Development of a Design Method to Control Vibrations Induced by Normal Walking Action in Wood-Based Floors

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Summary
Evidence shows that current approaches for vibration controlled design are inadequate for a broad range of wood floor construction and that an alternative design method is required. A new design method consisting of a vibration-controlled criterion and a calculation method to determine the criterion parameters was developed. The design criterion expresses that if the computed $(f_n/1\text{kN \, deflection})^{0.44}$ of an unoccupied floor is larger than 18.7, then the floor is most likely satisfactory to occupants. Preliminary indication is that the new design method leads to more appropriate spans for a broad range of wood floors than those predicted using the current design approaches. Additional calibration work may be required to apply the proposed design criterion to wood floor designs in other countries because it was calibrated to material properties published in the Canadian timber design code.

Keywords: Timber, Floor, Vibration, Walking, Design Method, Design Criterion

1. Introduction
Floor construction in light frame buildings has undergone a significant shift from the traditional decking-on-lumber construction. The availability of engineered wood products makes it possible to build wood-based floors having long spans and large open space. Moreover, building code requirements in North America for sound insulation have become more stringent, leading to the increased use of cementitious topping in multi-family and non-residential construction as a means to reduce airborne sound transmission between units. These changes increase the possibility for occupant complaints about excessive vibrations induced by normal walking in wood floors, particularly with long spans and large open space, or with cementitious toppings [1] and [2]. Some of these problem floors were designed according to current design approaches. Field inspection and testing of some of these floors revealed that the excessive vibrations were not always caused by construction defects [1]. This indicates that the current design approaches do not provide a satisfactory control over the vibration problems for all types of wood-based floors encountered in service.
A thorough review of design approaches already adopted in building codes and those proposed in
the literature has revealed that these approaches generally provide satisfactory solutions only for
certain classes of wood-based floors [3]. Further analysis of these design approaches has also
revealed that the limited application of these design approaches arises from the use of only a single
design parameter, such as static deflection recommended in Canadian National Building Codes [4-6],
fundamental frequency proposed by Dolan et.al.[7], initial peak velocity recommended in draft
Eurocode 5 [8] and used by Foschi et.al.in their proposed design guideline [9], and accelerations
proposed by Smith and Chui [10] to control the vibrations. Another source of problem with some of
these approaches is that the two-way system stiffness or mass characteristics of a floor is ignored. A
design method using multiple parameters and accounting for the two-way action and mass of a
floor, can be a more effective general solution to the problem. This thinking formed the basis of the
project undertaken by Forintek Canada Corp. to develop a universally acceptable floor vibration
design method in collaboration with the University of New Brunswick.

This paper describes the development of an improved design method to control vibrations induced
by normal activities of the occupants for a broad range of wood-based floor construction.

2. Approach

2.1 Assumption and Scope

The development of the proposed design method was based on bare floor assumption. It means that
the floor structures being designed have no partition wall, interior finishes, furniture and human
presence. The proposed design method accounts for common construction details found in current
construction, including various types of joist and sub-floor materials, semi-rigid connection
between joist and sheathing, performance enhancement construction details such as between-joist
bridging, strong-back and strapping, and cementitious topping.

2.2 Identification of the Correlation between Human Perception to Floor Vibration and
Vibration Performance Parameters

To develop a design method, the first task was to identify the correlation between human perception
to vibrations and vibration performance parameters. Therefore an occupant survey and field test
program, involving about 130 wood-based floors, was conducted in Canada. It was found that the
occupants’ perception to vibrations correlated with most of the parameters measured in these real
life floors, including 1 kN static deflection, fundamental natural frequency, initial velocity and
acceleration, and root-mean-square acceleration (rms). The correlation was described by five
equations using different combinations of measured 1 kN static deflection and fundamental natural
frequency, or other combinations of the measured fundamental natural frequency and one of the
dynamic parameters. These five equations were selected as potential performance criteria and
further evaluated. Validation tests showed that these five performance criteria were very similar in
terms of their ability to discriminate between acceptable and unacceptable floors. A detailed
description of this work was reported by Hu [11] at the 2002 WCTE.

2.3 Selection of Parameters for Vibration Controlled Floor Design

Based on the finding discussed in Section 2.2, it was decided to use 1 kN static deflection and
fundamental natural frequency as the design parameters to control vibrations in wood-based floors.
The rationale behind their selection was that, unlike other dynamic-based parameters such as peak
velocity and rms acceleration, they can be calculated using designer-useable equations or measured
using relatively simple equipment with acceptable accuracy.

2.4 Derivation of Formulas to Calculate Parameters for Vibration Controlled Floor Design

The second task for the development of a vibration controlled design method was to derive
designer-useable formulas to predict static deflections under a 1 kN concentrated load and
fundamental natural frequencies for a broad range of wood floor construction. This work was done
by Chui [12]. The formulas were based on the ribbed-plate theory and considered semi-rigid
connections between joist and sheathing, torsional rigidity of joists, and sheathing stiffness in the
span and across-joist directions. In addition, performance enhancement construction details such as
between-joist bridging, strong-back and strapping are accounted for in the formulas. Comparison with test results showed that the frequency formula tends to over-estimate fundamental natural frequency, and the deflection formula predicts static deflection well. Overall, the predictive capability is considered acceptable for design use [12]. A detailed description of the work can be found in Chui’s paper [12]. The formulas are given below.

Static deflection at floor centre under a point load P (N) can be calculated from the following series-type equation:

\[
d_p = \frac{4P}{ab\pi^2} \sum_{m=1,3,5,\ldots} \sum_{n=1,3,5,\ldots} \frac{1}{\left(\frac{m}{a}\right)^4 D_x + 4\left(\frac{mn}{ab}\right) D_{xy} + \left(\frac{n}{b}\right)^4 D_y } \text{ in m} (1)
\]

where,

\[ a = \text{floor span in m}; \]
\[ b = \text{floor width in m}; \]
\[ D_x = \frac{EICJ}{b_1} \text{ in Nm (System flexural rigidity in joist – direction)}; \]
\[ b_1 = \text{joist spacing in m}; \]
\[ D_y = \frac{\sum_i (EI_b)^i}{a} + \frac{EIp b_1}{b_1 - t + \alpha t} \text{ in Nm (System flexural rigidity in cross-joist -direction)}; \]
\[ t = \text{joist thickness in m}; \]
\[ D_{xy} = \frac{Gp h^3}{12} + \frac{C}{2 b_1} \text{ in Nm (Shear rigidity of multi-layered floor deck + torsion rigidity of joist)}; \]
\[ \alpha = \frac{h}{H}; \]
\[ h = \text{thickness of floor deck in m}; \]
\[ H = \text{height of floor system (joist depth + floor deck thickness) in m}; \]
\[ Gp = \text{shear modulus of floor deck in N/m}^2; \]
\[ EIp = \text{flexural rigidity of floor deck in Nm}; \]
\[ EICJ = \text{composite flexural rigidity of joist in Nm}^2; \]
\[ (EI_b)^i = \text{flexural rigidity of the i^{th} lateral bracing member in Nm}^2; \]
\[ k = \text{total number of rows of lateral bracing members}; \]
\[ C = \text{joist torsional constant}. \]

To ensure convergence of solution, it is recommended that three terms be used for \( m=1,3,5 \), and 17 terms for \( n=1,3,5,\ldots,35 \).

Using the same ribbed plate theory, the fundamental natural frequency of a floor system can be calculated as follows:

\[
f_1 = \frac{\pi}{2\sqrt{\rho}} \sqrt{\frac{D_x}{a} \left(\frac{1}{a}\right)^4 + 4D_{xy} \left(\frac{1}{ab}\right)^2 + D_y \left(\frac{1}{b}\right)^4} \text{ in Hz} (2)
\]
where,
\[ \rho = \frac{m_j}{b_1} + \rho_s t_s + \rho_c t_c \text{ in kg/m}^2; \]
\[ m_j = \text{mass per unit length of joists in kg/m}; \]
\[ \rho_c = \text{density of topping in kg/m}^3; \]
\[ \rho_s = \text{density of sub-floor in kg/m}^3; \]
\[ t_c = \text{thickness of topping in m}; \]
\[ t_s = \text{thickness of sub-floor in m}. \]

2.5 Assembling a Database of 106 Field Floors

The third task of the design method development was to derive a vibration controlled design criterion, i.e. the correlation between occupant ratings and predicted parameters (1 kN static deflection and fundamental natural frequency). To accomplish this task, a database of real life floors was needed. A database consisting of 106 field floors was assembled. In addition to measured floor responses, the database included a reasonably accurate description of floor construction details and available design values of the floor components. All these floors were subjectively rated for their acceptance. The database covers a broad range of construction parameters found in current wood-based floor construction practice in North America, and a wide range of spans from 3 m to 13 m. Formulas (1) and (2) were used to calculate deflection under a 1 kN applied at floor centre and fundamental natural frequency of each floor using the design properties for sub-floor and lumber joist materials published in Canadian Codes [13-14]. For engineered wood members, published design properties contained in the producers’ specifications were used. Properties for fastening and concrete topping were adopted based on a review of literature [15].

2.6 Formulation of a Vibration Controlled Design Criterion by Logistic Regression Analysis on the Field Floor Database

It was understood that the vibration controlled design criterion actually is the mathematical expression of the correlation between human perception to vibrations and the design parameters (i.e. 1 kN static deflection and fundamental natural frequency) of wood based floors. To identify the correlation, logistic regression analysis was performed on the 106 field floor database using a commercial statistical software.

3. Results and Discussion

3.1 Vibration Controlled Design Criterion

Through the logistic regression analysis on the 106 field floor database, the best correlation of the subjective rating with a combination of calculated 1 kN static deflection and fundamental natural frequency was determined to be of the form shown below:

\[ \frac{f}{d^{0.44}} > 18.7 \text{ or } d < \left( \frac{f}{18.7} \right)^{2.27} \]  

(3)

where d and f are the calculated 1 kN static deflection and fundamental natural frequency of a wood-based floor respectively using equations (1) and (2).
1005

1. A comparison between the subjective rating of 106 field floors and their acceptance predicted by the new design criterion

Equation (3) can be graphically expressed as the solid curve in Figure 1. For a floor, its calculated fundamental natural frequency and 1 kN static deflection can be plotted in the deflection-frequency plane as a symbol. If the symbol is above the curve, it means the floor vibration performance is not acceptable according to the criterion, and vice versa.

Figure 1 presents a comparison between the subjective rating of these 106 floors and their acceptance according to the proposed design criterion. It can be observed that the proposed design criterion provides a fairly effective tool in discriminating between unacceptable and acceptable floors.

3.2 Validation of Proposed Design Method

The new design method was validated by data obtained on floors built with wood I-joists, and solid sawn lumber joists. The depth of joists ranged from 140mm to 450mm. The floor spans determined from this new design method were compared with the spans published in [5] for lumber joist floors, and the spans determined using the method proposed for engineered wood members in Canada [6].

The detailed results from the validation work can be found in a report by Hu [15]. In a nutshell, the validation revealed that for floors having spans shorter than 4.8m the vibration-controlled spans allowed by the new design procedure were comparable with the spans allowed by the National Building Code of Canada [5] or the design method in [6]. For long-span floors, the new design procedure reduced the spans allowed by applying the span/480 deflection limit. Field survey results reported by Hu [1] and Johnson [2] revealed that the span/480 deflection limit did not provide an adequate control for long span floors. It was found that the proposed design method led to a more rational increase in spans due to the addition of performance enhancing features such as blocking and strapping than that allowed by the method proposed in [6]. This finding is supported by results reported by Taylor et al. [16]. For concrete topped wood-based floors, the new design method provided more rational solution than the method in [6]. In fact, contrary to the method proposed in [6], the addition of concrete topping led to a deterioration in vibrational performance according to the proposed design method. This is in agreement with our field testing experience of concrete topped floors [1] and the results reported by Taylor and Hua [17]. For floors with cementitious topping, the new design method reduced the spans by about 0.3m to 0.6m, depending on the wood-based floor spans and other construction details. The new design method showed great potential to properly address issues which are deemed to be problematic with the current design approaches. These include long span floors and the liberal treatment of lateral bracing members such as bridging, blocking, strapping and strong-backs, and heavy topping.

4. Conclusions and Recommendation

It can be concluded that the new design method shows great potential to provide rational vibration-controlled spans for a broad range of wood-based floor systems. The mechanics-based approach also lends itself to facilitate the acceptance of innovative building products. The new design approach presented in this paper will provide a framework for the formulation of an acceptable design method for a broad range of wood floors. Additional calibration work may be required to apply the proposed design criterion to wood floor designs in other countries because it was calibrated to material properties published in the Canadian literature.
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6. References


