

FLOOR VIBRATION DESIGN CRITERION FOR COLD-FORMED C-SHAPED SUPPORTED RESIDENTIAL FLOOR SYSTEMS

by

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

CIVIL ENGINEERING

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February 1997

Blacksburg, VA 24061

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(ABSTRACT)

Annoying floor vibration due to normal human activity was investigated for cold-formed C-shaped residential floors systems. Dynamic impact and static loading tests were performed on twelve full size laboratory floors and five two-joist line laboratory floors to determine the influencing characteristics of annoying vibrations in metal framed floors. Similar tests were conducted on eleven floors located in existing houses. Subjective evaluation, in terms of annoying vibration levels, of all floors was recorded.

Four existing floor vibration criteria were investigated: 1) *Australian Standard. Domestic Metal Framing Code*, 2) Swedish Building Technology Design Guide developed by Professor Sven Ohlsson, 3) United States Proposed Timber Floor Vibration Criterion developed by Johnson, and 4) Canadian Timber Floor Criterion developed by Donald Onysko. Data collected from testing was used to determine which of the four existing criteria best classified the perceived vibration level of the floors. One criterion is suggested as the most suitable for predicting the perceived vibration level of metal framed residential floors.

Three methods to predict the vertical deflection of a floor subject to a concentrated load at mid-bay were examined. The results of applying these methods to the laboratory floors were compared to the actual measured values. The method which correlated the best with the measured values was selected for use in the proposed criterion.

ACKNOWLEDGMENTS

I would thank Dr. Murray for his support, patience and guidance throughout the development of this thesis. Thanks are also due to Dr. Easterling and Dr. Plaut for serving on my committee.

I must also thank the National Association of Home Builders, the sponsor of the project, for their financial support.

Thanks go to Dennis Huffman and Brett Farmer, without their help I would still be in the laboratory building the first floor. I would also like to thank Ric Anderson and George Smith for their help with the testing and with their endless lifting of sand bags. Thanks, as well, must go to all my labmates who filled out a survey or helped to further this research in other ways.

I would like to thank Michelle Rambo-Roddenberry and Vickie Mouras for their constant support and encouragement. Extra thanks go to Michelle and Thomas for allowing me to invade their home while I finished my thesis.

Special thanks goes to Michael Otegui, without whom my time at Virginia Tech would be much less eventful and less memorable. His understanding and encouragement has been greatly appreciated.

Finally, I need to thank my family for their never ending belief in me and my ability to accomplish what I set out to do. Their constant support and love have allowed me to achieve this incredible goal.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Vibrations caused by human activity have long been recognized as a major serviceability concern for residential floor systems (Tredgold 1828). With the advancements in materials and technology, longer spanning and lighter weight floor systems are now available. Cold-formed C-section supported residential floor systems provide an alternative to traditional wood residential floor systems. Steel framed floors are typically lighter and have less damping than traditional wood floors. As a result, such systems designed for only strength may be more susceptible to excessive floor vibrations due to human footfalls. The easiest and most economical way to avoid a problem floor is to limit this possibility in the design stage of the floor system.

1.2 Objective

Floor vibration is a serviceability issue that is currently not addressed in North American residential floor system design, except for a recommended deflection limitation of span/360 due to a uniform live load. The National Association of Home Builders (NAHB), in conjunction with the U.S. Department of Housing and Urban Development, has proposed the use of a span/480 deflection criterion to address the concern of floor vibration problems in steel framed floor systems. The goal of this research, sponsored by NAHB, is to develop a method for insuring the vibration acceptability of cold-formed C-section floor systems during the design stage. The research has three primary objectives: (1) to select an appropriate tolerance criterion from existing criteria for lightweight wood floor and metal framed systems; (2) to develop an accurate method to predict the static deflection of the floor under a concentrated load located at mid-bay; (3) to develop an accurate method to predict the fundamental frequency of the floor.

1.3 Terminology

Response of a floor system is the ensuing motion after an initial displacement. It is represented as a time variation of displacement, velocity or acceleration. In this work, the response of each floor system is represented as a time variation of acceleration.

Dynamic loading, for the purpose of this work, is classified as either repetitive or transient loading. Both repetitive and transient loading can occur from the movements of people, i.e. walking, jumping, dancing (Murray et al. 1996).

Natural frequency is the frequency at which a structure will vibrate after sudden impact. Fundamental frequency technically refers to the lowest natural frequency present. In

this work “fundamental” frequency will refer to the lowest frequency of a bending mode of vibration.

Damping is a measure of how quickly the amplitudes of a freely vibrating system decay. It is usually expressed as a ratio of present system damping to critical damping. Typically, most floor systems have damping much less than critical damping (1% to 5% of critical). Lightweight floors systems (timber or light gauged steel framed) tend to have more internal damping than concrete slab-steel beam floor systems.

Resonance will occur in a system if the system is being excited by a force that has a frequency equal to the natural frequency of the system. The result is very large amplitudes which must be avoided.

1.4 Literature Review

The following literature review is limited to existing criteria for lightweight timber and metal framed floor systems and to the available literature on predicting the number of effective joists in a floor system.

1.4.1 Current Acceptability Criteria

There are many procedures available to determine the acceptability of a floor in terms of human perception. Current methods of predicting the acceptance of floors vary according to the material used in the construction of the floor. Lightweight wood floors and metal framed floors have been studied extensively over the past 20 years, in many different countries. Several acceptability criteria have been developed for such floor systems based on the static deflection of the floors. The intent of this work is to determine whether it is reasonable or not to apply these criteria to steel C-joist supported floor systems.

1.4.1.1 Ohlsson’s Criterion

A design procedure to limit annoying vibration caused by people in motion is presented in detail in a design guide published by the Swedish Council for Building Research (Ohlsson 1988). The guide is developed from years of research by Professor Sven Ohlsson at the Chalmers University of Technology. The majority of Ohlsson’s research involved timber floors. The guide includes a description of “springiness” and vibration problems, the development of the proposed dynamic expressions (Ohlsson 1982), the design procedure and design examples for various floor systems.

The design guide is applicable to all floor constructions (material independent) which have a lowest resonance frequency greater than 8 Hz. However, use of the method is limited to lightweight floors with span lengths less than 19.7-26.2 ft (6-8 meters). Resonance frequencies for a floor system are calculated assuming a simply supported rectangular orthotropic plate:

$$f_n = \frac{\pi}{2} \sqrt{\frac{D_x}{gL^4}} \sqrt{1 + \left[2n^2 \left(\frac{L}{B} \right)^2 + n^4 \left(\frac{L}{B} \right)^4 \right] \frac{D_y}{D_x}} \quad (1.1)$$

where

f_n = natural frequency in the n^{th} normal mode

g = unit weight

D_x = plate flexural stiffness in the x-direction (parallel to the joists) = EI_x/S

D_y = plate flexural stiffness in the y-direction (perpendicular to the joists) = $Et^3/12$

E = modulus of elasticity

I_x = transformed moment of inertia

S = joist spacing

t = plate thickness

L = span length of floor

n = modal number

B = width of floor

The moment of inertia used in Ohlsson's design guide does not have to take into account composite behavior between the joists and flooring. For floors with $D_y/D_x < 0.01$, the above equation can be simplified to:

$$f_n = \frac{\pi}{2} \sqrt{\frac{D_x}{gL^4}} \quad (1.2)$$

Ohlsson's criterion also requires a check on the static deflection, a check on the response to impulse load and, for longer span floors, a check on the response to continuous loading.

Deflection due to a concentrated load applied at the most flexible point on the floor is limited under the first check. When the value of D_y/D_x is low (<0.01), a point load is assumed to be carried by the joist directly under the load. The deflection of this single joist in a floor system is to be limited to 0.059 in. (1.5 mm) under the action of a 225 lb (1.0 kN) static concentrated load. Deflection of the joist is calculated from:

$$\delta_p = \frac{PL^3}{48EI_x} \quad (1.3)$$

where

δ_p = vertical displacement

P = applied load

L = joist length

E = modulus of elasticity of joist

I_x = moment of inertia of joist

A more accurate method of computing the deflection (i.e. computer modeling of the floor system) may be used if desired.

The second requirement is a check on the response to an impulse load of 1.0 N-s. The impulse velocity response, $h'_{\max}$, is “the initial vertical vibration velocity due to an idealized vertical force impulse (Ohlsson 1988). A better understanding of this parameter can be seen in Figure 1.1.

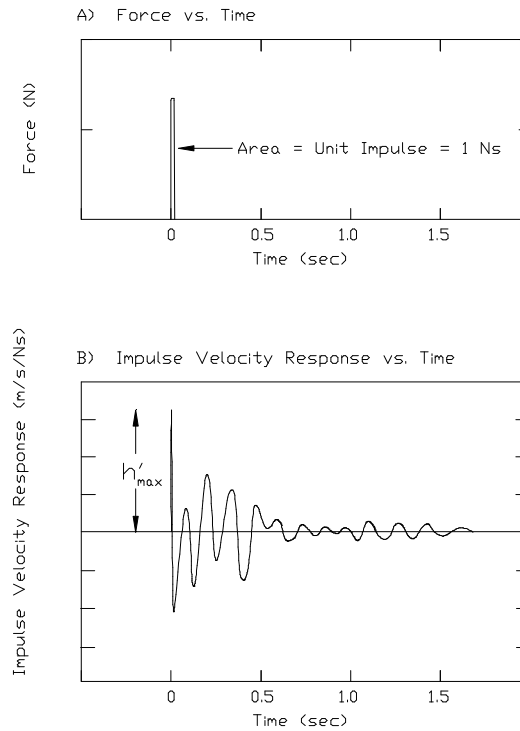


Figure 1.1 Idealized Impulse and Resulting Vibration Velocity for a Typical Floor (after Ohlsson 1988)

The initial impulse velocity response, $h'_{\max}$, is calculated as follows in SI units:

$$h'_{\max} = \frac{4(0.4 + 0.6N_{40})}{gBL + 200} \quad [m / s / Ns] \quad (1.4)$$

where

N_{40} = number of normal modes of frequencies ≤ 40 Hz

g = unit weight (kg/m^2)

B = width of floor (m)

L = span length of floor (m)

The value of N_{40} is found using charts which graph modal number versus normalized frequency ($40/f_1$). The charts are set up for various L/B and D_y/D_x ratios (Ohlsson 1988).

Before assessment of the floor due to impulse load response can be done, an estimate of the damping coefficient of the floor must be made. The damping coefficient is calculated as:

$$\sigma_0 = f_1 \zeta \quad (1.5)$$

where f_1 is the fundamental frequency calculated using Equation (1.1) with n equal to 1 and ζ is the relative damping. The value of the relative damping may be assumed to be 1% for normal lightweight floor systems and approximately 0.8% for larger span or larger weight (greater than 31 lb/ft^2 , 150 kg/m^2) floor systems. Such damping has the ability to reduce the dynamic response of a floor. The assessment of the response is then done through plotting σ_0 against h'_{max} on the chart in Figure 1.2.

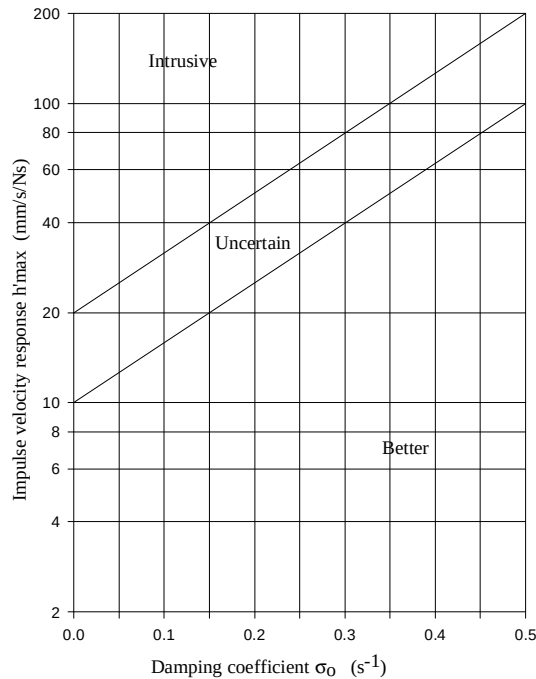


Figure 1.2 Preliminary Proposal for the Classification of the Response of a Floor System to an Impact Load (after Ohlsson 1988)

Any floor which falls into the Intrusive or Uncertain areas should be redesigned. Ohlsson gives many examples of how to improve floors in the design stage to limit vibration.

If the floor span, L , is greater than 13.1 ft (4 m) or if a shorter span contains long unobstructed passages (i.e. corridors) then a check of the response to continuous loading must be done. This check is made by calculating the root mean square (RMS) value of the vibration velocity (w'_{RMS}). The w'_{RMS} value is the resultant vibration due to one person performing continuous motion over a long period of time at the same location. It is calculated as follows in SI units:

$$w'_{\text{RMS}} = \frac{100}{gBL\sqrt{\zeta}} \sqrt{\left(\frac{N_{1.2}^2 + 1}{2f_1^3} \right)} \quad [(\text{m/s})_{\text{RMS}}] \quad (1.6)$$

where $N_{1.2}$ is the number of normal modes with natural frequencies $< 1.2f_1$ and all other values are as defined for Equation (1.4). The value of $N_{1.2}$ is obtained from the same charts as described for N_{40} .

Unfortunately, there is no limit specified in the design guide for the root mean square (RMS) value of vibration velocity. It is suggested that the calculated value be compared to that of a floor system which has been used previously and is considered to have acceptable vibration levels.

1.4.1.2 Australian Criterion

The *Australian Standard Domestic Metal Framing Code* (1993) was developed for residential steel framed construction and uses much of the criterion proposed by Ohlsson (1988). The dynamic serviceability requirements provided in this Code are limited to floors with a lowest natural frequency greater than 8 Hz. This frequency is calculated using Equation (1.1) with n equal to 1 and a uniformly distributed live load of 6.26 lb/ft² (0.3 kPa). Two requirements are to be used to assess the dynamic performance of a steel framed floor system.

The first requires that under the application of a static concentrated load of 225 lb (1.0 kN) anywhere on the floor, the floor deflection shall not exceed 0.0787 in. (2.0 mm). The Code suggests that this requirement will most likely govern the design of short open floors. However, the range of span lengths that correspond to short open floors is not specified in the Code. The midspan deflection of a floor joist is determined from the following equation:

$$\delta = \frac{P_d L^3}{48E_b I_b} \quad (1.7)$$

where

δ = midspan deflection of a single joist

P_d = effective applied load = $k_d P$

P = 225 lb (1.0 kN)

$$k_d = 0.883 - 0.34 \log_{10} \left[\left(\frac{k_c}{k_b} \right) + 0.44 \right]$$

$$k_c = \frac{E_c t_f^3 L}{12s^3} \text{ (for joist only systems)}$$

$$k_b = \frac{E_b I_b}{L^3}$$

E_c = modulus of elasticity of the crossing members (sub-flooring)

E_b = modulus of elasticity of the main members (joist)

t_f = thickness of the flooring

s = joist spacing

I_b = moment of inertia of a joist

L = span of the joists

The second requirement is likely to control in the design of long span floors. Again, guidance is not given as to what span lengths correspond to long span floors. Under the application of an ideal unit impulse load of 1.0 N-s anywhere on the floor, the maximum impact velocity $V_{\max}$ in SI units is:

$$V_{\max} = 4 \left(\frac{0.4 + 0.6N_{40}}{wLB + 200} \right) \quad [\text{m / s / Ns}] \quad (1.8)$$

but is limited in the Code to:

$$\log_{10}(V_{\max}) < 1.2 + 2\sigma_o \quad (1.9)$$

where

w = mass of the floor per unit area including the live load mass (kg/m^2)

L = span of the joists (m)

B = width of the floor (m)

σ_o = damping coefficient = $f_1 \zeta$

f_1 = lowest natural frequency of the floor system

ζ = modal damping ratio (assumed to be 0.9% unless otherwise noted)

$$N_{40} = \frac{B}{L} \sqrt{\left[\sqrt{\left(\frac{r + f^2 - 1}{r} \right)} - 1 \right]}$$

r = ratio of the floor stiffness in two directions (= K_y / K_x)

f = normalized frequency (= $40 / f_1$)

The value of f_1 is calculated using Equation (1.1) with $n = 1$; K_y and K_x are the flexural stiffnesses of the main members and the sub-flooring, respectively.

1.4.1.3 Onysko's Criterion

Onysko's criterion is based on the results of an extensive field study conducted in the 1970's in Canada (Onysko 1985). The survey involved the assessment of perceived acceptability of 646 floors in five cities of all types of wood construction. Great care was taken to obtain the subjective evaluation of the *suitability* of the floor from the homeowner, not the vibration performance. The judgment of acceptability was based on the everyday experiences of the homeowners and not on a specific excitation of the floor.

The study showed that the dynamic response due to an impact load and the deflection due to a static concentrated load were the two parameters that best correlated with perceived acceptability. The development of a criterion based on the dynamic response was abandoned because of the difficulty in assessing a suitable damping value for the floors and because fewer assumptions are required for computation of performance under a concentrated load.

The original recommendation (Onysko 1985) formed the basis for the adoption of a criterion in the 1990 National Building Code of Canada to accompany the span tables for solid sawn wood floors. This criterion has since been modified from its original form (Onysko 1995), and now has the form:

$$y \leq \frac{37.32}{L^{1.3}} \text{ [in.]} \quad (1.10)$$

where y is the central deflection due to a 225 lb load and L is the floor span in inches. A soft conversion from metric units to U.S. Customary units was used to convert Equation 1.10 from its original form:

$$y \leq \frac{8.0}{L^{1.3}} \text{ [mm]} \quad (1.11)$$

where y is the central deflection due to a 1.0 kN load and L is the floor span in meters. In addition, for floors with a span under 9.84 ft (3 m) the central deflection is limited to 0.0787 in. (2.0 mm). Again, a soft conversion was used to express the floor span in U. S. Customary units.

Recently, Onysko, in conjunction with a consortium of timber researchers and engineers, has proposed a new design procedure for limiting vibrations of timber floors in the design stage (Canadian Wood Council et al. 1996). The method results in a value for span length, calculated from the fundamental properties of the floor and construction variables (i.e. sub-flooring type, glued or fastened flooring, spacing and bridging), which satisfies the above deflection criterion. A computer program called PERF, which stands for "Performance", developed by Onysko for Forintek Canada Corporation forms the basis for this proposed

method. The method has been further developed to allow for the use of a hand calculation procedure rather than requiring the application of the computer program.

The calculation procedure begins with choosing a trial span. The stiffness of a joist is then calculated at this trial span from the following equation:

$$EI_{\text{joist}} = \frac{PL^3}{48\Delta} = \frac{PL^3}{48} \times \frac{1}{\left[\frac{PL^3}{48EI} + \frac{2PL}{K_s} \right]} \quad (1.12)$$

where

EI_{joist} = apparent bending stiffness of the joist calculated at the trial span

$P = 225 \text{ lb (1.0 kN)}$

L = trial span

Δ = deflection of a single joist

EI = published stiffness of floor joist

K_s = shear deflection coefficient

The effective composite bending stiffness is calculated from the stiffness of a fully composite section by:

$$EI_{\text{eff}} = C \times EI_{\text{comp}} + (1-C) \times EI_{\text{joist}} \quad (1.13)$$

where EI_{eff} is the effective composite bending stiffness, EI_{comp} is the bending stiffness of a fully composite section and C is a construction factor. The construction factor takes into account the type of overlay (concrete topping, nailed sub-floor and glued sub-floor) on the floor joists. If composite action is not considered, the value of “C” is taken as zero.

Load sharing of the joists is recognized and a distribution factor (DF) is employed in the hand calculation. The distribution factor is the portion of a 225 lb (1.0 kN) static, concentrated load applied at mid-bay carried by a joist in the floor system directly under the applied load. The factor is calculated as:

$$DF = A + B \ln \left(\frac{EI_{\text{eff}}}{K_2} \right) \quad (1.14)$$

where A and B are factors depending on the sub-flooring, bridging, connection and spacing between joists and sub-flooring, and K_2 is 1.0×10^6 for U. S. Customary units (2.87×10^9 for SI units). The factors A and B are provided in a table in the final report of the proposed method (Canadian Wood Council et al. 1996). Finally, the vibration controlled span can be computed from:

$$L_v = K_1 \left(\frac{EI_{\text{eff}}}{DF} \right)^{\frac{1}{4.3}} \quad (1.15)$$

where L_v is the vibration controlled span and K_1 is 1.62 for USC units (6.46 for metric units). The process is iterative and must be repeated until the trial span, L , and the vibration controlled span, L_v , are equal.

1.4.1.4 Johnson's Criterion

Johnson (1994) developed a design criterion for timber floors based on the results of 86 *in-situ* floors under construction. The original goal was to apply Murray's criterion (Murray 1991) for steel/concrete floor systems to timber floors. Instead, Johnson proposed that the fundamental frequency be greater than 15 Hz for a floor supporting only its own weight. Typically, the fundamental frequency is calculated from a single joist in the floor system. However, if a girder is contributing to the response of the floor, the system frequency is taken as the fundamental frequency. The fundamental frequency of a single joist is calculated from:

$$f = 1.57 \sqrt{\frac{gEI}{WL^3}} \quad (1.16)$$

where

- f = fundamental bending frequency
- g = acceleration due to gravity
- E = modulus of elasticity
- I = moment of inertia of joist alone
- W = self weight of the floor
- L = span length

Composite action is ignored in the calculation of the moment of inertia. The conclusion that effective sheathing width is negligible resulted from numerous static deflection tests performed on laboratory built floors (Johnson 1994). If girder effects cannot be ignored, Dunkerley's equation is used to calculate the fundamental frequency of the floor system. In simplified form:

$$f_{\text{system}} = \sqrt{\frac{f_{\text{joist}}^2 \cdot f_{\text{girder}}^2}{f_{\text{joist}}^2 + f_{\text{girder}}^2}} \quad (1.17)$$

where f_{system} is the fundamental frequency of the floor system, f_{joist} is the fundamental frequency of a joist and f_{girder} is the fundamental frequency of a girder. The 15 Hz criterion applies only to floors supporting their own weight and is intended to be used in the design stage to determine whether a floor system will be rated acceptable in terms of vibration level from human footfalls (Shue 1995).

1.4.2 Number of Effective Joists

An extensive study into the area of annoying floor vibrations in steel joist- and steel beam-concrete slab floors was conducted by Professor Kenneth H. Lenzen and his associates at the University of Kansas from 1959 to 1962. During the course of this research it was realized that all the joists present in a floor system may not contribute to the resistance of an applied load. As a result, Lenzen and Dorsett (1969) developed the concept of effective floor width: the width of the floor characteristic to how the floor behaves regardless of the actual width of the floor. The effective floor width is considered to extend to the location of zero deflection: the point at which no significant change in the floor characteristics occur. The distance between the center of the floor and the point of zero deflection, x_o , is shown in Figure 1.3 and can easily be determined by (Lenzen and Dorsett 1969):

$$x_o = 1.06\epsilon L \quad (1.18)$$

where L is the joist span, $\epsilon = (D_x/D_y)^{0.25}$ and D_x/D_y is the ratio of the flexural rigidity perpendicular to the joists to the flexural rigidity parallel to the joists.

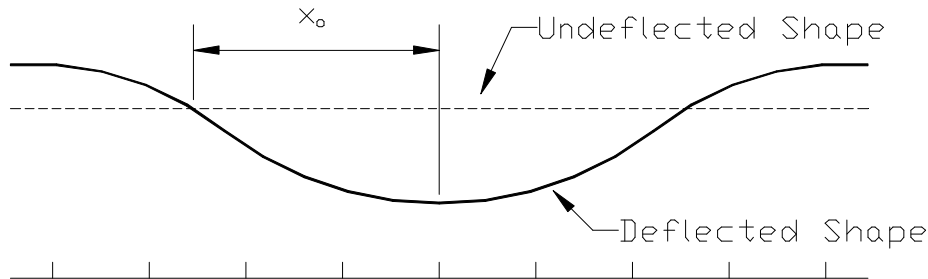


Figure 1.3 Deflection Profile Across Center of Floor

In later research, the effective floor width was expressed in terms of the joist spacing and an effective number of joists. The effective number of joists is said to be the number of joists in a floor system which contribute to the resistance of an applied concentrated load. The joist directly under the application of a concentrated load is assumed to be fully effective. The joists to either side of the loaded joist contribute less to the resistance of the load and are considered less effective. The effectiveness of a joist is determined by taking the ratio of the deflection of the joist under consideration to the deflection of the loaded joist. Joists beyond the location of zero deflection in a floor system are not considered.

The following sections discuss methods developed to predict the number of effective joists in a floor system believed to contribute to the resistance of an applied concentrated load.

1.4.2.1 SJI and AISC Equations

Lenzen and Dorsett developed an equation to predict the effective number of joists (N_{eff}) for steel joist-concrete slab floor systems (Galambos 1988). The research was funded by the Steel Joist Institute (SJI) and is now referred to as the SJI Equation:

$$N_{eff} = 1 + 2 \sum \left(\cos \frac{\pi x}{2x_o} \right) \quad \text{for } x \leq x_o \quad (1.19)$$

where

x = distance from the center joist to the joists under consideration

x_o = distance from the center joist to the edge of the effective floor = $1.06\epsilon L$

L = joist span

$\epsilon = (D_x/D_y)^{0.25}$

D_x = flexural stiffness perpendicular to the joists = $E_c t^3/12$

D_y = flexural stiffness parallel to the joists = $E I_t/S$

E_c = modulus of elasticity of concrete

E = modulus of elasticity of steel

t = slab thickness

I_t = transformed moment of inertia of the tee-beam

S = joist spacing

The SJI equation is intended to be used for floors with a beam spacing of less than or equal to 30 in. (762 mm) (Murray 1991).

Through a research project sponsored by the American Institute of Steel Construction (AISC), Saksena and Murray (1972) developed an equation to predict N_{eff} for floors with beam spacing between 6 ft (1.83 m) and 15 ft (4.57 m). Fifty steel beam-concrete slab floors using typical office building loads, span and beam spacing were designed and then analyzed by a computer program developed by Ohmart and Lenzen (1968) to determine the dynamic amplitude due to a heel drop or mechanical heel drop simulator. The predicted amplitude of the floor and the hand calculated amplitude of a tee-beam were used to compute the N_{eff} of each hypothetical floor and is represented as:

$$N_{eff} = \frac{A_{ot}}{A_o} \quad (1.20)$$

where A_{ot} is the maximum dynamic amplitude of a tee-beam subjected to a heel drop and A_o is the maximum dynamic amplitude of the floor system due to the same impact. A multiple linear regression analysis led to:

$$N_{eff} = 2.967 - 0.05776 \left(\frac{S}{d_e} \right) + 2.556 \times 10^{-8} \left(\frac{L^4}{I_t} \right) + 0.00010 \left(\frac{L}{S} \right)^3 \quad (1.21)$$

with limitations of

$$15 \leq \left(\frac{S}{d_e} \right) < 40 \text{ and } 1 \times 10^6 \leq \left(\frac{L^4}{I_t} \right) \leq 50 \times 10^6$$

where

d_e = effective slab depth

S = beam spacing

L = beam span

I_t = transformed moment of inertia of the tee-beam

The AISC equation is currently used for floors having a beam spacing greater than 30 in. (762 mm) although it was developed for beam spacing between 6 ft (1.83 m) and 15 ft (4.57 m) (Murray 1991).

1.4.2.2 Shamblin/Kitterman Equation

Shamblin (1989) reviewed the SJI and AISC equations and found that they do not converge at the 30 in. (762 mm) spacing. Shamblin performed a finite element analysis on 240 floor systems using ABAQUS (Hibbitt, et al. 1985) to determine the dynamic response to heel drop impact. A multiple linear regression analysis resulted in her proposed equation. Kitterman believed that the current equations, SJI Equation and the AISC Equation, were essentially accurate and that Shamblin's equation should give predictions close to their results.

Kitterman (1994) set out to evaluate and verify the Shamblin equation (Shamblin 1989) for predicting N_{eff} . Kitterman discovered that Shamblin's equation does not predict results close to the current equations, particularly in the region where beam spacing is outside the limits of the previous equations. The ABAQUS models used in Shamblin's research often predicted larger frequencies than the existing equations. Kitterman realized that one or all of the previous equations might not be accurate.

A re-analysis of the 240 floors using the finite element program SAP90 (Wilson and Habibullah 1992) was done and the results were compared to the three equations discussed above. Details of the SAP90 modeling and the dynamic analysis of the floor systems can be found in Kitterman (1994). The number of effective tee-beams for each floor was computed by dividing the amplitude of a single tee-beam by the floor amplitude predicted by the finite element analysis. The calculated number of effective tee-beams and various physical parameters were used in a multiple linear regression analysis to obtain a new equation:

$$N_{eff} = 0.4898 + 34.19 \frac{d_e}{S} + 8.99 \times 10^{-9} \frac{L^4}{I_t} - 0.000593 \left(\frac{L}{S} \right)^2 \quad (1.22)$$

with the limits of

$$0.018 \leq \frac{d_e}{S} < 0.208 \text{ and } 4.5 \times 10^6 \leq \left(\frac{L^4}{I_t} \right) \leq 257 \times 10^6 \text{ and } 2 < \frac{L}{S} < 30$$

Kitterman then judged the correlation between the results of his equation with the others by plotting the values predicted by one equation against the values predicted by another. The Kitterman equation was found to predict a smaller number for N_{eff} when compared to the SJI, AISC and Shamblin equations. Kitterman concluded that the system amplitude is greater and therefore this new equation is more conservative than the existing equations for most floors with beam spacing less than 5 feet (1.52 m).

1.4.3 NAHB Prescriptive Tables

The National Association of Home Builders sponsored the research discussed in this document to develop a method for determining, in the design stage, if a residential floor built of cold-formed C-shaped steel joists would have annoying floor vibrations due to human activity. A prescriptive method (NAHB 1995) for design and construction of residential cold-formed steel framed houses was developed by NAHB for the U. S. Department of Housing and Urban Development. The document provides minimum requirements for the construction of one- and two-family dwellings framed with cold-formed C-shaped steel members. Tables are provided for C-shape sizes, minimum material thickness, span length and other information related to steel framing.

Table 1.1 is reproduced from the Working Draft #4 Prescriptive Method for Residential Cold-Formed Steel Framing developed by NAHB. The table is set up for single spans with deflection criteria of span/480 for live loads and span/240 for total loads. It is noted that bearing stiffeners are to be installed at all supports and at concentrated loads.

**Table 1.1 Floor Joists Allowable Spans, Single Spans
(after NAHB 1995)**

Joist Size	10 psf D. L. + 30 psf L. L.			10 psf D. L. + 40 psf L. L.		
	Spacing (inches)			Spacing (inches)		
	12	16	24	12	16	24
2 x 6 x 33	11'-6"	10'-5"	8'-8"	10'-5"	9'-6"	7'-9"
2 x 6 x 43	12'-6"	11'-4"	9'-11"	11'-4"	10'-4"	9'-0"
2 x 6 x 54	13'-5"	12'-2"	10'-8"	12'-2"	11'-1"	9'-8"
2 x 6 x 68	14'-4"	13'-1"	11'-5"	13'-1"	11'-10"	10'-4"
2 x 6 x 97	15'-11"	14'-5"	12'-7"	14'-5"	13'-1"	11'-5"
2 x 8 x 33	14'-9"	12'-9"	8'-10"	13'-2"	10'-7"	7'-1"
2 x 8 x 43	16'-11"	15'-4"	13'-3"	15'-4"	13'-11"	11'-10"
2 x 8 x 54	18'-2"	16'-6"	14'-5"	16'-6"	15'-0"	13'-1"
2 x 8 x 68	19'-6"	17'-8"	15'-5"	17'-8"	16'-1"	14'-0"
2 x 8 x 97	21'-7"	19'-7"	17'-2"	19'-7"	17'-10"	15'-7"
2 x 10 x 43	20'-4"	17'-10"	14'-7"	18'-5"	15'-11"	13'-0"
2 x 10 x 54	21'-10"	19'-10"	17'-4"	19'-10"	18'-0"	15'-9"
2 x 10 x 68	23'-5"	21'-4"	18'-7"	21'-4"	19'-4"	16'-11"
2 x 10 x 97	26'-1"	23'-8"	20'-8"	23'-8"	21'-6"	18'-9"
2 x 12 x 54	25'-6"	23'-2"	19'-0"	23'-2"	20'-9"	17'-0"
2 x 12 x 68	27'-4"	24'-10"	21'-9"	24'-10"	22'-7"	19'-9"
2 x 12 x 97	30'-5"	27'-8"	24'-2"	27'-8"	25'-1"	21'-11"

1.5 Scope of Work

It is the goal of this work to develop a method for determining the vibration level of a cold-formed C-section steel joist floor in the design stage. Chapter 2 of this document discusses the design of the test floors and the tests performed and instrumentation used on each test floor. Chapter 3 explains the results of the testing and the selection of the proposed method. Design examples and results from *in-situ* testing are provided in Chapter 4.

CHAPTER 2

EXPERIMENTAL WORK

2.1 Overview

Twelve full size floors were constructed and tested to develop a method to determine vibration acceptability of cold-formed steel joist floor systems and to determine a method for predicting the fundamental frequency of these systems. The reader is reminded here that “fundamental” frequency, in this work, refers to the lowest frequency of a bending mode of vibration. Construction and testing of all floors along with a description of the instrumentation used for testing is discussed in detail in the following sections.

Each floor contained nine joists at 24 in. (610 mm) on center spacing, with 23/32 in. (19 mm) tongue-in-groove oriented strand board (OSB) sheathing as the sub-flooring. Two pilot full size floors were first constructed at 16 in. (406 mm) on center spacing. In addition, five, two joist line (tee-beam) test set-ups were constructed and tested to determine the composite action between the joists and the flooring.

Four tests were performed on each full floor set-up: subjective evaluation, heel drop impact, walking parallel and perpendicular to the joists and static, concentrated load applied at mid-bay. All tests were performed on the original floor set-up (with strapping only), with blocking at all locations between the joists and with drywall attachment. A general classification of the floor (acceptable, marginal or unacceptable) in terms of annoying vibration level was obtained from the subjective evaluations. A measurement of the floor deflection, to be used in the evaluation of the existing vibration criteria, was obtained from the application of a static, concentrated load at mid-bay. A measurement of the frequency of a floor system was determined from an acceleration trace generated by a heel drop impact. The walking tests provide an idea of the amount of damping that occurs in the floor system.

2.2 Multi-Joist Line Floors

A summary of the layout, parameters, section properties and measured values for each floor are provided in Appendix A. This section describes the general layout, construction and testing of the test floors.

2.2.1 Materials and Construction

Basic floor system designs were constructed with nine cold-formed C-shaped steel joists (CFSJ) at 24 in. (610 mm) spacing with 23/32 in. (19 mm) tongue-in-groove OSB decking (Figure 2.1). All multi-joist line floors were 16 ft (4.88 m) in width. Joist sizes, floor identification and span lengths used in this study are shown in Table 2.1. Span lengths corresponded to an earlier version of the NAHB Prescriptive Table referred to in Section 1.4.3.

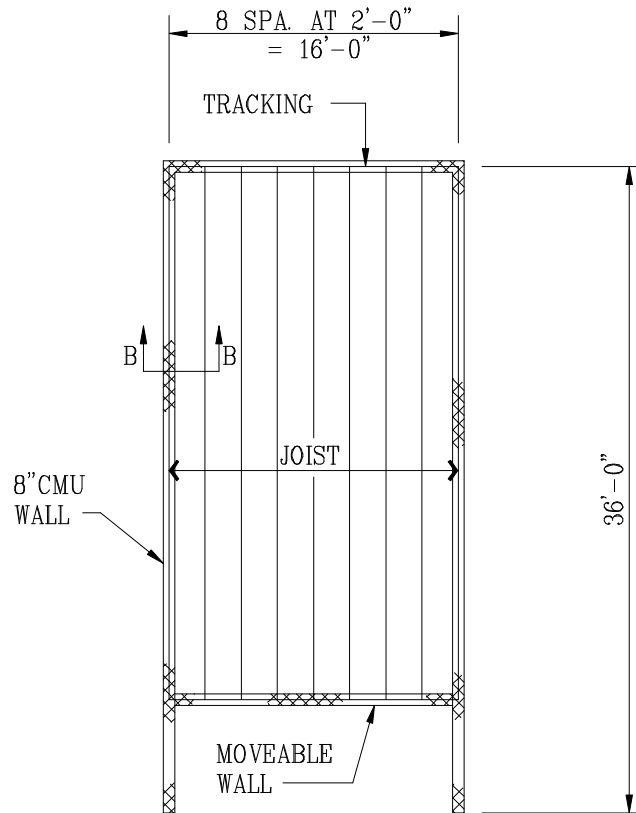


Figure 2.1 Test Floor Plan

Table 2.1 Test Floor Span Lengths

Floor	Joist Size	Deflection Limitation	Span
8A	2x8x43	L/360, 30psf LL	13'-9"
8B	2x8x43	L/480, 40psf LL	12'-3"
8C	2x8x43	L/720, 40psf LL	10'-9"
8D	2x8x33	L/360, 30psf LL	8'-10"
8E	2x8x33	L/480, 40psf LL	7'-1"
10C	2x10x43	L/360, 30psf LL	15'-3"
10D	2x10x43	L/480, 40psf LL	13'-1"
12A	2x12x54	L/360, 30psf LL	19'-7"
12B	2x12x54	L/480, 40psf LL	17'-6"
12C	2x12x54	L/720, 40psf LL	16'-2"
12D	2x12x43	L/360, 30psf LL	14'-1"
12E	2x12x43	L/480, 40psf LL	11'-3"

Each floor was assigned a number identifying the depth of the joists and a letter identifying the deflection limitation used to govern the span length. For example, Floor 8A was a floor built out of 2x8x43 CFSJ with a span length corresponding to a L/360, 30 psf (1.44 kN/m²) live load (LL) deflection limitation. Floor 8B was built out of 2x8x43 CFSJ with a span length corresponding to a L/480, 40 psf (1.92 kN/m²) LL deflection limitation. Each floor system was supported around the entire perimeter by 8 in. x 8 in. x 16 in. (203.2 mm x 203.2 mm x 406.4 mm) concrete masonry unit (CMU) walls four courses high. Three of these walls were stationary and the fourth wall was moveable, as shown in Figure 2.1, to allow for support of the differing span lengths.

The construction sequence for each floor began with the setup of the CMU walls. Sill plates were secured to all walls in the standard fashion. Track and joists were then fastened to the sill plates by #8 self-drilling bugle head fasteners. Bearing stiffeners were placed at every joist-track connection and extended the full length of the joist. Sub-flooring (OSB) was fastened perpendicular to the joists using #8 or #10 Wafer Phillips “Winged” screws (Figure 2.2). Fasteners were placed at 6 in. (152.4 mm) on center around the perimeter and 12 in. (304.8 mm) on center in the field of the panel.

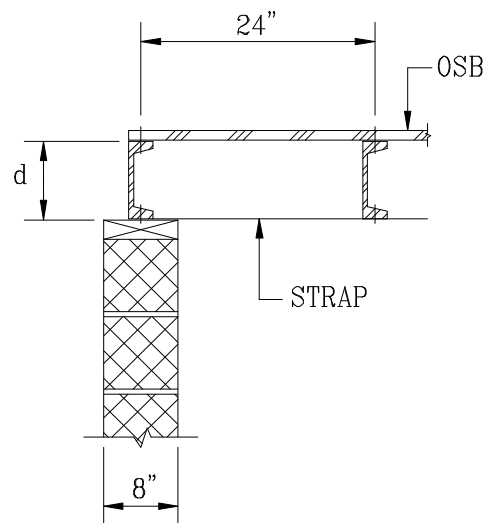
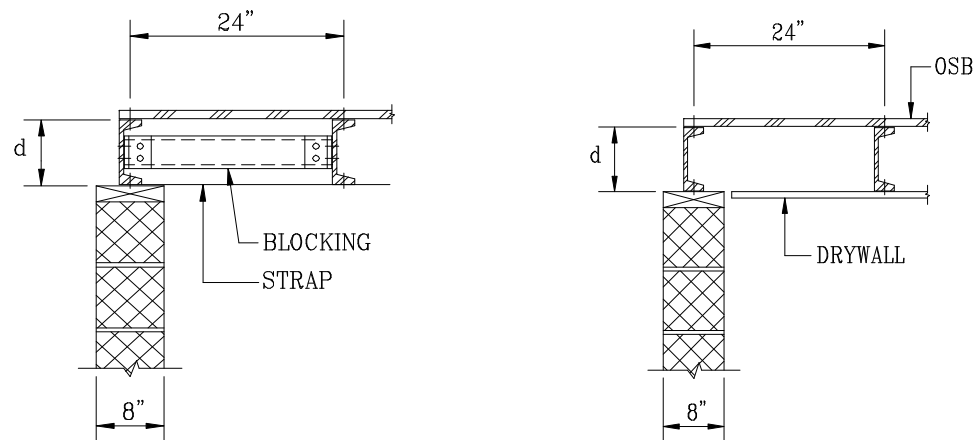


Figure 2.2 Test Floor Cross-Section

All floors were first constructed for a span length corresponding to an equivalent 30 psf (1.44 kN/m²) live load (LL) deflection of L/360. After dynamic and static testing and subjective evaluation, the floors were modified to an equivalent 40 psf (1.92 kN/m²) LL deflection of L/480. Finally, the floors were modified to an equivalent 40 psf (1.92 kN/m²) LL deflection of L/720. Not all floors were shortened to the L/720 deflection criterion, as shown in Table 2.1, because the decrease in span length amounted to 1 to 2 inches (25.4 to 50.8 mm).

Improvement of a floor system can often be accomplished through the addition of damping elements or stiffening elements to the floor. Several variations of the floor

configuration were studied to determine if they significantly affected the fundamental frequency of the floor system and the center floor deflection under application of concentrated load. These variations included: blocking between joists at midspan, strapping on bottom flange at midspan (with and without blocking), large holes in each joist web at midspan and drywall attachment to the underside of the floor. Strapping was fastened to the bottom flange of each joist using #8 self-drilling bugle head screws (Figure 2.2). Blocking was placed between the joists with #8 self-drilling bugle head or Phillips head screws (Figure 2.3). Drywall was attached to the bottom flange of each joist with #10 Cement Board screws (Figure 2.3).



**Figure 2.3 Test Floor Cross-Section
Showing Blocking and Drywall Attachment**

Blocking was constructed out of 8 in. (203.2 mm) or 4 in. (101.6 mm) cold-formed C-shaped steel joists. Blocking was placed at midspan and connected to the joist on either side with 2 fasteners. The 8 in. (203.2 mm) blocking was used for floors 10C through 12E and the 4 in. (101.6 mm) blocking was used for Floors 8A through 8E.

Table 2.2 is a summary of the parameters included in each floor. An “x” in the table denotes that the floor was tested with this parameter alone. For example, Floor 12E was tested twice; once with strapping attached to the bottom flanges and once with blocking in all locations. The no strap designation means that no parameters were added to the test floor. Blocking was attached in three different configurations and includes the attachment of the strapping unless otherwise noted. Figure 2.4 is a cross-section of a multi-line joist floor with the blocking locations labeled.

Four tests (subjective evaluation, dynamic excitation due to heel drop impact, concentrated load at mid-bay and dynamic excitation due to walking parallel and perpendicular to the joists) were conducted on every floor that included the strapping and/or the blocking in all locations, the drywall and the holes at midspan. Any floor with only partial blocking was subject to the dynamic excitation tests only.

Table 2.2 Summary of Floor Configurations

Floor	Blocking Size	Parameter							
		No Strap	Strap	Blocking Configurations				Drywall	5" x 5" Holes
				B0	B1	B2	B3		
8A	4 in.		X		X	X	X	X	
8B	4 in.		X		X				
8C	4 in.		X		X				
8D	4 in.		X		X				
8E	4 in.		X		X				
10C	8 in.	X	X		X	X	X	X	
10D	8 in.		X		X	X	X		X
12A	8 in.		X	X	X				
12B	8 in.		X	X	X				
12C	8 in.		X	X					
12D	8 in.		X	X	X				
12E	8 in.		X		X				

Note: B0 = blocking in all locations, no strap
 B1 = blocking in all locations
 B2 = blocking in locations 2, 4, 5 and 7
 B3 = blocking in locations 4 and 5

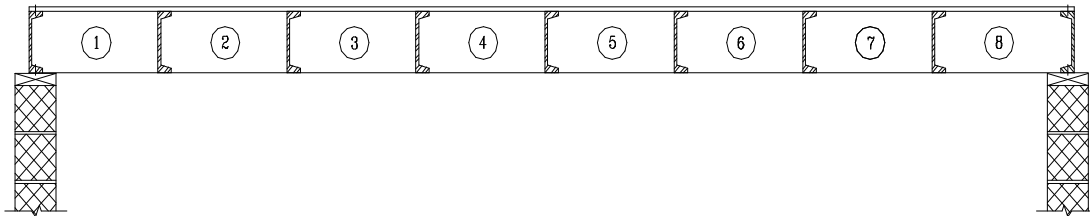


Figure 2.4 Test Floor Blocking Locations

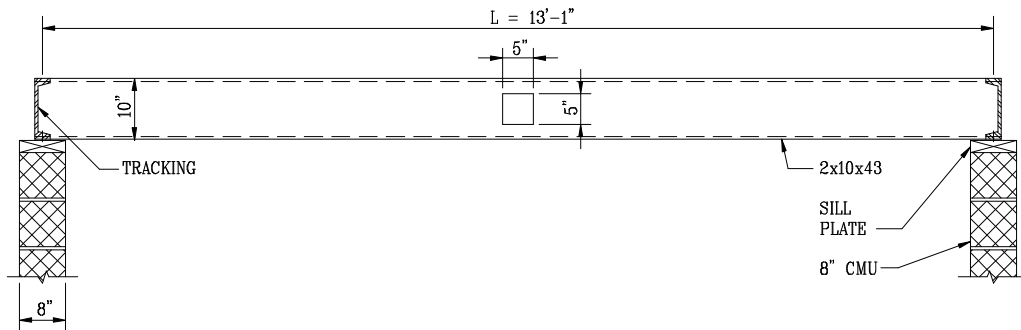


Figure 2.5 Floor 10D Cross-Section: 5"x5" Hole Cut at Midspan

All floors were tested with the strapping and with the blocking. Five floors were tested with blocking configurations B2 and B3. Four floors were tested with blocking in every location, but no strap. Two floors were tested with the addition of drywall. Neither blocking nor strapping was included in the floor system when drywall was included. Many floors were tested with the addition of a 30 lb (13.6 kg) bag at each quarter point on the floor to “clean up” the graph of the frequency domain.

Mechanical and duct work can often times be hung from the joists themselves. However, sometimes head space is limited and holes must be cut in the joists to allow for mechanical and duct work to pass. Large holes, 5 in. x 5 in., were cut at midspan in one of the test floors (Floor 10D) to determine their effect on the fundamental frequency of the floor system (Figure 2.5).

2.2.2 Description of Tests

Four tests were performed to determine the subjective evaluation, fundamental frequency, deflection due to a concentrated load at the center of the floor and magnitude of damping of each floor. Each test and the instrumentation used is discussed in detail in the following sections.

2.2.2.1 Subjective Evaluation

To examine the validity of applying the existing annoying floor vibration criteria to CFSJ floor systems, a classification of each test floor was made. A test subject was asked to sit in a straight legged chair at mid-bay for one minute to adjust to the setting. A 240 lb (109 kg) man then stepped onto the floor and walked around at a normal walking speed.

Test subjects were asked to rate the vibration level of the floor and to state whether they would find the floor acceptable, marginal or unacceptable if it were in a home. A standard questionnaire sheet was filled out by each test subject for each floor they observed (Figure 2.6). The final subjective evaluation of each floor was determined by taking an average of the responses. For instance, if seven responses were obtained for a floor, 2 acceptable, 2 unacceptable and 3 marginal, the overall classification of the floor is classified as marginal. The marginal classification expresses that the floor may be acceptable when part of a complete structure (i.e. a house).

2.2.2.2 Heel Drop Impact

The purpose of performing a heel drop impact is to obtain a measurement of the fundamental frequency of the floor. Excitation of each test floor at its center was performed by a 240 lb (109 kg) man standing on his toes, shifting his weight backward, and impacting the floor with his heels (commonly referred to as a heel drop). This heel drop was performed with and without simulated live load.

The motion of the floor was measured with a piezoelectric accelerometer located at the center of the test floor. The accelerometer was connected to a Conversion Adapter Model CF-0109 which was attached to a data acquisition system that would read the input voltage, converting the analog input to a series of digital readings. The series of readings are referred to as traces throughout this work. The time traces were recorded with the Ono Sokki CF-

HUMAN RESPONSE TEST DATA ON THE VIBRATION
CHARACTERISTICS OF FLOOR SYSTEMS

NAHB

Date: _____

NAME: _____

Floor: _____

How would you rate the floor in terms of vibration level?

- ☐ Imperceptible
- ☐ Barely Perceptible
- ☐ Distinctly Perceptible
- ☐ Strongly Perceptible
- ☐ Severe

If the floor was in your home, how would you rate it?

- ☐ Acceptable
- ☐ Marginal
- ☐ Unacceptable

Comments:

Walker: _____

Weight: _____

Figure 2.6 Questionnaire Used for Subjective Floor Classification

1200 Handheld FFT Analyzer. On occasion, when the Ono Sokki was not available, the accelerometer was connected to a Wilcoxon Model P-31 Power unit/Amplifier which was connected to an HP 35660A Dynamic Signal Analyzer. Both the Ono Sokki and the HP are specialized pieces of equipment which can perform a fast Fourier transform (FFT) internally, and a frequency domain graph can be viewed almost instantaneously.

Data is then saved as a time or frequency domain trace. The time domain trace is a record of the motion of the floor over time. The motion can be measured in terms of displacement, velocity or acceleration. The time trace for all test floors was recorded as acceleration and will be referred to as an “acceleration trace”. An example of a very “clean” acceleration trace is shown in Figure 2.7.

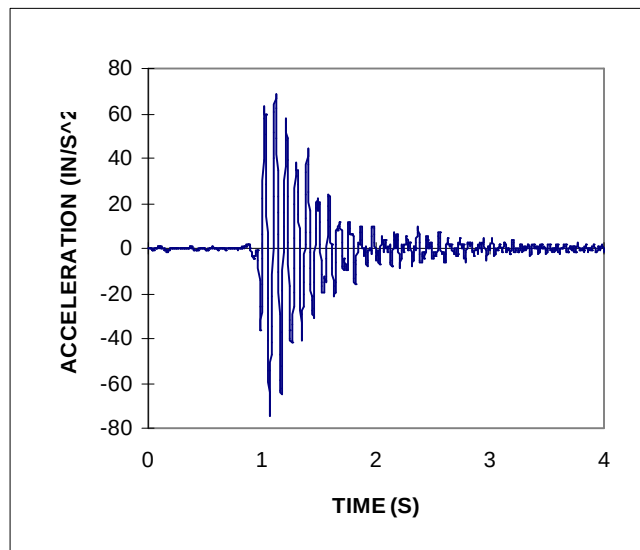


Figure 2.7 Example of Acceleration Trace

The frequency domain is a record of the amount of energy present in each excited frequency of the floor systems and is generated from the time domain trace by the use of a fast Fourier transform. The easiest way to view the frequency domain is graphically, referred to as a Power Spectrum. An example of a typical graph of the frequency domain is shown in Figure 2.8.

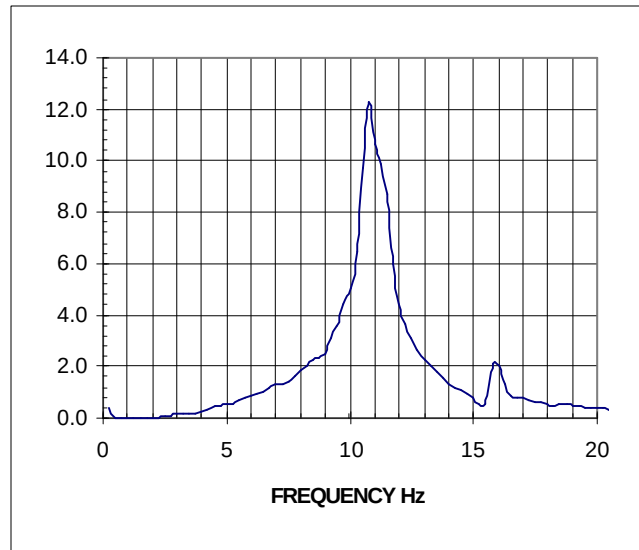


Figure 2.8 Example Power Spectrum

2.2.2.3 Concentrated Load

Floor deflection due to a static, concentrated load has long been recognized as an acceptable correlation to floor vibration performance (Ohlsson 1982, Onysko 1985). Three of the four vibration criteria examined in this study include a limiting value for this deflection. To determine the validity of the existing criteria, experimental values of the center deflection were obtained for each floor.

The central deflection due to a 225 lb (1 kN) static, concentrated load placed at mid-bay was recorded for each test floor. In earlier floor set-ups, one dial gage was placed under the center joist (loaded joist) at midspan to measure static deflection. In later floor set-ups, dial gages were placed under each joist at midspan to obtain a deflection profile of the floor. A complete record of central deflection for each floor and deflection profiles for the later floors can be found in Appendix A. A typical plot of a deflection profile is shown in Figure 2.9. Results of the measured floor deflection due to a static concentrated load at mid-bay are discussed in Chapter 3.

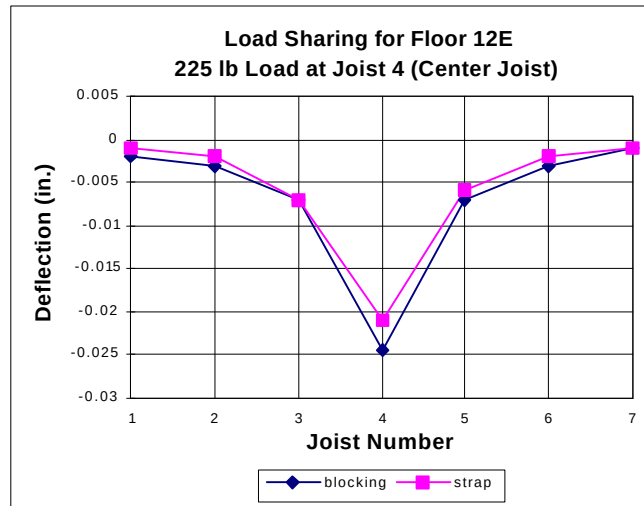


Figure 2.9 Typical Midspan Deflection Profile

2.2.2.4 Walking Parallel and Perpendicular to the Joists

All walking tests were performed by a 240 lb (109 kg) male. As the person was walking across the floor, acceleration traces were recorded with either the Ono Sokki or the HP Spectrum Analyzers in the manner described above. A typical walking acceleration trace is shown in Figure 2.10. A value for the percent gravity was recorded for all walking acceleration traces. The percent gravity is the root mean square (RMS) value of the acceleration data as a percentage of gravitational acceleration, and gives an indication as to how much damping occurs in the system. Damping is typically high in lightweight floor systems and not a source of annoying vibrations. The acceleration trace shown in Figure 2.10 has a recorded percent gravity of 0.056 g.

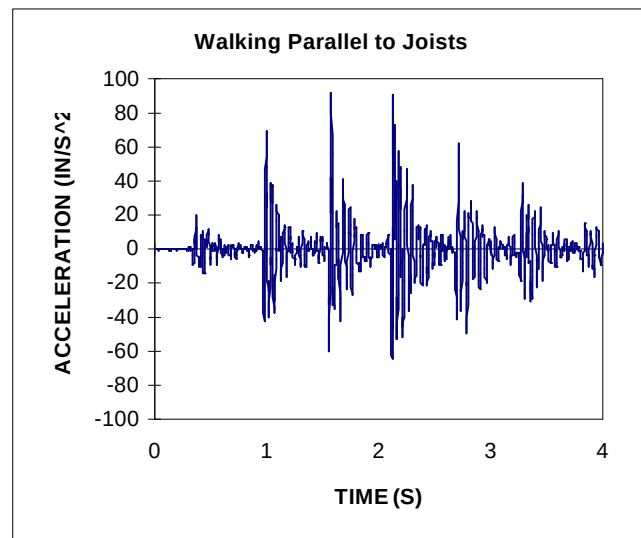


Figure 2.10 Typical Walking Acceleration Trace

2.3 Two Joist Line Test Setups

Two joist line tests were performed to determine the composite action of the test floor systems. Testing was performed on bare joist systems and again with the OSB attached. This section describes the general layout, construction and testing of the two joist line floors. A complete description of the layout, section properties and measured values for each two-joist line floor is provided in Appendix C.

2.3.1 Materials and Construction

Basic floor system designs were constructed with two cold-formed C-shaped steel joists, oriented face-to-face, at 24 in. (610 mm) spacing (Figure 2.11). The joists were oriented face-to-face to provide lateral stability in the system. Blocking, identical to that used in the full floor tests, was placed at midspan between the joists (Figure 2.11). The attachment of the 23/32 in. (19 mm) tongue-in-groove OSB decking to the joists was done in the same manner as that of the multi-joist line floor construction.

Joist and tracking were not fastened to the sill plates, as was described in the construction of the multi-joist line floors. Instead, the entire system was simply supported. An angle was welded to a steel plate to act as the base of the support. Another steel plate was placed on top of the angle and the two-joist line setup was placed on top of the second plate (Figure 2.12). All other construction procedures complied with NAHB specification as described for the multi-joist line floors. The entire system was supported on two CMU walls four courses high. Floor identification, joist size and corresponding span length used in the two-joist line tests are tabulated in Table 2.3.

Table 2.3 Two-Joist Line Span Lengths

FLOOR IDENTIFICATION	JOIST SIZE	CLEAR SPAN
2J8A	2x8x33	19'-11"
2J8B	2x8x43	19'-11"
2J10A	2x10x68	19'-11"
2J12A	2x12x54	19'-9"
2J12B	2x12x43	19'-11"

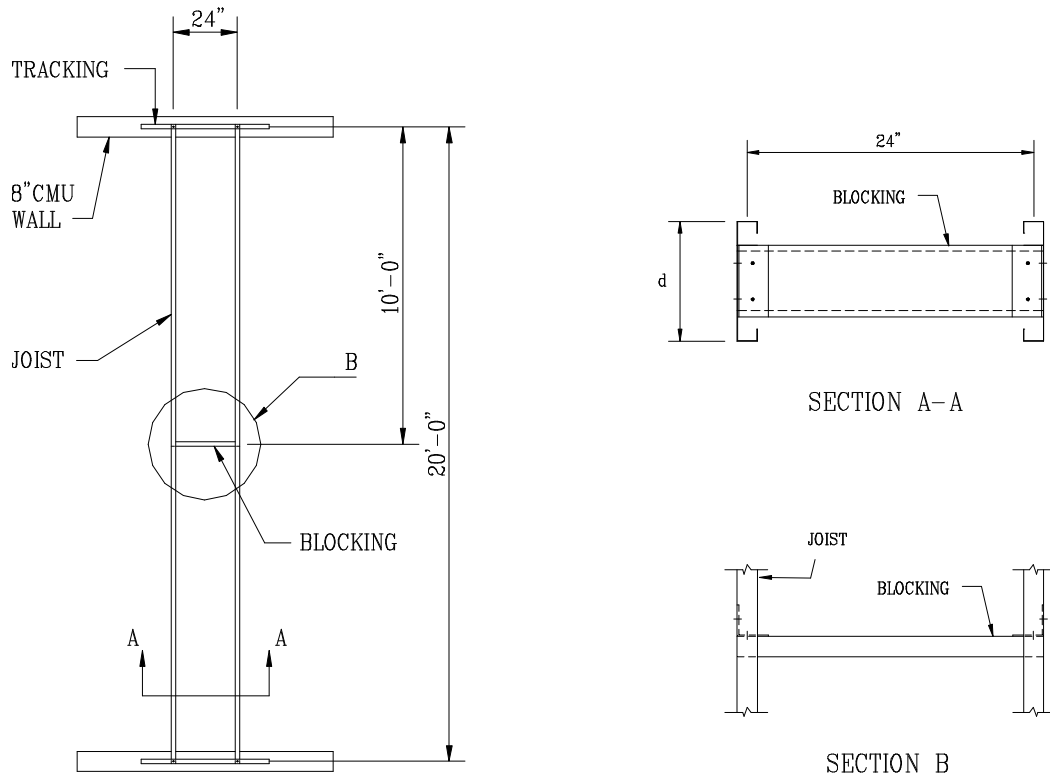


Figure 2.11 Two-Joist Line Plan and Blocking Detail

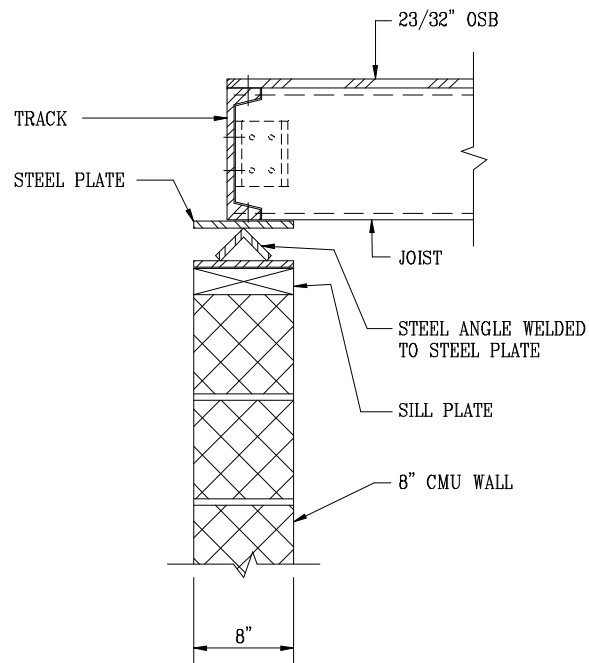


Figure 2.12 Two-Joist Line End Support Detail

2.3.2 Description of Tests

2.3.2.1 Concentrated Load

If significant composite action is present in a floor system, it must be accounted for in the calculation of the moment of inertia. Composite action between the sub-flooring and the joists contributes to the stiffness of a floor. Stiffness of a floor system can be back calculated from the measured deflection under a point load. The measured stiffness of the bare system and of the joist plus OSB system can be used to determine the effective width of sheathing and thus the percent composite action.

A static, concentrated, incremental load was applied to each joist. The maximum value of this load varied according to the design capacity of the joist, but the number of loading increments remained the same for each test (5 increments). Dial gages were used to measure the vertical deflection of the bottom flange of each joist at midspan and the top flange of each joist at the end supports. The average of the deflection readings from the top flange was subtracted from the midspan deflection reading to obtain the true center line deflection. Incremental readings were plotted against incremental load during the test to insure that the system was behaving linearly.

It became apparent in the first test of the bare joist system that achieving linear deflection would be difficult, unless twist of the joists was minimized. Several different methods were tried. Strapping was attached to the bottom flange of each joist at midspan connecting the two joists. Blocking was placed at midspan between the two joists. The entire system was turned upside down and rotated. Lateral bracing was provided on the outside of each joist at mid-height and midspan. It was finally decided that blocking placed at the midspan between the joists would sufficiently solve the twisting problem.

Through this type of testing, it was determined that composite action was not significant in the test floors. Determination of the joist moment of inertia from test data is discussed in Section 3.2.1.

2.3.2.2 Heel Drop Impact

A heel drop performed by a 135 lb (61.2 kg) female was used to impact the two-joist line test setup. Sub-flooring was attached to the joists for all heel drop tests. The accelerometer was placed on the OSB between the two joists at midspan and the floor was impacted next to the accelerometer. All data was taken with the Ono Sokki Handheld FFT Analyzer.

Frequency measurements were obtained for the test setup from fast Fourier transforms of the acceleration traces. Line loads, directly over the length of each joist, of 0 plf (0 N/m), 5 plf (73 N/m) or 10 plf (146 N/m) were in place when measurements were taken. Measured frequency was slightly lower than the predicted frequency when there was no extra weight added to the setup, but correlated well with the additional weight. Typical results are shown in Table 2.4.

Table 2.4 Frequency Comparison of 2J12A

2J12A	$f_{\text{predicted}}$	f_{measured}
0 plf	14.1	11.2
10 plf	9.2	9.6

2.4 In-Situ Floors

Three houses were visited in the Raleigh, North Carolina area to test *in-situ* steel cold-formed C-shaped supported residential floor systems. The floors were constructed using Unimast 925SJ joists, unless otherwise noted, with 23/32 in. (23 mm) plywood sheathing for sub-flooring. The sub-flooring was screwed and glued in each case and the joists were spaced at 16 in. (406 mm) on center. A summary of the layout, parameters, section properties and measured values for each floor is provided in Appendix B. This section describes the general layout and testing of the in-situ floors.

Because the houses where the floors were located were either partially or fully completed, the four tests described above were adjusted to fit the constraints of the site. Subjective evaluations were done with the evaluator sitting crossed-legged on the floor instead of in a straight legged chair as described in Section 2.2.2.1. Walking in place tests were performed in place of the standard walking tests when necessary.

2.4.1 Site 1

Site 1 was a completely furnished and occupied house. Six floor areas were tested at this site. Where possible, the underside of the floor was examined to determine if there were any other parameters involved in the basic construction of the floor (i.e. blocking, holes for mechanical and duct work, strapping, bearing stiffeners). A heel drop was performed in the approximate center of the floor by a 205 lb man. A 205 lb (93 kg) load was placed at midspan of the center joist and vertical displacement was measured by use of a dial gage and recorded. Extrapolation was used to determine the center joist deflection under a 225 lb (1.0 kN) load. Walking parallel and perpendicular to the joists could not be done because the floor was completely furnished. Walking in place in the center of a floor area was substituted for the typical walking procedure.

All dynamic test data was taken with the Ono Sokki CF-1200 Handheld FFT Analyzer and recorded on the accompanying memory card. The accelerometer and the floor excitation were both placed as close to the center of the floor as possible. The floor was subjectively evaluated by the measurement team. The occupant of the house was not aware of the survey conducted for each floor, but offered no complaint of the vibration level of any of the floors tested.

2.4.2 Site 2

Site 2 was a house under construction. The first floor of the entire house had only the sub-flooring attached and stud walls in place without any drywall hung. A crawl space under the entire house was available for inspection of the first floor joists and for set up of the center

joist deflection tests. No blocking, strapping, standard joist holes or holes for mechanical and duct work were found in the joists.

Three floor areas were tested at this site. Dynamic tests included a heel drop by a 205 lb (93 kg) man in the center of the bay and walking parallel and perpendicular to the joists. All acceleration and frequency data were taken with the Ono Sokki Analyzer and recorded on the accompanying data card. Midspan center joist deflection under the application of a 205 lb (93 kg) load was obtained for all three floors. Deflection was measured with a dial gage placed at midspan of the bottom flange center joist. Subjective evaluation by the measurement team was recorded for each floor as well.

2.4.3 Site 3

Two floor areas were inspected at Site 3. This house was furnished and occupied. One floor was in the process of being refinished and only had 23/32 in. (19 mm) plywood as the sub-flooring in place. The other floor was constructed out of Unimast 80SJ18 C-joists. Heel drop and walking tests were performed on each floor by a 205 lb (93 kg) man and recorded with the Ono Sokki. Walking in place was substituted for the standard walking tests on the floor constructed out of Unimast 80SJ18 joists. Mid-bay deflection was not taken on either floor because of the inability to get to the underside of the joists in each floor. Subjective evaluation was performed for the two floors with the evaluator sitting crossed-legged near the center of the floor.

CHAPTER 3

EVALUATION OF EXPERIMENTAL DATA

3.1 Existing Tolerance Criteria

The intent of this study was to determine which of the four criteria examined, Swedish, Australian, American or Canadian, would most accurately predict the vibration performance of CFSJ framed floors. As discussed in Chapter 2, twelve CFSJ laboratory floors of varying joist size and length and eleven *in-situ* floor areas were tested and classified with respect to vibration acceptability. The four criteria examined below have been thoroughly discussed in Sections 1.4.1.1 through 1.4.1.4 of this document. The results of the tests conducted, a comparison to the four criteria and the selection of the appropriate criterion for CFSJ floors will be discussed in this Chapter.

3.1.1 Evaluation of Existing Tolerance Criteria

3.1.1.1 Swedish Criterion

The current criterion used in Sweden for predicting vibration acceptability in floors was developed after years of research by Sven Ohlsson. Ohlsson's criterion (Ohlsson 1988) is a complete design guide to predict a floor's performance with respect to vibration when subject to human activity. The guide is said to be material independent and involves a check on three parameters believed to effect the level of vibration felt in a floor: static load, impulse velocity response and continuous loading. All three limitations must be met for a floor to have an acceptable rating.

The design methods in the Swedish Building Technology guide pertain only to floors for which the lowest natural frequency, f_1 , is greater than 8 Hz. All of the NAHB test floors had a measured fundamental frequency above this 8 Hz limit. Further discussion on measured fundamental frequencies is found in Section 3.3

Ohlsson's design guide specifies a check on the deflection of the floor due to a static load placed at the weakest point on the floor. A 225 lb (1.0 kN) load was placed at mid-bay of each test floor and the resulting deflection of the center joist was recorded. This deflection was then compared to the 0.059 in. (1.5 mm) limitation set by Ohlsson (Ohlsson 1988). As seen in Table 3.1, all configurations of floors 8A and 8B and floor 12A with strapping at midspan did not meet the limitation on static load deflection.

The classification chart shown in Figure 3.1 is used in the second check of Ohlsson's criterion, a check on the impulse velocity response, h'_{max} . Two parameters, h'_{max} and a damping coefficient, σ_o , for each floor are plotted on Figure 3.1 to obtain a rating of the floor. The chart is designed specifically for the values of h'_{max} to be calculated in SI units. For the purpose of computation and classification, a conversion of the necessary values from USC units to SI units was implemented.

**Table 3.1 Classification of all Test Floors According to the
Swedish Building Technology Design Guide**

Floor	Span (ft)	Parameter	δ_{meas} (in.)	δ_{crit} (in.)	Meet Check 1?	$\dot{h}_{\text{max}}$ (mm/s/Ns)	σ_o (s ⁻¹)	Check 2 Rating	Overall Classification
8A	13'-9"	strap	0.088	0.059	No	-	-	-	-
		blocking	0.090	0.059	No	32.0	0.20	M	U
		drywall	0.071	0.059	No	36.6	0.16	M	U
8B	12'-3"	strap	0.070	0.059	No	41.4	0.17	M	U
		blocking	0.068	0.059	No	41.4	0.17	M	U
8C	10'-9"	strap	0.054	0.059	Yes	35.1	0.29	A	A
		blocking	0.050	0.059	Yes	35.1	0.29	A	A
8D	8'-10"	strap	0.038	0.059	Yes	36.5	0.33	A	A
		blocking	0.049	0.059	Yes	40.7	0.31	A	A
8E	7'-1"	strap	0.012	0.059	Yes	41.8	0.31	A	A
		blocking	0.025	0.059	Yes	41.8	0.36	A	A
10C	15'-3"	strap	0.046	0.059	Yes	27.3	0.24	A	A
		blocking	0.041	0.059	Yes	27.8	0.23	A	A
		drywall	0.048	0.059	Yes	30.0	0.21	M	M
10D	13'-1"	strap	0.039	0.059	Yes	34.3	0.24	M	M
		blocking	0.051	0.059	Yes	33.4	0.25	M	M
		holes	0.042	0.059	Yes	34.8	0.23	M	M
12A	19'-7"	strap	0.061	0.059	No	25.9	0.19	M	U
		blocking	0.058	0.059	Yes	-	-	-	-
12B	17'-6"	strap	0.039	0.059	Yes	27.4	0.20	M	M
		blocking	0.045	0.059	Yes	26.8	0.21	M	M
12C	16'-2"	strap	0.044	0.059	Yes	25.8	0.24	A	A
		blocking	0.041	0.059	Yes	26.5	0.23	A	A
12D	14'-1"	strap	0.040	0.059	Yes	30.9	0.27	A	A
		blocking	0.037	0.059	Yes	31.8	0.27	A	A
12E	11'-3"	strap	0.019	0.059	Yes	40.8	0.29	M	M
		blocking	0.025	0.059	Yes	42.5	0.28	M	M

U = unacceptable

M = marginal

A = acceptable

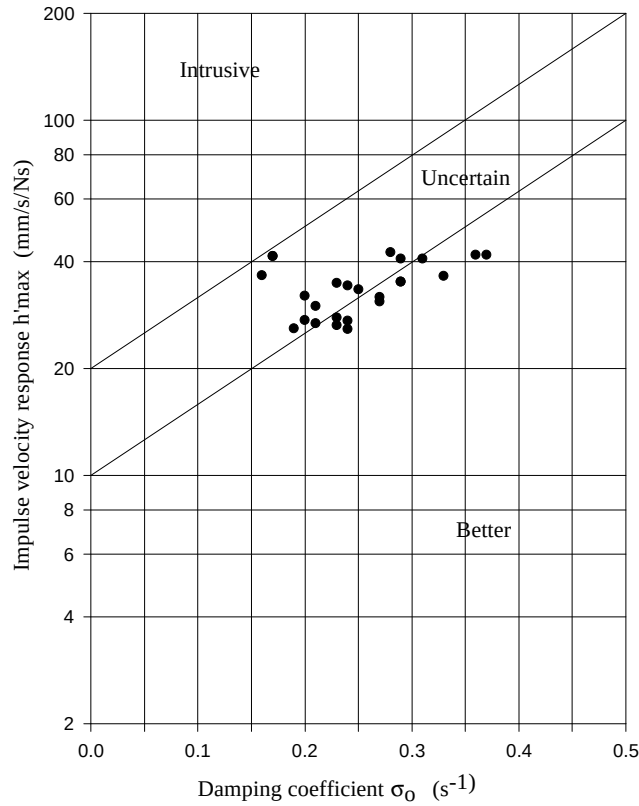


Figure 3.1 Plot of Laboratory Test Floor Data on Ohlsson's Classification Chart

The impulse velocity response, h'_{max} , is a response to an impulse load of 1.0 kN. The time domain data recorded for all test floors is an acceleration trace of a heel drop, not a velocity trace of a unit impulse. Thus, the initial vertical response of the time domain data generated in this study cannot be compared to the limitation for this parameter. As a result, Equation 1.4 was used to predict the impulse velocity response for each floor. Measured frequency values were used in the calculation of h'_{max} and σ_0 .

The damping coefficient, σ_0 , is the parameter that determines how rapidly a harmonic vibration is damped in time (Equation 1.5). Ohlsson points out that this value of the damping coefficient is more difficult to predict when several frequency components are involved. However, Equation 1.5 may be considered as an acceptable approximation. Again, because the recorded data was acceleration traces and not velocity traces, the equation for predicting the damping coefficient was used.

The Swedish design guide does not offer any advice on how to account for the effect of holes or blocking or other such variances in the floor system. It is assumed for the purpose

of this work that the determined classification from this guide applies to all possible variations of a given floor.

The classification determined from plotting the values of $h'_{\max}$ and σ_o for each test floor on Figure 3.1 are found in Table 3.1. All values used to calculate $h'_{\max}$ and σ_o for each floor are found in Appendix D. The floor classifications “Better”, “Uncertain” and “Intrusive” shown in Figure 3.1 correspond to the floor classifications “Acceptable”, “Marginal” and “Unacceptable”, respectively, listed in Table 3.1. The majority of the test floors fell under the uncertain category, which corresponds to marginal on the scale used for subjective evaluation of each floor.

All three criteria must be met for the floor to be rated acceptable. However, for the purpose of this work, the check on the response to continuous loading, w'_{RMS} (Equation 1.6), has not been done due to the lack of the necessary guidance as to what the limiting value should be (see Section 1.4.1.1). Ohlsson states that the value in question should be compared to the w'_{RMS} value of a floor of similar composition and construction which is considered to be acceptable. The check on the response to continuous loading is only applicable for floors with a span of 13.1 ft (4m) or greater. All floors tested in the laboratory exceeding this span length were classified as either marginal or unacceptable. Therefore, there is no acceptable test floor which would provide an approximate limitation to this third criterion.

The overall rating of each floor according to the criterion is tabulated in Table 3.1. Twelve of the 27 floors were found to be acceptable, eight floors were rated marginal and five floors were classified as unacceptable. Two floors could not be classified because frequency measurements were taken only when the floors were supporting additional weight.

3.1.1.2 Australian Code

The Australian Code is a modified version of the criterion developed by Ohlsson and is applicable for steel framed floor systems which have a lowest natural frequency above 8 Hz. All of the laboratory test floors had a measured fundamental frequency above 8 Hz. Two dynamic serviceability requirements, deflection due to static load and maximum impact velocity, must be satisfied to classify a floor as acceptable in terms of vibration level for this Code.

Deflection of a floor, subject to the application of a 225 lb (1.0 kN) static concentrated load anywhere on the floor, is limited by the Code to 0.079 in. (2.0 mm). Measured deflection resulting from a 225 lb (1.0 kN) load applied at mid-bay was compared to this limiting value for deflection and is shown in Table 3.2. Only one floor, 8A, exceeded the deflection limit. However, when floor 8A had drywall attached to its underside, the deflection was decreased and no longer exceeded the limiting value.

The maximum impact velocity, $V_{\max}$, is similar to the impulse velocity response, $h'_{\max}$, in the Swedish criterion. It is the maximum velocity response of the floor due to a unit impulse load of 1.0 N-s applied anywhere on the floor and is determined from Equation 1.8. The value of the maximum impact velocity is limited by a function of the damping coefficient, σ_o (Equation 1.9).

Measured frequency values of the floors were not used to calculate the values of $V_{\max}$ and s_o , because the Code requires that the floor system frequency include a uniformly

distributed live load of 6.26 psf (0.3 kPa). The necessary live load is more than the additional weight added to any floor system. All values used to compute $V_{\max}$ and σ_o can be found in Appendix D. A conversion of the necessary values from USC units to SI units was done to calculate the maximum impact velocity.

Table 3.2 Classification of all Test Floors According to the Australian Standard Domestic Metal Framing Code

Floor	Span (ft)	Parameter	δ_{meas} (in.)	δ_{crit} (in.)	Meet Check 1?	$\log_{10}(V_{\max})$ (mm/s/Ns)	$1.2 + \sigma_o$	Meet Check 2?	Overall Classification
8A	13'-9"	strap	0.088	0.079	No	1.32	1.38	Yes	U
		blocking	0.090	0.079	No	1.32	1.38	Yes	U
		drywall	0.071	0.079	Yes	1.32	1.38	Yes	A
8B	12'-3"	strap	0.070	0.079	Yes	1.35	1.43	Yes	A
		blocking	0.068	0.079	Yes	1.35	1.43	Yes	A
8C	10'-9"	strap	0.054	0.079	Yes	1.39	1.50	Yes	A
		blocking	0.050	0.079	Yes	1.39	1.50	Yes	A
8D	8'-10"	strap	0.038	0.079	Yes	1.45	1.58	Yes	A
		blocking	0.049	0.079	Yes	1.45	1.58	Yes	A
8E	7'-1"	strap	0.012	0.079	Yes	1.43	1.79	Yes	A
		blocking	0.025	0.079	Yes	1.43	1.79	Yes	A
10C	15'-3"	strap	0.046	0.079	Yes	1.28	1.39	Yes	A
		blocking	0.041	0.079	Yes	1.28	1.39	Yes	A
		drywall	0.048	0.079	Yes	1.28	1.39	Yes	A
10D	13'-1"	strap	0.039	0.079	Yes	1.32	1.46	Yes	A
		blocking	0.051	0.079	Yes	1.32	1.46	Yes	A
		holes	0.042	0.079	Yes	1.32	1.46	Yes	A
12A	19'-7"	strap	0.061	0.079	Yes	1.17	1.36	Yes	A
		blocking	0.058	0.079	Yes	1.17	1.36	Yes	A
12B	17'-6"	strap	0.039	0.079	Yes	1.21	1.40	Yes	A
		blocking	0.045	0.079	Yes	1.21	1.40	Yes	A
12C	16'-2"	strap	0.044	0.079	Yes	1.24	1.43	Yes	A
		blocking	0.041	0.079	Yes	1.24	1.43	Yes	A
12D	14'-1"	strap	0.040	0.079	Yes	1.29	1.48	Yes	A
		blocking	0.037	0.079	Yes	1.29	1.48	Yes	A
12E	11'-3"	strap	0.019	0.079	Yes	1.34	1.64	Yes	A
		blocking	0.025	0.079	Yes	1.34	1.64	Yes	A

U = unacceptable

M = marginal

A = acceptable

The calculated values of the right and left side of Equation 1.9 are tabulated in Table 3.2. All test floors met the requirement for limiting the maximum impact velocity. The final

classification of all floors using the Australian criterion is shown in Table 3.2. All floors except Floor 8A were classified as acceptable. Floor 8A was classified as unacceptable.

3.1.1.3 United States Criterion

Johnson (1994) proposed a simple criterion for determining the vibration acceptability of a timber floor at the design stage. His findings were based on the results of frequency measurements taken of 86 timber floors under construction. The fundamental frequency of a timber floor supporting only its own weight must be greater than 15 Hz to avoid annoying floor vibrations induced by human activity (Johnson 1994).

Measured fundamental frequency values for each test floor were compared to the limit proposed by Johnson and are tabulated in Table 3.3. All values are compiled from an average of the resulting frequency from at least three heel drop impacts. The classification of each floor based on the above criterion is summarized in Table 3.3.

The frequency measurements for Floor 8A with strapping and Floor 12A with blocking were taken with a 30 lb (13.6 kg) sand bag placed at each quarter point on the floor. These measurements cannot be compared to the criterion proposed by Johnson because of the additional weight supported by each floor. All remaining floors are classified as acceptable.

Table 3.3 Classification of all Test Floors According to the 1994 Proposed U.S. Timber Floor Criterion

Floor	Span (ft)	Parameter	Measured Frequency (Hz)	Johnson's Limit (Hz)	Classification
8A	13'-9"	strap	N-A	15.0	--
		blocking	20.3	15.0	A
		drywall	16.2	15.0	A
8B	12'-3"	strap	17.2	15.0	A
		blocking	17.4	15.0	A
8C	10'-9"	strap	29.2	15.0	A
		blocking	29.0	15.0	A
8D	8'-10"	strap	32.9	15.0	A
		blocking	31.4	15.0	A
8E	7'-1"	strap	37.2	15.0	A
		blocking	35.6	15.0	A
10C	15'-3"	strap	24.0	15.0	A
		blocking	22.0	15.0	A
		drywall	20.5	15.0	A
10D	13'-1"	strap	24.3	15.0	A
		blocking	25.0	15.0	A
		holes	23.4	15.0	A
12A	19'-7"	strap	19.1	15.0	A
		blocking	N-A	15.0	-
12B	17'-6"	strap	20.2	15.0	A
		blocking	20.6	15.0	A
12C	16'-2"	strap	23.6	15.0	A
		blocking	22.6	15.0	A
12D	14'-1"	strap	27.0	15.0	A
		blocking	26.5	15.0	A
12E	11'-3"	strap	29.3	15.0	A
		blocking	28.5	15.0	A

U = unacceptable

A = acceptable

N-A = no available data

3.1.1.4 Canadian Criterion

The current Canadian criterion for timber floors is based on the results of an extensive field study conducted in Canada in the 1970's (Onysko 1985). The survey involved the assessment of perceived acceptability of 646 timber floors. The original recommendation (Onysko 1985) formed the basis of the adoption of a timber floor vibration criterion in the 1990 National Building Code of Canada. A modified version of the criterion for floors with a span length of 9.84 feet (3.0 m) or greater has since been introduced (Onysko 1995) and is shown in Equation 1.10. The central floor deflection of a floor with a span length less than 9.84 feet (3.0 m) is limited to 0.079 in. (2.0 mm).

A static concentrated load of 225 lb (1.0 kN) was applied to all test floors at mid-bay. The resulting central deflection was measured as discussed in Section 2.2.2.3 and recorded for each floor. Comparison of the measured central deflection to the limiting deflection and the classification of each floor is shown in Table 3.4.

All floors with a measured deflection less than the limiting value are considered acceptable. For the purpose of this study, a floor classified as marginal had a measured deflection within 10 percent above the deflection limit. Fourteen floors were classified as acceptable, nine floors were classified as unacceptable and four floors were classified as marginal.

Table 3.4 Classification of all Test Floors According to the National Building Code of Canada Deflection Criterion

Floor	Span (ft)	Parameter	Measured Deflection (in.)	Onysko's Limit (in.)	Classification
8A	13'-9"	strap	0.088	0.049	U
		blocking	0.090	0.049	U
		drywall	0.071	0.049	U
8B	12'-3"	strap	0.070	0.057	U
		blocking	0.068	0.057	U
8C	10'-9"	strap	0.054	0.067	A
		blocking	0.050	0.067	A
8D	8'-10"	strap	0.038	0.079	A
		blocking	0.049	0.079	A
8E	7'-1"	strap	0.012	0.079	A
		blocking	0.025	0.079	A
10C	15'-3"	strap	0.046	0.043	M
		blocking	0.041	0.043	A
		drywall	0.048	0.043	U
10D	13'-1"	strap	0.039	0.052	A
		blocking	0.051	0.052	A
		holes	0.042	0.052	A
12A	19'-7"	strap	0.061	0.031	U
		blocking	0.058	0.031	U
12B	17'-6"	strap	0.039	0.036	M
		blocking	0.045	0.036	U
12C	16'-2"	strap	0.044	0.040	M
		blocking	0.041	0.040	M
12D	14'-1"	strap	0.040	0.047	A
		blocking	0.037	0.047	A
12E	11'-3"	strap	0.019	0.063	A
		blocking	0.025	0.063	A

U = unacceptable

M = marginal

A = acceptable

3.1.2 Selection of Acceptable Criterion

Table 3.5 is a summary and comparison of the classification of all floors using the four considered criteria (Australian, Canadian, Swedish and U. S.) with the subjective rating. All further discussion in this section will be in reference to Table 3.5.

It is obvious that both the U. S. criterion for timber floors and the Australian Code for metal framed floors are far too lenient in their classification for floor systems of the type investigated in this study. Neither criterion is judged acceptable for the classification of steel framed floors similar in nature and construction to the floors considered in this study.

Table 3.5 Comparison of the Classification of all Test Floors

Floor	Joist Size	Span	Parameters	Criterion Classification				Subjective Evaluation
				Australia	Canada	Sweden	US	
8A	2x8x43	13' 9"	strap blocking drywall	U	U	--	--	U
				U	U	U	A	U
				A	U	U	A	U
8B	2x8x43	12' 3"	strap blocking	A	U	U	A	U
				A	U	U	A	U
				A	A	A	A	A
8C	2x8x43	10' 9"	strap blocking	A	A	A	A	A
				A	A	A	A	A
				A	A	A	A	A
8D	2x8x33	8' 10"	strap blocking	A	A	A	A	A
				A	A	A	A	A
				A	A	A	A	A
8E	2x8x33	7' 1"	strap blocking	A	A	A	A	A
				A	A	A	A	A
				A	A	A	A	A
10C	2x10x43	15' 3"	strap blocking drywall	A	M	A	A	U
				A	A	A	A	U
				A	U	M	A	U
10D	2x10x43	13' 1"	strap blocking holes	A	A	M	A	U
				A	A	M	A	M
				A	A	M	A	--
12A	2x12x54	19' 7"	strap blocking	A	U	U	A	M
				A	U	--	--	M
				A	M	M	A	U
12B	2x12x54	17' 6"	strap blocking	A	U	M	A	M
				A	M	A	A	M
				A	M	A	A	M
12C	2x12x43	14' 1"	strap blocking	A	A	A	A	M
				A	A	A	A	M
				A	A	M	A	A
12D	2x12x43	11' 3"	strap blocking	A	A	M	A	A
				A	A	M	A	A
				A	A	M	A	A

U = unacceptable

M = marginal

A = acceptable

The classification from the Canadian criterion for timber floors matched the subjective classification for 16 out of the 26 tested floors. However, one must recall that the existing criterion does not account for any variation to the floor (i.e. blocking, drywall and holes). When these floors are taken out, seven of the remaining twelve floors are given the same classification.

Twelve out of 24 floors classified under the criterion developed by Ohlsson matched the subjective evaluation of the floors. As in the Canadian criterion, the Swedish criterion offers no guidance as to how to account for variations in the floor system. When only considering the floors with strapping attached at midspan, five out of the twelve floors are classified as they are in the subjective evaluations.

Many of the floors are given the same classification by the Canadian and Swedish criteria. The most noticeable difference is with the floors built from 10 in. deep joists; the Canadian criterion is slightly more accepting. However, neither criterion matches the subjective classification well for the 10 in. deep floors tested.

It appears that either the Swedish or Canadian criterion as they exist would be satisfactory for use in classifying the vibration acceptance of cold-formed C-shaped steel joist floor systems of the type considered in this study. Despite the slightly more lenient classification of the 10 in. deep joist floors, the Canadian and Swedish criteria tended to classify the test floors in a similar manner. However, the criterion developed by Ohlsson entails a much more complicated method of classification and appears to be slightly less accurate. Therefore, it is recommended that the Canadian criterion for timber floors be implemented as a satisfactory criterion for judging CFSJ floor systems similar in nature and construction to the floors considered in this study.

A review of the *in-situ* floor results is discussed in Chapter 4. Figure 3.2 is a plot of measured central deflection versus span length for the laboratory and *in-situ* floors with Onysko's Criterion. The classifications of acceptable, marginal and unacceptable correspond to the subjective ratings of each floor. Any floor which plots below the curve in Figure 3.2 should have acceptable vibration levels, due to human activity, according to Onysko's criterion.

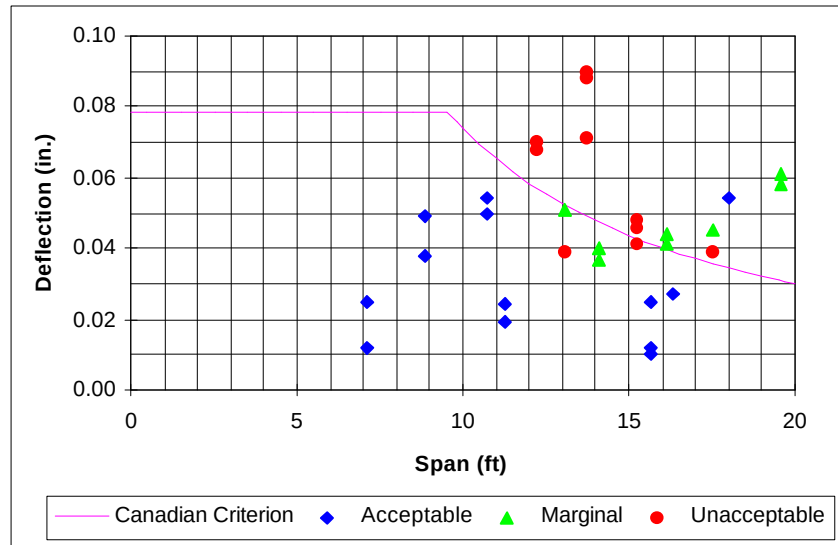


Figure 3.2 Canadian Criterion Curve with Laboratory and *In-Situ* Floor Data

3.2 Prediction of Central Floor Deflection

The criterion selected as the most suitable for predicting perceived acceptability of CFSJ floors of the type and construction considered in this study is the Canadian criterion. The criterion makes use of the central deflection of the floor system under the application of a 225 lb (1.0 kN) load at mid-bay. Deflection of a system is dependent on the stiffness of the system. Determination of significant composite action between the joists and sub-flooring is discussed in Section 3.2.1.

An acceptable method of predicting the central floor deflection must be available. Three such existing methods for predicting the central floor deflection are examined in the following sections. Two make use of the idea of load sharing (number of joists in a system which effectively carry the applied load) and one multiplies the applied load by a reduction factor. Predicted values of the floor deflection will be compared to the measured floor deflection of each laboratory floor.

3.2.1 Calculation of Moment of Inertia

The moment of inertia is used to calculate many floor properties such as deflection and frequency. If significant composite action occurs between the sub-flooring and the joists, then a transformed moment of inertia must be used to calculate all floor properties. The effective sheathing width of the sub-flooring is necessary in the calculation of the transformed moment of inertia. The method used in this study to determine the effective sheathing width is the deflection of a tee-beam under the application of a point load.

Five two-joist line (tee-beam) tests were conducted to determine the amount of composite action (effective sheathing width) in the floor system between the sub-flooring (OSB) and the joists. A complete description of the set-up and testing procedure was

discussed in Section 2.3.1. The two joists used for each test will be referred to as the north joist and the south joist based on their orientation in the laboratory during testing.

An incremental point load was placed above the center line of each joist and the resulting adjusted midspan deflection was recorded. Incremental load versus adjusted center line deflection was plotted during each test to insure that the system was behaving linearly (Appendix C). This testing procedure was used for the bare joist system and again for the joists with OSB attached.

An average center line deflection for each joist was determined from the load versus deflection graph plotted for each test. An average moment of inertia was then calculated using the standard deflection equation for both the bare joist system, I_{bare} , and the joist and OSB system, I_{OSB} (Table 3.6).

Back calculation of the transformed moment of inertia was used to determine the effective sheathing width for each two-joist line system. The procedure was taken directly from Runte (1993). Runte (1993) performed similar deflection tests on tee-beam models constructed from wood I-joists, solid sawn wood joists and wood trusses. The modulus of elasticity of OSB was taken as 580,000 psi ($4.01E+09$ N/m²) from the panel dry axial stiffness tabulated in the American Plywood Association technical Note N375B (1995). An example derivation of the effective sheathing width, b_e , from the two-joist line tests is shown in Appendix C. Table 3.6 provides a summary of b_e for each two-joist line test.

Table 3.6 Moment of Inertia Determined from Two-Joist Line Tests

Floor	Bare Joist Test				Joist + OSB Test				b _e (in.)
	Measured Deflection			I _{bare} (in ⁴)	Measured Deflection			I _{OSB} (in ⁴)	
	North Joist	South Joist	Average of Two Joists		North Joist	South Joist	Average of Two Joists		
2J8A	0.257	0.248	0.252	3.05	0.271	0.266	0.268	3.59	2.1
2J8B	0.209	0.234	0.221	4.35	0.174	0.185	0.179	5.38	4.2
2J10A	0.231	0.221	0.226	12.78	0.201	0.203	0.202	14.30	4.0
2J12A	0.0996	0.101	0.100	14.05	0.093	0.0905	0.092	15.36	2.4
2J12B	0.248	0.248	0.248	11.60	0.229	0.247	0.268	12.15	1.0

The results show that the actual amount of OSB that contributes to the stiffness of the system varies from one to four inches (25.4 to 101.6 mm). It is concluded that the OSB cannot be relied upon to provide a significant amount of composite action for design purposes. Thus, the moment of inertia that should be used in the calculation of deflection and frequency is simply the bare joist moment of inertia.

Table 3.7 is a summary of all laboratory test floor measured values. The moment of inertia determined from the two-joist line tests is tabulated for each floor. The value of the moment of inertia for Floors 10C and 10D was taken from the values tabulated by NAHB for 2x10x43 CFSJ because a two-joist line test was not conducted with this joist size. Calculated values of the moment of inertia for each joist are similar to the measured values.

Table 3.7 Experimental Data of Laboratory Floors

Floor	Joist	Span	Parameter	Measured Values			
				I_{bare}	A_o	A_{ot}	N_{eff}
				(in ⁴)	(in.)	(in.)	
8A	2x8x43	13'-9"	strap	4.35	0.088	0.164	1.86
			blocking	4.35	0.090	0.164	1.82
			drywall	4.35	0.071	0.164	2.31
8B		12'-3"	strap	4.35	0.070	0.116	1.66
			blocking	4.35	0.068	0.116	1.70
8C		10'-9"	strap	4.35	0.054	0.078	1.45
			blocking	4.35	0.050	0.078	1.57
8D	2x8x33	8'-10"	strap	3.06	0.038	0.062	1.63
			blocking	3.06	0.049	0.062	1.27
8E		7'-1"	strap	3.06	0.012	0.032	2.66
			blocking	3.06	0.025	0.032	1.28
10C	2x10x43	15'-3"	strap	7.38	0.046	0.132	2.87
			blocking	7.38	0.041	0.132	3.22
			drywall	7.38	0.048	0.132	2.75
10D		13'-1"	strap	7.38	0.039	0.083	2.13
			blocking	7.38	0.051	0.083	1.63
			holes	7.38	0.042	0.083	1.98
12A	2x12x54	19'-7"	strap	14.06	0.061	0.147	2.40
			blocking	14.06	0.058	0.147	2.53
12B		17'-6"	strap	14.06	0.039	0.105	2.68
			blocking	14.06	0.045	0.105	2.32
12C		16'-2"	strap	14.06	0.044	0.082	1.87
			blocking	14.06	0.041	0.082	2.01
12D	2x12x43	14'-1"	strap	11.6	0.040	0.066	1.65
			blocking	11.6	0.037	0.066	1.79
12E		11'-3"	strap	11.6	0.019	0.034	1.77
			blocking	11.6	0.025	0.034	1.35

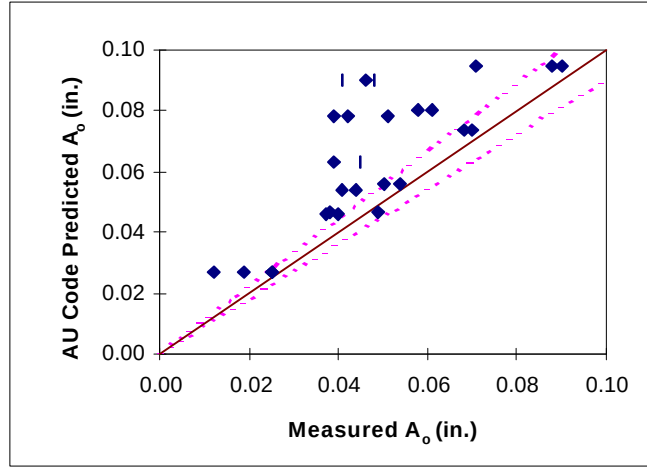
3.2.2 Load Reduction Factor to Account for Load Sharing

To estimate the center floor deflection, the Australian Standard Domestic Framing Code (1993) uses a reduction factor, k_d , based on the stiffness properties of the joists and sub-flooring, to modify the standard midspan beam deflection equation (Equation 1.7).

For the floors in this study, the modulus of elasticity of the sub-flooring was 580,000 psi ($4.01E+09$ N/m²) and the modulus of elasticity of the joists was 29,500,000 psi ($2.04E+11$ N/m²). As discussed in Section 3.2.1, the measured moment of inertia from the two-joist line

tests was used to calculate the predicted central floor deflection. A summary of the values used to predict the floor deflection of each laboratory test floor is found in Appendix D.

The applied load multiplied by the reduction factor, k_d , produces an effective applied load, the part of the load which causes deflection. The predicted central deflection for each test floor according to this method is plotted against the measured floor deflection in Figure 3.3. Eight predicted floor deflections out of the 27 floors tested are within ten percent of the measured value.



**Figure 3.3 Floor Deflection:
AU Code Predicted versus Measured Deflection**

3.2.3 Load Sharing Prediction, N_{eff}

The effective number of joists, N_{eff} , is said to be the number of joists in a floor system which contribute to the resistance of an applied load. In defining the number of effective joists, the load is assumed to be applied over a single joist. The loaded joist is considered to be fully effective and the neighboring joists become less and less effective as the distance from the loaded joist increases. It is possible that not all joists in a floor system play a role in resisting the displacement due to an applied load. Joists beyond the location of zero deflection, the point at which no significant change in the floor characteristics occur, are not considered. The calculation of the location of zero deflection, x_o , was discussed in Section 1.4.2.1. A discussion of the experimental method of determining the number of effective joists takes place in Section 3.2.3.1. Two methods for predicting the number of effective joists, N_{eff} , are examined in Section 3.2.3.2.

3.2.3.1 Experimental Method

The number of effective joists, N_{eff} , repeated here for convince, is defined as:

$$N_{eff} = \frac{A_{ot}}{A_o} \quad (1.20)$$

where A_{ot} is the maximum dynamic amplitude of a tee-beam subject to a heel drop and A_o is the maximum dynamic amplitude of a floor system due to a heel drop impact. Experimental values for A_o were obtained for each test floor in the manner described in Section 2.2.2.3. Likewise, experimental values for A_{ot} were obtained for each two-joist line test as described in Section 2.3.2.1. These values and Equation 1.20 were used to determine an experimental value of the number of effective joists in each floor system. All values of measured A_o , measured A_{ot} and corresponding N_{eff} are tabulated in Table 3.7.

3.2.3.2 Mathematical Methods

Two methods for predicting the number of effective joists in a floor system will be examined in this section. The first is a model developed for the Steel Joist Institute (Lenzen and Dorsett 1969) and applicable to steel beam- and steel joist-concrete slab floors with joist spacing of 30 in. (762 mm) or less. The second was developed by Kitterman (1994) and is applicable to steel joist- and steel beam-concrete slab floors with spacing less than five feet.

The SJI Equation (Equation 1.19) was developed by Lenzen and Dorsett (1969) to predict the number of effective joists in steel beam- and steel joist-concrete slab floor systems. The number of effective joists for all test floors was computed using the SJI Equation. Predicted and measured values of N_{eff} are tabulated in Table 3.8 for comparison. All values calculated for the equation variables are summarized in Appendix D. The calculated moment of inertia as described in Section 3.2.1 was used in all calculations.

Figure 3.4 is a graphical representation of the accuracy of the SJI Equation in predicting the number of effective joists for floors of the type and construction considered in this research. The SJI Equation predicts N_{eff} within ten percent for eleven out of the 27 test floors. The lone data point in the lower right corner of Figure 3.4 is attributed to a bad deflection reading for Floor 8E with strapping attached.

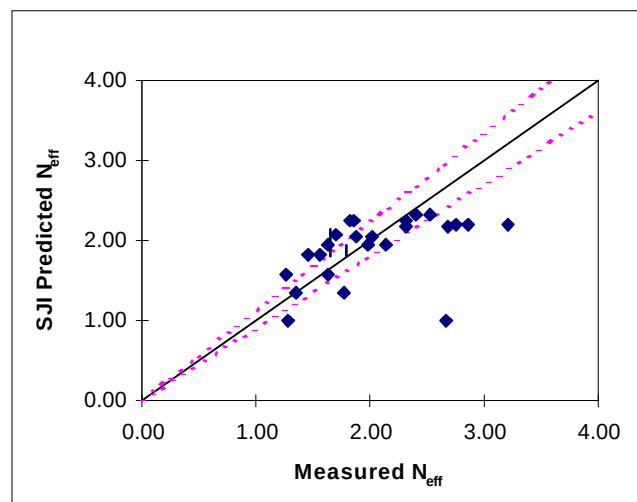


Figure 3.4 Number of Effective Joists: Measured versus SJI Predicted

The second equation for predicting the number of effective joists in a floor system is a result of the work done by Kitterman (1994). The current accepted equations for predicting the number of effective joists in a floor system are the SJI Equation discussed above and the AISC Equation, discussed in Section 1.4.2.1. The SJI Equation was developed for floor systems with a beam spacing of 30 in. (762 mm) (Murray 1991) and the AISC Equation (Equation 1.21) was developed for floor systems with a beam spacing between 6 ft (1.83 m) and 15 ft (4.57 m) (Saksena and Murray 1972). For floors with beam spacing between 30 in. (762 mm) and 6 ft (1.83 m) the AISC Equation is considered applicable by Murray (1991). Through use of a multiple linear regression analysis, Kitterman developed Equation 1.22 and concluded that it is accurate for floors with beam spacing of five feet and under.

Figure 3.5 is a graphical representation of the measured values of N_{eff} versus the values of N_{eff} predicted using Kitterman's Equation. Calculated values of N_{eff} for each floor are tabulated in Table 3.8. All values calculated for the prediction of N_{eff} using Kitterman's Equation are summarized in Appendix D.

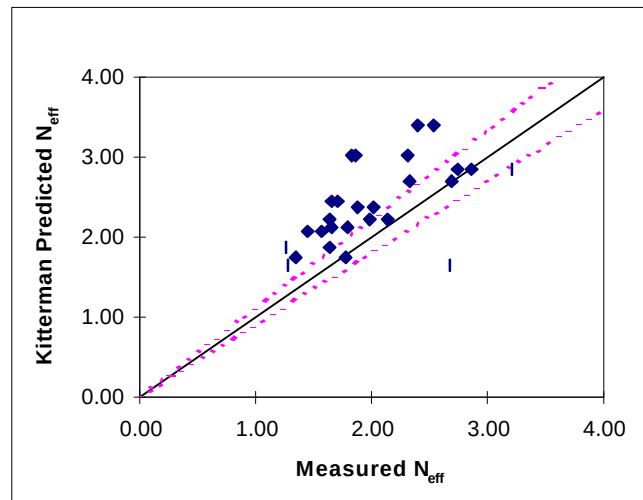


Figure 3.5 Number of Effective Joists: Measured versus Kitterman Predicted

The equation developed by Kitterman tends to overpredict the values of N_{eff} and thus underpredict the floor deflection. The number of effective joists for five out of the 27 test floors was predicted within ten percent of the measured value. The equation is judged to be unconservative for predicting the center floor deflection of CFSJ floor systems. The lone point under the curve is associated with the deflection recorded for Floor 8E with strapping.

Table 3.8 Number of Effective Joists: Measured and Predicted

Floor	Parameter	N_{eff}^*		
		Measured	Kitterman	SJI
8A	strap	1.86	3.02	2.25
	blocking	1.82	3.02	2.25
	drywall	2.31	3.02	2.25
8B	strap	1.66	2.46	2.07
	blocking	1.70	2.46	2.07
8C	strap	1.45	2.07	1.83
	blocking	1.57	2.07	1.83
8D	strap	1.63	1.87	1.58
	blocking	1.27	1.87	1.58
8E	strap	2.66	1.66	1.00
	blocking	1.28	1.66	1.00
10C	strap	2.87	2.85	2.21
	blocking	3.22	2.85	2.21
	drywall	2.75	2.85	2.21
10D	strap	2.13	2.23	1.95
	blocking	1.63	2.23	1.95
	holes	1.98	2.23	1.95
12A	strap	2.40	3.41	2.33
	blocking	2.53	3.41	2.33
12B	strap	2.68	2.71	2.17
	blocking	2.32	2.71	2.17
12C	strap	1.87	2.38	2.05
	blocking	2.01	2.38	2.05
12D	strap	1.65	2.12	1.88
	blocking	1.79	2.12	1.88
12E	strap	1.77	1.75	1.34
	blocking	1.35	1.75	1.34

*shaded regions are within 10% of measured

3.2.4 Acceptable Deflection Prediction Method

Three methods of predicting the central deflection of a floor system have been examined: Australian Standard, SJI Equation and Kitterman's Equation. Predicted central deflection is obtained from the values of N_{eff} predicted by the Kitterman Equation and the SJI Equation, the measured deflection from the two-joist tests, and Equation 1.20. The predicted values of central deflection from the three methods are tabulated in Table 3.9 along with the measured values for central floor deflection due to a concentrated load. A plot of the measured center floor deflections versus the predicted values is in Appendix D.

It is apparent that the SJI Equation in conjunction with Equation 1.20 is the most acceptable model reviewed. The SJI model provides an accurate prediction (within ten percent of measured) of the floor deflection for eleven of the 27 test floors. The Australian method predicts, within ten percent, the floor deflection of eight of the test floors and the model developed by Kitterman predicts the deflection of six floors within ten percent of the measured value. Because the SJI Equation underpredicts the values of N_{eff} , the resulting predicted central floor deflection is overestimated. For the vibration criterion selected in Section 3.1.2, a method which overpredicts the floor deflection is preferred over a method which underpredicts the floor deflection as the Kitterman model does. The overprediction of the floor deflection can be considered a more conservative model when used with the deflection criterion developed by Onysko. Onysko's criterion limits the amount of deflection acceptable for a floor free from annoying vibration problems. The Australian method overpredicts the floor deflection as well, but is extremely conservative compared to the SJI method.

It is recommended that the SJI Equation (Equation 1.19) in conjunction with Equation 1.20 be used as the method to predict floor deflection due to a 225 lb (1.0 kN) concentrated load applied at mid-bay. Such a method is satisfactory for floors of the type and construction similar to those considered in this study.

Table 3.9 Summary of Predicted Floor Deflections

Floor	Parameter	Measured A _{ot} (in.)	A _o *			
			Measured (in.)	Kitterman (in.)	SJI (in.)	AU Code (in.)
8A	strap	0.164	0.088	0.054	0.073	0.095
	blocking	0.164	0.090	0.054	0.073	0.095
	drywall	0.164	0.071	0.054	0.073	0.095
8B	strap	0.116	0.070	0.047	0.056	0.074
	blocking	0.116	0.068	0.047	0.056	0.074
8C	strap	0.078	0.054	0.038	0.043	0.056
	blocking	0.078	0.050	0.038	0.043	0.056
8D	strap	0.062	0.038	0.033	0.039	0.047
	blocking	0.062	0.049	0.033	0.039	0.047
8E	strap	0.032	0.012	0.019	0.032	0.027
	blocking	0.032	0.025	0.019	0.032	0.027
10C	strap	0.132	0.046	0.046	0.060	0.090
	blocking	0.132	0.041	0.046	0.060	0.090
	drywall	0.132	0.048	0.046	0.060	0.090
10D	strap	0.083	0.039	0.037	0.043	0.078
	blocking	0.083	0.051	0.037	0.043	0.078
	holes	0.083	0.042	0.037	0.043	0.078
12A	strap	0.147	0.061	0.043	0.063	0.080
	blocking	0.147	0.058	0.043	0.063	0.080
12B	strap	0.105	0.039	0.039	0.048	0.063
	blocking	0.105	0.045	0.039	0.048	0.063
12C	strap	0.082	0.044	0.035	0.040	0.054
	blocking	0.082	0.041	0.035	0.040	0.054
12D	strap	0.066	0.040	0.031	0.035	0.046
	blocking	0.066	0.037	0.031	0.035	0.046
12E	strap	0.034	0.019	0.019	0.025	0.027
	blocking	0.034	0.025	0.019	0.025	0.027

* shaded values are within 10 % of measured

3.3 Prediction of Frequency

The fundamental mode of vibration is not the only mode of vibration present in cold-formed C-shaped supported floor systems. Several peaks, representing different modes of vibration, are present in the graph of the frequency domain. The work reported by Johnson (1994) showed similar findings in timber floors. Johnson (1994) attributed these peaks to three types of vibration: fundamental bending mode, “multiple” modes and torsional modes.

3.3.1 Fundamental Frequency

The fundamental bending mode of a floor system is the easiest frequency to measure and to predict. It can oftentimes be a good measure of floor vibration problems due to human activity. A typical way to measure the fundamental frequency of a floor is to obtain a Power Spectrum of the frequency from a real time trace. This is done by performing a fast Fourier transform on the data recorded in the time trace.

The data gathered for a real time trace record of all test floors was taken with an accelerometer connected to a data acquisition system. The data was run through a fast Fourier transform internally and a Power Spectrum was viewed almost instantaneously. The Power Spectrum is a graph of the frequency domain versus relative power. A typical acceleration trace and the resulting Power Spectrum for the floors investigated in this study is shown in Figure 3.6.

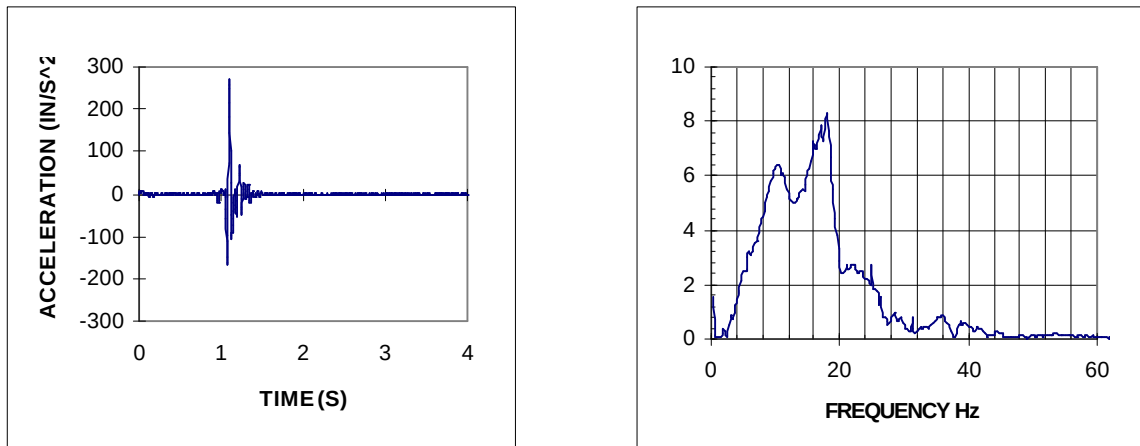


Figure 3.6 Acceleration Trace and FFT of Floor 8B

There is almost always a peak in the graph of the frequency domain that corresponds to the fundamental frequency of the floor. In the Power Spectrum shown in Figure 3.6, two dominant peaks are noticeable. The larger peak is representative of the fundamental frequency. The smaller peak (around 10 Hz) is considered to be attributed to the actual impact of the floor. A peak within the range of 8 to 12 Hz is detectable in every frequency graph taken on every floor. Because this peak is found in every Power Spectrum, regardless of the size of the joists, it is not considered to be representative of the fundamental frequency of the floor system.

The fundamental frequency is a function of the stiffness, weight and span of the floor system. Often, the predicted fundamental frequency is taken as the frequency of a single joist within the floor (Equation 1.16). Such a model has been found to be very accurate in predicting the fundamental frequency of timber, steel joist- and steel beam-concrete slab floors. The equation is repeated here for convince:

$$f = \frac{\pi}{2} \sqrt{\frac{gEI}{WL^3}} \quad (1.16)$$

where

f = fundamental frequency
g = 386.4 in/s² (9.81 m/s²)
E = modulus of elasticity
I = transformed moment of inertia
W = self weight of the floor
L = span length

Equation 1.16 is a modified version of the frequency model for simply supported rectangular orthotropic plates (Equation 1.1) applicable when $D_y/D_x < 0.01$. The predicted fundamental frequency of the floor represented in Figure 3.6 using Equation 1.16 is 18.1 Hz. As seen from the graph of the frequency domain, the measured fundamental frequency is 17.75 Hz.

A representative acceleration trace and corresponding FFT and a summary of the measured and predicted fundamental frequencies of each floor configuration is provided in Appendix A. The tabulated measured frequency values are an average from at least three heel drop impacts. The predicted frequency values are obtained from Equation 1.18 with the bare joist moment of inertia taken as the transformed moment of inertia as was determined in Section 3.2.1.

3.3.2 Multiple and Torsional Modes of Vibration

Johnson (1994) reported that several modes of vibration other than the fundamental bending mode contribute to the response of a timber floor represented in a Power Spectrum. It is difficult to excite a lightweight floor at only its fundamental frequency. A lightweight impact may excite certain modes of vibration that differ from those excited by a heavier impact. Higher frequencies in the floor may be excited if all the joists are not moving in unison (Johnson 1994).

Multiple and torsional modes of vibration as explained by Johnson (1994) are seen in many of the CFSJ test floor Power Spectrums. Examples of overlapping multiple and torsional modes of vibration are shown in Figures 3.7 and 3.8, respectively. Figure 3.7 is a trace from Floor 8B with strapping and 30 lb (13.6 kg) at each quarter point. Typically the additional weight “cleans up” the graph of the FFT and reduces the effect of the higher frequencies. The predicted fundamental frequency was 10.5 Hz. The dominant “peak” occurs at 17.25 Hz. Figure 3.8 is a trace from Floor 12E with blocking. The fundamental frequency was predicted to be 43 Hz. A peak around 44 Hz is significant, but the dominant peak is at 28.5 Hz.

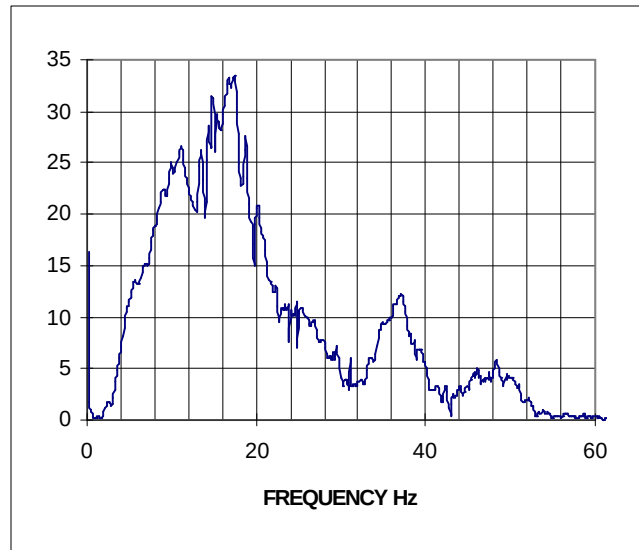


Figure 3.7 Overlapping Multiple Modes of Vibration in Floor 8B

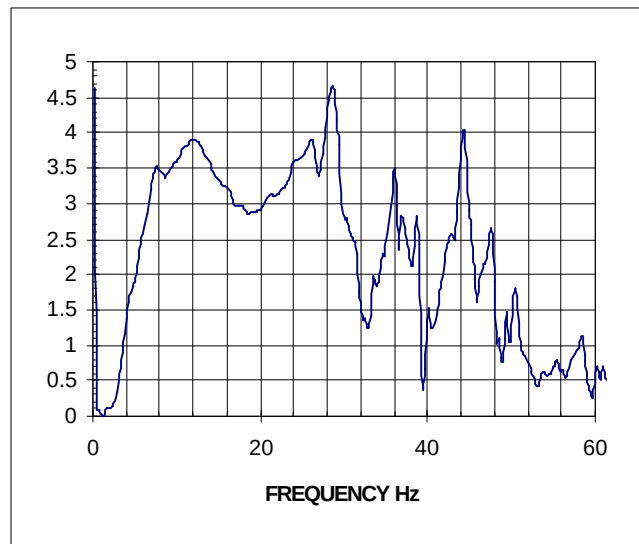


Figure 3.8 Torsional Modes of Vibration in Floor 12E

3.3.3 Conclusions

Fundamental frequency can be predicted and does appear in the graph of the frequency domain. However, many other modes of vibration are present and often cloud the clarity of the fundamental bending mode. Multiple modes of vibration, not just the fundamental bending mode, must contribute to the overall perception of the level of annoying vibrations in a cold-formed C-shaped steel joist floor.

CHAPTER 4

PROPOSED DESIGN PROCEDURE AND EVALUATION

4.1 Description of Method

The proposed method to determine subjective acceptability of a cold-formed, steel, C-joist supported residential floor system to vibration caused by normal occupant activity is compiled from a selection of the most suitable of the four criteria examined and the best fitting model to predict central floor deflection. The method is simple to apply in the design stage and depends only on the dimensions and cross-sectional properties of the floor. The method is applicable to steel floors similar in design and construction to the floors examined in this study. The proposed guideline is expressed in outline format in this section. Later sections offer design examples.

Proposed Guideline for Determining Vibration Acceptability in CFSJ Supported Residential Floor Systems due to Human Activity (USC Units):

1. Calculate the critical central floor deflection from Onysko's Criterion (Onysko 1995):

$$y_{\text{crit}} = \frac{37.32}{L^{1.3}} \quad (\text{in.})$$

where L is the floor span in inches.

2. Calculate the predicted deflection of a single joist, A_{ot} , due to a 225 lb concentrated load at midspan:

$$A_{\text{ot}} = \frac{225L^3}{48EI}$$

where

L = floor span

E = modulus of elasticity of the joists

I = moment of inertia of joist alone

3. Calculate the number of effective joists, N_{eff} , from the SJI Equation:

$$N_{\text{eff}} = 1 + 2 \sum \left(\cos \frac{x\pi}{2x_0} \right)$$

where

x = distance from the center joist to the joist under consideration

x_o = distance from center joist to the edge of the effective floor = $1.06\epsilon L$

L = joist span

$\epsilon = (D_x/D_y)^{0.25}$

D_x = flexural stiffness perpendicular to the joists = $E_c t^3/12$

D_y = flexural stiffness parallel to the joists = $E I_t/S$

E_c = modulus of elasticity of the sub-flooring

E = modulus of elasticity of the joists

t = sub-flooring thickness

I_t = moment of inertia of joist alone

S = joist spacing

4. Calculate the predicted central floor deflection, A_o :

$$A_o = \frac{A_{ot}}{N_{eff}}$$

where

A_o = deflection of floor at mid-bay

A_{ot} = deflection of a single joist due to a 225 lb concentrated load at midspan

N_{eff} = number of effective joists in the floor system

5. Compare the value of A_o to the critical deflection, y_{crit} :

If $A_o < y_{crit}$: Acceptable

If $A_o > y_{crit}$: Unacceptable

If $y_{crit} < A_o \leq 1.1(y_{crit})$: Marginal

4.1.1 Example 1

A floor is to be built using 2x12x54 C-Joists spaced 24 in. o.c.

The span is 19 ft - 0 in., single span.

The sub-flooring is 23/32 in. APA Rated STURD-I-FLOOR.

The floor is supported on a CMU foundation.

$$y_{crit} = \frac{37.32}{228^{1.3}} = 0.032 \text{ in.}$$

$$\Delta_{ot} = \frac{225 * 228^3}{48 * 29,500,000 * 15.65} = 0.120 \text{ in.}$$

$$D_x = \frac{580,000 * (23/32)^3}{12} = 1.79E + 04 \text{ lb - in.}$$

$$D_y = \frac{29,500,000 * 15.65}{24} = 1.92E + 07 \text{ lb - in.}$$

$$\epsilon = \left(\frac{1.79E + 04}{1.92E + 07} \right)^{.25} = 0.174$$

$$x_o = 1.06 * 0.174 * 228 = 42.2 \text{ in.}$$

$$\frac{x_o}{s} = \frac{42.2}{24} = 1.75$$

The summation is reduced to one term with $x = 24 \text{ in.}$

$$N_{\text{eff}} = 1 + 2 \left(\cos \frac{24\pi}{2 * 42.2} \right) = 2.25$$

$$A_o = \frac{0.120}{2.25} = 0.53 \text{ in.} > 0.032 \text{ in.}$$

This floor is rated as UNACCEPTABLE.

4.1.2 Example 2

A floor is to be built using 2x10x43 C-Joists spaced 24 in. o.c.

The span is 13 ft - 0 in., single span.

The sub-flooring is 23/32 in. APA Rated STURD-I-FLOOR.

The floor is supported on a CMU foundation.

$$y_{\text{crit}} = \frac{37.32}{156^{1.3}} = 0.052 \text{ in.}$$

$$\Delta_{\text{ot}} = \frac{225 * 156^3}{48 * 29,500,000 * 7.98} = 0.075 \text{ in.}$$

$$D_x = \frac{580,000 * (23 / 32)^3}{12} = 1.79E + 04 \text{ lb - in.}$$

$$D_y = \frac{29,500,000 * 7.98}{24} = 9.81E + 06 \text{ lb - in.}$$

$$\epsilon = \left(\frac{1.79E + 04}{9.81E + 06} \right)^{.25} = 0.207$$

$$x_o = 1.06 * 0.207 * 156 = 34.2 \text{ in.}$$

$$\frac{x_o}{s} = \frac{34.2}{24} = 1.42$$

The summation is reduced to a single term with $x = 24 \text{ in.}$

$$N_{\text{eff}} = 1 + 2 \left(\cos \frac{24\pi}{2 * 34.2} \right) = 1.90$$

$$A_o = \frac{0.075}{1.90} = 0.39 \text{ in.} < 0.052 \text{ in.}$$

This floor is rated as ACCEPTABLE.

4.2 Evaluation of *In-situ* Floors

The proposed method to determine subjective acceptability of CFSJ floors to annoying vibration is based on the results of the tests performed in the laboratory. It is useful to determine if the proposed model is suitable to evaluate the performance of occupied floors or floors under construction. Ten of the eleven *in-situ* floors were subjectively rated as acceptable; therefore the classification of the floors from the four criteria will not provide sufficient information to change the selected criterion. It can only be stated that the Canadian criterion is satisfactory for floor areas located in houses.

Eleven *in-situ* floors from three separate sites were evaluated. When possible the central floor deflection was measured. However, because the floors were parts of houses, it was not possible to reach the underside of every floor. Therefore, not all floors can be classified according to measured values. Classification of the floors by the investigating team will be referred to as “subjective evaluation”, as it has been throughout this document. Classification of the floors using measured deflection and Onysko’s Criterion will be referred to as “Criterion Evaluation”. The proposed method for classifying CFSJ floor systems was applied to all *in-situ* floors. Predicted central deflection was computed from the SJI Equation and compared to the critical deflection calculated from the Canadian criterion. Predicted values of N_{eff} , A_{ot} , and A_o are tabulated in Table 4.1. The classification resulting from the predicted values is also tabulated in Table 4.1 and will be referred to as the “Predicted Rating”. Frequency measurements due to heel drop impact and walking were recorded for all but one floor.

Table 4.1 Measured and Predicted Values of *In-situ* Floors

Floor	Joist	Span (in.)	f_{meas} (Hz)	f_{pred} (Hz)	δ_{meas} (in.)	δ_{crit} (in.)	Subjective Evaluation	Criterion Evaluation	N_{eff}	A_{ot} (in.)	A_o (in.)	Predicted Rating
S1LR	925SJ16	188	22.5	20.7	0.012	0.041	A	A	2.92	0.121	0.041	A
S1FYR	925SJ16	143.5	-	35.5	0.009	0.059	-	A	2.24	0.054	0.024	A
S1MBR	925SJ16	143	27.25	35.8	-	0.059	A	-	2.23	0.053	0.024	A
S1GR	925SJ16	188	13	20.7	0.01	0.041	A	A	2.92	0.121	0.041	A
S1BR#3	925SJ16	188	17.5	20.7	-	0.041	A	-	2.92	0.121	0.041	A
S1BR#4	925SJ16	188	17.5	20.7	-	0.041	A	-	2.92	0.121	0.041	A
S2DIN	925SJ16	196	19.3	19.0	0.027	0.039	A	A	3.07	0.137	0.045	U
S2LR	925SJ16	188	14.5	20.7	0.025	0.041	A	A	2.92	0.121	0.041	A
S2MBR	925SJ16	216	15.5	15.7	0.054	0.034	A	U	4.15	0.184	0.044	U
S3LR	925SJ16	164	25.5	27.2	-	0.049	A	-	2.41	0.080	0.033	A
S3BR	80SJ18	126	11.5	36.8	-	0.069	U	-	2.27	0.067	0.029	A

At Site 1, six floors were investigated. The house at the site was occupied; therefore all rooms were completely furnished. Table 4.1 is a summary of all measured and predicted values. Generally, the fundamental bending frequency was overpredicted. The floors in the master bedroom (S1MBR), great room (S1GR) and two bedrooms (S1BR#3, S1BR#4) were completely covered with thick wall-to-wall carpet. The accelerometer was placed on a hard

plate placed on the carpet as close to the center of the room as possible. The impact of the floor may have been softened by the carpeting, thus accounting for the difference in the measured and predicted values.

Not all floors were able to be classified by the Canadian criterion from Site 1, because measured floor values were only obtained from three floors. The classification of the floors using Onysko's Criterion is similar to the subjective evaluation for all but one floor. All floors were judged as acceptable by the investigating team. The proposed method for predicting subjective acceptability of floor vibration due to human activity gives a more conservative rating of the floors than the subjective evaluation by the investigating team.

Site 2 was a house under construction. Three floors on the first floor were investigated. Again, generally the predicted fundamental bending frequency was larger than the measured value. The living room (S2LR) is an exception. However, a large work table holding plans and tools was located on this floor, the weight of which was not included in the calculation of the predicted frequency.

The criterion rating of the vibration level for the master bedroom in this site is vastly different from the perceived vibration level. Upon inspection of the underside of the floor it was discovered that not all of the joists were fastened to the track at the time of the testing. It is suspected that this was the reason for the large measured value of central deflection and therefore the unacceptable classification from Onysko's Criterion.

Two floors were investigated at Site 3. The living room (S3LR) was in the process of being refinished; therefore the only flooring was plywood. The underside of the floors was not accessible; therefore measurement of the central floor deflection due to a concentrated load was not possible. The predicted rating of the living room floor does not agree with the evaluation by the investigation team. The small bedroom (S3BR) was located above the garage and appears to have been added to the house as an afterthought. Vibration in the floor was severely felt and a "drum" sound was perceptible when people walked around the room.

It appears that the proposed method of predicting subjective evaluation of vibration in CFSJ floors is conservative for floors that are in existing houses.

4.3 Conclusions

4.3.1 Summary of Research

"By developing a rational design procedure, fewer floors would be built that suffer from annoying vibrations" (Kitterman 1994). The development of a simple and accurate method of predicting the human reaction to annoying floor vibrations requires a vast amount of data. Three main concepts have been covered in this study. The results are briefly summarized.

Four existing criteria for predicting the subjective rating of timber floors to vibration have been reviewed. All test floors were classified by each criterion and the results were compared to the subjective evaluation. The Canadian Criterion developed by Onysko was selected to be proposed as a possible criterion for cold-formed steel joist residential floors because of its simplicity and satisfactory results.

A method of predicting the floor deflection at mid-bay is necessary to implement the recommended criterion at the design stage. Three existing methods were examined. The SJI method of calculating a value for the number of effective joists in a floor system was judged to correlate best with the measured values of mid-bay deflection. The deflection of the floor is then calculated by dividing the midspan deflection of a single joist under a concentrated load by the number of effective joists.

The fundamental bending frequency of a floor is the easiest frequency to predict and measure. When possible, it should be used in the investigation of a floor vibration problem. For many of the floors tested, the power spectrum did not show clearly defined peaks, but rather a “mound” of frequencies from which the fundamental frequency could not easily be determined. Such a circumstance was encountered by both Johnson (1994) and Shue (1995) in their research on timber floor vibration. The fundamental frequency was taken as the largest well defined peak in the power spectrum, unless that peak corresponded with a frequency within the 9 to 12 Hz range. A peak within that frequency range was apparent in every power spectrum and was taken as a function of the human impact rather than a direct response of the floor. Although this interpretation of the power spectrum was subject to skepticism, it was used for lack of a better method of determining the fundamental bending mode of floors with this type of recorded power spectrum.

The data presented and the conclusions drawn in this report represent only a beginning in the research of annoying floor vibration due to normal human occupancy in cold-formed C-joist supported residential floor systems. The report presents the best recommendations that can be made from examining existing guidelines to limit annoying floor vibration. Following the suggestions outlined in this document will lead to a smaller possibility of designing CFSJ floor systems with vibration problems due to human activity.

4.3.2 Future Research Needs

A larger database of tested and subjectively rated laboratory floors is needed to improve the accuracy of the proposed design criterion. It would be reasonable to investigate cold-formed C-shaped joists manufactured by other companies. The floors should vary in joist spacing and cover a wider range of span lengths. Research should also be conducted to investigate possible techniques for “correcting” an existing CFSJ floor with vibration problems.

The database for tested and subjectively rated *in-situ* floors should also be increased. The ideal floors would come from a series of houses still under construction. This would allow the investigating team to access the underside of the floor and obtain floor displacement measurements.

Further research needs to be conducted to investigate the mounds present in many of the power spectra of the test floors. Sample floors could be built and extensively tested. A mechanical heel drop resting on a force plate could be used to excite the floor. The floor could be impacted in the center and at each quarter point individually to determine the first two modes of vibration. The force plate would be used to obtain the force of the impact. This force could then be taken out of the power spectrum to obtain a true frequency spectrum. A series of tests could be performed with additional weight uniformly dispersed over the floor to

simulate an occupied floor. It appeared that the floors tested with additional weight had more clearly defined modes in their power spectra.

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APPENDIX A
SUMMARY OF LABORATORY FLOOR TESTS

Floor 8A (2x8x43 - 24" - 13'-9")
L/360, 30 psf LL (design deflection)

Joist Weight: 1.82 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue and Groove OSB

Fasteners: #8 x 1-1/4 Cement Board Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking, #8 self-drilling bugle-head screws for drywall

Parameters: Strap, Blocking, Drywall

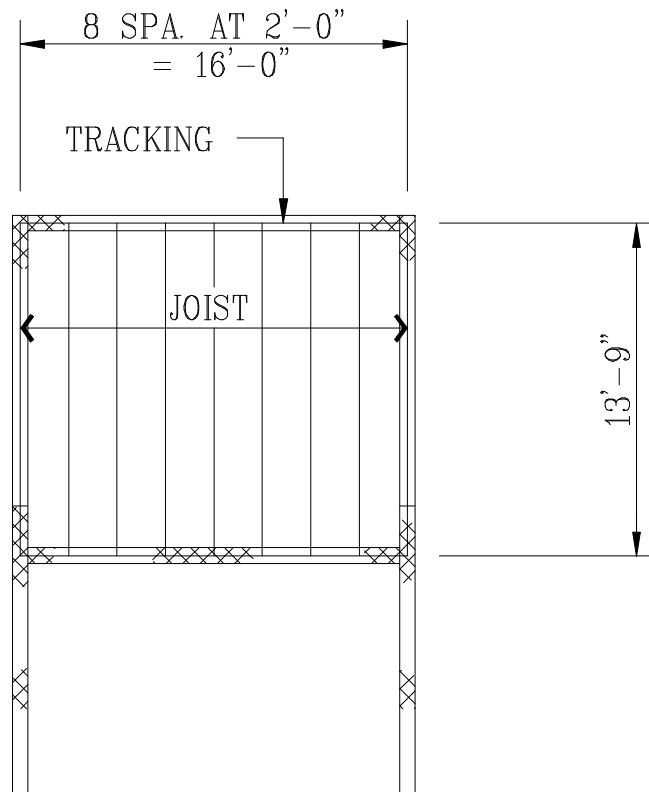


Figure A-1 Floor 8A Plan View

Floor 8A (cont.)

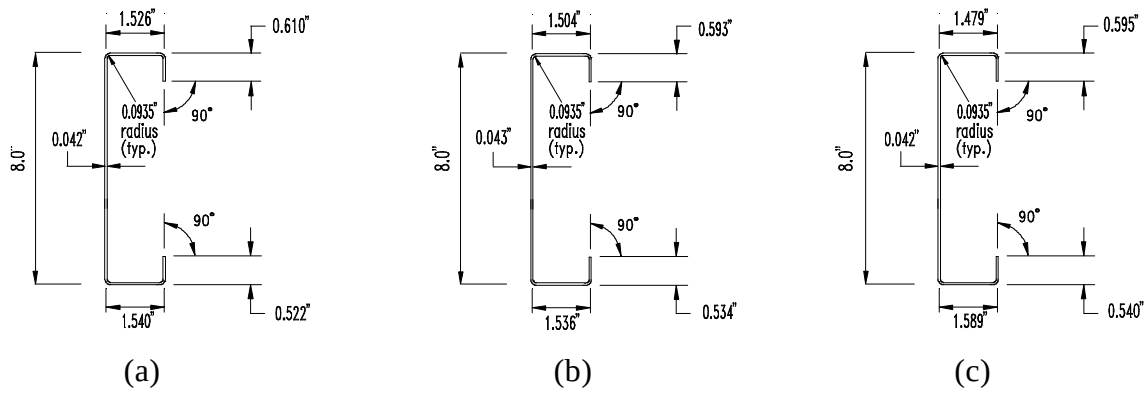


Figure A-2 Measured Joist Properties for Floors 8A, 8B and 8C

Table A-1 Floor 8A Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.50	0.51	0.50
I _x (in ⁴)	4.25	4.32	4.25
Frequency (Hz)	17.4	17.6	17.4

Table A-2

Parameter	Measured Moment of Inertia (in ⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid-bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S1	4.35	17.5	-	0.090	0.073
S1+30	4.35	8.7	9	-	-
B1	4.35	17.5	20.3	0.088	0.073
B1+30	4.35	8.7	9.6	-	-
B2+30	4.35	8.7	9.5	-	-
B3+30	4.35	8.7	9.4	-	-
DW	4.35	17.5	16.2	0.071	0.073

Floor 8A (cont.)

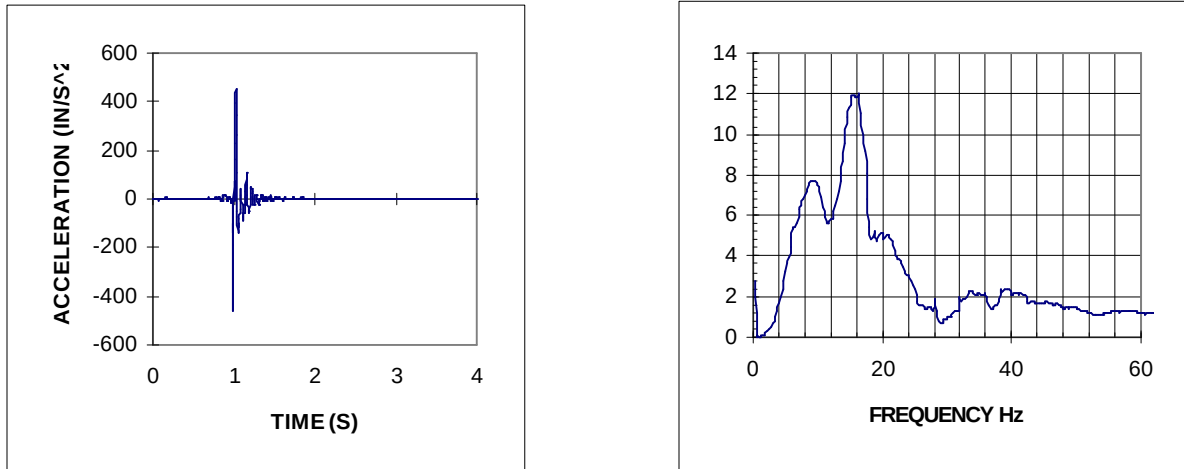


Figure A-3 Floor 8A Acceleration Trace and FFT

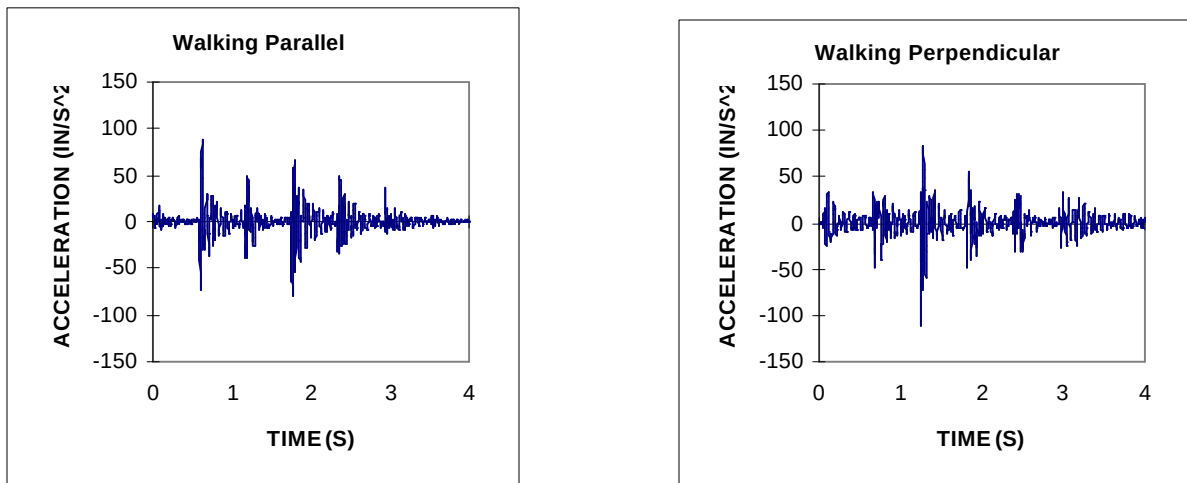


Figure A-4 Floor 8A Walking Acceleration Traces

Floor 8B (2x8x43 - 24" - 12'-3")
L/480, 40 psf LL (design deflection)

Joist Weight: 1.82 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue & Groove OSB

Fasteners: #8 x 1-1/4 Cement Board Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking.

Parameters: Strap, Blocking

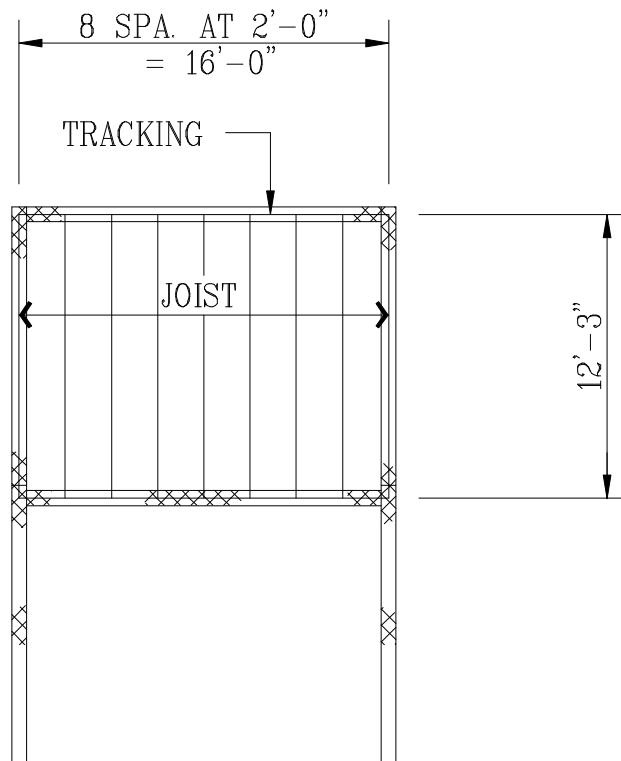


Figure A-5 Floor 8B Plan View

Measured Joist Properties: See Figure A-2

Floor 8B (cont.)

Table A-3 Floor 8B Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.50	0.51	0.50
I _x (in ⁴)	4.25	4.32	4.25
Frequency (Hz)	21.9	22.1	21.9

Table A-4

Parameter	Measured Moment of Inertia (in⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid-bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S1	4.35	22.0	17.2	0.070	0.056
B1	4.35	22.0	17.4	0.068	0.056

Floor 8B (cont.)

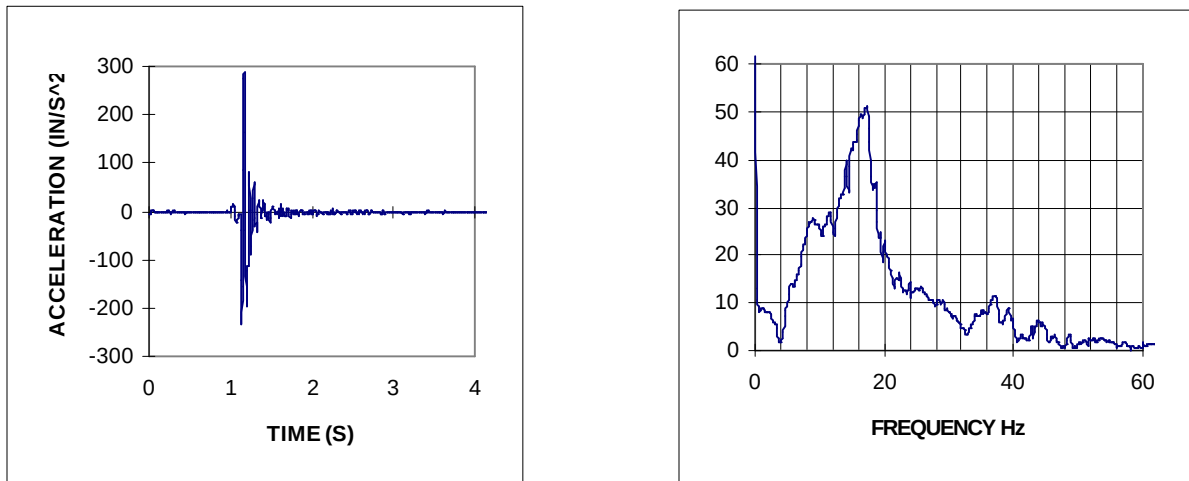


Figure A-6 Floor 8B Acceleration Trace and FFT

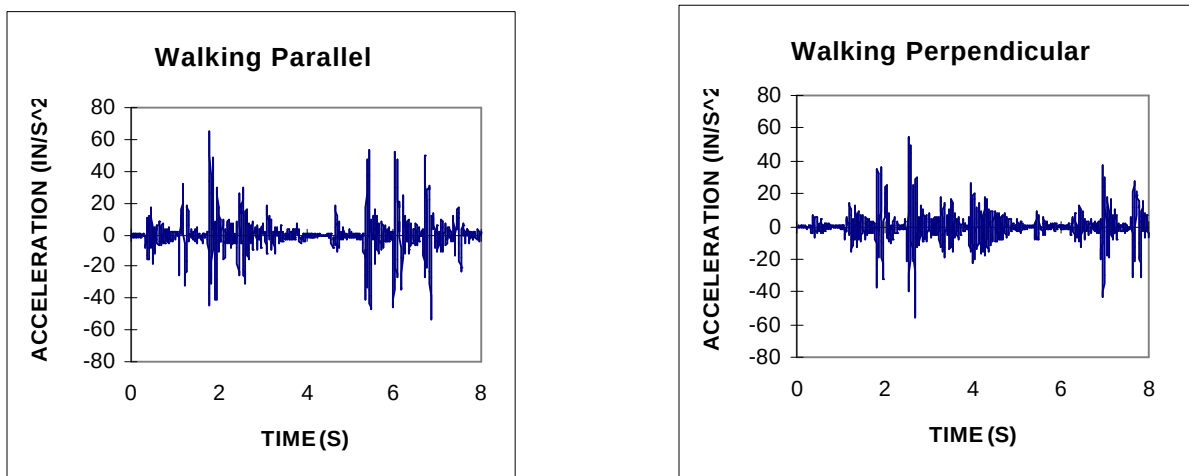


Figure A-7 Floor 8B Walking Acceleration Traces

Floor 8C (2x8x43 - 24" - 10'-9")
L/720, 40 psf LL (design deflection)

Joist Weight: 1.82 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue & Groove OSB

Fasteners: #8 x 1-1/4 Cement Board Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking.

Parameters: Strap, Blocking

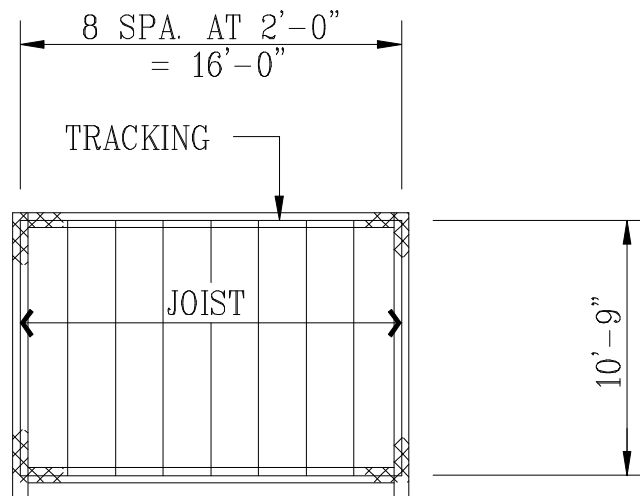


Figure A-8 Floor 8C Plan View

Measured Joist Properties: See Figure A-2

Floor 8C (cont.)

Table A-5 Floor 8C Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.50	0.51	0.50
I _x (in ⁴)	4.25	4.32	4.25
Frequency (Hz)	28.5	28.7	28.5

Table A-6

Parameter	Measured Moment of Inertia (in⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid-bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S1	4.35	28.8	29.2	0.054	0.043
S1+30	4.35	13.0	11.6	-	-
B1	4.35	28.8	29	0.050	0.043
B1+30	4.35	13.0	13.4	-	-

Floor 8C (cont.)

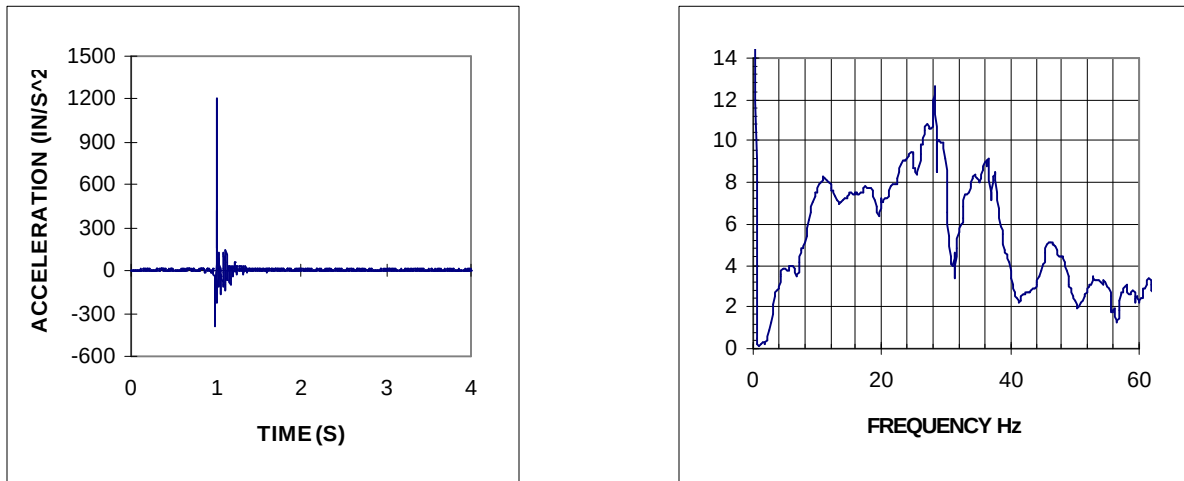


Figure A-9 Floor 8C Acceleration Trace and FFT

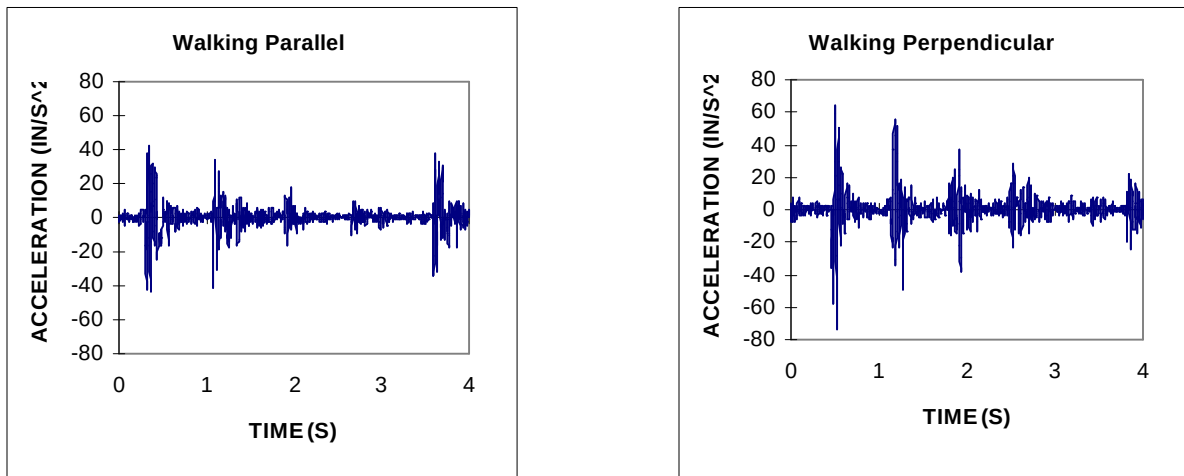


Figure A-10 Floor 8C Walking Acceleration Traces

Floor 8D (2x8x33 - 24" - 8'-10")
L/360, 30 psf LL (design deflection)

Joist Weight: 1.40 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue & Groove OSB

Fasteners: #10 x 1-7/16 Wafer Phillips "Winged" Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking.

Parameters: Strap, Blocking

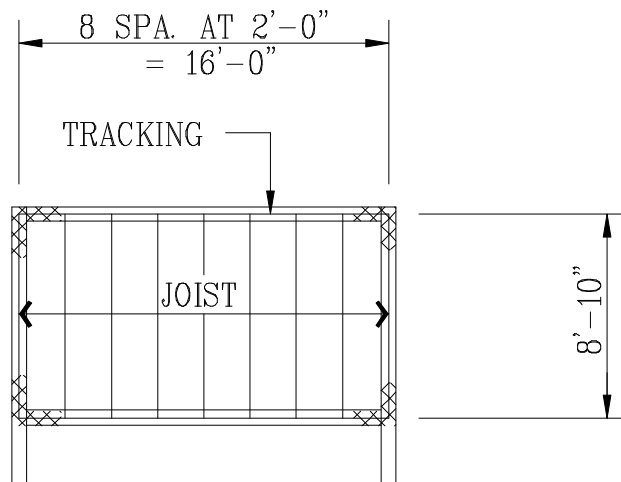


Figure A-11 Floor 8D Plan View

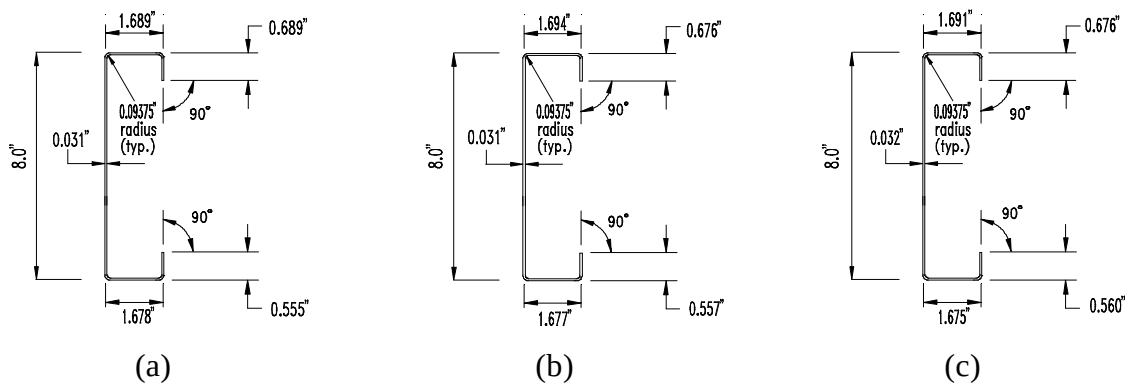


Figure A-12 Measured Joist Properties for Floors 8D and 8E

Floor 8D (cont.)

Table A-7 Floor 8D Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.381	0.381	0.393
I _x (in ⁴)	3.35	3.35	3.45
Frequency (Hz)	38.8	38.8	39.4

Table A-8

Parameter	Measured Moment of Inertia (in ⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid- bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S1	3.05	37.0	32.9	0.050	0.039
B1	3.05	37.0	31.4	0.040	0.039

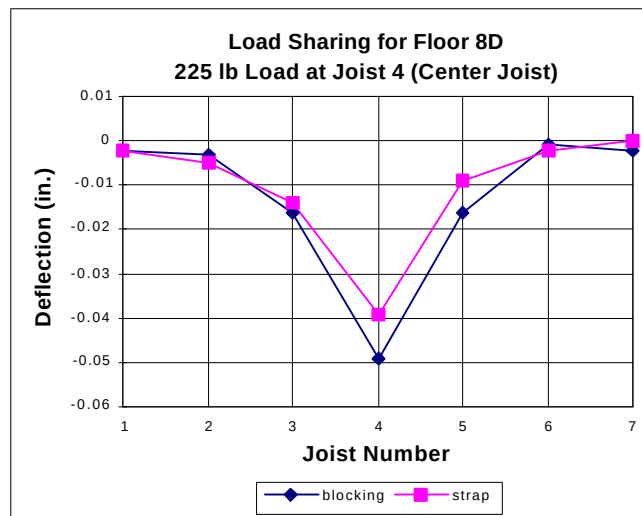


Figure A-13 Midspan Deflection Profile

Floor 8D (cont.)

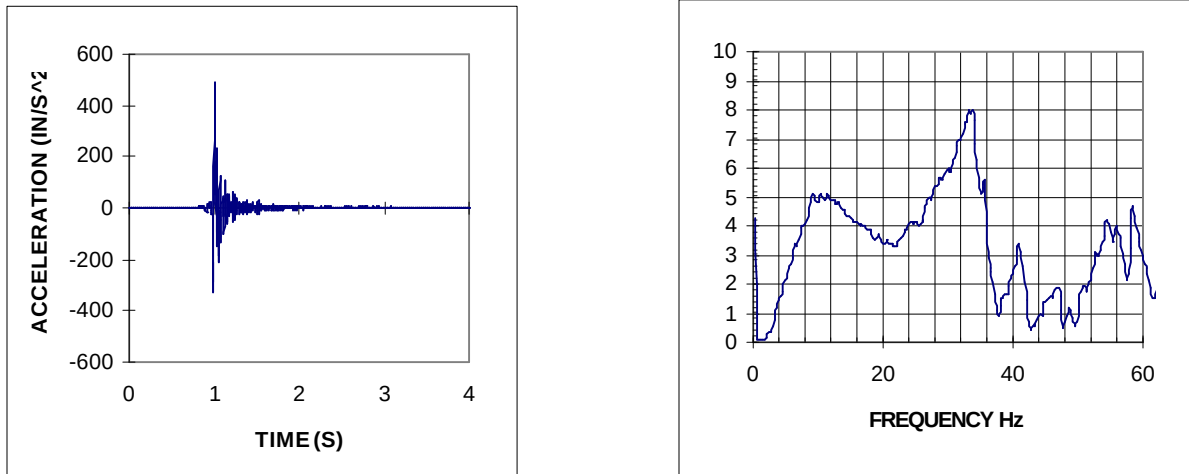


Figure A-14 Floor 8D Acceleration Trace and FFT

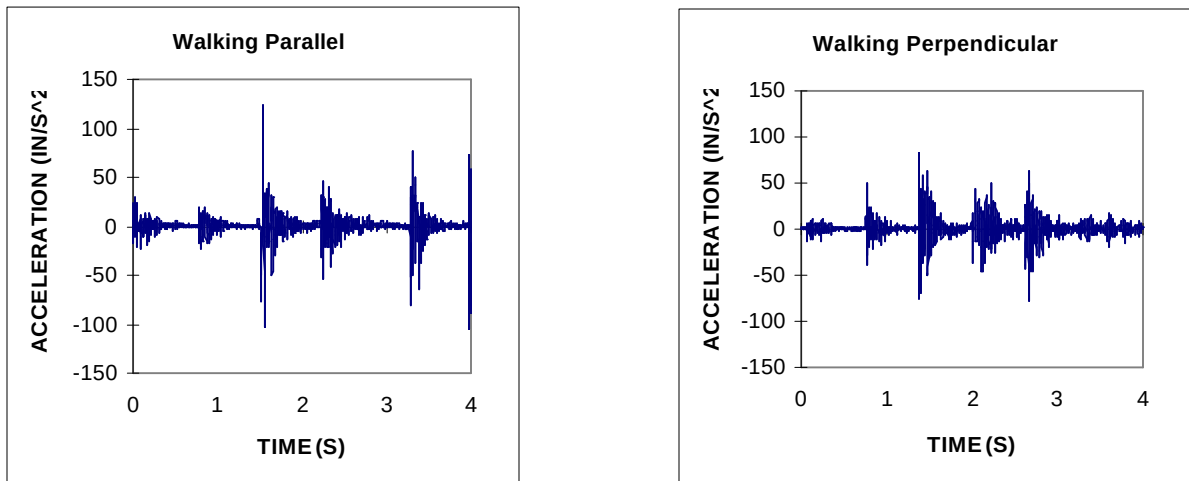


Figure A-15 Floor 8D Walking Acceleration Traces

Floor 8E (2x8x43 - 24" - 7'-1")
L/480, 40 psf LL (design deflection)

Joist Weight: 1.40 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue & Groove OSB

Fasteners: #10 x 1-7/16 Wafer Phillips "Winged" Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking.

Parameters: Strap, Blocking

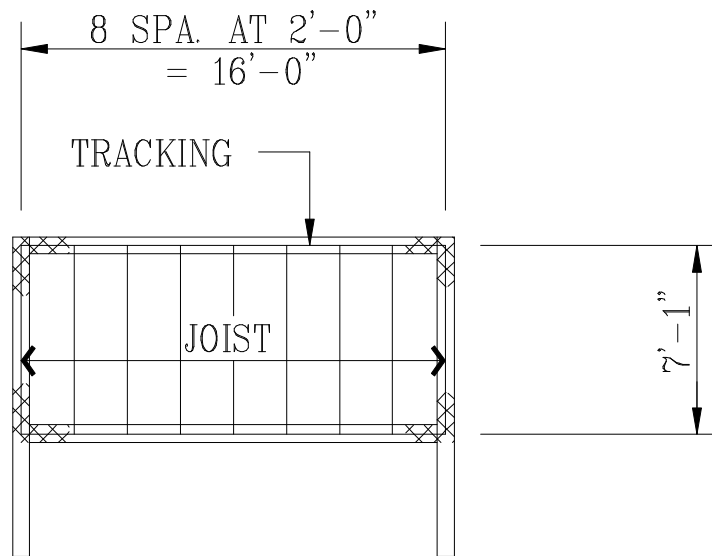


Figure A-16 Floor 8E Plan View

Measured Joist Properties: See Figure A-12

Floor 8E (cont.)

Table A-9 Floor 8E Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.381	0.381	0.393
I _x (in ⁴)	3.35	3.35	3.45
Frequency (Hz)	60.3	60.3	61.2

Table A-10

Parameter	Measured Moment of Inertia (in ⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid-bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S1	3.05	57.6	37.25	0.012	0.032
B1	3.05	57.6	35.6	0.025	0.032

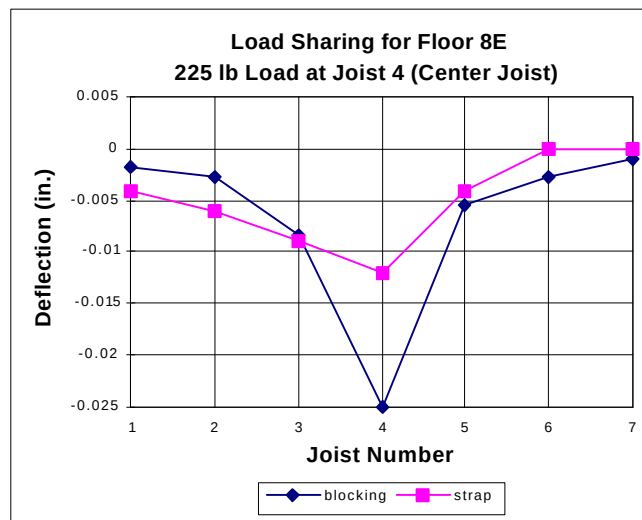


Figure A-17 Midspan Deflection Profile

Floor 8E (cont.)

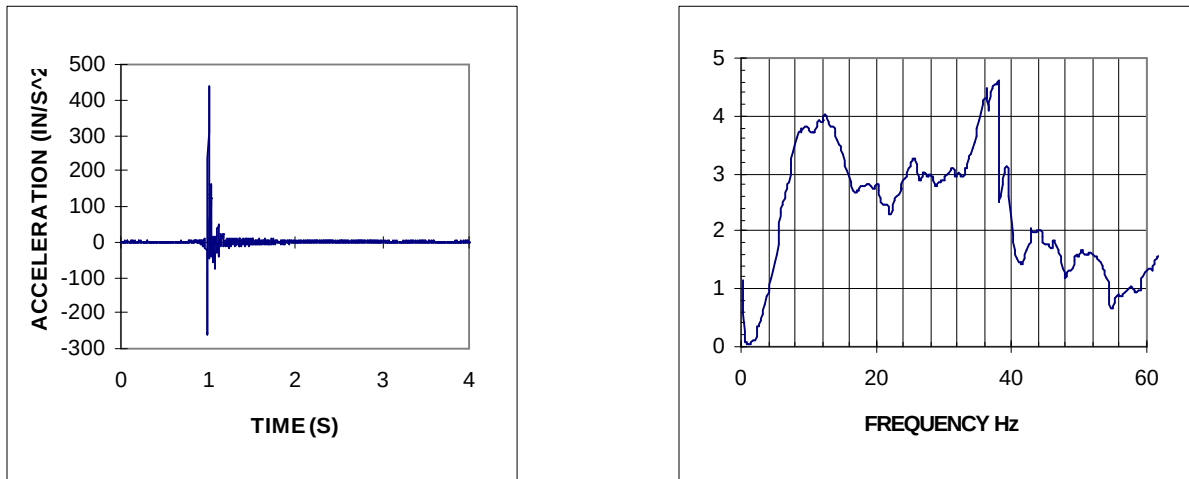


Figure A-18 Floor 8E Acceleration Trace and FFT

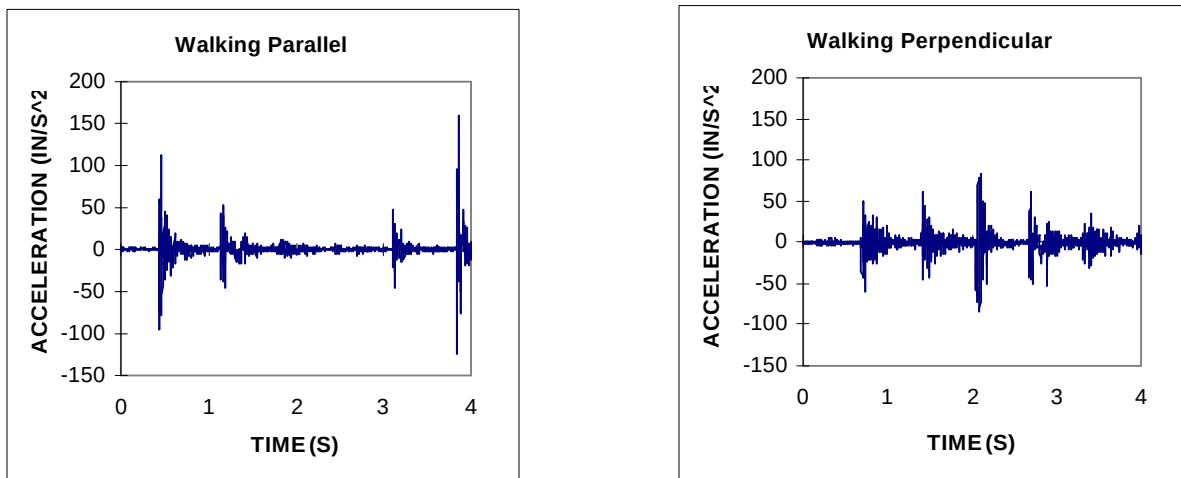


Figure A-19 Floor 8E Walking Acceleration Traces

Floor 10C (2x10x43 - 24" - 15'-3")
L/360, 30 psf LL (design deflection)

Joist Weight: 2.13 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue & Groove OSB

Fasteners: #10 x 1-7/16 Wafer Phillips "Winged" Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking, #8 self-drilling bugle-head screws for drywall.

Parameters: Strap, Blocking, Drywall

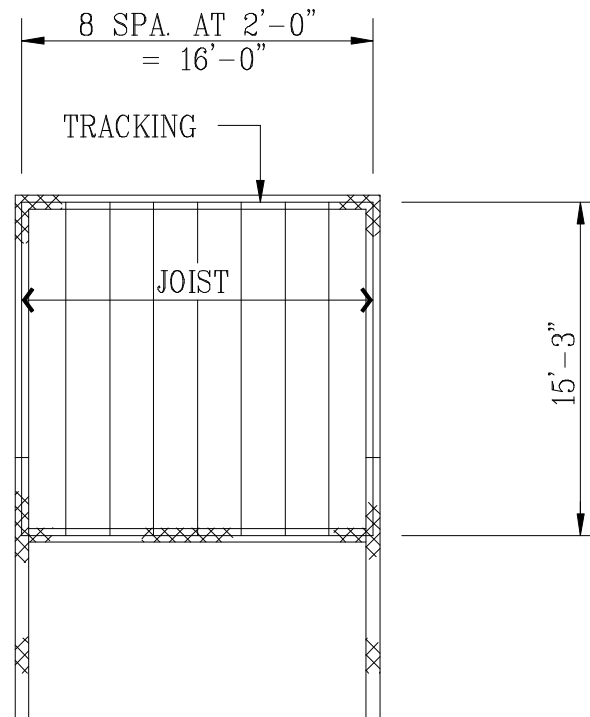


Figure A-20 Floor 10C Plan View

Floor 10C (cont.)

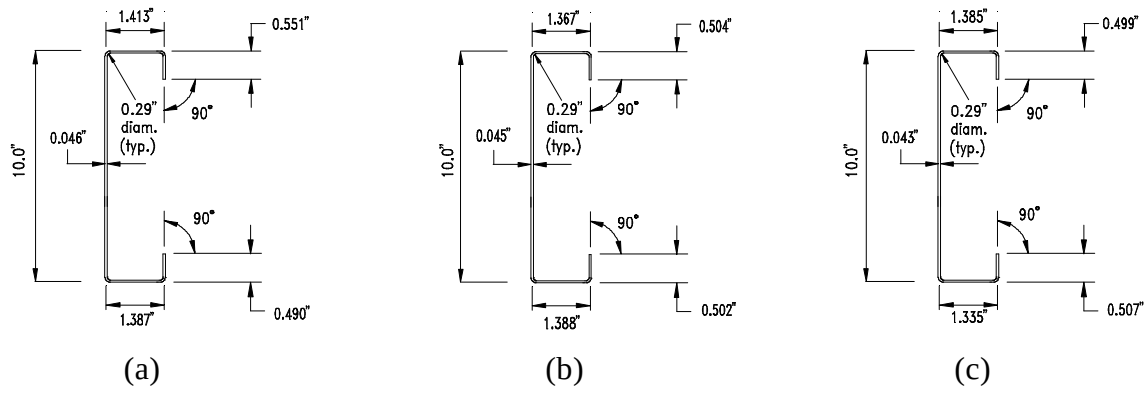


Figure A-21 Measured Joist Properties for Floors 10C and 10D

Table A-11 Floor 10C Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.62	0.60	0.57
I _x (in ⁴)	7.66	7.42	7.06
Frequency (Hz)	18.6	18.3	17.8

Table A-12

Parameter	Tabulated Moment of Inertia (in ⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid-bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S0	7.38	18.2	24.4	-	-
S1	7.38	18.2	24.0	0.046	0.060
B1	7.38	18.2	23.25	0.041	0.060
B2	7.38	18.2	23.25	-	-
B3	7.38	18.2	21.5	-	-
DW	7.38	18.2	20.5	0.048	0.060

Floor 10C (cont.)

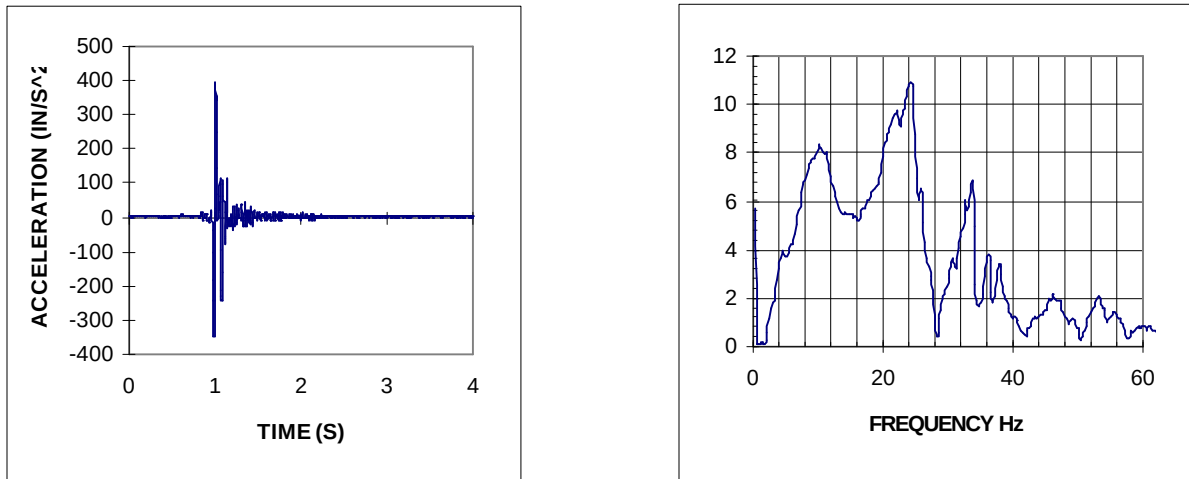


Figure A-22 Floor 10C Acceleration and FFT

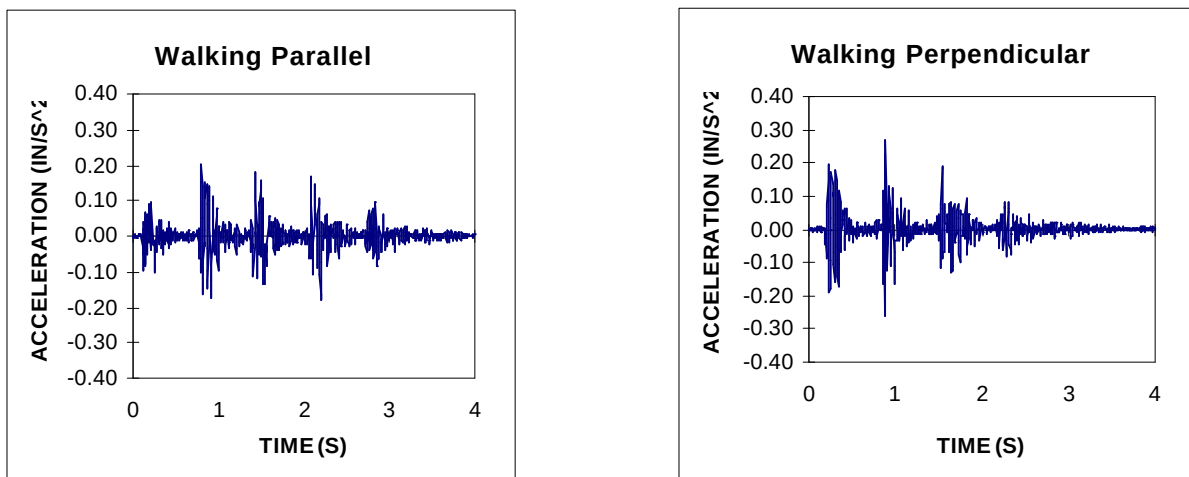


Figure A-23 Floor 10C Walking Acceleration Traces

Floor 10D (2x10x43 - 24" - 13'-1")
L/480, 40 psf LL (design deflection)

Joist Weight: 2.13 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue & Groove OSB

Fasteners: #10 x 1-7/16 Wafer Phillips "Winged" Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking.

Parameters: Strap, Blocking, Holes at Midspan

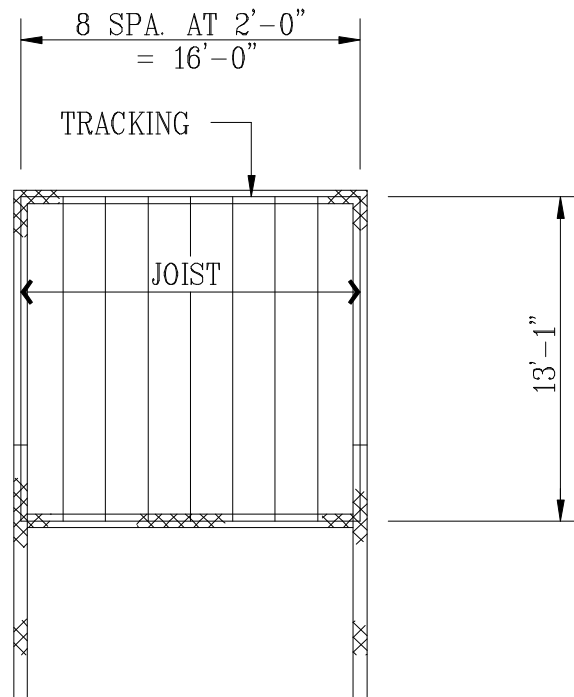


Figure A-24 Floor 10D Plan View

Measured Joist Properties: See Figure A-21

Floor 10D (cont.)

Table A-13 Floor 10D Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.62	0.60	0.57
I _x (in ⁴)	7.66	7.42	7.06
Frequency (Hz)	25.2	24.8	24.2

Table A-14

Parameter	Tabulated Moment of Inertia (in⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid-bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S1	7.38	24.8	23.9	0.039	0.043
S1+30	7.38	12.2	11.4	-	-
S1+60	7.38	9.2	11.25	-	-
B1	7.38	24.8	25.1	0.051	0.043
B2	7.38	24.8	22.5	-	-
B3	7.38	24.8	21.8	-	-
H	7.38	24.8	23.4	0.042	0.043
H+30	7.38	12.2	11.4	-	-

Floor 10D (cont.)

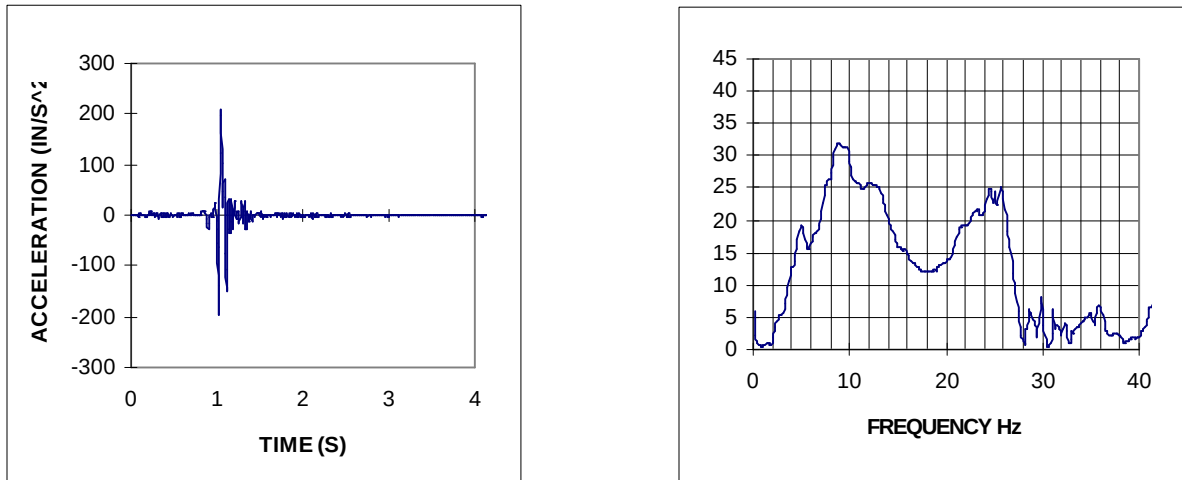


Figure A-25 Floor 10D Acceleration Trace and FFT

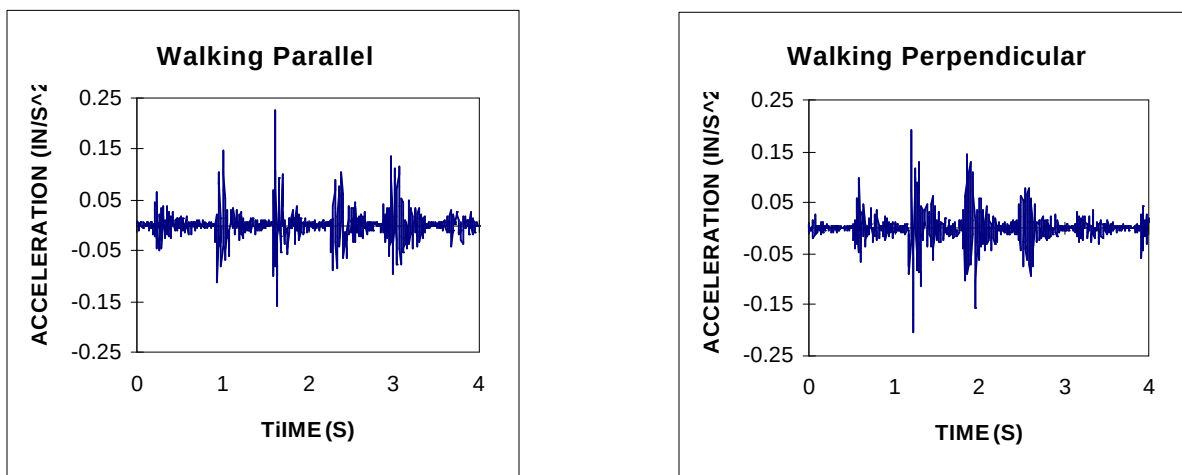


Figure A-26 Floor 10D Walking Acceleration Traces

Floor 12A (2x12x54 - 24" - 19'-7")
L/360, 30 psf LL (design deflection)

Joist Weight: 3.04 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue & Groove OSB

Fasteners: #8 x 1-1/4 Cement Board Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking

Parameters: Strap, Blocking

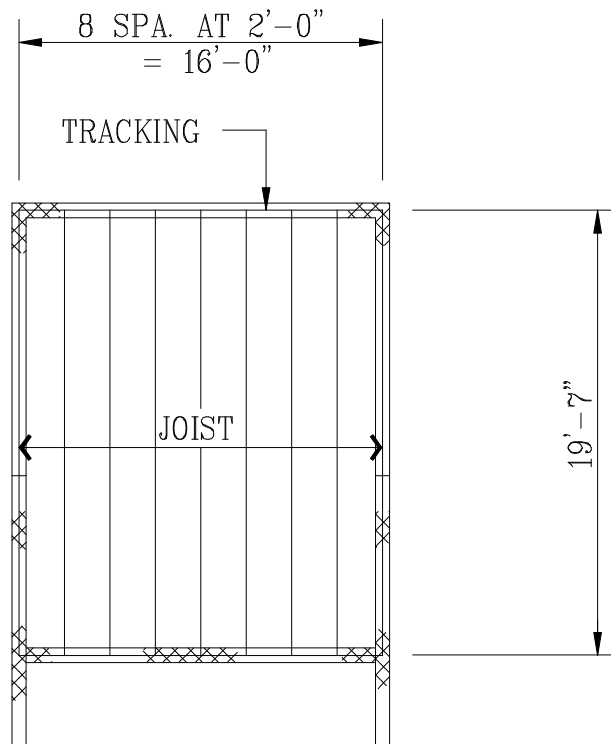


Figure A-27 Floor 12A Plan View

Floor 12A (cont.)

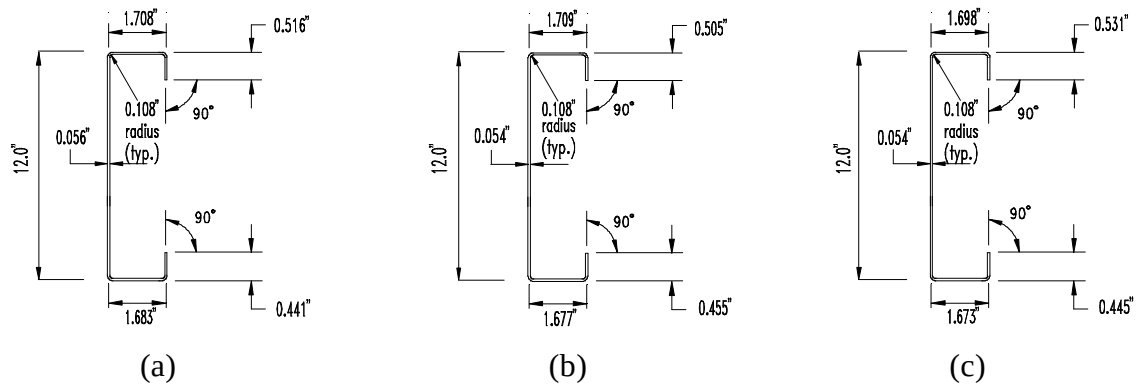


Figure A-28 Measured Joist Properties for Floors 12A, 12B and 12C

Table A-15 Floor 12A Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.89	0.86	0.86
I _x (in ⁴)	15.7	15.14	15.15
Frequency (Hz)	15.1	14.8	14.8

Table A-16

Parameter	Measured Moment of Inertia (in ⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid-bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S1	14.06	14.3	19.1	0.066	0.063
S1+30	14.06	8.5	9.45	-	-
B0+30	14.06	8.5	9	-	-
B1	14.06	14.3	19.2	0.058	0.063
B1+30	14.06	8.5	9	-	-

Floor 12A (cont.)

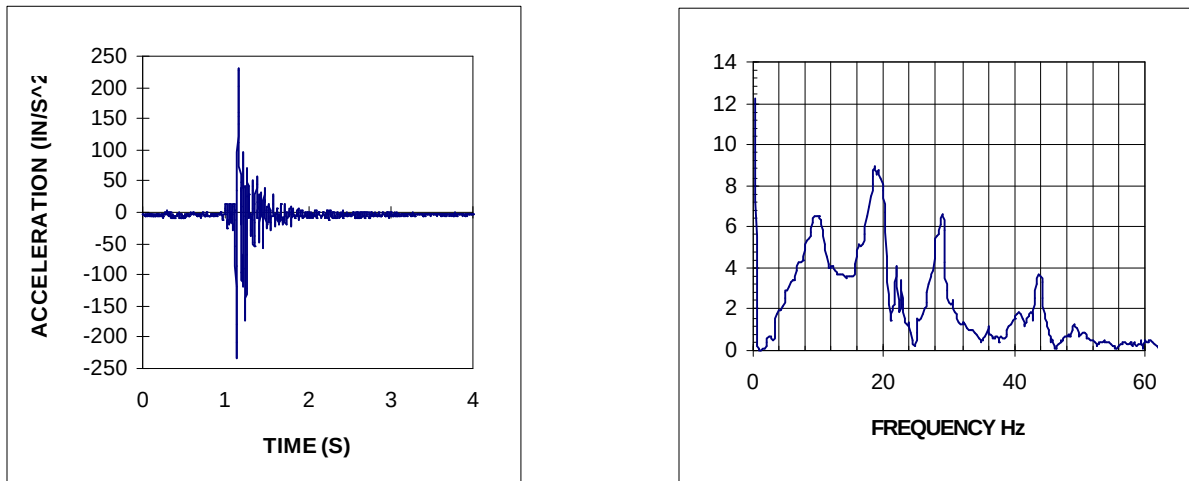


Figure A-29 Floor 12A Acceleration Trace and FFT

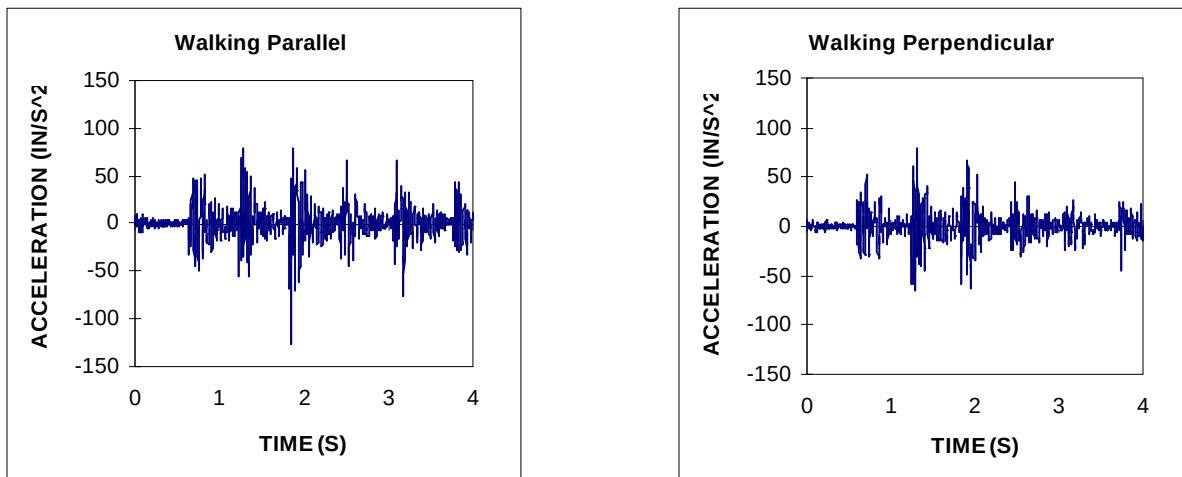


Figure A-30 Floor 12A Walking Acceleration Traces

Floor 12B (2x12x54 - 24" - 17'-6")
L/480, 40 psf LL (design deflection)

Joist Weight: 3.04 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue & Groove OSB

Fasteners: #8 x 1-1/4 Cement Board Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking

Parameters: Strap, Blocking

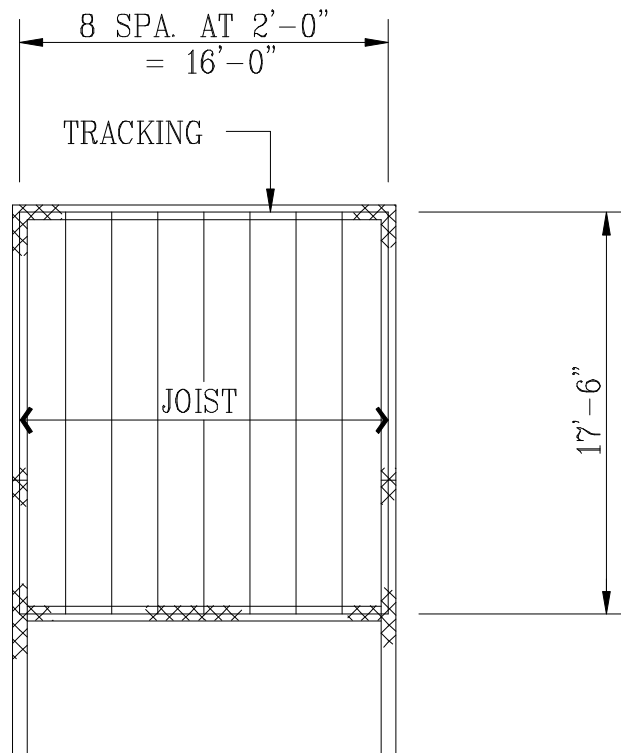


Figure A-31 Floor 12B Plan View

Measured Joist Properties: See Figure A-28

Floor 12B (cont.)

Table A-17 Floor 12B Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.89	0.86	0.86
I _x (in ⁴)	15.7	15.14	15.15
Frequency (Hz)	18.9	18.6	18.6

Table A-18

Parameter	Measured Moment of Inertia (in⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid-bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S1	14.06	17.9	20.25	0.039	0.048
S1+30	14.06	10.3	10.2	-	-
B0	14.06	17.9	20.9	-	-
B0+30	14.06	10.3	10.4	-	-
B1	14.06	17.9	20.6	0.045	0.048
B1+30	14.06	10.3	10	-	-

Floor 12B (cont.)

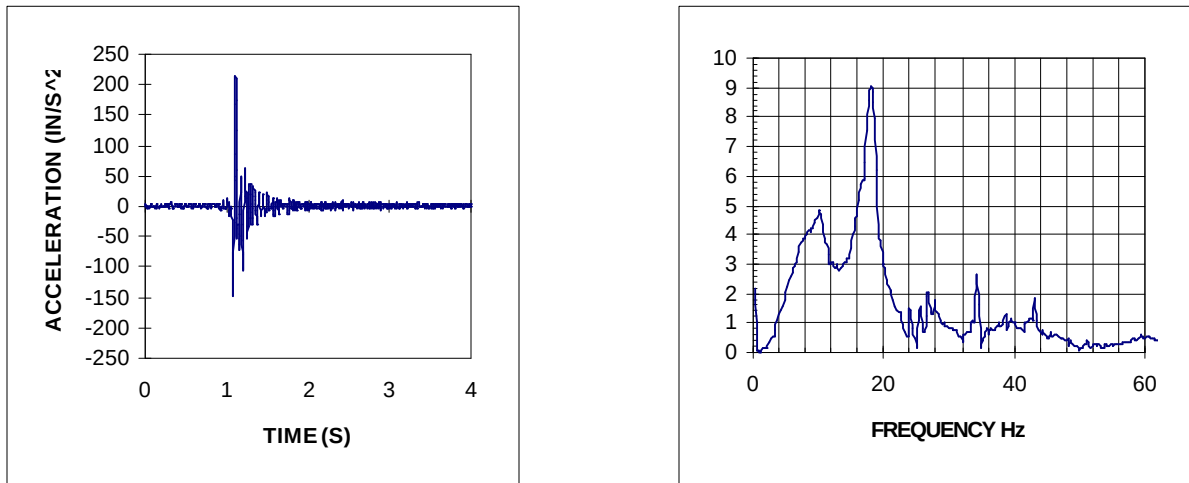


Figure A-32 Floor 12B Acceleration Trace and FFT

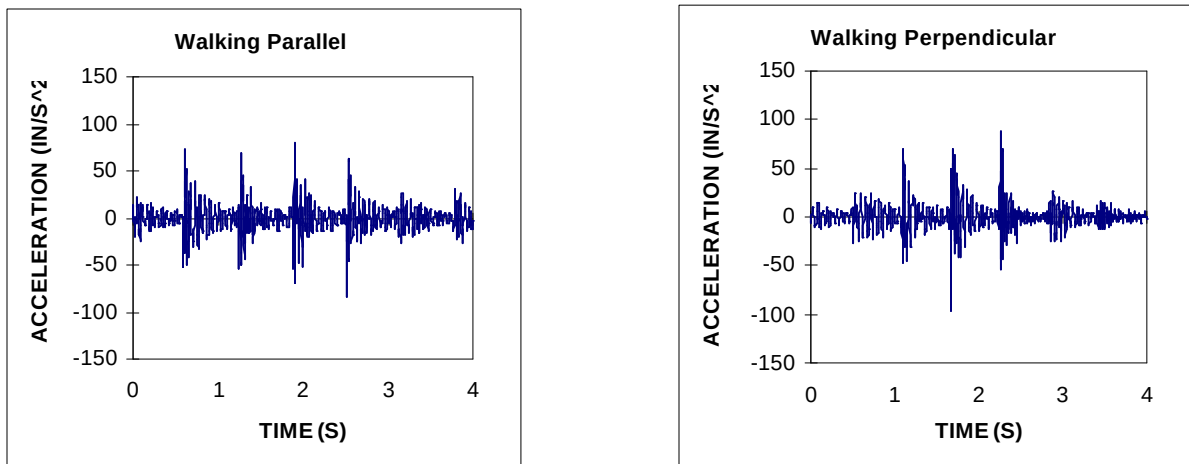


Figure A-33 Floor 12B Walking Acceleration Traces

Floor 12C (2x12x54 - 24" - 16'-2")
L/720, 40 psf LL (design deflection)

Joist Weight: 3.04 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue & Groove OSB

Fasteners: #8 x 1-1/4 Cement Board Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking

Parameters: Strap, Blocking

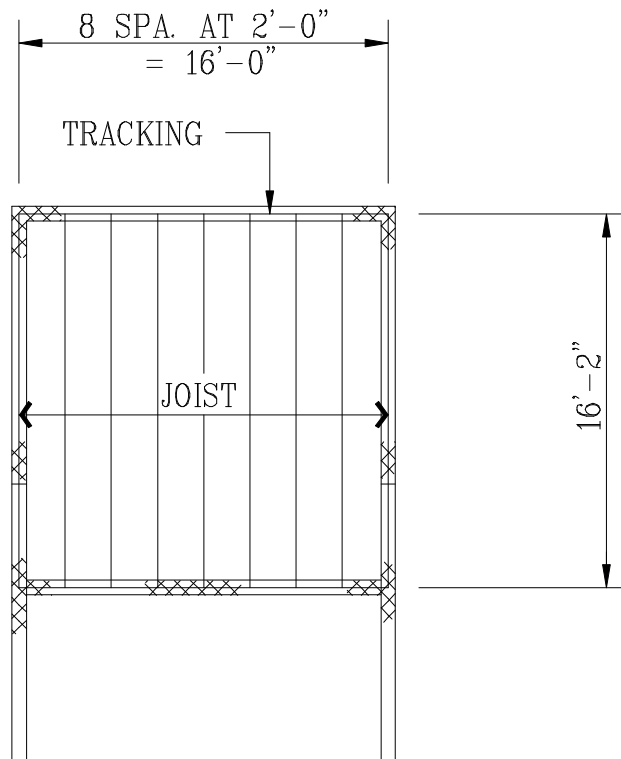


Figure A-34 Floor 12C Plan View

Measured Joist Properties: See Figure A-28

Floor 12C (cont.)

Table A-19 Floor 12C Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.89	0.86	0.86
I _x (in ⁴)	15.7	15.14	15.15
Frequency (Hz)	22.2	21.8	21.8

Table A-20

Parameter	Measured Moment of Inertia (in⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid-bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S1	14.06	21.0	23.6	0.044	0.040
S1+30	14.06	11.7	11.25	-	-
B0	14.06	21.0	22.6	0.041	0.040
B0+30	14.04	11.7	11.25	-	-

Floor 12C (cont.)

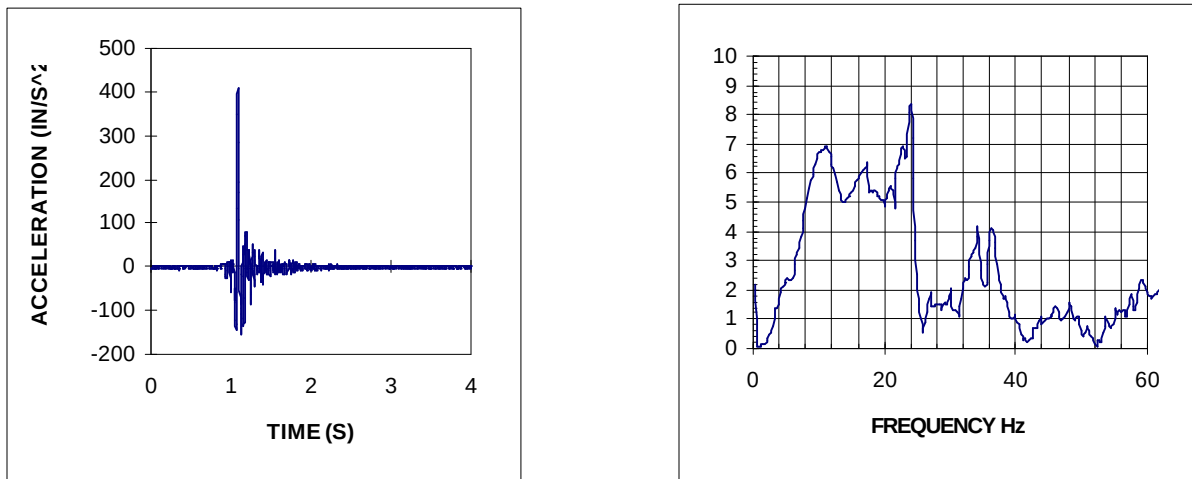


Figure A-35 Floor 12C Acceleration Trace and FFT

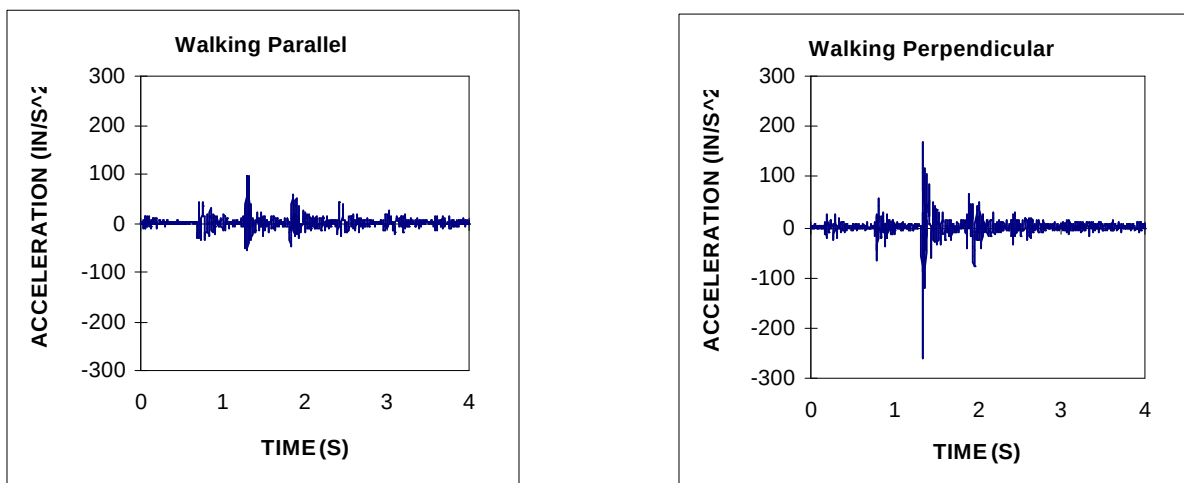


Figure A-36 Floor 12C Walking Acceleration Traces

Floor 12D (2x12x43 - 24" - 14'-1")
L/360, 30 psf LL (design deflection)

Joist Weight: 2.37 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue & Groove OSB

Fasteners: #8 x 1-1/4 Cement Board Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking

Parameters: Strap, Blocking

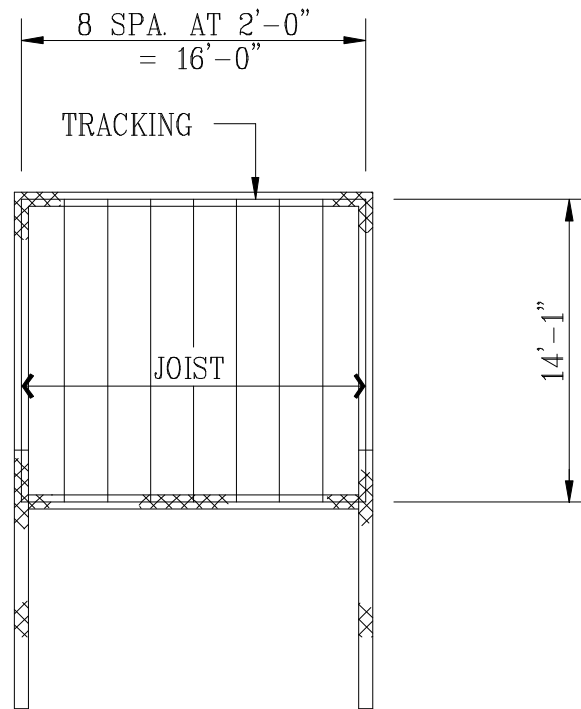


Figure A-37 Floor 12D Plan View

Floor 12D (cont.)

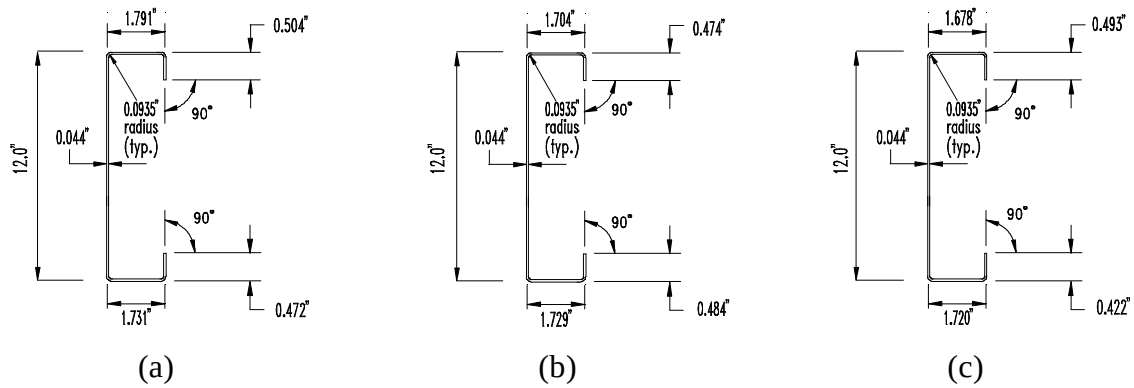


Figure A-38 Measured Joist Properties for Floors 12A, 12B and 12C

Table A-21 Floor 12D Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.71	0.70	0.70
I _x (in ⁴)	12.71	12.55	12.43
Frequency (Hz)	27.5	27.4	27.4

Table A-22

Parameter	Measured Moment of Inertia (in ⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid-bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S1	11.6	26.3	27.0	0.043	0.035
B0	11.6	26.3	26.5	0.040	0.035
B0+30	11.6	13.6	11.5	-	-
B1+30	11.6	13.6	11.9	-	-

Floor 12D (cont.)

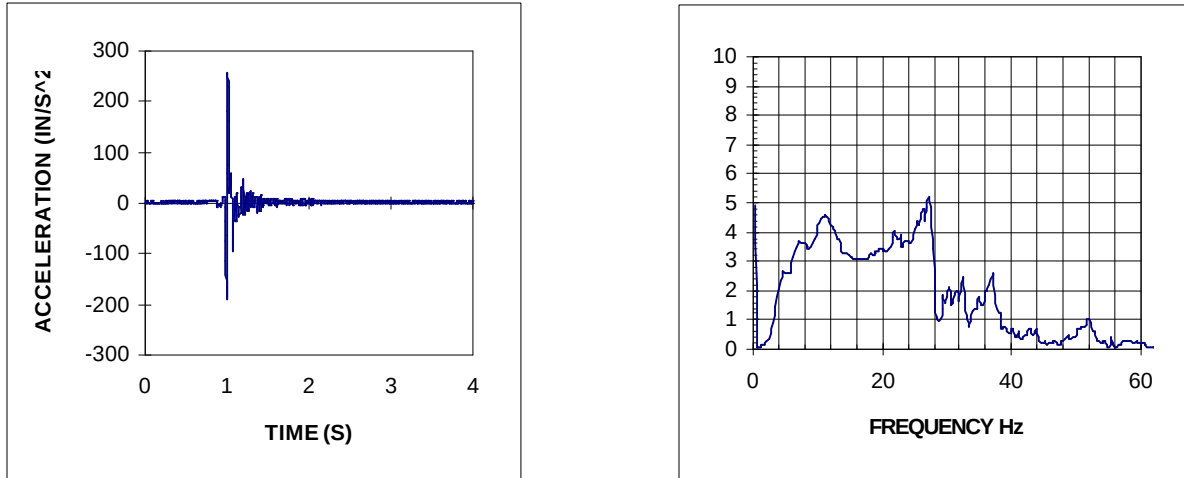


Figure A-39 Floor 12D Acceleration Trace and FFT

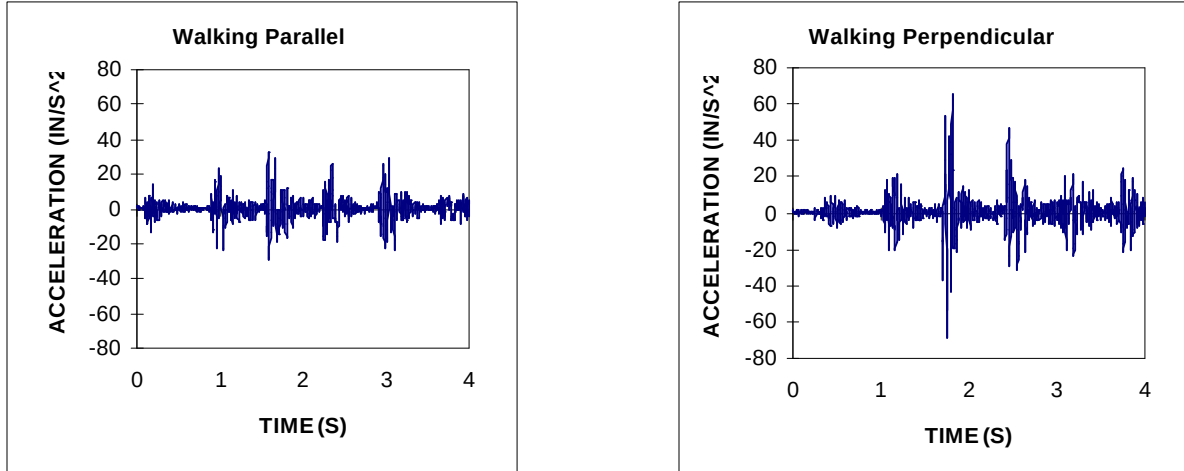


Figure A-40 Floor 12D Walking Acceleration Traces

Floor 12E (2x12x43 - 24" - 11'-3")
L/490, 40 psf LL (design deflection)

Joists: Weight: 2.37 plf

Sheeting: APA Rated Sturd-I-Floor, 23/32" Tongue & Groove OSB

Fasteners: #8 x 1-1/4 Cement Board Screws @ 6" along supporting panel edges and 12" in the field, #8 self-drilling hex-head screws for bearing stiffeners and blocking

Parameters: Strap, Blocking

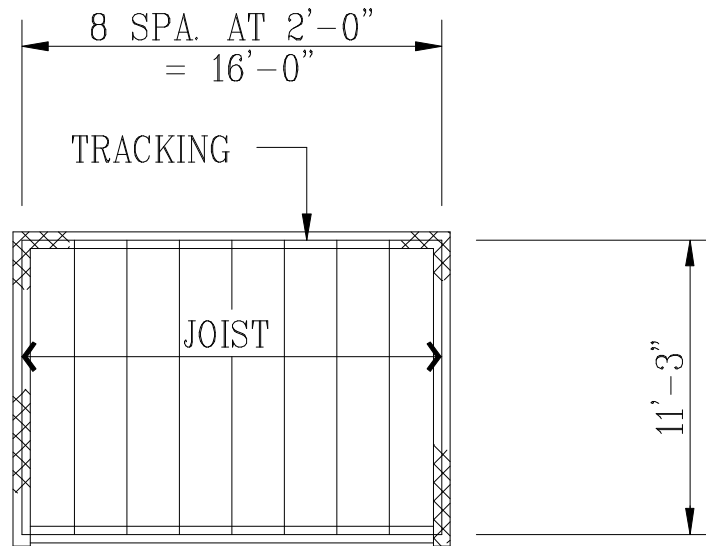


Figure A-41 Floor 12E Plan View

Measured Joist Properties: See Figure A-38

Floor 12E (cont.)

Table A-23 Floor 12E Calculated Joist Properties

Joist	a	b	c
A (in ²)	0.71	0.70	0.70
I _x (in ⁴)	12.71	12.55	12.43
Frequency (Hz)	43.1	42.9	42.7

Table A-24

Parameter	Measured Moment of Inertia (in ⁴)	Average Predicted Frequency (Hz)	Measured Frequency (Hz)	Deflection at Mid-bay due to 225 lb Concentrated Load	
				Measured (in.)	Predicted (in.)
S1	11.6	41.3	29.3	0.019	0.025
S1+30	11.6	19.5	23.8	-	-
B1	11.6	41.3	28	0.025	0.025
B1+30	11.6	19.5	25.6	-	-

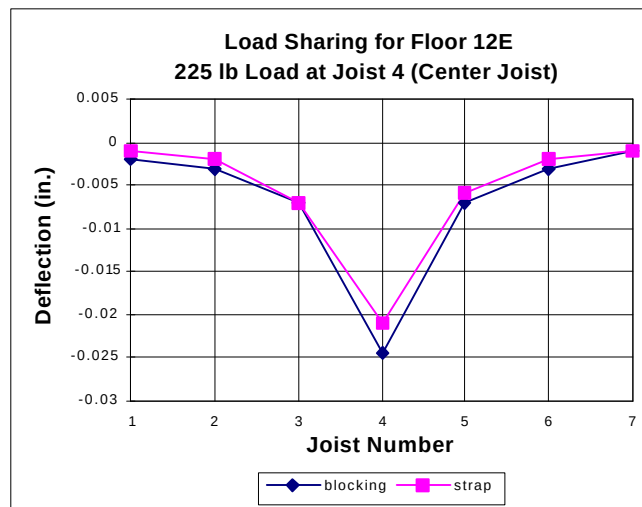


Figure A-42 Midspan Deflection Profile

Floor 12E (cont.)

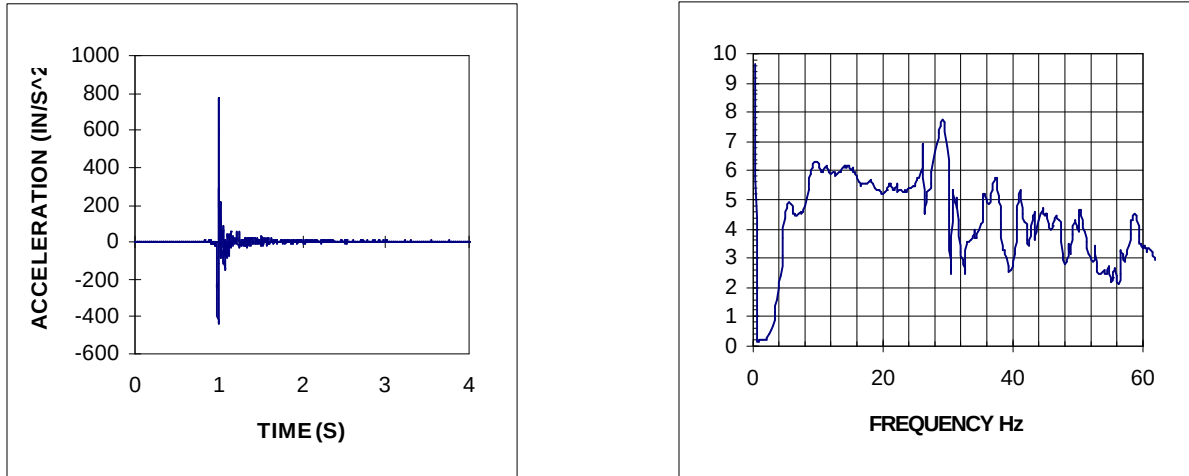


Figure A-44 Floor 12E Walking Acceleration Traces

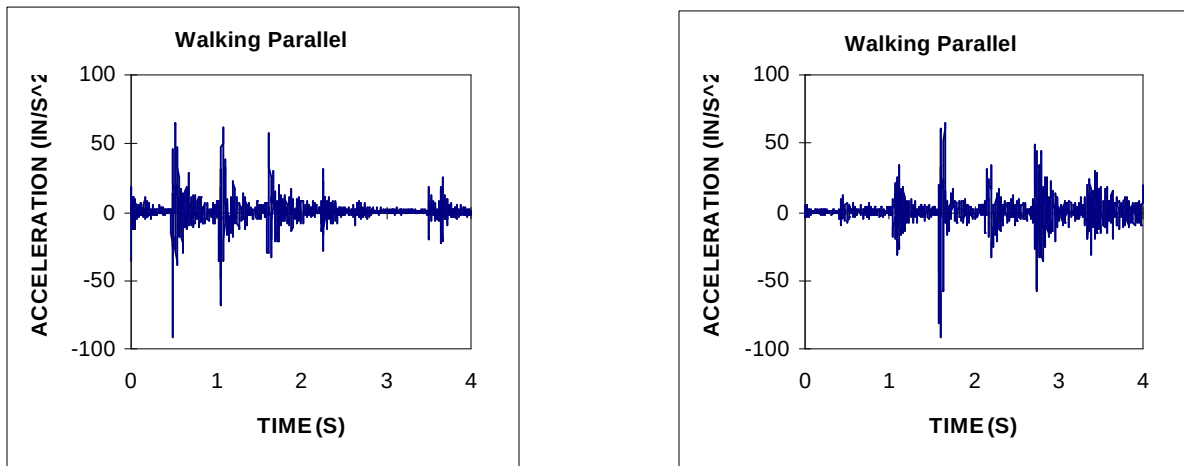


Figure A-43 Floor 12E Walking Acceleration Traces

APPENDIX B
SUMMARY OF *IN-SITU* FLOORS

Table B-1 Results of *In-Situ* Floor Test

Floor	Joist	Span (in.)	I (in ⁴)	w (plf)	s (in.)	f _{meas} (Hz)	f _{pred} (Hz)	δ _{meas} (in.)
S1LR	925SJ16	188	8.71	5.49	16	22.5	20.7	0.012
S1FYR	925SJ16	143.5	8.71	5.49	16	-	35.5	0.009
S1MBR	925SJ16	143	8.71	5.49	16	27.25	35.8	-
S1GR	925SJ16	188	8.71	5.49	16	13	20.7	0.01
S1BR#3	925SJ16	188	8.71	5.49	16	17.5	20.7	-
S1BR#4	925SJ16	188	8.71	5.49	16	17.5	20.7	-
S2DIN	925SJ16	196	8.71	5.49	16	19.3	19.0	0.027
S2LR	925SJ16	188	8.71	5.49	16	14.5	20.7	0.025
S2MBR	925SJ16	216	8.71	5.49	12	15.5	15.7	0.054
S3LR	925SJ16	164	8.71	5.49	16	25.5	27.2	-
S3BR	80SJ18	126	4.77	4.7	16	11.5	36.8	-

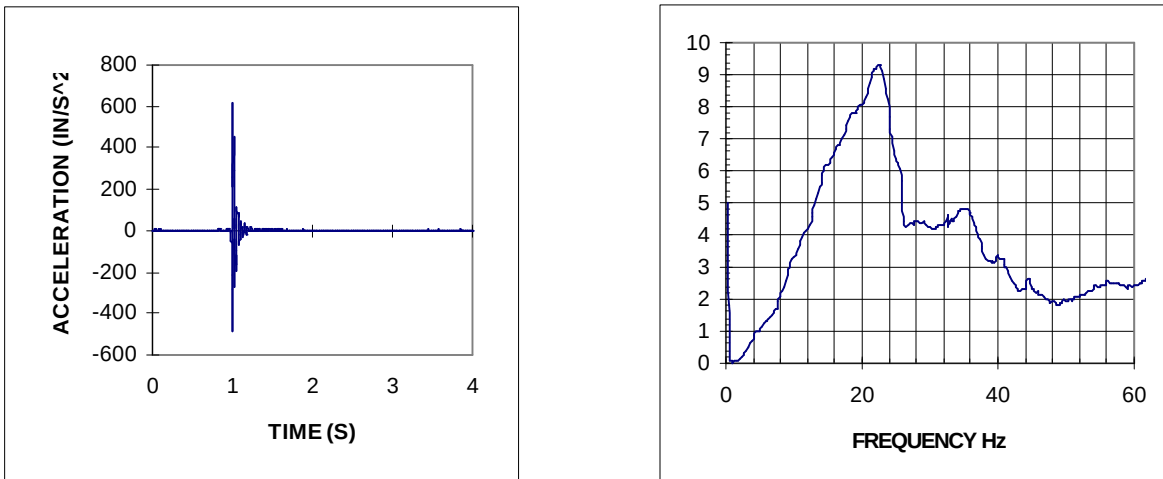


Figure B-1 Floor S1LR Acceleration Trace and FFT

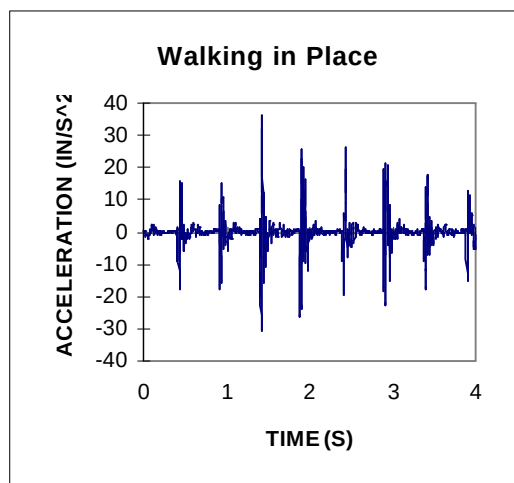


Figure B-2 Floor S1LR Walking Acceleration Trace

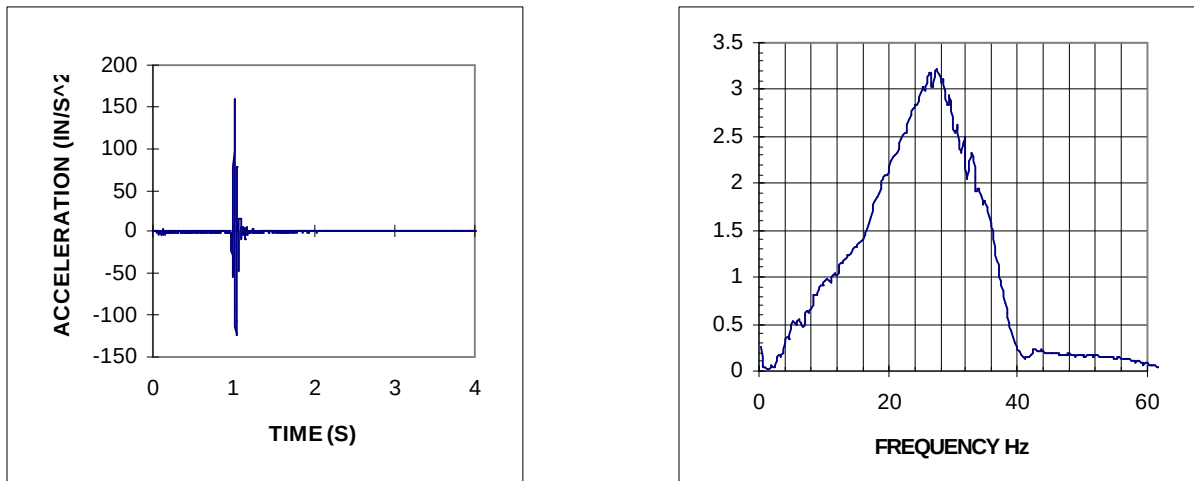


Figure B-3 Floor S1MBR Acceleration Trace and FFT

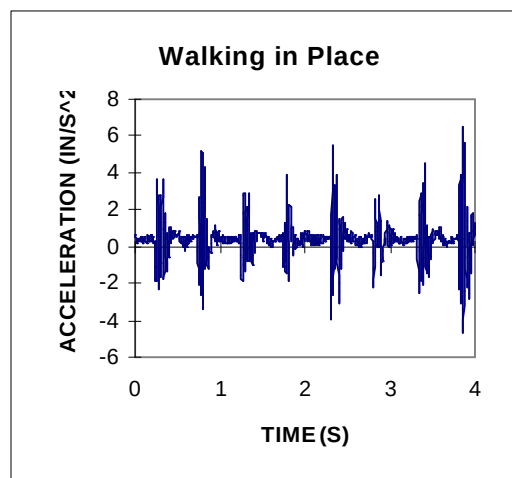


Figure B-4 Floor S1MBR Walking Acceleration Trace

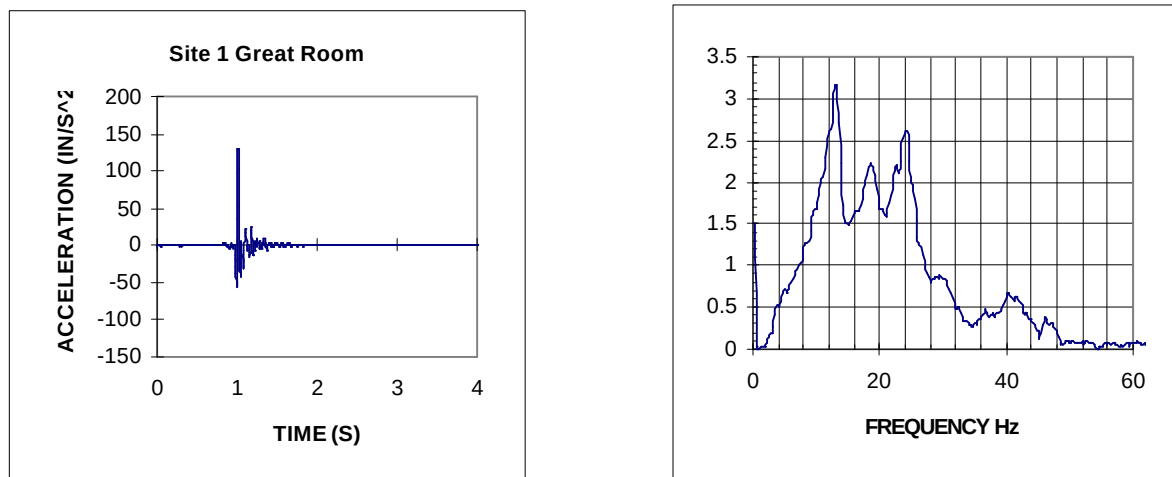


Figure B-5 Floor S1GR Acceleration Trace and FFT

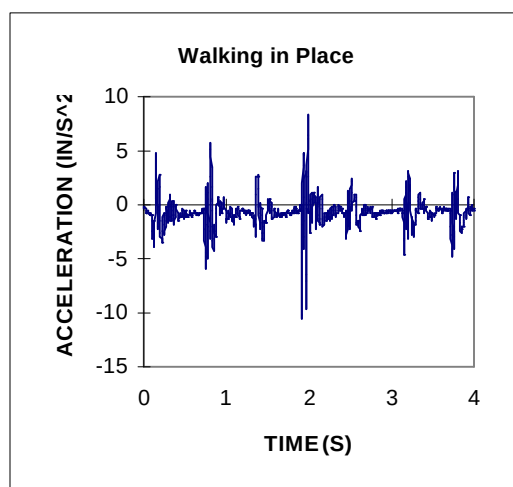


Figure B-6 Floor S1GR Walking Acceleration Trace

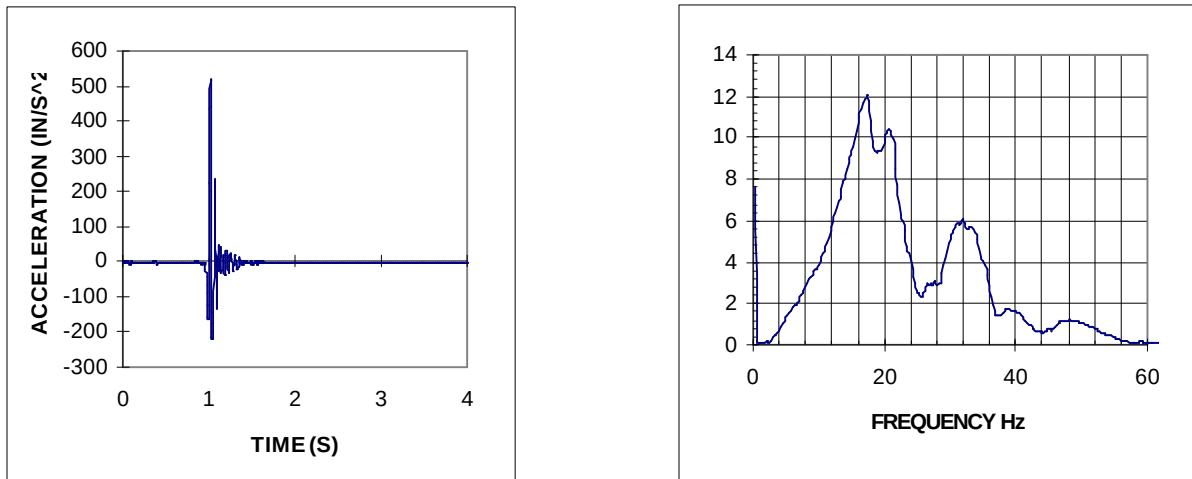


Figure B-7 Floor S1BR#3 Acceleration Trace and FFT

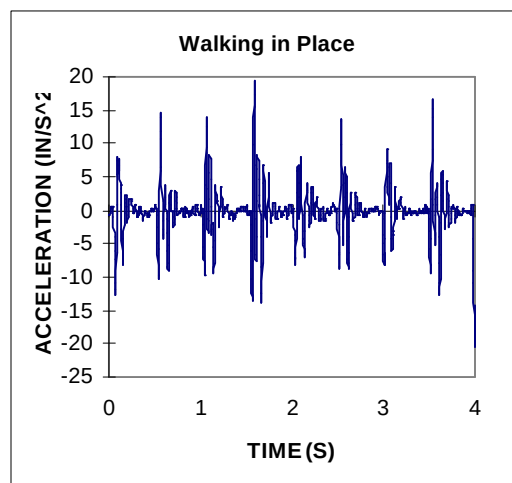


Figure B-8 Floor S1BR#3 Walking Acceleration Trace

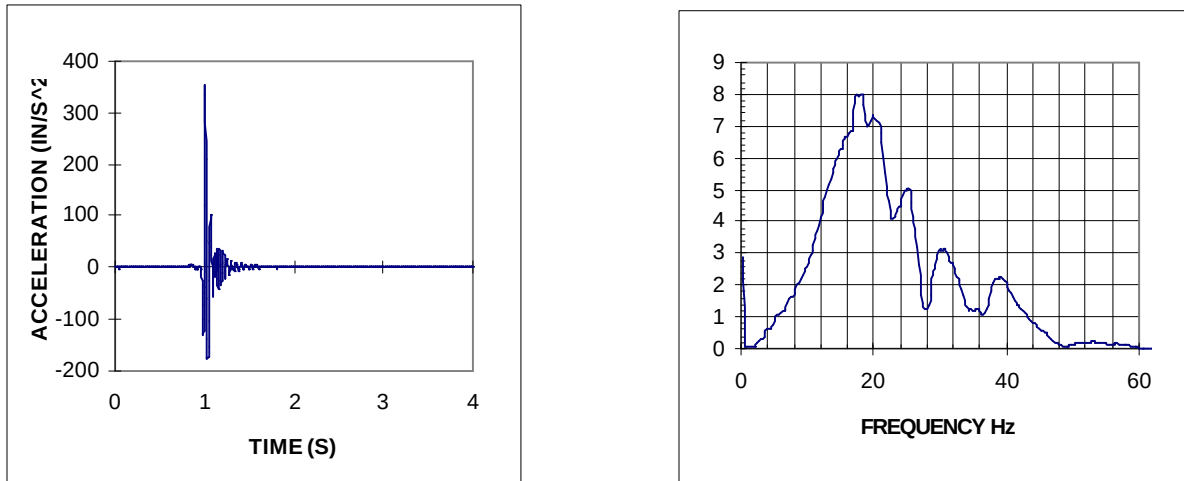


Figure B-9 Floor S1BR#4 Acceleration Trace and FFT

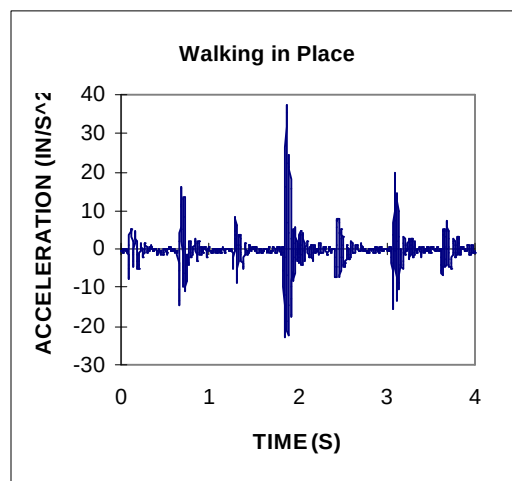


Figure B-10 Floor S1BR#4 Walking Acceleration Trace

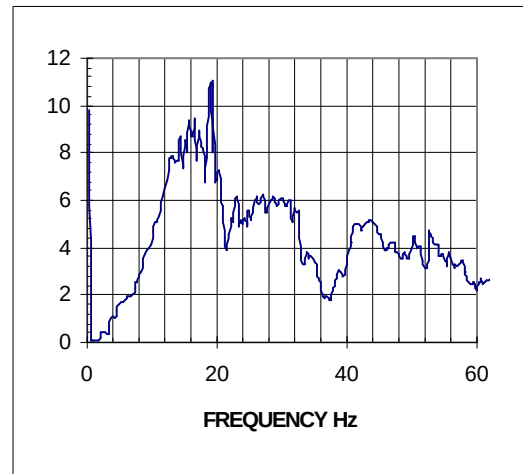
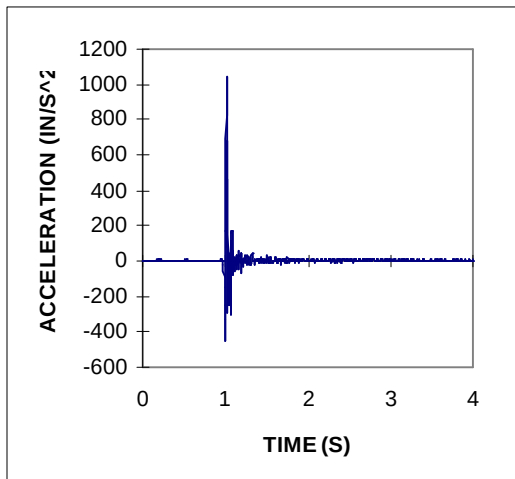


Figure B-11 Floor S2DR Acceleration Trace and FFT

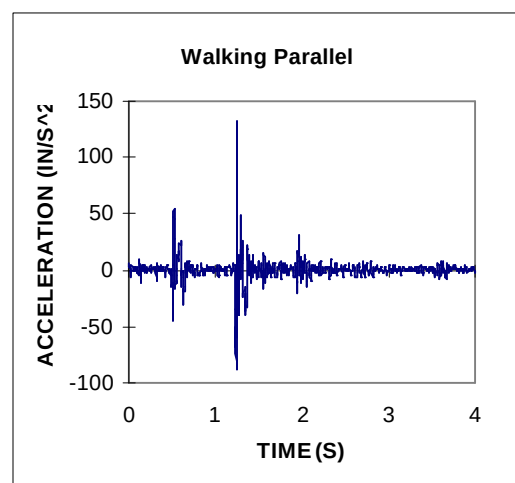
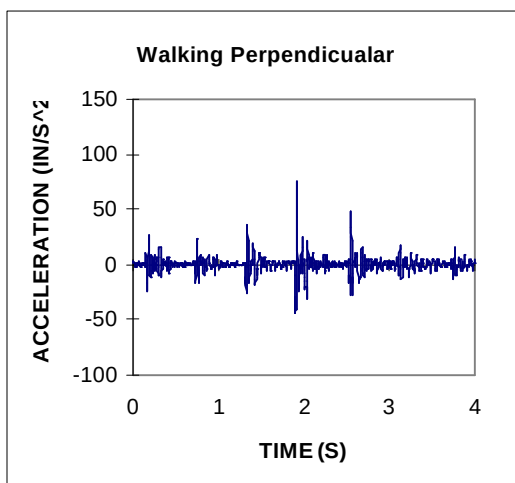


Figure B-12 Floor S2DR Walking Acceleration Trace

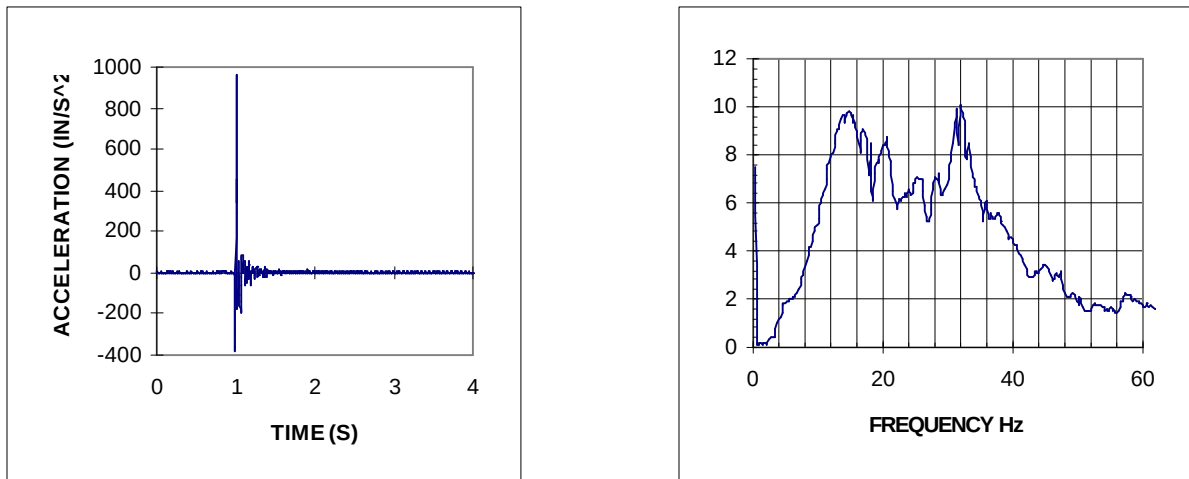


Figure B-13 Floor S2LR Acceleration Trace and FFT

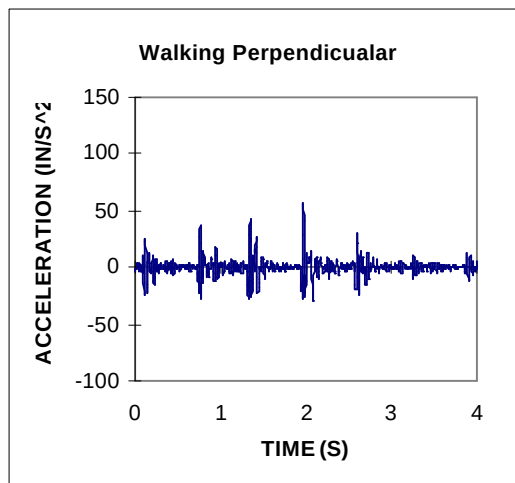


Figure B-14 Floor S2LR Walking Acceleration Trace

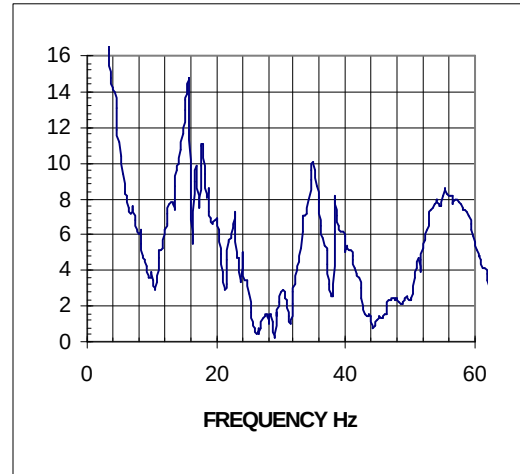
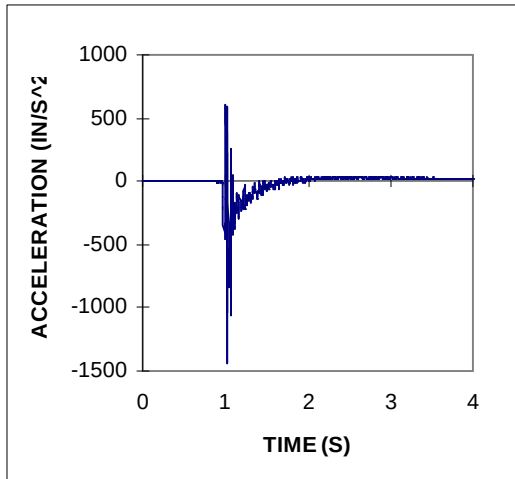


Figure B-15 Floor S2MBR Acceleration Trace and FFT

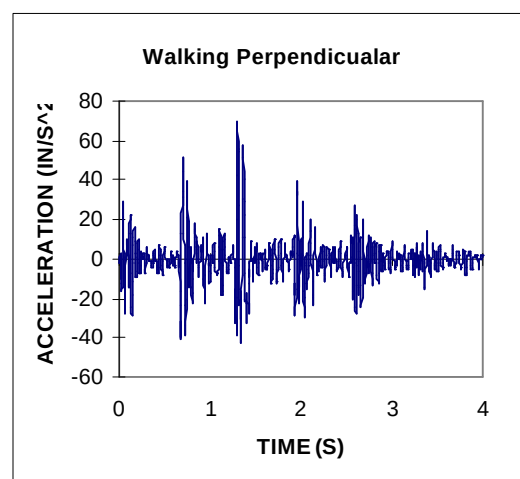
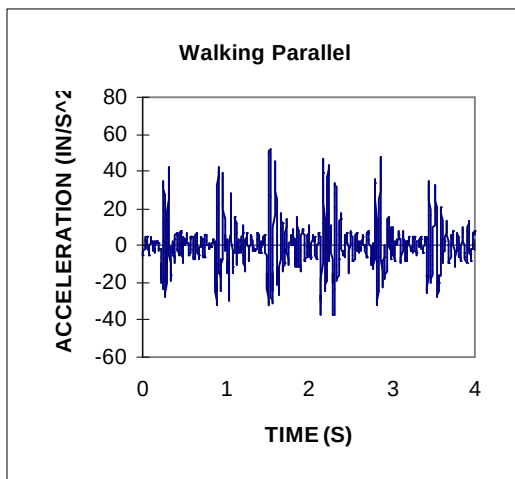


Figure B-16 Floor S2MBR Walking Acceleration Trace

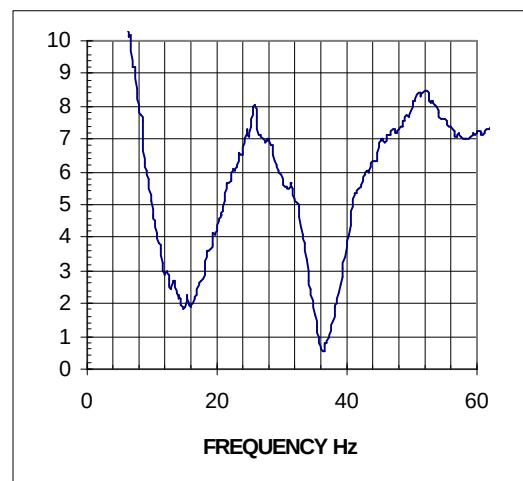
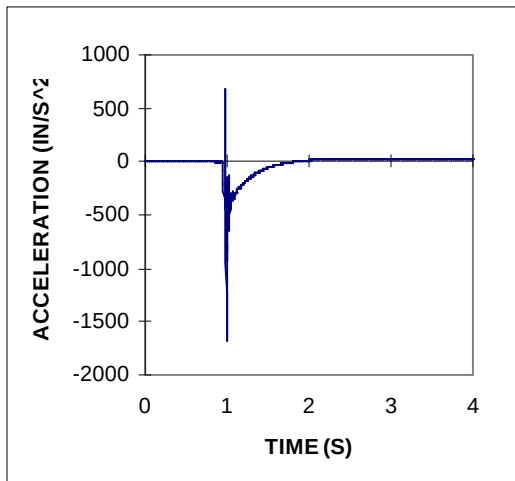


Figure B-17 Floor S3LR Acceleration Trace and FFT

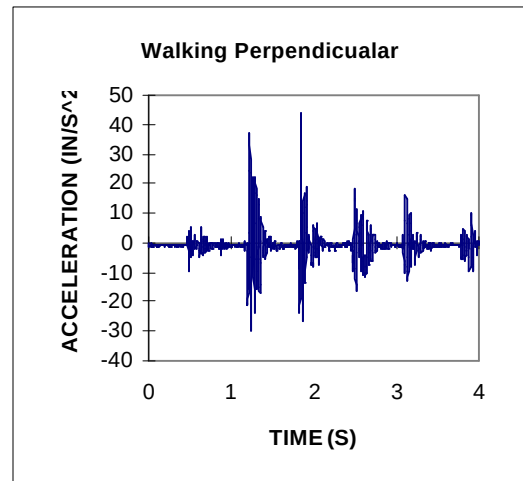
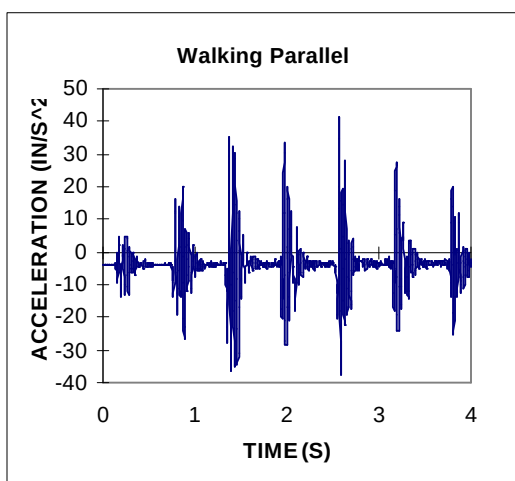


Figure B-18 Floor S3LR Walking Acceleration Trace

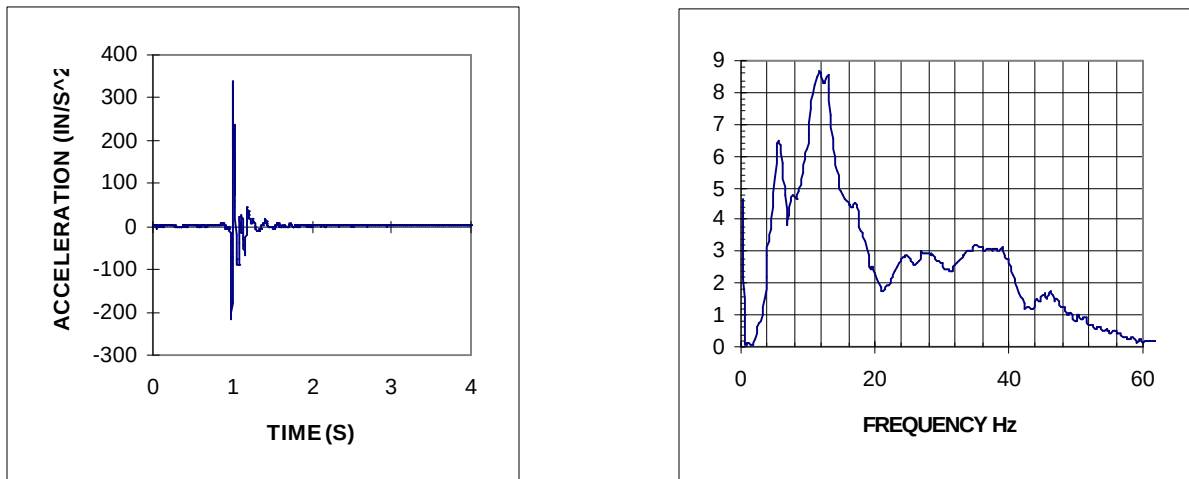


Figure B-19 Floor S3BR Acceleration Trace and FFT

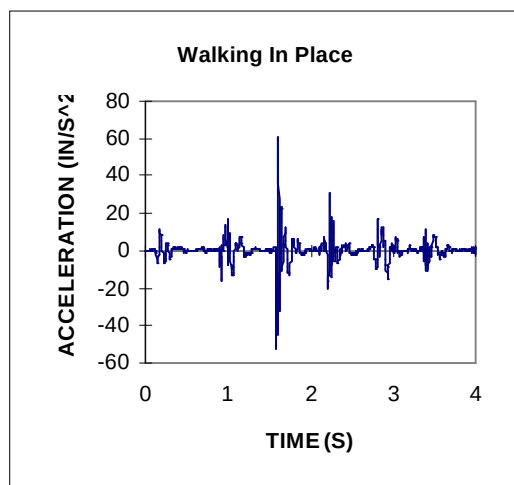


Figure B-20 Floor S3BR Walking Acceleration Trace

APPENDIX C
SUMMARY OF TWO JOIST LINE TESTS

Table C-1 Results from Two Joist Line Tests

Floor	Joist	Span	I_{bare} (in ⁴)	I_{OSB} (in ⁴)	b_e (in.)	Line Load					
						0 plf		5 plf		10 plf	
						f_{pred} (Hz)	f_{meas} (Hz)	f_{pred} (Hz)	f_{meas} (Hz)	f_{pred} (Hz)	f_{meas} (Hz)
2J8A	2x8x33	19'-11"	3.05	3.59	2.1	7.3	7.5	5.4	4.3	-	-
2J8B	2x8x43	19'-11"	4.35	5.38	4.2	8.4	8.8	6.3	6.5	-	-
2J10A	2x10x68	19'-11"	12.78	14.30	4.0	12.8	12.7	10.0	10.4	8.5	8.9
2J12A	2x12x54	19'-9"	14.05	15.36	2.4	14.1	11.0	-		9.2	9.3
2J12B	2x12x43	19'-11"	11.60	12.15	1.0	13.1	12.6	10.0	10.1	8.4	8.0

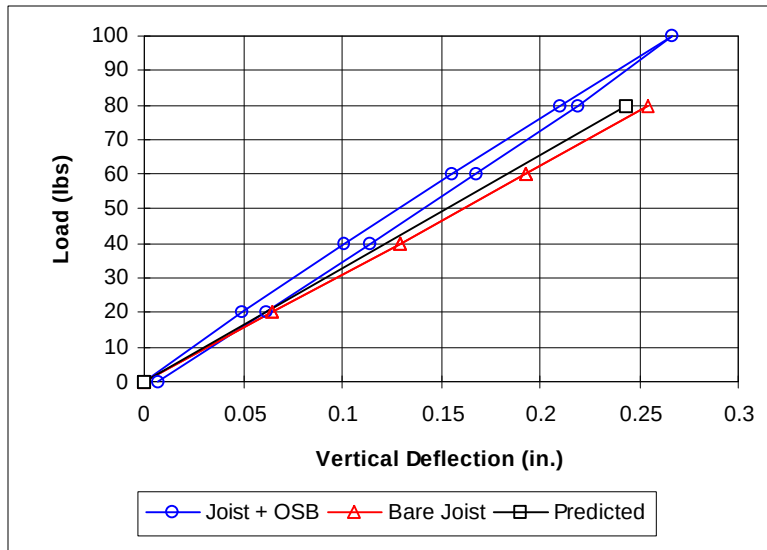


Figure C-1 Floor 2J8A North Joist Load vs. Deflection

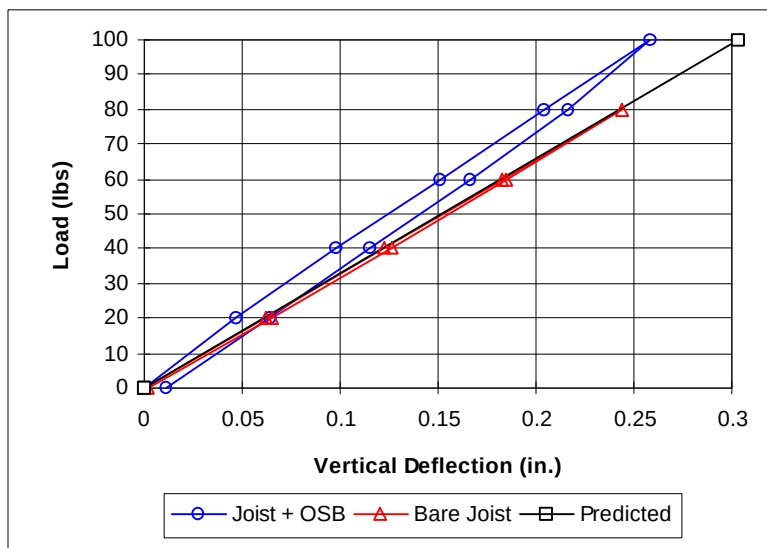


Figure C-2 Floor 2J8A South Joist Load vs. Deflection

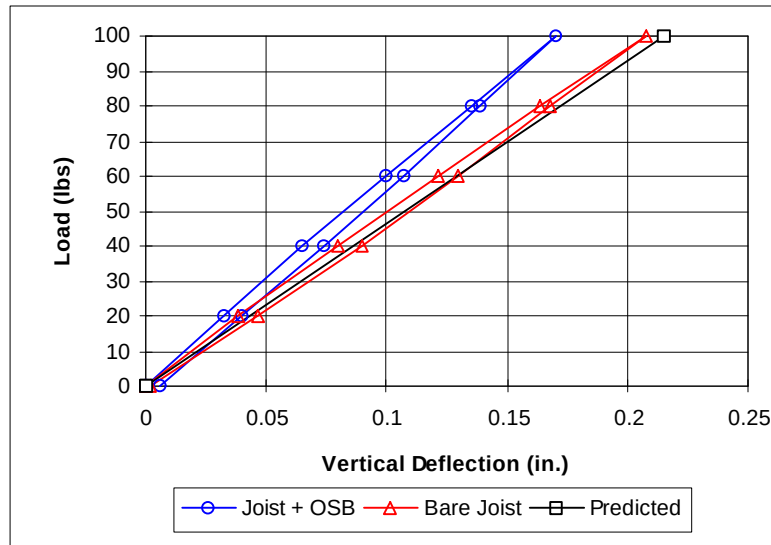


Figure C-3 Floor 2J8B North Joist Load vs. Deflection

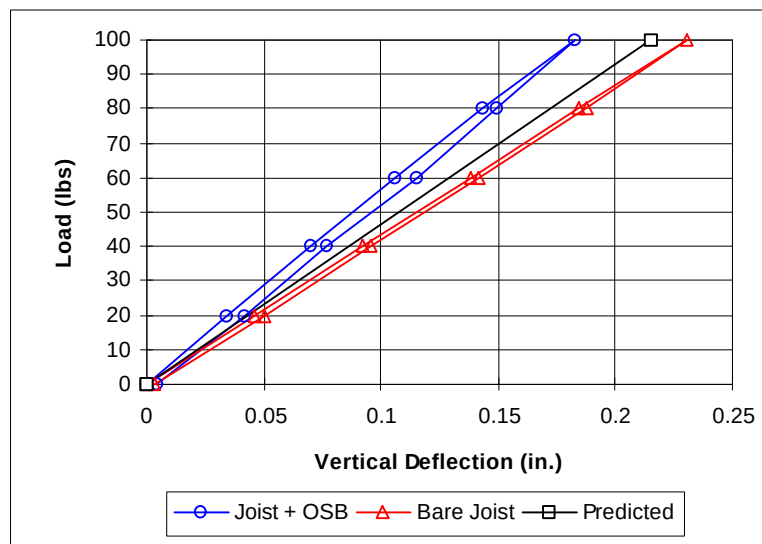


Figure C-4 Floor 2J8B South Joist Load vs. Deflection

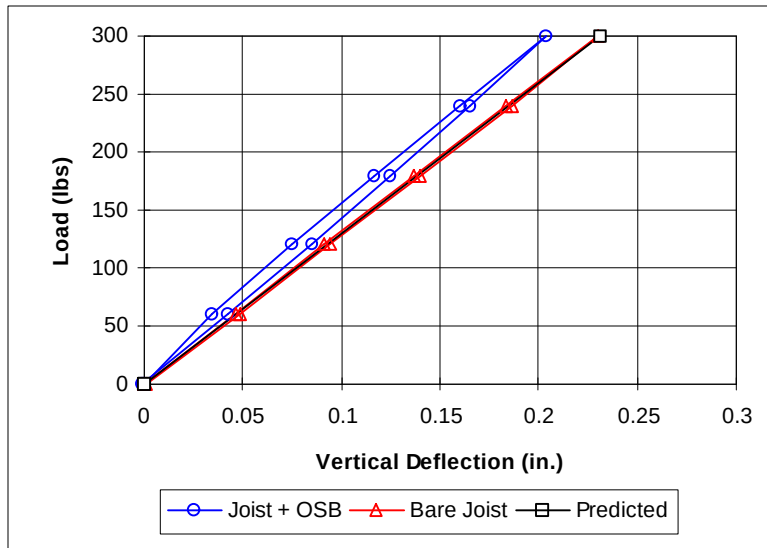


Figure C-5 Floor 2J10A North Joist Load vs. Deflection

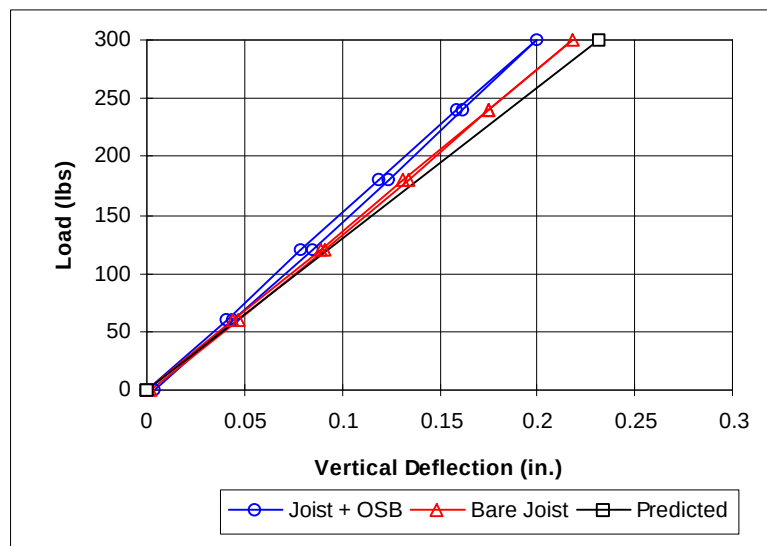


Figure C-6 Floor 2J10A South Joist Load vs. Deflection

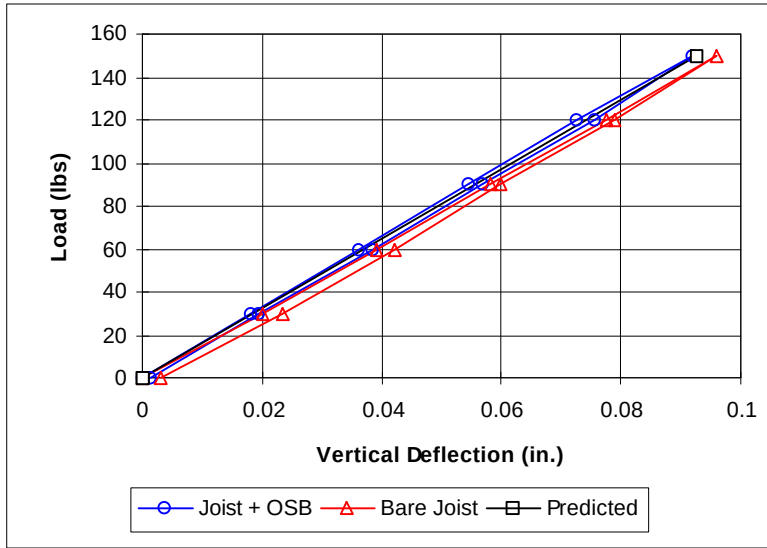


Figure C-7 Floor 2J12A North Joist Load vs. Deflection

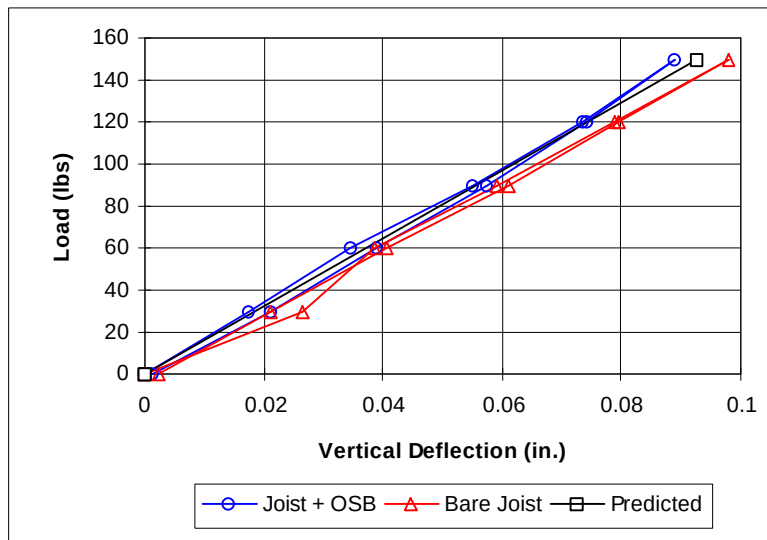


Figure C-8 Floor 2J12A South Joist Load vs. Deflection

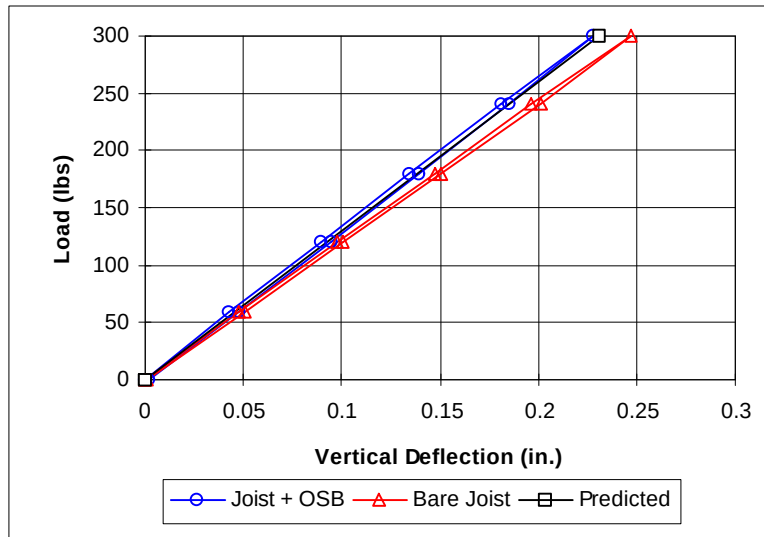


Figure C-9 Floor 2J12B North Joist Load vs. Deflection

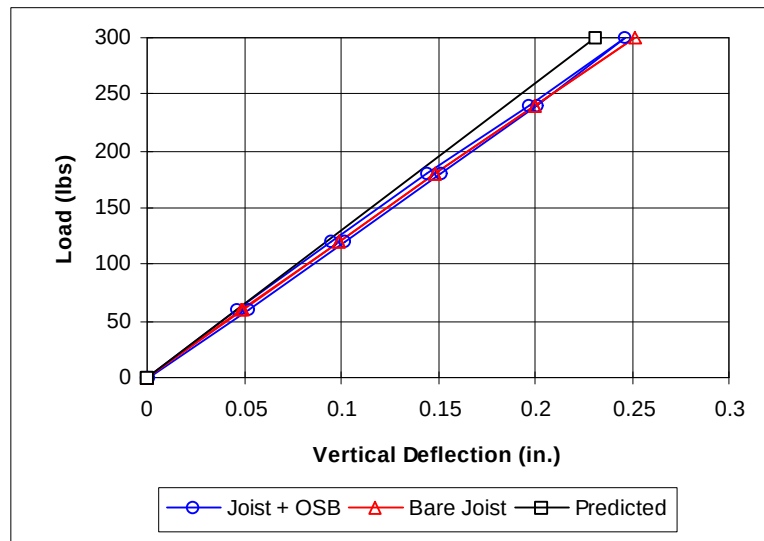


Figure C-10 Floor 2J12B South Joist Load vs. Deflection

Derivation of b_e for 2J12A Two Joist Line Test

$$\begin{aligned}
 E_{\text{joist}} &= 29,500,000 \text{ psi} & E_{\text{OSB}} &= 580,000 \text{ psi} \\
 W_{\text{joist}} &= 3.04 \text{ plf} & W_{\text{OSB}} &= 2.27 \text{ psf} \\
 I_{\text{joist}} &= 14.06 \text{ in}^4 & I_{\text{joist+OSB}} &= 15.26 \text{ in}^4 \\
 L &= 19'-9'' & h &= 12 \text{ in.} \\
 t_f &= 1.69 \text{ in.} & t_w &= 0.054 \text{ in.} \\
 h_f &= 0.488 \text{ in.}
 \end{aligned}$$

$$n = \frac{E_{\text{joist}}}{E_{\text{OSB}}} = 50.86$$

$$\begin{aligned}
 A_{\text{joist}} &= 2t_f t_w + (h-2t_w)t_w + 2(h_f-t_w)t_w \\
 &= 2(1.69)(0.054) + [12-2(0.054)]0.054 + 2(0.488-0.054)0.054 = 0.871 \text{ in}^2
 \end{aligned}$$

$$\bar{y} = \frac{(b_t \cdot t_f) \left(h + \frac{t_f}{2} \right) + A_{\text{joist}} \left(\frac{h}{2} \right)}{(b_t + t_f) + A_{\text{joist}}} = \frac{8.88b_t + 5.23}{0.719b_t + 0.871}$$

with $\bar{y}$, I_{joist} , and $I_{\text{joist+OSB}}$:

$$I_{\text{joist+OSB}} = \frac{1}{12} b_t (t_f)^3 + b_t (t_f) \left[h + \frac{t_f}{2} - \bar{y} \right]^2 + I_{\text{joist}} + A_{\text{joist}} \left(\bar{y} - \frac{h}{2} \right)^2$$

$$15.36 = \frac{1}{12} b_t \left(\frac{23}{32} \right)^3 + b_t \left(\frac{23}{32} \right) \left[12 + \frac{23/32}{2} - \left(\frac{8.88b_t + 5.23}{0.719b_t + 0.871} \right) \right]^2 + 14.06 + 0.871 \left(\frac{8.88b_t + 5.23}{0.719b_t + 0.871} - \frac{12}{6} \right)^2$$

$$15.36 = 0.0309b_t + 0.719b_t \left(12.359 - \frac{8.88b_t + 5.23}{0.719b_t + 0.871} \right)^2 + 14.06 + 0.871 \left(\frac{8.88b_t + 5.23}{0.719b_t + 0.871} - 6 \right)^2$$

Via MATHCAD (1994)

$$b_t = 0.0467 \text{ in.}$$

$$b_e = n b_t = 50.86(0.0467) = 2.4 \text{ in.}$$

APPENDIX D

**CALCULATED VALUES FOR
LABORATORY TEST FLOOR DATA**

**Table D-1 Summary of Values Used to Calculate
h'_{max} and σ_o in Ohlsson's Criterion**

Floor	L (m)	Parameter	B (m)	I _b (m ⁴)	D _y /D _x	w (kg/m ²)	f ₁ (Hz)	f = 40/f ₁ (Hz)	L/B	N ₄₀	h' _{max} (mm/s/Ns)	σ _o (s ⁻¹)
8A	4.191	s	4.89	1.81E-06	0.0034	16.09	-	-	0.86	-	-	-
	4.191	b	4.89	1.81E-06	0.0034	16.09	20.3	1.97	0.86	6.39	32.02	0.20
	4.191	dw	4.89	1.81E-06	0.0034	16.09	16.2	2.47	0.86	7.39	36.56	0.16
8B	3.734	s	4.89	1.81E-06	0.0034	16.09	17.2	2.33	0.76	7.83	41.36	0.17
	3.734	b	4.89	1.81E-06	0.0034	16.09	17.4	2.30	0.76	7.83	41.36	0.17
8C	3.277	s	4.89	1.81E-06	0.0034	16.09	29.2	1.37	0.67	6.01	35.05	0.29
	3.277	b	4.89	1.81E-06	0.0034	16.09	29.0	1.38	0.67	6.01	35.05	0.29
8D	2.691	s	4.89	1.27E-06	0.0048	14.94	32.9	1.22	0.55	5.35	36.45	0.33
	2.691	b	4.89	1.27E-06	0.0048	14.94	31.4	1.27	0.55	6.05	40.69	0.31
8E	2.158	s	4.89	1.27E-06	0.0048	14.94	37.3	1.07	0.44	5.56	41.83	0.37
	2.158	b	4.89	1.27E-06	0.0048	14.94	35.6	1.12	0.44	5.56	41.83	0.36
10C	4.648	s	4.89	3.07E-06	0.0020	16.93	24.0	1.67	0.95	5.98	27.32	0.24
	4.648	b	4.89	3.07E-06	0.0020	16.93	23.3	1.72	0.95	6.09	27.77	0.23
	4.648	dw	4.89	3.07E-06	0.0020	16.93	20.5	1.95	0.95	6.63	29.99	0.21
10D	3.987	s	4.89	3.07E-06	0.0020	16.93	23.9	1.67	0.82	6.90	34.31	0.24
	3.987	b	4.89	3.07E-06	0.0020	16.93	25.1	1.59	0.82	6.69	33.36	0.25
	3.987	h	4.89	3.07E-06	0.0020	16.93	23.4	1.71	0.82	7.00	34.76	0.23
12A	5.968	s	4.89	5.85E-06	0.0010	19.44	19.1	2.09	1.22	7.60	25.91	0.19
	5.968	b	4.89	5.85E-06	0.0010	19.44	-	-	1.22	-	-	-
12B	5.334	s	4.89	5.85E-06	0.0010	19.44	20.3	1.98	1.09	7.40	27.43	0.20
	5.334	b	4.89	5.85E-06	0.0010	19.44	20.6	1.94	1.09	7.20	26.75	0.21
12C	4.929	s	4.89	5.85E-06	0.0010	19.44	23.6	1.69	1.01	6.50	25.78	0.24
	4.929	b	4.89	5.85E-06	0.0010	19.44	22.6	1.77	1.01	6.70	26.50	0.23
12D	4.292	s	4.89	4.83E-06	0.0013	17.61	27.0	1.48	0.88	6.66	30.92	0.27
	4.292	b	4.89	4.83E-06	0.0013	17.61	26.5	1.51	0.88	6.86	31.77	0.27
12E	3.429	s	4.89	4.83E-06	0.0013	17.61	29.3	1.37	0.70	7.73	40.75	0.29
	3.429	b	4.89	4.83E-06	0.0013	17.61	28.0	1.43	0.70	8.10	42.55	0.28

Note: E_{josit} = 2.04E+11 N/m²
E_{OSB} = 4.01E+09 N/m²
t = 0.018 m
S = 0.6096 m

**Table D-2 Summary of Values Used to Calculate
 $V_{\max}$ and σ_o in Australian Code**

Floor	L (m)	Parameter	B (m)	I_b (m ⁴)	K_x (Nm)	r	w* (kg/m ²)	f_1 (Hz)	f (Hz)	N_{40}	$\log_{10}(V_{\max})$	$1.2+2\sigma_o$
8A	4.191	s	4.89	1.81E-06	6.06E+05	0.0034	46.67	10.2	3.93	9.37	1.32	1.38
	4.191	b	4.89	1.81E-06	6.06E+05	0.0034	46.67	10.2	3.93	9.37	1.32	1.38
	4.191	dw	4.89	1.81E-06	6.06E+05	0.0034	46.67	10.2	3.93	9.37	1.32	1.38
8B	3.734	s	4.89	1.81E-06	6.06E+05	0.0034	46.67	12.8	3.12	9.25	1.35	1.43
	3.734	b	4.89	1.81E-06	6.06E+05	0.0034	46.67	12.8	3.12	9.25	1.35	1.43
8C	3.277	s	4.89	1.81E-06	6.06E+05	0.0034	46.67	16.7	2.40	9.03	1.39	1.50
	3.277	b	4.89	1.81E-06	6.06E+05	0.0034	46.67	16.7	2.40	9.03	1.39	1.50
8D	2.691	s	4.89	1.27E-06	4.25E+05	0.0048	45.52	20.9	1.91	8.62	1.45	1.58
	2.691	b	4.89	1.27E-06	4.25E+05	0.0048	45.52	20.9	1.91	8.62	1.45	1.58
8E	2.158	s	4.89	1.27E-06	4.25E+05	0.0048	45.52	32.6	1.23	6.92	1.43	1.79
	2.158	b	4.89	1.27E-06	4.25E+05	0.0048	45.52	32.6	1.23	6.92	1.43	1.79
10C	4.648	s	4.89	3.07E-06	1.03E+06	0.0020	47.52	10.7	3.74	9.41	1.28	1.39
	4.648	b	4.89	3.07E-06	1.03E+06	0.0020	47.52	10.7	3.74	9.41	1.28	1.39
	4.648	dw	4.89	3.07E-06	1.03E+06	0.0020	47.52	10.7	3.74	9.41	1.28	1.39
10D	3.987	s	4.89	3.07E-06	1.03E+06	0.0020	47.52	14.5	2.75	9.23	1.32	1.46
	3.987	b	4.89	3.07E-06	1.03E+06	0.0020	47.52	14.5	2.75	9.23	1.32	1.46
	3.987	h	4.89	3.07E-06	1.03E+06	0.0020	47.52	14.5	2.75	9.23	1.32	1.46
12A	5.968	s	4.89	5.85E-06	1.96E+06	0.0010	50.02	8.7	4.59	9.62	1.17	1.36
	5.968	b	4.89	5.85E-06	1.96E+06	0.0010	50.02	8.7	4.59	9.62	1.17	1.36
12B	5.334	s	4.89	5.85E-06	1.96E+06	0.0010	50.02	10.9	3.66	9.54	1.21	1.40
	5.334	b	4.89	5.85E-06	1.96E+06	0.0010	50.02	10.9	3.66	9.54	1.21	1.40
12C	4.929	s	4.89	5.85E-06	1.96E+06	0.0010	50.02	12.8	3.13	9.46	1.24	1.43
	4.929	b	4.89	5.85E-06	1.96E+06	0.0010	50.02	12.8	3.13	9.46	1.24	1.43
12D	4.292	s	4.89	4.83E-06	1.62E+06	0.0013	48.19	15.6	2.56	9.22	1.29	1.48
	4.292	b	4.89	4.83E-06	1.62E+06	0.0013	48.19	15.6	2.56	9.22	1.29	1.48
12E	3.429	s	4.89	4.83E-06	1.62E+06	0.0013	48.19	24.5	1.64	8.49	1.34	1.64
	3.429	b	4.89	4.83E-06	1.62E+06	0.0013	48.19	24.5	1.64	8.49	1.34	1.64

Note: $E_b = 2.04E+11 \text{ N/m}^2$
 $E_c = 4.01E+09 \text{ N/m}^2$
 $t_f = 0.018 \text{ m}$
 $s = 0.6096 \text{ m}$
* weight includes a 0.3 kPa LL

**Table D-3 Summary of Values Used to Calculate
Predicted Deflection from Australian Code**

Floor	L (in.)	t_f (in.)	E_c (psi)	E_b (psi)	I_b (in⁴)	s (in.)	k_b (lb/in)	k_c (lb/in)	k_c/k_b	k_d	P (lb)	P_d (lb)	δ_{pred} (in.)
8A	165	0.719	5.80E+05	2.95E+07	4.35	24	28.57	214.21	7.50	0.58	225.0	129.85	0.095
8B	147	0.719	5.80E+05	2.95E+07	4.35	24	40.40	190.84	4.72	0.64	225.0	144.13	0.074
8C	129	0.719	5.80E+05	2.95E+07	4.35	24	59.78	167.47	2.80	0.71	225.0	159.60	0.056
8D	106	0.719	5.80E+05	2.95E+07	3.06	24	75.79	137.61	1.82	0.76	225.0	171.65	0.047
8E	85	0.719	5.80E+05	2.95E+07	3.06	24	146.99	110.35	0.75	0.86	225.0	192.88	0.027
10C	183	0.719	5.80E+05	2.95E+07	7.38	24	35.52	237.57	6.69	0.59	225.0	133.42	0.078
10D	157	0.719	5.80E+05	2.95E+07	7.38	24	56.26	203.82	3.62	0.68	225.0	152.10	0.056
12A	235	0.719	5.80E+05	2.95E+07	14.06	24	31.96	305.08	9.55	0.54	225.0	122.22	0.080
12B	210	0.719	5.80E+05	2.95E+07	14.06	24	44.79	272.63	6.09	0.61	225.0	136.35	0.063
12C	194	0.719	5.80E+05	2.95E+07	14.06	24	56.81	251.85	4.43	0.65	225.0	146.06	0.054
12D	169	0.719	5.80E+05	2.95E+07	11.6	24	70.90	219.40	3.09	0.70	225.0	156.73	0.046
12E	135	0.719	5.80E+05	2.95E+07	11.6	24	139.08	175.26	1.26	0.80	225.0	181.04	0.027

**Table D-4 Summary of Values Used to Calculate
N_{eff} from SJI Equation**

Floor	Parameter	L (in.)	I _t * (in ⁴)	D _x (lb in.)	D _y (lb in.)	ε	x _o (in.)	x _o /S	N _{eff}
8A	strap	165	4.35	1.79E+04	5.35E+06	0.241	42.10	1.75	2.25
	blocking	165	4.35	1.79E+04	5.35E+06	0.241	42.10	1.75	2.25
	drywall	165	4.35	1.79E+04	5.35E+06	0.241	42.10	1.75	2.25
8B	strap	147	4.35	1.79E+04	5.35E+06	0.241	37.51	1.56	2.07
	blocking	147	4.35	1.79E+04	5.35E+06	0.241	37.51	1.56	2.07
8C	strap	129	4.35	1.79E+04	5.35E+06	0.241	32.91	1.37	1.83
	blocking	129	4.35	1.79E+04	5.35E+06	0.241	32.91	1.37	1.83
8D	strap	106	3.05	1.79E+04	3.75E+06	0.263	29.55	1.23	1.58
	blocking	106	3.05	1.79E+04	3.75E+06	0.263	29.55	1.23	1.58
8E	strap	85	3.05	1.79E+04	3.75E+06	0.263	23.70	0.99	1.00
	blocking	85	3.05	1.79E+04	3.75E+06	0.263	23.70	0.99	1.00
10C	strap	183	7.38	1.79E+04	9.07E+06	0.211	40.91	1.70	2.21
	blocking	183	7.38	1.79E+04	9.07E+06	0.211	40.91	1.70	2.21
	drywall	183	7.38	1.79E+04	9.07E+06	0.211	40.91	1.70	2.21
10D	strap	157	7.38	1.79E+04	9.07E+06	0.211	35.10	1.46	1.95
	blocking	157	7.38	1.79E+04	9.07E+06	0.211	35.10	1.46	1.95
	holes	157	7.38	1.79E+04	9.07E+06	0.211	35.10	1.46	1.95
12A	strap	235	14.06	1.79E+04	1.73E+07	0.180	44.72	1.86	2.33
	blocking	235	14.06	1.79E+04	1.73E+07	0.180	44.72	1.86	2.33
12B	strap	210	14.06	1.79E+04	1.73E+07	0.180	39.96	1.66	2.17
	blocking	210	14.06	1.79E+04	1.73E+07	0.180	39.96	1.66	2.17
12C	strap	194	14.06	1.79E+04	1.73E+07	0.180	36.92	1.54	2.05
	blocking	194	14.06	1.79E+04	1.73E+07	0.180	36.92	1.54	2.05
12D	strap	169	11.6	1.79E+04	1.43E+07	0.188	33.74	1.41	1.88
	blocking	169	11.6	1.79E+04	1.43E+07	0.188	33.74	1.41	1.88
12E	strap	135	11.6	1.79E+04	1.43E+07	0.188	26.95	1.12	1.34
	blocking	135	11.6	1.79E+04	1.43E+07	0.188	26.95	1.12	1.34

Note: d_e = 23/32 in.

S = 24 in.

E_{joist} = 29,500,000 psi

E_{OSB} = 580,000 psi

* I_t for floors with 10 in. deep joists taken from tabulated values

**Table D-5 Summary of Values Used to Calculate
N_{eff} from Kitterman Equation**

Floor	Parameter	L (in.)	d _e (in.)	S (in.)	I _t * (in ⁴)	Kitterman Limits			N _{eff}
						Limit 1 (d _e /S)	Limit 2 (L ⁴ /I _t)	Limit 3 (L/S)	
8A	strap	165	0.719	24	4.35	0.030	170.4E+06	6.88	3.02
	blocking	165	0.719	24	4.35	0.030	170.4E+06	6.88	3.02
	drywall	165	0.719	24	4.35	0.030	170.4E+06	6.88	3.02
8B	strap	147	0.719	24	4.35	0.030	107.3E+06	6.13	2.46
	blocking	147	0.719	24	4.35	0.030	107.3E+06	6.13	2.46
8C	strap	129	0.719	24	4.35	0.030	63.7E+06	5.38	2.07
	blocking	129	0.719	24	4.35	0.030	63.7E+06	5.38	2.07
8D	strap	106	0.719	24	3.05	0.030	41.4E+06	4.42	1.87
	blocking	106	0.719	24	3.05	0.030	41.4E+06	4.42	1.87
8E	strap	85	0.719	24	3.05	0.030	17.1E+06	3.54	1.66
	blocking	85	0.719	24	3.05	0.030	17.1E+06	3.54	1.66
10C	strap	183	0.719	24	7.38	0.030	152.0E+06	7.63	2.85
	blocking	183	0.719	24	7.38	0.030	152.0E+06	7.63	2.85
	drywall	183	0.719	24	7.38	0.030	152.0E+06	7.63	2.85
10D	strap	157	0.719	24	7.38	0.030	82.3E+06	6.54	2.23
	blocking	157	0.719	24	7.38	0.030	82.3E+06	6.54	2.23
	holes	157	0.719	24	7.38	0.030	82.3E+06	6.54	2.23
12A	strap	235	0.719	24	14.06	0.030	216.9E+06	9.79	3.41
	blocking	235	0.719	24	14.06	0.030	216.9E+06	9.79	3.41
12B	strap	210	0.719	24	14.06	0.030	138.3E+06	8.75	2.71
	blocking	210	0.719	24	14.06	0.030	138.3E+06	8.75	2.71
12C	strap	194	0.719	24	14.06	0.0299	100744559	8.08	2.38
	blocking	194	0.719	24	14.06	0.0299	100744559	8.08	2.38
12D	strap	169	0.719	24	11.6	0.0299	7.03E+07	7.04	2.12
	blocking	169	0.719	24	11.6	0.0299	7.03E+07	7.04	2.12
12E	strap	135	0.719	24	11.6	0.0299	2.86E+07	5.63	1.75
	blocking	135	0.719	24	11.6	0.0299	2.86E+07	5.63	1.75

* I_t for floors with 10 in. deep joists taken from tabulated values

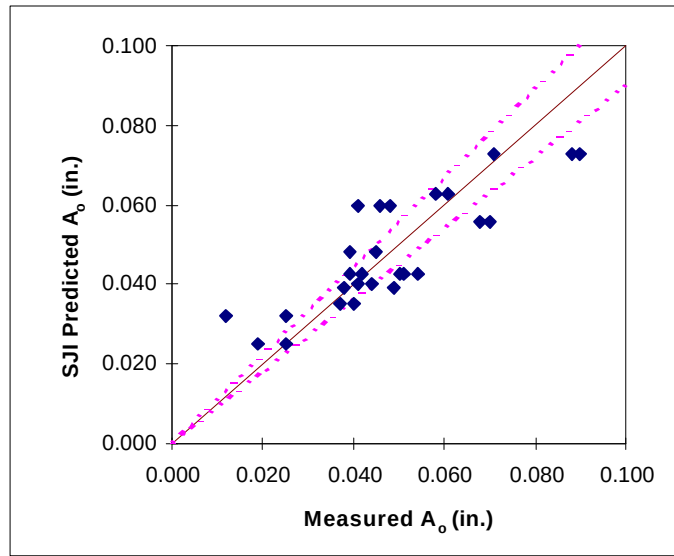


Figure D-1 SJI Equation Predicted Floor Deflection versus Measured Floor Deflection

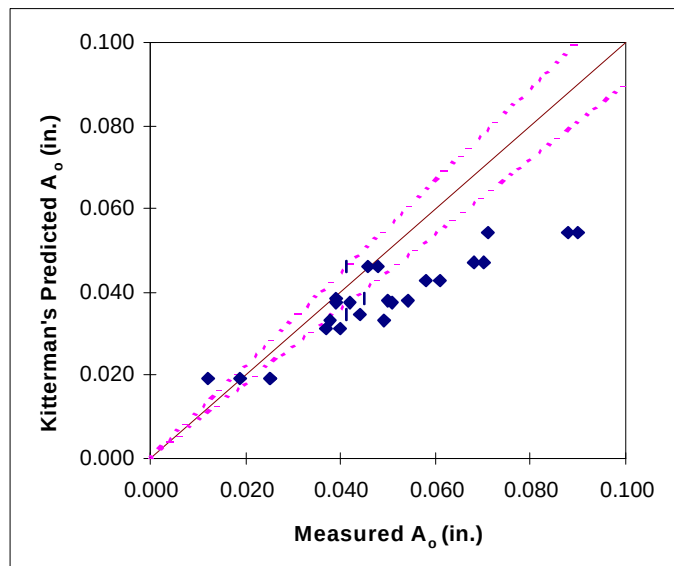


Figure D-2 Kitterman Equation Predicted Floor Deflection versus Measured Floor Deflection

VITA

Cynthia A. Kraus was born on April 6, 1973 in Urbana, Illinois. She was raised in Erie, Pennsylvania and graduated from Villa Maria Academy in 1991. In May 1995 she received a Bachelor of Science degree in Civil Engineering from The Pennsylvania State University. In August 1995 she entered the graduate program in the Structures Division of Civil Engineering at Virginia Polytechnic Institute and State University. In May 1997 she will receive a Master of Science degree in Civil Engineering from VPI&SU. In March 1997 she will begin working as an Assistant Bridge Engineer at Parsons Brinckerhoff in Norfolk, Virginia.