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DYNAMIC BEHAVIOUR OF FLOORS WITH COLD-FORMED STEEL JOISTS

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SUMMARY

Presented in this paper are the results of a recent study carried out at the University of Waterloo on the performance of residential floors supported by cold-formed steel C-section floor joists. Both static and dynamic tests were conducted on steel floors with different span lengths based on different design criteria. The purpose of the static tests was to evaluate the stiffness and load sharing among the joists, and the purpose of the dynamic tests was to evaluate the dynamic characteristics such as frequencies of the floor systems. To identify the critical parameters that contribute to the control of floor vibration, tests were also carried out on floors without attached ceiling materials, with different bridging and blocking patterns, and with different support conditions. Test results are presented in comparison with the analytical results obtained from different design models.

INTRODUCTION

Cold-formed steel has been used extensively as structural elements in residential and commercial construction in North America in recent years. As an alternative to wood construction, galvanised cold-formed steel provides an efficient and economical structural system. There are many advantages and benefits for using cold-formed steel in both residential and commercial construction over conventional wood construction. With the superior strength of steel, longer spanning and lighter weight is available for floor systems supported by cold-formed C-section floor joists. Compared to traditional wood floor systems, steel-framed floor systems are usually lighter and have less inherent damping. Therefore, floor vibration due to human activities such as walking becomes a concern in the selection and design of cold-formed steel floor systems. Thus,

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the evaluation of the vibration performance of floors using cold-formed steel joists due to human induced dynamic loads must be considered. To ensure the serviceability and comfort of the occupants, the most efficient and economical approach is to address this requirement in the design phase of the floor systems.

Floor vibration as a serviceability criterion has not been well addressed in North America for residential floor design. Current practice is based on 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.

Research on floor vibration in buildings is limited. The current criterion for timber floors contained in the National Building Code of Canada (1995) is based on the results of an extensive field study conducted in the 1970's (Onysko, 1985). The Swedish Council for Building Research published a design guide with the intention to limit floor vibration for all floor construction (Ohlsson, 1988). The Australian Standard for Domestic Metal Framing (1993) uses much of the criterion proposed by Ohlsson. Johnson (1994) developed a design criterion for timber floors. The Steel Joist Institute (SJI) developed a computer program to evaluate the vibration of open web steel joist-concrete slab floor systems (Galambos, 1988). AISC and CISC (Murray et al., 1997) published a steel design guide for *Floor Vibration due to Human Activity* based on the design procedure proposed by Allen and Murray (1993).

Recently, 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 test results. The report also points out that a method of predicting the floor deflection at mid-span is necessary to implement the recommended criterion. Among the existing three methods for estimating the number of effective joists that contribute to the floor deflection, it was found that the SJI method correlated best with the test results. A design procedure for vibration caused by normal occupant activities, which combines the Canadian Criterion with the SJI equation, was proposed for the evaluation of C-shaped cold-formed steel joists supporting residential floor systems.

Presented in this paper are the results of a recent study carried out at the University of Waterloo on the performance of residential floors supported by cold-formed steel C-section floor joists. Both static and dynamic tests were conducted on steel floors with different span lengths based on different design criteria. The purpose of the static tests was to evaluate the stiffness and load sharing among the joists, and the purpose of the dynamic tests was to evaluate the dynamic characteristics such as frequencies of the floor systems. To identify the critical parameters that contribute to the control of floor vibration, tests were also carried out on floors without attached ceiling materials, with different bridging and blocking patterns, and with different support conditions. Test results are presented in comparison with the analytical results obtained from different design models.

DESCRIPTION OF FLOOR SYSTEMS

The three full-scale floor systems tested are described as follows.

- **Basic floor system**

  With the floor span of 5000 mm (16.4 ft), all of the floor-joist design criteria including strength, deflection, and vibration are violated. The intention of investigating this system is to provide a base for comparative study of other systems.

- **L/480 bedroom floor system**

  The floor span was 4740 mm (15.6 ft), which is based on a deflection limit of *L*/480 under a specified live load of 1.4 kPa (30 lb/ ft^2).

- **L/480 living room floor system**

  The floor span was 4270 mm (14.0 ft), which is based on a deflection limit of *L*/480 under a specified live load of 1.9 kPa (40 lb/ ft^2).

The floor contained twelve C-section joists (C-203×41×1.22 mm) 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. Fasteners 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 original floor was simply supported by bearing on a 4×4 in. wood plate on each side, and the two free edges of the floor parallel to the joists were not supported. One row of strapping (58×1.44 mm) was placed at mid-span of the joists with a 6 in. (152 mm) channel blocking placed at every six joist-spacing (Figure 1).

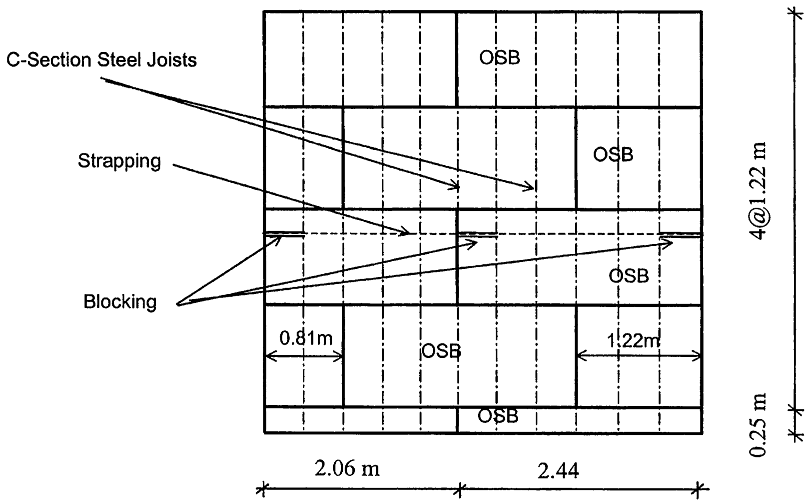


Figure 1. Floor layout (fl-5.0-2-6"-1/5-B0)

The joist ends were connected with a rim-track section (203×41×1.22 mm) and the rim-tracks were fastened to the 4×4 in. wood plates and bearing stiffeners were placed at every joist-track connection (Figure 2).

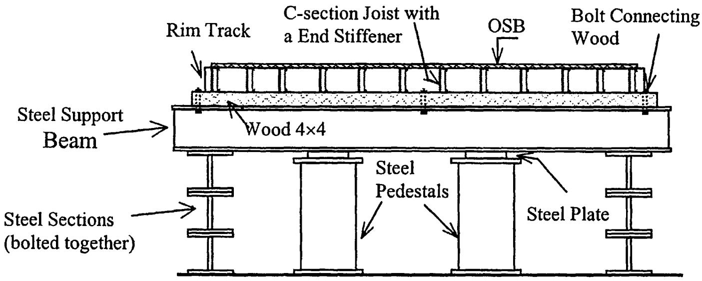


Figure 2. End detail of floor set-up (fl-5.0-2-6"-1/5-B0)

Several variations of the floor configuration were investigated to determine their effect on the dynamic behaviour of the floor system, as follows.

- **Blocking type:** The two types of solid blocking were made of 6 in. and 8 in. cold-formed steel channel sections, listed in the Steel Framing Installation Manual (CSSBI, 2000).
- **Blocking patterns:** Of the two blocking patterns were tested, one was positioned at every six joist spacing and the other was positioned at every joist spacing.
- **Supported conditions:** Two different support conditions were tested, i.e., one with two reaction supports and the other with four reaction supports.
- **Joist end rotation condition:**

  B0: The joist ends of the original floor were simply supported (B0).

  B2: To simulate the rotation restraints provided by a stud wall, a 4.5 m (14.8 ft) long WWF300×110 steel beam with 1×4 wood bearing plates was placed on top of the floor at each supported edge. Two 5.9 m (19.4 ft) long W200×27 beams were connected perpendicular to the two WWF300×110 beams to stabilize the restraining beams (Figure 3). The uniformly distributed line load due to the W200×27 and WWF300×110 beams was 1.43 kN/m (98 lb/ft).

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

fl - *span length – support conditions - blocking type - blocking pattern - joist end support condition*

For example, the designation of **fl-5.0-2-6"-1/5-B0** represents the floor assembly with a joist span length of 5.0 m, only two joist-end edges were supported, solid blocking was a 6 in. channel section, the blocking was at every sixth joist spacing, and no restraining beams were used.

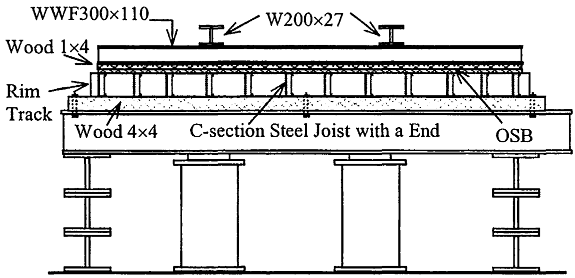


Figure 3. End details of floor set-up (fl-5.0-2-6"-1/5-B2)

TEST METHODS

Static Loading Test

Floor deflection due to a static concentrated load has long been recognized as an acceptable indication of floor vibration performance (Ohlsson, 1988; Onysko, 1985). A concentrated load P=1000 N (225 lb) was placed at the center of the floor. The deflection of the floor was measured using mechanical dial gages. Considering the symmetry of the floor, only one quarter of the floor was measured, as shown in Figure 4. Location 0 was placed at the center of the floor. Along the *X*-axis, locations 1 to 4 were measured from underneath of the sub-floor, while locations *j*1-*j*4 were measured underneath the joists. In the *Y*-axis direction, dial gages were placed underneath the joists at locations 0 to A'. The deflection at the free edge was measured at locations 1' to 4', with dial gages placed underneath the joists. The support reactions of the floor were measured by load cells, which were located at one end of the joists. Reaction data was collected directly via computer software LabView.

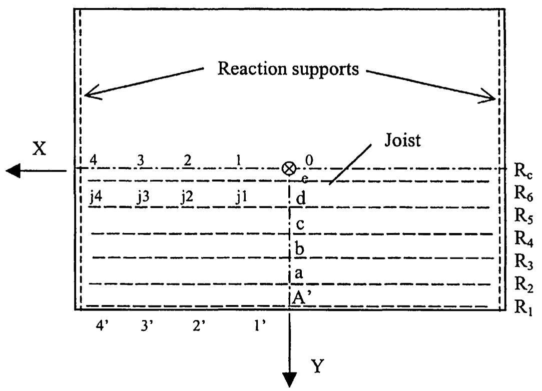


Figure 4. Distribution of measured points of floor

Impact Tests

The three types of dynamic loading usually applied in lab tests are weight drop impact, heel drop impact, and walking.

- *Weight drop impact:* A 10 kg (22 lb) sandbag was dropped at the center of the floor. The sandbag was hung on a crane and released at a height of 0.33 m (1 ft) from the floor. The dynamic response of the floor was recorded using accelerometers placed on the sub-floor.
- *Heel drop Impact:* A heel drop was performed by a 80 kg (176 lb) person standing at the center of the floor.
- *Walking:* Walking tests were performed by a person walking across the floor. The response of the floor was recorded using accelerometers placed on the sub-floor.

In order to describe the dynamic characteristics of the floor systems under impact loading quantitatively, some test results of the floor systems under weight drop impact are presented.

(1) Data Acquisition

The dropping position was at the center of the floor and the response of the floor was measured with a piezoelectric accelerometer located at different locations. During weight dropping, the dynamic response of the floor was measured by an accelerometer (k_a=101.4 or 104.6 mv-pk/g-pk) and was recorded using a Nicolet Digital Oscilloscope. For data acquisition, the number of sampling points for the tests were set to be between 2000 and 5000 and sampling frequencies were 1000-2500 Hz, resulting in a sampling duration between 2 to 4 seconds.

(2) Response of Floor Systems

Figures 5a and 5b show typical responses of the acceleration of the floor system as a function of time, which is commonly referred to as "time traces".

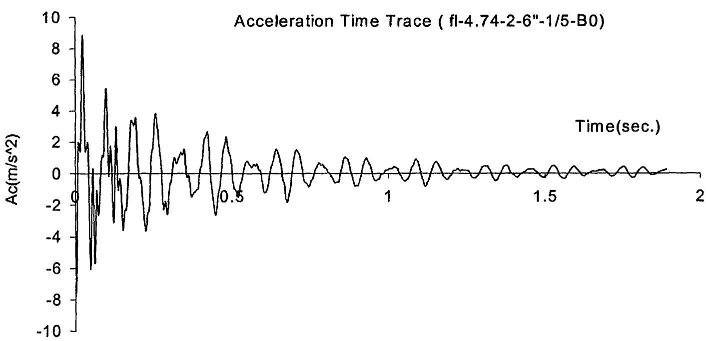


Figure 5 (a). Typical time trace of acceleration of floor system

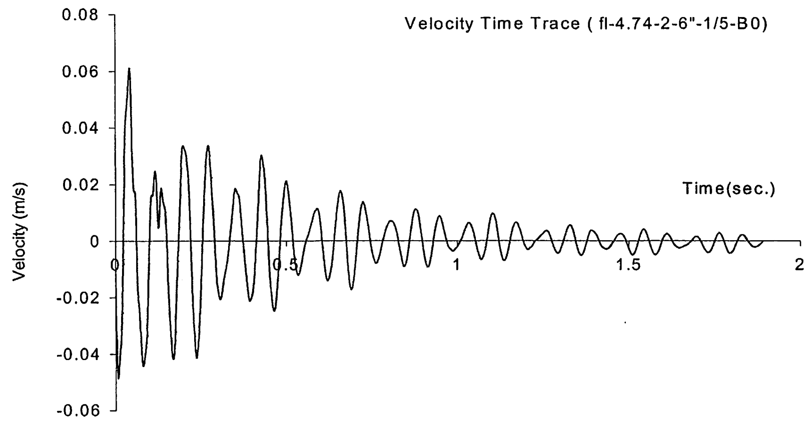


Figure 5(b). Typical velocity time trace of floor system

(3) Power Spectrum Density (PSD) of Floor System

Fast Fourier Transforms (FFT) were applied to obtain frequency spectrums of the floor response, from which the natural frequencies of the floor systems could be obtained. Figure 6 shows the Fourier frequency spectra of the floor responses measured at different locations along the Y-axis of the floor in weight-dropping tests. For the same structure, its fundamental frequency obtained from the frequency spectrum is independent of the location of the measured point. Figure 7 shows the power spectrum densities of the same structure from which the natural frequencies of the floor system can be easily determined. The different power spectrum densities are influenced by the different locations of the measurements.

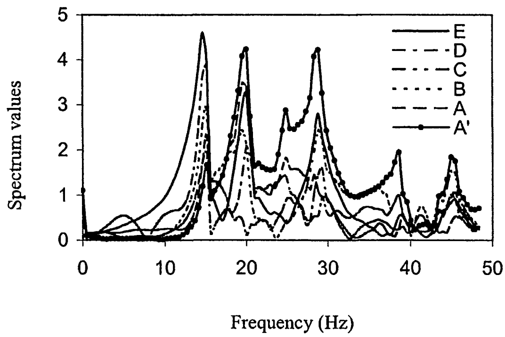


Figure 6. Fourier spectrum along the Y-axis (fl-4.27-2-6"-1/5-B0)

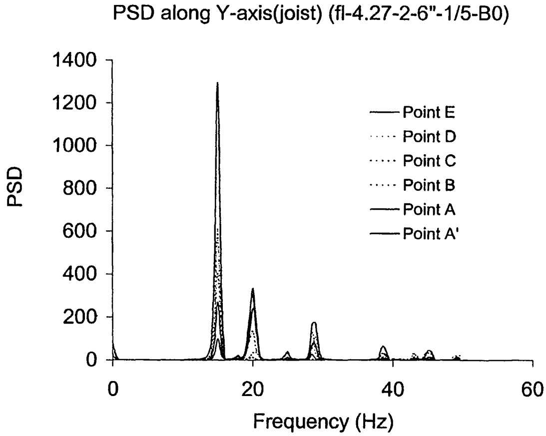


Figure 7. Power spectrum density distribution along the Y-axis

Shown in Figure 8 is the effect of the weight-dropping height with regard to the resulting acceleration responses of floor system (fl-5.00-2-6"-1/5-B2). The results illustrate that, at the same point on the floor, the maximum acceleration of the floor is associated with the total energy of the impact load. In other words, the acceleration of the floor was proportional to the height of weight dropping. In the current investigation, the same dropping height of 0.33 m (1 ft) was maintained in the impact tests.

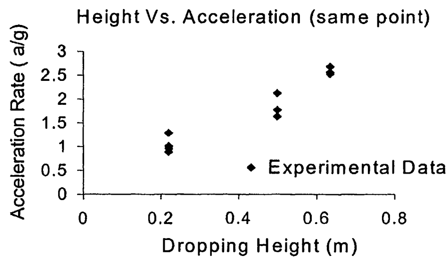


Figure 8. Weight-dropping height vs. acceleration response of floor system (fl-5.00-2-6"-1/5-B2)

RESULTS AND DISCUSSION

Impact Loading

(1) Natural Frequencies of Floor Systems

Effect of Support Rotation Restraint: Summarized in Table 1 are the frequencies of the floor systems with and without the two restraining beams in the weight drop impact tests. Adding two restraining beams at the sides of these floor systems has changed the natural frequencies of these floor systems. For the two sides of the simply supported floor systems fl-5.0-2-6"-1/5-B0, the natural frequencies are 13 Hz without the restraining beams and 14 Hz with the restraining beams. Further increasing the weight of the restraining beams has no significant effect on the frequency. Changing the supports from two sides to four sides, say fl-5.0-2-6"-1/5-B0 and fl-5.0-4-6"-1/5-B2, the frequency would change from 13.Hz to 13.5 Hz. For the floors with span lengths of 4.74 m (15.6 ft) and 4.27 m (14 ft), adding the restraining beams at the two sides also changed the natural frequencies of the floor systems.

Table 1. The first three frequencies of floor systems under weight drop impact

Floor	Span (l)	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)
fl-5.00-2-6"-1/5-B0	5.00 m	12.21	16.11	25.88
fl-5.00-2-6"-1/5-B2	5.00 m	13.92	18.55	26.37
fl-5.00-4-6"-1/5-B0	5.00 m	13.67	18.55	24.41
fl-4.74-2-6"-1/5-B0	4.74 m	13.18	18.07	25.39
fl-4.74-2-6"-1/5-B2	4.74 m	14.65	19.04	26.37
fl-4.74-4-6"-1/5-B0	4.74 m	13.67	20.51	32.22
fl-4.74-4-6"-1/5-B2	4.74 m	15.14	23.44	37.11
fl-4.27-2-6"-1/5-B0	4.27 m	15.14	20.02	28.81
fl-4.27-2-6"-1/5-B2	4.27 m	16.11	22.46	29.79
fl-4.27-2-8"-1/5-B0	4.27 m	15.14	20.02	30.76
fl-4.27-2-8"-1/5-B2	4.27 m	16.11	22.46	29.79

Influence of Floor System Span Length: The natural frequencies of the floor systems change as the span length of the floor system changes, as shown in Table 2. The third frequency of these floor systems seems to change more significantly than the first and second frequencies when the floor span length changes.

Influence of Blocking Type: As shown in Table 3, the frequencies of floor systems do not change significantly when the blocking arrangement is changed. It seems that adding restraint to the supports of a floor system would increase the natural frequencies of the floor system only slightly.

Table 2. Influence on frequencies due to different span lengths

Floor	Span (l)	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)
fl-5.0-2-6"-1/5-B0	5.00 m	12.21	16.11	25.88
fl-4.74-2-6"-1/5-B0	4.74 m	13.18	18.07	25.39
fl-4.27-2-6"-1/5-B0	4.27 m	15.14	20.02	28.81

Table 3. Influence on frequencies due to different blocking arrangements

Floor	Blocking	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)
fl-4.27-2-6"-1/5-B0	6"-1/5	15.14	20.02	28.81
fl-4.27-2-8"-1/5-B0	8"-1/5	15.14	20.02	30.76
fl-4.27-2-6"-1/5-B2	6"-1/5	16.11	22.46	27.79
fl-4.27-2-8"-1/5-B2	8"-1/5	16.11	22.46	29.79

(2) Power Spectrum Densities (PSD) of Different Floor Systems

As mentioned above, the acceleration measured using accelerometers is related to the height of dropping weight, that is, related to the energy of the floor system under weight dropping. The power spectrum density characterizes how energy distributes in the frequency domain for the floor system vibration. The highest value of the power spectrum density indicates that the energy of the system is concentrated at the corresponding frequency, which is called the fundamental frequency of the system. For different measuring locations of the same floor system, the accelerations obtained using accelerometers and the power spectrum densities are different. However, for the same floor system, the fundamental frequency and the frequency domain distribution do not vary with measuring locations. Some typical PSD distributions are shown in Figures 9-11 for different floor systems.

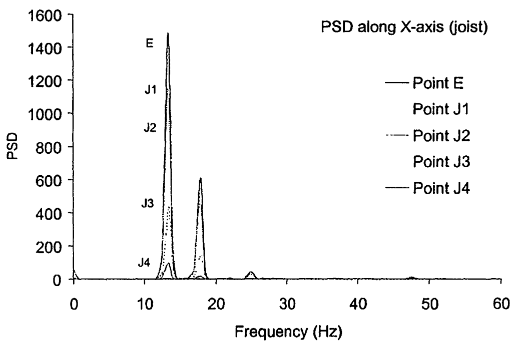


Figure 9. PSD of floor system fl-4.74-2-6"-1/5-B0

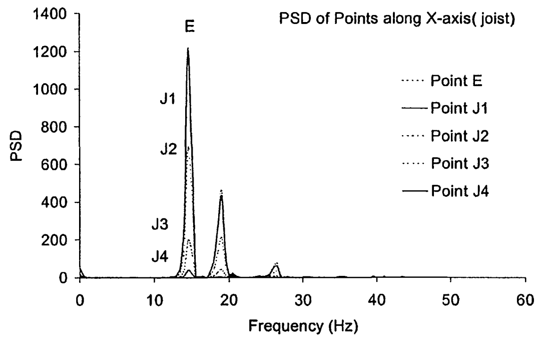


Figure 10. PSD of floor system fl-4.74-2-6"-1/5-B2

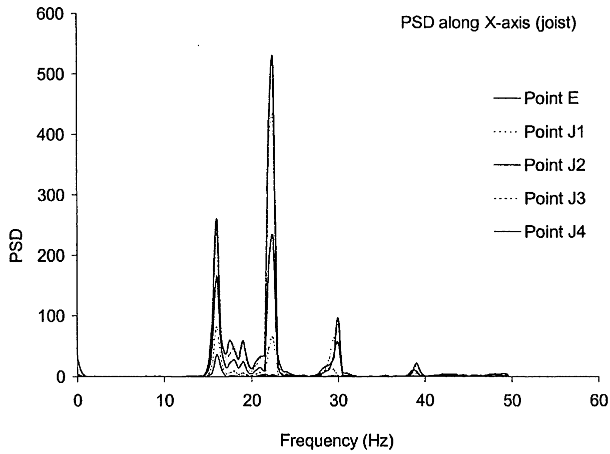


Figure 11 (a). PSD of floor system along one joist (fl-4.27-2-6"-1/5-B2)

In the power spectrum densities of almost all floor systems in the current investigation, there are several dominant peaks noticeable. Usually, the largest peak is representative to the fundamental frequency of the floor system. It means that most of the energy of the floor system during vibration is concentrated at this frequency. For floor systems with different span lengths, the largest peak corresponds to the first frequency, f_1 (see Figures 9-10). For some other floor systems, the largest peak corresponds to the second frequency, f_2, and their frequency spectrum domains are wider (Figures 11(a) and (b)). Figure 11(a) shows the PSD at different locations along one joist of the floor system (fl-4.27-2-6"-1/5-B2). The values of the PSD distributions are different, as the measuring locations are different. However, the shapes of the PSD distributions are in unison since these measuring locations are under the same joist. Figure 11(b) shows the PSD distribution obtained from measurements at different joists in the same floor system. The PSD distributions in Figure 11(b) are slightly different from those in Figure 11(a). It may be partly due to the fact that these joists in the floor system did not move in unison during one impact excitation, which leads to the dominant frequency being the second frequency instead of the first frequency. Furthermore, for different floor systems, the PSD distribution and the dominant frequency may change as the structure changes.

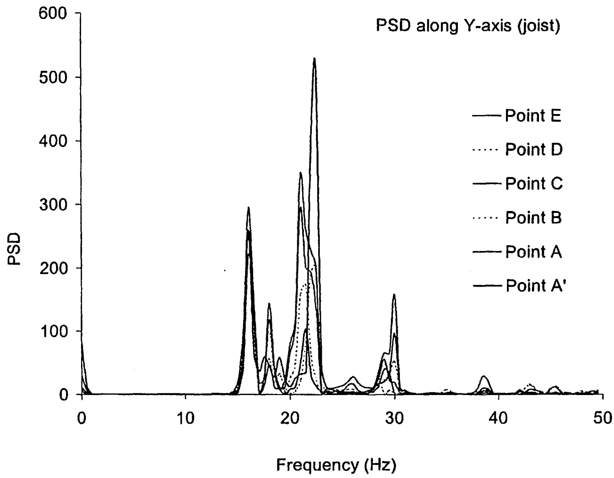


Figure 11 (b). PSD of floor system at different joists along Y-axis (fl-4.27-2-6”-1/5-B2)

Static Loading [*P* = 1000N (225 lb)]

(1) Deflection

Deflections of floor systems are sensitive to any changes to the floor structure, such as rotation restraint of the supports, changing the blocking arrangement, reducing the span length of the floor system. Usually, any change to the floor system would influence the deflection of the floor system, as changing any of these parameters of the floor system would change the stiffness of the floor system. This is evident from the typical test results of different floor systems as shown in Figures 12-15.

- **Effect of Support Rotation Restraint**

The deflections of the floor systems were restrained at different levels by adding two small steel beams at the two supports of the floor systems. Figures 12, 13(a), and 14(a) show the mid-span deflection profiles, i.e. deflection of the mid-point of different joists along the Y-axis. Figures 13(b) and 14(b) are the deflections along one joist, i.e. along the X-axis. These different deflection profiles illustrate the influence of the stiffness in two different directions of the floor system to the deflections.

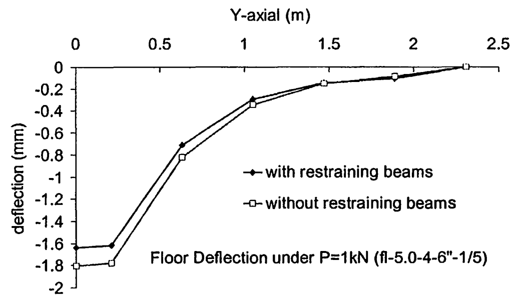
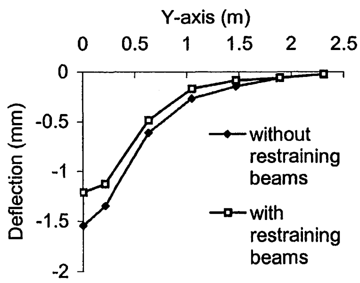
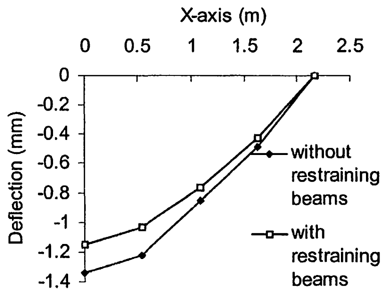


Figure 12. Effect of support rotation restraint vs. deflection along Y-axis



(a) Deflection along Y-axis

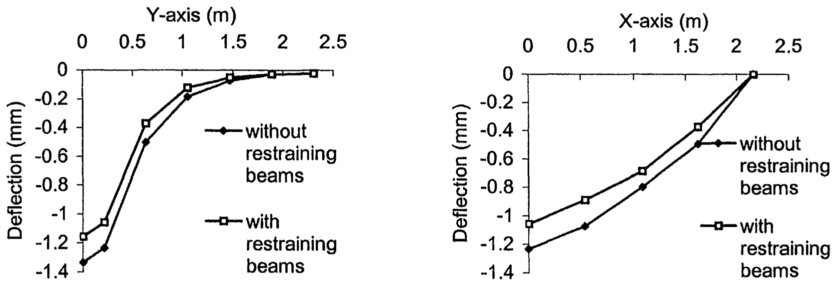


(b) Deflection along X-axis

Figure 13. Deflections of floor system (fl-4.27-2-6"-1/5)

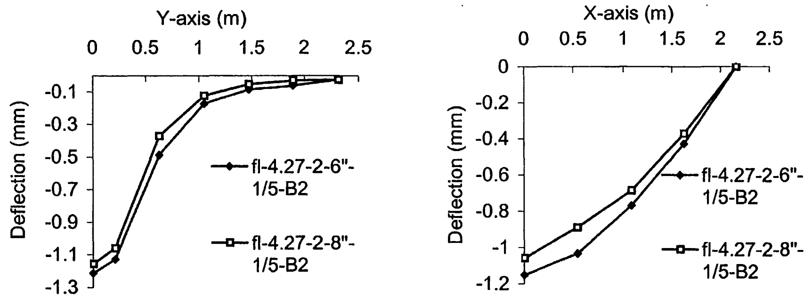
- **Influence of Blocking**

Changing the manner of blocking will restrain the deflection of the floor system. Figure 15 shows the measured deflections of the floor systems under loading $P = 1000N$ (225 lb). Figure 15(a) shows the deflection profiles at mid-span of the floor systems, and Figure 15(b) shows the deflection profiles of points of the same joist along the X-axis. Along both the Y-axis and X-axis, the deflections of the floor system with 8 in.-1/5 blocking are smaller than those of the floor system with 6 in.-1/5 blocking.



(a) Deflection along Y-axis (b) Deflection along X-axis

Figure 14. Deflections of floor system (fl-4.27-2-8"-1/5)



(a) Deflection along Y-axis (b) Deflection long X-axis

Figure 15. Deflection of floor system with 6 in. and 8 in. blocking

- **Influence of Floor Span**

Table 5 shows the maximum deflections of joist R6 of different span lengths under the 1000 N (225 lb) concentrated load.

(2) Reactions

Figures 16 and 17 show the reaction distributions of the floor systems with different blockings and span lengths.

Table 5. Deflection of joist at mid-span

Floor System	$\Delta_{max\text{-}joist}$ (mm)	$\Delta_{max\text{-}joist}$ / L_{span} (10^{-4})
fl-5.00-2-6"-1/5-B0	1.79	3.58
fl-5.00-2-6"-1/5-B2	1.68	3.36
fl-4.74-2-6"-1/5-B2	1.61	3.40
fl-4.27-2-6"-1/5-B0	1.34	3.13
fl-4.27-2-6"-1/5-B2	1.15	2.69
fl-4.27-2-8"-1/5-B0	1.23	2.88
fl-4.27-2-8"-1/5-B2	1.05	2.46

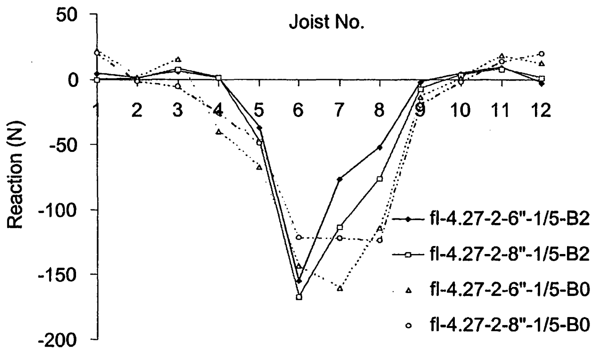


Figure 16. Reactions of floor systems with different blockings

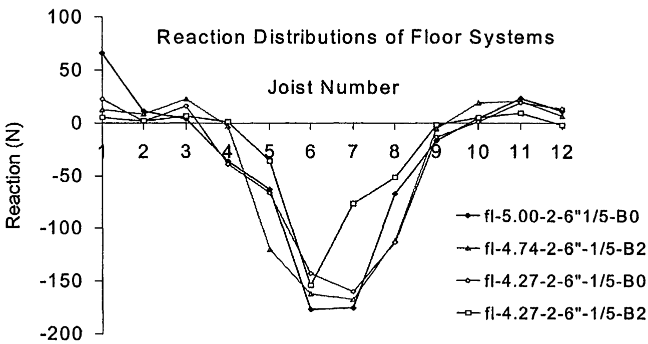


Figure 17. Reaction distributions of floor systems with different spans

CONCLUSIONS

In this paper, the results of a recent study of the performance of residential floors supported by cold-formed steel C-section floor joists are presented. Both static and dynamic tests were conducted of cold-formed steel floors with different span lengths that were based on different design criteria.

It was found that adding two restraining beams at two sides of the floor systems changed the natural frequencies of these floor systems. However, further increase of the weight of restraining had no significant effects on the frequency. The natural frequencies of the floor systems increased as the span length of the floor system was reduced. It was found that the frequencies of floor systems did not change significant when the blocking details were changed.

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