SERVICEABILITY SENSITIVITY ANALYSIS OF WOOD FLOORS ALLOWING FOR SHEATHING DISCONTINUITIES

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Abstract. This study compares several design criteria for preventing unacceptable wood floor vibrations under occupant-induced loads and presents a sensitivity analysis based on static and dynamic responses of wood floors with engineered I-joists. Responses of floors with continuous and discontinuous (jointed) sheathing were compared. To accomplish this task, a user interface for the OpenSees finite element analysis program was developed. The interface was created in Excel (Microsoft, Redmond, WA) and allows user input for various floor system properties, which are used as input for OpenSees. Results from the OpenSees program are imported into the user interface and compared with multiple acceptance criteria that have been established by researchers to determine the vibration perception acceptability of the floor system. It was determined that a system with a 1.92-kPa uniform load modeled with one continuous piece of sheathing covering the entire floor system produced deflections that averaged 32% to a maximum of 45% lower than a floor system modeled with jointed sheathing. For a 1-kN force applied at the center of the floor, floors with jointed sheathing had an average of 12% and a maximum of 15% greater displacements compared with floors with continuous sheathing. Floors with jointed sheathing had an average of 8% and a maximum of 12% lower unoccupied natural frequencies compared with floors with continuous sheathing. Floors with jointed sheathing had an average of 10% and a maximum of 13.4% lower occupied natural frequencies compared with floors with continuous sheathing. Floors with jointed sheathing also had an average of 19% and a maximum of 41% greater frequency-weighted 1-s root-mean-square acceleration values compared with floors with continuous sheathing. The results show that great care must be taken when simplifying the sheathing setup on a floor model because the results create the illusion of better serviceability performance than actual installed floors will achieve.

Keywords: Sensitivity analysis, wood floors, engineered joists, vibrations, OpenSees, finite element analysis, spreadsheet.

INTRODUCTION

Annoying floor vibrations in wood floor construction have become a major issue that needs to be considered at the time of design. The widespread use of engineered wood I-joist systems has allowed for longer spans and lighter construction. This advancement has come with many benefits but also with an increase in the vibrational response of floor systems. Footfall impact has been the most common source of annoying vibrations for wood floors (Burch 2013). In the

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past, the design recommendation to limit deflection produced by a uniformly distributed static load of 1.9 kN/m^2 has been span/360. But, this requirement is insufficient in avoiding excessive vibrations. Researchers have presented other design criteria that limit vibrations in wood floors. However, some of the criteria need intensive calculations that require knowledge of structural dynamics.

The criteria studied were those of the International Building Code (ICC 2012; Foschi and Gupta 1987; Onysko et al 2000; Dolan et al 1999; Hu 2007; Smith and Chui 1988). The first three criteria deal with static deflection. The International Building Code requires that the maximum allowable deflection for floor members with an applied live load be less than or equal to span/360. Foschi and Gupta's criterion requires that a "bare" joist loaded at the center with a concentrated load of 1 kN have a 1-mm deflection or smaller deflection. This deflection is found using Eq 1:

$$\delta = PL^3/48\,EI \tag{1}$$

where δ = joist deflection, $P = 1$ kN, L = span length, E = joist modulus of elasticity (MOE), I = joist moment of inertia. Onysko et al (2000) proposed a criterion that limits floor vibration more accurately than the standard span/360. They proposed that to limit floor vibrations, the following should be used:

1. $\Delta \le 8.0/L^{1.3}$ for spans beyond approximately 3.0 and 5.5 m
2. $\Delta \le 2.55/L^{0.63}$ for spans between 5.5 and approximately 9.9 m
3. $\Delta \le 0.6$ for spans beyond approximately 9.9 m
4. $\Delta \le 2.0$ for spans under approximately 3.0 m
5. $\Delta_{udl} \le L/360$ for all spans

where Δ = floor system deflection in millimeters under 1 kN, L = span length in meters, and Δ_{udl} = maximum deflection of a floor member under the action of a uniformly distributed load of 1.9 kN/m^2.

The next three criteria predict acceptability of a floor by calculating the natural frequency of a floor system. Dolan et al (1999) provided a simple method of estimating the natural frequency. Their criterion proposes that the natural frequency be calculated using the following equation:

$$f = \frac{\pi}{2}\sqrt{\frac{gEI}{WL^3}} \tag{2}$$

where g = acceleration of gravity, E = joist MOE, I = moment of inertia of joist alone, W = weight of floor system supported by joist, and L = span length.

Based on results of 180 floors tested, the acceptability criterion by Dolan et al (1999) states that for a floor to be adequate, the unoccupied natural frequencies must be at least 15 Hz. For an occupied floor, the natural frequency must be more than 14 Hz.

Hu's (2007) criterion deals with a combination of natural frequency and static displacement. This criterion was validated with a database of 160 floors. The floors were rated by occupants as to their vibration acceptability. Hu (2007) stated that the allowed deflection could be determined using the following equation:

$$d < \left(\frac{f}{18.7}\right)^{2.27} \tag{3}$$

where f = natural frequency (Hz) and d = deflection (millimeters). The static deflection is measured after a load of 1 kN is applied at midspan.

The last criterion is that proposed by Smith and Chui (1988). Smith and Chui's research focuses on providing a method to predict the dynamic behavior of lightweight wood-joist floors. These floors are semirigid and are attached to wood-based sheathing. Their method allows the user to predict the natural frequencies and the 1-s root-mean-square (RMS) acceleration under a simplified force function. Because humans are more sensitive to vibrations with natural frequencies between 4 and 8 Hz, Smith and Chui (1988) require that a floor system have a natural frequency greater than 8 Hz. In addition, the criterion specifies that the frequency-weighted RMS acceleration experienced by the observer must not exceed a threshold value. This value is a result of the heel-drop test impact in which acceptable RMS acceleration must be less than 0.45 m/s^2. Smith and Chui (1988) propose the following equation to estimate the floor natural frequency:

$$f_o \cong \frac{\pi}{2a^2}\sqrt{\frac{E_j I_j (n-1)}{\rho_s hb + \rho_j cd(n-1)}} \tag{4}$$

where f_o = fundamental natural frequency, a = floor span, b = floor width, c = joist width, d = joist depth, h = sheathing thickness, E_j = MOE of joist, I_j = area moment of inertia of joist, n = number of joist, ρ_s = density of sheathing, ρ_j = density of joist.

The objective of this study is to provide a tool for designers that evaluate floor systems in the design stage. The system is evaluated without requiring knowledge of structural dynamics and without the difficulties associated with modeling a complex system in finite element analysis software. The Excel user interface works with the OpenSees finite element package and returns results based on the previously mentioned acceptability criteria.

PROGRAM CALIBRATION

Finite element modeling software has become a powerful tool for engineers. For this study, OpenSees (2015) was used. OpenSees is an open software created and maintained by the University of California, Berkley. This program has received constant verification at an academic level through an ongoing peer-review process.

The program developed for this study was calibrated using the experimental work by Wolfe (2007). Wolfe measured deflections and vibrations of a single joist, a single joist and sheathing, and a full floor system composed of five joists and sheathing. Most material values found by Wolfe were used for comparison with the OpenSees model results. But, the effects of joist torsional properties were also included to better match the experimental results. Details of the program are provided in Burch (2013).

SENSITIVITY ANALYSIS

Using the program developed in this study, several sensitivity analyses were performed on a floor system. The objective was to see the relation between deflection, natural frequency, and the 1-s RMS acceleration response and floor width for both continuous and jointed sheathing. For this study, the floor system with parameters given in Table 1 was considered. The floor span was 4.93 m, and the width was varied from 1.27 to 5.33 m.

Figure 1 shows the change in static deflection for the widths considered when the floor model

Table 1. Constant parameters for a floor system with all edges simply supported.

Floor boundary condition	All four edges simply supported
Joist type	Engineered I-joist
Joist center-to-center spacing	406 mm
Joist depth	241 mm
Joist model	110
Joist torsional rigidity (GJ)	574 Nm^2
Span rating	24 on center single floor
Sheathing thickness	18.3 mm
Sheathing MOE	3.19 GPa
Sheathing Poisson's ratio	0.092
Fastener spacing	254 mm
Fastener stiffness (horizontal plane)	5318 N/mm
Fastener stiffness (vertical plane—pullout)	17,513 N/mm
Fastener stiffness (horizontal axis)	17,513 N/mm
Fastener stiffness (vertical axis)	0 N/mm
Occupancy load	0.096 kPa
Floor damping	3%

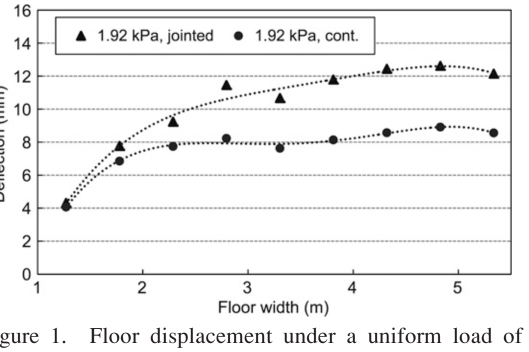

Figure 1. Floor displacement under a uniform load of 1.92 kPa.

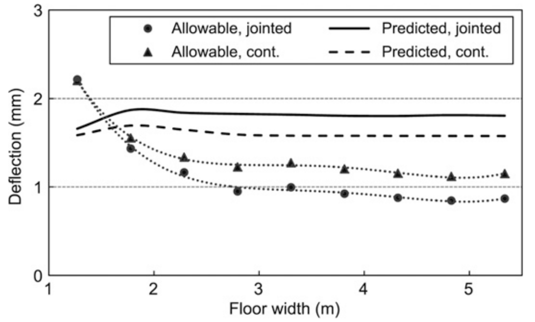

Figure 2. Displacement under 1-kN force.

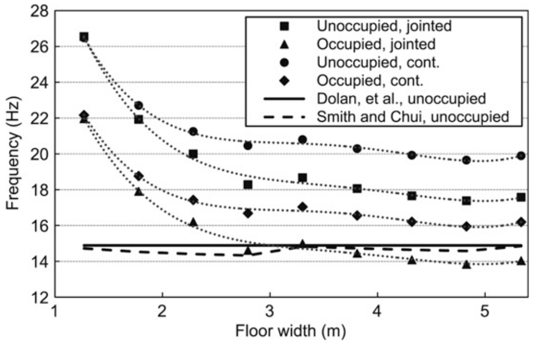

Figure 3. Natural frequency vs floor width.

was loaded with a uniformly distributed load of 1.92 kPa for continuous and jointed sheathing.

Several researchers have noted that the assumption of continuous sheathing is acceptable with respect to deflections and vibrations of floor systems. However, as Fig 1 shows, under a uniform load, jointed sheathing had considerably greater deflection, especially as the floor width increased. At floor width of 4.3 m, floors with jointed sheathing had an average of 32% and a maximum of 45% greater displacements under a 1.92-kPa uniform load compared with floors with continuous sheathing.

Figure 2 shows the OpenSees (predicted) deflections under 1-kN force at the center of the floor and the allowable deflections based on Hu's (2007) recommended formula (Eq 3).

As Fig 2 shows, the floor with jointed sheathing had greater deflection, and yet, because of lower natural frequency, it was allowed to deflect less under the 1-kN force. For a 1-kN force applied at the center of the floor, floors with jointed sheathing had an average of 12% and a maximum of 15% greater displacements compared with floors with continuous sheathing (at floor width of 4.8 m).

Figure 3 shows the occupied and unoccupied natural frequencies obtained from OpenSees for floors with continuous sheathing and jointed sheathing. For comparison, Fig 3 also shows the calculated natural frequencies based on Dolan et al (1999) and Smith and Chui (1988) formulas, which are both based on an unoccupied floor (Eqs 2 and 4, respectively). For floors with both jointed and continuous sheathing, the occupied and unoccupied natural frequencies decreased as the floor width increased.

In addition, for the system with jointed sheathing, both occupied and unoccupied frequencies were lower than the corresponding continuous sheathing floor. Floors with jointed sheathing had an average of 8% and a maximum of 12% lower unoccupied natural frequencies compared with floors with continuous sheathing (at floor width of 5.3 m). Floors with jointed sheathing had an average of 10% and a maximum of 13.4% lower occupied natural frequencies compared with floors with continuous sheathing (at floor width 5.3 m).

Figure 4 shows the frequency-weighted 1-s RMS acceleration values with respect to the floor width for both jointed and continuous sheathing in terms

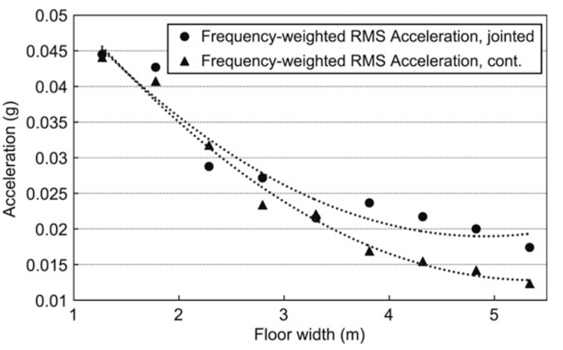

Figure 4. Frequency-weighted 1-s RMS acceleration responses. $g = 9.81$ m/s^2.

of acceleration of gravity ($g = 9.81$ m/s^2). These values were based on the equation proposed by Smith and Chui (1988) to determine the RMS acceleration values. The values were then adjusted by a factor of $8/f_o$ (f_o being the floor fundamental natural frequency in Hz) for frequencies greater than 8 Hz. As Fig 4 shows, RMS of acceleration was initially the same for systems modeled with jointed sheathing and continuous sheathing. But, the value for the jointed sheathing floor decreased at a slower rate as the floor width increased. Floors with jointed sheathing had an average of 19% and a maximum of 41% greater frequency-weighted RMS acceleration values compared with floors with continuous sheathing (at floor width 5.3 m).

SUMMARY AND CONCLUSIONS

Design criteria have been developed by researchers to help designers eliminate annoying floor vibrations. However, applications of most of these criteria require knowledge of structural dynamics and involve complicated calculations. The program developed in this study requires no knowledge of dynamics or the OpenSees software. It only requires users to enter the design parameters in the Excel interface. To quantify the effects of jointed floor sheathing, a series of sensitivity analyses were performed.

Floors modeled with continuous sheathing had lower displacement values than floors modeled with jointed sheathing. For a 1.92-kPa uniform load, floors with jointed sheathing had an average of 32% to a maximum of 45% greater displacement than floors with continuous sheathing. For a 1-kN force applied at the center of the floor, floors with jointed sheathing had an average of 12% and a maximum of 15% greater displacement compared with floors with continuous sheathing.

For unoccupied floors, floors with jointed sheathing had an average of 8% and maximum of 12% lower natural frequencies compared with floors with continuous sheathing. Percentage decreased as floor width increased. Floors with jointed sheathing had an average of 10% and a maximum of 13.3% lower occupied natural frequencies compared with floors with continuous sheathing. For 1-s RMS acceleration values, floors with jointed sheathing had an average of 19% and a maximum of 41% greater RMS acceleration values compared with floors with continuous sheathing.

It can be concluded that modeling floor systems with once piece of continuous sheathing will give less conservative values than the actual values. To obtain more accurate results, floor systems should be modeled with jointed sheathing. Therefore, the program developed in this study is a useful tool because it allows users to examine the changes in displacement, natural frequencies, and RMS accelerations with different system parameters, including the option of jointed sheathing.

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