CLT Handbook

CROSS-LAMINATED TIMBER

U.S. EDITION

The U.S. Edition of the CLT Handbook: cross-laminated timber can be electronically downloaded without charge from the website www.masstimber.com. Additional information can be obtained by visiting the websites of FPInnovations, USFPL, American Wood Council (AWC), APA and U.S. WoodWorks. Hard copies can be obtained through AWC (www.awc.org).

CLT Handbook

CROSS-LAMINATED TIMBER

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FPInnovations

Pointe-Claire, QC

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PREFACE

Expansion into mid-rise, high-rise and non-residential applications presents one of the most promising avenues for the North American wood industry to diversify its end use markets. This may be achieved by:

- Designing to new building heights with **Light Frame Wood Construction**
- Revival of **Heavy Timber Frame Construction**
- Adoption of **Cross-laminated Timber** (CLT)
- Facilitating **Hybrid Construction**

There are concerted efforts both in Canada and in the United States towards realizing that goal. In fact, the Canadian provinces of British Columbia and Quebec went even further and created specific initiatives to support the use of wood in those applications.

This Handbook is focused on one of these options – adoption of cross-laminated timber (CLT). CLT is an innovative wood product that was introduced in the early 1990s in Austria and Germany and has been gaining popularity in residential and non-residential applications in Europe. The Research and Standards Subcommittee of the industry's CLT Steering Committee identified CLT as a great addition to the "**wood product toolbox**" and expects CLT to enhance the re-introduction of wood-based systems in applications such as 5- to 10-story buildings where heavy timber systems were used a century ago. Several manufacturers have started to produce CLT in North America, and their products have already been used in the construction of a number of buildings.

CLT, like other structural wood-based products, lends itself well to prefabrication, resulting in very rapid construction, and dismantling at the end of its service life. The added benefit of being made from a renewable resource makes all wood-based systems desirable from a sustainability point of view.

In Canada, in order to facilitate the adoption of CLT, FPInnovations published the Canadian edition of the CLT Handbook in 2011 under the Transformative Technologies Program of Natural Resources Canada. The broad acceptance of the Canadian CLT Handbook in Canada encouraged this project, to develop a U.S. Edition of the CLT Handbook. Funding for this project was received from the Binational Softwood Lumber Council, Forestry Innovation Investment in British Columbia, and three CLT manufacturers, and was spearheaded by a Working Group from FPInnovations, the American Wood Council (AWC), the U.S. Forest Products Laboratory, APA-The Engineered Wood Association and U.S. WoodWorks. The U.S. CLT Handbook was developed by a team of over 40 experts from all over the world.

Both CLT handbooks serve two objectives:

- Provide immediate support for the design and construction of CLT systems under the alternative or innovative solutions path in design standards and building codes;
- Provide technical information that can be used for implementation of CLT systems as acceptable solutions in building codes and design standards to achieve broader acceptance.

The implementation of CLT in North America marks a new opportunity for cross-border cooperation, as five organizations worked together with the design and construction community, industry, universities, and regulatory officials in the development of this Handbook. This multi-disciplinary, peer-reviewed CLT Handbook is designed to facilitate the adoption of an innovative wood product to enhance the selection of wood-based solutions in non-residential and multi-storey construction.

Credible design teams in different parts of the world are advocating for larger and taller wood structures, as high as 30 stories. When asked, they identified the technical information compiled in this Handbook as what was needed for those applications.

A Renaissance in wood construction is underway; stay connected.

ACKNOWLEDGEMENTS

The great challenge with this U.S. Edition of the CLT Handbook was to gather experts from the United States, Canada and Europe to bring together their expertise and knowledge into a state-of-the-art reference document. The realization of this Handbook was made possible with the contribution of many people and numerous national and international organizations.

Such a piece of work would not be possible without the support from financing partners and, as such, we would like to express our special thanks to Binational Softwood Lumber Council, Forestry Innovation Investment (FII), Nordic Engineered Wood, Structurlam, and CLT Canada for their financial contribution to this project.

First and most of all, we would like to express our gratitude to AWC, APA, USFPL, FPInnovations, U.S. WoodWorks and their staff for providing the effort and expertise needed to prepare this work. We would also like to express our special thanks to all chapter authors, co-authors, and reviewers who shared their precious time and expertise in improving this manual.

Our very special thanks go to Loren Ross at AWC and Sylvain Gagnon at FPInnovations for their work as project leaders and for their special efforts in gathering the expertise of everyone into a unique document. Special thanks also go to the Working Group, Dr. Borjen Yeh from APA, Dave Kretschmann from the U.S. Forest Products Laboratory, and Lisa Podesto from U.S. WoodWorks. Thanks also to Madeline Leroux for her work on the drawings, Odile Fleury for her help with bibliographic references, and Marie-Claude Thibault for her support in editing and coordination work.

Erol Karacabeyli, P.Eng. and **Brad Douglas**, P.E.
Co-editors
CLT Handbook, U.S. Edition

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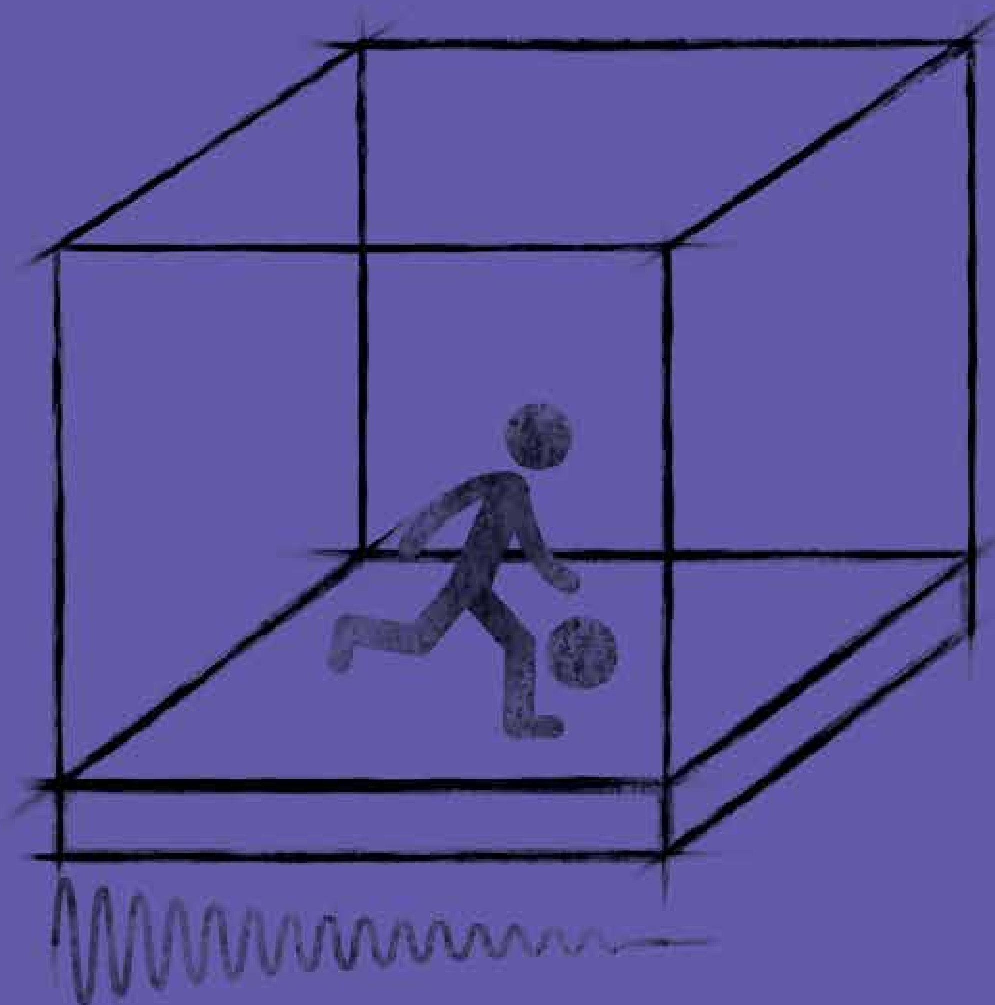

Vibration

Vibration performance of cross-laminated timber floors

CHAPTER 7

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The U.S. Edition of the CLT Handbook: *cross-laminated timber* combines the work and knowledge of American, Canadian and European specialists. The handbook is based on the original Canadian Edition of the CLT Handbook: *cross-laminated timber*, that was developed using a series of reports initially prepared by FPInnovations and collaborators to support the introduction of CLT in the North American market. A multi-disciplinary team revised, updated and implemented their know-how and technologies to adapt this document to U.S. standards.

The publication of this handbook was made possible with the special collaboration of the following partners:

The editing partners would also like to express their special thanks to Binational Softwood Lumber Council, Forestry Innovation Investment (FII), Nordic Engineered Wood, Structurlam, and CLT Canada for their financial contribution to studies in support of the introduction of cross-laminated timber products in the United States of America.

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ABSTRACT

Cross-laminated timber (CLT) is proving to be a promising solution for wood to compete in building sectors where steel and concrete have traditionally predominated. Studies at FPInnovations found that bare CLT floor systems differ from traditional lightweight wood joisted floors with typical mass around 4 lb./ft.^{2} (20 kg/m^2) and fundamental natural frequency above 15 Hz, and heavy concrete slab floors with a mass above 40 lb./ft.^{2} (200 kg/m^2) and fundamental natural frequency below 8 Hz. Based on FPInnovations' test results, bare CLT floors were found to have mass varying from approximately 6 lb./ft.^{2} (30 kg/m^2) to 30 lb./ft.^{2} (150 kg/m^2), and a fundamental natural frequency above 9 Hz. Due to these special properties, the existing standard vibration controlled design methods for lightweight and heavy floors may not be applicable for CLT floors.

Some CLT manufacturers have recommended that deflection under a uniformly distribution load (UDL) be used to control floor vibration problems. Using this approach, the success in avoiding excessive vibrations in CLT floors relies mostly on the designers' judgement. Besides, static deflection criteria can only be used as an indirect control method because designers ignore the influence of mass characteristics of the floors. Therefore, a new design methodology is needed to determine the vibration controlled spans for CLT floors.

SINTEF's extensive CLT floor vibration field study found that FPInnovations' proposed design method, which uses a 225 lb. (1 kN) static deflection and fundamental natural frequency as design parameters to control vibration in lightweight joisted wood floor systems, predicted field CLT floor vibration performance that matched well with occupants' expectations. The proposed design method for CLT floors is a modified version of the original FPInnovations design method for wood joisted floors. It was based on FPInnovations laboratory study and the understanding that limiting the combination of the longitudinal stiffness and mass of CLT floors can effectively control CLT floor vibrations. This led to a proposed equation to directly calculate the vibration controlled spans from CLT longitudinal stiffness and density. Verification using results from CLT floor testing conducted by FPInnovations that included subjective ratings of the floor vibration performance showed that the proposed design method predicted well the vibration performance of the tested CLT floors. An impact study showed that the vibration controlled spans of CLT floors predicted by the proposed design method were almost identical to those calculated by the *CLTdesigner* software that was developed by researchers of University of Gratz, in Austria. Working examples are given to demonstrate the procedure of using the proposed design method. This method can be used for bare CLT floors, continuous multi-span CLT floors and CLT floors with a ceiling and topping.

It is concluded that the proposed design methodology to determine vibration controlled spans of CLT floors is simple as it only uses the design properties of CLT panels, and is user-friendly and reliable.

Wide acceptance of the proposed design method relies on the use and evaluation of the method by products manufacturers and designers. Authors of this Chapter are open to feedbacks and ready to evolve the design method according to the needs of the manufacturers and designers.

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1 FUNDAMENTALS OF CLT FLOOR VIBRATIONS INDUCED BY FOOTSTEPS OF HUMAN NORMAL WALKING

1.1 Understanding Footstep Force

Significant efforts were made towards understanding the nature of footstep force of human normal walking (Rainer and Pernica, 1986; Ohlsson, 1991; Ebrahimpour *et al*., 1994; Keer and Bishop, 2001). Based on these findings, it can be concluded that the footstep force generated by walking comprises two components, as described in Ohlsson (1991). 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 (that of the floor and the footwear of the walking person), and on the weight and gait of the person. The other component is the walking rate, a series of footsteps consisting of a wave train of harmonics, at multiples of about 2 Hz (Figure 2).

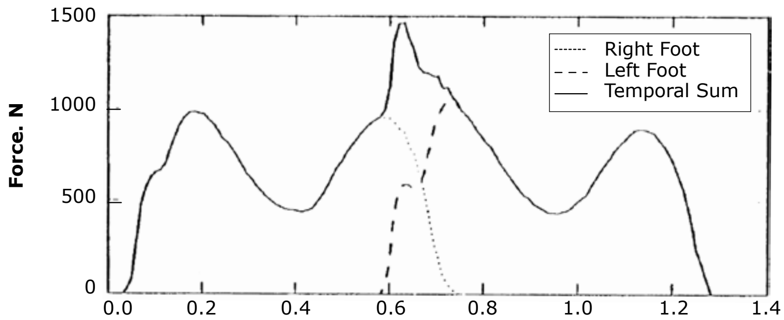

Figure 1
Measured load-time histories of footsteps from a person walking normally, by Ebrahimpour et al. (1994) (X-axis units is second)

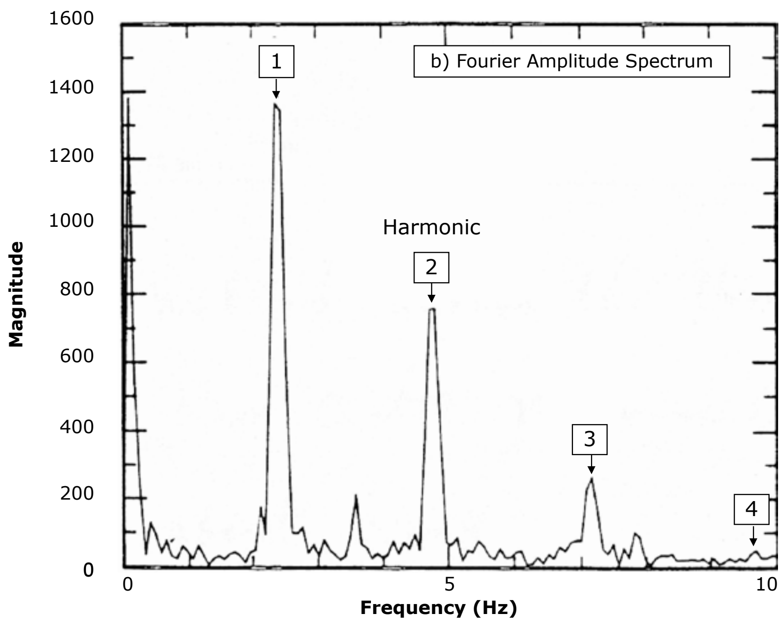

Figure 2
Fourier transform spectrum of the load-time history of normal walking action by a person, by Rainer and Pernica (1986) (Y-axis unit is Newton)

1.2 Unique Features of CLT Floors – Special Dynamic Properties

Figure 3 illustrates the cross-section of a bare CLT floor. Laboratory and field tests on CLT floors (Gagnon and Hu, 2007) have found that the vibration behavior of CLT floors is different from lightweight wood joisted floors and heavy concrete slab floors. Some explanations for such differences are given hereafter. Table 1 summarizes CLT floor dynamic properties.

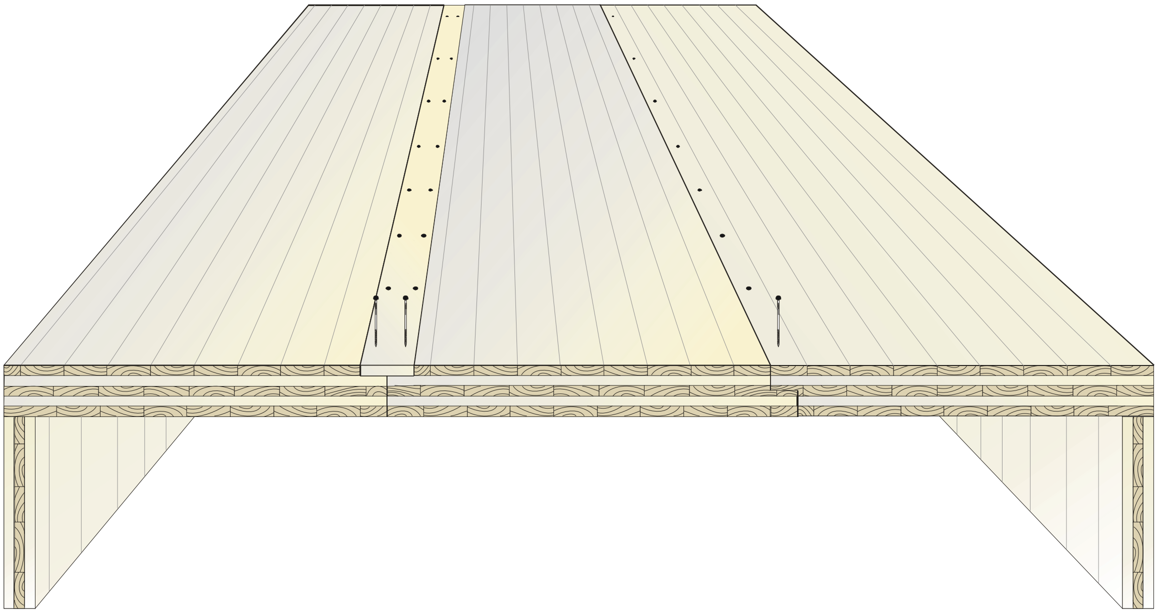

Figure 3
Cross-section of a bare CLT floor

1.2.1 Construction

Conventional lightweight wood joisted floors are usually built with joists spaced no more than 24 in. (600 mm) o.c. with a wood subfloor of 5/8 in. (15.5 mm) or 11/16 in. (18 mm) thick depending on the joist spacing (Figure 4). Conversely, CLT floors have no joists and are solid (Figure 3). The appearance of CLT plates is similar to concrete slabs.

Furthermore, in comparison with joisted floors having the same span and equivalent vibration performance, CLT floors are generally shallower than conventional lightweight joisted floors. For example, a 21 ft. (6.5 m) span floor can usually be built using 9 in. (230 mm) thick CLT panels. If the same floor is built using conventional wood joists, then at least 12 in. (300 mm) deep joists are needed.

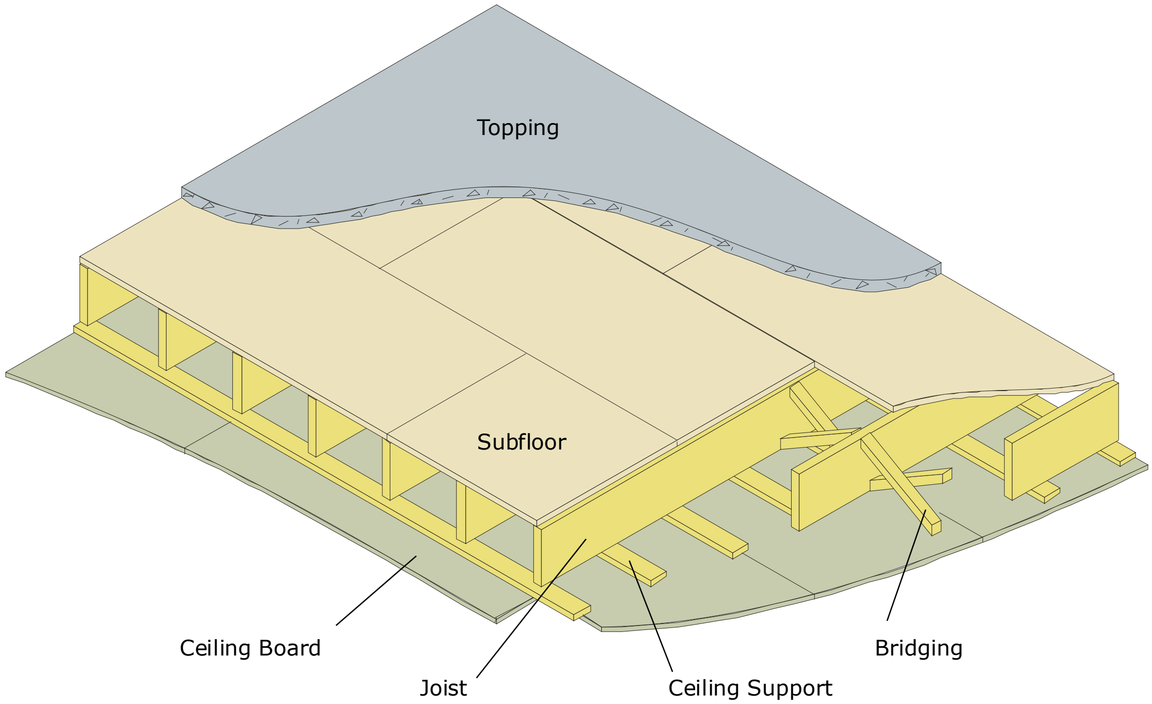

Figure 4
Conventional lightweight wood floor built with joists and subfloor

1.2.2 Dead Load

CLT floors are heavier than conventional joisted wood floors and lighter than concrete slab floors. Currently, thickness of CLT panels available on the market varies from about 2 3/8 in. (60 mm) to 12 5/8 in. (320 mm). For floor application, the minimum thickness will be about 4 in. (100 mm). Therefore, the area mass of CLT floors varies from about 10 lb./ft.^{2} (50 kg/m^2) to 30 lb./ft.^{2} (150 kg/m^2). Conventional wood joisted floor systems have an area mass of about 4 lb./ft.^{2} (20 kg/m^2) for bare floors and about 23 lb./ft.^{2} (110 kg/m^2) for bare floors with a 1 1/2 in. (38 mm) thick normal weight concrete topping. Concrete slab floors normally have an area mass above 40 lb./ft.^{2} (200 kg/m^2).

1.2.3 Fundamental Natural Frequency

Due to the specific mass to stiffness characteristic of CLT floors, their vibrations exhibit unique behavior indicated by the fundamental natural frequency. The lower bound of the measured fundamental natural frequencies for satisfactory bare CLT floors tested in our laboratory was found to be around 10 Hz (Hu, 2012).

We found that above 15 Hz is usually measured for satisfactory bare conventional wood joisted floors and above 10 Hz for satisfactory bare joisted floors with a concrete topping. The satisfactory concrete slab floors normally have a fundamental natural frequency below 8 Hz.

Humans are generally sensitive to vibration frequency within the range of 4 – 8 Hz. Therefore, the further away the natural frequencies of a floor from this sensitive range, the better the vibrational performance perceived by occupants.

1.2.4 Damping

The measured modal damping ratios of bare CLT floor specimens built with 5- or 7-layer CLT elements tested at FPInnovations were about 1% of the critical damping ratio (Hu, 2012). Conventional wood joisted floor systems normally have damping ratios around 3%. Low damping results in the vibrations of CLT floors persisting longer and being more annoying to occupants than that in conventional lightweight wood joisted floors. The higher the damping, the easier it is to control vibrations. Damping is determined by the material and the construction details including structural and non-structural elements, supporting systems, etc. The detailed discussion on structural damping and its sources is provided by Ungar (1992).

Table 1
Summary of dynamic characteristics of bare CLT floors with satisfactory vibration performance

Damping	About 1%
Area Mass	About 10-30 lb./ft.^{2} (50-150 kg/m^2)
Fundamental Natural Frequency	> 9 Hz

1.3 Features of CLT Floor Responses to Footstep Force

The way a floor responds to footstep excitation depends on its inherent properties such as mass, stiffness, and capacity to absorb the excitation energy, i.e., damping of the floor system. Understanding the nature of the footstep force leads to the conclusion that the two components in the walking excitation can initiate two types of vibrations in a floor system, i.e., transient vibration or resonance, depending on the inherent properties of the floor.

If the fundamental natural frequency of a floor is above 8-10 Hz and far above the footstep frequency and its predominant 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 disappears quickly, and occurs at the harmonics of the floor. The peak values of a transient vibration are mainly governed by the stiffness and mass of the system. On the other hand, if the floor fundamental natural frequency is below 8-10 Hz, and in the range of the footstep frequency and its predominant harmonics, then the floor will most likely resonate with one of the harmonics, and the resonance will be constantly maintained by the action of the walking excitation.

The fundamental natural frequency of a floor is governed by the stiffness and mass of the system. As previously discussed, the satisfactory bare CLT floors generally have fundamental natural frequency above 9 Hz. Therefore, in CLT floors, the footstep forces most likely cause transient vibrations which can be controlled by the stiffness and mass of the CLT floors. This understanding forms the basis for the development of the vibration controlled design method for CLT floors.

1.4 Factors Affecting Human Perception of CLT Floor Vibration

FPInnovations conducted subjective evaluations on series of CLT floors built with different types of joints between two adjacent CLT elements (Hu, 2012). It was found that the evaluators did not feel any difference in vibration responses when the types of joints were changed, and whether the joints were connected or not. The joint types and the joint connections also did not significantly affect the measured dynamic characteristics of the test floors. The longitudinal stiffness and mass of CLT floors were the two significant factors affecting human perception of CLT floor vibrations. This finding led to the conclusion that a simple design method to control CLT floor vibrations can be developed by using only the longitudinal stiffness and mass as the design parameters.

2

REVIEW OF THE EXISTING DESIGN METHODS FOR CLT FLOORS

2.1 Uniformly Distributed Load (UDL) Deflection Method

The uniformly distributed load (UDL) deflection method attempts to control vibrations by limiting the static deflection of a CLT floor under a uniform design load. For example, some CLT and indeed other engineered wood product (EWP) manufacturers recommend limiting the total UDL deflection to span/400. This approach assumes that the allowable deflection for controlling vibration is linearly proportional to the span of a floor. It means that the longer the span, the more deflection is allowed. This may explain why it was found in previous studies of light-framed floors that the UDL deflection method did not eliminate vibration problems in the long span category.

Therefore, if rationally using this method to avoid excessive vibrations in CLT floors, the engineer needs a good judgment to select a proper UDL deflection limit according to the floor spans. A standardized calculation procedure is then needed for CLT floor vibration controlled design so that all CLT floors can be economically designed with satisfactory in-service performance.

2.2 Conventional Design Methods for Wood and Steel-Concrete Floors

There are no floor vibration provisions in the U.S. codes. However, the 2005 National Building Code of Canada (NBCC) (NRC, 2005) recommends limits for static deflections of lightweight lumber joisted floors under 225 lb. (1 kN) static concentrated load at floor center. It was shown that this method is only applicable to wood joisted floors without topping, i.e., floors having an area mass less than 6 lb./ft.^{2} (30 kg/m^2) (Hu and Gagnon, 2009).

A design method was developed by Murray *et al.* (1997) for heavy steel joist-concrete slab floors having fundamental natural frequency below 9 Hz and is proposed in the Steel Design Guide (Murray *et al.*, 1997). This method limits the peak acceleration of a floor to control the vibrations of heavy floors.

Table 2 summarizes the scope of the two design methods. Also shown in Table 2 are the types of floor construction not currently covered or not covered adequately by existing design methods. As can be noted, the scope of the existing design methods in codes does not cover CLT floors.

Table 2
Summary of floor design methods in codes proposed for wood and steel-concrete floors and their scope

Design Method	2005 National Building Code of Canada (NRC 2005)	Currently not addressed in Codes	Murray *et al.* (1997) for Steel-Concrete
Floor Construction	Lightweight joisted floors without topping	1. Joisted floors with concrete topping 2. CLT	Steel joist-concrete slab
Floor Area Mass lb./ft.^{2} (kg/m^2)	3-6 (15-30)	6-30 (30-150)	> 30 (150)
Floor Natural Frequency Characteristics (Hz)	> 15	9-15	< 9

2.3 FPInnovations' Design Method for Joisted Wood Floors

FPInnovations and the University of New Brunswick (UNB) in Canada developed a design method to control vibrations in a broad range of wood joisted floor systems with an area mass varying from 3 lb./ft.^{2} (15 kg/m^2) to 30 lb./ft.^{2} (150 kg/m^2) and for fundamental natural frequency above 9 Hz (Hu, 2007). The design method uses 225 lb. (1 kN) static deflection and fundamental natural frequency as design parameters so that the floor stiffness and mass are accounted for.

SINTEF (Homb, 2008), from Norway, has conducted extensive field and laboratory studies on the vibration performance of CLT floors. SINTEF found that the FPInnovations' performance criterion, originally developed for lightweight wood joisted floors, predicted the vibration performance of CLT field floors that matched well the occupants' expectation, as illustrated in Figure 5. Each symbol in the figure represents a CLT field floor. If the symbol is below the curve, it means that the CLT floor performance is acceptable according to the criterion. SINTEF's field study has shown that the occupants were generally satisfied with the vibration performance of the floors tested.

SINTEF's study confirmed that FPInnovations' design criterion for joisted wood floors is applicable to CLT floors. However, the equations in FPInnovations' design method were originally derived from conventional wood joisted floors (Chui, 2002) based on ribbed plate theory, not for non-joisted slab floors like CLT floors. New equations for calculation of the static deflection at mid-span under a concentrated load of 225 lb. (1 kN) and fundamental natural frequency of CLT floors needed to be developed. Meanwhile, the form of the criterion shown in Figure 5 also needed to be calibrated to the new equations to achieve a new design criterion for CLT floors. The next section provides details on the new proposed design method, including design criterion and calculation equations for CLT floors.

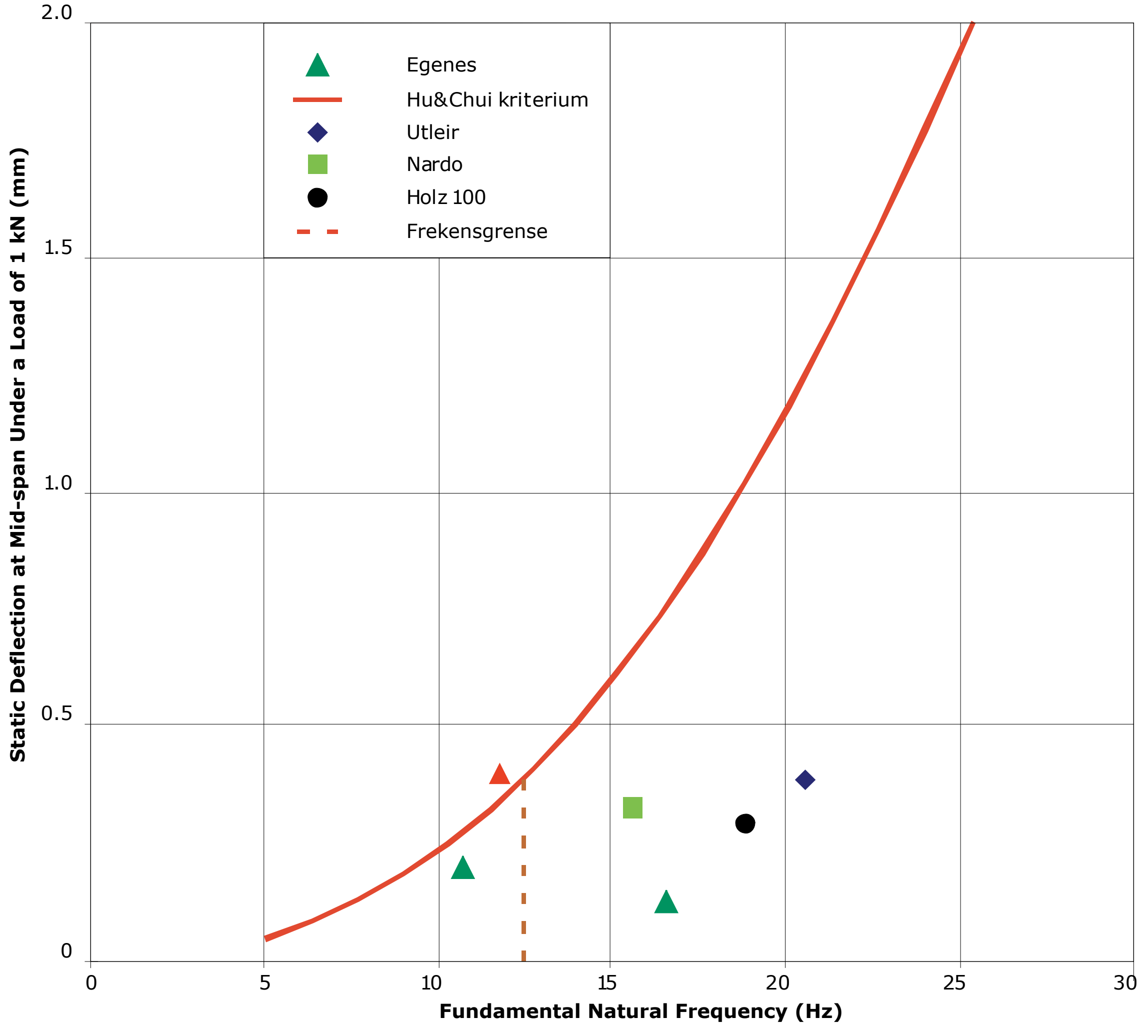

Figure 5
Comparison of FPInnovations' design criterion for joisted wood floors (Hu & Chui criterion) with the vibration performance of field CLT floors studied at SINTEF (Byggforsk, Norway) (Homb, 2008)

Note: The legend of each symbol was the test site name in Norway.

3

PROPOSED DESIGN METHOD FOR CLT FLOORS

3.1 Scope

At this point, the proposed new design method to control vibrations of CLT floors is applicable to the following situations:

1. Floors with or without topping and ceiling;
2. Simple or continuous multi-span system;
3. Vibrations induced by normal walking;
4. Well-supported floors;
5. Well-connected CLT panels.

The design method uses only the structure mass (dead load) in its calculation since FPInnovations' study found that the live load (such as occupants, furniture, etc.) enhances floor vibration performance to some degree; as live load changes from time to time, it should not be used as design parameters (Hu, 2007).

The proposed design method is user-friendly, with only hand calculations required. It is mechanics-based, requiring mechanical and physical properties of CLT panels, which are readily available from CLT manufacturers, as input properties.

3.2 Design Criterion

The design criterion is expressed in equation [1].

$$\frac{f}{d^{0.7}} \geq 125.1 \qquad \text{or} \qquad d \leq \frac{f^{1.43}}{993.3} \qquad [1]$$

Where:

f = fundamental natural frequency calculated using equation [2] (Hz)
d = point load static deflection at middle span of a simple beam calculated using equation [3] (in.)

3.3 Equations for Calculating the Criterion Parameters

The fundamental natural frequency can be obtained as:

$$f = \frac{2.188}{2l^2}\sqrt{\frac{EI_{app}}{\rho A}} \qquad [2]$$

Where:

f = fundamental natural frequency of a 1ft. wide CLT panel simply supported at both ends (Hz)
l = CLT floor span (ft.)
EI_{app} = apparent stiffness in the span direction for a 1 ft. wide panel (lb.-in.^{2})
= apparent stiffness is the effective stiffness, EI_{eff}, adjusted for the effects of shear deformation
ρ = specific gravity of CLT (=1.0625 x oven-dry specific gravity of wood used for fabricating the CLT)
A = cross sectional area of a 1 ft. wide CLT panel, i.e. thickness x 12 in. wide (in.^{2})

$$d = \frac{1728Pl^3}{48EI_{app}} \qquad [3]$$

Where:

P = 68.56 lb.

3.4 Simple Form of Design Method

Substituting equations [2] and [3] into equation [1], we obtain the simple form of the design method expressed by equation [4].

$$l \le \frac{1}{12.05}\frac{(EI_{app})^{0.293}}{(\rho A)^{0.122}} \qquad [4]$$

Using equation [4], we can determine the vibration controlled spans for CLT floors directly from the apparent stiffness in the span direction, density and cross-section area of 1 ft. wide CLT panels.

3.5 Verification

The design method was verified using FPInnovations' tests data (Hu, 2012) obtained from a limited laboratory study on floors built with 5- or 7-layer CLT panels having three thicknesses: 5 $^1/_2$ in. (140 mm), 7 $^3/_{16}$ in. (182 mm) and 9 in. (230 mm). In these tests, the performance of each floor was rated by a group of participants (subjective evaluation) using the rating scale and procedure originally developed at FPInnovations in the 1970's (Onysko and Bellosillo, 1978), evolved in the 1990's by Hu (1997), and recently simplified by Hu and Gagnon (2010). Figure 6 shows one CLT floor built in the laboratory for the vibration tests and subjective evaluation.

A point load of 225 lb. (1 kN) is assumed to be resisted by a 3.28 ft. (1 m) wide strip. That converts to 68.56 lb./ft. The static deflection and fundamental natural frequency of the loaded strip were calculated using equations [3] and [2] respectively. This allowed for the calculation of the performance parameter using equation [1].

Figure 6
CLT floor built in laboratory for the vibration tests and subjective evaluation

The comparison was also plotted on Figure 7. In the graph, each symbol represents a CLT floor while the curve is the design criterion defined by equation [1]. If the symbol is below the curve, it means the floor vibration performance is satisfactory and vice visa. The plot clearly demonstrates the reliability of the proposed design method for CLT floors.

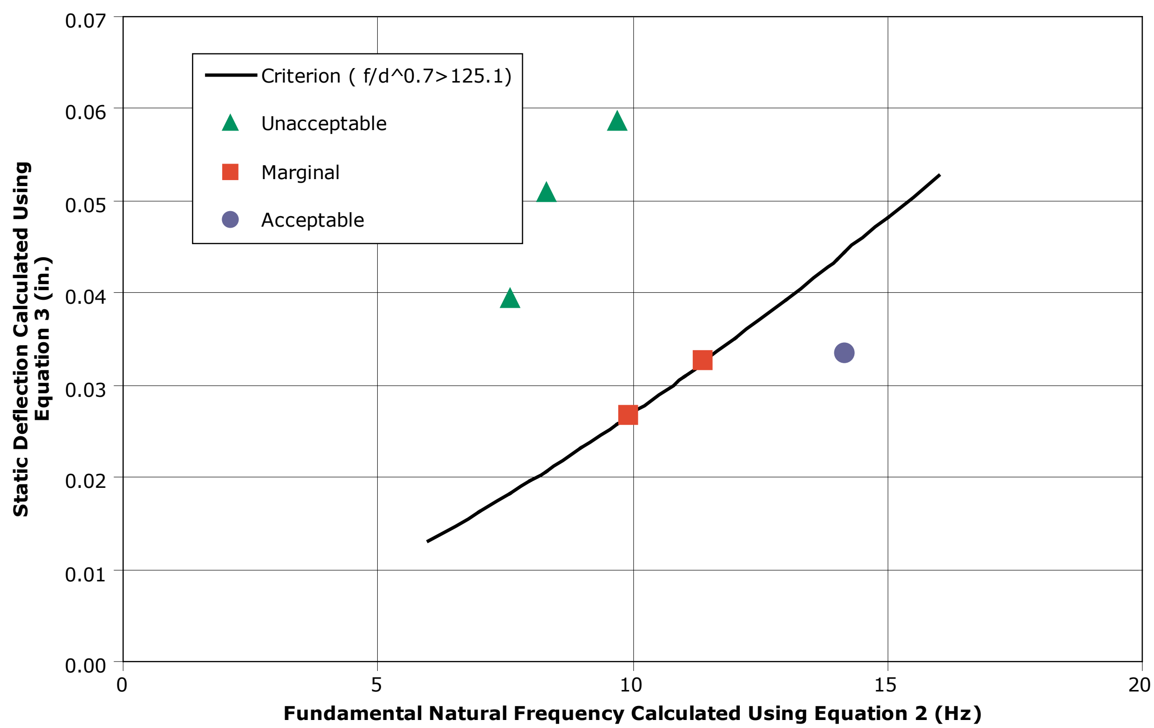

Figure 7
Predicted CLT floor vibration performance by the proposed design method vs. subjective rating by participants

3.6 Impact Study

3.6.1 Comparing Proposed Design Method with UDL Deflection Method

The vibration controlled CLT floor spans determined using the proposed design method were used to derive the equivalent UDL deflection limits on products from KLH in Austria (2008) as an example. The total design load was 81.5 lb./ft.^{2} (3.9 kN/m^2), which consisted of 31.3 lb./ft.^{2} (1.5 kN/m^2) dead load and 50.2 lb./ft.^{2} (2.4 kN/m^2) live load. The UDL deflection limit would be span/400.

Table 3
Vibration controlled CLT floor spans determined using the proposed design method and equivalent UDL deflection criterion

Type of CLT	Thickness (in.)	Vibration Controlled Span, L (ft.)	Equivalent UDL Criterion
5-layer (5s)	5 1/2	15.6	Span/417
5-layer (5s)	7 3/16	18.0	Span/497
7-layer (7ss)	9	23.0	Span/606

Note:

5s stands for 5-layer CLT with single longitudinal layers on faces of panel (KLH, 2008)

7ss stands for 7-layer CLT with double longitudinal layers on faces of panel (KLH, 2008)

As shown in Table 3, according to the proposed design method, more stringent UDL deflection limits should be imposed for longer span floors. This is more rational than the traditional approach of adopting a fixed ratio, such as span/400, for all spans.

3.6.2 Comparing CLT Floor Spans Determined Using the Proposed Design Method with Spans Determined Using the CLTdesigner Software

The vibration controlled CLT floor spans determined using the proposed design method were compared with the spans determined using CLTdesigner (Holz.Bau Forschungs GmbH, 2010), a software developed at the Graz University of Technology, Austria (Schickhofer and Thiel, 2010). Table 4 provides the comparison.

Table 4
Vibration controlled CLT floor spans determined using the new design method vs. spans determined using the CLTdesigner software

CLT Thickness (in.)	FPInnovations' Design Method Proposed Span (ft.-in.)	CLTdesigner Proposed Span for 1% Damping and Floors without Topping (Schickhofer and Thiel, 2010) (ft.-in.)
3 15/16	11-9	11-7
4 3/4	12-4	12-4
5 3/4	14-9	14-6
6 5/16	15-9	15-7
7 1/8	16-11	16-10
7 7/8	18-7	18-7
8 11/16	19-1	19-4
9 7/16	20-0	20-3

As shown in Table 4, the vibration controlled spans of bare CLT floors predicted by the proposed design method are almost the same as the spans determined using the CLTdesigner software.

3.7 Work Example for the Design Method

Example is given below to calculate the vibration controlled spans of two CLT floors using the simple form of the proposed design method given in equation [4].

This example demonstrates the procedure to determine the vibration controlled spans for floors using CLT panels with the given EI_{eff} and GA_{eff}. The apparent bending stiffness EI_{app} can be determined using the following equation:

$$EI_{app} = \frac{1}{\frac{1}{EI_{eff}} + \frac{11.52}{GA_{eff} * (12 * l)^2}} \qquad [5]$$

Design values of the CLT panel properties are provided by APA (PRG 320, 2011):

- Grade = E1
- Thickness = 6 7/8 in. (0.175 m)
- Specific gravity = 0.56 (560.66 kg/m^3)
- EI_{eff} = 440 x 10^6 lb.-in.^{2}/ft. (4.140 x 10^6 N-m^2/m)
- GA_{eff} = 0.92 x 10^6 lb./ft. (1.343 x 10^7 N/m)
- l = vibration controlled span (ft.)

Calculation of the vibration controlled span for the above floor follows the steps below.

Step 1: Calculate the first trial span, assuming that the trial span is 30 times the thickness; this leads to the first trial span of 17.188 ft. (5.25 m).

Step 2: Insert the first trial span of 17.188 ft. (5.25 m) into equation [5] to determine the trial apparent stiffness, EI_{app}, from the design value of the EI_{eff} and GA_{eff}; this leads to the new span of 17.100 ft.:

$$EI_{app} = 3.895 \text{x} 10^8 \text{ lb.-in.}^2/\text{ft.}$$

Step 3: Insert the value of trial EI_{app}, the design values of density, thickness and 1 ft. width of the CLT panel into equation [4] to calculate the vibration controlled span; this leads to the new span of 17.100 ft.

Step 4: If the calculated new span in step 3 differs from the previous span, then repeat steps 2 and 3 using the calculated span in step 3 as the new trial span until the solution converges. The iterative calculation procedure can be implemented into an Excel spreadsheet, as shown in Table 5.

Table 5
Excel calculation for the example

Thickness (in.)	Trial Span (ft.)	EI_{eff} (x10^6 lb.-in.^{2}/ft.)	GA_{eff} (x10^6 lb./ft.)	EI_{app} Equation [5] (x10^6 lb.-in.^{2}/ft.)	Specific Gravity	New Span Equation [4] (ft.)
6.875	17.188	440	0.92	389.5	0.56	17.10
6.875	17.100	440	0.92	389.1	0.56	17.09
6.875	17.090	440	0.92	389.0	0.56	17.09

Finally, examining the iteration results shown in Table 5, we found that the solution converges to a span of 17.09 ft., which is the vibration controlled span for the CLT floor built with the 6 7/8 in. thick panels.

4 APPROACHES FOR SPECIAL CASES

4.1 Continuous Multi-span CLT Floors

FPInnovations and University of New Brunswick studies found that, in comparison with the single span floors, the continuous multi-span floors are stiffer, which is indicated by the reduced 225 lb. (1 kN) static deflection. But the increase in stiffness of the floor is not very significant (Hu, 2007). Therefore, we have recommended that, for continuous multi-span CLT floors, the design equation [4] be used for estimating the vibration controlled CLT floor, assuming that the floor is a single span system with its span equal to the longest span in the actual multi-span system. Due to the significant flank transmission through the continuous multi-span floor systems, it is recommended to avoid using the continuous multi-span CLT floor system over two adjacent units in multi-family dwellings.

4.2 CLT Floor with a Suspended Ceiling

FPInnovations' laboratory study found that adding a suspended ceiling to a CLT floor increased the damping ratio to 2-3%, and the mass of the CLT floor (Hu, 2012). The overall level of the vibration performance was not negatively affected according to the evaluators. Therefore, equation [4] can be used for CLT floors with suspended ceiling based on the bare floor properties.

4.3 CLT Floor with a Suspended Ceiling and a Lightweight Overlay

FPInnovations' laboratory study also found that adding a suspended ceiling and a lightweight overlay such as wood panels onto a CLT floor increased the damping ratio to 2-3%, as well as stiffness and the mass of the CLT floor (Hu, 2012). The overall level of the vibration performance was not changed according to the evaluators. Therefore, equation [4] can be used for CLT floors with both a suspended ceiling and a lightweight overlay based on the bare floor properties.

4.4 CLT Floor with a Heavy Topping [>20 lb./ft.^{2} (100 kg/m^2)]

It is known that without a suspended ceiling, a heavy topping is normally necessary for CLT floor to achieve the satisfactory airborne and impact sound insulation. The heavy topping adds significant mass to the floor system, and reduces the fundamental natural frequency to below 9 Hz. Based on the experience of the authors, even though the topping increases the floor stiffness, the low first natural frequency makes the floor susceptible to annoying vibrations (Hu, 2007). For lightweight wood-joisted floor systems, the design method requires to reduce the spans of the joisted floors after a heavy cementitious topping is added (Hu, 2007). A similar approach should be applied to CLT floors with a heavy topping. As an interim measure, it is recommended that the span be calculated using equation [4] for vibration controlled design of such heavy topping CLT floor system, assuming the bare CLT floor mass and stiffness be reduced by 10%. This interim recommendation will be further refined through laboratory study.

5 CONCLUSION

It is concluded that the proposed design method to determine vibration controlled spans of CLT floors is mechanics-based, utilizes the fundamental mechanical properties of CLT, and is user-friendly and reliable.

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6 RECOMMENDATIONS

Wide acceptance of the proposed design method relies on its use and evaluation by product designers and manufacturers. Authors of this Chapter welcome feedback on the proposed design method. From a vibration control point of view, the perceived low damping ratio can be one of the major weaknesses of bare CLT floors. Any measures for increasing the damping ratio through CLT product design and floor construction detail will enhance the vibration performance of CLT floor systems.

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