CHAPTER I
INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Economic factors help drive the development of more reliable and lighter materials in the design of longer span floor systems. Steel joist supported wood floor systems have a longer span and a lighter weight when compared to timber supported wood floor systems making them a very competitive floor system. Although these lighter and longer span floor systems may be able to withstand anticipated loading conditions, they may also create vibration problems that might render the floor system unusable for its intended purpose.

Vibration problems in floor systems have long been a serviceability concern of engineers (Murray 1991). Although these floor vibrations are no threat to the structural integrity of the floor system, they can be so uncomfortable to the occupants that the floor system may be rendered useless. Since the amplitude required to annoy occupants and the frequency range of most floor systems are both small, it is usually difficult to correct the problem after construction.

Although there are many different methods to correct annoying floor systems, they are usually expensive and inconvenient to the occupant. The best time to consider vibration acceptability is during the design process. There have been several design procedures established worldwide that address the serviceability of very lightweight floor systems. This study uses these design procedures to determine if the floor systems tested are acceptable and compares the results to actual floor conditions.

1.2 Scope of Research

Steel joist supported wood floor systems have several advantages over traditional wood joist floor systems. Steel is a homogeneous material that is much stronger and can produce lighter floor systems than wood joist supported floor systems. Steel joist supported wood floor systems can also span much farther lengths than wood joist systems. This study investigates the serviceability of steel joist supported wood floor systems using previously established design criteria and compares the performance of the tested floor systems to these criteria.

1.3 Terminology

Since many lightweight floor system design codes require the structural engineer to check vibration response of floor systems, it is important that the terms used are understood by all. The following terms are presented with a brief description of each.

Amplitude. When an elastic system is subjected to an excitation, either an exterior force or impulse force, it will tend to oscillate about the original equilibrium position. One can trace a

variation -- displacement, velocity, or acceleration -- that any point in the system undergoes during a finite time. Measuring the absolute height the point moves from equilibrium on any of the three traces is called the amplitude as shown in Figure 1.1. Engineers are generally interested in only the maximum height the point moves from equilibrium, which is called the maximum amplitude. For the remainder of this thesis, the maximum amplitude will be specified simply as amplitude.

Frequency. The time it takes each point in question to make a complete oscillation is called a cycle of motion or period (T) which is reported in seconds. For floor vibrations, it is convenient to not describe the number of seconds in a cycle, but the number of cycles in a second (s). Frequency (f) is the number of cycles a point undergoes within a second, which is 1/s or Hertz (Hz). Frequency is inversely related to period as shown in Equation 1.1.
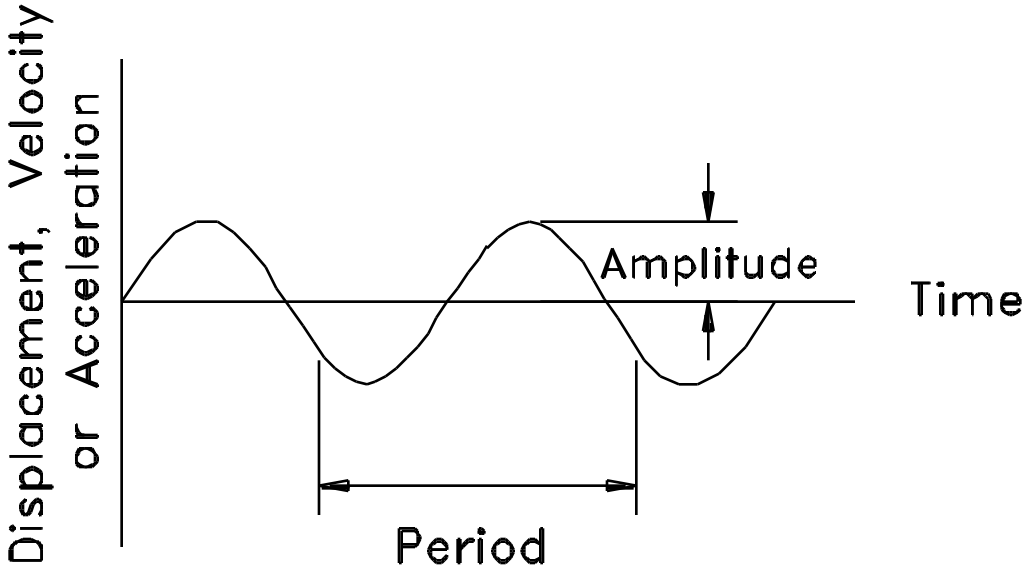
$$f = \frac{1}{T} \qquad (Hz) \tag{1.1}$$

Figure 1.1 Typical Variation Trace

Dynamic Loading. An external force applied to a system that varies with time is defined as a dynamic load. These can be categorized into four different types: harmonic, repetitive, transient, or impulse as shown in Figure 1.2. Harmonic dynamic loading is usually caused by an unbalanced rotating machine that can repeat the same force at a consistent time interval. Transient dynamic loading is a force applied at random to a system. They are usually associated with wind loads but can also be associated with the movement of people (Murray, et al 1997). An

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impulse load is a single dynamic load or force that is applied in a relatively short period of time. Repetitive dynamic loadings are impulse loads applied frequently to the system, such as human movement (walking, running, dancing, etc.). Repetitive forces are more of a concern in lightweight floor systems since they tend to be more annoying to people.
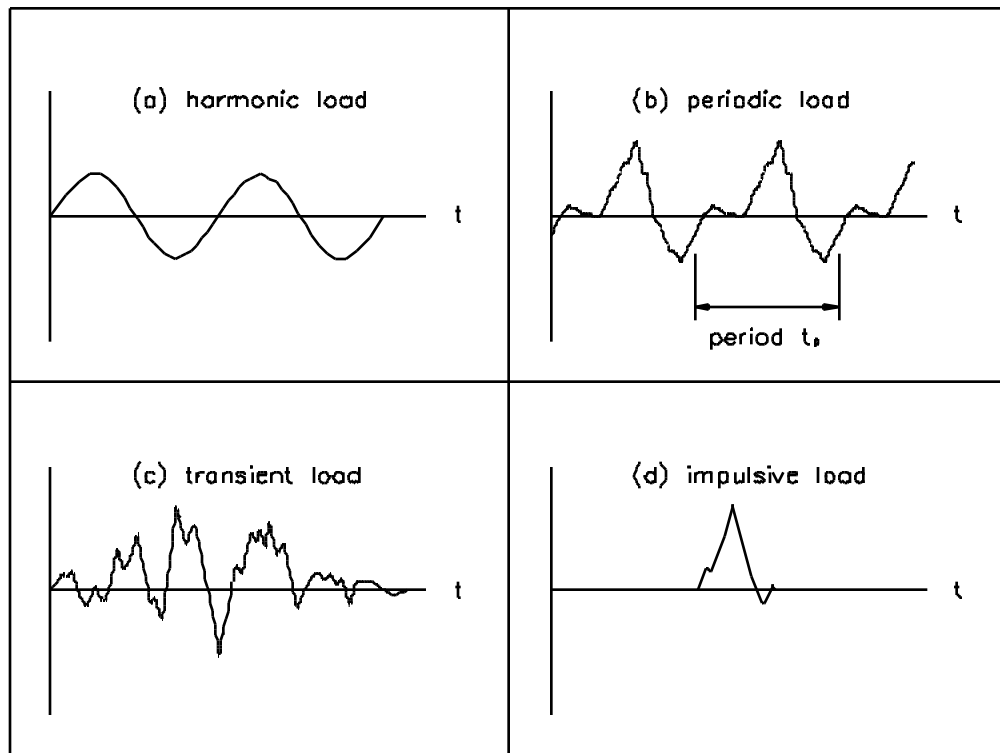

Figure 1.2 Types of Dynamic Loading (After Murray, et al 1997)

Damping. Damping is simply the rate of decay of the amplitude.   The system is considered to be in a state of undamped vibration if the amplitude remains constant indefinitely. If the system's amplitude returns to equilibrium within a finite time, the system is considered to have undergone damped vibration.

Damping is the phenomenon associated with the energy dissipated in a system caused by internal friction (hysteresis phenomenon), external friction (Coulomb damping), or fluid friction (Viscous damping). Viscous damping is generally assumed to be the only damping involved in floor vibrations since it is mathematically easier to model and the results generally coincide with the experimental results (Clough 1993).
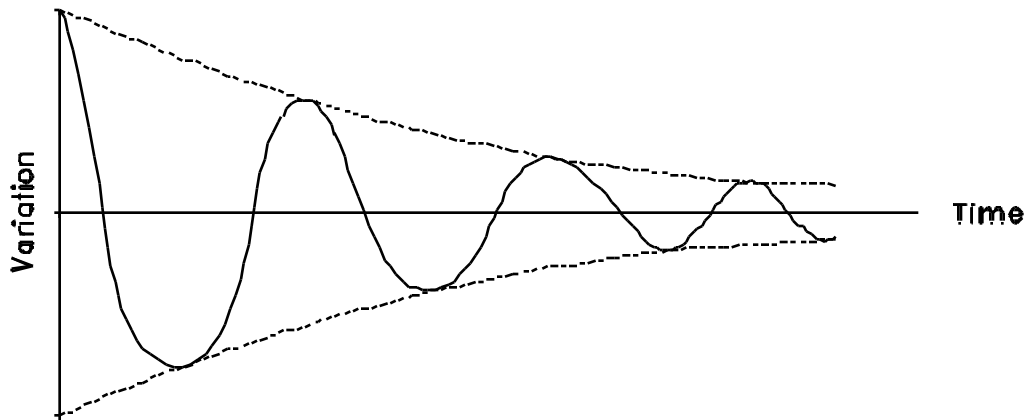
Figure 1.3. Effect of Damping to a Variation

Resonance. Resonance is when a dynamic load applied to a floor system causes the system to vibrate at or near the same frequency as the fundamental frequency. This causes the floor system to undergo large amplitudes which can be dangerous and should be avoided.

One should note that people are more sensitive to frequencies between 5 and 8 Hz since most major organs of the human body have a natural frequency in this range. This is why floors with a fundamental frequency in this range must be designed with care as to not be annoying to the human occupants.

1.4 Literature Review

1.4.1 Scope of Review
This literature review will discuss the existing criteria used to evaluate lightweight floor systems and methods to predict the response of a floor system to walking excitation.

1.4.2 Current Acceptability Criteria

1.4.2.1 Ohlsson's Criterion
Ohlsson performed more than ten years of research on lightweight floor systems (Ohlsson 1988a) and developed a design guide for the Swedish Council for Building Research (Ohlsson 1988b). Although he performed most of his research on timber floor systems, the design criterion is presented for use with any construction material and structural configuration. The design procedure is broken into three distinct parts.

The first part is a static load test. Floor systems must undergo no more than 1.5mm (0.059 in.) deflection when subjected to a 1kN (225 lb.) concentrated load located at the midspan of the floor system. Deflection of a simply supported joist is then given by:

$$\Delta = \frac{PL^3}{48E_j I_j} \quad (m) \tag{1.2}$$

where

Δ	=	Vertical Deflection at the Midspan of the floor Joist (m)
P	=	Concentrated Point Load at midspan (N)
L	=	Span of the floor joist (m)
E_j	=	Modulus of Elasticity of Joist (Pa)
I_j	=	Moment of Inertia of Joist (m^4)

Ohlsson's next criterion states all floor systems must have a fundamental frequency greater than 8 Hz. This is to ensure that the velocities produced by impulse and continuous dynamic loads are within an acceptable limit. To predict the fundamental frequency of a floor system, he suggests the following formula for a rectangular orthotropic plate:

$$f_n = \frac{\pi}{2}\sqrt{\frac{D_x}{gL^4}}\sqrt{1 + 2n^2 \left(\frac{L}{B}\right)^2 + n^4 \left(\frac{L}{B}\right)^4 \frac{D_x}{D_y}} \quad (Hz) \tag{1.3}$$

where

D_x	=	Deck Stiffness Parallel to the Joists (X - Direction) (Nm^2/m)
	=	$\dfrac{E_j I_j}{s}$ (N-m) (1.4)
s	=	Joist Spacing (m)
D_y	=	Deck Stiffness Perpendicular to the Joists (Y - Direction) (Nm^2/m)
	=	$\dfrac{E_f t_f^{\,3}}{12}$ (N-m) (1.5)
E_f	=	Modulus of Elasticity of the Decking (Pa)
t_f	=	Thickness of the Decking (m)
B	=	Width of the Floor Perpendicular to the Joists (m)
m	=	Unit Mass of the Floor System (Kg/m^2)
n	=	Modal Number (1 for Fundamental Frequency)

If the fundamental frequency is desired of a floor system that has a D_y/D_x ratio less than 0.01, the frequency equation can be reduced to:

$$f_1 = \frac{\pi}{2} \sqrt{\frac{D_x}{mL^4}} \quad \text{(Hz)} \tag{1.6}$$

which is the same as the frequency equation for a simple beam with uniformly distributed mass derived in most elementary vibration textbooks.

If the fundamental frequency is above 8 Hz, then the floor system must be checked for vibrations caused by a dynamic impulse loading. Impulse velocity response is the initial vertical vibration velocity caused by an idealized vertical impulse as shown in Figure 1.4. Ohlsson greatly simplified the impulse velocity resonance equation to:

$$h'_{max} = \frac{4(04 + 0.6N_{40})}{mBL} \quad \text{(m/s/Ns)} \tag{1.7}$$

where

h'_{max} = Impulse Velocity Response (m/s/Ns)

N_{40} = Number of Frequency Modes less than 40 Hz

Realizing the weight of the human body is damping the system, Ohlsson added 50 Kg (110 lb.) to simulate the weight of the non-vibrating mass of the person (1988b). His final approximation of h'_{max} is:

$$h'_{max} = \frac{4(04 + 0.6N_{40})}{mBL + 200} \quad \text{(m/s/Ns)} \tag{1.8}$$

Ohlsson plotted modal number versus the standard resonant frequency for different values of D_x/D_y and L/B. The standard resonant frequency is a frequency normalized to N_{40} ($40/f_1$).
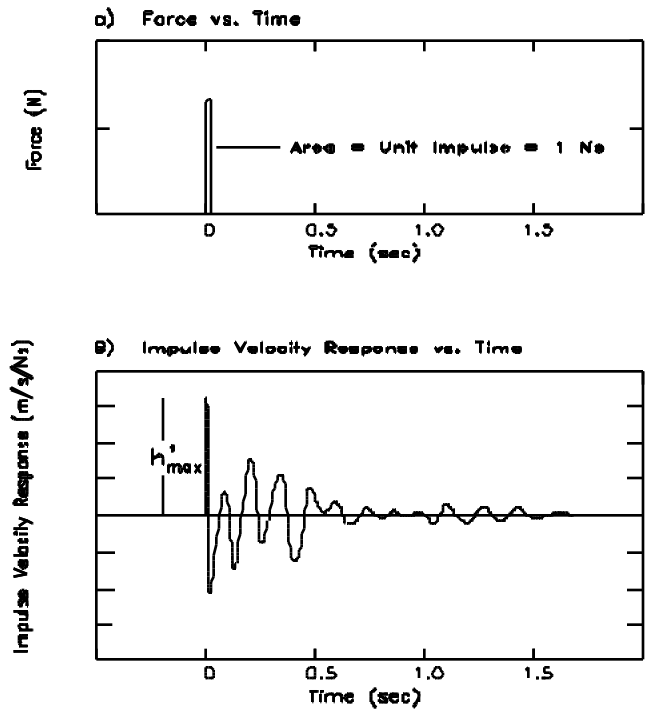
Figure 1.4 Idealized Impulse and Resulting Vibration Velocity for a Typical Floor (After Ohlsson 1988b)

The damping coefficient relates how rapidly harmonic vibration decays in time and is found by multiplying the fundamental frequency calculated in Equation 1.3 by the relative modal damping:

$$\sigma_o = \zeta f_1 \quad \text{(Hz)} \tag{1.9}$$

Relative damping is a value that should be taken to be 1 per cent for traditional floor construction, but a smaller value should be used for large spans or where there will be few partitions. Ohlsson (1988b) also recommended that ζ should be as low as 0.8 per cent for floor systems with a mass greater than 150 Kg/m^3 (9.4 lb/ft^3).
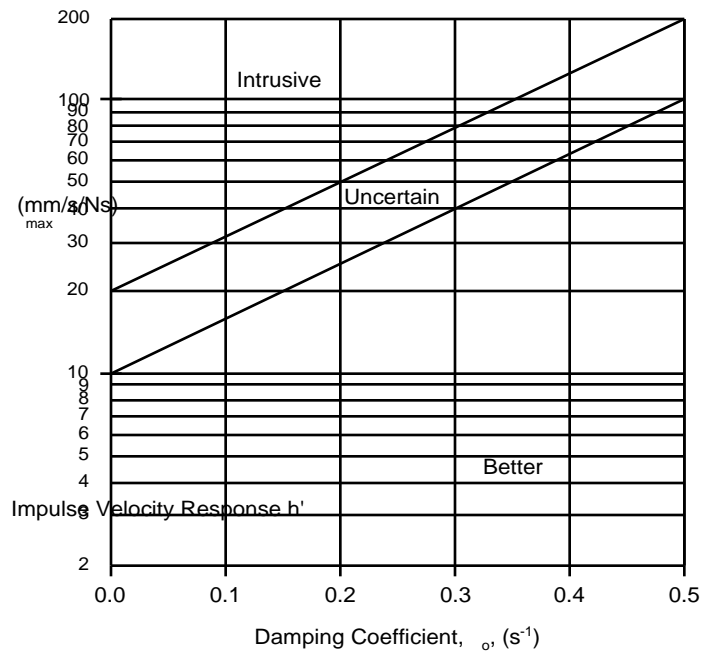
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Figure 1.5 Preliminary Proposal for the Classification of the Response of a Floor System to an Impact Load (After Ohlsson 1988b)

Impulsive velocity response is plotted against the damping coefficient as shown in Figure 1.5 to determine the acceptability of the floor system. If a floor system is located in the intrusive or uncertain regions, it should be redesigned. Ohlsson points out that *in situ* floors have given a very large scatter for damping and one may have to guess the relative damping coefficient (1988a).

Floor systems that fall within the "better" range on Figure 1.5 must go through a third and final design phase. If the floor system contains unobstructed room lengths less than 6-7 m (20-23 ft) or has a span length greater than 4 m (13 ft), then a response to a continuous loading must be performed. Ohlsson found, as other researchers, that annoying vibrations could be eliminated by limiting the root mean square (RMS) of the vertical vibration velocity, w'$_{RMS}$. This is found by a person walking continuously over a long period of time and is calculated as:

$$w'_{RMS} = \frac{100}{mBL\sqrt{\xi}} \sqrt{\frac{N_{1.2}^{2}+1}{2f_1^{3}}} \qquad [(m/s)_{RMS}] \tag{1.10}$$

where $N_{1.2}$ is the number of normal modes with a resonant frequency less than $1.2f_1$. $N_{1.2}$ can be obtained from the same charts as N_{40}.

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There was no limiting w'$_{RMS}$ value suggested in this design guide. It is recommended to compare the calculated value to previous floor systems with acceptable vibration levels. Ohlsson (1988a) warns the designer that many of these values used in this criterion are "guessed" and one should be "humble when discussing different proposed vibrational design criteria."

1.4.2.2 Australian Criterion

The *Australian Standard Domestic Metal Framing Code* (1993) analyzes the serviceability of cold formed steel joist floor systems. Since this criterion adopted much of Ohlsson's guidelines, the two criteria are very similar. For a floor system to be considered acceptable, it must first have a fundamental frequency above 8 Hz which is found by Equation 1.3 with n = 1 and w = dead load plus an additional 0.3 kN/m^2 (6.27 psf) live load. There are only two other conditions that must be satisfied for a floor to be considered dynamically acceptable.

The first is a static deflection test which requires that the floor deflect no more than 2mm (0.0787 in.) for a 1kN (225 lb.) concentrated load placed anywhere on the floor. Equation 1.11 is used to obtain the midspan deflection of the floor system. The single joist deflection factor, k_d, is used to account for more than one joist supporting the 1 kN concentrated load:

$$= \frac{k_d P L^3}{48 E_j I_j} \quad \text{(m)} \tag{1.11}$$

where

$$k_d = 0883 - 034 Log_{10} \left(\frac{k_c}{k_b}\right) + 044 \quad \text{or from Figure 1.6} \tag{1.12}$$

$$k_c = \frac{E_f t_f^3 L}{12 s^3} \quad \text{(N/m)} \quad \text{(for joist only systems)} \tag{1.13}$$

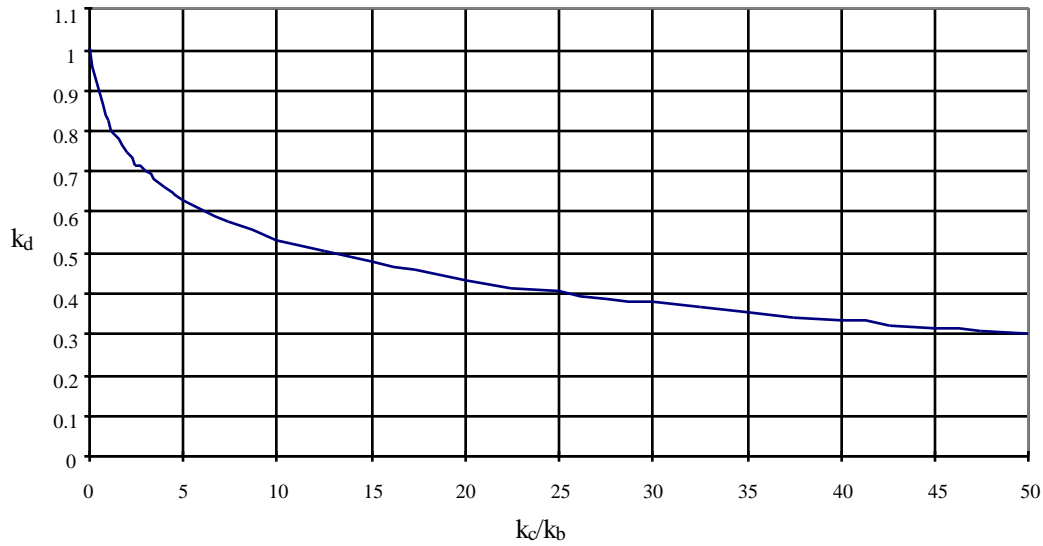$$k_b = \frac{E_j I_j}{L^3} \quad \text{(N/m)} \tag{1.14}$$

Figure 1.6 Deflection Factor, k_d

The second requirement is based on the application of an unit impulse load of 1.0 N-s (0.225 lb-s) located anywhere on the floor system. The maximum impact velocity, V_{max}, is:

$$V_{max} = \frac{4\left(0.4 + 0.6\,N_{40}\right)}{mBL + 200} \quad \text{(m/s/Ns)} \tag{1.15}$$

but must be less than:

$$Log_{10}(V_{max}) = 1.2 + 2\,\xi_o \tag{1.16}$$

for the floor to be acceptable where

w	=	Mass of the Floor Including the Live Load Mass (kg/m^2)
ξ_o	=	f_1
f_1	=	Fundamental Frequency of the Floor System
ξ	=	Modal Damping Ratio

$$N_{40} = \frac{B}{L}\sqrt{\sqrt{\frac{r + f^2 - 1}{r}} - 1} \tag{1.17}$$

r	=	Ratio of Floor Stiffness in Two Directions ($= K_y/K_x$)
f	=	Frequency Ratio ($= 40/f_1$)
L	=	Span Length (m)
B	=	Width of Floor (m)

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Although the specification states that the static load test will generally govern for short spans and impact velocity will control for long spans, it does not distinguish between the two span lengths.

1.4.2.3 Canadian Criterion

Onysko (1985) designed a criterion based on the results of an extensive survey and testing program that included the assessment of 646 wood floors of different types in the 1970's. The occupants were provided with a well planned questionnaire about   their   perception of the behavior of the floors in their home and then vibration measurements were taken of each floor.

It was found that the best correlation to perceived acceptability was dynamic response due to an impact load and floor deflection due to a static load test. He initially planned to develop a design criterion based on the dynamic response of an impulse load on the floor systems. Since this required the knowledge of the damping values which are dependent on the use of the floor system and are usually unknown, he chose to use the deflection due to a static load test in his design procedure.

A criterion developed from his research was adopted into the 1990 National Building Code of Canada as a reference for the span tables of solid sawn wood floors (Onysko 1995). Onysko has since refined his criterion and the relationship is now:

$$y \le \frac{8.0}{L^{1.3}} \quad \text{[mm]} \tag{1.18}$$

where

$$
\begin{aligned}
y &= \text{Central Deflection of the Floor (mm)} \\
L &= \text{Span Length of Floor (m)}
\end{aligned}
$$

The central deflection is due to a static concentrated load of 1 kN (225 lb) placed at midspan. In addition to this, floors with a span length less than 3.0 m (9.8 ft) must not deflect more than 2 mm (0.0787 in.) under a 1 kN static load placed at midspan.

1.4.2.4 Murray's Criterion

Murray's design criterion was developed from the results of 91 steel joist or steel beam concrete slab floor systems (Murray 1979). He compared the subjective reaction of these floor systems to four previous design guidelines used in practice and found their results to be inconsistent and inaccurate with respect to the test floors. Murray developed another design procedure that relates damping, frequency, and peak displacement due to a heel drop impact. Plotting the product of frequency and measured amplitude of each floor system versus damping, he separated the acceptable floors from the unacceptable floors, shown in Figure 1.7, by a line with the following equation:

$$D > 35\,A_o\,f + 2.5 \qquad\qquad\qquad\qquad\qquad\qquad (1.19)$$

where

D	=	Damping in Percent of Critical
A_o	=	Maximum Initial Displacement of a Floor System Due to a Heel Drop Excitation (in.)
f	=	Fundamental Frequency (Hz)

Since most of the floor systems in this research had a fundamental frequency below 10 Hz, Murray recommends use of this criterion with floors having a fundamental frequency below 10 Hz (Murray 1991). So far there have been no known acceptability problems associated with floor systems satisfying his criterion.
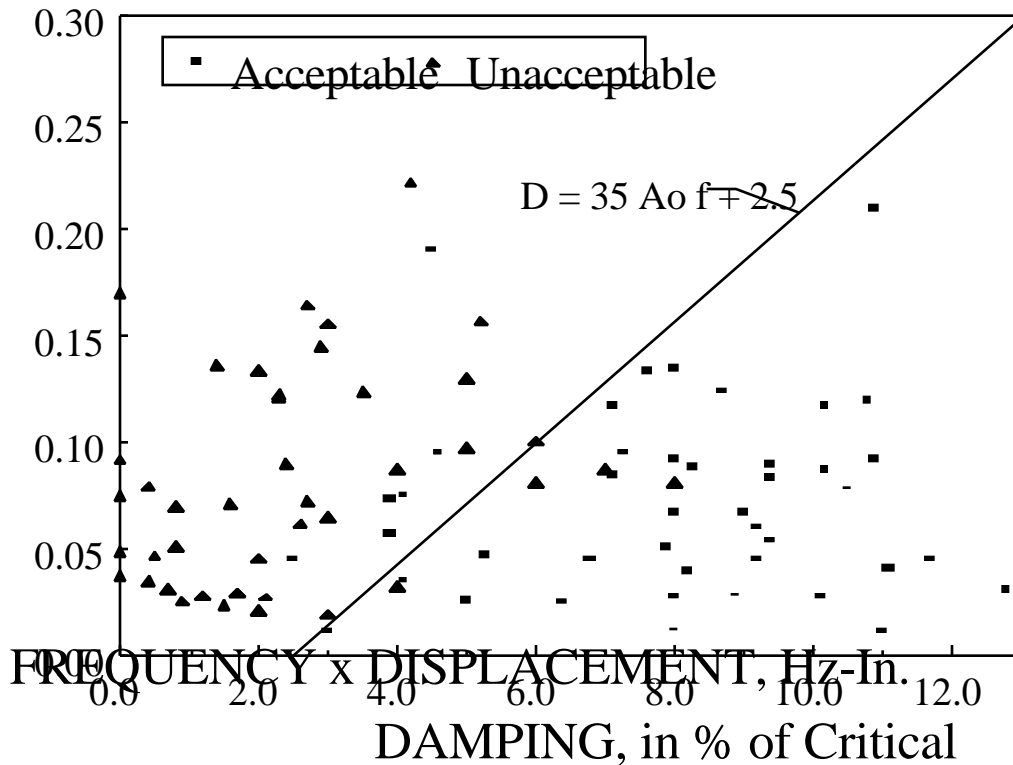

Figure 1.7 Murray Acceptability Criterion

To excite the floor system, Murray's criterion uses a heel drop. Murray's heel drop excitation was first proposed by Ohmart (1968) to determine the dynamic displacement of a floor system due to human occupancy. A heel drop is performed by a 190 lb. man who rocks up on the balls of his feet, with heels approximately 2.5 in. above the floor, and then relaxes and allows his heels to impact the floor. A standard heel drop is then approximated using the decreasing ramp function as shown in Figure 1.8.
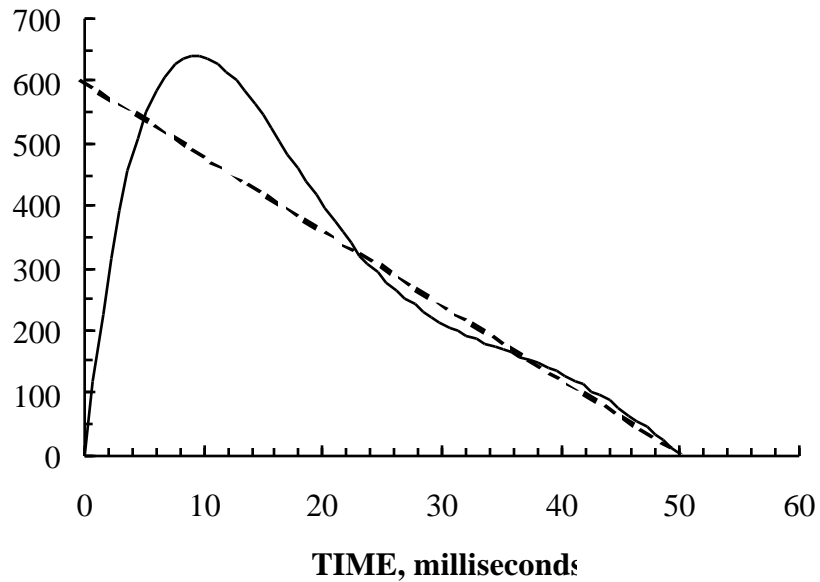
Figure 1.8 Heel Drop Impact

The initial dynamic displacement of a floor system, $_{static}$, can be found by calculating the static displacement of the girder or beam due to a 600 lb. concentrated force (initial value of the decreasing ramp function) applied at the center. Since forces applied dynamically to a floor system can have a displacement of almost twice the static displacement of the same force, the static deflection calculated must be multiplied by a dynamic load factor (DLF). The equation for initial amplitude of a single tee-beam due to a heel drop impact, A_{ot}, is now:

$$A_{ot} = (DLF)_{max} \ \frac{600L^3}{48EI_t} \qquad\qquad (1.20)$$

The $(DLF)_{max}$ is the maximum dynamic load factor and can be obtained using Figure 1.9.
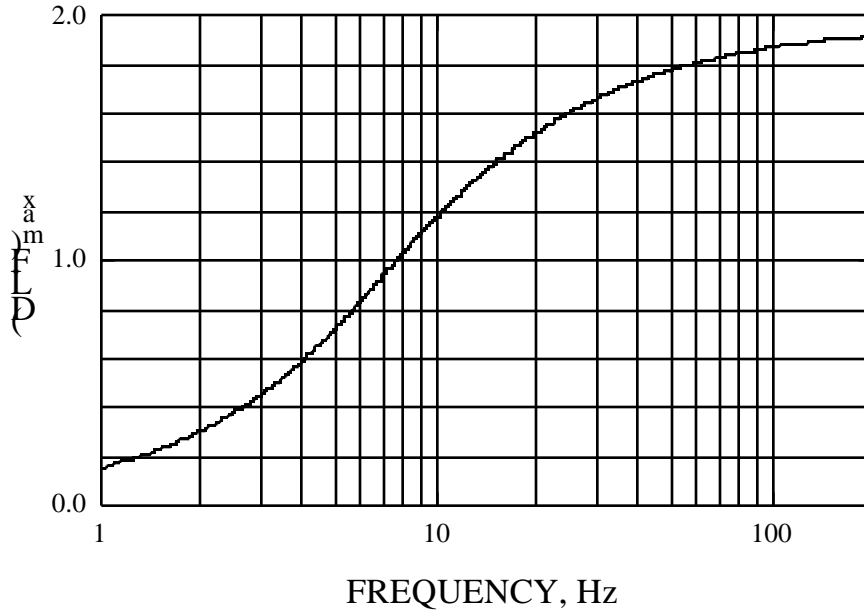
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Figure 1.9 Dynamic Load Factor

Since the centerline static deflection will be carried by more than one joist in a floor system, the number of joists effectively carrying the load of the floor system must be determined. This will be fully discussed in the next section of this report and it is assumed that the number of effective joists, N_{eff}, is known. Knowing the above quantities, the actual displacement due to a heel drop can be calculated using Equation 1.21:

$$A_o = \frac{A_{ot}}{N_{eff}} \qquad (1.21)$$

Knowing the value A_o, the minimum damping can be calculated and compared to the estimated damping. Table 1.1 gives a list of typical damping values for a floor system based on observation (Murray 1991).

Table 1.1 Typical Damping Values

Building Component	Range	Comments
Bare Floor	1-3 %	Lower Limit for Lightweight Floors
Ceiling	1-3 %	Lower Limit for Hung Ceiling, Upper Limit for Sheetrock on Furring Attached to Beam or Joist
Ductwork and Mechanical	1-10 %	Depends on amount and attachment
Partitions	10-20 %	If Attached to the Floor and Spaced Not Less Than Five Beams or Joists

If the floor joists are supported by a beam or joist-girder, the above criterion must be checked for the combined results of both the joist floor system beam and/or girder as well as the individual joist floor system. To obtain the combined frequency of the floor system, Dunkerley's equation is used:

$$\frac{1}{f_s^{\,2}} = \frac{1}{f_g^{\,2}} + \frac{1}{f_b^{\,2}} \tag{1.22}$$

where

f_s = Fundamental Frequency of the System
f_g = Fundamental Frequency of a Girder or Joist Girder
f_b = Fundamental Frequency of a Floor Joist or Beam

The system deflection due to a heel drop is calculated using (Murray 1991):

$$A_o = A_{ob} + \frac{A_{og}}{2} \tag{1.23}$$

where

A_o = System Displacement Due to a Heel Drop
A_{ob} = Beam or Joist Displacement Due to a Heel Drop (using Equation 1.21)
A_{og} = Girder or Joist Girder Displacement Due to a Heel Drop

1.4.2.5 Johnson's Criterion

Johnson (1994) originally applied Murray's acceptability criterion to wood floor systems. After comparing Murray's criterion to 86 *in-situ* floors under construction, he decided to abandon this approach and proposed a criterion of his own for wood floor systems. He proposes that if the fundamental frequency of the floor system is above 15 Hz under normal construction loading, then it is acceptable. The fundamental frequency is found by Equation 1.24 which is the fundamental frequency equation of a simple beam or joist:

$$f = 157 \sqrt{\frac{gEI_t}{wL^4}} \quad \text{(Hz)} \tag{1.24}$$

where

f	=	Fundamental Frequency
g	=	Acceleration Due to Gravity (386 in./s^2)
E	=	Modulus of Elasticity (psi)
I	=	Moment of Inertia of a Single Joist (in^4)
w	=	Self Weight of the Floor Per Linear Foot (lb/ft)
L	=	Span Length (ft)

Johnson concluded from the results of numerous static deflection tests that the effective sheeting width was found to be negligible. Thus the moment of inertia of a single joist can be used instead of using the transformed moment of inertia. If the floor joists are supported by a girder, then Equation 1.22 is used to find the floor system's fundamental frequency. Shue (1995) tested an additional 78 floor systems under the same conditions as Johnson and found Johnson's criterion to be acceptable for unoccupied floor systems with regard to vibration produced by human footfalls.

1.4.3 Number of Effective Joists

As stated above under Murray's criterion, a force applied to a floor system will distribute itself over a certain number of joists in the floor system. Lenzen and Dorsett (1969) denoted this as the effective floor width. Effective floor width is twice the measured distance perpendicular to the floor joist, x_o, from the centerline of the floor system to where the deflection due to a concentrated load at the centerline reaches zero. This is shown in Figure 1.10. They proposed a mathematical equation to find x_o :

$$x_o = 1.06 \quad L \quad \text{(ft)} \tag{1.25}$$

where

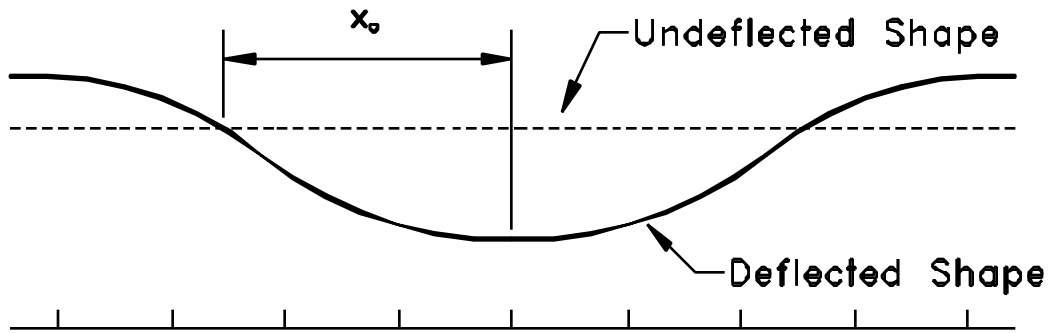|		
x_o	=	Distance From the Center of the Floor to the Point of Zero Deflection (in.)
	=	$(D_x/D_y)^{0.25}$
L	=	Span Length of Floor Joists (in.)

Figure 1.10 Deflection Profile Across Center of Floor

After comparing the effective floor width to actual floor systems, Lenzen and Dorsett (1969) found the prediction equation was close for joists spaced at 24 in. but not for joists with a spacing of 48 in. They then decided to express the effective floor width in terms of the joists and their spacing. The number of joists that will resist a concentrated load is known as the effective number of joists in a floor system. The joist directly under the concentrated load is considered to be fully effective with the joists on either side contributing less to the resistance of the load. The effectiveness of a joist is a ratio of the deflection of the joist under consideration to the deflection of a joist acting individually under a given loading. The following sections discuss three procedures used to determine the number of effective joists in a floor system.

1.4.3.1 SJI and AISC Equations

Lenzen and Dorsett (1969) approximated the two points of zero deflection using a sine curve. The joist locations are then superimposed on the approximate deflected shape of the sine curve and their contributing values are directly related to the location of the joist. The number of effective joists is then the summation of the effective contribution of the floor joists between the zero points of deflection and is approximated by the equation:

$$N_{eff} = 1 + 2 \quad \cos\frac{\pi x}{2x_o} \quad \text{for x} \quad x_o \tag{1.26}$$

where

x	=	Distance From the Center Joist to the Joists Under Consideration (in.)
x_o	=	Distance From the Center Joist to the Edge of the Effective Floor
	=	1.06 L (in.)
	=	$(D_x/D_y)^{0.25}$
D_x	=	Flexural Stiffness Perpendicular to the Joists

$$= \frac{E_f t_f{}^3}{12} \text{ (lb.-in.)} \tag{1.27}$$

D_y =   Flexural Stiffness Parallel to the Joists

$$= \frac{E_j I_j}{s} \text{ (lb.-in.)} \tag{1.28}$$

E_f =   Modulus of Elasticity of Flooring (in^4)
E_j =   Modulus of Elasticity of Joist (in^4)
t_f =   Thickness of Flooring (in.)
I_j =   Transformed Moment of Inertia of the Tee-Beam (in^4)
s   =   Joist Spacing (in.)

Since the Steel Joist Institute (SJI) funded this research, Equation 1.26 is known as the SJI equation for N_{eff}. The SJI equation is intended to be used with floors with a joist spacing up to 30 in.

Saksena and Murray (1972) designed 50 steel beam-concrete floors based on typical office design loads, spans, spacing, and slab thickness. They used a computer program developed by Ohmart (1968) to determine the dynamic amplitude due to a heel drop for each floor system. Having the predicted amplitude from Ohmart's program and hand calculations for the predicted frequency of the Tee-Beams, Saksena and Murray (1972) computed the N_{eff} of each floor system by the following relation:

$$N_{eff} = \frac{A_{ot}}{A_o} \tag{1.29}$$

where

N_{eff} =   Number of Effective Joists
A_{ot} =   Maximum Dynamic Amplitude of a Tee-Beam Subjected to a
            Heel Drop Impact (in.)
A_o =   Maximum Dynamic Amplitude of the Floor System Due to a Heel
            Drop Impact (in.)

A multiple linear regression analysis was performed on the values obtained to arrive at the following formula:

$$N_{eff} = 2.967 - 005776 \frac{S}{d_e} + 2556x10^{-8} \frac{L^4}{I_t} + 000010 \left(\frac{L}{S}\right)^3 \tag{1.30}$$

where

d_e =   Effective Slab Depth (in.)
S   =   Beam Spacing (in.)
L   =   Beam Span (in.)

I_t = Transformed Moment of Inertia of the Tee-Beam (in^4)

Equation 1.30 has the following limitations:

$$15 \leq \frac{S}{d_e} < 40 \text{ and } 1\text{x}10^6 \leq \frac{L^4}{I_t} \leq 50\text{x}10^6$$

This research was sponsored by the American Institute for Steel Construction (AISC) and will be called the AISC equation for N_{eff}. This equation is to be used for floor systems with a beam spacing greater than 30 in., although it was developed for floors with a beam spacing between 60 in. to 180 in.

1.4.3.2 Kitterman's Equation

Shamblin (1989) found that the SJI and the AISC equations do not converge at the 30 in. spacing. She also noted that the AISC equation did not consider open web joist floor systems. She developed an equation to be used at any spacing with either beam or open web joist floor systems with a concrete slab. A finite element analysis was performed on 240 floor systems designed using traditional strength criteria. ABAQUS (Hibbitt, et al. 1984) was used to determine the dynamic response to a heel drop impact. After N_{eff} was calculated, the same procedure as by Saksena and Murray (1972), a multiple linear regression analysis was performed to generate her proposed equation.

Kitterman (1994) planned to verify Shamblin's proposed equation by comparing her results with the SJI and AISC equations. He found that Shamblin's equation predicted larger frequencies than the previous equations. Kitterman then tested the 240 floors Shamblin used with another finite element program, SAP90 (Wilson and Habibullah 1992). The number of effective tee-beams for each floor system was found by dividing the amplitude of a single tee-beam by the predicted floor amplitude. He then performed a multiple linear regression analysis to obtain:

$$N_{eff} = 0.4898 + 34.19 \frac{d_e}{S} + 8.99\text{x}10^{-9} \frac{L^4}{I_t} - 0.000593 \left(\frac{L}{S}\right)^2 \tag{1.31}$$

with the limits of

$$0.018 \leq \frac{d_e}{S} < 0.208 \text{ and } 4.5\text{x}10^6 \leq \frac{L^4}{I_t} \leq 257\text{x}10^6 \text{ and } 2 < \frac{L}{S} < 30$$

After plotting the values predicted by the other equations and the values from his equation, he concluded that his equation calculated a smaller N_{eff} than the others for floor systems with a spacing less than 60 in. This means that Kitterman's equation would predict a larger system amplitude than the other equations for floors with a spacing of less than 60 in. He also states that there is little change in the system amplitude for floor systems with a large

spacing. Kitterman recommends his proposed equation be used in conjunction with the Murray criterion to evaluate both existing and designed floor systems.

1.5 Scope of Work

This thesis is part of a continuation of a research project sponsored by Nucor Research and Development to better understand the vibration characteristics of joist supported floor systems. The goal of this research is to analyze steel joist supported wood floor systems and to determine the best acceptability criterion for predicting the acceptability of these floors.