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FROM CANADA TO THE WORLD:
FPINNOVATIONS' THREE-GENERATION FLOOR VIBRATION RESEARCH AND CODE IMPLEMENTATION

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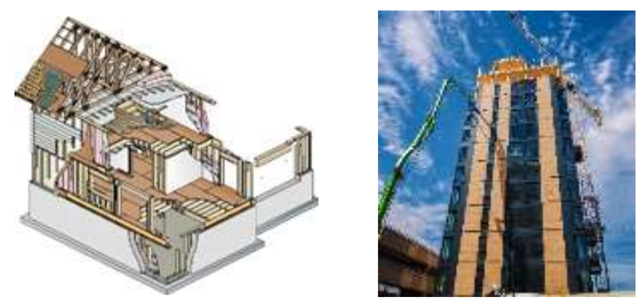
FPInnovations' involvement in various codes and standards technical committees aims to monitor, contribute or propose changes for improvement as well as to create new standards to include new wood products and systems based on knowledge developed from FPInnovations' research activities. Involvement also allows FPInnovations to be aware of any potential changes to codes and standards and to recognize and address threats and opportunities for wood use. Codes and standards exist to protect consumers but are written to reflect the current practices and knowledge based on a consensus agreement by committee members. FPInnovations' involvement in codes and standards committees helps to align the coming changes with new wood products. This InfoNote reports on FPInnovations' contribution to the floor vibration-control design methods on codes and standards implementation and research.

Evolution of the Wood Construction Industry

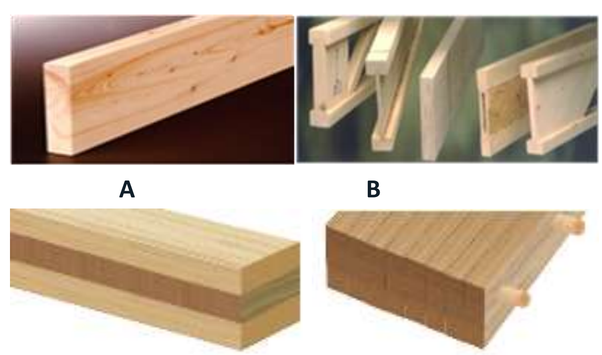
Floor vibration is not a safety issue, but it affects the comfort of occupants and consequently the market acceptance of wood construction. FPInnovations has conducted floor vibration-control research since the 1970s to ensure wood floor systems meet consumer expectations for performance and comfort. Wood floor products and the method of construction have greatly evolved over time. This led to the implementation of five floor vibration-controlled design methods, developed at FPInnovations, in the National Building Code of Canada (NBCC), the engineering design in wood CSA O86 and in several International Organization for Standardization (ISO) standards.

Since the 1970s, wood construction materials and technologies have been constantly evolving. There have been significant advances in the height and size of wood buildings, from small 1-2 story single-family carpenter's light wood-framed houses (Figure 1A) to tall mass timber buildings (Figure 1B). This has led to a revolution of wood floor systems from solid sawn lumber joisted floors (Figure 2A) slowly being replaced by engineered wood floors in the 1980s (Figure 2B) and the new market available to the wood industry with mass timber products leading to a new generation of mass timber floors (Figure 2C).



A B

Figure 1. Evolution of construction from the carpenter-stick house using solid sawn lumber (A) to high-rise buildings using mass timber products as shown in an 18-story mass timber building at the University of British Columbia in Vancouver (B).



A B

C

Figure 2. Three-generation wood floor products: Solid sawn lumber joists (A), engineered wood joists (B) and mass timber slabs (C).

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FPInnovations Has Played a Significant Role in the Evolution of Structural Wood Products

FPInnovations has actively supported the evolution of wood products and construction through the development of new wood building materials, novel construction technologies and new design methods for various building codes. One example is the constant development and implementation of floor vibration-controlled design methods for the three generations of wood floor systems.

In the 1970s-1980s, the first-generation floor vibration-controlled design method for lumber joisted floors was developed by Dr. Donald Onysko. To develop the method, Forintek Canada Corp. (now FPInnovations) conducted an extensive field study on the performance of over 300 residential floors built with sawn lumber joists through consumer surveys, performance tests and modelling. Dr. Onysko showed that for the sawn lumber joisted floors in residential houses, a better variable to predict the human response to floor vibration is the static deflection under a point load. Consequently, a new method that uses the static deflection limit under a 1 kN point load at the centre of a two-way floor system was proposed. This approach was eventually adopted as the basis for deriving allowable spans for floors built with sawn lumber joists in Part 9 of the 1990 NBCC. For these floor systems, the deflection limits are:

$$\Delta \leq 2.0 \text{ mm} \qquad \text{For span under 3.0 m}$$

$$\Delta \leq \frac{8}{L^{1.3}} \text{ mm} \qquad \text{For span over 3.0 m}$$

where Δ is the maximum deflection of a floor under 1 kN static point load, and L is the vibration-controlled span in metres. The NBCC Commentary provides procedures for calculating vibration-controlled spans for wood-frame floors that may contain lateral bracing elements, such as bridging, blocking and strapping, a rigidly connected drywall ceiling, and concrete topping (NRC, 2020).

In the 1990s, the second generation of floor joists such as wood I-joists and metal-plated wood trusses were invented, which are lighter, stiffer and stronger compared to solid lumber joists. Engineered wood joists also have higher strength to mass and stiffness to mass ratios than solid lumber joists. These changes led the wood industry to step into longer span construction markets such as non-residential and multi-family buildings. In multi-family and non-residential construction, concrete topping is often added to meet the sound insulation requirement prescribed by building codes. This new type of floor challenged the first-generation floor vibration-controlled design method. This led to the development of the second-generation wood floor vibration design method applicable to a broader range of wood joisted floors.

The approach to develop the second-generation vibration design method was similar to that used for the development of the first-generation design method. An extensive field study on the performance of over 100 floors built mostly with engineered wood joists were performed through consumer surveys, performance tests and modelling. It was found that in addition to the 1 kN point load static deflection, the floor fundamental natural frequency is also a key predictor of human response to vibration induced by normal walking, especially for the multi-family and non-residential wood floors that usually have a heavy topping. Therefore, a new design criterion for controlled walking-vibration in a broad range of wood joisted floors was derived combining these two parameters:

$$\frac{f}{d_{1kN}^{0.46}} \geq 20$$

Where f is the fundamental natural frequency of a floor, and d_{1kN} is the floor maximum deflection under 1 kN point load.

Equations were provided to calculate the 1 kN static deflection, the frequency and the composite stiffness of the wood floor and concrete topping. The deflection equation is similar to the equation for the lumber joisted floors which is able to account of the lateral bracing element. The fundamental natural frequencies are evaluated based on a T-beam model accounting for the joist and the composite floor deck including the subfloor and the topping. Substituting the frequency and deflection equations into the design criterion resulted in a simple design method to limit floor vibration-controlled maximum span (*L*) determined by its linear mass (m_L) and effective stiffness in the joist span direction (EI_{eff} and F_{tss}), as expressed below. This equation was finally adopted in CSA O86-19 (CSA, 2019):

$$L \leq \frac{0.122\,(EI_{eff})^{0.284}}{F_{tss}{}^{0.14} m_L{}^{0.15}}$$

In the 2000s, the third generation of wood floor products, i.e. cross-laminated timber (CLT), was implemented and commercialized in Canada. CLT is more like a solid slab, which challenged the vibration controlled-design methods for wood joisted floors that are more like a ribbed plate. CLT is a mass timber slab, similar to a concrete slab which is able to act to some extent in a two-way manner as a plate. There was no design method, in Canada, to control the vibration of mass timber slab floors. Therefore, since 2008, FPInnovations has conducted research on the development of a vibration-controlled design method for mass timber slab floors. Similar to the vibration-controlled design equation developed for engineered wood joisted floors, the design criterion used 1 kN static deflection and the fundamental natural frequencies as design variables as expressed below:

$$\frac{\mathrm{f}}{d_{1kN}^{0.7}} \geq 13$$

The equations to calculate the *f* and the 1 kN deflection were based on the one-meter-wide wood beam model. By substituting the deflection and the fundamental natural frequencies equations into the CLT floor design criterion, a simple design method to control the maximum vibration-controlled spans (L) for CLT floors was developed:

$$L \leq 0.11 \frac{\left(\frac{EI_{eff}}{10^6}\right)^{0.29}}{(m)^{0.12}}$$

It was published in CSA O86-19 (CSA, 2019). However, there are some limitations regarding the proposed design method which concerns the effect of multi-span, the effect of the concrete topping and the applicability of the equation to other mass timber products such as nail-laminated timber (NLT), dowel-laminated timber (DLT) and glue-laminated timber (GLT) decking. FPInnovations continues to develop solutions to expand the CLT floor design method to cover a broad range of mass timber products aiming for implementation in the next edition of CSA O86.

Impact in Canada

FPInnovations' three-generation floor vibration-controlled design methods in NBCC and CSA O86 ensure market acceptance by consumers. Since 1990, there have been very few consumer complaints. This reinforces the use of wood as a quality building material and contributes to expanding market shares of wood construction in Canada.

International Impacts

The approaches developed by Dr. Onysko for the development of design methods and timber floor field-testing methods were standardized at the ISO to benefit international researchers (ISO 2016; ISO 2017). This has attracted more international collaboration. A third ISO method for timber floor vibration control was developed using the FPInnovations' approach with the contributions of the timber floor databases from Finnish and German researchers. It is currently undergoing the voting process at the ISO/TC 165 committee. Final adoption in ISO will benefit consumers and the wood construction industry globally.

In conclusion

As demonstrated from the development and code implementation of the three-generation floor vibration-controlled design methods, FPInnovations plays an important role in Canada and internationally in codes and standards committees to protect consumers and the wood industry and contributes to the continuous market growth of wood construction globally.

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