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VIBRATION CHARACTERISTICS OF LIGHTWEIGHT FLOORS USING COLD-FORMED STEEL JOIST

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ABSTRACT

Presented in this paper are the results of a recent study carried out at the University of Waterloo on vibration characteristics of cold-formed steel-supported residential floor systems and different design criteria available for the evaluation of lightweight floor systems. Laboratory tests were conducted for the floors with different spans and assemblies. Both static and dynamic tests were carried out on the floor systems. The static tests were used to evaluate the stiffness and the load sharing among the joists, while the dynamic tests were used to evaluate the relevant dynamic characteristics, such as natural frequencies and damping ratios, of the floor systems. The test results were then compared with those obtained from different design methods. Concluding remarks regarding the acceptance criteria from the comparison are also presented.

1. INTRODUCTION

Vibrations associated with lightweight floor systems, as a serviceability criterion, have not been well addressed in current residential construction practice. Most of North American homebuilders, in constructing lightweight floors, follow the recommendation of the National Association of Home Builders in the United States, which limits the span deflection to *L*/480 under specified uniform live loads, where *L* is the span length. Such recommendation was established based on the long-term practice on residential floors with solid lumber joists, which provides floor systems with limited span lengths. However, the performance of timber floor systems based on such oversimplified design criterion may still be susceptible to annoying floor vibration induced by human activities.

Recent economical developments have led homebuilders to explore cold-formed steel as an alternative building material to timber for residential construction. Cold-formed steel offers design flexibility and numerous advantages for architects, engineers, and builders, as it is impervious to termite attack and has the highest strength-to-weight ratio of any building material. Therefore, floor systems supported by cold-formed steel joists provide an economical solution for the longer spanning structures, which are often desired by both of homeowners and architects in creating the so-called open concept design. Unfortunately, steel-framed floor systems are usually lighter and therefore have less inherent damping. They may become vulnerable to

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human-induced floor vibrations if the associated dynamical behavior is not appropriately addressed in design of such floor systems. Correcting for these inadequacies after construction usually proves very costly. To partially address this issue, the evaluation of vibration performance of lightweight steel floors due to human-induced dynamic loads needs to be studied.

A limited number of recommended design criteria for lightweight residential floors are available (Onysko 1985, Ohlsson 1988a, AS3623 1993, Johnson 1994, NBCC 1995, CWC 1996, and ATC 1999), most of which are primarily focused on to timber floor applications. Kraus and Murray (1997) conducted a series of tests on residential floor systems supported by C-shaped cold-formed steel members. The test results were compared with four floor vibration criteria: 1) the Australian Standard, 2) the Swedish Design Guide developed by Ohlsson, 3) the U.S. Timber Floor Vibration Criterion proposed by Johnson, and 4) the Canadian Timber Floor Criterion developed by Onysko. Their report recommends that the Canadian Timber Floor Criterion developed by Onysko be used as a possible criterion for cold-formed steel joist residential floors because of its simplicity and satisfactory agreement with the test results.

Presented in this paper are the recent test results on the performance of cold-formed steel-supported residential floor systems, a multi-phase study carried out at the University of Waterloo (Xu *et al.* 2000). The tests are focused on lightweight residential floors supported by C-shape cold-formed steel joists. Various spans and floor assemblies (details) were tested. The floor systems were subjected to both static and dynamic loadings. The static tests were used to evaluate the stiffness and the load sharing among the joists, while the dynamic tests were used to evaluate the relevant dynamic characteristics, such as frequencies and damping ratios, of the floor systems. The details on the apparatus and procedure for each type of test were presented in Xu *et al.* (2000). The test results are in comparison with the analytical results obtained from different design criteria.

2. DESCRIPTION OF FLOOR SYSTEMS

In order to cover a larger range of floor span lengths, two types of C-shape cold-formed steel joists (C-203×41×1.22 mm and C-254×41×1.91 mm) were selected. The section depths for C-203×41×1.22 and C-254×41×1.91 joists are 8 in. (203 mm) and 10 in. (254 mm), respectively, while the corresponding section thickness for the two joists are 0.048 in. (1.22 mm) and 0.075 in. (1.91 mm). The three full-scale floor systems with different span lengths tested are described as follows.

- **L/480 bedroom floor system**
  The floor span lengths were determined based on a deflection limit of *L*/480 under a specified live load of 30 lb/ft^2 (1.4 kPa). The corresponding floor spans for joist depth of 8 in. (203 mm) and 10 in. (254 mm) were 15.6 ft (4740 mm) and 22.2 ft (6754 mm) (CSSBI 1999), respectively.

- **L/480 living room floor system**
  The floor span lengths were determined based on a deflection limit of *L*/480 under a specified live load of 40 lb/ft^2 (1.9 kPa). The corresponding floor spans for joist depth of 8 in.

(203 mm) and 10 in. (254 mm) were 14 ft (4270 mm) and 20.1 ft (6114 mm) (CSSBI 1999), respectively.

- **ATC floor system**
  The floor span lengths were determined based on the vibration design criterion of "Minimizing Floor Vibration" (ATC, 1999). The corresponding floor spans for joist depth of 8 in. (203 mm) and 10 in. (254 mm) were 13.5 ft (4120 mm) and 17.5 ft (5330 mm) (CSSBI 1999), respectively.

It can be seen from the foregoing that the maximum spans for C-203×41×1.22 floor joist range between 13.5 ft (4120 mm) and 15.6 ft (4740 mm), while for C-254×41×1.91 spans between 17.5 ft (5330 mm) and 22.2 ft (6754 mm).

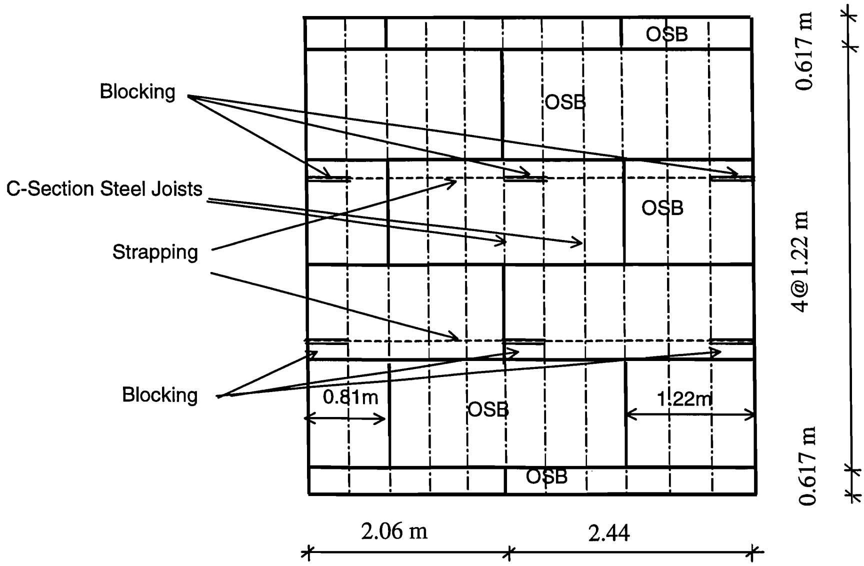

Figure 1. Floor layout (fl-6.114-2-6"-1/5-B0)

Each floor contained twelve C-section joists with 16 in. (400 mm) on center spacing, and 5/8 in. (16 mm) tongue-in-groove oriented strand board (OSB) sheathing as the sub-flooring (Figure 1). The OSB sub-flooring was fastened to the joists using self-drilling screws. Self-drilling screws were placed at 6 in. (152 mm) on center around the perimeter and 12 in. (305 mm) on center in the field of the panel. The bridging and solid blocking were installed as per the requirements of Steel Framing Installation Manual (CSSBI, 2000) to provide the lateral stability of the joists and integrity of the floor system. For floors with C-203×41×1.22 joists, one row of steel strapping (58×1.44 mm) was placed at mid-span of the joists with a 6 in. (152 mm) cold-formed steel channel blocking placed at every five joist-spacing while two rows of steel strapping were located at 1/3 and 2/3 of the span length for floors with C-254×41×1.91 joists as shown in Figure

1. The floor joist ends were simply supported by bearing on a 4×4 in. wood block on each side while the two edges of the floor parallel to the joists were not supported. The joist ends were connected to a cold-formed steel rim-track section (203×41×1.22 mm or 254×41×1.91) and the rim-tracks were fastened to the 4×4 in. wood block. C-shape steel bearing stiffeners were placed at every joist-track connection (Figure 2).

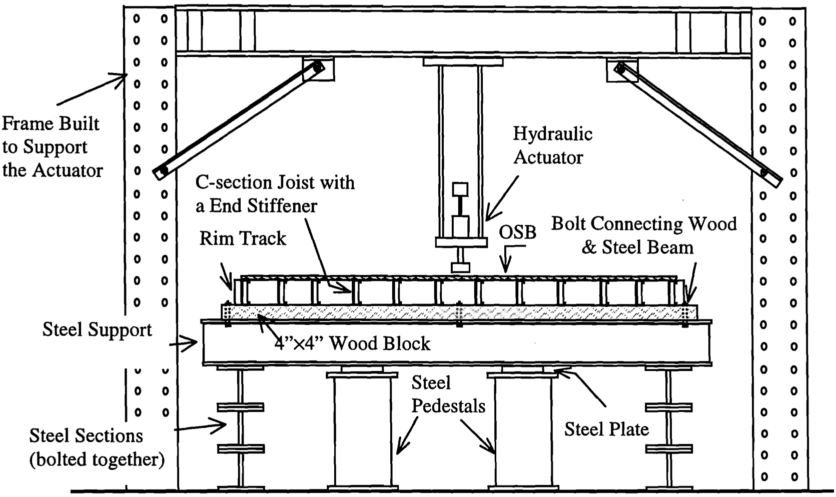

Figure 2. End detail of floor set-up (fl-6.114-2-6"-1/5-B0)

In addition to the foregoing floor assemblies, several variations of the floor configuration were investigated to determine their effect on the dynamic behavior of the floor systems. Those variations include the alternatives on the blocking type and pattern, the floor edge support condition, the joist end support condition, and the screw spacing pattern, which were described in Xu *et al.* (2000) with some previous test results.

To identify the different floor assemblies, the following designation was adopted:

> **fl** - *span length – support conditions - blocking type - blocking pattern - joist end support condition - screw pattern – number of bridging - ceiling – glued sub-floor*

For example, the designation of fl-6.114-2-6-1/5-B2-2b-Ce-g represents the floor assembly with the following characteristics: the joist span length is 6.114 meters (20.1 ft.); only two joist-end edges were supported; solid blocking is a 6 in. channel section; the blocking pattern is at every five joist spacing; the joist-end rotation is partially restrained by placing a restraining beam which provides a uniformly distributed line load (approximately 100 lb/ft) on top of the sub-floor at each joist-end edge (Figure 3) (B0 indicated the joist-end is not restrained); screws are placed at 6 in. (152 mm) on center around the perimeter and 12 in. (305 mm) on center in the field of the panel; two rows of bridging; half inch thick gypsum board ceiling is attached to the bottom flange of joists; and the sub-floor is glued and screw fastened to the joists. The distributed line load at each joist-end edge is intended to simulate the restraining effect of the walls.

3. ANALYTIC METHODS

The criteria used to evaluate the fitness of the floors tested are provided by the following analytical methods: Canadian Wood Council (CWC) Design Method (CWC *et al.* 1996); Applied Technology Council (ATC) Design Method (ATC, 1999); Swedish Design Guide Method (Ohlsson, 1988a); Australian Design Method (AS3623, 1993); and Johnson's Design Method (Johnson, 1994). A brief description of each method is provided in the following subsections.

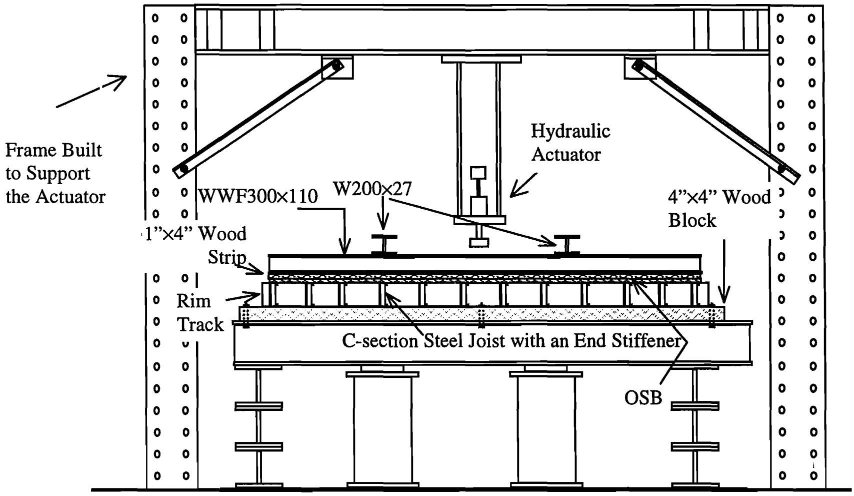

Figure 3. End details of floor set-up (fl-6.114-2-6"-1/5-B2)

3.1 Canadian Wood Council (CWC) Design Method

The design method offered by the Canadian Wood Council (CWC *et al.*, 1996) provides a procedure to predict the lightweight wood floor vibration characteristics by evaluating the floor deflection under a concentrated load. The predicted deflection is determined using the concept of "effective number of joist". That is, through empirical equations, the number of joists effectively contributing to resisting 1 kN load in the center of the floor is determined. In order to have adequate stiffness, limits on the floor span are imposed on the predicted deflection as

$$\Delta \leq 2.0 \text{ mm} \qquad (L < 3.0 \text{ m}) \tag{1a}$$

$$\Delta \leq 8.0/L^{1.3} \qquad (3.0 \text{ m} \leq L < 5.5 \text{ m}) \tag{1b}$$

$$\Delta \leq 2.55/L^{0.63} \qquad (5.5 \text{ m} \leq L < 9.9 \text{ m}) \tag{1c}$$

$$\Delta \leq 0.6 \text{ mm} \qquad (L > 9.9 \text{ m}) \tag{1d}$$

where Δ is the midspan deflection of the floor system due to a static concentrated load of 1 kN at midspan, and L is the span length of the floor.

The CWC method allows accounting for various floor configurations, such as the presence of ceiling, different blocking patterns, nailed or glued-and-nailed sub-floors, etc. The method also considers whether the sub-floor material is OSB alone or OSB with concrete toping. However, CWC does not provide a procedure to determine the natural frequency of the floors.

3.2 Applied Technology Council (ATC) Design Method

The method for evaluating vibration performance of lightweight floors proposed by ATC (1999) was based on the CWC procedure of predicting the center deflection of the floor under a 225-lb (1-kN) concentrated load. In addition to limiting the floor deflection to ensure adequate stiffness as shown in Eq. (2), a lower-bound limit of 8 Hz is imposed on the fundamental natural frequency. The method actually suggested that a floor with the fundamental natural frequency less than 10 Hz would result in unacceptable discomfort to the occupants, as resonant amplification of footstep impulse vibration occurs.

$$\Delta_p \leq 0.024 + 0.1e^{-0.18(L-6.4)} \leq 0.08 \text{ in.} \qquad \text{(U.S. Customary Units)} \qquad (2a)$$

$$\Delta_p \leq 0.61 + 2.54e^{-0.59(L-1.95)} \leq 2.03 \text{ mm} \qquad \text{(SI Units)} \qquad (2b)$$

where Δ_p is the midspan deflection of the floor system in inches or millimeters due to a static concentrated load of 225 lb (1kN) at midspan, and L is the span length of the floor.

Similar to the CWC method, the ATC method accounts for various floor configurations and sub-floor materials. The method is also applicable to lightweight floors supported by cold-formed steel joist. Additionally, the ATC method provides a procedure to determine the natural frequency of the floor based on an equivalent one-way joist or beam evaluated by the concept of "effective number of joist".

3.3 Swedish Design Method

This methodology is based on over ten years of research on lightweight floors done by Ohlsson (Ohlsson 1988a and 1988b). This design method presents the advantage of being applicable to all construction materials used for the floor systems. That is, both the predicted floor deflection and natural frequency are computed based on the materials used in the floor construction, whereas other design methods, such as the CWC method, involve parameters or formulas that are established based on a specific construction material, such as wood. In addition, this method allows taking into account the presence (or lack thereof) of ceiling and blocking. Therefore, it does not account for the sub-floor being glued to the joist.

In order to have adequate stiffness, a deflection limit of 0.059 in. (1.5 mm) is imposed on the predicted deflection on a single floor joist or beam, regardless of floor span, under a 225 lb (1 kN) applied concentrated load. The model of equivalent joist or beam, based on the concept of "effective number of joist", was not adopted in the stiffness evaluation. A frequency limit of 8 Hz is imposed as a lower bound on the floor's fundamental natural frequency. The Swedish methodology also provides a procedure to determine the natural frequency of a floor based on the flexural stiffnesses parallel and perpendicular to the joist direction.

For floor spans greater than 13 ft (4 m) with long unobstructed passages for pedestrians, the method requires that the root mean square (RMS) vertical vibration velocity ($\dot{w}_{\text{RMS}}$) must be checked. However, this criterion is usually not applicable to private dwellings. Ohlsson (1988a) provided no limiting value to $\dot{w}_{\text{RMS}}$, but suggested comparing the calculated value with corresponding values of floors, which have proven to be satisfactory.

3.4 Australian Design Method

The Australian Standard Domestic Metal Framing Code (AS3623, 1993) adopted Ohlsson's (Ohlsson, 1988a) method to determine the natural frequency of a floor. Therefore it requires that the fundamental natural frequency be not less than 8 Hz. For the floor stiffness requirement, regardless of floor span length, the method imposes an upper limit of 0.0787 in. (2 mm) on the span deflection of a single floor joist under a 225 lb (1 kN) applied load. The predicted deflection considers the flexural stiffnesses parallel and perpendicular to the joist direction. In addition, this method allows taking into account the presence (or lack thereof) of blocking.

3.5 Johnson's Design Method

Johnson (1994) proposed that a lightweight wood floor system would be acceptable if its lowest natural frequency under the self-weight of the floor was greater that 15 Hz. Also, Johnson provided a predictor equation for the natural frequency of a floor, which is based on the fundamental frequency of a simple wood beam, as it was determined that the effective sheathing width was negligible.

4. TEST RESULTS AND COMPARISON WITH DESIGN METHODS

In the following sections, the results from laboratory testing are summarized and compared with the predicted results obtained from each of the design methods described above. Details on both of tested and predicted results, including the deflection and fundamental natural frequency of each floor, are presented in Appendix B. The floors with span lengths of 13.5 ft (4.12 m), 14 ft (4.27 m), and 15.6 ft (4.74 m) are supported by C-203×41×1.22 joists while floor spans of 17.5 ft (5.33 m), 20.1 ft (6.114 m), and 22.2 ft (6.754 m) are by C-254×41×1.91 joists.

4.1 Comparison of experimental results with CWC Design Method

The CWC method was developed based on the characteristics of lightweight wood floor. In order to use the CWC procedure in this study to predict the deflection of the floor supported by cold-formed steel C-shape joists, the cross-sectional properties of wood floor joists were replaced by those of steel. In addition, since the CWC method did not provide a procedure to determine the natural frequency for the floor, the procedure provided by ATC (1999) was used in its place due to the similarity of the two methods.

The comparison of tested results to the predicted floor responses is presented in Table B1. It can be seen from Table B1 that the accuracy of predicted natural frequencies decreases with increase in floor span. Comparing the results obtained from unrestrained (BO) and partially restrained (B2) joist-end rotation, better-predicted values were obtained for both the floor deflection and frequency for the latter case. A positive percent difference indicates that the floor response is overestimated. The percent differences of floor frequencies are all positive and show considerable discrepancies, suggesting that the method is not a good predictor of floor natural frequencies. With regards to floor deflection, the predicted displacements (Δ_{CWC}) underestimate the measured displacements (Δ_{test}), as the majority of the percent differences are negative (20 out of 30).

4.2 Comparison of experimental results with ATC Design Method

In general, the ATC method provides better predictions of floor responses than the CWC method. It can be seen from Table B2 that the accuracy of the predicted natural frequency (f_{1_ATC}) associated with ATC method improves as the span of the floor increases. Moreover, for the longer span floors (6.114-m and 6.754-m) the method provides conservative results when predicting the fundamental natural frequency of the floor with attached ceiling and attached ceiling and glued sub-floor. Similar to the CWC method, better-predicted values of floor deflection and frequency for the case of partially restrained (B2) joist-end rotation are obtained. This might suggest that the method accounted for the end rotation restraining effect due to the walls located above the joist ends or joist continuity.

It can also be seen from Table B2 that for floors with attached ceiling and attached ceiling with glued sub-floor, the method provides conservative predicted displacements (Δ_{ATC}) as the percent differences are positive. This suggests that the ATC method is conservative in predicting the deflection of realistic floor configurations.

4.3 Comparison of experimental results with Swedish Design Method

Comparing with the two previous methods, the Swedish Method yields larger discrepancies between the tested and predicted floor responses as shown in Table B3. It overestimates both floor deflections and natural frequencies, and particularly the floor deflections, as the lowest percent difference is 179.2. For the longer span floors (6.114-m and 6.754-m) the method provides predicted deflections with errors of over 220%. Although the overestimation of floor deflection turns out to be conservative, the significant errors associated with the method suggest that the method is a poor predictor of floor deflection. Comparing the results from unrestrained (BO) and partially restrained (B2) joist-end rotation, the worse predicted values are obtained for the floor deflection for latter case. This suggests that the Swedish method may not be a good predictor for realistic floor configurations.

4.4 Comparison of experimental results with Australian Design Method

Since the Australian method (AS3623, 1993) adopted the Swedish method (Ohlsson, 1988a) to determine the natural frequency of a floor, the predicted floor natural frequencies are identical to those shown in Table B3. Therefore such values were not re-presented in Table B4. With regards to floor deflections, the Australian method generally provides less accurate results when compared to the ATC method. The accuracy of the predicted displacement (Δ_{AUST}) improves as the span of the floor increases, except for floors with ceiling attached. However, the poorer prediction of restrained (B2) joist-end rotation compared to the unrestrained (B0) results, combined with larger discrepancies for floors with ceiling attached, might suggest that the method may not be a good predictor for realistic floor configurations.

4.5 Comparison of experimental results with Johnson's Design Method

The results obtained using Johnson's (1994) criterion are summarized in Table B5. The measured natural frequency was compared against the 15-Hz criterion. The measured frequency was not compared with the predicted natural frequency as the proposed equation (Johnson, 1994) was calibrated for wood joist and, in a laboratory environment, was found to be a poor predictor for floors supported by cold-formed steel joists (Tangorra, 2001).

4.6 Evaluation of all floor systems

In addition to predicting equations for natural frequencies and deflection, each foregoing design method also provides limits to indicate whether a floor may be considered acceptable. Categorized by the design criteria that stipulate the floor span length, the comparison of tested results with such limits is summarized in Table B5.

It can be seen from Table B5 that the ATC (1999) and CWC (1996) methods yield the identical outcome with regards to the acceptance of tested floors with the exception of fl-5.33-2-6-1/5-B2S6-2b. Comparing the results obtained from the Swedish method (Ohlsson, 1988a) and Australian method (AS3623, 1993), according to the Australian method all floors are acceptable because of its less stringent limit on floor deflection, while only 20 out 30 floors would be acceptable according to the Swedish method. This result is significant when compared to the evaluations provided by the other three methods, which reject twice as many floors. This suggests that, perhaps, more stringent deflection limits should be imposed for the Swedish and Australian methods. The criterion proposed by Johnson (1994) is almost as conservative as the ATC and CWC methods, by evaluating as acceptable 9 out of 30 floors compared with the 7 out of 30 for ATC and 6 out of 30 for CWC. This suggests that Johnson's criterion will produce similar results to those imposed by ATC (1999) and CWC (1996).

5.0 CONCLUSIONS

The test results show that the fundamental frequencies of all tested floors are greater than 8 Hz. Therefore, resonant amplification of footstep impulse vibration appears to be not a concern for lightweight steel floors.

Floors with span lengths limited by the ATC method provide the satisfactory vibration performance for all five evaluation criteria. Floors with span lengths determined based on a deflection limit of *L*/480 under living room occupancy, with live load of 40 lb/ft^2 (1.9 kPa), which satisfy both the Swedish and Australian criteria, are generally not accepted according to limitations of the ATC, the CWC, and Johnson's methods with the exception of a few cases. Floors with span lengths determined based on a deflection limit of *L*/480 under bedroom occupancy, with live load of 30 lb/ft^2 (1.4 kPa) are generally not accepted by all criteria with the exception of the Australian one.

The test results indicate that the ATC (1999) method provides better results than the other four methods for predicting natural frequencies and deflections for realistic floor configurations. However, this study also finds that a few shortcomings associated with the ATC method. The slip modulus, which account for the interaction between sub-flooring material and floor joists, is not provided for lightweight floors supported by cold-formed steel joists. In addition, the values of effective shear area and shear moduli provided for bridging and blocking conditions are based on wood construction. When using the equivalent values associated with cold-formed steel construction details, unrealistic values result (Rizwan, 2000). Therefore, tests need to be carried out to determine the slip moduli of OSB sub-flooring connected to cold-formed steel joists.

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APPENDIX B - TABLES

TABLE B1: EVALUATION OF FLOOR VIBRATION PARAMETERS USING CWC'S METHOD

Floor designation	Δ_{test} (mm)	Δ_{CWC} (mm)	% Difference	f_{1_test} (Hz)	f_{1_CWC} (Hz)	% Difference
normal screw spacing with blocking at every five-joist spacing						
fl-4.12-2-6-1/5-B0-S12-2b	1.230	1.063	-13.58	15.260	21.489	40.82
fl-4.12-2-6-1/5-B2-S12-2b	0.980	1.063	8.47	17.090	21.489	25.74
fl-4.27-2-6-1/5-B0-S6-1b	1.340	1.131	-15.56	15.140	20.011	32.18
fl-4.27-2-6-1/5-B2-S6-1b	1.160	1.131	-2.46	16.110	20.011	24.22
fl-4.27-2-6-1/5-B0-S6-3b	1.410	1.162	-17.56	14.040	20.011	42.53
fl-4.27-2-6-1/5-B2-S6-3b	1.090	1.162	6.64	16.480	20.011	21.43
fl-4.74-2-6-1/5-B0-S6-2b	N/A			13.180	16.252	23.31
fl-4.74-2-6-1/5-B2-S6-2b	1.610	1.345	-16.44	14.650	16.252	10.94
fl-5.33-2-6-1/5-B0-S6-2b	1.012	0.872	-13.83	16.342	17.918	9.64
fl-5.33-2-6-1/5-B2-S6-2b	0.943	0.872	-7.52	16.693	17.918	7.34
fl-6.114-2-6-1/5-B0-S6-2b	1.359	1.208	-11.14	12.909	21.047	63.04
fl-6.114-2-6-1/5-B2-S6-2b	1.334	1.208	-9.48	13.245	21.047	58.90
fl-6.754-2-6-1/5-B0-S6-2b	1.689	1.478	-12.51	10.513	17.268	64.25
fl-6.754-2-6-1/5-B2-S6-2b	1.653	1.478	-10.60	10.727	17.268	60.97
double screw spacing with glued sub-floor						
fl-6.754-2-6-1/5-B0-S12-2b-g	1.630	1.478	-9.34	10.910	17.268	58.28
fl-6.754-2-6-1/5-B2-S12-2b-g	1.576	1.478	-6.24	11.200	17.268	54.18
normal screw spacing with blocking at every joist spacing						
fl-6.114-2-6-1/1-B0-S6-2b	1.160	1.208	4.10	12.941	20.701	59.97
fl-6.114-2-6-1/1-B2-S6-2b	1.121	1.208	7.72	13.368	20.701	54.86
fl-6.754-2-6-1/1-B0-S6-2b	1.615	1.478	-8.50	10.651	17.010	59.70
normal screw spacing with glued sub-floor						
fl-4.12-2-6-1/5-B0-S6-2b-g	0.980	0.714	-27.11	15.870	26.218	65.20
fl-4.12-2-6-1/5-B2-S6-2b-g	0.860	0.714	-16.94	18.920	26.218	38.57
fl-6.114-2-6-1/5-B0-S6-2b-g	1.336	1.208	-9.62	13.031	21.047	61.51
fl-6.114-2-6-1/5-B2-S6-2b-g	1.304	1.208	-7.40	13.519	21.047	55.68
fl-6.754-2-6-1/5-B0-S6-2b-g	1.615	1.478	-8.50	10.849	17.268	59.17
fl-6.754-2-6-1/5-B2-S6-2b-g	1.571	1.478	-5.94	11.078	17.268	55.88
normal screw spacing with ceiling						
fl-4.27-2-6-1/5-B0-S6-1b-Ce	N/A			14.160	20.011	41.32
fl-4.27-2-6-1/5-B2-S6-1b-Ce	N/A			15.630	20.011	28.03
fl-6.114-2-6-1/5-B0-S6-2b-Ce	1.163	0.756	-35.03	11.917	20.407	71.24
fl-6.114-2-6-1/5-B2-S6-2b-Ce	1.040	0.756	-27.34	12.314	20.407	65.72
fl-6.754-2-6-1/5-B0-S6-2b-Ce	1.278	0.923	-27.76	9.766	16.735	71.36
fl-6.754-2-6-1/5-B2-S6-2b-Ce	1.234	0.923	-25.18	9.918	16.735	68.74
normal screw spacing with ceiling & gluing						
fl-6.114-2-6-1/5-B0-S6-2b-Ce-g	1.163	0.756	-35.03	11.917	20.407	71.24
fl-6.114-2-6-1/5-B2-S6-2b-Ce-g	1.040	0.756	-27.34	12.314	20.407	65.72

TABLE B2: EVALUATION OF FLOOR VIBRATION PARAMETERS USING ATC'S METHOD

Floor designation	Δ_{test} (mm)	Δ_{ATC} (mm)	% Difference	f_{1_test} (Hz)	f_{1_ATC} (Hz)	% Difference
normal screw spacing with blocking at every five-joist spacing						
fl-4.12-2-6-1/5-B0-S12-2b	1.230	1.080	-12.22	15.260	21.326	39.75
fl-4.12-2-6-1/5-B2-S12-2b	0.980	1.080	10.17	17.090	21.326	24.78
fl-4.27-2-6-1/5-B0-S6-1b	1.340	1.149	-14.26	15.140	19.859	31.17
fl-4.27-2-6-1/5-B2-S6-1b	1.160	1.149	-0.96	16.110	19.859	23.27
fl-4.27-2-6-1/5-B0-S6-3b	1.410	1.18	-16.31	14.040	19.859	41.45
fl-4.27-2-6-1/5-B2-S6-3b	1.090	1.18	8.26	16.480	19.859	20.51
fl-4.74-2-6-1/5-B0-S6-2b	N/A			13.180	16.129	22.37
fl-4.74-2-6-1/5-B2-S6-2b	1.610	1.366	-15.15	14.650	16.129	10.10
fl-5.33-2-6-1/5-B0-S6-2b	1.012	0.880	-13.02	16.342	17.834	9.13
fl-5.33-2-6-1/5-B2-S6-2b	0.943	0.880	-6.65	16.693	17.834	6.83
fl-6.114-2-6-1/5-B0-S6-2b	1.359	1.106	-18.59	12.909	13.570	5.12
fl-6.114-2-6-1/5-B2-S6-2b	1.334	1.106	-17.06	13.245	13.570	2.45
fl-6.754-2-6-1/5-B0-S6-2b	1.689	1.254	-25.77	10.513	11.439	8.81
fl-6.754-2-6-1/5-B2-S6-2b	1.653	1.254	-24.15	10.727	11.439	6.64
double screw spacing with glued sub-floor						
fl-6.754-2-6-1/5-B0-S12-2b-g	1.630	1.254	-23.08	10.910	11.439	4.85
fl-6.754-2-6-1/5-B2-S12-2b-g	1.576	1.254	-20.45	11.200	11.439	2.13
normal screw spacing with blocking. at every joist spacing						
fl-6.114-2-6-1/1-B0-S6-2b	1.160	1.106	-4.62	12.941	13.422	3.72
fl-6.114-2-6-1/1-B2-S6-2b	1.121	1.106	-1.30	13.368	13.422	0.41
fl-6.754-2-6-1/1-B0-S6-2b	1.615	1.254	-22.37	10.651	11.326	6.34
normal screw spacing with glued sub-floor						
fl-4.12-2-6-1/5-B0-S6-2b-g	0.980	1.080	10.17	15.870	21.326	34.38
fl-4.12-2-6-1/5-B2-S6-2b-g	0.860	1.080	25.54	18.920	21.326	12.71
fl-6.114-2-6-1/5-B0-S6-2b-g	1.336	1.106	-17.19	13.031	13.570	4.14
fl-6.114-2-6-1/5-B2-S6-2b-g	1.304	1.106	-15.15	13.519	13.570	0.38
fl-6.754-2-6-1/5-B0-S6-2b-g	1.615	1.254	-22.37	10.849	11.439	5.44
fl-6.754-2-6-1/5-B2-S6-2b-g	1.571	1.254	-20.20	11.078	11.439	3.26
normal screw spacing with ceiling						
fl-4.27-2-6-1/5-B0-S6-1b-Ce	N/A			14.160	19.859	40.25
fl-4.27-2-6-1/5-B2-S6-1b-Ce	N/A			15.630	19.859	27.06
fl-6.114-2-6-1/5-B0-S6-2b-Ce	1.163	1.279	9.94	11.917	11.456	-3.87
fl-6.114-2-6-1/5-B2-S6-2b-Ce	1.040	1.279	22.94	12.314	11.456	-6.97
fl-6.754-2-6-1/5-B0-S6-2b-Ce	1.278	1.469	14.93	9.766	9.655	-1.14
fl-6.754-2-6-1/5-B2-S6-2b-Ce	1.234	1.469	19.03	9.918	9.655	-2.65
normal screw spacing with ceiling & gluing						
fl-6.114-2-6-1/5-B0-S6-2b-Ce-g	0.961	1.279	33.04	12.085	11.46	-5.20
fl-6.114-2-6-1/5-B2-S6-2b-Ce-g	0.911	1.279	40.35	12.405	11.46	-7.65

TABLE B3: EVALUATION OF FLOOR DEFLECTIONS USING SWEDISH METHOD

Floor designation	Δ_{test} (mm)	$\Delta_{Ohlsson}$ (mm)	% Difference	f_{1_test} (Hz)	$f_{1\_Ohlsson}$ (Hz)	% Difference
normal screw spacing with blocking at every five-joist spacing						
fl-4.12-2-6-1/5-B0-S12-2b	1.230	3.54	187.44	15.260	27.709	81.58
fl-4.12-2-6-1/5-B2-S12-2b	0.980	3.54	260.77	17.090	27.709	62.14
fl-4.27-2-6-1/5-B0-S6-1b	1.340	3.94	193.73	15.140	25.804	70.44
fl-4.27-2-6-1/5-B2-S6-1b	1.160	3.94	239.31	16.110	25.804	60.17
fl-4.27-2-6-1/5-B0-S6-3b	1.410	3.94	179.15	14.040	25.405	80.95
fl-4.27-2-6-1/5-B2-S6-3b	1.090	3.94	261.10	16.480	25.405	54.16
fl-4.74-2-6-1/5-B0-S6-2b	N/A			13.180	20.957	59.01
fl-4.74-2-6-1/5-B2-S6-2b	1.610	5.38	234.41	14.650	20.957	43.05
fl-5.33-2-6-1/5-B0-S6-2b	1.012	2.93	189.18	16.342	21.699	32.78
fl-5.33-2-6-1/5-B2-S6-2b	0.943	2.93	210.34	16.693	21.699	29.99
fl-6.114-2-6-1/5-B0-S6-2b	1.359	4.42	225.03	12.909	15.825	22.59
fl-6.114-2-6-1/5-B2-S6-2b	1.334	4.42	231.12	13.245	15.825	19.48
fl-6.754-2-6-1/5-B0-S6-2b	1.689	5.95	252.55	10.513	12.978	23.45
fl-6.754-2-6-1/5-B2-S6-2b	1.653	5.95	260.23	10.727	12.978	20.99
double screw spacing with glued sub-floor						
fl-6.754-2-6-1/5-B0-S12-2b-g	1.630	5.95	265.31	10.910	12.978	18.96
fl-6.754-2-6-1/5-B2-S12-2b-g	1.576	5.95	277.83	11.200	12.978	15.88
normal screw spacing with blocking at every joist spacing						
fl-6.114-2-6-1/1-B0-S6-2b	1.160	4.42	280.79	12.941	15.653	20.96
fl-6.114-2-6-1/1-B2-S6-2b	1.121	4.42	294.04	13.368	15.653	17.09
fl-6.754-2-6-1/1-B0-S6-2b	1.615	5.95	268.70	10.651	12.978	21.85
normal screw spacing with glued sub-floor						
fl-4.12-2-6-1/5-B0-S6-2b-g	0.980	3.54	260.77	15.870	36.460	129.74
fl-4.12-2-6-1/5-B2-S6-2b-g	0.860	3.54	311.11	18.920	36.460	92.71
fl-6.114-2-6-1/5-B0-S6-2b-g	1.336	4.42	230.63	13.031	15.825	21.44
fl-6.114-2-6-1/5-B2-S6-2b-g	1.304	4.42	238.74	13.519	15.825	17.06
fl-6.754-2-6-1/5-B0-S6-2b-g	1.615	5.95	268.70	10.849	12.978	19.63
fl-6.754-2-6-1/5-B2-S6-2b-g	1.571	5.95	279.03	11.078	12.978	17.15
normal screw spacing with ceiling						
fl-4.27-2-6-1/5-B0-S6-1b-Ce	N/A			14.160	25.405	79.41
fl-4.27-2-6-1/5-B2-S6-1b-Ce	N/A			15.630	25.405	62.54
fl-6.114-2-6-1/5-B0-S6-2b-Ce	1.163	4.42	279.81	11.917	17.719	48.69
fl-6.114-2-6-1/5-B2-S6-2b-Ce	1.040	4.42	324.73	12.314	17.719	43.89
fl-6.754-2-6-1/5-B0-S6-2b-Ce	1.278	5.95	365.93	9.766	14.528	48.76
fl-6.754-2-6-1/5-B2-S6-2b-Ce	1.234	5.95	382.54	9.918	14.528	46.48
normal screw spacing with ceiling & gluing						
fl-6.114-2-6-1/5-B0-S6-2b-Ce-g	0.961	4.42	359.64	12.085	17.719	46.62
fl-6.114-2-6-1/5-B2-S6-2b-Ce-g	0.911	4.42	384.87	12.405	17.719	42.84

Table B4: Evaluation of Floor Vibration Parameters using Australian Method

Floor designation	Δ_{test} (mm)	Δ_{AUST} (mm)	% Difference
normal screw spacing with blocking at every five-joist spacing			
fl-4.12-2-6-1/5-B0-S12-2b	1.230	1.663	35.20
fl-4.12-2-6-1/5-B2-S12-2b	0.980	1.663	69.69
fl-4.27-2-6-1/5-B0-S6-1b	1.340	1.770	32.10
fl-4.27-2-6-1/5-B2-S6-1b	1.160	1.770	52.60
fl-4.27-2-6-1/5-B0-S6-3b	1.410	1.770	25.54
fl-4.27-2-6-1/5-B2-S6-3b	1.090	1.770	62.40
fl-4.74-2-6-1/5-B0-S6-2b	N/A		
fl-4.74-2-6-1/5-B2-S6-2b	1.610	2.096	30.17
fl-5.33-2-6-1/5-B0-S6-2b	1.012	1.291	27.61
fl-5.33-2-6-1/5-B2-S6-2b	0.943	1.291	36.95
fl-6.114-2-6-1/5-B0-S6-2b	1.359	1.543	13.52
fl-6.114-2-6-1/5-B2-S6-2b	1.334	1.543	15.64
fl-6.754-2-6-1/5-B0-S6-2b	1.689	1.733	2.60
fl-6.754-2-6-1/5-B2-S6-2b	1.653	1.733	4.84
double screw spacing with glued sub-floor			
fl-6.754-2-6-1/5-B0-S12-2b-g	1.630	1.733	6.31
fl-6.754-2-6-1/5-B2-S12-2b-g	1.576	1.733	9.96
normal screw spacing with blocking at every joist spacing			
fl-6.114-2-6-1/1-B0-S6-2b	1.160	1.543	32.99
fl-6.114-2-6-1/1-B2-S6-2b	1.121	1.543	37.62
fl-6.754-2-6-1/1-B0-S6-2b	1.615	1.594	-1.33
normal screw spacing with glued sub-floor			
fl-4.12-2-6-1/5-B0-S6-2b-g	0.980	1.663	69.68
fl-4.12-2-6-1/5-B2-S6-2b-g	0.860	1.663	93.36
fl-6.114-2-6-1/5-B0-S6-2b-g	1.336	1.543	15.47
fl-6.114-2-6-1/5-B2-S6-2b-g	1.304	1.543	18.30
fl-6.754-2-6-1/5-B0-S6-2b-g	1.615	1.733	7.30
fl-6.754-2-6-1/5-B2-S6-2b-g	1.571	1.733	10.31
normal screw spacing with ceiling			
fl-4.27-2-6-1/5-B0-S6-1b-Ce	N/A		
fl-4.27-2-6-1/5-B2-S6-1b-Ce	N/A		
fl-6.114-2-6-1/5-B0-S6-2b-Ce	1.163	1.846	58.69
fl-6.114-2-6-1/5-B2-S6-2b-Ce	1.040	1.846	77.46
fl-6.754-2-6-1/5-B0-S6-2b-Ce	1.278	2.143	67.70
fl-6.754-2-6-1/5-B2-S6-2b-Ce	1.234	2.143	73.68
normal screw spacing with ceiling & gluing			
fl-6.114-2-6-1/5-B0-S6-2b-Ce-g	0.961	1.846	92.05
fl-6.114-2-6-1/5-B2-S6-2b-Ce-g	0.911	1.846	102.59

TABLE B5: ACCEPTABILITY OF ALL TESTED FLOOR'S ACCORDING TO THE VARIOUS METHODS

Description	Floor designation	ATC (Y/N)	CWC (Y/N)	Swedish (Y/N)	Australian (Y/N)	Johnson (Y/N)
normal screw spacing with blocking at every five-joist spacing						
ATC floor	fl-4.12-2-6-1/5-B0-S12-2b	Y	Y	Y	Y	Y
	fl-4.12-2-6-1/5-B2-S12-2b	Y	Y	Y	Y	Y
L/480 living room	fl-4.27-2-6-1/5-B0-S6-1b	N	N	Y	Y	Y
	fl-4.27-2-6-1/5-B2-S6-1b	Y	Y	Y	Y	Y
	fl-4.27-2-6-1/5-B0-S6-3b	N	N	Y	Y	N
	fl-4.27-2-6-1/5-B2-S6-3b	Y	Y	Y	Y	Y
L/480 bed room	fl-4.74-2-6-1/5-B0-S6-2b	N/A	N/A	N/A	N/A	N
	fl-4.74-2-6-1/5-B2-S6-2b	N	N	N	Y	N
ATC floor	fl-5.33-2-6-1/5-B0-S6-2b	N	N	Y	Y	Y
	fl-5.33-2-6-1/5-B2-S6-2b	Y	N	Y	Y	Y
L/480 living room	fl-6.114-2-6-1/5-B0-S6-2b	N	N	Y	Y	N
	fl-6.114-2-6-1/5-B2-S6-2b	N	N	Y	Y	N
L/480 bed room	fl-6.754-2-6-1/5-B0-S6-2b	N	N	N	Y	N
	fl-6.754-2-6-1/5-B2-S6-2b	N	N	N	Y	N
double screw spacing with glued sub-floor						
L/480 bed room	fl-6.754-2-6-1/5-B0-S12-2b-g	N	N	N	Y	N
	fl-6.754-2-6-1/5-B2-S12-2b-g	N	N	N	Y	N
normal screw spacing with blocking at every joist spacing						
L/480 living room	fl-6.114-2-6-1/1-B0-S6-2b	N	N	Y	Y	N
	fl-6.114-2-6-1/1-B2-S6-2b	N	N	Y	Y	N
L/480 bed room	fl-6.754-2-6-1/1-B0-S6-2b	N	N	N	Y	N
normal screw spacing with glued sub-floor						
ATC floor	fl-4.12-2-6-1/5-B0-S6-2b-g	Y	Y	Y	Y	Y
	fl-4.12-2-6-1/5-B2-S6-2b-g	Y	Y	Y	Y	Y
L/480 living room	fl-6.114-2-6-1/5-B0-S6-2b-g	N	N	Y	Y	N
	fl-6.114-2-6-1/5-B2-S6-2b-g	N	N	Y	Y	N
L/480 bed room	fl-6.754-2-6-1/5-B0-S6-2b-g	N	N	N	Y	N
	fl-6.754-2-6-1/5-B2-S6-2b-g	N	N	N	Y	N
normal screw spacing with ceiling						
L/480 living room	fl-6.114-2-6-1/5-B0-S6-2b-Ce	N	N	Y	Y	N
	fl-6.114-2-6-1/5-B2-S6-2b-Ce	N	N	Y	Y	N
L/480 bed room	fl-6.754-2-6-1/5-B0-S6-2b-Ce	N	N	Y	Y	N
	fl-6.754-2-6-1/5-B2-S6-2b-Ce	N	N	Y	Y	N
normal screw spacing with ceiling & gluing						
L/480 living room	fl-6.114-2-6-1/5-B0-S6-2b-Ce-g	N	N	N	Y	N
	fl-6.114-2-6-1/5-B2-S6-2b-Ce-g	N	N	N	Y	N
	Number of "Y"	7/30	6/30	20/30	30/30	9/30
	Number of "N"	23/30	24/30	10/30	0/30	21/30