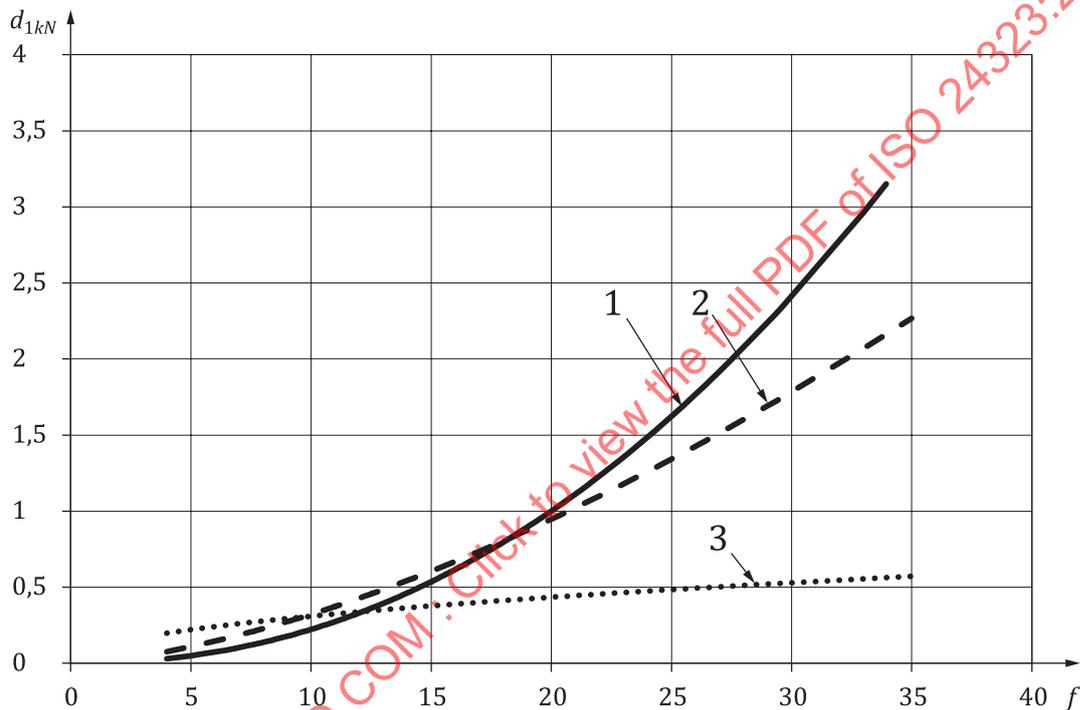
Key

f calculated fundamental natural frequency (Hz)

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

1      $\dfrac{f}{d_{1\,kN}^{0,46}} \geq 20,2$ design criterion using only Canadian data

2      $\dfrac{f}{d_{1\,kN}^{0,64}} \geq 20,6$ design criterion using Canadian and German data

3      $\dfrac{f}{d_{1\,kN}^{0,21}} \geq 108,4$ design criterion using only German data

Figure A.1 — Comparison of the design criteria derived from German, Canadian, and combined German and Canadian databases

Key

f calculated fundamental natural frequency (Hz)

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

—————— $d_{1\,kN} \leq \dfrac{f^{1,56}}{112,2}$

▪   acceptable floor

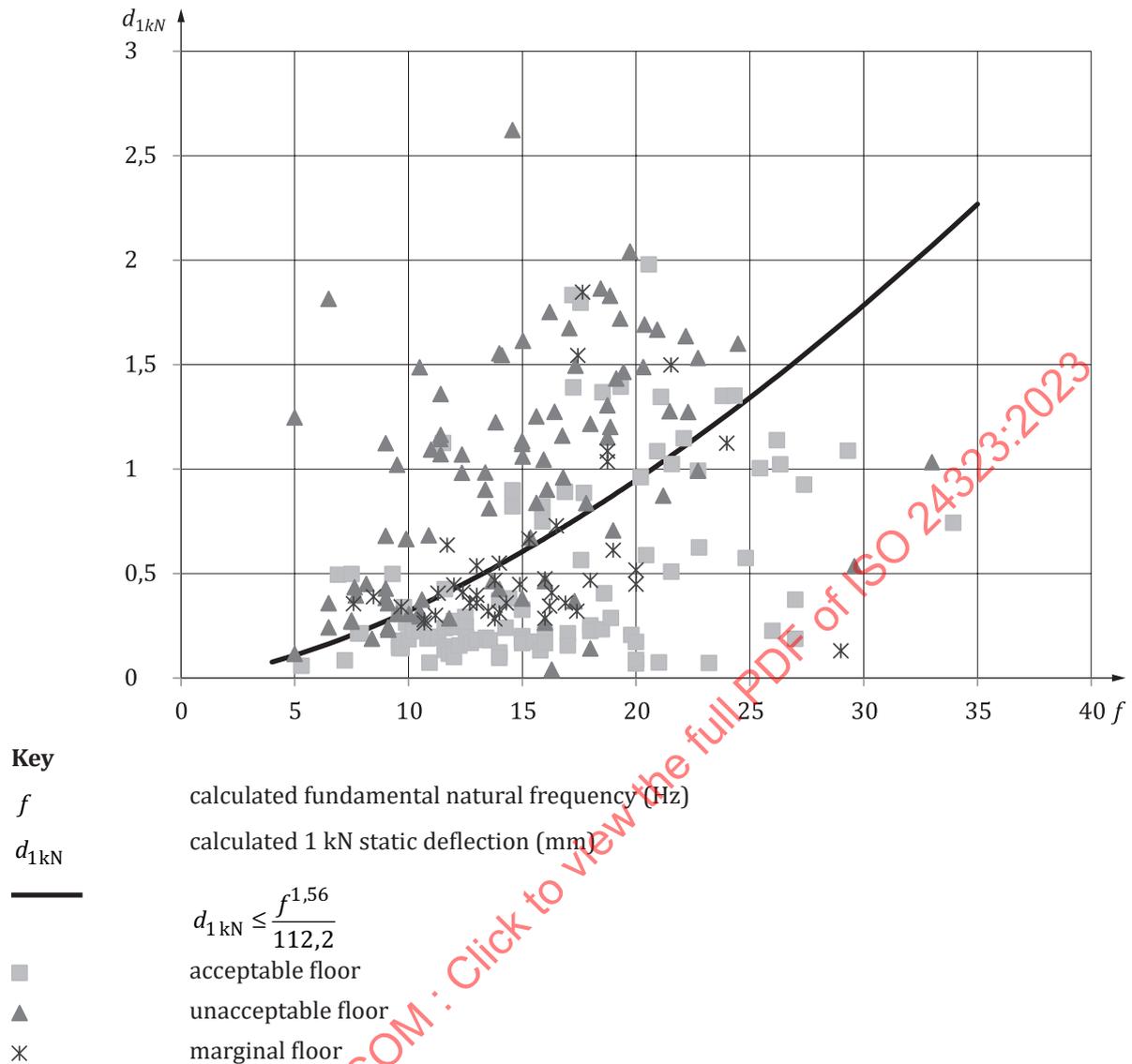▲   unacceptable floor

✳   marginal floor

Figure A.2 — Baseline design criteria derived from combined German and Canadian databases