SOME ASPECTS OF VIBRATION SERVICEABILITY IN WOOD FLOOR SYSTEMS

by

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(ABSTRACT)

Two related areas of research are presented in this thesis. In one area, 106 in-situ wood floor systems were subjectively rated and tested to determine fundamental frequency values. This database of wood floor systems was used to provide further validation of a recently proposed design criterion which uses fundamental frequency to predict acceptability of wood floor systems to vibrations resulting from human footfall impacts. Included in the database are floors tested previously unoccupied which were tested again with occupancy loading. Additional occupied and unoccupied wood floor systems not included in the original study were tested. A second area of research was conducted to quantify the changes in frequency content and modal damping values through construction of six typical wood residences. The data from these floors provided insight into the dynamic behavior of wood floor systems and provided further data to validate the above design criterion.

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CHAPTER 1

INTRODUCTION

1.1 Background

Traditional wood floors were constructed using solid sawn lumber joists, board subflooring and strip hardwood finish flooring. The stiffness, mass and typical spans of these floor systems resulted in satisfactory performance with regard to vibration produced from human footfalls. Due to escalating material costs, today's wood floor systems utilize lightweight, high strength engineered wood products (i.e. parallel chord trusses, I-joists, laminated veneer lumber, etc.) which permit longer spans with lighter structural components. Additionally, many of today's floors use a single layer of plywood or oriented strandboard (OSB) subfloor with carpet used as the finishing material. As a result, today's wood floors are often lighter and less rigid than floors of "traditional construction," and may be particularly susceptible to excessive floor vibration caused by impacts from human footfalls. A modern wood floor designed for strength only may not be acceptable with regard to floor vibration produced from human footfalls. Although certainly not as severe as a structural failure, excessive floor vibration may limit the usefulness of a structure and require modification to alleviate the problem. Modifications to existing wood floors to improve vibration performance are often costly and inconvenient to the owner of the structure. A better approach is to insure vibration acceptability during the design stage of the floor system. Human discomfort resulting from excessive floor vibration is a serviceability issue that is currently not addressed in North American design practices except for a recommended deflection limitation of span/360 due to a uniform live load. However, more stringent deflection limitations have appeared in span tables supplied by manufacturers of engineered wood products.

Extensive research programs have been conducted in Canada, Sweden, United Kingdom and the United States to examine the problem of excessive wood floor vibrations. Different design criteria have been proposed based on these research programs. However, none of these criteria have been universally accepted. Research was also conducted at Virginia Tech and a design criterion was proposed based on the fundamental frequency of the floor system. This criterion is simple to use and provides a quick check on vibration acceptability. All of the above criteria are thoroughly discussed in the literature review section of this study. The complexity and abstract parameters used in the criteria from Canada and Sweden are believed to be the main reasons why they are not more widely used in design of wood floor systems. These criteria also require damping to be used which is exceedingly variable in reality. It is interesting to note that no two design criteria thus far proposed use the same dynamic parameters to insure acceptable floors. This shows that the problem is complex and that there is little agreement on which specific dynamic parameters are important in the design of wood floor systems. The three general dynamic parameters relating human discomfort and floor vibration that are universally agreed upon are frequency, amplitude and damping. Human discomfort to floor vibration is inversely proportional to frequency and damping and directly proportional to amplitude. Thus, a higher amplitude of vibration can be tolerated at higher frequencies. Large damping values limit vibration amplitudes for steady state vibration as well as govern the rate of decay for transient vibration. Quantifying and predicting these parameters for wood floors is often difficult and inaccurate and this problem is discussed in this study.

1.2 Objectives

There were two main objectives for the research conducted in this study.

1.2.1 Validation of 15 Hz Criterion

The first objective was to provide validation for the recently proposed design criterion requiring the fundamental frequency of a wood floor system be greater than or equal to 15 Hz. This criterion was the result of research done at Virginia Tech by J.R. Johnson

(1994). The research presented in this study is a continuation and extension of the work done by Johnson. Particularly, validation was needed for wood floors with occupancy loading since all of Johnson's research was conducted on unoccupied "bare" floors under construction. There was also a general need for a larger database of in-situ floors, both occupied and unoccupied, to provide further validation of this criterion.

1.2.2 Quantification of Dynamic Parameters for Various Levels of Construction

The second objective of the research was to quantify the changes in the dynamic parameters of floor frequency and damping at various stages of construction (from a bare floor to a completed structure). It was hoped that this area of research would provide damping values for wood floors at various levels of construction, provide information on the dominant frequencies of a wood floor system, and examine the effects of partitions and overall structure on the controlling frequencies. This is important because all of the present design criteria, including Johnson's, calculate dynamic properties based on bare floors and do not take into account the effects of partitions or overall structure itself on the vibration response of the floor system. Thus, the dynamic response of a wood floor system must not change significantly from a bare floor to that of the completed structure if a design criterion based on bare floor response is to be considered acceptable.

1.3 Literature Review

1.3.1 Scope of Review

Due to the volume of research that has been completed on the subject of floor vibration serviceability, this literature review is necessarily restricted to the objectives of this study. After a thorough investigation of previous research conducted on the subject of wood floor vibration, the work of five authors: Y.H. Chui, S.V. Ohlsson, R.O. Foschi, D.M. Onoysko, and J.R. Johnson, was determined to be of most relevance to the objectives of this research. A design criterion by T.M. Murray is also reviewed. Although Murray's criterion was developed for steel/concrete floor systems, it is included because the original goal of the wood floor vibration research conducted at Virginia Tech was to develop a similar criterion for wood floors.

1.3.2 Chui

Chui (1988) conducted a study to investigate the vibration performance of typical wood floors in the United Kingdom. Both laboratory built floors and in-situ floors were included in the study. Chui (1988) presented a two part design criterion for the vibration acceptability of wood floors. Chui simplified a wood floor system from a multi-degree of freedom system to a single-degree of freedom system on the assumption that if a disturbance is applied to the center of a floor and the response is measured at the same point, the vibration would be dominated by the fundamental natural frequency. The magnitude of the response for this case would also be the highest possible (Chui, 1988). The worst case for a particular floor is, therefore, represented by using this simplification. The above simplification also allows a design method based on simple equations that can be evaluated using a calculator. The limitation of Chui's design criterion is that it only applies to rectangular wood floors with no openings that are constructed with equally spaced joists. This limitation excludes many floors with stairwell openings.

The first part of Chui's design criterion requires the fundamental natural frequency of the floor system to exceed 8 Hz. This requirement is due to the fact that the natural frequencies of the organs of the human body are in the range of 4 to 8 Hz. From a derivation found in Smith and Chui (1988), the fundamental natural frequency of a wood floor system can be calculated with the following equation, which does not take into account any composite action between the sheathing and the joists.

$$f_o = \frac{\pi}{2a^2}\sqrt{\frac{EI(N_j - 1)}{p_f hb + p_j A(N_j - 1)}} \quad \text{(Hz)} \tag{1.1}$$

where: EI = mean joist stiffness (N m^2)

N_j = total number of joists

a = span of floor (m)

b = width of floor (m)

h = flooring thickness (m)

A = cross sectional area of joists (m^2)

p_f = density of flooring (Kg/m^3)

p_j = mean density of joists (Kg/m^3)

The second part of Chui's design criterion requires that the frequency weighted root-mean square acceleration (Ar) of the vibration resulting from a heel-drop impact load not exceed 0.45 m/s^2 for the first one second of vibration. A_r is weighted to the fundamental natural frequency of the floor. Chui (1988) states that the parameter A_r is a good indicator of floor performance since it incorporates the frequency, damping and amplitude of the floor system. The limiting value of frequency weighted A_r of 0.45m/s^2 was used because it is referenced in the British Standard BS (6472) as a limiting value in the determination of a human discomfort limit for building vibrations and it correlated well with Chui's test results (Chui 1988). From Chui (1988), A_r can be calculated from the following:

$$A_r = \frac{2000}{m\pi f_n^2} K \quad (\text{m/s}^2) \tag{1.2}$$

in which

$$m = \frac{a}{2}\left[p_f hb + p_j(n-1) + \frac{280}{a}\right] \tag{1.3}$$

$$f_n = \frac{\pi}{2a^2}\sqrt{\frac{EI_j(n-1)}{p_f hb + p_j(n-1) + \frac{280}{a}}} \tag{1.4}$$

K is determined using the table given by Chui (1988).

Equation 1.4 for the calculation of the fundamental natural frequency f_n of the floor system differs from Equation 1.1 in that it includes the effect on fundamental frequency of a person standing at the center of the floor. This effect is included since the values of A_r were measured from human heel-drop impacts (Chui, 1988).

In developing his design criterion, Chui (1988) also studied the effect of different construction methods on floor performance and methods to improve floor performance with regard to vibration produced from human footfalls. The significant results are listed below.

- A reduction of joist spacing or an introduction of extra joists led to an increase in the fundamental natural frequency and a reduction between the fundamental frequency and higher frequencies.
- A benefit was found for having all four edges of the floor supported due to the increase in the natural frequencies of higher order modes of vibration and subsequent increase in the interval between the fundamental frequency and higher frequencies.

- Viscous damping ratios were in the range of 2 percent and 3 percent for occupied and unoccupied floors respectively.
- The addition of between-joist solid wooden blocking had no affect on fundamental frequency but did raise the higher natural frequencies.
- Well separated modes of vibration distinguished good performing floors. This is because the effects of closely spaced modes can combine and thus magnify the response of the floor.

The dynamic response of floors with wood I-joists was also studied by Chui (1991). From this research, Chui concluded that long span wood I-joist floors do not necessarily have unacceptable vibration if deep sections are used and that floors built with shallow I-joists are more prone to producing unacceptable vibration due to their small mass. Additionally, it was determined that wood I-joists have higher frequencies than equivalent lumber joists of equal span due to their decreased mass. All of the measured frequency weighted A_r values of the I-joist floors tested exceeded Chui's design limit of $0.45 m/s^2$. The damping ratios of wood I-joist floors were found to be significantly larger than those of solid sawn joist floors.

1.3.3 Ohlsson

Sven Ohlsson has devoted a significant number of years to the study of floor vibration serviceability. In response to Chui's proposed criterion, Ohlsson cited problems with it and recommended that it not be included in design codes. The limitations of Chui's criterion as given by Ohlsson (1988c) are listed below.

- Only the response from the fundamental mode is taken into account. Thus, the stiffness perpendicular to the joists is not considered in the response of the floor.
- Vibration acceleration is used as the design parameter instead of vibration velocity, which is generally agreed upon to control human disturbance for the frequency ranges of wood floors.

- It is unconventional to apply RMS-averaging to transient signals and there is no justification for the averaging time of 1 s.

According to Ohlsson (1988), a design method with respect to floor vibration should:

- Reflect the degree of vibration serviceability.
- Be neutral with regard to construction material and structural configuration.
- Only include parameters that can be accurately and easily calculated and measured.
- Be physically understandable so that engineers can predict effects of structural modifications.

Ohlsson's design criterion to limit vibrations in floor systems uses three design parameters: static flexibility, unit impulse velocity response, and steady velocity response (Ohlsson, 1988b). The design criterion is restricted to floors with a fundamental frequency greater than 8 Hz and is independent of construction material and structural configuration. However, it is used almost exclusively for wood floors. A detailed explanation of Ohlsson's criterion and numerous examples on how it should be applied are given in *Springiness and Human-induced Floor Vibrations-A Design Guide* (Ohlsson, 1988b). The design criterion has been used in Sweden since 1984 and consists of three separate checks for vibration acceptability.

The first check is for low frequency forced vibration with major force components at frequencies around the step frequency (Ohlsson, 1988b). Since this type of response is below the lowest natural frequencies of short and medium span floors, the response can be regarded as semi-static (Ohlsson, 1988b). The check is a maximum static flexibility of 1.5 mm/kN for a concentrated force acting at midspan of the joist.

The rest of Ohlsson's criterion applies to floors with a fundamental natural frequency of 8 Hz or greater. Ohlsson gives the following formula to calculate the first order mode resonant frequencies for an orthotropic plate.

$$f_n = \frac{\pi}{2}\sqrt{\frac{D_x}{gL^4}}\sqrt{1+\left[2n^2\left(\frac{L}{B}\right)^2+n^4\left(\frac{L}{B}\right)^4\right]\cdot\frac{D_y}{D_x}} \quad \text{(Hz)} \qquad (1.5)$$

where: D_x = plate stiffness in the x-direction (parallel to the joists) (Nm^2/m)

D_y = plate stiffness in the y-direction (perpendicular to the joists) ($N{\cdot}m^2/m$)

g = unit mass (kg/m^2)

B = width of the floor in the y-direction (m)

L = span of the floor in the x-direction (m)

n = modal number

For $D_y/D_x<0.01$, the equation reduces to:

$$f_1 = \frac{\pi}{2}\sqrt{\frac{D_x}{g\cdot L^4}} \quad \text{(Hz)} \qquad (1.6)$$

for the first resonant frequency.

If the fundamental frequency from above is greater than 8 Hz, then Ohlsson's criterion requires that a factor h'_{max} be calculated. The parameter h'_{max} is the impulse velocity response resulting from a force pulse of zero duration but with the impulse value equal to unity (Ohlsson, 1988b). Ohlsson has determined that impact loads caused by footsteps excite frequencies equal to or less than 40 Hz. This is accounted for by calculating h'max using only the number of modes with frequencies less than 40 Hz. A frequency normalized to 40 Hz (40/f1) is used with charts provided in Ohlsson's Design Guide (Ohlsson, 1988) to calculate the number of modes with frequencies less than 40 Hz (N_{40}). The impulse velocity response is then calculated by:

$$h'_{max} = \frac{4 \cdot (0.4 + 0.6N_{40})}{gBL + 200} \quad (m/s/Ns) \qquad (1.7)$$

Once h'_{max} is calculated, a damping parameter σ_0 is calculated by multiplying the relative damping coefficient ζ by the frequency calculated previously. The damping parameter σ_0 relates how quickly vibrations for a particular floor are damped out with respect to time. Ohlsson (1988b) suggests using a value of 0.01 for ζ for normal lightweight floors.

The impulse velocity and damping coefficient are then plotted in a graph provided by Ohlsson (1988) which labels the floor as intrusive, uncertain, or better. A plot in the "better" region is needed to pass the second check.

For floors with a span length greater than 4m and long unobstructed passages open to pedestrian traffic, a third check for vibrations resulting from continuous dynamic loading is needed (Ohlsson, 1988b). For this check a r.m.s. value of the vibration velocity, $w'_{r.m.s.}$, is calculated according to the following formula.

$$w'_{r.m.s.} = \frac{100}{gBL \cdot \sqrt{\varsigma}} \cdot \sqrt{\frac{N^2_{1.2} + 1}{2f_1^3}} \quad [(m/s)_{rms}] \qquad (1.8)$$

Where $N_{1.2}$ is the number of first order modes with resonant frequencies less than $1.2 \cdot f_1$. $N_{1.2}$ is calculated using the same charts as for N_{40}. Ohlsson presents this design parameter but states that he as yet does not have general limits to compare it to. He suggests that the calculated $w_{r.m.s.}$ values be compared to those of previously designed floors of acceptable performance.

Ohlsson (1988) states that one should be "humble" when discussing different proposed design criterion due to the difficulties of estimating the actual dynamic loading, the fact that damping cannot be controlled by the designer of the floor and basically can only be guessed, and because the effects of partitions and other non-load bearing components on the dynamic response of the floor system are unknown. Due to the latter uncertainty, Ohlsson is of the opinion that the serviceability limit state design should not rely upon non-load bearing components of the floor system.

1.3.4 Foschi and Gupta

Foschi and Gupta (1987) used a finite strip analysis of a floor system that was previously developed for static loads and extended it to dynamic loads. Four floors were built and tested using heel-drop heights of 25 mm and 50 mm. Each floor tested had a person at midspan who impacted the floor and another person at midspan of an adjacent joist to evaluate the vibration. Fundamental frequency and peak displacement were measured for each floor. Human response to vibration was calculated using the Wiss and Parmelee equation. This equation subjectively rates a floor with numerical values from 1 to 5 based on the fundamental frequency, peak displacement and damping of the floor system. (Wiss and Parmelee, 1974). The subjective ratings are as follows: 1 = imperceptible, 2 = barely perceptible, 3 = distinctly perceptible, 4 = strongly perceptible, 5 = severe. The equation is given below.

$$R = 5.08 \cdot \left(\frac{FA}{D^{0.217}} \right)^{0.265} \tag{1.9}$$

where: A=Peak Amplitude (in.)

F=Frequency (Hz)
D=Viscous Damping Ratio

To calculate a rating for the floors, a measured damping value of 0.15 was used. A reliability index was then calculated based on span and footfall height (Foschi and Gupta, 1987). The reliability index was based on a failure subjective rating of R equal to 3. Permissible spans were then calculated to give a reliability index of 2 in 100 floors having an R rating greater than or equal to 3. Based on these spans, allowable deflections due to a 1 kN load acting at midspan were calculated. From this data, an allowable deflection of 1 mm due to a 1 kN load acting at midspan was proposed (Foschi and Gupta, 1987). Foschi and Gupta also calculated allowable deflection limitations based on the permissible spans from above and a 40 psf load that is used in North America design codes. The results were in the range of span/1000 to span/1140. The current serviceability criterion used in the United States is a limit on deflection of span/360 due to a load of 40 psf. Based on the work by Foschi and Gupta, the current limit is too lenient with regard to vibration serviceability.

1.3.5 Onysko

Onysko proposed a design criterion for vibration of wood floors after detailed interview and inspections were held in 107 residences providing data for 646 floors (Onysko, 1988). In each case the floor was rated as acceptable, unacceptable, undecided or motion not noticed. Onysko (1988) first tried to develop a criterion based on dynamic impulse loading. Difficulties in assigning damping values to different floor systems and in estimating the amount of mass provided by furniture loading resulted in a static criterion to be developed rather than a dynamic criterion.

The final design criterion proposed by Onysko is a limit on the deflection under a concentrated load of 1 kN applied at midspan of the floor. The deflection limit is given by:

$$y = \frac{8.0}{L^{1.3}} \leq 2.0 \tag{1.10}$$

where: L = clearspan length (m)

y = midspan deflection (mm)

Onysko's criterion is calibrated to a floor system considered to have provided satisfactory performance in the past (Onysko, 1988).

1.3.6 Murray

Murray's design criterion for residential or office type environments is formulated using the test results of 100 steel/concrete floor systems (Murray, 1991). The design criterion determines the acceptability of a floor system based on the parameters of first natural frequency, amplitude, and damping. The amplitude used is the maximum which occurs due to a heel-drop excitation of the floor.

Murray (1981) gives the following inequality for the design criterion.

$$D > 35A_of + 2.5 \tag{1.11}$$

where: D = damping in percent of critical

A_0 = maximum initial amplitude due to heel-drop excitation (in.)

f = first natural frequency of the floor system (Hz)

Murray (1991), does not recommend the use of the design criterion for floor systems with fundamental frequencies above 10 Hz.

The frequency of a beam or girder in the floor can be calculated using the simple beam equation:

$$f = K\sqrt{\frac{gEI_t}{WL^3}} \quad \text{(Hz)} \tag{1.12}$$

where: f = first natural frequency, Hz

K = 1.57 for simply supported beams

= 0.56 for cantilevered beams

g = acceleration of gravity (386 in./sec^2)

E = modulus of elasticity, lb/in.^{2}

I_t = transformed moment of inertia of the tee-beam model, in.^{4}

W = weight supported by the beam or girder, lb.

L = span length, in.

The system frequency is calculated using Dunkerley's equation:

$$\frac{1}{f^2_s} = \frac{1}{f_b^2} + \frac{1}{f_g^2} \tag{1.13}$$

where: f_s = system frequency, Hz

f_b = beam frequency, Hz

f_g = girder frequency, Hz

The maximum dynamic amplitude of a beam or girder is determined by first calculating the static deflection resulting from a 600 lb. load applied at midspan of the beam or girder. The dynamic amplitude is then determined by multiplying the static deflection by a dynamic load factor. Murray (1975, 1991) provides tables to determine the dynamic load factor based on natural frequency and equations for calculating it directly.

The dynamic amplitude is then divided by the number of beams resisting the applied load of 600 lb. This is referred to as N_{eff}. Murray uses two equations to calculate N_{eff} depending on the beam spacing.

For beams with spacing less than 2.5 ft.

$$N_{eff} = 1 + 2\sum\left(\cos\frac{\pi x}{2x_o}\right) \quad \text{for } x \le x_o \tag{1.14}$$

where: x = distance from the center joist to the joist under consideration (in.)

x_o = distance from the center joist to the edge of the effective floor (in.)

$= 1.06\varepsilon L$

L = joist span (in.)

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

D_X = flexural stiffness perpendicular to the joists

$= E_c t^3/12$

D_y = flexural stiffness parallel to the joists

$= EI_t/S$

E_c = modulus of elasticity of concrete (psi.)

E = modulus of elasticity of steel (psi.)

t = slab thickness (in.)

I_t = transformed moment of inertia of the tee beam (in.^{4})

S = joist spacing (in.)

For beams with spacing greater than 2.5 ft.

$$N_{eff} = 2.97 - \frac{S}{17.3d_e} + \frac{L^4}{1.35EI_t} \tag{1.15}$$

where: S = beam spacing (in.)

d_e = effective slab depth (in.)

L = beam span (in.)

N_{eff} for a girder is 1.0.

Once N_{eff} is calculated, the amplitude of the beam and girder is determined by:

$$A_o = \frac{A_{ot}}{N_{eff}} \tag{1.16}$$

The amplitude of the floor system is determined by:

$$A_{os} = A_{ob} + \frac{A_{og}}{2} \tag{1.17}$$

where: A_{os} = system amplitude

A_{ob} = A_o for beam

A_{og} = A_o for girder

The required damping for the beam, girder and floor system are then calculated separately using the inequality given previously and compared to the estimated amount of damping provided. Murray (1991) provides estimates of damping for various components of a completed floor system that can be used to compare the computed values to required damping values.

1.3.7 Johnson

Johnson (1994) provides a design criterion for wood floors based on the test results of 86 floors under construction. Most of the floors were tested before the entire structure was completed and often wall braces anchored to the floors were still in place. Johnson originally tried to apply the design criterion developed by Murray to his data. Due to difficulties in calculating damping values from his data and predicting measured deflections, Murray's criterion could not be used (Johnson, 1994). The trend that best fit Johnson's data was a design criterion that required the fundamental natural frequency of each component of the floor and the floor system as a whole be greater than 15 Hz.

To apply the design criterion, the fundamental frequency of the joists and girders are first calculated by:

$$f = 1.57 \cdot \sqrt{\frac{386EI}{WL^3}} \quad (\text{Hz}) \tag{1.18}$$

where: f = fundamental natural frequency (Hz)
E = modulus of elasticity (psi)
I = moment of inertia of joist alone (in.^{4})
W = total supported permanent load (lb.)
L = length of span (in.)

In calculating fundamental frequency, any composite action between the sheathing and joists is neglected. Justification for this simplification was provided by performing static deflection tests on lab built floors (Johnson, 1994).

The fundamental natural frequency of the floor system is calculated using Dunkerley's equation. A simplified form of this equation is:

$$f = \sqrt{\frac{f^2_{\text{joist}} \cdot f^2_{\text{girder}}}{f^2_{\text{joist}} + f^2_{\text{girder}}}} \quad (\text{Hz}) \qquad (1.19)$$

The fundamental natural frequencies of the joists, girders and the overall floor system are all required to be greater than 15 Hz for the floor system to be rated acceptable.

1.4 Scope of Work

This study is the final installment of a research project sponsored by the United States Department of Agriculture National Research Initiative Competitive Grants Program in the area of *Improved Utilization of Wood and Wood Fiber.* Previous research has provided a procedure to accurately calculate the fundamental frequency of a wood floor and a design criterion has been developed to promote vibration acceptability by requiring the fundamental natural frequency of a wood floor system be greater than or equal to 15 Hz. The scope of the research for this study was the testing of additional floors to provide a large database of subjectively rated floor systems from which the 15 Hz design criterion could further be validated. To achieve this, over 100 different floor systems were rated and tested. Unoccupied floors under construction that had been previously tested in developing the design criterion were tested again with occupancy loading. To provide data to further validate the design criterion, additional occupied and unoccupied floor systems were tested and rated. Additionally, research was conducted to quantify the changes in frequency content and modal damping values through construction of typical wood residences. The data from these floors provided insight into the behavior of wood floor systems and provided further data to validate the above design criterion.

CHAPTER 2

GENERAL ANALYSIS AND TESTING PROCEDURES

2.1 Overview

This chapter discusses the methods that were followed to determine the frequency content and modal damping values for the data that was collected for this study. The method used to predict fundamental frequencies of the tested floor systems is also discussed. Additionally, a description of the test equipment that was used for data acquisition is given. In this chapter, only a general description is given for each. Additional detail is given where appropriate in subsequent chapters.

2.2 Analysis of Data

Before the actual methods used to analyze the data are given, a brief overview of the fundamentals of vibration testing and analysis is needed. The general procedures are the same regardless of what type of data acquisition systems is used. When a floor is impacted, the resulting vibration is measured with either an accelerometer, velocity transducer, or displacement transducer and recorded with some type of data acquisition system. All of the data used in this study was recorded with an accelerometer and so only this type of vibration measurement instrument will be discussed. The continuous signal that is sent to the data acquisition system from the accelerometer is sampled at a certain sample rate for a specified number of data points. The sample rate which has units of points/second (pts/s) and the number of recorded points determine for what length of time the data is recorded. A typical sample rate used for wood floors is 256 pts/s. By using a fast sample rate, the recorded data points provide a close approximation of the actual continuous signal. Data recorded in this manner is known as time domain data. By plotting the data points versus the time at which they were recorded, an acceleration trace is produced. A typical time domain acceleration trace due to a heel-drop impact is shown in Figure 2-1.

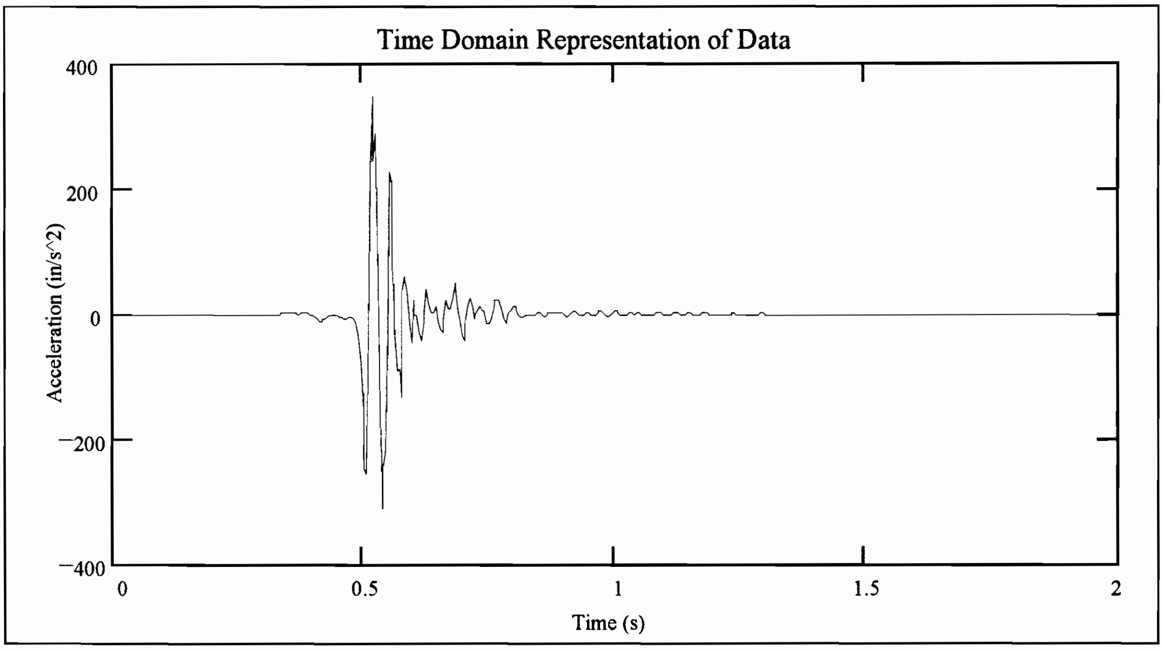


Figure 2-1 Example of Time Domain Data

To analyze the frequency content of a time domain trace, a fast Fourier transform, FFT, algorithm is performed on the time domain data points. The FFT algorithm transforms the time domain data to frequency domain data. To use a FFT, the number of sampled points must be a power of two. The FFT algorithm returns the same number of complex numbers plus one. These complex numbers are known as FFT coefficients. The FFT coefficients are incremented at the frequency step for which the data was recorded. The frequency step is given by:

$$\text{frequency step} = \frac{\text{Sample rate}}{\text{Number of data points}} \quad \text{(Hz)} \tag{2.1}$$

To construct a spectrum of the frequency content of an acceleration trace, the magnitudes of the FFT coefficients are plotted against corresponding multiples of the frequency step. To construct a power spectrum of the frequency content of an acceleration trace, the square of the magnitudes of the FFT coefficients are plotted against the corresponding multiples of the frequency step. For example, the frequency corresponding to the twentieth FFT coefficient would be twenty times the frequency step. The power spectrum of Figure 2-1 is shown in Figure 2-2.

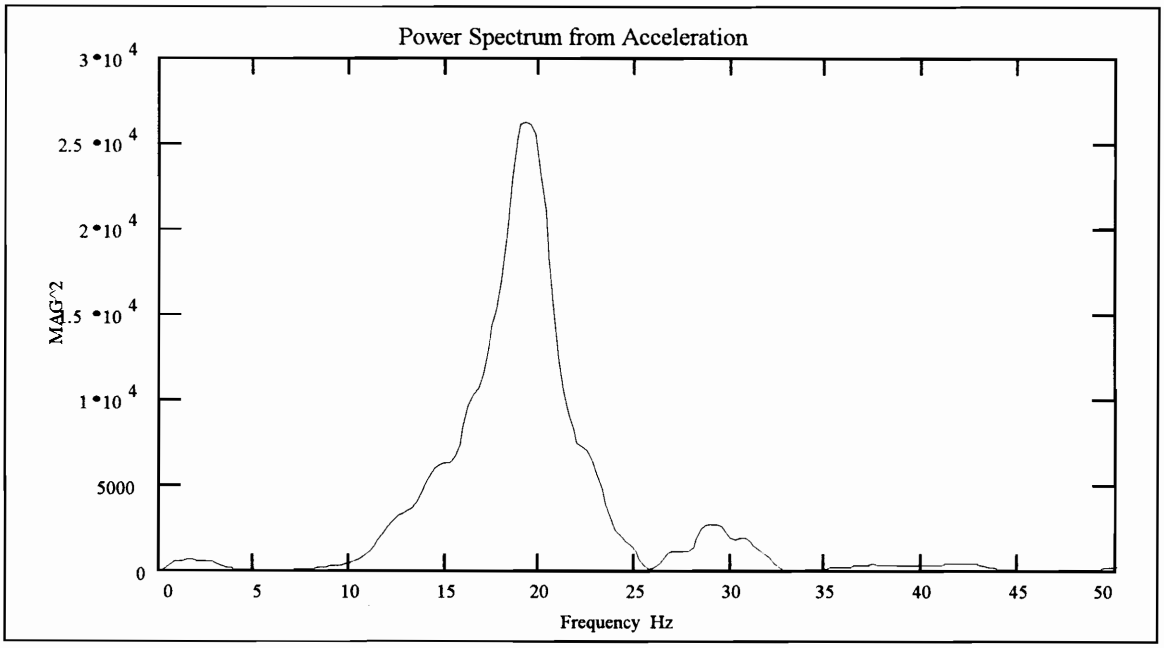


Figure 2-2 Example of Power Spectrum

For free vibration, the spikes or peaks of the spectrum or power spectrum indicate the natural resonant frequencies of the floor system. The magnitude of the spike represents the energy associated with that particular resonant frequency of vibration. The floor associated with the power spectrum of Figure 2-2 has a natural frequency of 19.8 Hz.

All of the data for this study was analyzed using the software package Mathcad Plus 5.0 (1994). With Mathcad, the time domain data points are imported into a vector variable and a detrend function is used to remove any linear trend in the data. The FFT algorithm is then applied to the time domain data points to produce a vector of frequency domain FFT coefficients. With these two vectors, time domain and frequency domain graphs can be constructed.

The analysis of the data consists of reading off the frequencies corresponding to the peaks of the power spectrum. This process is straight forward when there are clearly defined spikes. However, many times the spikes are not clearly defined and the response of the floor system seems to be represented by a mound spread over a large frequency band. This same phenomenon was experienced by Johnson and is described thoroughly by him. Johnson (1994). A thorough examination of this phenomenon and how it was dealt with in the data analysis is discussed in subsequent chapters.

There are two main methods of determining damping values from vibration data. One is the log decrement method. This method is based on the fact that for an underdamped system, amplitudes decay exponentially with time (Humar, 1990). Therefore, the viscous damping ratio can be calculated from the natural log of the ratio of successive peak values for one period of vibration in the time domain. This method has often been applied to wood floors, but is not a good method to use since it was derived for vibration consisting of a single mode. Wood floors seldom have only one mode of vibration but generally possess multiple modes. It is generally impossible to distinguish modes of vibration when analyzing time domain data. Therefore, if the log decrement method is used with time domain data consisting of multiple modes, the peaks used in the calculation will probably correspond to different modes of vibration and, consequently, the vibration will no longer be exponentially decaying in nature. Another problem with applying the log decrement method to multi-mode vibration is due to the fact that the vibration from different modes damps out at different rates. Thus, log decrement values calculated for multiple mode floors have little analytical value.

Another method that is used to calculate viscous damping values is the half power method. This method allows damping values of individual modes of vibration to be calculated. With this method, modal damping values are calculated by determining the peak power associated with the spike of interest in the power spectrum. The peak power is then divided by two if the power spectrum is being analyzed, or the square root of two if the spectrum is being analyzed, and the two corresponding frequencies associated with this half power are determined. These frequencies are commonly referred to as f_1 and f_2 with f_1 being the smaller frequency. The value of modal damping is given by:

$$\delta = \frac{f_2 - f_1}{f_1 + f_2} * 100 \quad \text{(\% critical)} \qquad (2.2)$$

where: δ = modal damping, % critical

f_1 = smaller frequency corresponding to half of peak power, Hz

f_2 = larger frequency corresponding to half of peak power, Hz

Poorly defined spikes in the power spectrum and closely spaced modes often made this method difficult to apply to the data for this study. This problem is discussed in detail in Chapter 3.

2.3 Test Equipment

The instrument used to measure the vibration of the floors was a Wilcoxon Model 731, liquid damped, piezoelectric accelerometer. The accelerometer was powered by a Wilcoxon P-31 Power Unit/Amplifier. The accelerometer is calibrated to output a certain voltage in relation to the acceleration of the floor. The calibration factor depends on the gain setting of the amplifier. All the data for this research used a calibration factor of 10 V/g. The accelerometer was mounted with wax onto a 380 mm x 200 mm, 156 N (15 in. x 8 in., 35 lb) steel plate. The plate was used to provide a good surface on which to mount the accelerometer.

The floors were excited with a heel-drop impact. The heel-drop impact consisted of an 845 N (190 lb) male researcher raising up on his toes approximately 76 mm (3 in.) and then suddenly dropping down onto his heels. The heel-drop impact was performed approximately 300 mm (1 ft.) from the plate. Although this method of impact cannot be repeated exactly each time, it is easy to use and does not require special equipment.

Other methods such as dropping weights were not used because this research was performed by one person and that type of equipment weighs a few hundred pounds and cannot be moved and handled by a single person. Hammer impacts were experimented with, but the hammer was not able to consistently excite low frequencies for many of the floors. Also, the impact from the hammer often caused the plate to bounce off the floor, which caused rigid body displacements in the acceleration traces. Because of this, heel-drop impacts were adopted as the sole means of impacting the floors.

For the floors of the monitored houses, the heel-drops were performed on a force plate so that a time trace of the input force could be recorded. The force plate consists of a 406 mm x 406 mm x 10 mm (16 in. x 16 in. x 3/8 in.) top plate supported at each corner by a cantilever type load cell. The load cells are, in turn, supported by a 305 mm x 305 mm x 10 mm (12 in. x 12 in. x 3/8 in.) bottom plate. The load cells produce a voltage proportional to the force being measured. The voltages from the load cells are summed, producing a single voltage that is sent to the data acquisition system. The calibration factor for the force plate was 303 kN (68,124 lb/V). For floors other than those being monitored throughout construction, the heel-drops were performed directly on the floor and no input force was measured.

Three different data acquisition systems were used to record the vibration measurements. The data acquisition system takes the analog voltage signal from the accelerometer or force plate and converts it to digital format which is then usually stored as ASCII files. Availability of equipment was the main reason for using three different acquisition systems.

Floors tested early in the research were recorded on a Daqbook/100 Data Acquisition System. The Daqbook is used in conjunction with a laptop computer to record vibration measurement. The Daqbook is configured with software on the laptop and the measurements can either be stored on the laptop's hard-drive or a floppy disk. The configuration of the Daqbook was such that it was capable of recording vibration measurement only. It does not have the ability to display the time domain or frequency domain traces of the recorded data. Another limitation of the Daqbook is that the input range for vibration measurement is limited to ± 5 V. For acceleration values of wood floors impacted with a standard heel-drop, this range is easily exceeded. Exceeding the input range caused the recorded acceleration traces to be "clipped". An example of clipped data is shown in Figure 2-3.

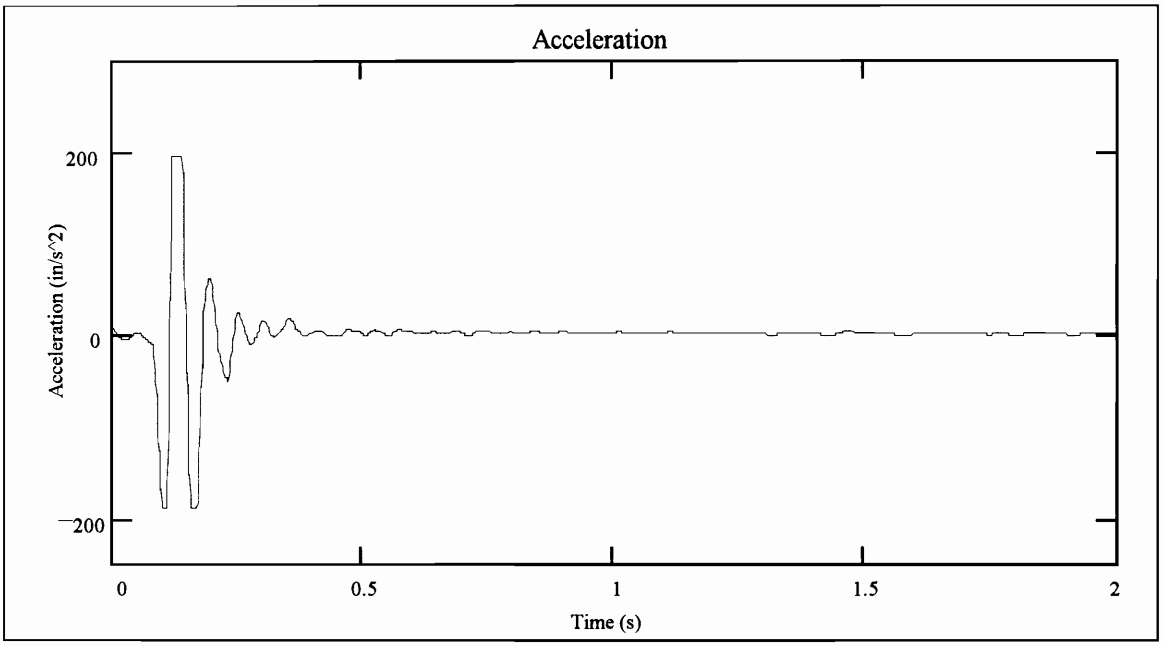


Figure 2-3 Example of Clipped Data

To avoid clipping the data when using the Daqbook, lighter heel-drops were used to excite the floors. The use of light heel-drops for occupied floors does not seem to provide enough input force to sufficiently excite the floor. However, to avoid clipped data, this was the only option available.

The preferred data acquisition system was a Hewlett Packard 35660A Dynamic Signal Analyzer. The HP analyzer was used for a majority of the floors tested. When possible, floors tested previously with the Daqbook were retested with the HP analyzer. The HP has an adjustable input range to tailor the sensitivity of the analyzer to the vibration being measured. This improves the clarity of the recorded data. The HP can also display time domain and frequency domain traces of the recorded data. Thus, it is possible to immediately see if satisfactory readings are being taken for the floor. Data recorded with the HP analyzer must be converted to ASCII format with software provided by Hewlett Packard. The ASCII files must then be edited before they can be analyzed to remove file headers and footers attached to the data. Another beneficial feature of the HP analyzer is that it uses anti-aliasing filters to filter out frequencies of the floor greater than half of the sampling rate being used. Thus, slower sampling rates can be used to record the vibration data. A limitation of the HP is that the maximum number of recorded points is set at 1024.

A third data acquisition system that was used late in the research was an Ono Sokki CF-1200 hand held analyzer. The CF-1200 analyzer is convenient to use due to its small size and weight. However, because it is a single channel analyzer, it could not be used for the monitored houses, since acceleration and input force data were recorded simultaneously for these houses. Like the HP analyzer, the CF-1200 has an adjustable input range and can immediately display time and frequency domain traces. The CF-1200 analyzer was used to test additional floors that became available towards the end of the research. Traces recorded on the CF-1200 were stored on a RAM card which must be converted to ASCII format with software provided by Ono Sokki.

Regardless of the analyzer used, a trigger mechanism was needed to start the vibration recording. The HP and CF-1200 were configured to trigger when a certain percentage of the input signal was exceeded. The Daqbook was triggered manually by the researcher performing the heel-drop with a hand-held trigger mechanism.

2.4 Calculation of Fundamental Frequency

The procedure used to calculate the fundamental frequency of the floor system was the same one used by Johnson (1994). Runte (1992) had previously verified this method for wood floor systems. The only change Johnson made to Runte's procedure was to ignore any composite action between the floor sheathing and the joists. Thus, the fundamental frequency is calculated using the stiffness of the joists alone. The procedure to calculate fundamental frequency and the equations involved in the procedure were reviewed in Section 1.3.7 of Chapter 1.

CHAPTER 3

MONITORED HOUSES

3.1 Introduction

One of the two objectives in this study was to monitor the change in the dynamic parameters of typical wood floor systems through various levels of construction. At the present time, there has not been significant research on the effects of partition walls and the overall structure itself on the dynamic response of wood floor systems. Because wood floors are less massive than steel/concrete floor systems, the magnitude of changes in performance was predicted to be more pronounced for wood floor systems. The second objective of this study was to provide validation of the 15 Hz design criterion which was discussed in the literature review Section 1.3.7 of Chapter 1. Because this criterion was predominately based on test data from bare floors under construction, the research presented in this chapter is particularly significant. For this criterion to be accepted, the dynamic response of wood floors in occupied structures must not change so as to increase human discomfort. The only acceptable changes due to occupancy would be those that lessen human discomfort.

For this study, the change in the fundamental frequencies and corresponding modal damping values were quantified at various stages of construction for the wood floor systems of six residences. The monitored houses were selected to include all different types of wood floor systems that are currently being used for residential construction. The monitored houses included two solid sawn joist floors utilizing 51 mm x 305 mm (2 in. x 12 in.) and 51 mm x 254 mm (2 in. x 10 in.) Spruce-Pine-Fir No.2 lumber joists, three parallel chord truss floors utilizing 560 mm (22 in.), 457 mm (18 in.), and 356 mm (14 in.) deep sections and constructed of 51 mm x 102 mm (2 in. x 4 in.) Southern Pine No.1 chord members, and a floor utilizing 11 7/8 in. wood engineered I-joists. First, the testing procedures used for each of the six houses monitored for the study are discussed and then the results for each of the six houses are presented. Due to construction schedules and different construction methods, some testing procedures were common to all of the monitored houses, while others differed slightly depending on the circumstances of each house. Therefore, a general description is given first, then the specifics for each monitored house are discussed.

3.2 Testing and Analysis Procedures

3.2.1 General

Although the test procedures differed slightly for each of the six monitored houses, some procedures were common to all. The HP analyzer was used exclusively for the monitored floors. Additionally, a force plate was used in conjunction with an accelerometer to record both the heel-drop impact force used to excite the floors and resulting acceleration response of the floors. A complete description of the test equipment used was provided in Chapter 2 and only a brief summary is given here. The accelerometer was mounted onto a steel plate with wax. The accelerometer was connected to a power/unit amplifier set to a calibration factor of 10 V/g of acceleration. The power/unit amplifier was, in turn, connected to the second channel of the HP analyzer. The force plate was positioned on the same joist approximately 300 mm (1ft) from the accelerometer. The force plate has a built in amplifier configured to 303 N/V (68,124 lb/V). The force plate was connected to the first channel of the HP analyzer. The HP analyzer was always placed on a floor other than the one being tested. For each test, the input range of the HP analyzer was set by first performing a few heel-drops on the force plate without recording the vibration. To record the acceleration of the floors, the HP analyzer was configured to average ten RMS (root mean square) traces. Averaging was used for both the acceleration and heel-drop time traces. Averaging was used to determine a more accurate response of the floor system compared to that provided by single acceleration and heel-drop time traces. Averaging also compensates for the effects of inconsistencies in using heel-drops to excite the floor. These inconsistencies involved impacting the floor with a different force each time and variations in how each heel-drop was performed. The HP analyzer was configured to start recording or trigger when the acceleration of the floor exceeded ten percent of the input range.

The procedure used to measure the vibration response of the floors was as follows. Once all of the equipment was in place, the researcher would start the averaging procedure on the HP analyzer. With this procedure, the HP analyzer automatically arms itself and waits for a trigger to occur. The floor is then impacted and the acceleration and heel-drop time traces are recorded independently. Then, the HP arms itself again and waits for another trigger. Once the recording process was initiated, the researcher would step onto the force plate and perform the first heel-drop. The researcher would then wait for the analyzer to finish recording and re-arm itself. Then another heel-drop would be performed. This procedure was repeated a total of ten times and the response was averaged to obtain a record used for analysis. Once the averaging was complete, the researcher would store the traces onto a floppy disk. For each floor measurement, an acceleration time trace, a force plate time trace, an acceleration power spectrum, and a frequency response trace were recorded.

The frequency response trace was not discussed in Chapter 2 and, therefore, is presented here. The frequency response of a floor relates how the floor responds to the input being applied. Thus, if a floor is excited with a frequency near or exactly at a resonant natural frequency of the floor, the frequency response will be greater due to the floor being put into resonance. A frequency response trace is traditionally defined as the coefficients from the FFT of a response time trace divided by the corresponding coefficients from the FFT of the forcing function. The response time trace is either the acceleration, velocity or displacement of the floor. For this study, the response was the acceleration time trace of the floor. The forcing function was produced from the time history of the impact force used to excite the floor. For this study, the forcing function was the time history of a heel-drop impact. A typical time history of a heel-drop impact is shown in Figure 3-1.

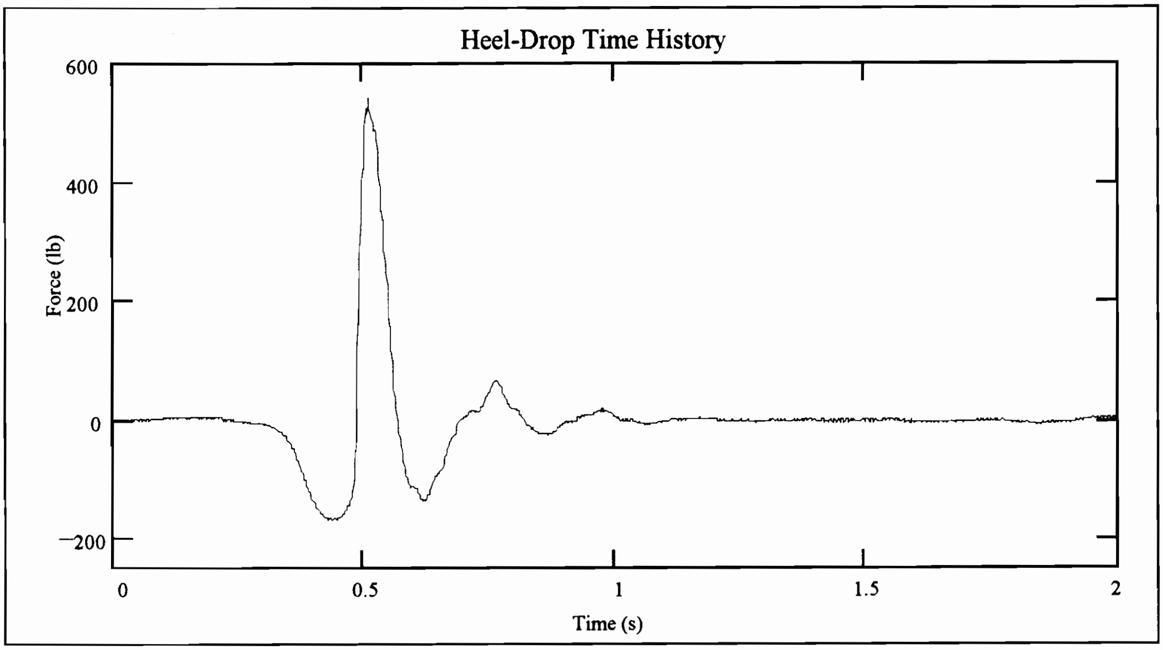


Figure 3-1 Example of Time History of Heel-Drop Impact

The HP analyzer calculates frequency response using a slightly different equation. This equation is given below.

$$\text{Frequency Response} = \frac{X^{*} \cdot Y}{X \cdot X^{*}} \tag{3.1}$$

in which

X = FFT coefficient of input

X^{*} = complex conjugate of FFT coefficient of input

Y = FFT coefficient of output

Just as with an acceleration power spectrum, the number of frequency response coefficients is equal to half the number of sample points plus one. By taking the square of the magnitude of each frequency response coefficient and plotting them against their corresponding multiple of the frequency step, a frequency response plot is produced.

The sole reason for using the force plate for the monitored houses was to be able to record the forcing function or heel-drop impacts used to excite the floor so that frequency response traces could be produced. The force plate was not used for any other floors tested in this study except for those of the six monitored houses. Frequency response traces were intended to yield better results for modal analysis purposes than the acceleration traces alone. Particularly, it was thought that it would be advantageous to analyze the natural frequency content of the monitored floors and the corresponding modal damping values using frequency response measurements. For all of the floors monitored, however, the frequency response traces did not yield significantly better results than analyzing the acceleration traces alone. To see why, a typical power spectrum from an acceleration time history and heel-drop time history, and the corresponding frequency response function calculated from the two, are shown in Figures 3-2, 3-3 and 3-4, respectively.

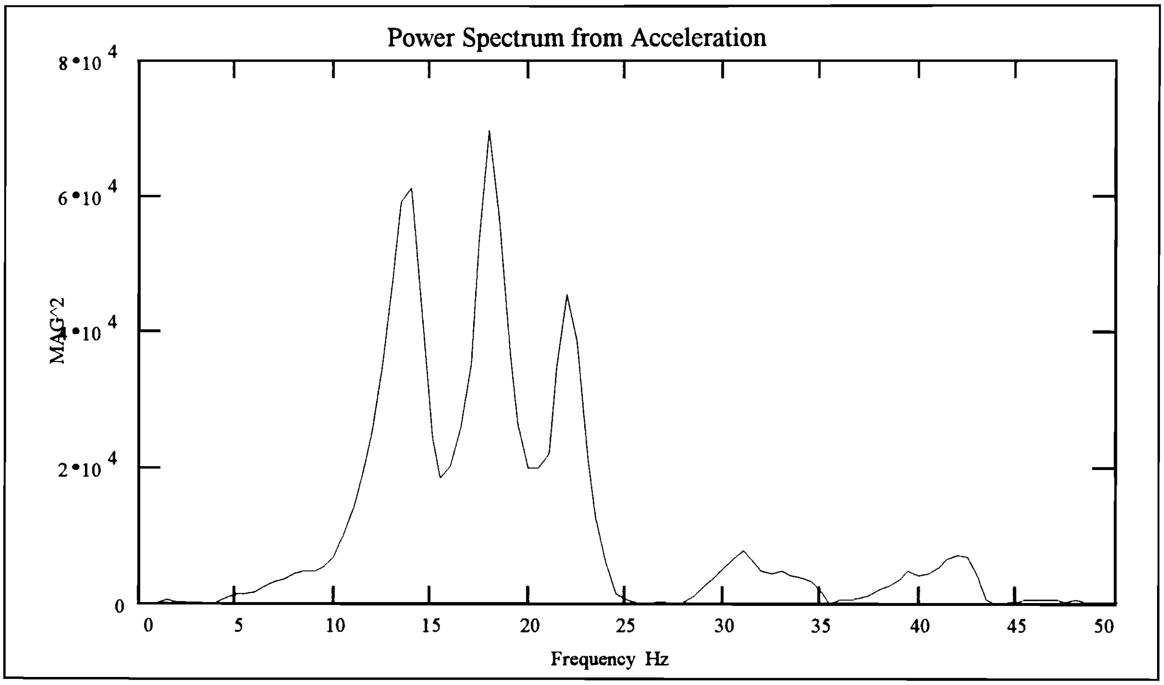


Figure 3-2 Power Spectrum of Response from Position 1 of Floor 1 of Parallel Chord Truss House #1

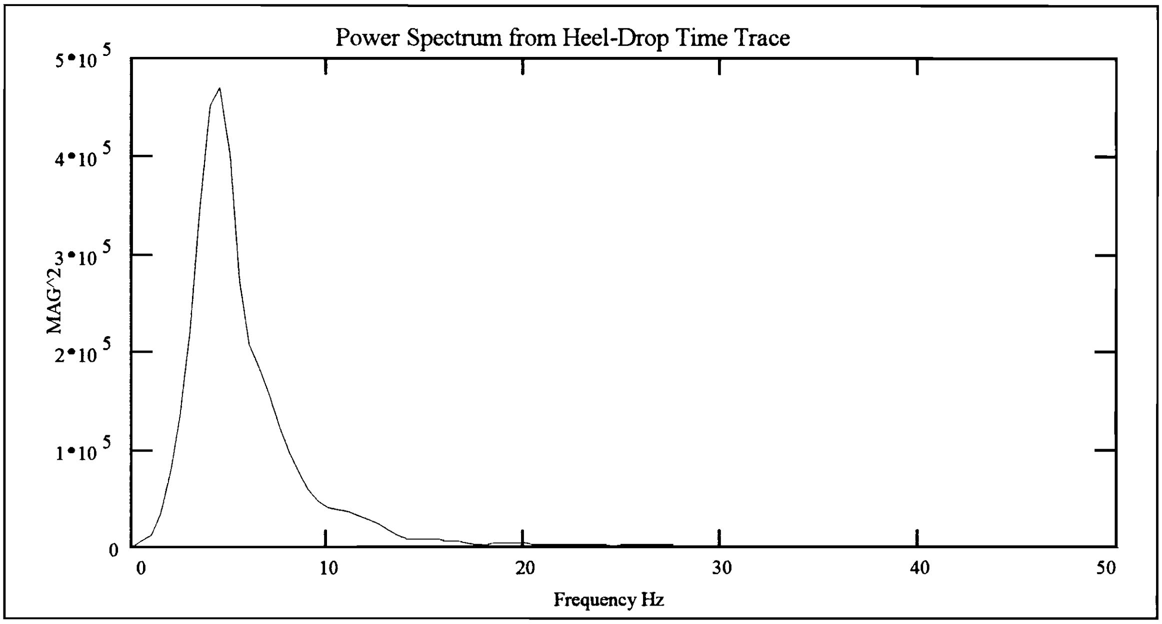


Figure 3-3 Power Spectrum from Heel-Drop on Position 1 of Floor 1 of Parallel Chord Truss House #1

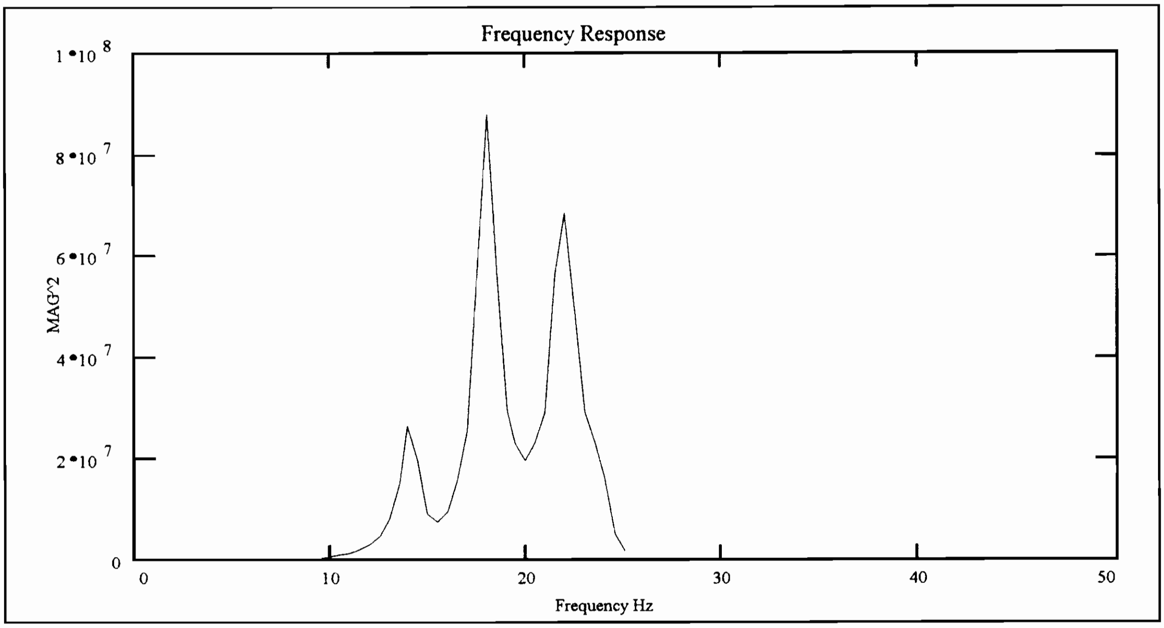


Figure 3-4 Frequency Response for Position 1 of Floor 1 of Parallel Chord Truss House #1

From Figure 3-2, the power spectrum for this particular floor shows this floor has three natural frequencies of 14 Hz, 18 Hz and 22 Hz, respectively. From Figure 3-4, the frequency response of the floor gives the identical same three natural frequencies for this floor. The frequency response data produced the same results as that of the power spectrum from the acceleration trace alone. The reason for this can be seen when examining Figure 3-3 which is a power spectrum showing the frequency content of the heel-drop impact used to impact this particular floor. From Figure 3-2, it can be seen that the heel-drop impact has a natural frequency of around 4.5 Hz and that the energy associated with the heel-drop impact is spread over a narrow frequency band. This was the case for all of the heel-drops performed on all of the floors of the monitored houses. Generally, wood floors do not have natural frequencies below 9 Hz, although there are exceptions. All of the monitored floors tested had frequencies greater than or equal to 10 Hz. Therefore, because the heel-drop impacts used to excite the floors in this study only added significant energy to the floor systems for frequencies in the 4 Hz to 5 Hz frequency band, the natural frequencies of the floor system were basically unaffected by the impact, and thus the floors could be considered to be in free vibration. This is why the power spectrum from the acceleration trace alone produces satisfactory results.

The fact that the heel-drop impact used to excite the floors consistently had a fundamental frequency of around 4.5 Hz is surprising when one considers that the heel-drop impact is not a periodic force, but rather the heel-drop impact is ideally an impulse load lasting approximately 50 ms. From this definition, it would seem that the heel-drop impact would have an infinite period or a fundamental frequency of zero. The explanation as to why the fundamental frequency is not zero is probably due to the heel-drop not being ideal, but actually represented by the time history shown in Figure 3-1. From Figure 3-1, it is seen that the heel-drop impact consists of an initial large impact followed by another much smaller cycle of force. This second cycle of force was believed to be caused by the researcher's body vibrating from the initial impact and the unconscious muscle contractions of the researcher. Thus, there was periodic motion involved with the heel-drop impact used in this study and it had a consistent fundamental frequency of approximately 4.5 Hz for the monitored floors in this study. This can only be said about the heel-drops performed by the particular researcher in this study. Heel-drops performed by other researchers may produce different results. However, it is unlikely that a human can induce frequencies above 9 Hz by performing heel-drops. This indicates that frequency response calculations are more appropriate when using a device that excites the floors over a broad frequency band and not a heel-drop impact, which only excites the floor over a narrow frequency band.

A problem associated with using frequency response data for wood floors impacted with heel-drops is that since frequency response is calculated by dividing the output signal by the input signal, the frequency content of the acceleration time trace above approximately 15 Hz is divided by small numbers since the frequency content of the heel-drop impact approaches zero for frequencies above 10 Hz. This results in extremely large magnitudes for this portion of the frequency content of the frequency response plot. Often, the frequencies with the largest magnitudes in the frequency response plot would not even be visual in the corresponding power spectrum from acceleration. Likewise, often natural frequencies in the range of 10 Hz to 15 Hz shown on the power spectrum from acceleration would not be visible in the corresponding frequency response plot because they were being distorted in relation to the large magnitudes resulting from the division of the higher frequency content by small numbers. Figure 3-5 is the same frequency response plot of Figure 3-4 except that the lower natural frequencies have not been isolated as they were in Figure 3-4. As can be seen from Figure 3-5, the higher frequency content of the acceleration time trace has been distorted due to being divided by small values of the heel-drop frequency content in this range. The lower natural frequencies are hardly visible and must be isolated and scaled to effectively view them. The frequency response plot shows a 42 Hz natural frequency to be the dominant frequency of this particular floor. This natural frequency is not shown by the power spectrum from the acceleration time trace. Thus, using frequency response data with heel-drop impacts distorts the frequency content of the floor, making it difficult or erroneous to analyze.

Based on the above, wood floors impacted with heel-drops can be analyzed as a floor with free vibration for natural frequencies above a certain value in which the input force is not adding significant energy. Based on examining the heel-drop power spectrums from all of the monitored floors, this value was determined to be 10 Hz, and since all of the monitored floors except one had fundamental frequencies greater than 10 Hz, all of the monitored floors were analyzed using acceleration only traces.

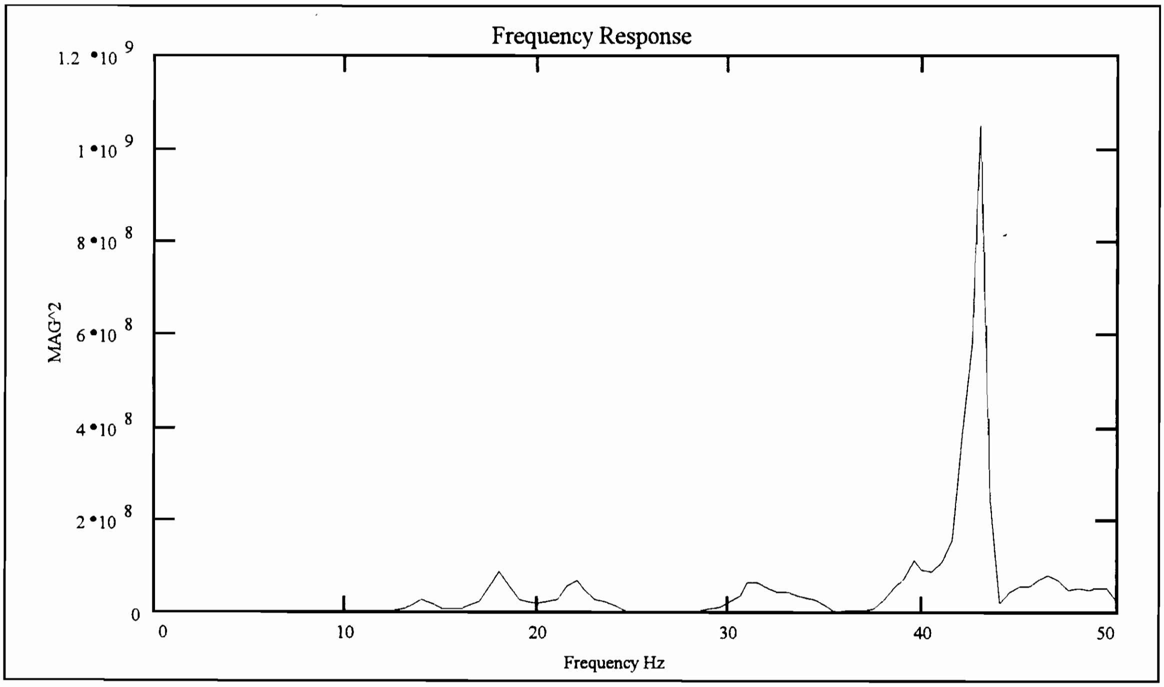


Figure 3-5 Full Range of Frequency Response Plot for Position 1 of Floor 1 of Parallel Chord Truss House #1

3.2.2 Parallel Chord Truss House #1

The structural plan of the house is shown in Figure 3-6. The strongbacks were attached to the tops of the vertical web members with three nails at each truss. The house had a second story above Floor 2 and a vaulted ceiling above Floor 1. Figure 3-6 shows the two floors that were tested (labeled as Floor 1 and Floor 2 respectively) and the positions on the floors that measurements were taken for each stage of construction.

Measurements from these two floors were taken for six levels of construction. The test dates and the construction level on each were:

- 4/2/95 - Floor 1 was a bare floor with sheathed floor trusses. The strongbacks had not been installed at this time.

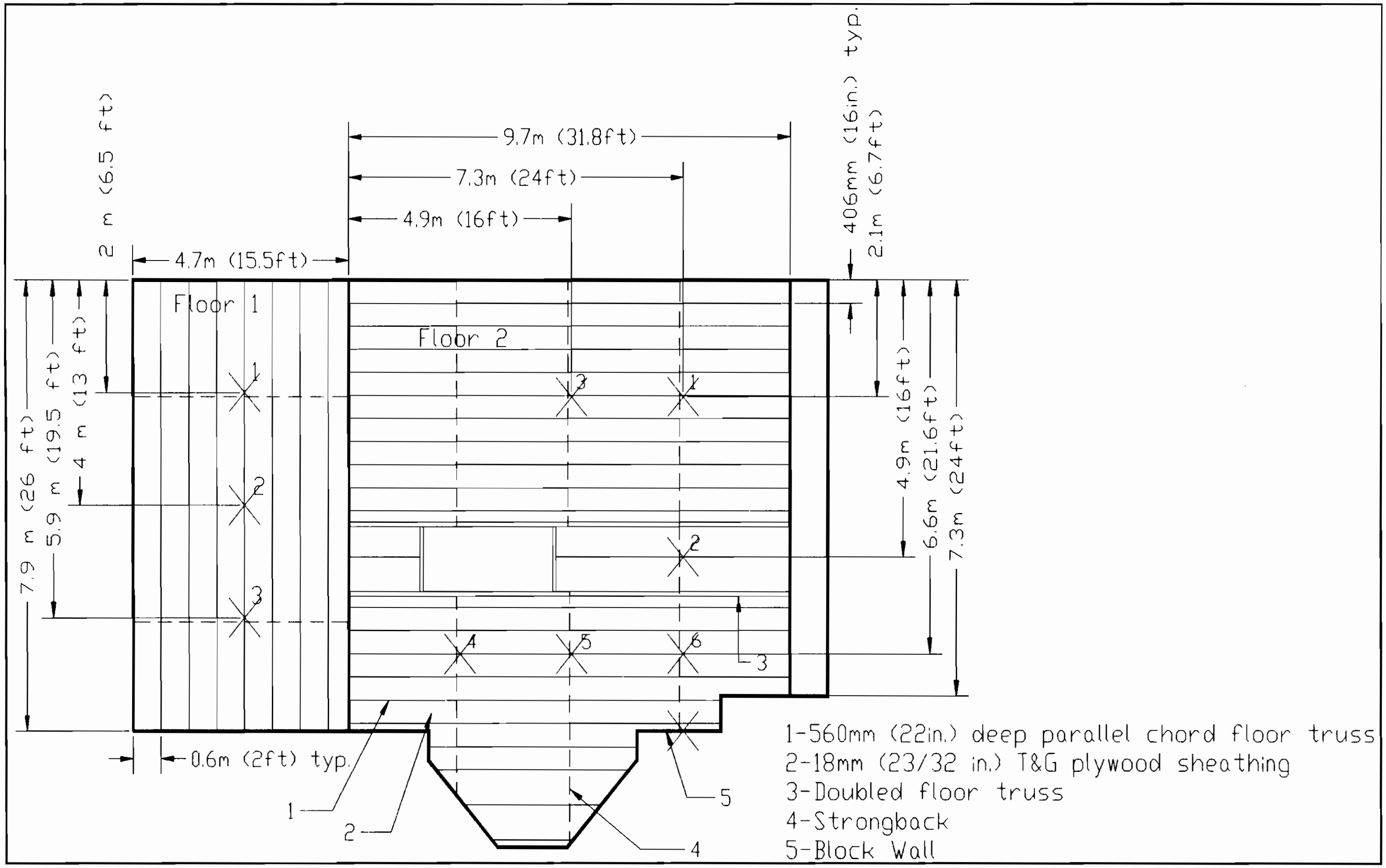


Figure 3-6 Structural Plan of Parallel Chord Truss House #1

- 4/3/95 - Floor 2 was a bare floor with sheathed floor trusses and strongbacks in place.

- 4/5/95 - Floor 1 had sheathed outside walls in place. Braces for the outside walls were anchored to the floor. Brace was directly beside P3. Floor 2 had sheathed exterior walls and unsheathed interior stud walls in place. Braces were extending from walls to the floor. All positions except P3 of Floor 2 were tested.

- 4/8/95 - Floor 1 was in the same state as for 4/5/95. Floor 2 had the second story sheathed floor trusses in place. The second story had sheathed exterior walls and interior stud walls were in place. All positions on both floors were tested.

- 4/10/95 - The roof trusses above Floor 1 had been installed and sheathed. Braces extended from the exterior walls to the floor. Floor 2 had unsheathed roof trusses in place. All positions on both floors were tested.

- 4/15/95 - Both floors were tested with the sheathed roof in place and all braces removed. The interior stud walls were bare at this point. The positions directly above Floor 2 were tested for the second story floor.

- 6/19/95 - Both floors were tested with all drywall and mechanical systems in place. Positions 1 - 3 were tested for Floor 1. Positions 3 - 5 were tested for Floor 2. Positions 3 and 5 were tested for the second story floor.

Position 3 of Floor 2 was not tested until 4/8/95 because of construction material covering this position. Position 3 was included in the study because it was at midspan of Floor 2. The second story floor above Floor 2 was structurally identical to Floor 2 except for the location of interior walls. Measurements were taken on 4/15/95 and 6/19/95 for this floor at the same positions shown on Figure 3-6 for Floor 2. The intent was to study the effect of partition wall location for two identical structural floors. The second story floor was not tested for all levels of construction because it was not accessible. For identification purposes, this floor is called Floor 3.

3.2.3 Parallel Chord Truss House #2

The structural plan for this house is shown in Figure 3-7. The strongbacks were attached near the top of the vertical web members with three nails at each truss. The temporary column support shown in Figure 3-7 was in place for all tests before 4/29/95 after which load bearing stud walls were placed under the double trusses and the temporary column was removed. The test dates and the construction level on each were:

- 4/18/95 - Bare floor throughout. Strongbacks were attached. Three foot high stack of 2x4 lumber were near positions 2 and 3.
- 4/19/95 - Sheathed outside walls were in place. Wall braces were anchored to floor. Three foot high stack of 2x4 lumber were near positions 2 and 3.
- 4/21/95 - Sheathed roof was in place. Wall braces were anchored to floor.
- 4/29/95 - Load bearing stud wall was in place under doubled trusses. Temporary column had been removed. Wall braces were anchored to floor.
- 5/13/95 - The structure was complete except for drywall. Wall braces were removed. Ductwork and plumbing was in place.
- 6/13/95 -Drywall was installed on all of the stud walls and the underside of the trusses.

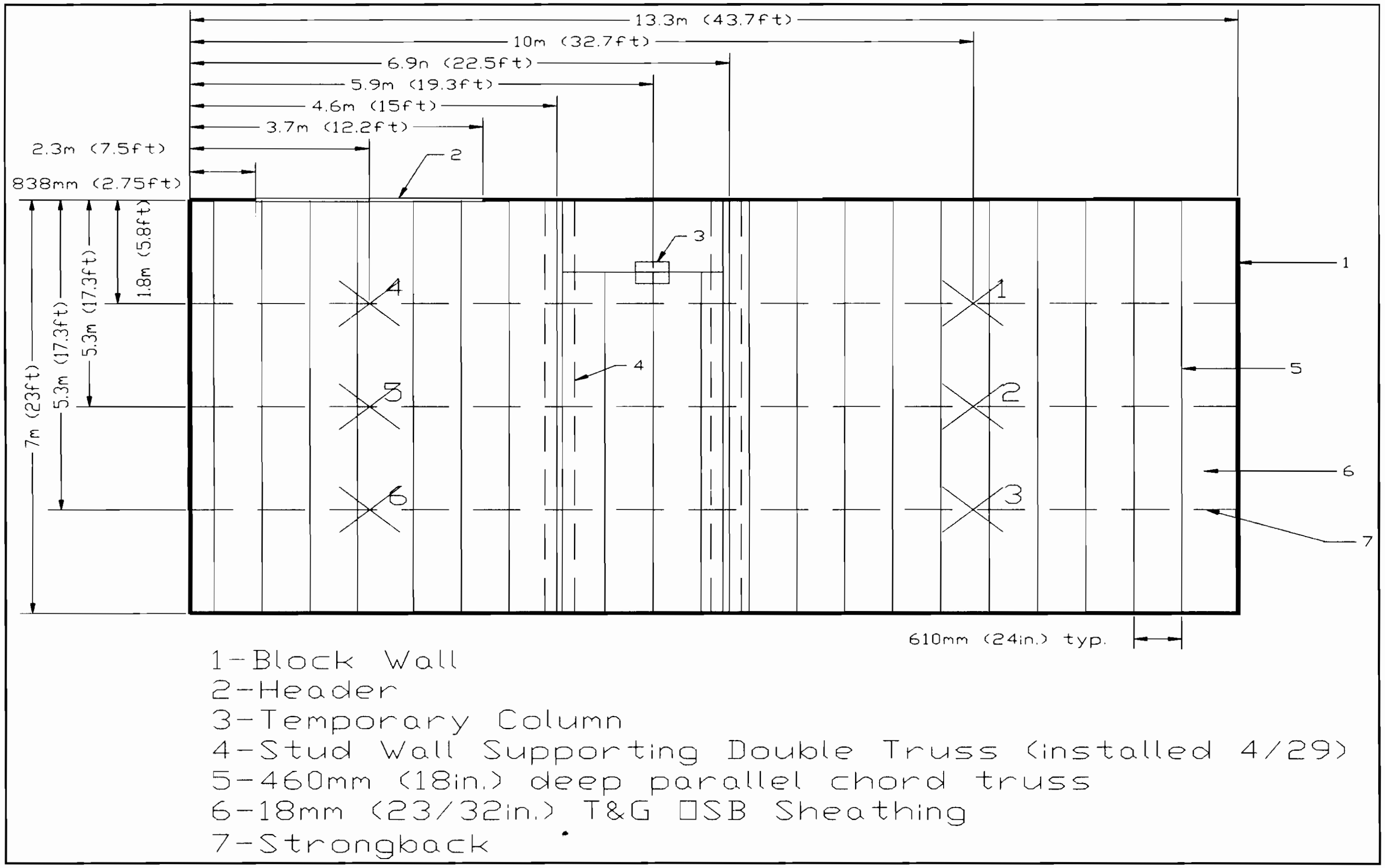


Figure 3-7 Structural Plan of Parallel Chord Truss House #2

3.2.4 Parallel Chord Truss Townhouse

The structural plan of the town house is shown in Figure 3-8. The strongbacks were attached to the top of the vertical web members with three nails at each truss. The test dates and the construction level on each were:

- 4/22/95 - The floor was sheathed with strongbacks in place. A two foot stack of plywood sheathing extending the length of the floor was near positions 1, 2, and 3.

- 4/29/95 - Sheathed exterior walls and interior stud walls were in place. Wall braces were anchored to the floor. A fiberglass shower was installed over position 6.

- 5/17/95 - The roof, plumbing and ductwork were in place. All wall braces were removed. Strongbacks under positions 1, 2, 3, 7, 8, and 9 were cut for ductwork. Drywall was not installed on the stud walls.

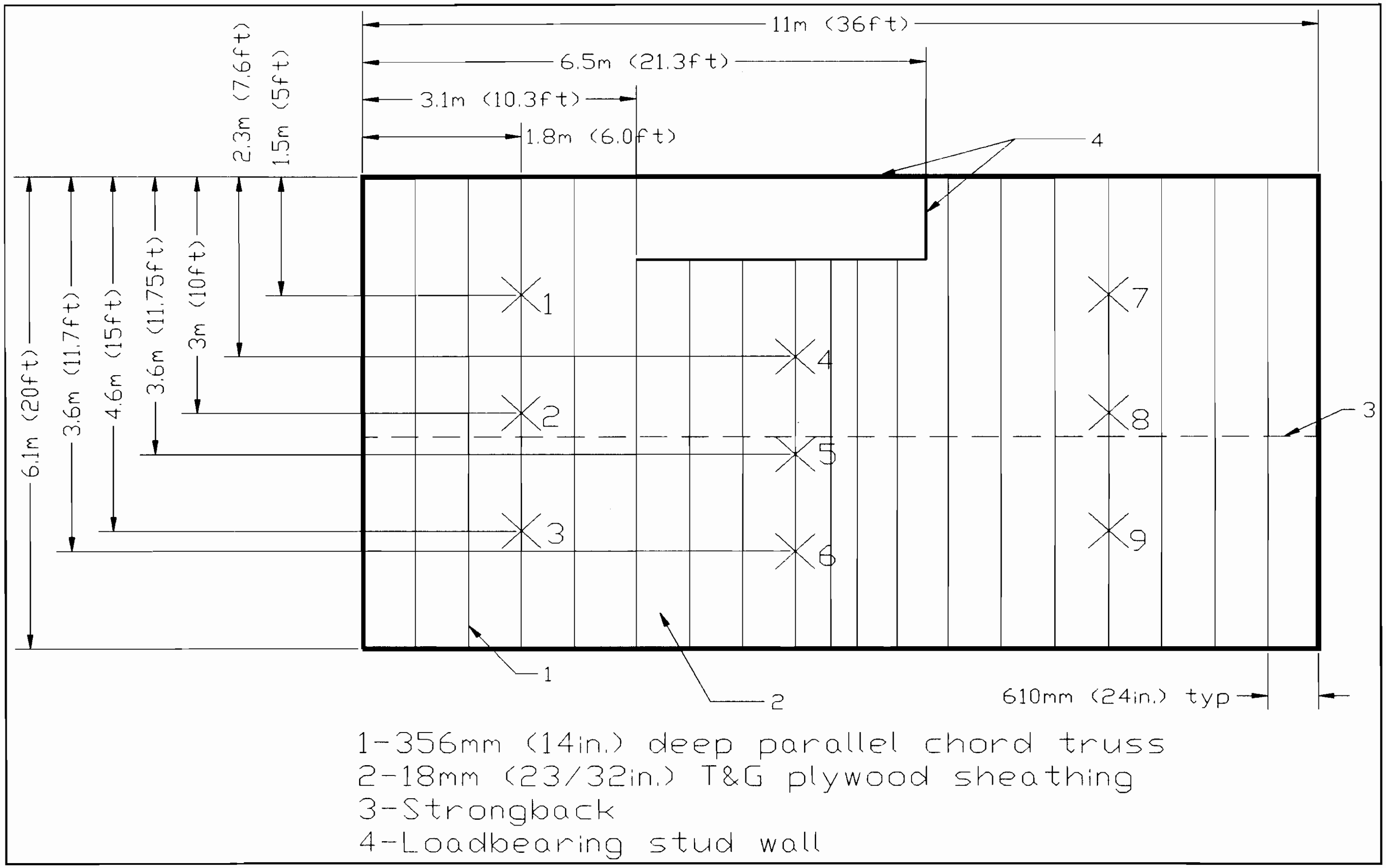


Figure 3-8 Structural Plan of Parallel Chord Truss Townhouse

3.2.5 Solid Sawn Joist House #1

The house utilized 51 mm x 305 mm (2 in. x 12 in.) Spruce-Pine-Fir (SPF) No.1 lumber joists and 18mm (23/32 in.) thick T&G plywood sheathing. The structural plan of the house is shown in Figure 3-9. The positions on the floor where measurements were taken are labeled 1-6. The house featured a second story above positions 2-5 and a cathedral ceiling utilizing scissor trusses above positions 1 and 6. The test dates and the level of construction on each were:

- 4/13/95, 4/14/95, 4/16/95 - The floor was completely bare. Metal strap bridging on the joists had not been installed. The edges of the floor had not been nailed into the band.
- 4/17/95 - Exterior and interior stud walls had been installed and braces for the walls were anchored to the floor close to positions 1,2,3 and 6.
- 4/20/95 - The second story floor joists and sheathing had been installed over positions 2-5. Fiberglass showers had been installed near positions 1 and 6.
- 4/26/95 - The exterior and interior stud walls for the second story over positions 2-5 had been installed. Roof rafters over the second story had been installed as well.
- 5/17/95 - The structure was basically complete except for the installation of drywall and mechanical/electrical. The metal strap bridging had been installed at this time.

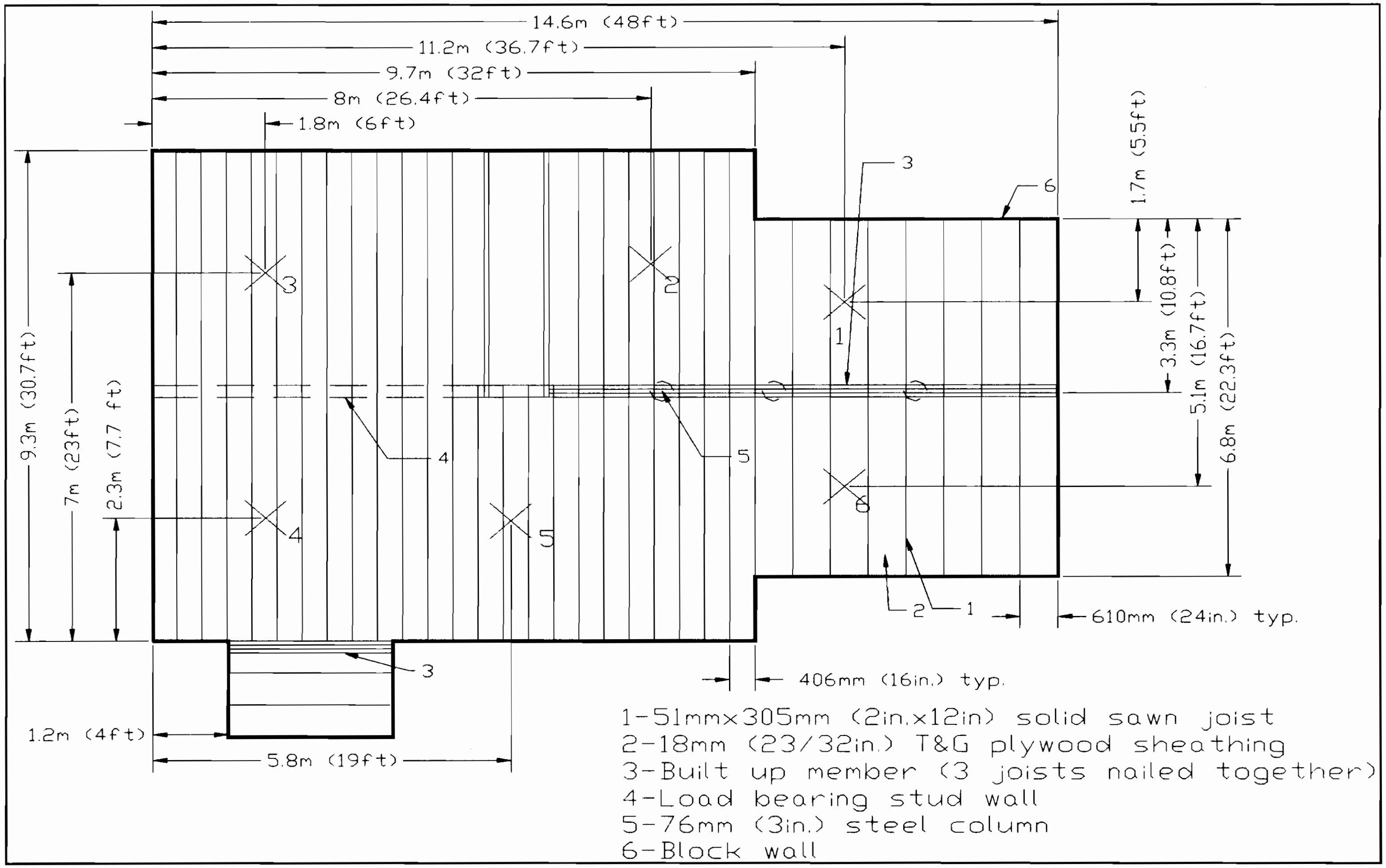


Figure 3-9 Structural Plan of Solid Sawn Joist House #1

3.2.6 Solid Sawn Joist House #2

The structural plan of the house is shown in Figure 3-10. The test dates and the construction level on each were:

- 5/10/95 - The floors were bare consisting of joists sheathed with plywood. No bridging was installed.
- 5/23/95 - Exterior and interior stud walls were in place. Wall braces anchored to floor.
- 6/19/95 - Roof was installed and wall braces were removed. Drywall had not been installed. Bridging was in place. Fiberglass shower close to position 3.

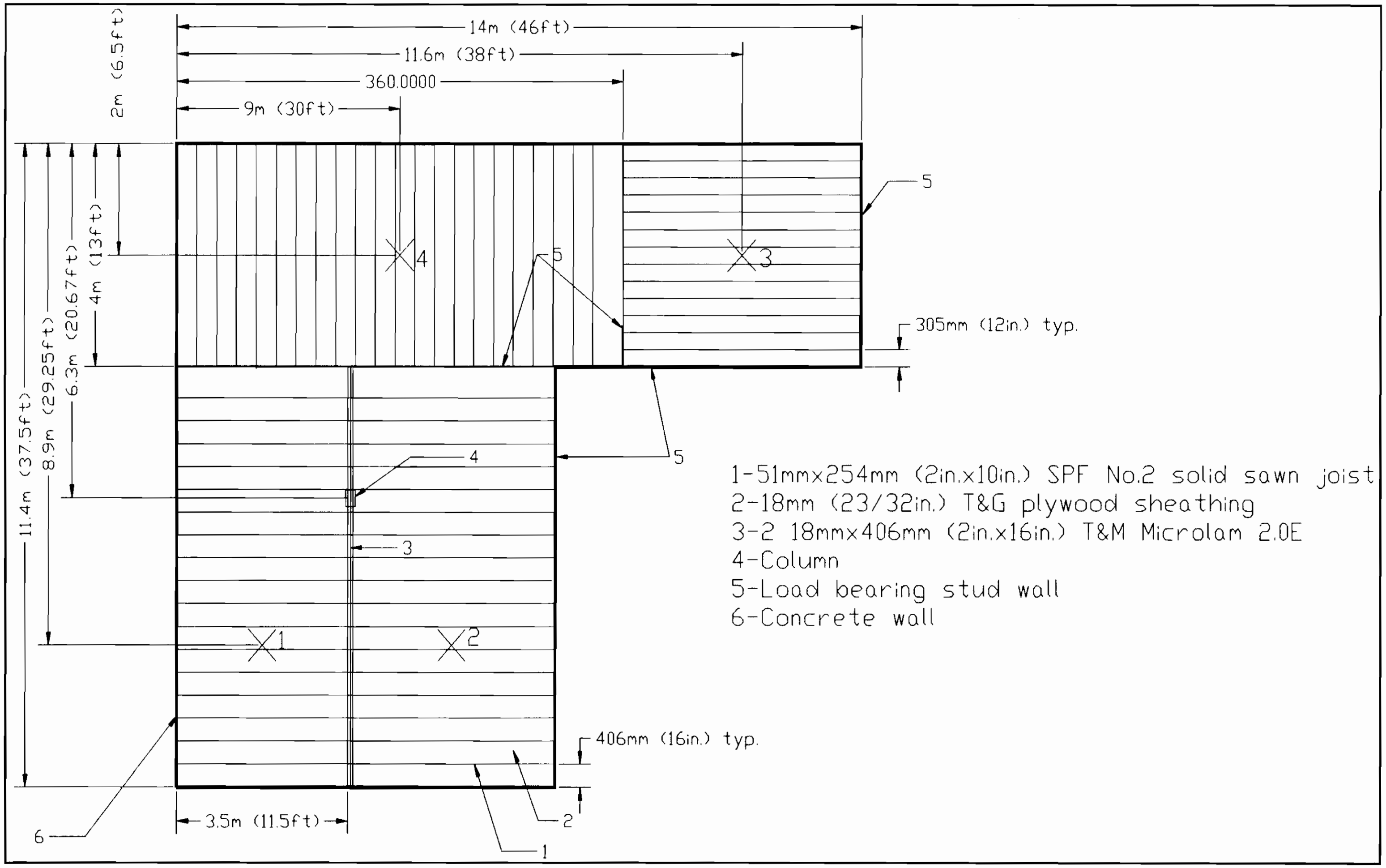


Figure 3-10 Structural Plan of Solid Sawn Joist House #2

3.2.7 I-Joist House

The structural plan of the house is given in Figure 3-11. Six positions on the floor were tested. However, the material properties of the glue laminated girder could not be obtained, and, therefore positions 3 - 6 were not included in the study. The exterior walls of this house consisted of cold formed steel studs and foam insulation. The interior walls also used cold formed steel studs. The test dates and the construction level on each were:

- 5/6/95 - Floor was bare.
- 5/8/95 - Exterior and interior walls were in place. Roof was in place. Wall braces were anchored to the floor.
- 5/25/95 - Ductwork was in place and wall braces were removed. No drywall on interior or exterior walls.

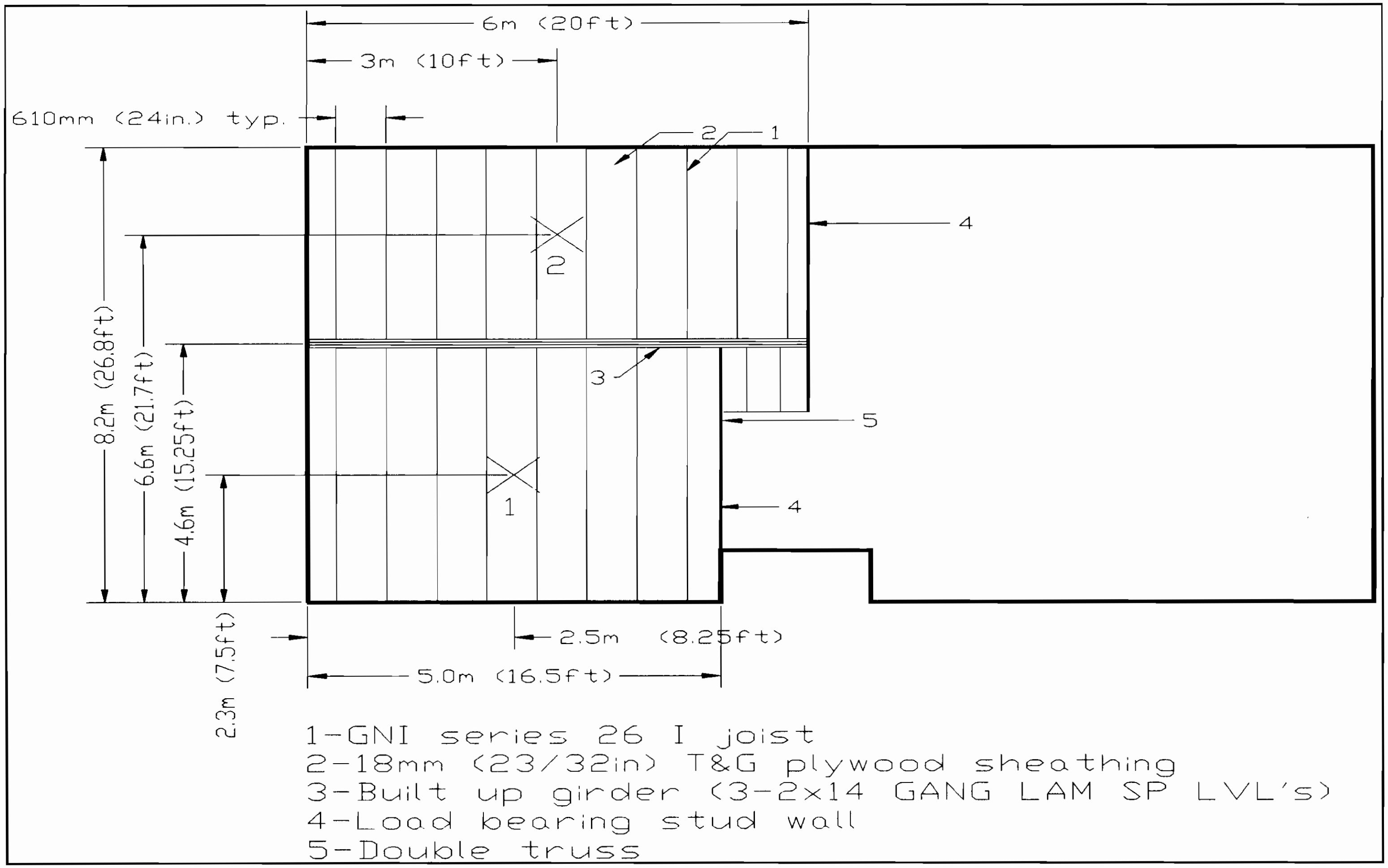


Figure 3-11 Structural Plan of I-Joist House

3.3 Results

3.3.1 Limitation of Results

Before detailed results of the six monitored houses are presented, a few limitations and problems encountered in analyzing the data need to be discussed.

3.3.1.1 Effects of Wall Braces on Measured Data

A phenomenon common to all of the monitored houses was the distortion of power spectrums resulting from the effects of walls braces anchored to the floors. This effect was worse for some floors than others, but it was always present to some degree. The effect of wall braces on the floor vibration can clearly be seen by examining the power spectrums of a bare floor before any braces were installed, after the installation of wall braces, and after removal of the wall braces. Figures 3-12, 3-13 and 3-14 show the power spectrums of a floor for these three conditions. As can be seen from these figures, the power spectrum for the bare floor shows clearly defined natural frequencies of the floor. The power spectrum from the floor after the wall braces had been installed still includes the same frequencies, but they are not clearly defined and other interference has been added to the power spectrum as compared to that of the bare floor. Once the braces were removed, it can be seen that the power spectrum again shows clearly defined natural frequencies with some change in the relative magnitudes.

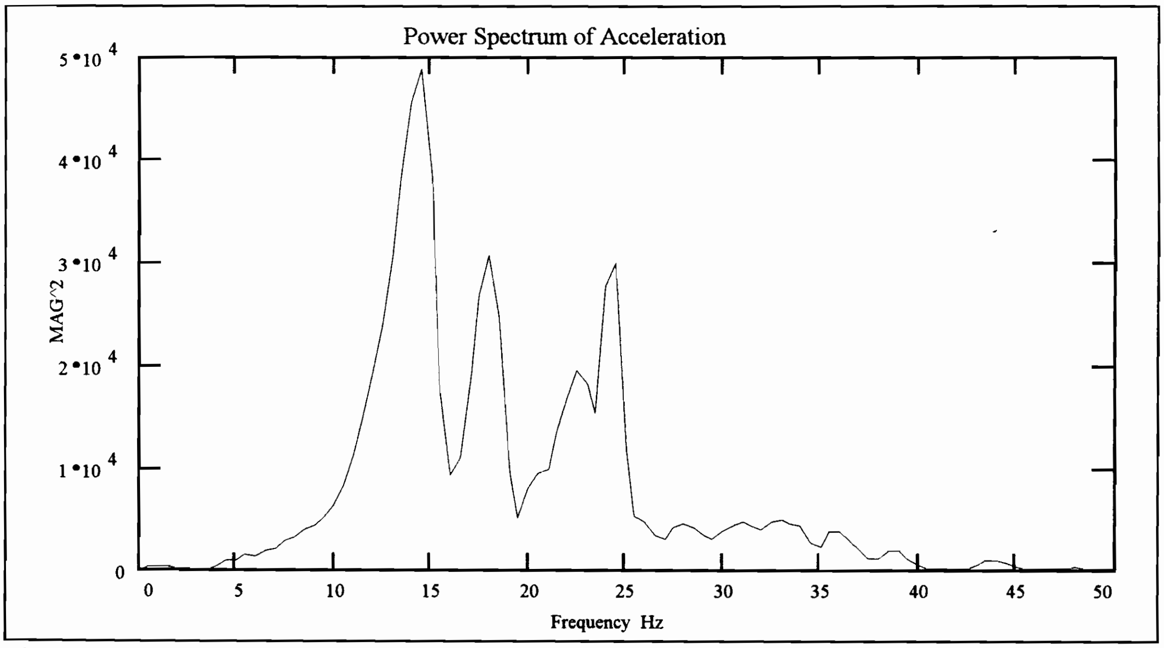


Figure 3-12 Power Spectrum Before Installation of Wall Braces

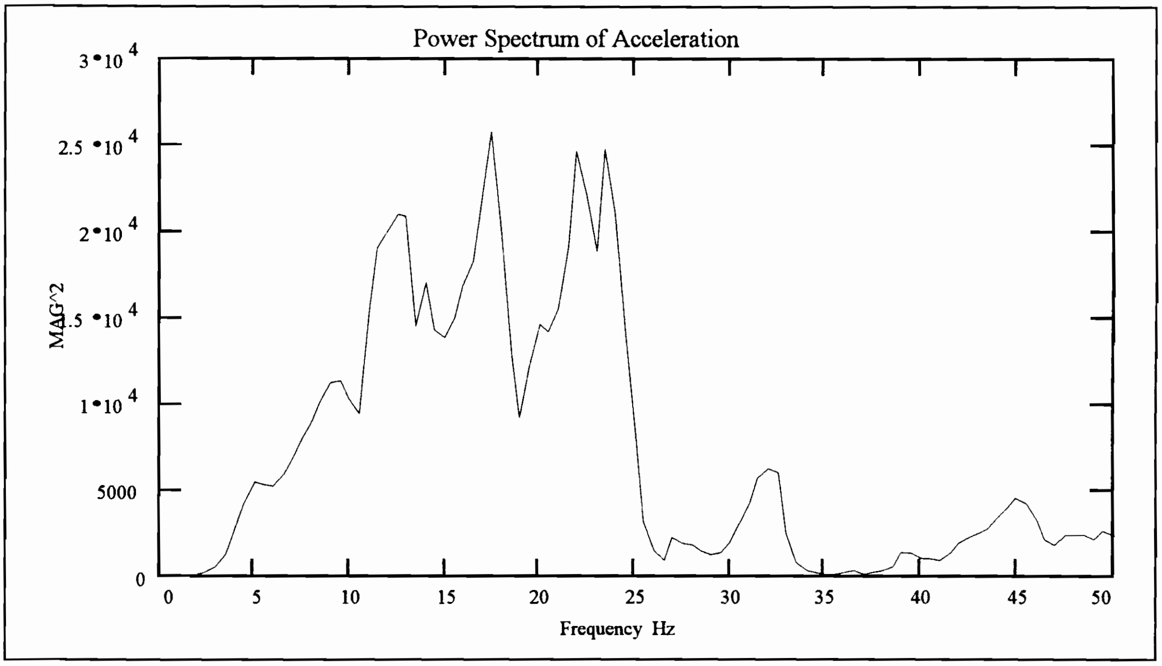


Figure 3-13 Power Spectrum After Installation of Wall Braces

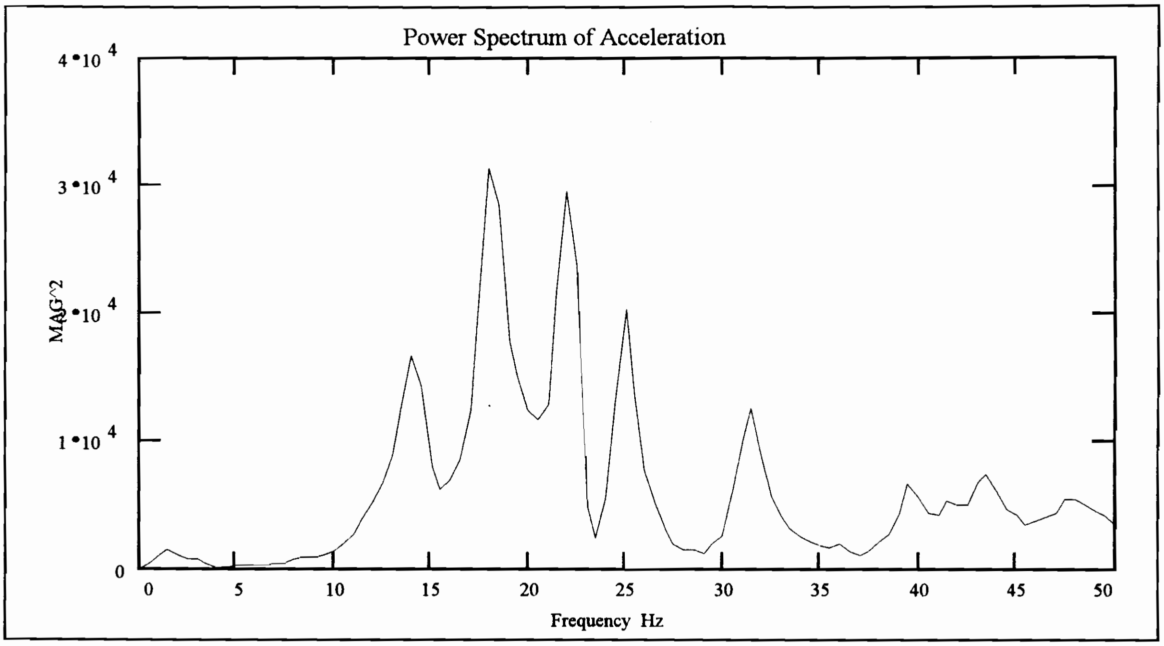


Figure 3-14 Power Spectrum After Removal of Wall Braces

The effects of wall braces, as shown in Figure 3-13, varied for each floor of each monitored house. For some of the floors, the effects were not as severe as that shown in Figure 3-13 but, for others, the effects were to an extent that analysis of the power spectrums was very difficult, and the fundamental frequency could only be determined through the judgment of the researcher. The wall braces seem to add significant damping to the floor which causes the spikes representing the natural frequencies to become broader and smear together, making it difficult to analyze the frequency content of the floor. Although all of the data from the floors is presented including that taken with wall braces installed, for comparison between different levels of construction without wall braces installed, only the data taken from bare floors and completed structures should be considered. All other data includes the effects of wall braces on the response of the floor system.

3.3.1.2 Difficulties in Calculating Modal Damping Values

Due to closely spaced modes of vibration which are characteristic of wood floors, and the effects of wall braces, calculation of fundamental modal damping values was often difficult or impossible for a large percentage of the monitored floors. The problem with calculating fundamental modal damping values for floors with closely spaced modes of vibration using the half power method is that the half power points often fall below the spike or peak, and therefore, the spike must be extrapolated in order to perform the calculation. Figure 3-13 shows an example of where extrapolation of the spike is needed in order to calculate the fundamental modal damping value.

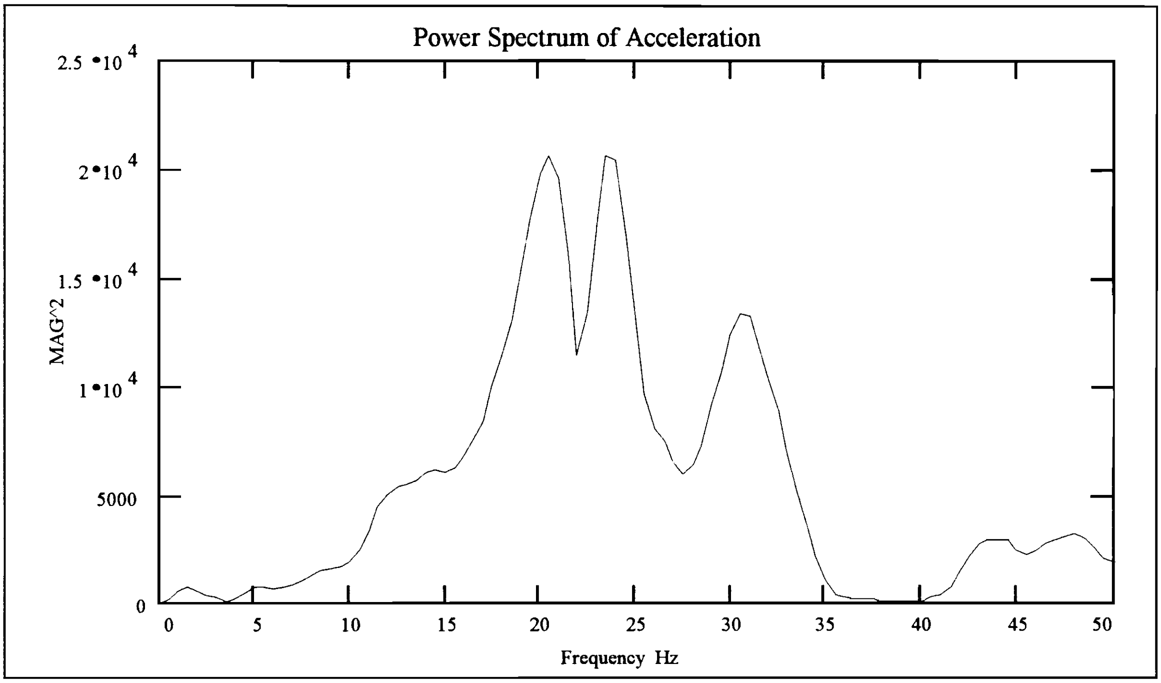


Figure 3-15 Example of Closely Spaced Modes of Vibration

The magnitude for the fundamental frequency of the floor represented by Figure 3-15 is 20,682. The half power points needed to calculate the damping for the fundamental mode are the frequency values on the fundamental spike with half of the peak magnitude (10,341). As can be seen from Figure 3-15, due to the second mode of vibration being close to the fundamental mode, the fundamental spike does not descend far enough for the second half power frequency to be read directly from the graph. In order to calculate the second half power frequency, the right side of the fundamental spike must be extrapolated to 10,341. This was accomplished by extending a straight line from the end of the right side of the spike being analyzed with the slope of the extrapolated line approximating that of the original spike. Although there is error involved in extrapolating, significant error could be involved in using the half power method for power spectrums with closely spaced modes of vibration, since it is this researcher's understanding that the method only applies to vibration with well separated modes of vibration. Additionally, the half power method is only valid for modal damping values of 10 percent of critical damping or less. Often the modal damping values calculated in this study exceeded this limit. The second problem associated with using the half power method to calculate modal damping values was that for many floors, the spikes in the power spectrums were not well defined, making it difficult or impossible to calculate modal damping for these floors. A third and final problem in calculating modal damping values was the significant increase in damping due to the presence of the researcher on the floor performing the heel-drops. This was determined by comparing the modal damping values from heel-drop impacts and hammer impacts. The latter were performed without the researcher on the floor. However, hammer impacts were only used for a few floors tested early in the research and due to difficulties in achieving consistent results, they were abandoned. Although not enough data was gathered in order to quantify the increase in damping due to the presence of the researcher, the increase was observed for the few floors tested with both types of impacts. Therefore, modal damping values presented for the monitored floors should be viewed with consideration to the above discussion before any conclusions are drawn from them.

3.3.2 Parallel Chord Truss House #1

3.3.2.1 Predicted Fundamental Frequencies

Fundamental frequencies were predicted for Floors 1 and 2 for bare floors only. Predicted fundamental frequencies for other levels of construction were not calculated because of the inability to include construction variables such as partition walls and finished ceilings in the equation for fundamental frequency. Material properties were taken from the NDS supplement (NFPA, 1991). The full moment of inertia of the floor trusses was used in the calculations, and composite action between the sheathing and the floor trusses was assumed to be non-existent. Damping values were not predicted since there are no known methods for calculating this parameter for wood floor systems.

3.3.2.2 Measured Fundamental Frequencies and Modal Damping Values

The measured fundamental frequencies and corresponding modal damping values for Floors 1, 2 and 3 are given in Tables 3-1, 3-2 and 3-3, respectively.

Table 3-1 Measured Fundamental Frequencies and Modal Damping Values for Floor 1 for Parallel Chord Truss House #1

Test Date	Position	Fundamental Frequency (Hz)	Fundamental Modal Damping (%)	Vibration Rating	Dominant Frequency ?
4/2/95	1	14.5	10.0	DP	Y
4/5/95		12.0	CNC	DP	N
4/8/95		13.5	CNC	DP	N
4/10/95		14.0	9.4	DP	M
4/15/95		14.0	9.3	DP	M
6/19/95		18.3	11.3	SLP	Y
4/2/95	2	14.5	11.0	DP	Y
4/5/95		14.0	10.0	DP	M
4/8/95		13.0	8.6	DP	M
4/10/95		14.0	9.1	DP	M
4/15/95		14.0	9.5	DP	M
6/19/95		18.3	8.4	SLP	Y
4/2/95	3	14.5	11.6	DP	Y
4/5/95		12.5	CNC	DP	N
4/8/95		13.5	CNC	DP	N
4/10/95		14	8.9	DP	N
4/15/95		14	9.6	DP	M
6/19/95		18.3	CNC	SLP	M

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

Table 3-2 Measured Fundamental Frequencies and Modal Damping Values for Floor 2 for Parallel Chord Truss House #1

Test Date	Position	Fundamental Frequency (Hz)	Fundamental Modal Damping (%)	Vibration Rating	Dominant Frequency ?
4/3/9	1	10.5	8.9	DP	N
4/5/95		13.5	4.9	DP	M
4/8/95		13.0	7.0	DP	M
4/10/95		12.0	12.5	DP	M
4/15/95		10.5	7.2	DP	M
4/3/95	2	12.5	CNC	DP	M
4/5/95		12.0	8.6	DP	Y
4/8/95		12.0	CNC	DP	N
4/10/95		11.5	8.4	DP	M
4/15/95		11.5	5.8	DP	N
4/8/95	3	13.0	8.2	DP	Y
4/10/95		12.0	6.7	DP	M
4/15/95		10.5	9.3	DP	N
6/19/95		Frequency Spread	CNC	SLP	M

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

Table 3-2 Cont.

Test Date	**Position**	**Fundamental Frequency (Hz)**	**Fundamental Modal Damping (%)**	**Vibration Rating**	**Dominant Frequency ?**
4/3/95	4	12.5	9.3	DP	M
4/5/95		12.0	7.1	DP	M
4/8/95		13.0	11.4	DP	N
4/10/95		15.5	7.9	DP	Y
4/15/95		11.5	9.0	DP	N
6/19/95		17.5	CNC	SLP	M
4/3/95	5	12.0	10.0	DP	Y
4/5/95		Data Lost	Data Lost	Data Lost	Data Lost
4/8/95		13.0	11.5	DP	N
4/10/95		15.0	10.3	DP	Y
4/15/95		11.5	CNC	DP	N
6/19/95		14.5	18.6	SLP	M
4/3/95	6	12.0	9.7	DP	Y
4/5/95		12.0	7.0	DP	N
4/8/95		13.0	12.2	DP	N
4/10/95		15.5	7.0	DP	N
4/15/95		11.5	CNC	SLP	N

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

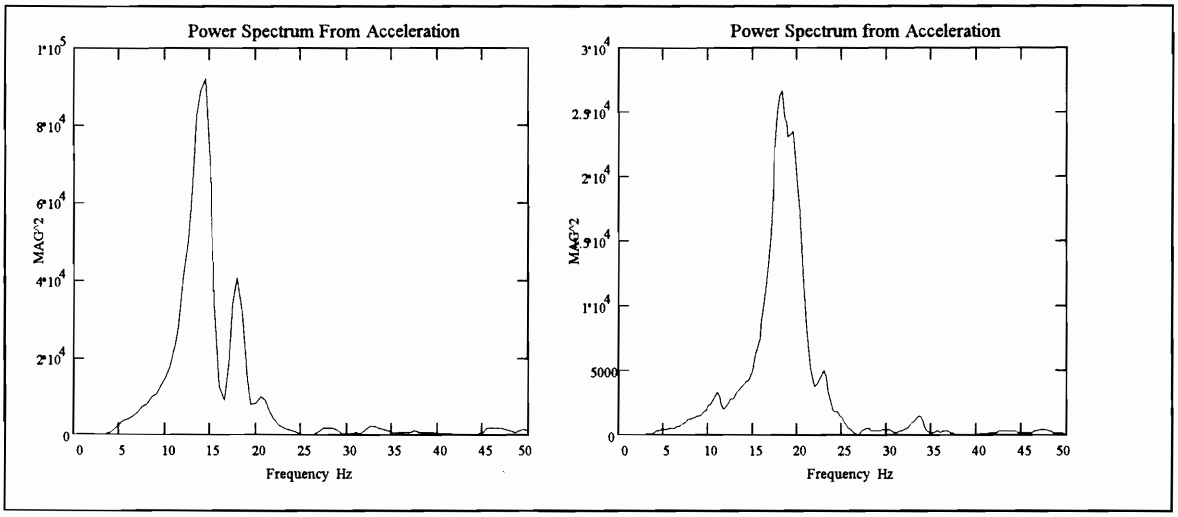
Table 3-3 Measured Fundamental Frequencies and Modal Damping Values for Floor 3 for Parallel Chord Truss House #1

Test Date	**Position**	**Fundamental Frequency (Hz)**	**Fundamental Modal Damping (%)**	**Vibration Rating**	**Dominant Frequency ?**
4/15/95	3	10.5	6.3	DP	Y
6/19/95		14.5	11.4	SLP	M
4/15/95	5	11.5	5.5	DP	Y
6/19/95		13.8	19.7	NP	M

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

3.3.2.3 Discussion

The predicted bare floor fundamental natural frequency for Floor 1 was 14.2 Hz. The measured bare floor fundamental frequency at positions 1 through 3 was 14.5 Hz, which compares well to the predicted value. Floor 1 was characterized by two dominant frequencies throughout the testing, and although the fundamental frequency was the dominant frequency for the bare floor, it was not the dominant frequency for the completed structure. As can be seen from Table 3-1, there was no significant change in the fundamental frequency of Floor 1 or the perceived vibration of Floor 1 until the drywall was installed. After the installation of the drywall, the fundamental frequency increased significantly from 14 Hz to 18.3 Hz. The perceived vibration also went from being distinctly perceptible throughout the construction of the house to being only slightly perceptible after the drywall was installed. Thus, the drywall added significant mass and stiffness to the floor and improved its performance. The added mass to the floor made it more difficult to put the floor into motion using heel-drop impacts due to the concept of conservation of momentum. The change in the response of Floor 1 in terms of frequency is shown in Figure 3-16, which shows the power spectrums for position 2 for the bare floor and completed structure.



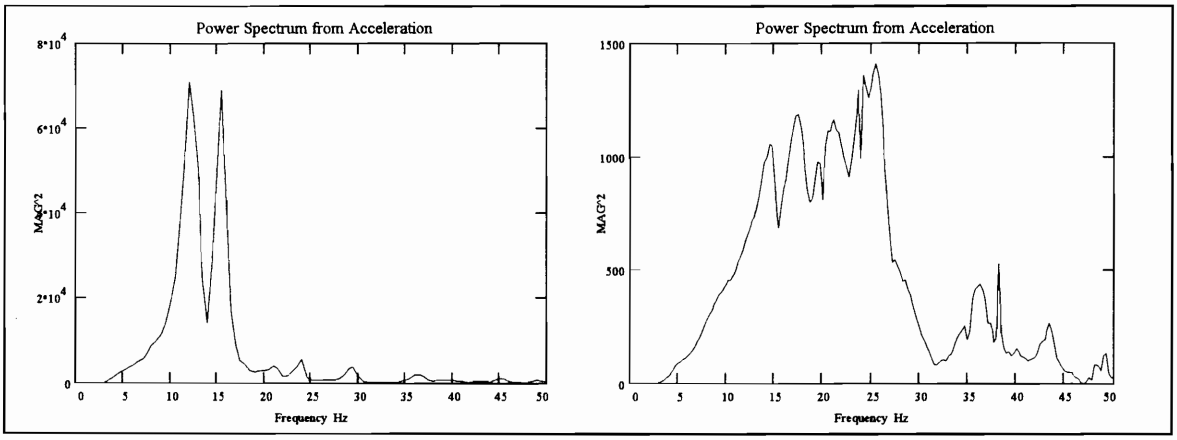
(a) Bare Floor (b) Completed Structure

Figure 3-16 Comparison of Bare Floor and Completed Structure Power Spectrums for Position 2 of Floor 1

The shift in the fundamental frequency can be seen in Figure 3-16. The second mode of vibration is difficult to see in the power spectrum for the completed structure with drywall. If the minor peak to the right of the fundamental is taken as the second mode, then the conclusion is that there was an increase in the natural frequency for the second mode of vibration as well as fundamental frequency. The increase was not as large as for the fundamental frequency, however, causing the fundamental and second modes to become more closely spaced together.

Floor 2 was divided into two regions, one on either side of a stairway. The predicted bare floor fundamental frequency for Floor 2 was 10.4 Hz. The measured bare floor fundamental frequencies of Floor 2 were 10.5 Hz for position 1 and 12 Hz for positions 4-6. The explanation for the close agreement to the predicted fundamental frequency for one region of Floor 2 and a higher than predicted fundamental frequency for the other region can be seen by examining the structural plan of Figure 3-6. The measurements for the region with the higher measured fundamental frequency were taken close to a double truss used in the stair framing. Thus, the stiffness would be higher, causing an increase in the fundamental frequency. There was not a significant change in fundamental frequency for Floor 2 between a bare and completed structure with no drywall installed. The perceived vibration was distinctly perceptible throughout this period also. Only after drywall was installed did a significant change in fundamental frequency and perceived vibration occur. After the installation of drywall, the perceived vibration went from being distinctly perceptible to slightly perceptible and the fundamental frequency increased to the values given in Table 3-2. Thus, as in Floor 1, the addition of drywall significantly improved the dynamic performance of this floor system.

Another conclusion that can be made from the monitoring of Floor 2 is that the effects of interior partition walls is minimal with respect to fundamental frequency until the drywall is attached to them. The change in response of Floor 2 can be seen visually by comparing the power spectrums from those of the bare floor to those of the completed structure with drywall. These are shown for position 5 of Floor 2 in Figure 3-17.



(a) Bare Floor (c) Completed Structure

Figure 3-17 Comparison of Power Spectrums for Bare Floor and Completed Structure with Drywall Installed for Position 5 of Floor 2

The increase in the fundamental frequency from the bare floor to the completed structure can be seen from Figure 3-17. There are additional modes of vibration for the completed structure that were not present for the bare floor. The fundamental frequency is no longer the dominant frequency of the floor for the completed structure and the magnitudes of the power spectrum for the completed structure are considerably lower when compared to those of the power spectrum for the bare floor. Thus, the response of the floor to heel-drop impacts was reduced between a bare floor and completed structure conditions. This trend is supported by the perceived vibration rated as distinctly perceptible on the bare floor and slightly perceptible for the completed structure.

The fundamental frequency of positions 3 and 5 of the second story floor directly above Floor 2 were exactly the same on 4/15/95 as they were for the ground floor, even though the location of partition walls was different for each floor. Thus, stud walls did not seem to have an effect on the fundamental frequency of the floor. There was a significant increase in fundamental frequency for both of these positions after the drywall was installed. The perceived vibration changed from distinctly perceptible before the drywall was added to slightly perceptible and not perceptible for positions 3 and 5, respectively. As was the case for Floors 1 and 2, the response of the second story floor to heel-drop impacts was improved after the installation of drywall.

No significant trends were seen in the fundamental modal damping values of Floors 1 and 2, except that no values less than 7 percent of critical were observed. This value is considerably higher than most of the reported damping values found in related literature.

3.3.3 Parallel Chord Truss House #2

3.3.3.1 Predicted Fundamental Frequencies

Predicted fundamental frequencies were calculated assuming no composite action between the floor sheathing and the floor trusses. Full moment of inertia of the top and bottom chords of the floor trusses was used in the calculation of fundamental frequency. For positions 4-6, a predicted fundamental system frequency was calculated using the fundamental frequency of the floor trusses and the fundamental frequency of the header over the garage door opening.

3.3.3.2 Measured Fundamental Frequencies and Modal Damping Values

The measured fundamental frequencies and corresponding modal damping values for the positions tested are given in Table 3-4.

Table 3-4 Measured Fundamental Frequencies and Modal Damping Values for Parallel Chord Truss House #2

Test Date	Position	Fundamental Frequency (Hz)	Fundamental Modal Damping (%)	Vibration Rating	Dominant Frequency ?
4/18/95	1	14.3	12.2	SLP	N
4/19/95		13.0	8.5	SLP	N
4/21/95		CNC	CNC	SLP	CNC
4/29/95		CNC	CNC	SLP	CNC
5/13/95		13.5	12.3	SLP	N
6/14/95		17.0	19.6	NP	N
4/18/95	2	14.0	13.5	SLP	N
4/21/95		CNC	CNC	SLP	CNC
4/29/95		CNC	CNC	SLP	CNC
5/13/95		15.3	5.3	SLP	N
6/14/95		17.3	9.7	NP	Y
4/18/95	3	14.3	15.3	SLP	N
4/21/95		CNC	CNC	SLP	CNC
4/29/95		CNC	CNC	SLP	CNC
5/13/95		13.5	14.5	SLP	Y
6/14/95		17.0	16.4	NP	N

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

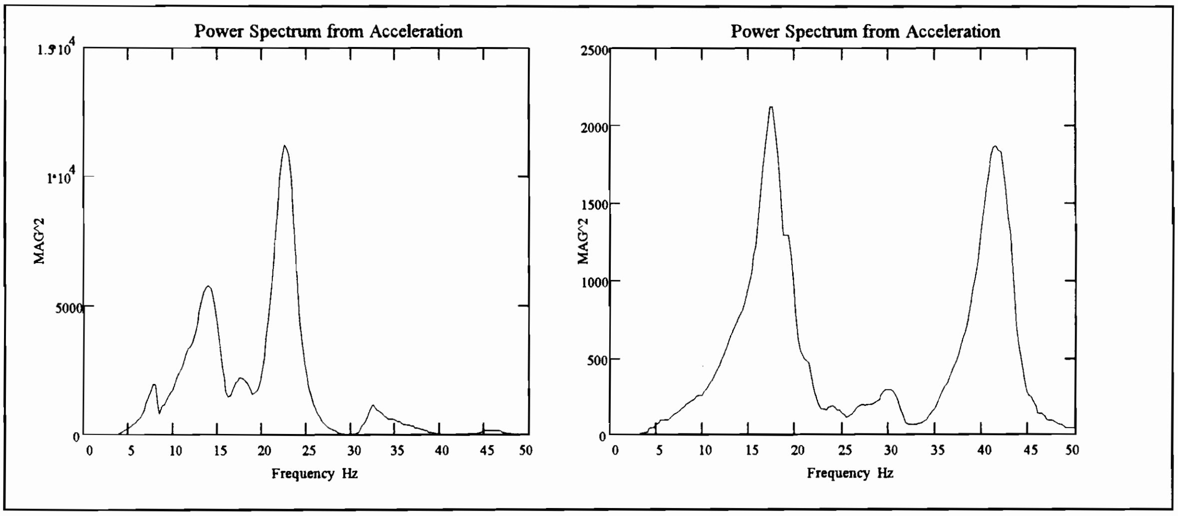
Table 3-4 Cont.

Test Date	Position	Fundamental Frequency (Hz)	Fundamental Modal Damping (%)	Vibration Rating	Dominant Frequency ?
4/18/95	4	8.3	6.6	DP	N
4/21/95		CNC	CNC	DP	CNC
4/29/95		CNC	CNC	SLP	CNC
5/13/95		12.3	11.5	SLP	Y
6/14/95		14.5	10.8	SLP	Y
4/18/95	5	8.5	6.8	DP	Y
4/21/95		CNC	CNC	DP	CNC
4/29/95		18.5	7.0	DP	N
5/13/95		12.3	12.0	DP	Y
6/14/95		14.5	9.7	DP	Y
4/18/95	6	8.5	7.8	SLP	N
4/21/95		CNC	CNC	SLP	CNC
4/29/95		CNC	CNC	DP	CNC
5/13/95		12.3	12.2	SLP	Y
6/14/95		14.5	17.4	SLP	N

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

3.3.3.3 Discussion

Predicted bare floor fundamental frequency for positions 1-3 was 14.6 Hz which compares well to the measured bare floor frequencies of positions 1-3 given in Table 3-4. In comparing the fundamental frequencies for the bare floor to that of the completed structure with no drywall installed, there was no significant change in fundamental frequency for positions 1-3. After the drywall was installed, an approximate 2 Hz increase in fundamental frequency occurred. The perceived vibration of the floor was also reduced after the drywall was installed. As for Parallel Chord Truss House #1, the drywall significantly increased the fundamental frequency of the floor and reduced the perceived vibration on the floor. The increase in fundamental frequency is shown in Figure 3-18, which shows the power spectrums for position 2 for bare floor and completed structure with drywall installed.

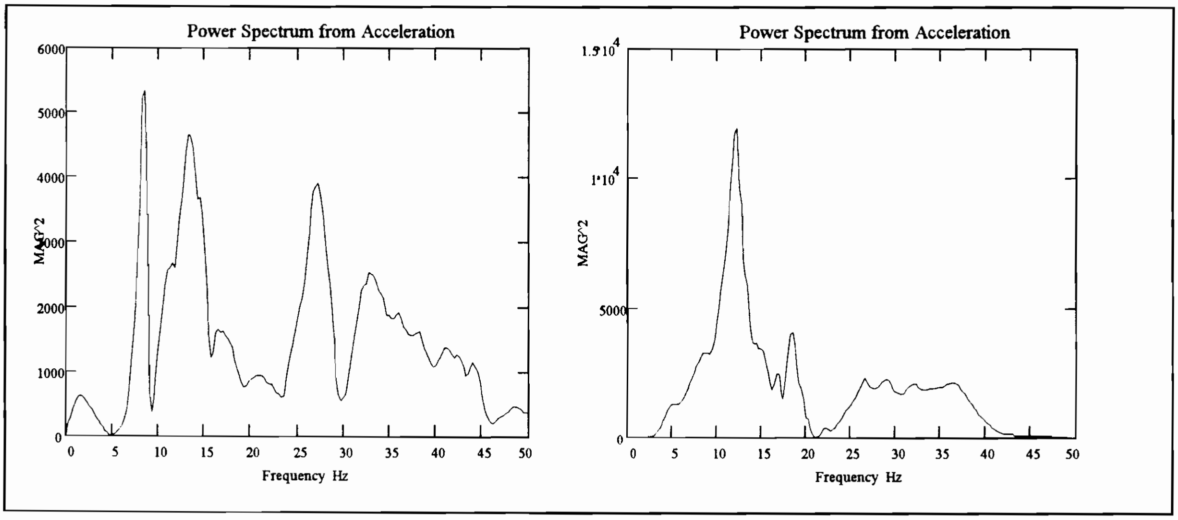


(a) Bare Floor (b) Completed Structure

Figure 3-18 Comparison of Power Spectrums for Bare Floor and Completed Structure with Drywall Installed for Position 2 of Parallel Chord Truss House #2

As shown in Figure 3-18, the fundamental frequency is not the dominant frequency for the bare floor but is the dominant frequency for the completed structure. A comparison of the power spectrums also shows a significant decrease in the square of the magnitudes for the fundamental frequency corresponding to the completed structure compared to that of the bare floor. Thus, the response of the floor to a heel-drop impact was reduced and is reflected in the perceived vibration changing from slightly perceptible to not perceptible.

Predicted bare floor fundamental frequency for positions 4-6 was 12.3 Hz, while the measured bare floor frequency was only 8.5 Hz. The discrepancy was the largest of all of the monitored floors and was attributed to a torsion mode of vibration with a low frequency. The torsion mode was assumed to be caused by the temporary support conditions that were present before 4/29/95. As shown in Figure 3-7, a temporary column was supporting the center truss of the stairway opening. The truss on each side of the center stairway truss was unsupported and was basically hanging from the sheathing. This resulted in a torsion mode with a low fundamental frequency. The 8 Hz mode was a dominant mode of vibration for positions 4-6 until the temporary column was replaced with load bearing stud walls running full length under the double trusses. The 8 Hz mode can also be seen in Figure 3-18 for the power spectrum corresponding to the bare floor for position 2. However, the mode is not nearly as dominant as it is for position 5, and therefore, can be considered not to be contributing to the response of the floor for positions 1-3. After the support conditions were changed, the 8 Hz mode is still present in the power spectrums for positions 4-6, but its magnitude is significantly reduced. Since the predicted fundamental frequency was calculated assuming a simple beam vibration mode as the lowest mode of vibration, the measured fundamental frequency associated with the torsion mode was significantly lower than the predicted fundamental frequency. By comparing the power spectrum of position 5 for the bare floor with the temporary support condition to that of the completed structure with the load bearing stud walls installed, the change in the response of the floor for the two support conditions can be seen. Figure 3-19 shows this comparison.



(a) Bare Floor (b) Completed Structure

Figure 3-19 Comparison of Effect of Support Conditions on Response of Position 5 of Parallel Chord Truss House #2

The 8 Hz mode is clearly seen for the left power spectrum of Figure 3-19. After the temporary support was replaced with the load bearing stud walls, the 8 Hz mode is not present as shown by the right power spectrum of Figure 3-19. The fundamental frequency for the permanent support conditions is 12.25 Hz which compares well with the predicted fundamental frequency of 12.3 Hz. Thus, the 8 Hz mode was assumed to be due to temporary support conditions and the predicted fundamental frequency is accurate for the permanent support conditions of the floor.

There was an increase in fundamental frequency from 12.3 Hz to 14.5 Hz for positions 4-6 for the completed structure with drywall installed compared to the completed structure without drywall. The perceived vibration did not change, however, and was distinctly perceptible for the midspan position (position 5) with the drywall installed. This occurrence provides support for the 15 Hz design criterion described earlier, in that the fundamental frequency for this floor is less than 15 Hz and could be deemed as marginal or unacceptable.

No noticeable trends were seen from examining the modal damping values except that the lowest measured value was 5.3 percent of critical.

3.3.4 Parallel Chord Truss Townhouse

3.3.4.1 Predicted Fundamental Frequencies

Predicted fundamental frequencies were calculated assuming no composite action between the sheathing and floor truss. The full moment of inertia of the top and bottom chords of the truss was used in the calculations. Nominal material values from the NDS supplement (NFPA, 1991) were used in all calculations.

3.3.4.2 Measured Fundamental Frequencies and Modal Damping Values

Measured fundamental frequencies and corresponding modal damping values are given in Table 3-5. Positions 4 and 6 are not included in Table 3-5 because they were not tested on all of the test dates due to accessibility problems.

Table 3-5 Measured Fundamental Frequencies and Modal Damping Values for Parallel Chord Truss Townhouse

Test Date	Position	Fundamental Frequency (Hz)	Fundamental Modal Damping (%)	Vibration Rating	Dominant Frequency ?
4/22/95	1	13.0	13.0	SLP	Y
4/29/95		16.0	5.8	SP	Y
5/17/95		13.0	11.4	SP	Y
4/22/95	2	13.0	11.0	SLP	Y
4/29/95		15.5	6.9	SP	Y
5/17/95		13.5	13.5	SP	Y
4/22/95	3	13.0	12.2	SLP	Y
4/29/95		16.0	5.1	DP	Y
5/17/95		13.8	9.7	SLP	Y
4/22/95	5	18.3	10.4	SLP	Y
4/29/95		13.0	CNC	SLP	Y
5/17/95		12.5	11.8	NP	Y

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

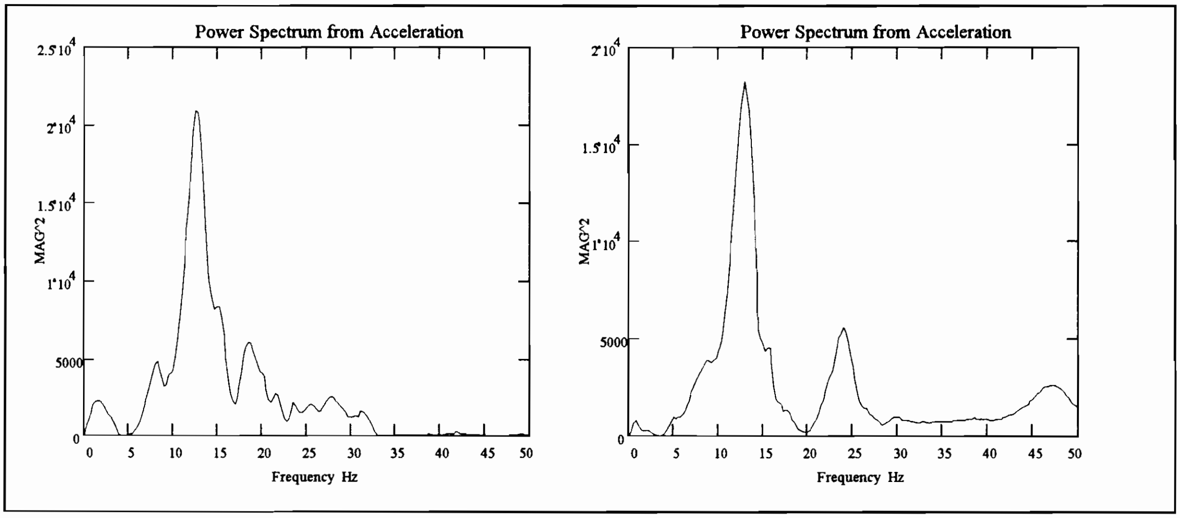
Table 3-5 Cont.

Test Date	Position	Fundamental Frequency (Hz)	Fundamental Modal Damping (%)	Vibration Rating	Dominant Frequency ?
4/22/95	7	13.3	9.9	DP	Y
4/29/95		11.0	CNC	SP	N
5/17/95		12.0	24.0	SP	Y
4/22/95	8	13.3	11.5	DP	Y
4/29/95		11.0	8.7	SP	Y
5/17/95		12.5	13.3	SP	Y
4/22/95	9	13.3	11.5	DP	Y
4/29/95		11.0	8.9	DP	N
5/17/95		12.8	15.4	SP	Y

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

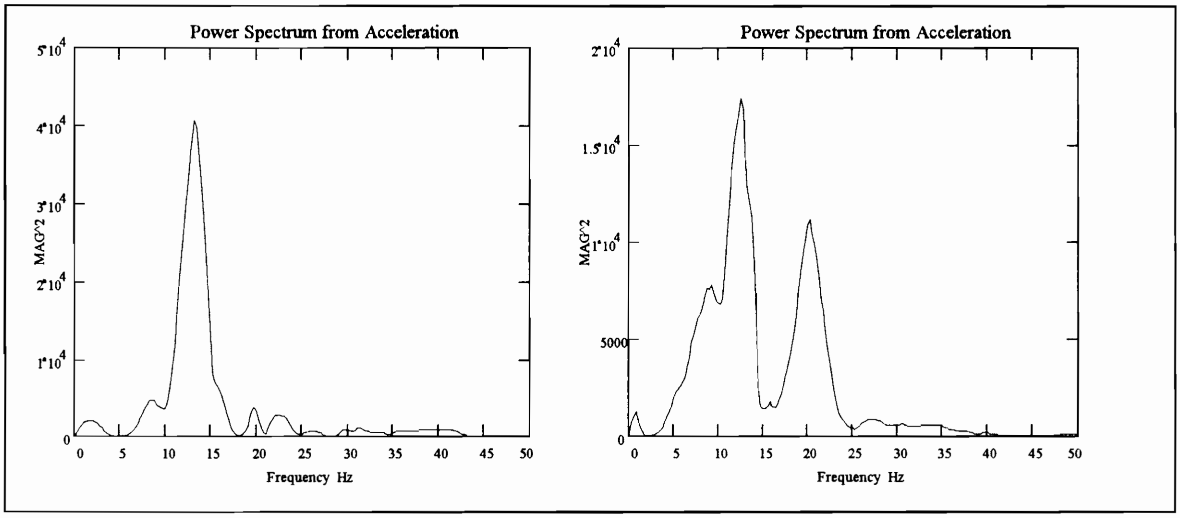
3.3.4.3 Discussion

The predicted bare floor simple beam frequency of positions 1-3 and 7-9 was 14.9 Hz. As can be seen in Table 3-5, the measured bare floor frequencies for these positions were approximately 2 Hz lower than predicted. The explanation for the discrepancy was first thought to be due to the stack of lumber that was beside positions 1-3 during the bare floor testing. The weight of the lumber was thought to have caused a decrease in the fundamental frequency for these positions. However, the same frequencies were measured for positions 7-9, which were measured with no weight on the floor except self weight and are on a section of floor structurally identical to that for positions 1-3. The only possible explanation was found from examining the floor trusses. These floor trusses differ from those of parallel chord houses #1 and #2 in that they have only diagonal web members. The floor trusses of the other houses have both diagonal and vertical web members. Consequently, the shear deformation of the web would be greater for trusses with diagonal web members only. The use of the full moment inertia of the top and bottom chords is probably not accurate for these trusses. If the rule of thumb of using 85 percent of the top and bottom chord moment of inertia is applied for the trusses of this floor, the predicted fundamental frequency is reduced to 13.8 Hz, which agrees more closely with the measured values. The significant increase in the fundamental frequencies from 4/22/95 to 4/29/95 for positions 1-3 and the decrease in fundamental frequencies for positions 7-9 was attributed to the effect of wall braces on the floor. The power spectrums for the measurements taken when wall braces were in place did not look similar to those taken before the wall braces were installed or after the wall braces were removed. Therefore, no conclusions were drawn from the measurements taken when the wall braces were in place. The change in the response of the floor can be seen in Figure 3-20 and Figure 3-21 which show the power spectrums for the bare floor and the completed structure for positions 2 and 8, respectively. Positions 2 and 8 are shown because they are at midspan of their respective floors and therefore represent the positions of maximum response for the floor.



(a) Bare Floor (b) Completed Structure

Figure 3-20 Power Spectrums for Position 2 for Bare Floor and Completed Structure

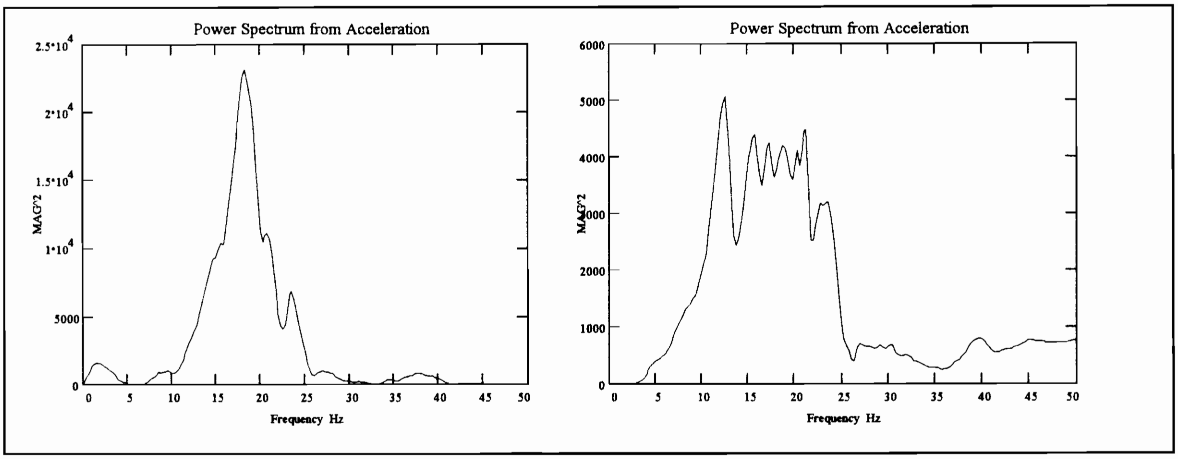


(a) Bare Floor (b) Completed Structure

Figure 3-21 Power Spectrums for Position 8 for Bare Floor and Completed Structure

As shown in Figures 3-20 and 3-21, the response at positions 2 and 8 does not change significantly between the bare floor and completed structure conditions. The squared magnitude of the fundamental frequency in the power spectrum for the completed structure is reduced compared to that of the bare floor, but the reduction is not as significant as was observed in other monitored houses. This is reflected in the perceived vibration rating remaining strongly perceptible for the completed structure for positions 2 and 8. Figures 3-20 and 3-21 also show that there may be a lower mode of vibration than the simple beam mode for positions 2 and 8 if the slight peak just below 10 Hz is interpreted as a mode of vibration. However, this peak is small compared to that of the simple beam mode and the contribution to the response of the floor is probably insignificant.

The predicted fundamental frequency for position 5 was 22 Hz which is significantly higher than the measured value of 18.3 Hz. From the discussion above, the discrepancy was attributed to shear deformation of the web. Using 85 percent of the full moment of inertia of the top and bottom chords of the truss reduced the predicted frequency to 20.3 Hz which compares more favorably with measured value. There was a significant decrease in the fundamental frequency for position 5 for the bare floor compared to the completed structure. This decrease was attributed to the increase in supported weight due to a shower installed close to position 5 and a stud wall that was framed directly into the floor beside this position. The change in response of the floor at position 5 is shown in Figure 3-22.



(a) Bare Floor (b) Completed Structure

Figure 3-22 Power Spectrums for Position 5 for Bare Floor and Completed Structure

The reduction in fundamental frequency for the completed structure compared to bare floor conditions for position 5 is clearly shown in Figure 3-22. However, the perceived vibration at this position improved from slightly perceptible for the bare floor to not perceptible for the completed structure. This is, seemingly, a direct contradiction to the proposed 15 Hz design criterion which would predict that the perceived vibration at this position should have become worse. The explanation can be seen from examining the squared magnitudes of the fundamental frequencies in the power spectrums for the bare floor and completed structure. The fundamental frequency of the bare floor has a squared magnitude of 23,000 while the fundamental frequency of the completed structure has a squared magnitude of 5,708. Thus, the response of the floor at position 5 is significantly reduced for the completed structure. Therefore, even though the floor is vibrating at a lower frequency, the response is smaller. This implies that the 15 Hz design criterion is basically a requirement on the stiffness of the floor controlled by the fundamental frequency of the bare floor. Thus, even though the fundamental frequency of the floor was reduced due to the extra supported weight, the stiffness did not change and the perceived vibration did not become worse.

3.3.5 Solid Sawn Joist House #1

3.3.5.1 Predicted Fundamental Frequencies

Predicted fundamental frequencies were calculated for positions 1-6 for bare floors only. Nominal material properties, taken from the NDS supplement (NFPA, 1991), were used for the calculations. Because predicted girder frequencies were approximately 10 Hz higher then the predicted joist frequencies, system frequencies were used for positions 1 and 6. Usually, fundamental frequencies of a continuous girder supported at short intervals are large compared to that of joists and can be ignored in the calculation of fundamental frequency. However, the large joists and short spans in this house produced large predicted fundamental joist frequencies for positions 1 and 6, and therefore, the effects of the girders had to be included. The predicted fundamental frequency for positions 1-6 are given in Table 3-6.

Table 3-6 Predicted Fundamental Frequencies
for Solid Sawn Joist House #1

Position	**Predicted Fundamental Frequency (Hz)**
1	23.8
2	18.7
3	18.7
4	19.4
5	19.4
6	23.8

3.3.5.2 Measured Fundamental Frequencies and Modal Damping Values

The measured fundamental frequencies and corresponding modal damping values for positions 1-6 for each test date are given in Table 3-7.

Table 3-7 Measured Fundamental Frequencies and Modal Damping Values for Solid Sawn Joist House #1

Test Date	**Position**	**Fundamental Frequency (Hz)**	**Fundamental Modal Damping (%)**	**Perceived Vibration**	**Dominant Frequency ?**
4/14/95	1	20.5	11.2	NP	Y
4/17/95		22.5	12	NP	N
4/20/95		23.8	6.8	NP	N
5/17/95		20.5	8.1	NP	Y
4/16/95	2	18.5	11.5	SLP	Y
4/17/95		18.5	9.5	SLP	Y
4/20/95		19.3	7.2	SLP	Y
4/26/95		20.3	6.0	SLP	N
5/17/95		21	11.4	SLP	Y
4/16/95	3	17.5	7.4	SLP	Y
4/17/95		17.3	7.1	SLP	Y
4/20/95		CNC	CNC	SLP	CNC
4/26/95		18.3	3.0	SLP	N
5/17/95		17.5	CNC	NP	N

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

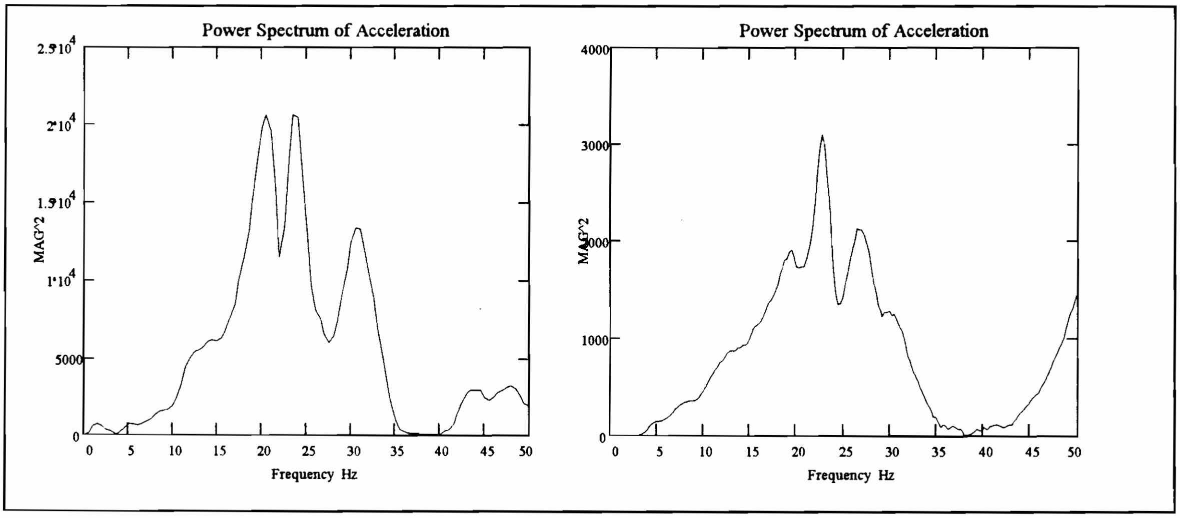
Table 3-7 Cont.

Test Date	Position	Fundamental Frequency (Hz)	Fundamental Modal Damping (%)	Perceived Vibration	Dominant Frequency ?
4/16/95	4	17.5	10.0	SLP	Y
4/17/95		CNC	CNC	SLP	CNC
4/20/95		17.8	5.8	SLP	Y
4/26/95		CNC	CNC	SLP	CNC
5/17/95		21.0	3.6	NP	Y
4/13/95	5	19.0	7.7	SLP	Y
4/17/95		18.5	7.4	SLP	Y
4/20/95		18.0	7.6	SLP	N
4/26/95		21.0	9.8	SLP	Y
5/17/95		21.0	8.9	NP	Y
4/13/95	6	23.5	11.3	NP	Y
4/17/95		21.0	8.5	NP	Y
4/20/95		CNC	CNC	NP	CNC
5/17/95		20.0	13.0	NP	N

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

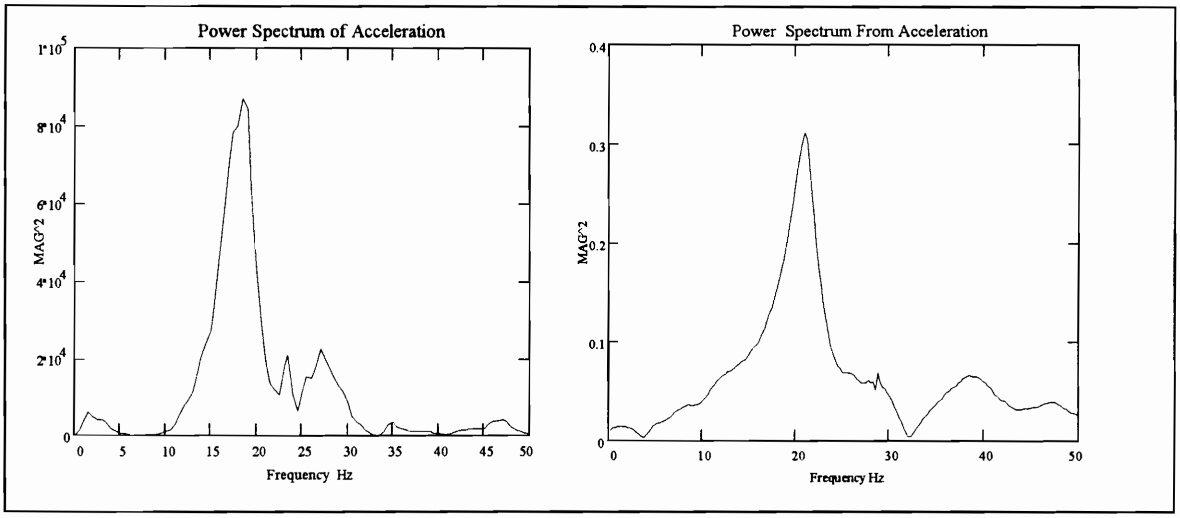
3.3.5.3 Discussion

Predicted bare floor fundamental frequencies compared well to the measured bare floor frequencies except for positions 1 and 3. For these positions the predicted bare floor fundamental frequency was 3.8 Hz and 1.9 Hz higher than the measured bare floor fundamental frequency, respectively. To observe the effect of construction level on the frequency content of the floor system, the power spectrums for the bare floor and the completed structure are shown for positions 1-6 in Figures 3-23 - 3-28.



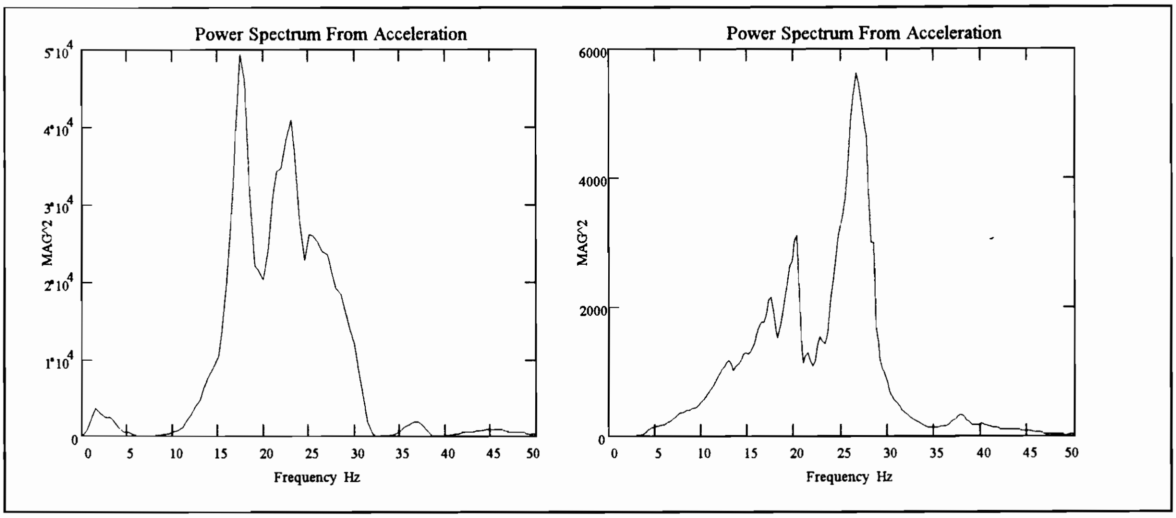
(a) Bare Floor (b) Completed Structure

Figure 3-23 Power Spectrums for Position 1 for Bare Floor and Completed Structure



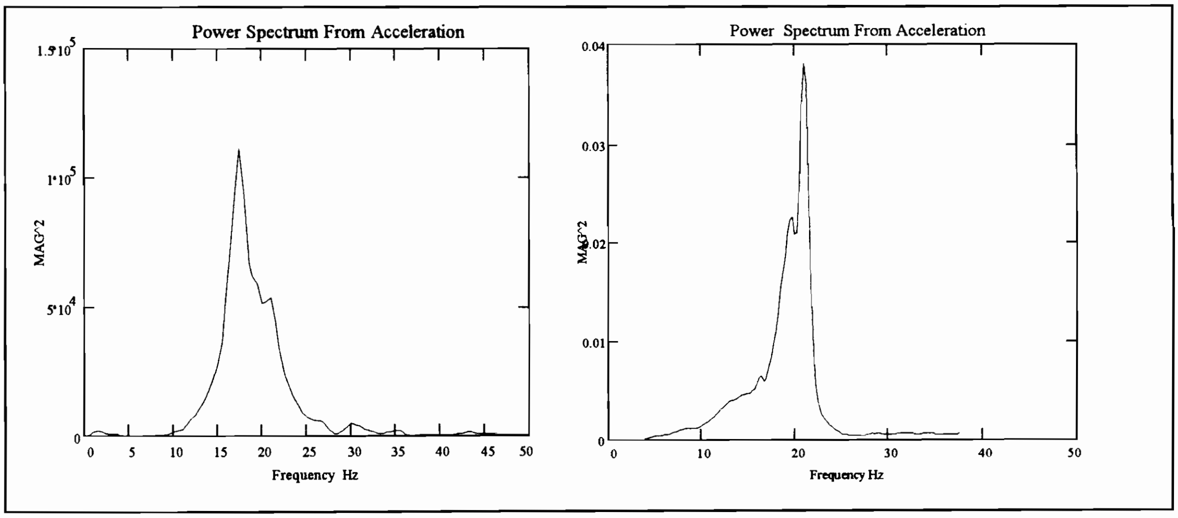
(a) Bare Floor (b) Completed Structure

Figure 3-24 Power Spectrums for Position 2 for Bare Floor and Completed Structure



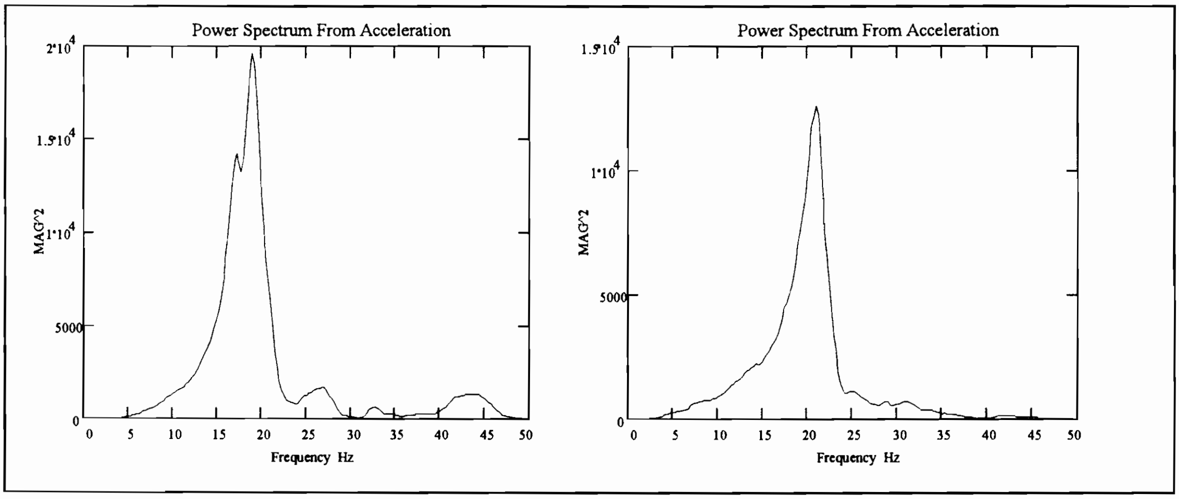
(a) Bare Floor (b) Completed Structure

Figure 3-25 Power Spectrums for Position 3 for Bare Floor and Completed Structure



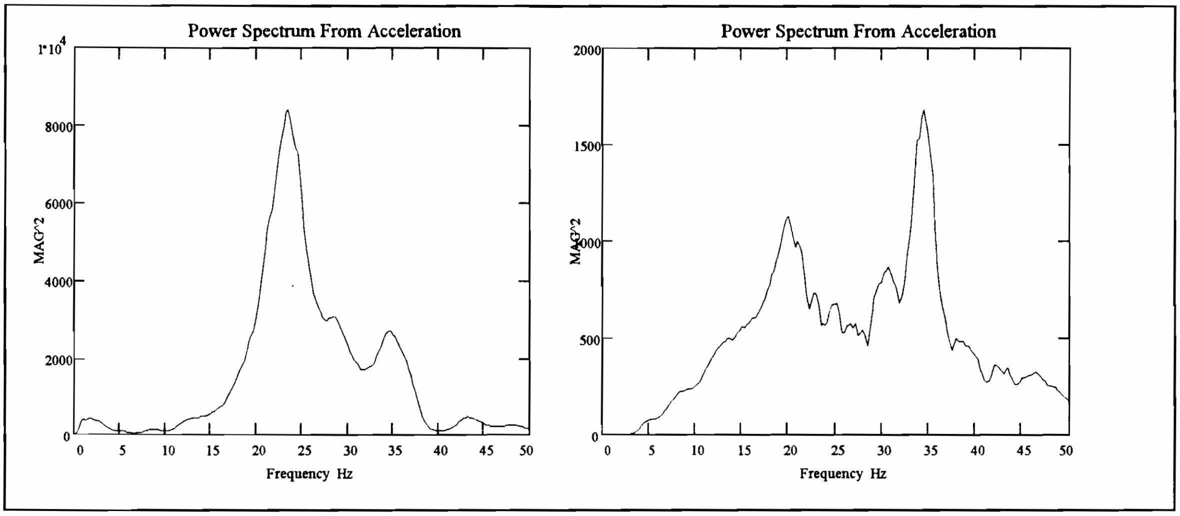
(a) Bare Floor (b) Completed Structure

Figure 3-26 Power Spectrums for Position 4 for Bare Floor and Completed Structure



(a) Bare Floor (b) Completed Structure

Figure 3-27 Power Spectrums for Position 5 for Bare Floor and Completed Structure



(a) Bare Floor (b) Completed Structure

Figure 3-28 Power Spectrums for Position 6 for Bare Floor and Completed Structure

There is a noticeable trend seen in Figures 3-21 - 3-28. For positions 2 and 5 which were located in open areas of the house, the fundamental frequency is the dominant frequency for the bare floor and remains the dominant frequency for the completed structure. For positions 1, 3, 4 and 6 which were located near partition walls, the fundamental frequency is the dominant frequency for the bare floor, but due to the effect of the partition walls, higher modes dominate the response of the floor for the completed structure and not the fundamental frequency. The square of the magnitudes of the power spectrum, which to an extent represent the magnitude of response of the floor, are greatly reduced for the completed structure compared to those for the bare floor for positions near partitions. Thus, as can be expected, the partitions diminished the response of the floor for heel-drop impacts performed near them. The perceived vibration for all positions on this floor was very small throughout construction.

No trends or patterns were seen for the fundamental modal damping values through construction.

3.3.6 Solid Sawn Joist House #2

3.3.6.1 Predicted Fundamental Frequencies

Predicted fundamental frequencies were calculated using nominal values from the NDS supplement (NFPA, 1991) for the joists and a Trus Joist MacMillan (1984) catalog for the laminated veneer girder. A system frequency was calculated for positions 1 and 2 using the fundamental frequencies of the joists and girder, respectively. No composite action between the plywood sheathing and the joists was considered in the calculations. Predicted fundamental frequencies for each position are given in Table 3-8.

Table 3-8 Predicted Fundamental Frequencies for Solid Sawn Joist House #2

Position	Predicted Fundamental Frequency (Hz)
1	14.9
2	14.9
3	15.3
4	21.6

3.3.6.2 Measured Fundamental Frequencies and Modal Damping Values

The measured fundamental frequencies and corresponding modal damping values for each position and test date are given in Table 3-9.

Table 3-9 Measured Fundamental Frequencies and Modal Damping Values for Solid Sawn Joist House #2

Test Date	Position	Fundamental Frequency (Hz)	Fundamental Modal Damping (%)	Perceived Vibration	Dominant Frequency ?
5/10/05	1	15.5	4.5	DP	N
5/23/95		12.8	CNC	DP	N
6/19/95		13.0	10.9	SP	N
5/10/95	2	15.3	6.1	DP	Y
5/23/95		13.0	CNC	DP	Y
6/19/95		11.5	3.2	SP	Y
5/10/95	3	17.0	12.1	SLP	Y
5/23/95		13.0	17.4	SLP	Y
6/19/95		12.0	9.4	SLP	Y
5/10/95	4	22.3	5.2	SLP	Y
5/23/95		22.8	CNC	SLP	Y
6/19/95		23.0	7.8	NP	Y

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

3.3.6.3 Discussion

Predicted fundamental bare floor frequencies for positions 1 and 2 compare favorably to the measured values. Perceived vibration of positions 1 and 2 was initially distinctly perceptible for the bare floor and remained distinctly perceptible for the completed structure. Fundamental frequencies of positions 1 and 2 decreased significantly from the bare floor to the completed structure. This was attributed to the weight of the wall framing on the floor. A significant decrease in fundamental frequency due to the weight of the wall framing as seen for positions 1 and 2 was not seen for other floors that were monitored. Wall framing only effected the magnitudes of energy associated with each natural frequency, not the frequencies. The difference for positions 1 and 2 was that this floor consisted of joists framing into a girder with a 5m (16.5 ft) clearspan. The use of long spanning girders is being used more often to span garages without intermediate column supports. The result is a garage with an open area which is desirable to the residents. This type of floor framing is possible for residential structures using new wood engineered products such as laminated veneer lumber. However, unlike the fundamental frequency of a girder supported at short distances by steel columns which is generally high compared to that of the joists framing into it, the fundamental frequency of a girder with a large clearspan is generally considerably lower than that of the joists framing into it. The low fundamental frequency of the girder drives the fundamental system frequency of the floor down. The reason that the weight of wall framing significantly decreases the fundamental frequency of this type of floor compared to a floor using only joists, is that the weight supported by the girder is calculated assuming the tributary width to be half of the clearspan of the joists framing into it on each side. Thus, the girder carries a large percentage of the weight of the wall framing compared to that of a joist which has a tributary area equal to the joist spacing. This is the reason that the fundamental frequency of positions 1 and 2 was decreased due to the weight of the wall framing.

The predicted bare floor fundamental frequency of position 3 compares favorably to the measured bare floor fundamental frequency. The drop in the fundamental frequency for the test dates of 5/23/95 and 6/19/95 was attributed to a heavy bathtub that was temporarily located next to position 3 during these test dates. The perceived vibration remained slightly perceptible throughout construction of the house.

The predicted bare floor fundamental frequency of position 4 compares favorably to the measured bare floor value. The perceived vibration of this floor was initially slightly perceptible for the bare floor and was rated as not perceptible for the completed structure.

No significant trends were seen for the fundamental modal damping values.

3.3.7 I-Joist House

3.3.7.1 Predicted Fundamental Frequencies

Predicted bare floor fundamental system frequencies for positions 1 and 2 were calculated using the fundamental frequency of the joists and girder. Nominal material properties for the solid sawn joists were taken from the NDS supplement (NFPA, 1991). Material properties for the built up girder composed of laminated veneer lumber were taken from the manufacturer's design guide (Louisiana Pacific, 1992). A problem in calculating the bare floor system frequency was that the joist spans on each side of the girder were not the same. Thus, the predicted fundamental frequency of each joist was different. To calculate a fundamental system frequency, only one joist fundamental frequency can be used. It was decided to use the fundamental frequency of the longer spanning joist on the assumption that the lowest joist frequency would control. This is the same assumption that is used for steel/concrete floors.

3.3.7.2 Measured Fundamental Frequencies and Modal Damping Values

Measured fundamental frequencies and corresponding modal damping values for positions 1 and 2 for each test date are given in Table 3-10.

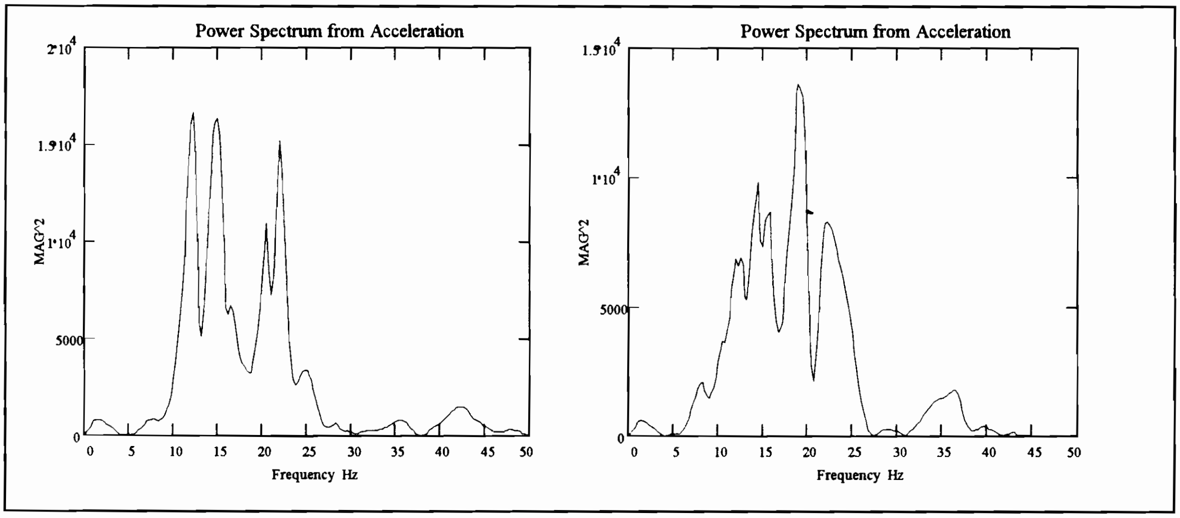
Table 3-10 Measured Fundamental Frequencies and Modal Damping Values for I-Joist House

Test Date	**Position**	**Fundamental Frequency (Hz)**	**Fundamental Modal Damping (%)**	**Perceived Vibration**	**Dominant Frequency ?**
5/6/95	1	12.3	7.2	DP	Y
5/10/95		Data Lost	Data Lost	Data Lost	Data Lost
5/25/95		12.3	7.5	DP	N
5/6/95	2	12.0	9.7	NP	N
5/10/95		Data Lost	Data Lost	Data Lost	Data Lost
5/25/95		19.3	5.4	NP	Y

Y=Yes, N=No, M=Multiple Dominant Frequencies, NP=Not Perceptible, SLP=Slightly Perceptible, DP=Distinctly Perceptible, SP=Strongly Perceptible, CNC=Could Not Calculate

3.3.7.3 Discussion

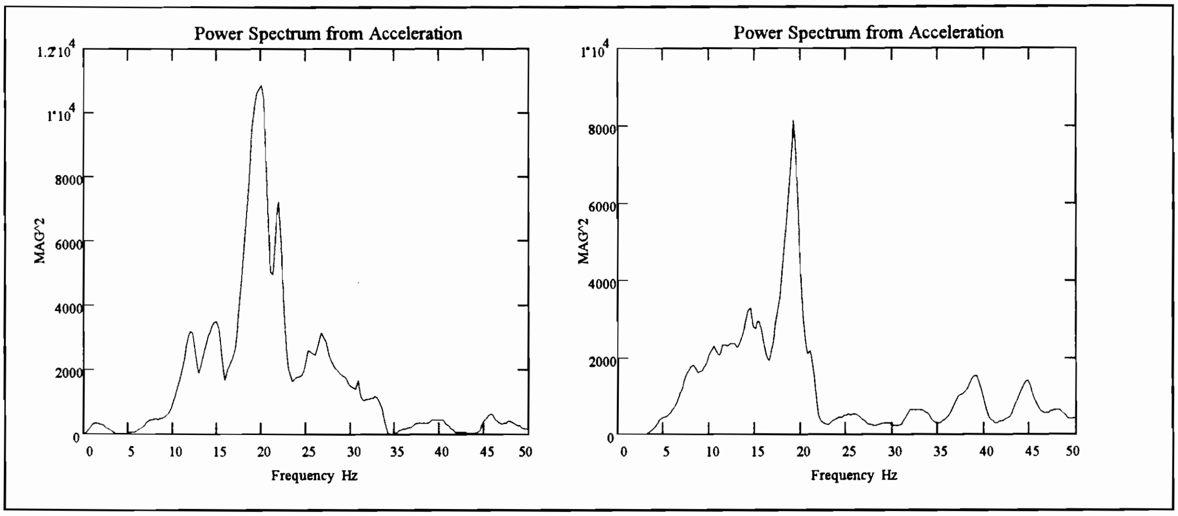
The predicted bare floor fundamental frequency was 11.2 Hz which was approximately 1 Hz lower than the measured bare floor fundamental frequency for positions 1 and 2. The behavior of the floor system was different depending on which side of the floor system was impacted. Perceived vibration of position 1 was distinctly perceptible for the bare floor and remained distinctly perceptible for the completed structure. Perceived vibration of position 2 was not perceptible for all stages of construction. Using the 15 Hz design criterion, both positions would be predicted to be unacceptable. However, only position 1 was rated as unacceptable while there was no perceived vibration for position 2. The response of both positions are given in Figures 3-34 and 3-25, which show the power spectrums for positions 1 and 2 for the bare floor and the completed structure.



(a) Bare Floor

(b) Completed Structure

Figure 3-29 Power Spectrums for Position 1 for Bare Floor and Completed Structure



(a) Bare Floor (b) Completed Structure

Figure 3-30 Power Spectrums for Position 2 for Bare Floor and Completed Structure

From Figure 3-29, it is seen that the fundamental frequency of position 1 for the bare floor is the dominant frequency which correlates well with the vibration rating of distinctly perceptible. However, the fundamental frequency of position 1 is not the dominant frequency for the completed structure. Although the fundamental frequency is still present, a natural frequency of approximately 19 Hz is the dominant frequency. However, the perceived vibration of the completed structure was still distinctly perceptible.

As shown by Figure 3-30, the fundamental frequency was never the dominant frequency for position 2. The 19 Hz natural frequency was dominant for the bare floor and remained the dominant frequency for the completed structure. The spike representing the fundamental frequency is visible in the bare floor power spectrum of Figure 3-30 but is not visible for the power spectrum of the completed structure. The natural frequencies below 19 Hz appear to be smeared together with no distinguishable spikes. However, unlike position 2, a natural frequency below 15 Hz is contributing to the response of position 1 for the completed structure. This is the only difference that was seen between the power spectrums for the completed structure for positions 1 and 2 and was assumed to be the reason for the difference in perceived vibration ratings.

CHAPTER 4

FURTHER VALIDATION OF 15 Hz DESIGN CRITERION

4.1 Introduction

One of the main purposes of this study was to provide further validation of a design criterion for vibration acceptability in residential wood structures recently proposed by Johnson (1994). The criterion was discussed in the literature review section of this study. To summarize, the criterion requires the fundamental natural frequency of the joists and girders of a residential wood floor system to be greater than or equal to 15 Hz. A physical interpretation of the criterion given by Johnson was that the faster a floor is moving, the greater the amplitudes of the floor can be before the vibration will become annoying to the occupants of the floor (Johnson, 1994). The criterion provides a quick check for vibration serviceability at the design stage of a wood floor system. However, as discussed previously, wood floors generally have multiple modes of vibration and a design criterion based on only the fundamental natural frequency will likely be viewed with skepticism by other researchers in the field of wood floor vibration. Therefore, further validation of this criterion with actual test data was needed.

The criterion was originally developed using test data from 86 in-situ floors in various stages of construction (Johnson, 1994). Consequently, all of the floors were tested "bare" with the only load on the floors being the weight of the researcher performing the heel-drops and the self weight of the structure and floor components. Because the fundamental natural frequency of a floor system in general is dependent in part on the supported load, wood floors tend to have lower fundamental natural frequencies when occupied than when "bare." Therefore, data from occupied floors needed to be collected and analyzed to see if the 15 Hz criterion was valid for occupied floors and, if not, to determine if a different limit on fundamental natural frequency should be applied to occupied floors.

A problem with validating the design criterion for occupied wood floors is that while designing a wood floor for strength using uniform loads is sufficient, a uniform load does not accurately predict the effect of live load masses on the dynamic performance of the floor system. Due to their light weight and small mass, wood floors are significantly affected by the presence of live loads when impacted with heel-drops. Particularly, furniture loading varies for each floor and cannot be directly addressed in the calculation of fundamental frequencies.

Hardwood flooring and finished ceilings increase the stiffness of the floor but also add to the supported load of the floor. Stiffening tends to increase the fundamental natural frequency of the floor while, added weight decreases it. Which effect dominates over the other depends on the material used and installation procedures. The effects of both cannot be accurately quantified or predicted during the design of a wood floor but can only be measured after the floor has been built.

All of the above make it difficult to predict the dynamic behavior of an occupied wood floor system. Nevertheless, data was collected and analyzed for approximately 70 occupied wood floor systems. Due to the difficulties in predicting the dynamic response of occupied floor systems, additional bare floors were tested on the premise that a bare floor designed to be acceptable with regard to vibration will be acceptable under occupancy loading. Predicted values from bare floors tend to be more accurate than those for occupied floors due to the fact that the only mass that is vibrating is the self weight of the floor itself. The results from the monitored houses of Chapter 3 provides support for this premise.

This chapter first discusses the occupied and unoccupied floors that were used in the research and the procedures that were used to test them. The results from the tests are then given comparing measured versus predicted fundamental frequencies and agreement with the 15 Hz criterion. Included with the results are some of the difficulties that were encountered in analyzing the data from both tests conducted for this study and those of Johnson. Some limitations and considerations are discussed as a result of these difficulties.

4.2 Test Floors

4.2.1 General

Most of the floors tested were located in or around the town of Blacksburg, Virginia. All of the floors tested were in residential structures representing typical construction practices. The support conditions varied from floor to floor. Most older first story floors tested were supported by either block or concrete walls on one end and a continuous built-up wood girder supported at short distances by steel or block columns on the other end. For this type of floor, the fundamental frequencies of the girders are high compared to those of the joists and are ignored for analysis purposes. Most second story floors were supported by load bearing stud walls on both ends. Due to the emergence of engineered wood products, many newly constructed floors have joists that frame into some type of laminated veneer wood girder with spans in the range of 4.6 m to 7.6 m (15 ft to 25 ft). For these floors, the fundamental frequency of the girders is in the same range or lower than the fundamental frequency of the joists and cannot be ignored and, therefore, is included in the analysis of the floor system using Dunkerly's equation (Equation 1.13).

4.2.2 Occupied Floors

For the occupied floor data, it was originally intended to retest the floors that Johnson had previously used to develop his design criterion, since most of these floors had become occupied by the time the research for this study was begun. For this part of the research, all of the street addresses for the residences of Johnson's test floors were obtained, and a letter was sent to each resident describing the research and testing procedures and requesting permission to test his residence. The number of positive responses was not as large as anticipated, and only 20 of the original 73 floors tested by Johnson were retested.

For additional occupied floor data, permission was obtained to test approximately 40 occupied floors that had not been previously tested by Johnson. Two types of floor systems were used predominately in the occupied floors tested. A majority used solid lumber joists while the remaining used parallel chord trusses. A specific break down of the occupied test floors follows:

- 1 - 50 mm x 300 (2 in.x12 in) lumber joist floor spanning 5.5 m (18 ft).,
- 44 - 50 mm x 250 mm (2 in.x 10 in.) lumber joist floors spanning from 3.4 m to 4.6 m (11 ft to 15 ft).,
- 5 - 50 mm x 200 mm (2 in. x 8 in.) lumber joist floors spanning 3.4 m to 4.9 m (11 ft to 16 ft).,
- 9 - 500 mm (20 in.) deep parallel chord truss floors spanning 7 m to 9.1 m (23 ft to 30 ft).,
- 1 - 460 mm (18 in.) deep parallel chord truss spanning 6.9 m (22.5 ft).

The joist spacing ranged from 305 mm to 610 mm (12 in. to 24 in.) on center with a typical spacing of 406 mm (16 in.).

4.2.3 Unoccupied Floors

Additional unoccupied floor data was collected as floors became available to test. The data from the floors of the monitored houses is also included in this chapter to provide further validation of the 15 Hz design criterion. Excluding the monitored houses, the data from the unoccupied floors was either taken when the floors were completely bare (i.e. no walls or partitions) or when the structure was completed with the walls and roof in place and the wall braces removed. Most of the data taken from the completed structures had bare stud walls with no drywall in place. Two of the unoccupied floors had drywall and finished ceilings in place. For the monitored houses, the data used for validation purposes was that taken from the bare floors. A breakdown of the unoccupied floors is given below. A complete description of the floors from the monitored houses was given in Chapter 3.

- 1 - 50 mm x 300 mm (2 in.x 12 in.) lumber joist floor spanning 3.7 m (12 ft).,
- 14 - 50 mm x 250 mm (2 in. x 10 in.) lumber joist floors spanning from 3.9 m to 4.9 m (13 ft to 16 ft).,
- 3 - 610 mm (24 in.) deep parallel chord truss floors spanning from 8.2 m to 8.8 m (27 ft to 29 ft).,
- 5 - 460 mm 18 in. deep parallel chord truss floors spanning from 2.7 m to 5.2 m (9 ft to 17 ft).

The joist spacing ranged from 305 mm to 610 mm (12 in. to 24 in.) on center with the most common spacing being 406 mm (16 in.).

4.3 Test Equipment

4.3.1 Occupied Floors

Originally, all of the data for the occupied floors was recorded using a Daqbook/100 acquisition system. With this system, an accelerometer was connected to a power unit/amplifier which, in turn, was connected to the first channel of the Daqbook. The power unit/amplifier was set to return 10 V/g from the accelerometer. The Daqbook was connected to an IBM PS/2 L40SX laptop computer which recorded the test data and a push-button hand-held external trigger was also connected to the Daqbook to use to start recording data. As stated previously, the accelerometer was mounted with wax on a 381 mm x 200 mm x 25 mm, 156 N (15 in. x 8 in. x 1 in., 35 lb.) steel plate. Further into the research, a HP 35660A Dynamic Signal Analyzer became available and was used for the remainder of the research. Approximately half of the occupied floors previously tested with the Daqbook were retested using the HP analyzer. It was not possible to retest all of the floors with the HP analyzer because permission could not be obtained from all of the residents that would allow this. The setup for the HP analyzer was basically the same as for the Daqbook except that the HP was configured to trigger internally when the acceleration from the floor exceeded 15 percent of the input range. As described in Chapter 3, the HP analyzer was typically set up to average six traces. Late in the research, an Ono Sokki CF-1200 hand-held analyzer became available. This analyzer possesses all of the features of the much larger and heavier HP analyzer except that it only has one channel to record data. The CF-1200 was used for approximately ten floors.

4.3.2 Unoccupied Floors

The test equipment used for the unoccupied floors from the monitored houses was described in Chapter 3. For unoccupied floors, other than those monitored, the HP analyzer was used exclusively and the test equipment description given for the occupied floors tested by the HP analyzer applies to these floors.

4.4 Test Procedures

4.4.1 General

Regardless of the data acquisition system used, the floors were first rated by a single researcher performing a few heel-drops at the center of the floor and subjectively rating the floor as either acceptable, marginal or unacceptable. This method is significantly different than the method that was used to rate the floors of Johnson's research. All of the floors tested for Johnson's research was conducted by two researchers, where the first researcher would walk around and perform heel-drops while the other researcher stood at various locations on the floor and subjectively rated the floor as acceptable, marginal or unacceptable. This procedure was then repeated with the roles of the researchers switched. The two researchers would then agree on a subjective rating for the floor system. For the floors tested for this study, only one researcher was available. Thus, the rating of the floor was derived from of a single researcher performing heel-drops and rating the floor from the self performed heel-drops. The use of one researcher to rate the floors was unavoidable but it did impose several limitations on the subjective ratings of all the floor systems tested. First, it is known that floor vibration is more annoying to the person or persons who are not directly involved in the activities producing the vibration. Thus, the use of only one researcher to subjectively rate the floor as in this study may result in a floor rated as acceptable that could be rated as marginal or unacceptable if the floor was rated using two researchers. A second limitation as a result of using only one researcher to subjectively rate the floor systems is that the vibration on which the rating is based is felt at the same position at which it is produced. Thus, it is not possible to rate the floor based on impacts at one location and vibrations felt at another. These limitations need to be kept in mind when evaluating the results of this research.

4.4.2 Occupied Floors

The occupied floors that had been previously tested unoccupied by Johnson were tested using the same test parameters and procedures given by Johnson in his research field notes. After the floor was rated, the plate and accelerometer were positioned at the center of the floor according to the dimensions given by Johnson. A heel-drop was then performed approximately 305 mm (1 ft) from the plate on the same joist as the plate. The data was then recorded. When the Daqbook was used, the data was recorded at sample rates of 128 pts/s, 256 pts/s, and 512 pts/s, respectively. For each sample rate, two light heel-drops and two full heel-drops were performed and the resulting vibration recorded for each. This resulted in a total of 12 acceleration time histories being recorded for each floor. As discussed in Chapter 2, light heel-drops were needed when using the Daqbook because full heel-drops often exceeded the input range of the Daqbook. For occupied floors tested with the HP analyzer, the sample rate was set at either 256 pts/s or 512 pts/s and six traces were averaged and a single averaged acceleration time history was recorded.

For occupied floors not previously tested by Johnson, the researcher would first determine which floors of the residence were suitable to test. Living room floors were used the most because these floors generally have open traffic areas and are more susceptible to annoying vibration from human footfalls. A sketch of the structural system was made and the joist type/grade, sheathing type/grade and other relevant information was recorded. Often, for the older residences tested, a grade stamp could not be located on the joists or sheathing. In these cases, the type and grade of joist and sheathing had to be determined by visual inspection. The plate and accelerometer would then be placed at the center of the structural floor. The center of the structural floor was determined by the joist framing and not by the floor plan (i.e. non-load bearing walls) of the residence. The remainder of the test procedure is identical to that given in the previous chapter for the Daqbook and HP analyzer, respectively.

4.4.3 Unoccupied Floors

The HP analyzer was used exclusively for the unoccupied test floors and the test procedures described previously for the occupied floors tested with this analyzer apply to the unoccupied floors as well.

4.5 Results

4.5.1 Occupied Floors

4.5.1.1 Measured Frequencies

Before the results of the measured frequencies of the occupied floors are presented, a discussion of the difficulties encountered in analyzing the frequency content of the test floors is presented. Measuring the natural frequencies of a floor system is usually a straightforward process in which time domain traces recorded with the accelerometer are converted to the frequency domain traces using the FFT algorithm. Ideally, the natural frequencies of the floor system are identified by well defined spikes or peaks on the frequency domain graph. An example of a floor with well defined natural frequencies is shown in Figure 4-1.

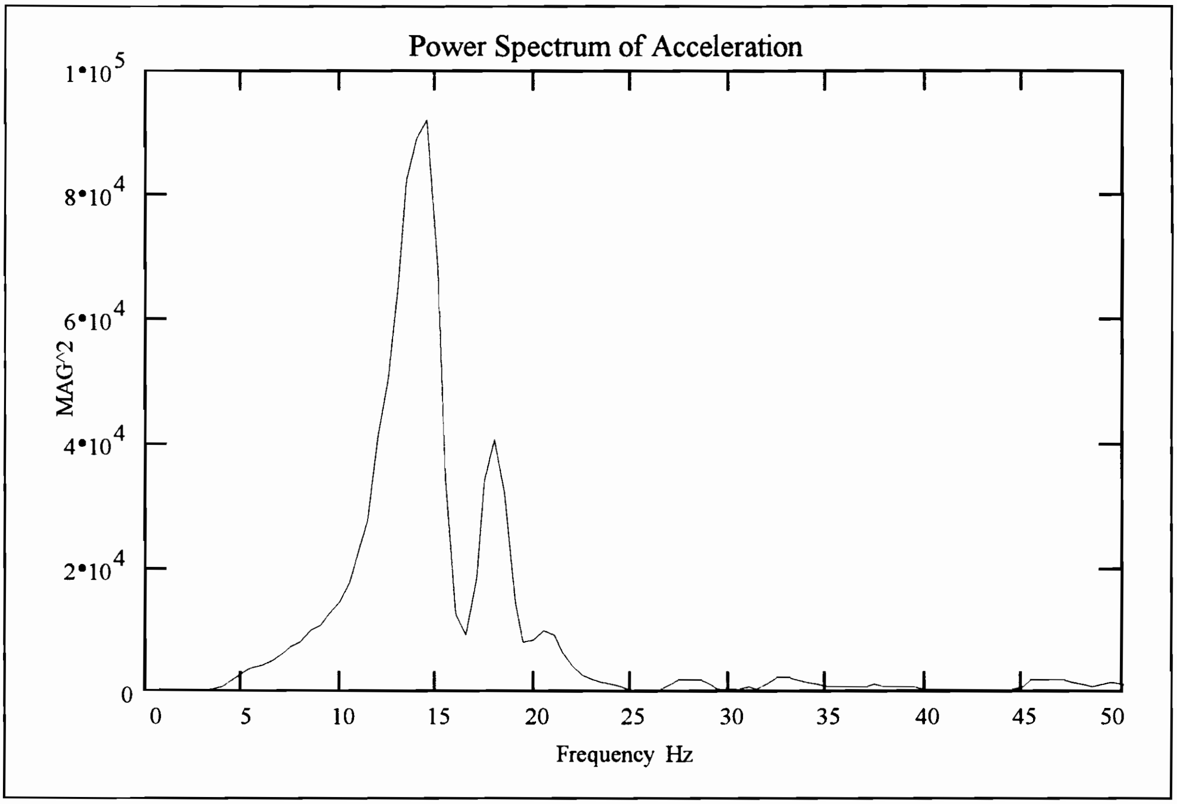


Figure 4-1 Example of Floor with Clearly Defined Natural Frequencies

The floor to which Figure 4-1 corresponds clearly has two natural frequencies that can easily be read off the power spectrum. From the Figure 4-1 they are approximately 15 Hz and 18 Hz, respectively, and they correspond to the natural frequencies of the first two modes of vibration for this particular floor.

However, for many of the floors tested, the power spectrums did not show clearly defined spikes from which the fundamental natural frequency could easily be determined. For these floors, the power spectrums resembled mountain ranges with no visible sharp spikes or peaks. For these floors, the frequency content seems to be spread across a wide frequency band. An example of a power spectrum for a floor with poorly defined natural frequencies is shown in Figure 4-2.

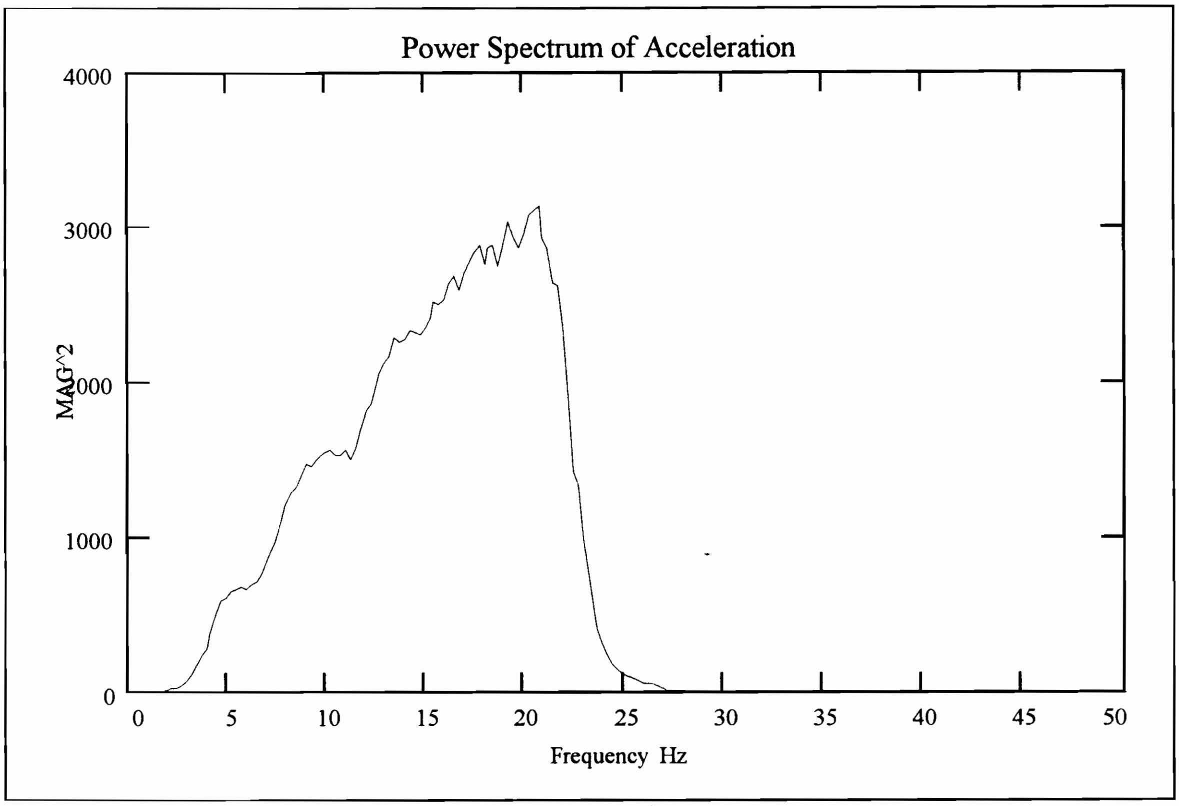


Figure 4-2 Example of Floor with Poorly Defined Natural Frequencies

As can be seen, it is difficult to determine the fundamental natural frequency of this floor. Johnson also encountered this problem in analyzing the data from his test floors. His solution was to use the frequency corresponding to the largest magnitude in the power spectrum as the dominant frequency of the floor. For the floor of Figure 4-2, this corresponds to a fundamental frequency of approximately 21 Hz. Although confidence was lacking in using this assumption, it was used for lack of a better method of determining the fundamental frequency of floors with this type of power spectrum.

The poorly defined power spectrums, like the one shown in Figure 4-2, are puzzling when the acceleration time history from which the power spectrum was derived is examined. The acceleration trace corresponding to the power spectrum of Figure 4-2 is shown in Figure 4-3.

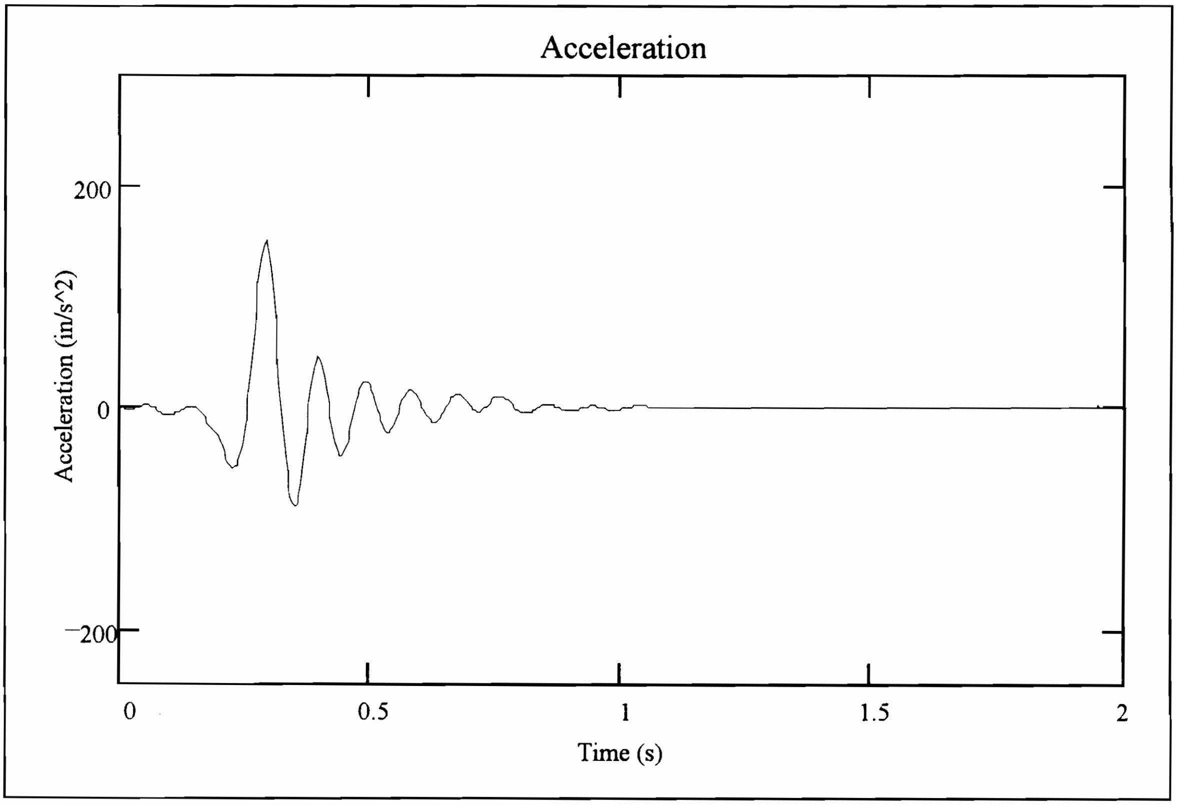


Figure 4-3 Acceleration Trace Corresponding to Power Spectrum of Figure 4-2

As can be seen from the acceleration time history, the vibration of this floor appears to be periodic and thus should produce a power spectrum with a clearly defined fundamental natural frequency. This problem existed for approximately 40 percent of the occupied floors tested and it was dealt with by the aforementioned procedure of using the frequency corresponding to that of the highest magnitude in the individual mounds of the power spectrum.

The results of the floors that were tested unoccupied by Johnson and tested again occupied are shown in Table 4-1.

Table 4-1 Measured Unoccupied and Occupied Fundamental Frequencies

FLOOR	UNOCCUPIED		OCCUPIED	
	Fundamental Frequency (Hz)	Floor Rating	Fundamental Frequency (Hz)	Floor Rating
1	17.8	A	15.3	A
2	15.5	A	15.3	A
3	15.7	A	12.3	A
4	20.3	A	18.0	A
5	18.3	A	15.0	A
6	20.0	A	19.5	A
7	13.2	A	15.0	A
8	28.3	A	19.3	A
9	24.2	A	7.0	A
10	20.6	A	13.0	A
11	19.8	A	15.5	A
12	18.1	A	17.5	A
13	16.1	A	12.5	A
14	28.8	A	20.0	A
15	12.0	A	21.5	A
16	16.3	A	16.5	A
17	22.3	A	16.5	A
18	20.9	A	17.8	A
19	21.8	A	16.5	A

A=Acceptable, M=Marginal, U=Unacceptable

Before Table 4-1 is discussed, an explanation of Johnson's analysis procedures is needed. Johnson tested floors using both an accelerometer and a velocity transducer simultaneously to record the vibration of the floors. The power spectrums from these two measuring instruments often showed different dominant natural frequencies. Johnson handled this by selecting the dominant natural frequency from each acceleration and velocity power spectrum and then averaging them to produce a single dominant frequency.

Often a difference as large as 10 Hz existed between the dominant natural frequency given by the acceleration and velocity power spectrums respectively. The use of averaging when a discrepancy of this magnitude occurred was viewed as inappropriate. For Table 4-1, Johnson's original data was re-analyzed and only the acceleration power spectrums were used for averaging. The general trend of the data from Table 4-1 is a drop in fundamental natural frequency from an unoccupied floor to an occupied floor.

However, the decrease in the fundamental frequency is often not as large as Table 4-1 indicates. The reason for this is that when Johnson analyzed the power spectrums from his floors, he always selected the natural frequency with the largest spike as the controlling or dominant frequency of the floor (Johnson, 1994). Often, the dominant frequency of Johnson's floors was not the lowest or fundamental natural frequency. For this study, the fundamental natural frequency, when it could be determined, was used exclusively even though for a small percentage of floors it was not the dominant frequency. Therefore, the drop in fundamental natural frequency between unoccupied floors and occupied floors is sometimes less than Table 4-1 indicates.

A few of the floors had an increase in the fundamental natural frequency between an unoccupied floor and an occupied floor. A possible explanation for this is that increases in floor stiffness from hardwood flooring and increases in the modulus of elasticity of the joists due to a drop in moisture content from drying of the wood were not accounted for. A drop in moisture content also decreases the weight of the floor system which would cause an increase in the fundamental natural frequency. All of the above factors may offset the effect of occupied loads on the floor system causing an increase in the fundamental natural frequency.

No floors rated as acceptable for unoccupied conditions were rated as marginal/unacceptable when tested with occupancy loading. Thus, occupancy loading did not cause a decrease in the performance of the floor with regard to vibration from heel-drop impacts.

4.5.1.2 Predicted Frequencies

The equations used to predict the fundamental natural frequency of the tested occupied floor systems were given in Section 1.3.7 of Chapter 1. Using these procedures, a fundamental natural frequency was predicted for each floor based on nominal values for the material properties. The nominal properties were obtained from reference guides supplied by the manufacturers of the engineered wood products and the 1991 NDS Supplement (NFPA, 1991). To account for occupancy live load, two different uniform loads were used. It is general practice to use ten percent of the design uniform live load as the expected load level. For wood floors, this would usually be 83.5 mPa (4 psf). However, a lower uniform live load was used for lightly loaded floors or when the live load was not concentrated around the center of the floor. For lightly loaded occupied floors or floors with furniture located at the edges of the floor system, a value of 41.8 mPa (2 psf) was used. For heavily loaded occupied floors or floors with furniture located near and around the center of the floor, a uniform load of 83.5 mPa (4 psf) was used. If present, hardwood flooring and drywall ceilings were ignored in the calculations because their effects were not known.

For occupied floors in service for more than one year, a moisture content of 11 percent was assumed. For these floors, the nominal material properties were adjusted for this reduced moisture content based on an original moisture content of 19 percent. Figure 6-7 of the Wood Handbook (1974) was used to determine the adjusted modulus of elasticity values. For occupied floors in service less than one year, a moisture content of 19 percent was assumed. For floors with girders, a system frequency was calculated based on the fundamental frequencies of the joists and girders respectively. The effects of girders was ignored if the predicted fundamental frequency of the girder was 10 Hz higher than the predicted fundamental frequency of the joists. For those cases, the floor was assumed to vibrate at the joist fundamental frequency.

For floors with continuous girders, the fundamental frequency of the continuous girder was calculated using a span length equal to the length of the positive moment region of the continuous girder. This length was also used to calculate the load supported by the girder. The use of the positive moment length instead of the clear span for continuous girders produced a much better correlation between predicted and measured fundamental frequencies.

For floors with parallel chord wood trusses, predicted fundamental frequencies were calculated using the full moment of inertia of the top and bottom chords of the truss. Standard practice for steel joist floors is to use 85 percent of the full moment of inertia to account for shear deformation of the web. However, using computer generated output from a local wood truss manufacturer, it was determined that the full moment of inertia of the top and bottom chords was being used to calculate allowable deflections. Because a large percentage of the parallel chord trusses tested in this study came from this manufacturer, the full moment of inertia was used for calculation purposes.

Figure 4-4 shows measured fundamental frequencies versus predicted fundamental frequencies for the 54 occupied floors tested.

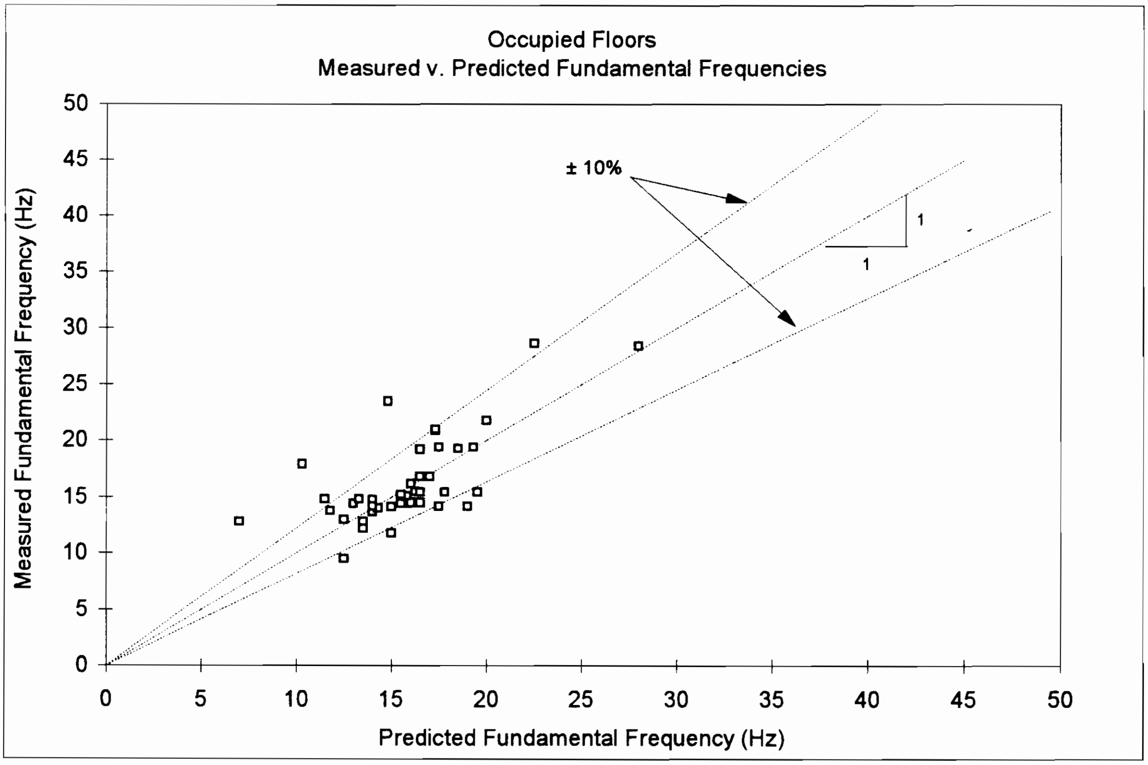


Figure 4-4 Occupied Measured vs. Predicted Fundamental Frequencies

No definite trend is seen from Figure 4-4 relating predicted versus measured fundamental frequency for the occupied floors. Nine occupied floors have predicted fundamental frequencies not within 10 percent of the measured fundamental frequencies as indicated by the 10 percent lines shown on the Figure 4-4. The procedures used to predict fundamental frequency for the occupied floors seem to overestimate and underestimate the measured fundamental frequency about equally.

4.5.1.3 Agreement with 15 Hz Criterion

One of the primary objectives of this study was to provide further validation of the recently proposed vibration serviceability design criterion for residential wood floors requiring each component of the floor system and the floor system itself to have a fundamental frequency greater than or equal to 15 Hz (Johnson, 1994). Particularly, validation was needed for occupied floors since no occupied floors were included in the original study. In developing the criterion, Johnson originally saw the best correlation from a plot of the product of measured dominant frequencies and peak displacement versus peak displacement of the floors. When this plot was simplified, the design criterion reduced to a requirement that the dominant mode of vibration be greater than 15 Hz (Johnson, 1994). The final criterion was shown graphically with a plot of measured dominant frequency and peak displacement versus the dominant frequency of the floors.

For this study, no peak displacements were calculated due to difficulty in achieving satisfactory results from integrating the measured acceleration traces to produce displacement traces. Therefore, the plot used to show correlation for the original study could not be used for this study. However, since the criterion reduced to a requirement on fundamental frequency alone, a plot of the product of measured acceleration and fundamental frequency versus measured fundamental frequency should show the same correlation as the original. This is because the peak displacements used in the original study and the peak acceleration values used in this study merely allow the data to be shown graphically but do not enter into the final result of a limiting value for the fundamental frequency of the floor. Indeed this was the case, and Figure 4-5 shows this plot for all of the occupied floors tested.

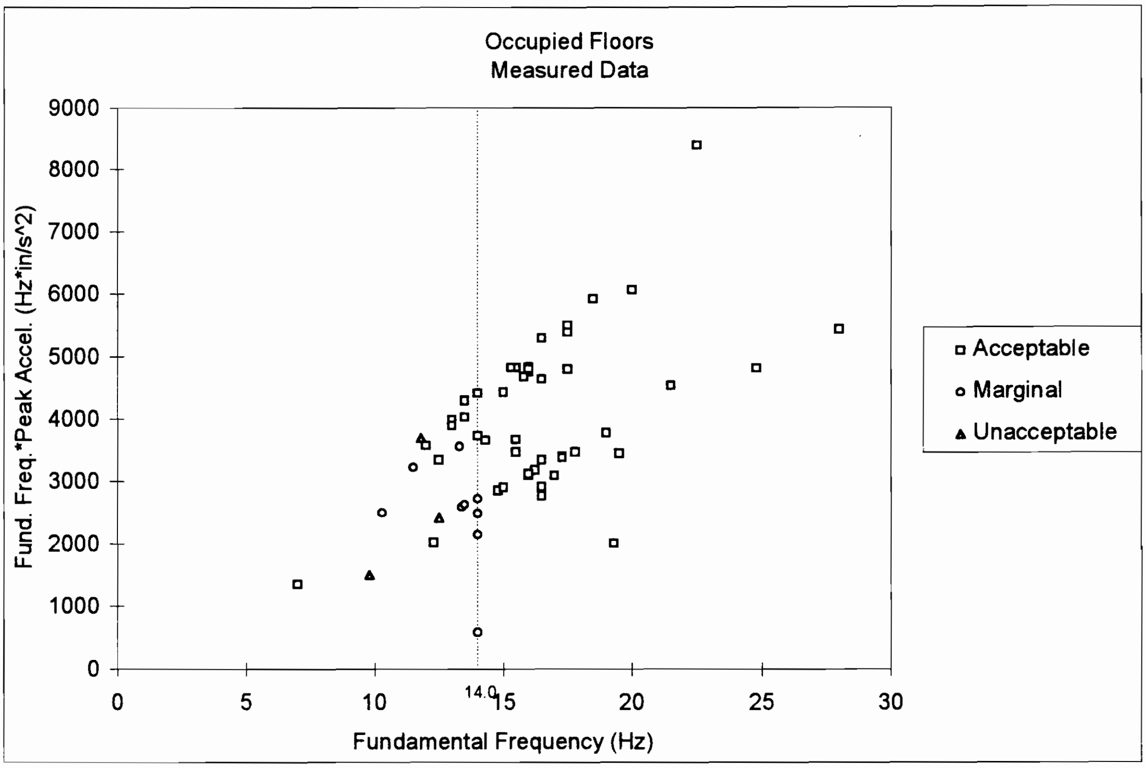


Figure 4-5 Measured Fundamental Frequency*Peak Acceleration vs. Measured Fundamental Frequency

Figure 4-5 shows a clear distinction between acceptable and unacceptable occupied floors based on fundamental natural frequency. Approximately 37 occupied floors that were rated as acceptable had measured fundamental frequencies greater than 14.0 Hz. Seven occupied floors rated as acceptable have fundamental frequencies less than 14 Hz. The occupied floor rated as acceptable with a measured fundamental frequency of 7 Hz shown in Figure 4-5 is a kitchen floor. The large live load from the kitchen appliances and furnishings resulted in the low measured frequency. All occupied floors rated as marginal or unacceptable have measured fundamental frequencies less than or equal to 14.0 Hz. Thus, the measured data shows that for occupied floors there is a reduction in the required fundamental frequency from the proposed design criterion value of 15 Hz to 14.0 Hz for a floor to be rated as acceptable. This reduction reflects the added mass due to occupancy. Even though there was a reduction in the required fundamental frequency of an acceptable floor, a strong correlation between perceived vibration and fundamental frequency is apparent from Figure 4-5.

A criterion that can be used for design must be able to show the same correlation for the predicted response of the floor system as is shown by the measured response of the floor system. Figure 4-6 shows a plot using the predicted fundamental frequencies of the occupied floor systems.

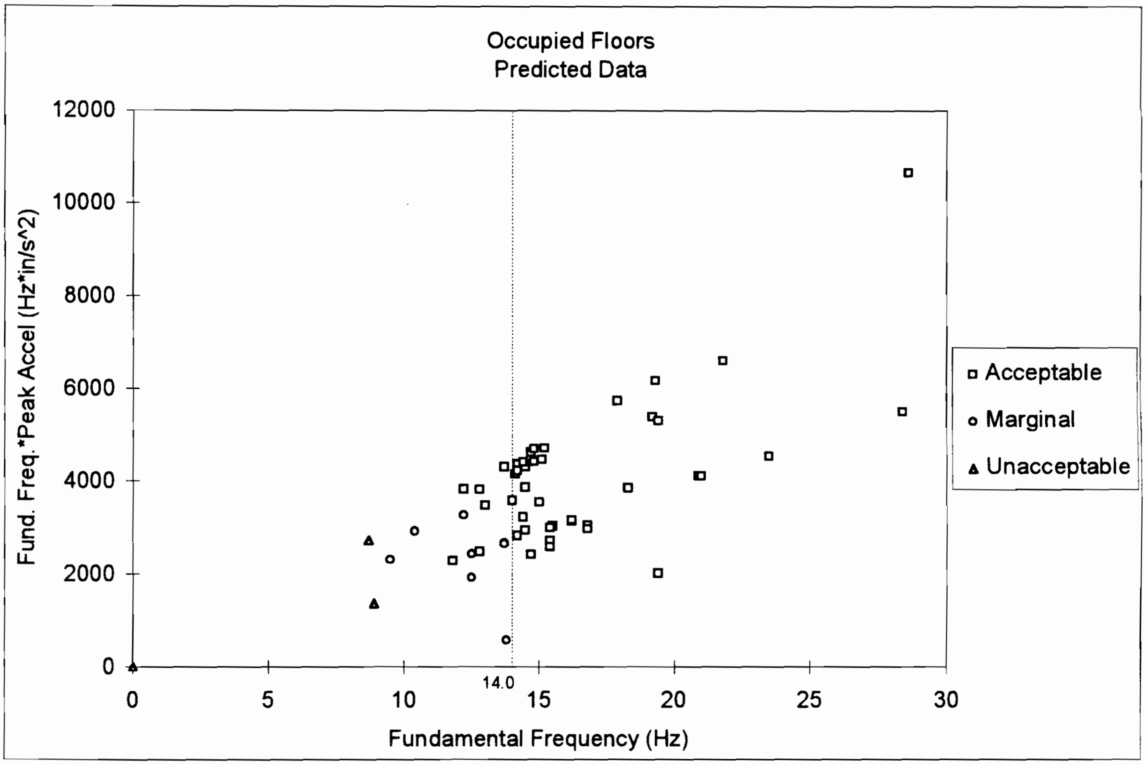


Figure 4-6 Predicted Fundamental Frequency*Peak Acceleration vs. Predicted Fundamental Frequency

Again, Figure 4-6 shows a strong correlation between acceptable and unacceptable occupied floors based on fundamental frequency. The predicted occupied fundamental frequencies show the same relationship as the measured fundamental frequencies which is a required fundamental frequency of 14 Hz for an occupied floor to be acceptable with regard to vibration from a heel-drop impact. No occupied floors with predicted fundamental frequencies greater than 14 Hz were rated as marginal or unacceptable. Six occupied floors rated as acceptable had predicted fundamental frequencies less than 14 Hz. Thus, the predicted occupied fundamental frequencies show that a reduction from the proposed design criterion value of 15 Hz to 14 Hz is warranted for residential wood floors with typical occupancy loading.

4.5.2 Unoccupied Floors

4.5.2.1 Measured Frequencies

For the unoccupied floors tested, fundamental natural frequencies were determined using power spectrums produced from acceleration traces. The lowest frequency contained in the power spectrum was chosen as the fundamental natural frequency. The power spectrums for the unoccupied floors showed clearly defined spikes representing the natural frequencies of the floor system a larger percentage of the time than did the power spectrums from the occupied floors. This is attributed to the absence of carpet and furniture effects for the unoccupied floors as compared to the occupied floors. All of the data from the unoccupied floors was measured using the HP analyzer. The HP was configured to average ten acceleration traces for each occupied floor tested.

4.5.2.2 Predicted Frequencies

The procedures for calculating fundamental frequencies of the unoccupied test floors are much the same as that given in Section 4.3.1.2. The only difference was that since these floors were tested bare, only the self weight of the joists and sheathing was used to predict the fundamental frequencies. Figure 4-7 shows measured versus predicted fundamental frequencies for the 45 unoccupied floors tested.

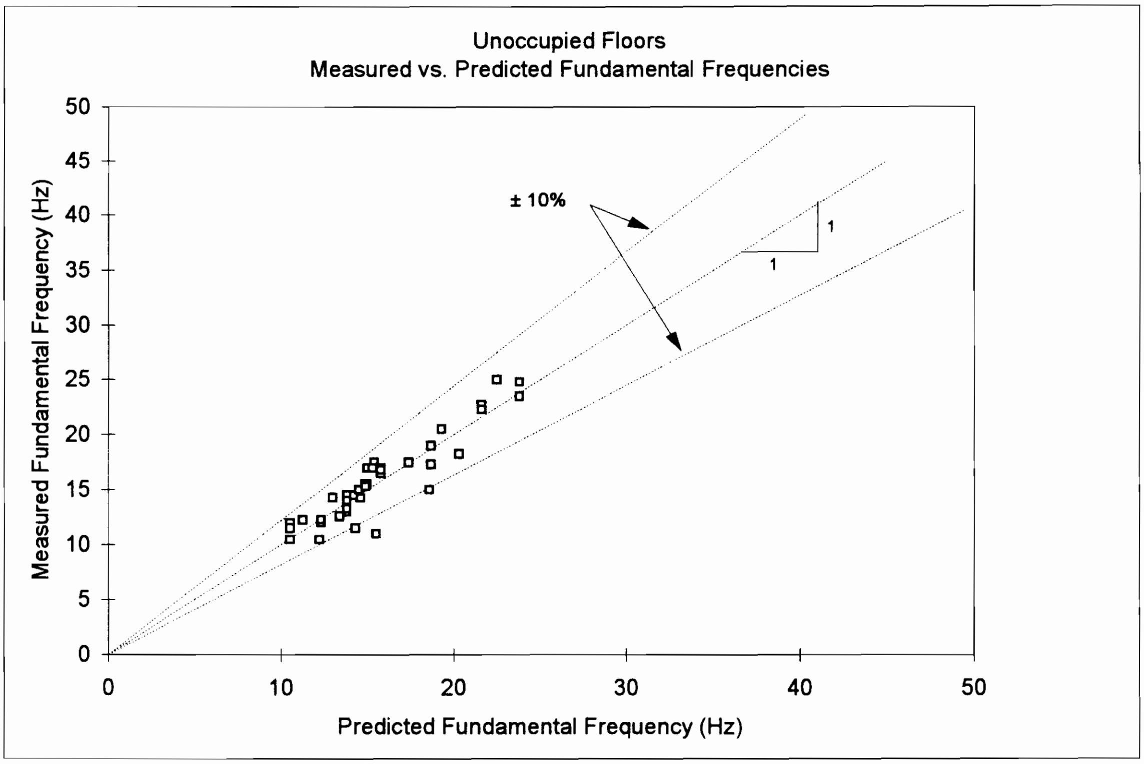


Figure 4-7 Unoccupied Measured vs. Predicted Fundamental Frequencies

As shown by Figure 4-7, the predicted fundamental frequencies are very close to the measured fundamental frequencies for the unoccupied floors. The agreement is considerably stronger than that shown by Figure 4-4 for the occupied floors. Only one unoccupied floor has a predicted bare floor fundamental frequency not within 10 percent of the measured fundamental bare floor frequency. This particular floor was tested with a heavy piece of construction equipment on it which caused a significant reduction in the measured fundamental frequency. This load was not accounted for in calculating the predicted fundamental frequency, causing the large discrepancy between the predicted and measured frequency shown in Figure 4-7. The stronger correlation for predicted and measured fundamental frequency for the bare floors compared to the occupied floors is attributed to not being able to accurately account for the effects of the live load masses for the occupied floors. A uniform load was used to approximate these live loads, but this simplification does not accurately predict the actual response of the floor system due to these live loads. The effects of live load masses are more prevalent for wood floors than for steel floors due to the low mass of the wood floor itself compared to the loads acting upon it.

4.5.2.3 Agreement with 15 Hz Criterion

To check how the unoccupied floors compared to the 15 Hz design criterion, a plot of measured fundamental frequency multiplied by peak acceleration versus measured fundamental frequency was created. This plot is shown in Figure 4-8.

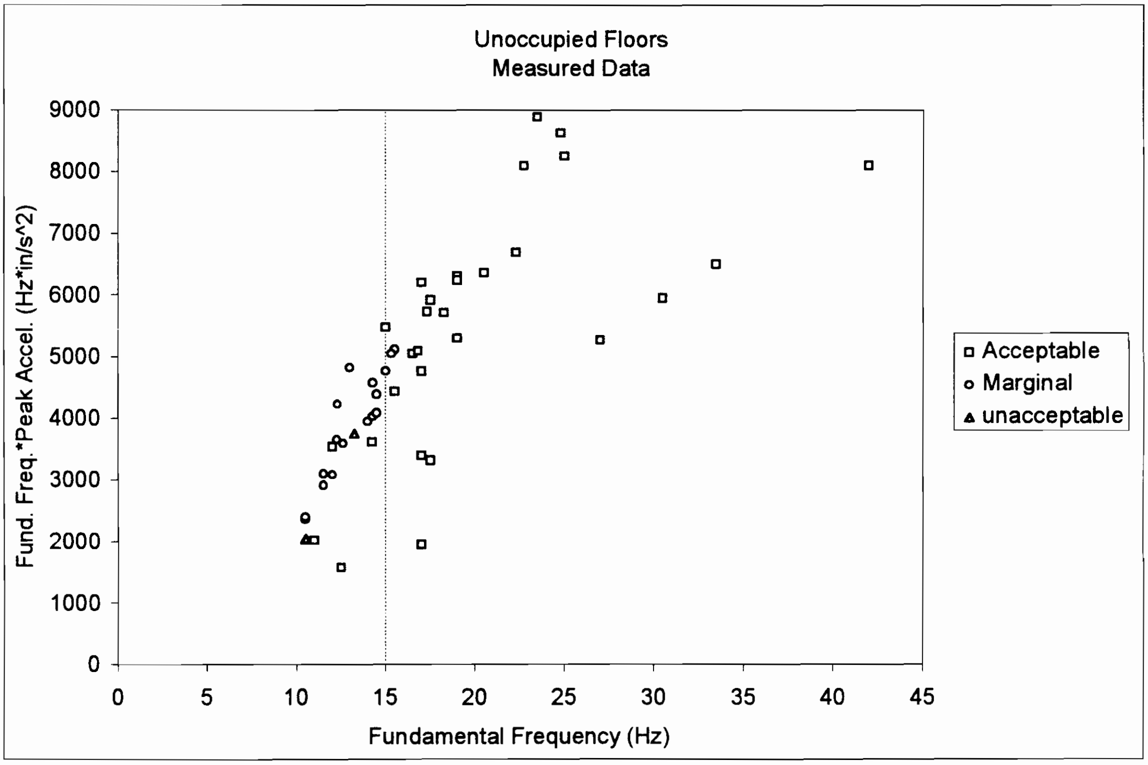


Figure 4-8 Measured Fundamental Frequency*Peak Acceleration vs. Measured Fundamental Frequency

The proposed 15 Hz design criterion correlates well with the measured values from the unoccupied floors. The 15 Hz requirement for an acceptable unoccupied wood floor is clearly shown from Figure 4-8. Four unoccupied floors rated as acceptable have measured fundamental frequencies less than 15 Hz. The unoccupied floor rated as acceptable with the measured fundamental frequency of 11 Hz is the floor which had the heavy piece of construction equipment on it. The unoccupied floor rated as acceptable with a measured fundamental frequency of 12.5 Hz was tested with a finished drywall ceiling attached to the underside of it. The added mass from the ceiling caused the decrease in the measured fundamental frequency shown in Figure 4-8. It is believed that the added mass of the ceiling also was a factor in the rating of the floor. No movement of this floor was noticed when impacted with a heel-drop. Thus, due to conservation of momentum of this floor with the added mass from the drywall ceiling, it was not possible to produce any noticeable movement of the floor using the heel-drop impact of one researcher. The occupied floor rated as acceptable with a measured fundamental frequency of 12.0 Hz was one of the monitored floors that was discussed in Section 3.3.7.3 of Chapter 3. Figure 4-8 shows two unoccupied floors which were rated as marginal with a measured fundamental frequency slightly larger than 15 Hz. Both of these floors were part of a joist/girder floor system of the same house.

To see how the predicted fundamental frequencies of the unoccupied floors agreed with the proposed design criterion, a plot was created using the predicted values for the bare floor. This plot is shown in Figure 4-9.

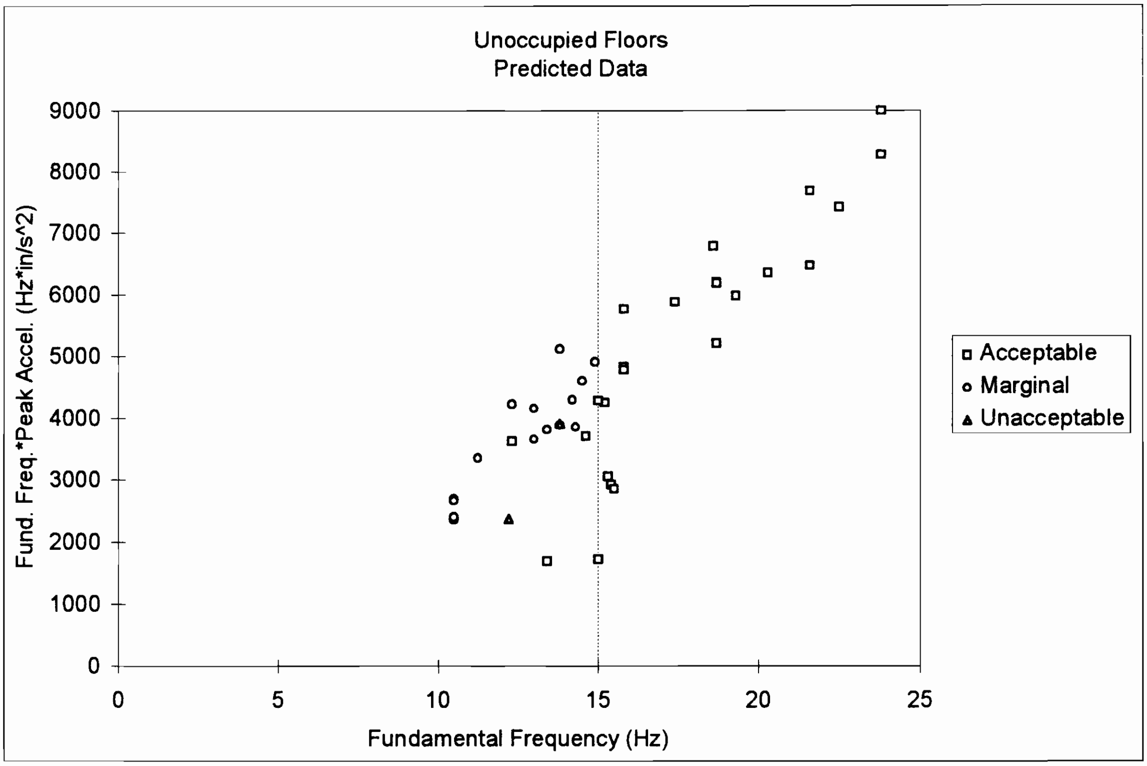


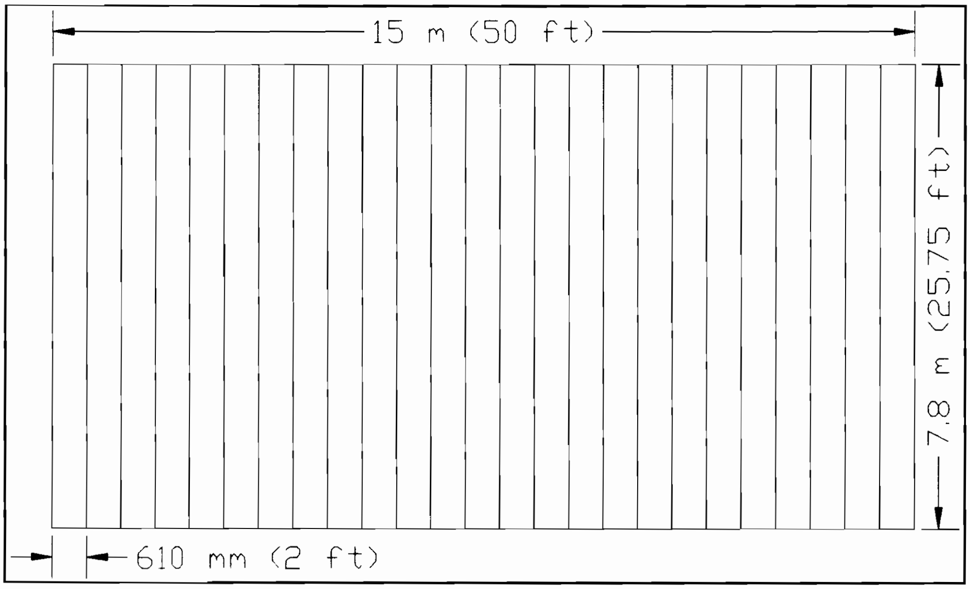
Figure 4-9 Predicted Fundamental Frequency*Peak Acceleration vs. Predicted Fundamental Frequency

Again, the predicted fundamental frequencies from the unoccupied floors correlate well with the 15 Hz design criterion. Three unoccupied floors rated as acceptable have predicted fundamental frequencies less than 15 Hz. Of the three, the two with the lowest predicted fundamental frequencies are the floor with the drywall ceiling installed and the monitored floor discussed in Section 3.3.7.3 of Chapter 3 which were mentioned in the discussion of the measured fundamental frequencies of the unoccupied floors. No bare floors rated as marginal have predicted fundamental frequencies larger than 15 Hz. Thus, although the 15 Hz criterion eliminates three floors rated as acceptable based on predicted bare floor fundamental frequencies, it does not allow any floors rated as marginal or unacceptable.

4.6 Predicted Improvement in Floor Performance using SAP90 Models

To improve floor performance with respect to the 15 Hz criterion, an increase in fundamental frequency of the floor system is needed. At the design stage this involves increasing the floor stiffness. This can be accomplished by reducing the floor span or by increasing the stiffness of the joists themselves. The latter is controlled by the moment of inertia of the joist and its corresponding modulus of elasticity. Increasing the moment of inertia usually requires increasing the depth of the joist while modulus of elasticity can be increased by using a higher grade of lumber. A simpler solution would be to add an extra joist every few joist spacings. To see if this procedure has the desired effect of increasing the fundamental frequency of a typical wood floor system, several SAP90 (1992) models were developed. SAP90 is a finite element program used to model structural systems. For this study, beam elements and plate elements were used to model the wood floor systems. Floor 1 from the monitored 560 mm (22 in.) deep parallel chord truss house was modeled first to see if the fundamental frequency of a measured floor could be accurately predicted using the SAP90 model. The floor was modeled using only the stiffness of the trusses and the plywood sheathing alone assuming no composite action between the trusses and the plywood sheathing. The SAP90 model predicted a fundamental frequency of 14.1 Hz which compares favorably to the measured fundamental frequency of 14.5 Hz. Since the model accurately predicted the fundamental frequency of an actual floor, four additional floors were modeled to see the effect of doubling the trusses at various locations on the floor. These floors were not actual test floors but were numerical models developed for the study. The floors in the study used 560 mm (22 in.) deep parallel chord floor trusses spanning 7.8 m (25.75 ft). For the study, all four edges of the floors were modeled as simply supported. The width of the floor was 15.2 m (50 ft). The sheathing was 18 mm (23/32 in.) plywood. The floors were labeled A through D for identification purposes. Floor A is a standard floor with no doubled floor trusses. Floors B through D had doubled floor trusses at predetermined spacings. Figures 4-10 and 4-11 show the four floors and the locations of the doubled floor trusses for floors B through D.

FLOOR A



FLOOR B

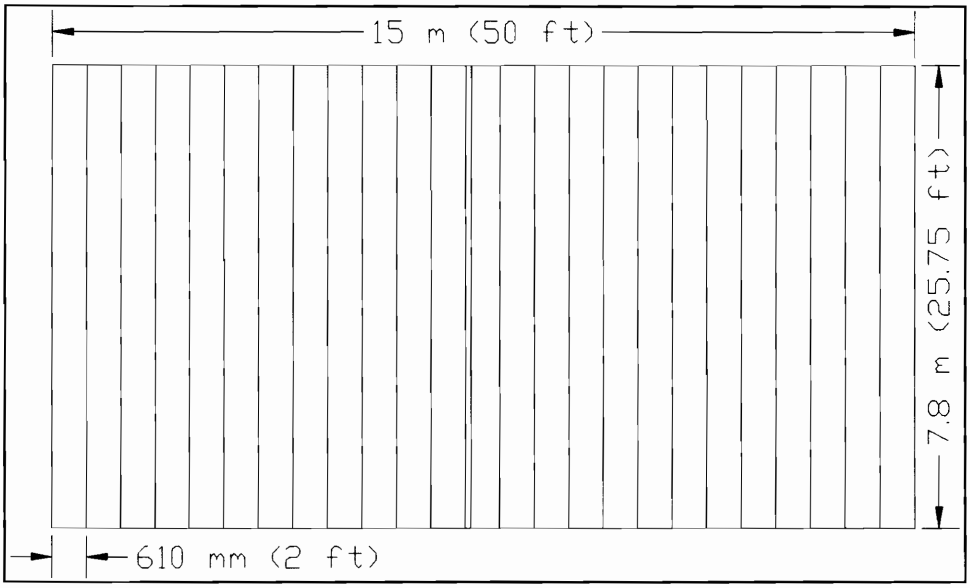
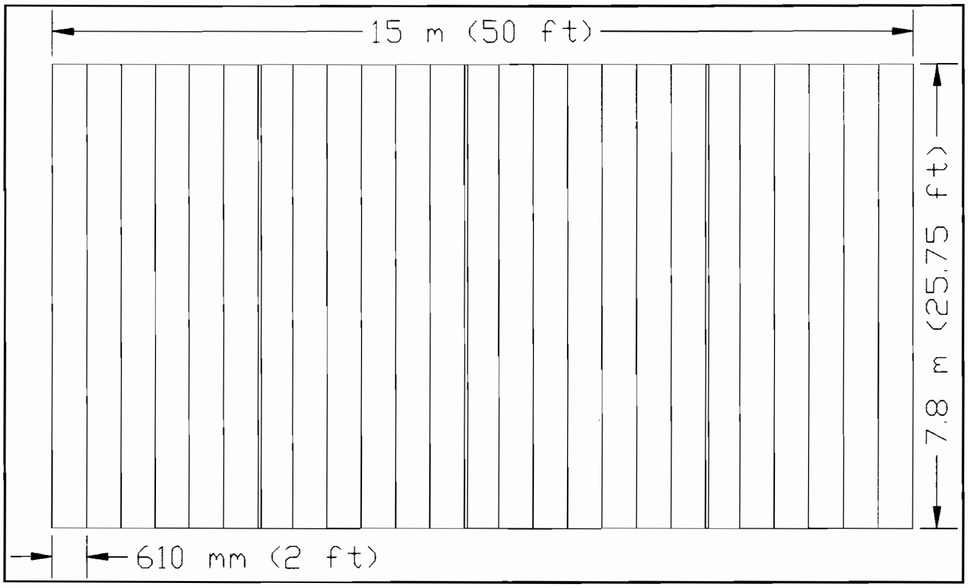


Figure 4-10 Floors A and B of SAP90 Study

FLOOR C



FLOOR D

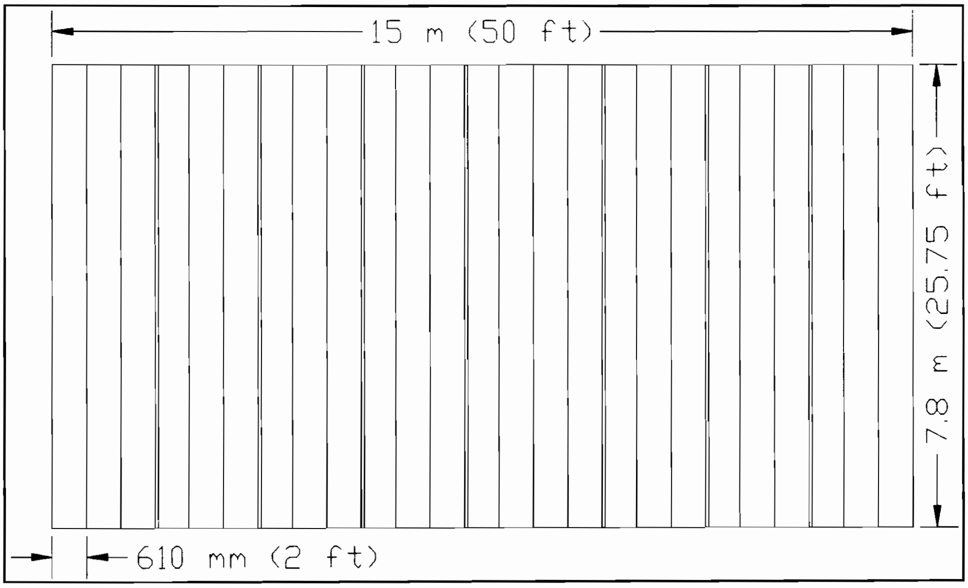


Figure 4-11 Floors C and D of SAP90 Study

The fundamental frequencies from the SAP90 analysis are given in Table 4-2.

Table 4-2 Summary of SAP90 Study

FLOOR	FUNDAMENTAL FREQUENCY (Hz)
A	14.08
B	14.19
C	14.39
D	14.76

From Table 4-2, it would seem that doubling the joists is not an effective procedure to increase the fundamental frequency of a wood floor above 15 Hz. Compared to Floor A which had no doubled trusses, an increase of only 0.68 Hz was achieved for Floor D which had a doubled truss at every third joist spacing. Based on the above, other methods should be used to increase the fundamental frequency of wood floors.

CHAPTER 5

CONCLUSIONS

5.1 Summary of Study

5.1.1 Monitored Houses

From the study of the six monitored houses some general conclusions can be drawn. First, the simple beam frequency can be most accurately calculated for a bare floor consisting of the sheathing and floor joists only. Second, there is no significant change in the measured fundamental frequency of a wood floor due to construction of the remainder of the building until drywall is installed. Although only two of the six monitored houses were tested with drywall in place, in both cases an increase in fundamental frequency was observed for all positions tested. The increase in fundamental frequency ranged from a low of 2 Hz to a high of 5 Hz with an average increase of 2.7 Hz. In both cases, the perceived vibration was also significantly reduced after drywall had been installed. Thus, the addition of drywall to the studs and the underside of the joists significantly improved the performance of the floor with regard to floor vibration produced from heel-drop impacts.

To increase the fundamental frequency of the floors, the drywall must increase the stiffness of the floor. For drywall attached to the underside of the joists, a percentage of the increase in stiffness can be attributed to composite action between the joists and the drywall. However, to increase the fundamental frequency of the floor, the increase in stiffness from any composite action must be large enough to more than offset the decrease in fundamental frequency due to the additional dead load.

The increase in floor stiffness after the addition of drywall was also attributed to increased fixity of the floor joist end restraints resulting from the weight of the walls with drywall and the weight of the roof acting on the ends of the floor joists. Although minimal increases in fundamental frequency have been reported in related literature from end wall fixity (1-2 percent), the tests conducted in these studies were done using lab-built floors and joist end fixity was simulated using clamps (Chui, 1986). These tests did not, therefore, represent the conditions of an actual residential structure. The results from this study, although somewhat limited in the number of tests, do show an increase in floor stiffness associated with increased joist end restraint. It must be stated that the increase in joist end fixity just described is applicable for wood floors in which the walls frame into the joist ends. Therefore, no increase in joist end fixity could be expected for joists supported by joist hangers.

A third conclusion drawn from the study of the monitored houses is that the weight of wall framing significantly decreases the fundamental frequency of a wood floor having joists which frame into a girder with a large clearspan. This conclusion is limited because only one of the monitored houses had a floor of this type, and therefore the conclusion is based on test data from a single floor. The decrease was due to the large increase in supported weight carried by the girder. As was explained in Chapter 3, the girder for this type of floor carries a large percentage of the wall framing weight as compared to that of a typical floor joist. This is due to the fact that the girder must carry half the load of all the joists framing into it, whereas, a floor joist only carries the floor load located within a joist spacing. Thus, the girder carries a much larger percentage of the wall framing weight than does a floor joist, causing a significant decrease in the fundamental frequency of the girder and the floor system itself.

Another effect from wall framing was a decrease in the response of the fundamental frequency compared to the higher modes of vibration for positions located near stud walls. The decrease in response was characterized by a reduction in the squared magnitudes of the power spectrum associated with the fundamental frequency between a bare floor without wall framing and a floor with wall framing in place. Positions located in open areas, free from wall framing, were not affected.

Other decreases in fundamental frequencies observed were due to a heavy shower or bathtub placed on the floor where vibration measurements were taken. However, even though the fundamental frequency decreased for these positions, the floor response decreased as well, due to the large mass on the floor.

No conclusions were drawn from the measured damping values for the fundamental mode of vibration. For all of the floors monitored, there was a wide scatter in the measured values and no significant patterns or trends were seen. A lot of this scatter was associated with the use of the half power method to obtain the damping of the fundamental mode. Poorly defined spikes in the power spectrum and closely spaced modes of vibration often made application of the half power method difficult or impossible. Even if accurate fundamental modal damping values could be measured for wood floor systems, predicting these values during the design stage of the floor is not possible.

Damping in wood floor systems is a highly variable property dependent on the construction material as well as the method of construction itself. The type of glue used between the floor joists and sheathing, as well as the type and number of nails used to attach the sheathing, affect the damping of the floor. Additionally, because the person impacting the floor represents a large percentage of the vibrating mass for wood floor systems, the presence of occupants on the floor significantly affects damping. Wall framing, ductwork and plumbing also contribute to the total damping of the floor system. Thus, although damping is an important parameter of a wood floor system with regard to vibration acceptably, it is not possible at the present time to predict in the design stage of a wood floor system and can only be measured after the structure has been constructed.

Therefore, the inclusion of damping in any design criterion for vibration acceptability in wood floors is not recommended.

From the research conducted in this study, the conclusion is that the damping is large enough in residential structures so that only the first two to three oscillations of vibration are felt by the persons on the floor. By monitoring houses through construction, the performance of the same floors was evaluated many different times. Based on this experience and that from the testing of over 80 other wood floor systems not part of the monitored study, it may be concluded that human discomfort from a heel-drop impact, which is similar to the impacts caused by human foot falls, is not due to the vibration of the floor, but is associated with the initial deflection from the heel-drop impact. Thus, the problem is not a vibration problem but rather a deflection problem. This statement is limited in that the research for this study was conducted by a single researcher in a stationary position. The response of the floors was evaluated by the researcher at the same position the floors were impacted. The response of the floors was not evaluated at other positions on the floor away from the point of impact. However, the conclusion arrived at from this study is that initial deflection caused by a heel-drop impact is controlling the perceived performance of wood floor systems.

5.1.2 Validation of 15 Hz Criterion

5.1.2.1 Occupied Floors

The measured and predicted fundamental frequencies showed strong correlation between fundamental frequency and acceptability with regard to vibration from heel-drop impacts. However, the requirement on fundamental frequency for an acceptable floor was 14 Hz. This is a 1 Hz reduction compared to the limit proposed by Johnson for unoccupied floors. There were no marginal or unacceptable rated floors which had a measured or predicted fundamental frequency greater than 14 Hz. Seven occupied floors rated as acceptable had measured fundamental frequencies less than 14 Hz, while six occupied floors rated as acceptable had predicted fundamental frequencies less than 14 Hz. Additionally, of the 20 floors rated acceptable by Johnson for bare floor conditions, none were rated as marginal/unacceptable when retested with occupancy loading in this study. Thus, the performance of a wood floor with respect to vibration from impact loading is not decreased due to the addition of occupancy loading. Based on the above, it is suggested that an occupied wood floor system should have a predicted fundamental frequency greater than 14 Hz.

There was, however, large scatter between the occupied predicted fundamental frequencies and measured fundamental frequencies. There was no trend to the scatter, with an approximate equal number of occupied floors with predicted fundamental frequencies both higher and lower than the corresponding measured fundamental frequencies.

The large scatter for the predicted and measured fundamental frequencies was attributed to the analysis procedure of accounting for occupancy live loads using a uniform distributed load. The uniform load does not effectively account for the effect of live load masses on the dynamic response of the occupied floor systems. Also, the scatter was associated with effects of hardwood flooring which were not accounted for in the prediction models. Additionally, based from the conclusions above for the monitored houses, neglecting the effects of drywall in predicting fundamental frequency of wood floor systems is probably contributing to the scatter between predicted and measured fundamental frequencies of the occupied floors.

5.1.2.2 Unoccupied Floors

The predicted and measured fundamental frequencies of the unoccupied floors based on bare floor properties agreed extremely well with the proposed 15 Hz design criterion.

There were two unoccupied floors rated as marginal which had measured fundamental frequencies of 15.5 Hz. There were no unoccupied floors rated as acceptable which had measured and predicted fundamental frequencies below 15 Hz.. The agreement between the measured and predicted fundamental frequencies was significantly closer for the unoccupied floors than for the occupied floors. There was no significant scatter and a large percentage of the unoccupied floors had measured fundamental frequencies that were greater than the corresponding predicted values. This was expected because of the assumption of no composite action between the joists and the sheathing for the predicted fundamental frequencies. The reduced scatter between predicted and measured fundamental frequencies for the unoccupied floors was due to the fact that, unlike occupied floors, the only vibrating mass of an unoccupied floor is the self weight of the floor components, which can be accurately accounted for in the prediction equations for fundamental frequency. Because a majority of the measured fundamental frequencies were larger than the predicted values, the procedure used to predict fundamental frequencies is conservative when used with the proposed 15 Hz design criterion.

5.1.2.3 Summary of Floors from Johnson and Current Study

A summary of predicted bare floor fundamental frequencies and corresponding in-situ ratings are given in Table 5-1 for all of the floors of this study and Johnson's study. From the two studies, a total of 164 individual wood floor systems were tested and rated. Of the 164 floors, 18 were common to both studies. They were tested as bare floors by Johnson and as occupied floors in this study. For comparison purposes, these 18 floors are included with Johnson's floors in Table 5-1. For the occupied floors of this study, predicted bare floor fundamental frequencies were calculated using the self weight of the joists and sheathing as the only vibrating mass. The in-situ ratings of these floors were determined under occupancy conditions.

Table 5-1 Summary of Floors from Johnson and Current Study

	Acceptable Floors		**Marginal Floors**		**Unacceptable Floors**	
	>15 Hz	**≤ 15 Hz**	**>15 Hz**	**≤15 Hz**	**>15 Hz**	**≤15 Hz**
Johnson	52	12	2	5	1	14
Current Study	45	5	2	21	0	5

Table 5-1 shows good correlation between acceptable and marginal/unacceptable wood floor systems with respect to deflection from heel-drop impacts as reflected by fundamental frequency. Of the 164 wood floors included in the database, 85 percent of the floors rated as acceptable have predicted bare floor fundamental frequencies greater than 15 Hz, 87 percent of the marginal floors have predicted bare floor fundamental frequencies less than or equal to 15 Hz, and 95 percent of the unacceptable floors have predicted bare floor fundamental frequencies less than or equal to 15 Hz. The two marginal floors of this study with fundamental frequencies greater than 15 Hz were occupied floors of the same residence. The rooms of these floors were decorated with numerous ceramic ornaments and decorations placed on shelves and tables. These ceramics made considerable noise when the floors were impacted using full heel-drops. The marginal rating given by the researcher for these two floors may have been influenced by the noise created by these ceramics rather than any excess deflection of the floor itself. Thus, these two floors perhaps would have been given an acceptable rating in the absence of the noise created by the ceramics.

Of the 15 percent of the acceptable floors with predicted bare floor fundamental frequencies less than or equal to 15 Hz, 60 percent of those had predicted bare floor fundamental frequencies between 14 and 15 Hz.

Figure 5-1 shows a visual representation of the results from the floors from both studies in terms of percentage of acceptable and marginal/unacceptable floor systems with predicted bare floor fundamental frequencies less than or equal to 15 Hz or greater than 15 Hz.

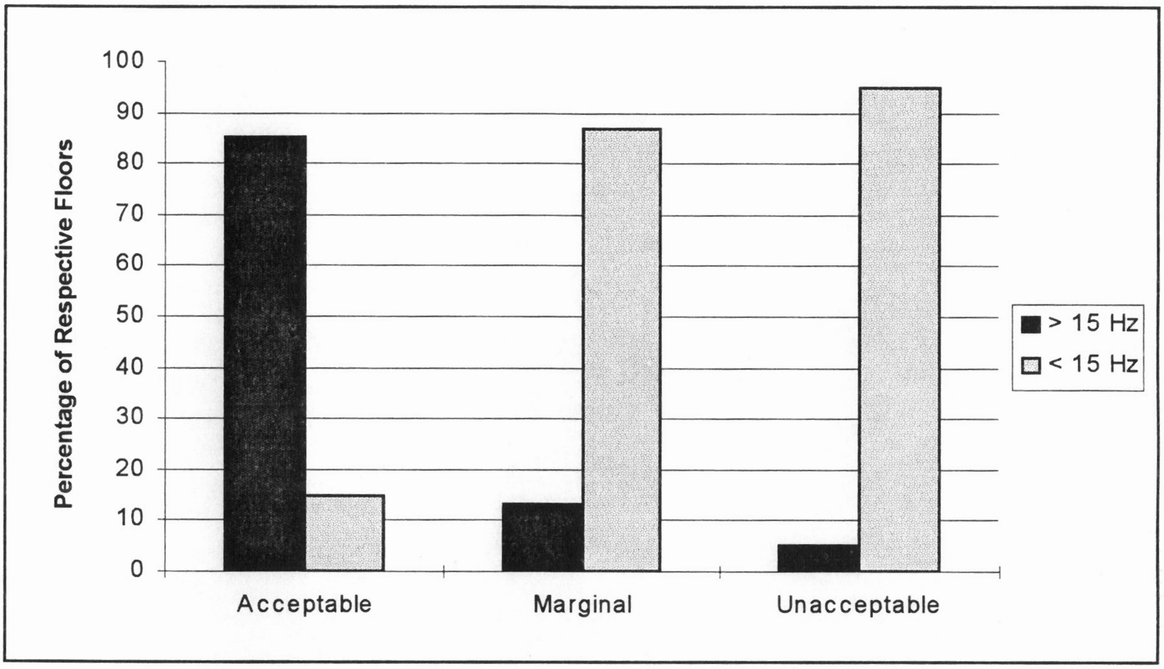


Figure 5-1 Summary of Floors from Johnson and Current Study

5.2 Recommendations

Based on the above summary of this study, the 15 Hz criterion for unoccupied floors or a 14 Hz criterion for occupied floors can be used as a check during the design stage for determining whether a wood floor system will be acceptable with regard to vibration produced from human footfalls. It is recommended that the 15 Hz criterion for unoccupied floors should be used due to better agreement between predicted and measured fundamental frequencies for occupied floors compared to unoccupied floors. As stated previously, the 15 Hz requirement on fundamental frequency is reflecting a limit on required stiffness of a residential wood floor system for a heel-drop impact.

As discussed in the summary of the monitored houses, for all of the over 100 residential wood floor systems tested, the initial deflection from the heel-drop impact used to excite the floors caused discomfort rather than any continued vibration of the floor. For all of the floors tested, the damping was sufficiently large that only one or two oscillations were felt after the initial impact. It was concluded that maximum floor deflection from a heel-drop impact governs the acceptability of residential wood floor systems with respect to vibration from human footfalls. It would, therefore, be appropriate to base a design criterion on a deflection limitation. Johnson (1994) concluded that deflections from a heel-drop impact could not be accurately predicted for wood floor systems applying the same equations used in Murray's design criterion for steel/concrete floor systems. Therefore, no accurate, simple method is available except the use of finite element models to accurately predict deflections for residential wood floor systems due to a heel-drop impact. Although the expense of finite element modeling is justified for large projects, it would not be accepted for use in designing residential wood structures. The only parameter that can be accurately predicted for a wood floor system using simple design equations is the fundamental frequency of the bare floor. The vibrating mass of the bare floor can accurately be accounted for because it involves only the self-weight of the floor. Since it is not possible at the present time to accurately predict deflections from a heel-drop impact for wood floor systems using simple design equations, the use of fundamental frequency of the bare floor, which is a dependent on floor stiffness and can accurately be predicted using simple design equations, is justified as a limitation on deflection resulting from a heel-drop impact.

A concern of basing the 15 Hz design criterion on bare floor properties is that the fundamental frequency will likely decrease for an occupied residence due to the presence of live load. However, since the 15 Hz criterion is a reflection of required stiffness to limit the initial deflection of the wood floor system due to a heel-drop impact, the decrease in fundamental frequency due to occupancy loading is not reflecting a decrease in the stiffness of the floor system. The amount of stiffness resisting the heel-drop impact is the same as that for the bare floor. This premise is supported by the results from the occupied floors. For the occupied floors, the required fundamental frequency for an acceptable floor was 14.0 Hz, a 1.0 Hz reduction from the requirement for an unoccupied floor. Thus, it would seem that the researcher was able to tolerate a lower frequency on the occupied floors compared to the unoccupied floors. If frequency was determining the rating of the floor given by the researcher, then the same required fundamental frequency for an acceptable floor should have resulted for both the occupied and unoccupied floors. However, if deflection from the heel-drop impact was determining the rating of the floor, then the lower limit on fundamental frequency for the occupied floors is logical. The stiffness, and therefore the deflection due to a heel-drop impact, would be the same for both an occupied and unoccupied floor and so a floor rated as acceptable for the unoccupied state would be acceptable under occupancy loading, even though the fundamental frequency decreased due to the addition of live load mass.

The study of the monitored houses revealed that drywall significantly increases the stiffness and reduces the response of the floor. Thus, the performance of a bare floor is improved for the completed structure. Additional live load mass will also decrease the mean levels of response of the wood floor system due to a heel-drop impact. As a result, a wood floor that is designed for acceptability based on bare floor response will be acceptable for occupancy loading as well.

Of the 165 wood floor systems tested for the current study and that of Johnson, only 30 percent were rated as marginal or unacceptable. Therefore, the design methods which are being used at the present time are producing acceptable wood floor systems with respect to deflection from human footfalls approximately 70 percent time.

The 15 Hz criterion should provide a quick check during the design to eliminate a large majority of these marginal/unacceptable wood floor systems.

5.3 Design Example

A complete design guide on how to apply the 15 Hz criterion for floors utilizing solid sawn joists, parallel chord trusses and I joists is given by Johnson (1994). For this study, one of the marginal floors will be examined and redesigned to raise the fundamental frequency above 15 Hz. For simplicity, all design values are given in U.S. customary units.

The original design consisted of 22 in. deep parallel chord trusses spanning 25.75 ft. spaced 24 in. on center. The sheathing is 23/32 in. tongue and groove plywood. The lumber used for the top and bottom chords of the parallel chord truss is 2x4 in. Southern Pine No.1.

To calculate the bare floor fundamental frequency of this floor system, the total weight of the parallel chord truss and the weight of the plywood sheathing supported by the truss is needed along with the moment of inertia of the truss and the modulus of elasticity of the lumber of the top and bottom chords of the truss. A 22 in. deep parallel chord truss weighs approximately 7.3 plf and 23/32 in. plywood sheathing weighs approximately 2.2 psf. The modulus of elasticity taken from the NDS supplement for No. 1 Southern Pine is 1,700,000 psi.

A cross section of the parallel chord truss is show in Figure 5-2 and the calculations for determining the fundamental frequency of this floor system using the original design specifications are given below. Consistent units must be used in the equation for fundamental frequency. For this example, the units are pounds and inches.

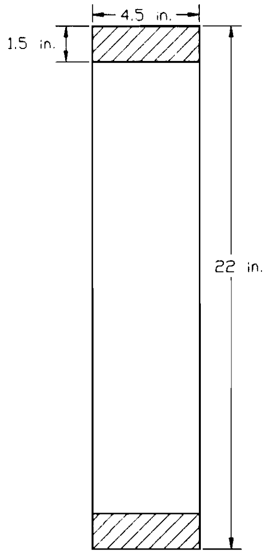


Figure 5-2 Cross Section of PCT of Design Example

Moment of Inertia of Parallel Chord Truss

$$I = 2 \times \left[\left(\frac{4.5 \times 1.5^3}{12} \right) + 5.25 \times \left(\frac{22 - 1.5}{2} \right)^2 \right]$$

$$I = 1106 \text{ in.}^4$$

Weight of Parallel Chord Truss

$$W_{PCT} = 7.30 \, \text{plf} \times 25.75 \, \text{ft}$$

$$W_{PCT} = 188 \, \text{lb}$$

Weight of Plywood Supported by Truss

$$W_{plywood} = 2.2 \, \text{psf} \times \frac{24 \, \text{in.}}{12 \, \text{in./ft}} \times 25.75 \, \text{ft}$$

$$W_{plywood} = 113.3 \text{ lb}$$

Total Weight

$$W_{total} = 188\,\text{lb} + 113.3\,\text{lb}$$

$$W_{total} = 301.3\,\text{lb}$$

Length of Parallel Chord Truss

$$L_{PCT} = 25.75\,\text{ft} \times 12\,\text{in.}$$

$$L_{PCT} = 309\,\text{in.}$$

Fundamental Frequency of Parallel Chord Truss

Using Equation 1.18

$$f_{PCT} = 1.57 \times \sqrt{\frac{386.4 \times E \times I_{PCT}}{W_{total} \times L_{PCT}{}^{3}}}$$

$$f_{PCT} = 1.57 \times \sqrt{\frac{386.4 \times 1700000 \times 1106}{301.3 \times 309^{3}}}$$

$$f_{PCT} = 14.2\ \text{Hz} < 15\,\text{Hz}$$

The floor is rated as Marginal for the original design.

To raise the fundamental frequency of this floor system above 15 Hz, a possible solution is to change the truss spacing from 24 in on center to 16 in. on center. The fundamental frequency of the floor system is calculated below for a truss spacing of 16 in. on center.

Weight of Plywood

$$W_{plywood} = 2.2\,\text{psf} \times \frac{16\,\text{in.}}{12\,\text{in./ft}} \times 25.75\,\text{ft}$$

$$W_{plywood} = 75.5\,\text{lb}$$

Total Weight

$$W_{total} = 188\,lb + 75.5\,lb$$

$$W_{total} = 263.5\,lb$$

Fundamental Frequency of Parallel Chord Truss

$$f_{PCT} = 1.57\sqrt{\frac{386.4 \times 1700000 \times 1106}{263.5 \times 309^3}}$$

$$f_{PCT} = 15.2\ Hz > 15\ Hz$$

Thus, reducing the truss spacing from 24 in. on center to 16 in. on center raised the fundamental frequency above 15 Hz. The floor system should now be acceptable with regard to deflection from footfall impacts.

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APPENDIX A

SUMMARY OF TEST FLOORS

Table A-1 Summary of Occupied Floors

	Floor	Sheathing	Joist (in.)	Spacing o.c. (in.)	Wood Species and Grade	Span (ft)	Girder (in.)	Wood Species and Grade	Span (ft)	Frequency			Relative Power from Power Spectrum	Peak Accel (in/s^2)	Rating
										Bare Floor	Occupied				
										(Hz) Predicted	(Hz) Measured	(Hz) Predicted	MAG^2		
1	West 1	23/32" T&G	2x8	16.0	SP No.2	11.2	3-2x10	SP No.2	8.0	18.0	17.0	16.8	3053	182	A
2	West 2	23/32" T&G	2x8	16.0	SP No.2	11.2	3-2x10	SP No.2	8.0	18.0	16.5	16.8	2654	177	A
3	Anne 1	23/32" T&G	2x10	16.0	SPF No.2	13.0	na	na	na	21.6	18.5	19.3	9617	320	A
4	Anne 2	23/32" T&G	2x10	16.0	SPF No.2	12.5	na	na	na	22.9	15.5	15.0	2504	237	A
5	Anne 3	23/32" T&G	2x10	16.0	SPF No.2	15.0	2-1 3/4"x11 1/4"	Gang Lam LVL 2.0 E	15.0	11.6	10.3	9.5	14671	243	M
6	Anne 4	23/32" T&G	2x10	16.0	SPF No.2	15.0	na	na	na	16.2	14.0	14.5	5480	267	A
7	Anne 5	23/32" T&G	2x10	16.0	SPF No.2	14.0	na	na	na	18.6	16.3	15.5	2634	196	A
8	Rollie 1	23/32" T&G	2x10	16.0	?	9.0	Steel Beam	?	18.0	CNC	24.8	CNC	1862	194	A
9	Rollie 2	23/32" T&G	2x10	16.0	?	15.3	Steel Beam	?	?	CNC	14.3	CNC	6048	178	M
10	T.T. #1	23/32" T&G	18" PCT	24.0	SP No.1 T&B Chords	22.5	na	na	na	16.0	14.0	13.7	85843	315	A
11	T.T. #2	23/32" T&G	20" PCT	24.0	SP No.1 T&B Chords	24.0	na	na	na	14.9	13.5	12.8	52589	299	A
12	T.T. #3	23/32" T&G	16" PCT	24.0	SP No.1 T&B Chords	14.0	na	na	na	36.6	22.5	28.6	6554	373	A
13	T.T. #4	23/32" T&G	16" PCT	24.0	SP No.1 T&B Chords	20.0	na	na	na	17.9	14.3	14.0	883	256	A
14	T.T. #5	23/32" T&G	20" PCT	19.2	SP No.1 T&B Chords	24.0	na	na	na	15.5	17.5	12.2	8977	314	A
15	T.T. #6	23/32" T&G	20" PCT	19.2	SP No.1 T&B Chords	28.0	na	na	na	11.4	9.8	8.9	5077	154	U
16	T.T. #7	23/32" T&G	20" PCT	19.2	SP No.1 T&B Chords	30.0	na	na	na	9.9	11.8	8.7	15353	314	U
17	T.T. #8	23/32" T&G	20" PCT	16.0	SP No.1 T&B Chords	28.0	na	na	na	11.7	11.5	10.4	4091	281	M
18	AJ	23/32" T&G	2x10	14.0	SPF No.2 (Assumed)	11.0	na	na	na	31.0	17.3	20.9	2250	197	A
19	Lofer 1	23/32" T&G	2x10	16.0	SPF No.2	14.0	na	na	na	18.6	16.0	14.5	128303	302	A
20	Lofer 2	23/32" T&G	2x10	16.0	SPF No.2	14.0	na	na	na	36.5	16.0	14.5	60359	297	A
21	Lofer 3	23/32" T&G	2x10	16.0	SPF No.2	10.0	na	na	na	18.6	28.0	28.4	16047	194	A
22	Garst 1	3/4"x6" Strip Subfloor	2x8	16.0	SP No.1 (Assumed)	14.0	na	na	na	13.3	13.3	12.2	17387	268	M
23	Garst 2	23/32" T&G	2x8	16.0	SP No.1	12.0	na	na	na	19.3	15.0	14.1	16249	295	A
24	Garst 3	1"x8" Strip Subfloor	2x10	16.0	SP No.1	13.0	na	na	na	19.1	15.8	15.1	4584	296	A
25	Murray	23/32" T&G	2x12	12.0	?	18.0	Steel Beam	?	?	CNC	16.0	CNC	40000	300	A
26	Davids 1	23/32" T&G	2x10	16.0	SP No.2 (Assumed)	14.0	na	na	na	19.2	16.0	16.2	11085	194	A
27	Davids 2	23/32" T&G	2x10	16.0	SP No.2 (Assumed)	14.0	na	na	na	19.2	16.0	16.2	15867	195	A
28	Araman 1	23/32" T&G	2x10	16.0	SPF No.2	13.0	3 - 2x10	SPF No.2	8.0	17.4	14.0	13.7	9527	195	M
29	Araman 2	23/32" T&G	2x10	16.0	SPF No.2	11.0	na	na	na	30.2	14.8	23.5	5540	193	A
30	Araman 3	23/32" T&G	2x10	16.0	SPF No.2	13.0	3 - 2x10	SPF No.2	8.0	17.4	13.4	13.7	1306	194	M
31	K 1	23/32" T&G	2x10	16.0	SPF No.2 (Assumed)	14.0	na	na	na	18.6	15.5	15.2	55524	311	A
32	K 1	23/32" T&G	2x10	16.0	SPF No.2 (Assumed)	14.5	na	na	na	17.4	17.5	14.2	73695	308	A
33	K 1	23/32" T&G	2x10	16.0	SPF No.2 (Assumed)	14.5	na	na	na	17.4	19.0	14.2	6100	199	A
34	JOEM 1*	23/32" T&G	2x10	16.0	SPF No.2	12.0	na	na	na	25.4	17.3	21.0	16495	196	A
35	JOEM 2*	23/32" T&G	2x10	16.0	SPF No.2	16.0	na	na	na	14.4	15.0	11.8	6552	194	A
36	JOEM 3*	23/32" T&G	2x10	16.0	SPF No.2	14.0	na	na	na	18.7	19.5	15.4	2358	177	A
37	JOEM 5*	23/32" T&G	2x10	16.0	SPF No.2	12.5	na	na	na	23.4	19.3	19.4	3419	104	A
38	JOEM 6*	23/32" T&G	2x10	16.0	SPF No.2	12.5	na	na	na	23.4	7.0	12.8	11670	194	A
39	Dowling 1*	15/32" T&G	2x10	16.0	SPF No.2	15.0	na	na	na	18.1	16.5	14.5	29165	203	A
40	Dowling 2*	15/32" T&G	2x10	16.0	SPF No.2	13.0	na	na	na	24.1	16.5	19.2	49557	281	A
41	Yancey 1*	23/32" T&G	2x10	16.0	SPF No.2	14.0	na	na	na	18.7	17.8	15.4	5023	195	A
42	Yancey 2*	23/32" T&G	2x10	16.0	SPF No.2	14.0	na	na	na	18.7	16.5	15.4	1207	168	A
43	Johnson 2*	23/32" T&G	2x10	16.0	SPF No.2	13.5	na	na	na	20.1	13.0	14.4	27344	307	A
44	Johnson 1*	23/32" T&G	2x10	16.0	SPF No.2	13.5	na	na	na	20.1	15.5	14.4	8897	224	A
45	Johnson 5*	23/32" T&G	2x10	16.0	SPF No.2	12.5	na	na	na	23.4	17.5	19.4	16380	274	A
46	Johnson 6*	23/32" T&G	2x10	16.0	SPF No.2	13.0	2-3 1/2"x16 3/4"	Tec Lam LVL	na	14.3	12.5	13.0	19484	268	A
47	Johnson 9*	23/32" T&G	2x10	16.0	SPF No.2	11.0	na	na	na	30.3	20.0	21.8	17396	303	A
48	Johnson 8*	23/32" T&G	2x10	16.0	SPF No.2	12.0	na	na	na	25.4	21.5	18.3	8919	211	A
49	Simp 2*	23/32" T&G	2x10	16.0	SPF No.2	13.0	na	na	na	21.7	16.5	17.9	4773	321	A
50	Simp 1*	23/32" T&G	2x10	12.0	SPF No.2	15.0	na	na	na	17.4	15.3	14.7	2931	315	A
51	Simp 3*	23/32" T&G	2x10	12.0	SPF No.2	15.0	na	na	na	17.4	15.0	14.7	3252	165	A
52	Simp ROG	23/32" T&G	20" PCT	16.0	SP No.1 T&B Chords	24.0	na	na	na	16.0	12.0	14.2	2645	298	A
53	Terrace View 1	23/32" T&G	2x8	16.0	SP No.1	12.0	na	na	na	19.3	13.5	14.8	129677	318	A
54	Terrace View 2	23/32" T&G	2x8	16.0	SP No.1	12.0	na	na	na	19.3	13.0	14.8	129500	300	A

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Table A-1 Cont.

	Floor	Sheathing	Joist (in.)	Spacing o.c. (in.)	Wood Species and Grade	Span (ft)	Girder (in.)	Wood Species and Grade	Span (ft)	Frequency			Relative Power from Power Spectrum	Peak Accel (in/s^2)	Rating
										Bare Floor	Occupied				
										(Hz) Predicted	(Hz) Measured	(Hz) Predicted	MAG^2		
55	Pete	23/32" T&G	2x10	16.0	?	14.0	na	na	na	CNC	12.5	CNC	8476	194	U
56	Mark 1	23/32" T&G	2x10	16.0	SPF No.2	13.0	3-2x8	SPF No.2	8.0	15.0	13.5	12.5	40770	195	M
57	Mark 2	23/32" T&G	2x10	16.0	SPF No.2	13.0	3-2x8	SPF No.2	8.0	15.0	14	12.5	28421	154	M
58	Badger	23/32" T&G	2x10	16.0	SP No.2	14.0	3-2x10	SP No.2	11.0	12.2	14	13.8	463	42	M

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Table A-2 Summary of Unoccupied Floors (Bare Floor)

	Floor	Sheathing	Joist	Spacing o.c. (in.)	Wood Species and Grade	Span (ft)	Girder	Wood Species and Grade	Span (ft)	Frequency Unoccupied (Bare Floor) (Hz) Measured	Frequency Unoccupied (Bare Floor) (Hz) Predicted	Relative Power from Power Spectrum (MAG²)	Peak Accel. (in/s²)	Rating
59	Col Park 1	23/32" T&G	2x10	16.0	SP No.1	13.0	na	na	na	25.0	22.5	2666	330	A
60	Col Park 2	23/32" T&G	24" PCT	16.0	SP No.1 T&B Chords	28.5	na	na	na	12.5	13.4	8553	126	A
61	Col Park 3	23/32" T&G	24" PCT	28.5	SP No.1 T&B Chords	26.5	na	na	na	17.5	15.4	2207	190	A
62	Clemons 1	23/32" T&G	2x10	12.0	SPF No.2	15.0	3-1 3/4"x 11 7/8"	2.0 E LVL	13.0	17.0	15.2	43231	280	A
63	Clemons 2	23/32" T&G	2x10	16.0	SPF No.2	11.8	3-1 3/4"x 11 7/8"	2.0 E LVL	13.0	11.0	15.5	9638.5	184	A
64	Clemons 3	23/32" T&G	2x10	16.0	SPF No.2	11.8	3-1 3/4"x 11 7/8"	2.0 E LVL	10.0	20.5	19.3	145694	310	A
65	Clemons 4	23/32" T&G	2x10	12.0	SPF No.2	15.0	3-1 3/4"x 11 7/8"	2.0 E LVL	10.0	17.0	15.0	2235.7	115	A
66	Wyatt 1	23/32" T&G	2x10	16.0	SPF No.2	13.0	3-2x12	SPF No.2	9.0	17.0	15.8	0.42	365	A
67	Wyatt 2	23/32" T&G	2x10	16.0	SPF No.2	13.0	3-2x12	SPF No.2	9.0	16.5	15.8	22247.7	306	A
68	Wyatt 3	23/32" T&G	2x10	16.0	SPF No.2	13.0	3-2x12	SPF No.2	9.0	16.8	15.8	20882.7	303	A
69	Wyatt 4	23/32" T&G	2x10	16.0	SPF No.2	13.0	3-2x12	SPF No.2	12.5	14.3	13.0	8434.6	320	M
70	Wyatt 5	23/32" T&G	2x10	12.0	SPF No.2	16.0	3-2x12	SPF No.2	12.5	14.3	13.0	31598.9	282	M
71	Karr 1	23/32" T&G	2x10	16.0	SPF No.2	14.0	na	na	na	22.8	21.6	19177.9	356	A
72	Karr 2	23/32" T&G	2x10	16.0	SPF No.2	13.0	na	na	na	15.0	18.6	18853.2	365	A
73	2x12 1	23/32" T&G	2x12	24.0	SPF No.2	12.0	3-2x12	SPF No.2	7.5	24.8	20.5	9123.8	348	A
74	2x12 2	23/32" T&G	2x12	16.0	SPF No.2	15.8	3-2x12	SPF No.2	6.0	18.2	18.7	26298	332	A
75	2x12 3	23/32" T&G	2x12	16.0	SPF No.2	15.8	na	na	na	17.3	18.7	14129	331	A
76	2x12 4	23/32" T&G	2x12	16.0	SPF No.2	15.5	3-2x12	SPF No.2	8.8	17.5	17.4	10830	338	A
77	2x12 5	23/32" T&G	2x12	16.0	SPF No.2	15.5	3-2x12	SPF No.2	6.0	19.0	18.7	19651	279	A
78	2x12 6	23/32" T&G	2x12	24.0	SPF No.2	12.0	3-2x12	SPF No.2	7.5	23.5	23.8	8410	378	A
79	2x12 7	23/32" T&G	2x10	16.0	SPF No.2	15.8	na	na	na	15.0	14.7	17000	318	M
80	2x12 8	23/32" T&G	2x10	16.0	SPF No.2	15.5	na	na	na	15.5	15.2	30945	286	A
81	PR 1	23/32" T&G	14" PCT	24.0	SP No.1	20.0	na	na	na	13.0	13.8	20933	371	M
82	PR 2	23/32" T&G	14" PCT	24.0	SP No.1	16.5	na	na	na	18.3	20.3	23077	313	A
83	PR 3	23/32" T&G	14" PCT	24.0	SP No.1	20.0	na	na	na	13.3	13.8	40685	283	U
84	PR 4	23/32" T&G	14" PCT	24.0	SP No.1	20.0	na	na	na	14.5	13.8	22215	282	M
85	PR 5	23/32" T&G	14" PCT	24.0	SP No.1	20.0	na	na	na	14.0	13.8	20215	282	M
86	TJI 1	23/32" T&G	11 7/8" I Joist	24.0	GNI 26 Series	15.0	3-1 3/4x14	Gang Lam LVL 2.0 E	19.0	12.3	11.3	16689	299	M
87	TJI 2	23/32" T&G	11 7/8" I Joist	24.0	GNI 26 Series	10.3	3-1 3/4x14	Gang Lam LVL 2.0 E	19.0	12.0	12.3	3119	295	A
88	Powell 1	23/32" OSB T&G	18" PCT	24.0	SP No.1 T&B Chords	23.0	na	na	na	14.3	14.6	6500	254	A
89	Powell 2	23/32" OSB T&G	18" PCT	24.0	SP No.1 T&B Chords	23.0	3-2x10's	SP No.1	9.8	12.3	12.3	11946	344	M
90	Simp2 1	23/32" T&G	2x10	16.0	SPF No.2	14.0	2-1 3/4x16	MicroLam LVL 2.0 E	16.5	15.5	14.9	8000	330	M
91	Simp2 2	23/32" T&G	2x10	16.0	SPF No.2	11.0	2-1 3/4x16	MicroLam LVL 2.0 E	16.6	15.3	14.9	13000	330	M
92	Simp2 3	23/32" T&G	2x10	12.0	SPF No.2	16.0	na	na	na	17.0	15.3	14000	200	A
93	Simp2 4	23/32" T&G	2x10	16.0	SPF No.2	13.0	na	na	na	22.3	21.6	18000	300	A
94	Snyder 1	23/32" T&G	22" PCT	24.0	SP No.1 T&B Chords	25.8	na	na	na	14.5	14.2	92230	303	M
95	Snyder 2	23/32" T&G	22" PCT	24.0	SP No.1 T&B Chords	31.0	na	na	na	10.5	10.5	28530	225	M
96	Snyder 3	23/32" T&G	22" PCT	16.0	SP No.1 T&B Chords	31.0	na	na	na	12.0	10.5	70950	257	M
97	Snyder 4	23/32" T&G	22" PCT	16.0	SP No.1 T&B Chords	31.0	na	na	na	10.5	10.5	114800	229	M
98	Snyder 5	23/32" T&G	22" PCT	16.0	SP No.1 T&B Chords	31.0	na	na	na	11.5	10.5	41140	254	M
99	Jones/Wyatt	23/32" T&G	2x10	16.0	SPF No.2	16.0	na	na	na	11.5	14.3	31306	270	M
100	Fall Wall	23/32" T&G	24" PCT	16.0	SP No.1 T&B Chords	29.0	na	na	na	12.6	13.4	78128.6	285	M
101	Kline 5	23/32" T&G	2x12	16.0	SPF No.1	12.0	W 16x31	E=29,000 KSI (Assumed)	25.0	10.5	12.2	16912.3	194	U
102	Kline 6	23/32 T&G	2x12	16.0	SPF No.1	12.0	W 16x31	E=29,000 KSI (Assumed)	25.0	10.5	12.2	50954.8	195	U
103	Kline 2	23/32 T&G	18" PCT	16.0	SP No.1 T&B Chords	?	na	na	na	30.5	CNC	17646.2	195	A
104	Kline 3	23/32 T&G	18" PCT	16.0	SP No.1 T&B Chords	?	na	na	na	27.0	CNC	19196.6	195	A
105	Kline 4	23/32 T&G	18" PCT	16.0	SP No.1 T&B Chords	?	na	na	na	33.5	CNC	7037.6	194	A
106	Kline 10	23/32 T&G	18" PCT	16.0	SP No.1 T&B Chords	?	na	na	na	42.0	CNC	9004.3	193	A

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VITA

Bruce C. Shue was born on October 15, 1970, in Hagerstown, Maryland. He graduated from South Hagerstown High School in June, 1989. In December, 1993, he received his Bachelor of Science degree in Civil Engineering, magna cum laude, from Virginia Tech. He was awarded the Charles Via Scholarship in December, 1993, and entered the graduate program in the Structures Division of the Civil Engineering Department at Virginia Tech. He received a Master of Science degree in Civil Engineering in July, 1995.

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