

# CHAPTER 1

## INTRODUCTION AND LITERATURE SURVEY

### 1.1 Introduction

Low-frequency floor vibration serviceability problems typically arise when a floor is excited in resonance due to a walking excitation and the resulting accelerations exceed human comfort levels (Murray et al. 1997). Excessive discomfort of occupants can result in complaints or even loss of productivity. If the discomfort of the affected personnel becomes overwhelming, the occupants may opt for extreme measures such as litigation or relocation to another facility, and consequently the unoccupied structure will no longer fulfill its intended purpose. While most floor vibration problems are not this extreme, the scenario highlights the potential significance of this serviceability problem. The measures required to resolve an annoying floor vibration problem after the building is constructed can be very difficult and expensive to implement. In most cases, the costs of fixing the problem in-situ are much greater than tackling the problem in the design phase prior to the floor's construction, which doesn't even include the potential cost to building owners from legal expenses, loss of rental revenue, or consultation fees (Hanagan 2005). The easiest "fix" for a floor vibration problem is avoidance: simply designing a floor such that it's unlikely to experience a vibration serviceability problem. Avoidance becomes particularly important in the design of tall buildings, which can have the same floor framing plan for 20+ stories at a time. The key to avoidance is the ability to predict the dynamic behavior of the floor in the design stage and to determine if it will be a problem under service conditions, a task much easier said than done, and the subject of much of the floor vibration research to date.

The popularity of open office plans has led to the specification of larger bay sizes and longer spans in floor systems. In such cases, the economical floor of choice is typically a steel composite floor design that includes concrete on metal deck supported by steel framing members. Unfortunately, despite satisfying strength requirements and traditional live load stiffness criteria, this floor type coupled with the fit out (or lack thereof) of open office floor

plans can be quite susceptible to annoying floor vibration problems due to walking excitation and consequently is the subject of this research effort.

Various design guides and codes around the world address vibration serviceability in the same general manner: outline simplified hand calculation methods for estimating the dynamic properties of a floor system, estimate an applied dynamic load that simulates walking forces, and finally compute the dynamic response of the system to the applied loads for comparison with an established level of acceptability. Although the current design guidance is generally acceptable, it is filled with generalizations for application to the widest variety of floor layouts, and thus predictions of frequency or other dynamic properties may differ considerably from the actual properties of the floor. Unique or non-standard framing, different beam sizes between columns, moment connections, and interior floor-to-ceiling partitions are all examples of common deviations not typically accounted for in the simplified design methods. However, such deviations can be addressed when floors are modeled in a finite element (FE) analysis program. Unfortunately, the simple mention of a finite element model of a floor system elevates the level of effort for checking floor vibration serviceability well beyond “a simplified hand calculation method.”

Finite element modeling for vibration serviceability is not meant to be a replacement for standard evaluation methods, but a specialized approach to be used when needed. A good analogy of this approach is current practices in seismic analysis, where lower levels of analysis such as the Equivalent Lateral Force procedure satisfy most requirements, but further interest in the response of a structure may call for a more advanced inelastic response history analysis. The development of finite element models of any level of complexity is fairly involved and requires some amount of experience. However, despite the level of experience of the individual creating the model, the one thing that holds true is that the model is only as good as the assumptions and parameters used in its creation. Research in developing FE models of floor systems validated by high-quality experimental measurements provides the best way for identifying fundamental modeling techniques, including the validation of assumptions, and paves the way for advanced vibration serviceability evaluation using the finite element method.

## **1.2 Scope of Research**

The purpose of this study is to examine the dynamic behavior of in-situ composite steel floors and to generate a set of general FE modeling techniques for modeling these floor systems

using a commercially available FE analysis program, where the resulting dynamic analysis yields an acceptable prediction of response for evaluation of vibration serviceability. The desired goals of the research are as follows:

- Identify and summarize best practices in dynamic testing of in-situ floor systems, including comments on equipment, experimental techniques, and measurement analysis. Develop a classification system for floor vibration testing for use by researchers, consultants, and building owners, broken down by equipment and techniques employed, as well as the information available from each class of testing.
- Conduct experimental dynamic testing of in-situ multi-bay steel composite office floors using an electrodynamic shaker to identify general trends in dynamic behavior of the floor system. Directly measure response of the floor system to steady-state and broadband excitation and determine the dynamic properties of frequencies, damping, and mode shapes.
- Create finite element models of the tested floors and use the experimentally measured dynamic properties to validate each floor's corresponding FE model. From the validated FE models, the identified fundamental modeling techniques include methods for representing the mass, stiffness, and boundary conditions of the floor, as well as incorporating an assumed (or measured) level of damping into the model for use in dynamic response analysis.
- Propose a method for floor vibration serviceability evaluation using the finite element method.

Chapter 2 provides background theory on experimental modal analysis and highlights the testing techniques employed to identify the dynamic properties and behavior of the floor systems. Besides describing some best practice techniques for testing floor systems, Chapter 2 also provides a classification system for different levels of dynamic floor testing as described above. A data set of high quality dynamic measurements was obtained through experimental testing of three in-situ steel composite office floors, as summarized in Chapter 3. Measurements from these in-situ floors provide an adequate sample of stiffness, geometry, and boundary conditions for identification of the FE modeling trends required to bring experimental and analytical results into agreement. Although three in-situ floors may seem to be a low number of test specimens, additional samples come from bays of variable geometry and boundary conditions within each floor's own assemblage. The parameters and validation of the tested floor systems' FE models are presented in Chapter 4. The fundamental techniques used in

creating the models are a product of validation using the high quality dynamic measurements described in Chapter 3. Chapter 4 also includes a proposed method for using the results of the finite element analysis as a tool for floor vibration serviceability evaluation due to walking excitation. Finally, Chapter 5 summarizes the results from the entirety of the presented research and provides recommendations for future endeavors in the topic.

### **1.3 Literature Survey**

Structures susceptible to vibration serviceability problems include floors, footbridges, stadia, and even stairs, among others. The available literature on vibration serviceability is vast when considering the multidisciplinary aspects of the subject, which includes the physical components and properties of the structure, the biomechanics of the imperfect and probabilistic nature of human walking, the dynamic response of the structures to such loads, and even identifying the actual level of dynamic response that is unacceptable to the human receptor. The information presented in the following literature survey does not cover all aspects of vibration serviceability; it only focuses on summarizing the state of the practice as it pertains to the presented research. Additionally, some summaries presented in the literature survey are cursory, as more detailed coverage of the subject is more appropriately presented in the chapters that delve deeper into that topic.

#### ***1.3.1 Background***

Vibration serviceability is by no means a new issue for designers to tackle, as indicated by Tredgold (1828), who published one of the first known stiffness criteria with the intent of avoiding vibration problems. This criterion simply suggested sufficient depth of girders with long spans to avoid “shaking everything in the room.” Nearly 40 years ago, Lenzen (1966) noticed that advances in technology and materials led to lighter types of floors with little decrease in factors of safety. As a result, the economical floor systems occasionally resulted in noticeable floor vibrations caused by human impact even though the designs satisfied code stiffness criteria. As such, the Steel Joist Institute sponsored its first initiative to research the vibration of steel joist-concrete slab floor systems (Lenzen 1966). Research in the subject persisted in the following years and continues today.

While not listed here in detail, the subsequent research studied and refined techniques for evaluating the two most basic components of the vibration serviceability issue (1) the dynamic

response of a floor system subject to human excitation and (2) the tolerance levels of human subject to the dynamic response. Presently in North America, the design guidance most often used for composite steel framed floor systems is the *AISC/CISC Steel Design Guide Series 11: Floor Vibrations Due to Human Activity* (Murray et al. 1997).

### ***1.3.2 AISC/CISC Steel Design Guide Series 11: Vibrations Due to Human Activity***

Design Guide 11 (DG11) contains simplified hand calculation methods for evaluating the vibration serviceability of floors. In short, each bay (as defined as a generally rectangular area between four or more columns) within the floor system that has unique framing is evaluated using DG11's procedures for walking excitation. Each evaluation involves two sets of calculations: one to compute the fundamental frequency of the bay and another to compute the maximum amplitude of acceleration. Evaluation results from comparing the predicted peak acceleration with human tolerance levels. The following inequality represents the comparison:

$$\frac{a_o}{g} \geq \frac{a_p}{g} = \frac{P_o e^{-0.35 f_n}}{\beta W} \quad (1.1)$$

where

$a_o/g$  = human tolerance level of peak acceleration (as a fraction of gravity)

$a_p/g$  = estimated peak acceleration due to walking excitation (as a fraction of gravity)

$P_o$  = a constant force

$f_n$  = fundamental natural frequency of the system

$\beta$  = modal damping ratio

$W$  = effective weight of the system

The left side of Inequality (1.1) represents the human tolerance level of peak acceleration, expressed as a fraction of gravity. The right side of the inequality represents the computed peak acceleration within the bay due to walking excitation, expressed as a fraction of gravity. The individual parameters involved in the evaluation are discussed further in the remainder of this section but will not be expanded upon beyond the extent that they relate to the presented research. Detailed treatises of the parameters can be found either directly within DG11 or the corresponding references listed in DG11. The topics that are of particular interest are the human perception limits due to walking excitation, the representation of stiffness in steel composite floor systems (for use in determining natural frequency), and the dynamic forces involved with walking excitation.

## Human Perceptibility

The human response to floor motion is a complex perception issue that involves a variety of environmental factors, most notably the magnitude and duration of the motion, visual or audible cues, and activity (or lack thereof) of the affected person (Hanes 1970). In general, studies of human perception and tolerance of vibrations indicate that acceleration is the best overall indicator of potential discomfort of humans due to floor motion (Ellingwood 1989). DG11 acceleration criteria are based on the chart shown in Figure 1.1, which was developed using baseline acceleration limits recommended by the International Standards Organization (ISO 2631-2 1989) that were adjusted for intended occupancy and experience (Allen and Murray 1993).

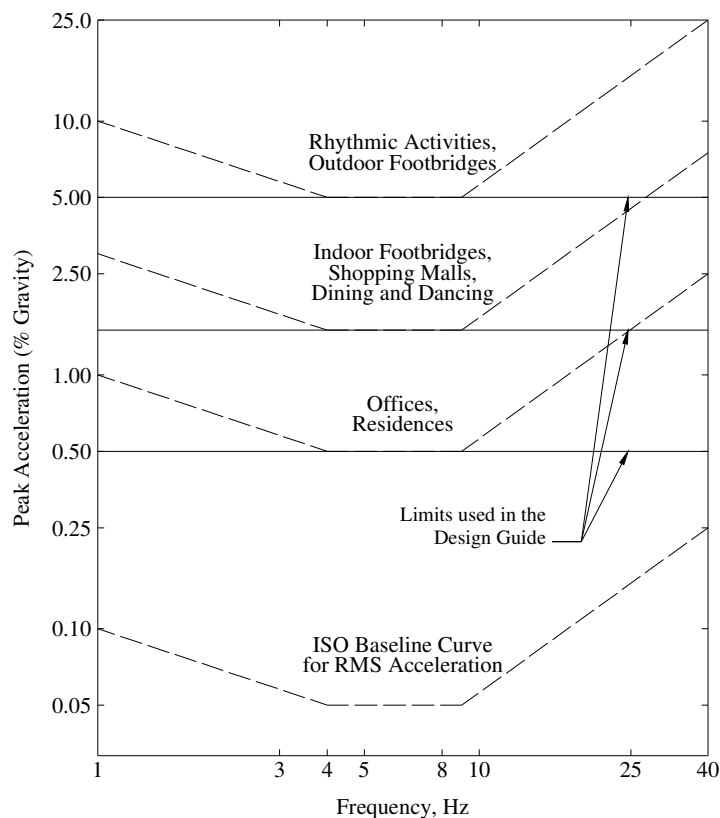


Figure 1.1: Recommended Peak Accelerations for Human Comfort due to Human Activities (Allen and Murray 1993; ISO 2631-2 1989)

DG11 suggests the peak acceleration used as the threshold for human comfort in offices or residences subjected to vibration frequencies between 4 Hz and 8 Hz is 0.005g, or 0.5% of gravity. The lower threshold within the frequency range of 4 to 8 Hz can be explained by studies showing humans are particularly sensitive to vibrations with frequencies in the 5-8 Hz range,

corresponding with typical natural frequencies of many of the main organs in the body (Griffin 1990, Murray 1991).

The 0.5%g acceleration limit within a range of 4 to 8 Hz is highlighted because it represents the frequency range that may be excited with the second or third harmonic of walking, where a harmonic is defined as an integer multiple of the step frequency. Under normal walking, human footfalls average about 2 steps per second, but can get up to about 2.4 steps per second. If each downward step is seen as an input force, then for instance, the second and third harmonic of the 2.4 Hz input force are 4.8 Hz and 7.2 Hz, respectively. Floors that have a natural frequency at or near one of these harmonics may exhibit an excessive response because the input force component of the harmonic may coincide with the resonant frequency of the floor (Bachmann 1995).

### ***Acceleration Response***

The expression for estimated peak acceleration shown in Inequality (1.1) was determined by modeling the floor (or more appropriately one bay of a floor system with some corresponding effective weight) as a simplified spring-mass-damper system driven at its natural frequency by an effective harmonic force due to walking, resulting in a resonant response.

The effective harmonic force term  $P_0 e^{-0.35 f_n}$  of Inequality (1.1) is based on representing the time-dependent repeated force of a person walking across a floor,  $F(t)$ , as a Fourier series, or combination of sinusoidal forces, comprised of the harmonics of the walking pace:

$$F(t) = P \left[ 1 + \sum_i \alpha_i \cos(2\pi i f_{step} t + \phi_i) \right] \quad (1.2)$$

- where  $P$  = person's weight (taken as 157 lbs in DG11)  
 $\alpha_i$  = dynamic coefficient for the  $i^{\text{th}}$  harmonic force component  
 $i$  = harmonic multiple of the step frequency  
 $f_{step}$  = step frequency of the person walking  
 $t$  = time  
 $\phi_i$  = phase angle for the harmonic

DG11 assumes that only one of the harmonic components of Equation (1.2) will be associated with the floor's natural frequency, inciting resonant response of that mode, and that the response due to all other harmonics of the step frequency will be small in comparison. Thus, the time-dependent harmonic force component corresponding to the natural frequency of the floor is:

$$F_i(t) = P\alpha_i \cos(2\pi i f_{step} t) \quad (1.3)$$

DG11 suggests the dynamic coefficients for walking excitation shown in Table 1.1. This stepped relationship for the dynamic coefficients was simplified by approximating the steps at the various frequency ranges by the term  $\alpha = 0.83e^{-0.35f_n}$ .

Table 1.1: Common Forcing Frequencies and Dynamic Coefficients (Murray et al. 1997)

Harmonic $i$	Person Walking	
	$f$ (Hz)	$\alpha_i$
1	1.6 - 2.2	0.5
2	3.2 - 4.4	0.2
3	4.8 - 6.6	0.1
4	6.4 - 8.8	0.05
$\alpha$ is the peak sinusoidal force divided by the weight of the person(s)		

Pernica (1990) also computed the dynamic coefficients from measured forces of individuals performing rhythmic activities, including walking, which fell within the range of those suggested in Table 1.1. Kerr (1998) conducted an extensive experimental study on vertical footfall forces. Young (2001) analyzed the harmonic components of each of Kerr’s 882 single step force time histories and developed a similar table of dynamic coefficients for the first four harmonics of walking. Rather than constant values for the dynamic coefficient for frequencies that fell within a particular harmonic range, he developed linear functions within the ranges. Although not shown here, they are in general agreement with the values suggested by Table 1.1. They are similarly stepped in nature within various frequency ranges, although Young’s steps have a slight upward slope.

The resonant response function presented in DG11, resulting from the single harmonic force component causing the resonant response, is in the form:

$$\frac{a}{g} = \frac{R\alpha_i P}{\beta W} \cos(2\pi i f_{step} t) \quad (1.4)$$

where  $a/g$  is the floor acceleration, expressed as a fraction of gravity.  $R$  is a reduction factor taken as 0.5 for floor structures with two-way mode shape configurations to account for the fact that “full steady-state motion is not achieved for walking and that the walking person and the person annoyed are not simultaneously at the location of maximum modal displacement.” This expression for steady-state acceleration due to harmonic resonance is given by Rainer et al. (1988) and Allen and Murray (1993). For evaluation purposes, Equation (1.4) reduces to the



peak acceleration expression on the right side of Inequality (1.1), where the numerator,  $P_o e^{-0.35 f_n}$  is just a simplified expression containing the 157 lb person's weight, the 0.5 reduction factor mentioned above, and the dynamic coefficient in the form  $\alpha = 0.83 e^{-0.35 f_n}$ , and can be viewed as the effective harmonic force applied at the midpoint of the bay that represents the forces generated by a person walking.

### ***Frequency and Effective Weight Estimation***

DG11 procedures for predicting the natural frequency of a floor system for use in Inequality (1.1) consists of a series of calculations for the simply supported beam/joist and girder panel frequencies and ultimately a combination of these to represent the system frequency,  $f_n$ , using Dunkerly's relationship:

$$\frac{1}{f_n^2} = \frac{1}{f_j^2} + \frac{1}{f_g^2} \quad (1.5)$$

where  $f_j, f_g$  = fundamental frequency of the joist and girder panel, respectively

Although the equations are not shown here for the individual panel frequencies, the procedure involves computing the maximum static deflection of the beam/joist or girder panel assuming it is uniformly loaded, simple supported, and exhibits composite action between the deck/slab system and the steel framing member, provided they are in continuous contact, regardless of whether or not the floor was designed with composite connectors. The latter assumption is based on the extremely small displacements involved with floor vibrations, in which the resulting shear forces at the slab/member interface are resisted by construction spot welds or friction.

The DG11 recommendations for computation of the beam/joist and girder panel stiffness are noted because the methods for computing stiffness are applied to the framing members in the finite element models of the presented research. DG11 recommends that when calculating the transformed moment of inertia for the beam/joist or girder panel, the modulus of elasticity of concrete is taken as 1.35 times the current structural standard, as shown in Equation (1.6), to account for the greater stiffness of concrete on metal deck under dynamic loading.

$$E_c = w^{1.5} \sqrt{f_c'} \quad (1.6)$$

where  $E_c$  = modulus of elasticity of concrete (ksi)

$w$  = unit weight of concrete (lb/ft<sup>3</sup>)

$f_c'$  = compressive strength of concrete (ksi)

There are additional recommended limitations on effective width of the concrete slab that differ from those currently used for strength design. For beam and girders, the effective slab width is taken as the member spacing, but not greater than 0.4 of the member span. This limitation is cut in half for spandrel members, where the effective slab width is half the adjacent spacing (plus spandrel edge overhang), but not more than 0.2 of the member span. Stiffness adjustments are recommended for open web joists and joist girders to account for the effects of joist seats, web shear deformation, and eccentricity or joints.

The final two parameters required for the right side of Inequality (1.1) to estimate the peak acceleration response are the effective panel weight,  $W$ , and the modal damping,  $\beta$ . DG11 outlines a series of calculations used to determine the effective panel weight of the system as a function of relative stiffness of components, continuity factors, and floor geometry. Unless otherwise measured, the modal damping parameter must be estimated based on experience and recommended values for the expected final condition (office fit out) of the evaluated floor. For offices (the type of floor use of this research), DG11 recommends the following values for damping ratios: 0.02 for floors with few non-structural components (ceilings, ducts, partitions, etc.), 0.03 for floors with non-structural components and furnishings, but with only small demountable partitions, and 0.05 for full height partitions between floors.

### ***1.3.3 Floor Vibration Experimental Testing and Finite Element Modeling***

The following is a survey of the literature with particular regard to experimentally tested steel composite floor systems (or similar), measurement comparison of finite element models with tested systems, and general steel composite floor finite element modeling techniques. Note that the phrase “unreferenced measurement” used throughout is meant to describe vibration response measurements taken outside the traditional experimental modal analysis setup whereby the input force is explicitly measured simultaneously with the response. This typically applies where just the acceleration response from heel drop and walking excitations were measured, unless expressly noted as an instrumented heel drop. A more detailed explanation of experimental modal testing is presented in Chapter 2; however a brief summary of experimental modal testing as it applies to floor structures is presented, as this is the basis of the experimental work in the presented research.

## ***Modal Testing***

In contrast to response-only dynamic measurements, modal testing offers an expanded capability to characterize the dynamic properties of a floor by measuring both the input force and output response and forming a frequency response function (FRF) between the excitation and measurement locations. The advantage of knowing this relationship for a set of points on a structure is that in addition to frequency and damping estimates, the mode shapes can be estimated from the magnitude and phase information contained in the complex frequency domain FRFs (Ewins 2000). Hanagan et al. (2003) noted the ability to express the behavior of a floor system in terms of its modal properties provides a consistent baseline for comparing the results of finite element analysis and actual measured behavior.

A “heel drop” refers to an impulse load excitation frequently used to evaluate floors. A heel drop is an impact force caused by a person assuming a natural stance, maintaining straight knees, shifting their weight to the balls of the feet, rising approximately 2.5 in. on their toes, and then suddenly relaxing to allow their full weight to freefall and strike the floor with their heels. The force-time relationship of the resulting impulse load is normally approximated by a triangular pulse load with an initial magnitude of 600 lbs. decreasing to zero over 0.05 seconds (Ohmart 1968). An obvious advantage of this type of impulse excitation is how easy it is to perform and that it does not require any equipment other than what is needed to measure the response (Blakeborough and Williams 2003). Unfortunately, no matter how consistent experimentalists are in performing heel drops, it still remains an unmeasured input unless conducted on an instrumented device. To that end, Blakeborough and Williams (2003) evaluated the use of an instrumented heel drop test as an alternative source of excitation for performing modal analysis on floor systems. They concluded the instrumented heel drop was a more effective modal testing technique than an instrumented impact hammer because it gave better results at lower frequencies, while sufficiently exciting the structures with frequencies in the range of 1 to 15 Hz, which is the range of interest for floor vibration problems due to walking excitation. Hanagan et al. (2003) also concluded the instrumented heel drop yielded high quality data and served as a good alternative to an electrodynamic shaker when cost and portability are an issue.

The literature covering the techniques and application of the different methods of modal testing to obtain quality and consistent measurements is quite vast as it mostly spans the

automotive and aerospace industries. Ewins (2000) text is a very comprehensive source on modal testing theory, practice, and application. A few researchers in floor vibration research have published works evaluating the most common techniques for testing floors and procedures for ensuring quality and consistent measurements. Most notably, Pavic and Reynolds published a series of articles on experimental assessment of office floors using modal testing, impact hammer versus shaker excitation, and quality assurance procedures for modal testing of building floors (Pavic and Reynolds 1999, Reynolds and Pavic 2000a, 2000b). Hanagan et al. (2003) expanded on the articles by applying the different modal testing techniques and quality control procedures to a steel composite laboratory floor with the intent of characterizing the best technique and providing a set of guidelines for others performing future research. Pavic, Reynolds, and Hanagan all agreed that modal testing using an electrodynamic shaker yielded the highest quality experimental data, albeit at a much higher equipment cost.

### ***Laboratory/In-situ Floor Testing and Finite Element Modeling Techniques***

The following is a chronological survey of the selected literature involving experimental testing and modeling of floor systems. The topics of experimental testing of laboratory floors, in-situ floors, and finite element modeling are presented in a single section because most of the literature found contained all three topics, and it would be difficult or repetitive to discuss separately.

Pernica and Allen (1982) tested several floor areas of a shopping center of steel beam composite deck construction. Dynamic properties, including peak accelerations, were determined from un-measured heel drop and walking input excitations.

Rainer and Swallow (1986) tested a very long span (105 ft) steel-joist concrete-slab gymnasium floor using two electrodynamic shakers to drive the floor sinusoidally at varying frequencies to determine the floor's frequencies, mode shapes, and damping. Although peak acceleration levels were reported for various rhythmic activities, the peak acceleration levels and corresponding input forces from the steady-state shaker excitation were not.

Eriksson (1994) investigated the behavior of in-situ low-frequency floors constructed of prestressed concrete elements. He performed experimental modal analysis on six in-situ floors and performed analytical studies on three of the floors using finite element analysis.

Shope and Murray (1994) recorded accelerations on a laboratory test floor and an in-situ long span (52 ft) steel joist composite floor identified from occupant complaints of excessive levels of vibrations. The authors presented unreferenced acceleration time histories of both structures from heel drop and walking excitations, and the study included the successful implementation of tuned-mass dampers to reduce the acceleration response.

Kitterman (1994) investigated several vibration characteristics of steel member supported floors, particularly the effective width of one-way steel joist and steel beam-concrete slab floors and the effective moments of inertia of steel joist and joist-girder members. The author created finite element models of numerous theoretical floors and performed a dynamic response analyses to synthesized heel drop impacts. The only experimental work conducted was on an atypical steel joist and joist-girder laboratory floor, investigating the ability of joist seats to transfer shear from the supporting girder to the overlying slab. The experimental work included finite element modeling and frequency measurements. Finite element modeling techniques recommended by Kitterman were incorporated in the presented research.

Pavic et al. (1995) performed impact hammer modal testing of a large concrete parking garage floor and performed finite element modeling. Although his investigation involved a concrete structure and not a steel composite structure, Pavic concluded that using significantly higher values for modulus of elasticity of concrete was needed to bring computed results into agreement with measured frequencies. This agreed with the DG11 recommendation of using 1.35 times the computed modulus of elasticity for concrete (Murray et al. 1997).

Rottmann (1996) investigated the use of tuned mass dampers to control annoying floor vibrations in steel composite floor systems, which involved experimental measurements of a laboratory test floor and multiple bays of an in-situ office floor found to have problems. The study included acceleration time history response measurements due to heel drop and walking excitation, as well as the Fast Fourier Transform (FFT) of the time history data to examine frequency content and determine the floor's frequencies (response measurements only, not input force). The author created finite element models of the tested structures and used explicit springs at the boundaries to account for support flexibility and to bring computed frequencies into agreement with those measured. Dynamic response analysis due to a synthesized heel drop function was conducted on the FE model.

Band (1996) investigated the vibration characteristics of long span composite joist floors. He tested four in-situ floors with spans ranging from 45 ft to 117 ft by measuring the time history acceleration response due to heel drop impact and performing an FFT to evaluate the frequency content. He chose to report all response measurements in terms of peak displacement, which was derived from integrating the acceleration response. A test floor was constructed with the intent of evaluating modification techniques to joist floors for increasing floor frequency.

The research conducted by Khoncarly (1997) most closely follows the presented research. The objective of his study was to develop practical guidelines, in the form of simplified response spectra, for use in the evaluation and design of steel composite office floor systems subject to walking excitation. The researcher measured the response due to unreferenced heel drop and walking excitation of one in-situ steel joist composite office floor identified to have problems with annoying floor vibrations. Khoncarly identified that loads from footfall excitation should be modeled within a dynamic finite element analysis by taking into account the time-dependent spatial variability of each footfall as the repeated footfalls move across a floor (i.e. applying footfall pulse loads at different stride locations in sequence at their respective arrival times). The response measurements taken from the in-situ floor were used to calibrate his finite element model. From this single floor test and model, he expanded the modeling technique to a variety of “ideal” office floor models and computed the dynamic response from walking excitation, which was used to generate the response spectra for evaluating acceptability. Like most floor vibration researchers, he had no way to directly measure the spatially varying footfall forces on the in-situ floor at the same time the response measurements were obtained. The calibration of his finite element model of the in-situ floor (and all subsequent models) was based on the comparison of the computed response due to a simulated load to an unreferenced measured response of the in-situ floor due to an actual walking load. In reality, the actual load may have varied more significantly than the assumed simulation. To account for this, the simulated load was based on his research that included measuring the actual force-time history records of different individuals walking at various paces to model the magnitude, duration, stride length, and overlap of the footfall forces. It is this writer’s opinion that the reference “ideal” floors the author modeled and used to develop the design/evaluation response spectra were overly simplified for use with many floor systems of different geometry,

although the response spectra approach may be worthwhile for future research provided a valid modeling technique is used.

Beavers (1998) investigated the most effective way of finite element modeling steel joist supported floors to predict the first natural frequency. His models were compared to the experimentally measured natural frequencies of six concrete slab steel joist floors: four laboratory test floors and two in-situ office floors. His modeling technique explicitly defined each of the joist web and chord members and used rigid links to position the plate elements at the slab centroid to the proper distance above the centerline of the top joist chords. With this technique, he successfully matched the first natural frequency. Beavers reported measured and modeled first natural frequencies, but did not include any force-response measurements or analyses.

Falati (1999) mainly investigated the effects of non-structural components on the dynamic behavior of concrete floors using a slender one-way span, 50% scaled post-tensioned concrete slab, although his research also included testing of an in-situ steel composite concrete floor subject to various excitations. He recorded the acceleration response to unreferenced heel drop and walking excitations as well as measured forced-vibration testing using a shaker, allowing him to estimate frequencies, mode shapes, and damping. Shaker testing only included measurements from the mid-bay location of one bay on one in-situ occupied floor. Accelerance frequency response functions (acceleration response per unit of input force) from the modal testing were reported, as were the acceleration response time histories from the unreferenced excitations. He reported the quality of the accelerance frequency response function measurements were much higher for an in-situ floor using shaker excitation than for impact hammer excitation due to the shaker's ability to provide more energy to the larger system.

Sladki (1999) used finite element modeling of steel composite floors to predict the fundamental frequency of vibration and the peak acceleration due to walking excitation as given in DG11. He concluded his modeling techniques were able to predict the fundamental frequency of the floor more accurately than DG11, but were unable to accurately predict the acceleration response of the floor to a given dynamic load. He concluded the inaccurate predictions were the result of applying dynamic loads to the models that were not measured values, but were estimations of the applied force.

Alvis (2001) used finite element modeling of steel composite floors to predict peak

accelerations due to sinusoidal loads with magnitudes suggested by DG11. He conducted experimental modal analysis on several laboratory test floors to obtain their dynamic properties, and applied known (measured) sinusoidal loads to measure peak response. While the frequency and mode shapes of the FE models matched well, he concluded the computed peak accelerations did not match well with the measured values, and speculated the value of damping used in the FE model was the source of the discrepancy. Alvis also compared peak accelerations predicted by the FE method and DG11, which did not correlate well. He concluded the source of discrepancy between the two was that the modeling technique did not account for the effective area of the floor system that actually vibrates due to energy dispersion and frictional damping.

El-Dardiry et al. (2002) conducted a vibration study on the long span (25 ft) flat plate concrete floor of a full-scale laboratory test building and calibrated a finite element model on the floor from only natural frequency measurements of unreferenced heel drop excitations. The researchers concluded that to match natural frequencies, the FE models had to include column elements at the supports to account for the rotational restraint provided to the slab at its boundaries. Reynolds et al. (1999) and Pavic et al. (2001) also suggested to explicitly include columns when modeling reinforced concrete and post-tensioned concrete floors.

Warmoth (2002) investigated the effect of joist seats on effective girder moment of inertia and girder frequency of steel joist composite systems. The frequency spectra of several laboratory test floors were measured. He proposed a method for calculating the effective moment of inertia based on the type of joist seats used in the composite construction, which is insightful for use of the presented research techniques for FE modeling of the stiffness of steel joist floor systems.

Boice (2003) evaluated different methods for predicting the fundamental frequency for a bay as well as the predicted acceptability of a floor system based on computed peak accelerations. He evaluated the different methods by comparing measured fundamental frequencies and subjective floor evaluations with the corresponding values predicted by four commonly used methods: AISC/CISC Design Guide 11, Steel Construction Institute (SCI) *Design Guide for Vibrations of Long Span Composite Floors* (UK standard, Hicks et al. 2000), Murray Criterion (Murray 1979), and the Modified Reiher-Meister scale (Lenzen 1966; Murray 1975). He concluded that the SCI procedure most accurately predicted the fundamental



frequency of the bay, but overall DG11 most accurately evaluated a floor's acceptability based on comparison to 78 existing in-situ floor case studies.

Ritchey (2003) investigated the use of specialized tuned-mass dampers to reduce floor vibrations. His research included experimental modal testing of a one-way steel composite laboratory test floor both with and without the device installed. The experimental testing he accomplished was conducted with the same test equipment as the presented research.

Like the presented research, Perry (2003) studied computer modeling techniques using commercially available finite element software to evaluate the acceptability of floors. His research objective was to model floors in a way that computed an acceleration response (due to walking excitation) that matched the response predicted by DG11. He calibrated his modeling techniques by analyzing ideal floor systems (both partial and full floor models) and adjusting parameters and loading protocols until the fundamental frequencies and computed accelerations approached those predicted by the DG11 techniques. Perry applied the same modeling techniques to case study floors and compared the computed frequencies and accelerations to the measured frequencies and subjective evaluations. He found that while his techniques gave a better prediction of fundamental frequency than the DG11 techniques, the computed accelerations were not an accurate way to predict the acceptability of a floor system because they did not correlate well with the subjective evaluations of the tested floors. It should be noted that Perry's techniques never included matching actual measured acceleration response to a measured input force. Perry attributed the error in response prediction to the inability of the computer model to adequately represent the effective mass of the floor in its fundamental mode. Perry recommended future research on in-situ floors to include experimental measurement of response to known dynamic loads and the discrepancies between measured and predicted results to be resolved.

Salyards and Hanagan (2005) presented research on modeling a stadium facility for evaluation and prediction of dynamic response. The research included incremental FE modeling of the stadium and tuning based on experimental modal measurements taken by others. The researchers also used SAP2000 (CSI 2004) to create the FE models, the same program used in the presented research. While the structure differed considerably from the type of structure in this research, a particular observation demonstrated a similar phenomenon found in floor testing. It was noted by the researchers that the cantilever mode of the roof structure was the lowest

frequency mode computed by the FE model and was not found in the experimental data. They stated that because the shaker excitation was applied to the seating areas, the vertical force likely did not excite this particular mode. Additionally, only modes that show considerable response in occupied areas of the seating should be considered critical, even if these are not the lowest (fundamental) frequency modes of the structure.

El-Dardiry et al. (2006) investigated the finite element modeling of profiled composite floors. The detailed methods for creating equivalent isotropic and orthotropic shell sections to represent the composite steel deck concrete slab are insightful; however the application of their methods to experimental data is rather sparse. The only experimental measurements for comparison were from a three-bay by five-bay composite steel test floor within a full scale multi-story building built in 1994 for the exclusive purpose of research for the construction industry. However, only a single bay was dynamically tested by an unreferenced response to a person jumping, which yielded a single frequency measurement of 8.50 Hz. The researchers constructed a detailed FE model of the entire floor and found that the corresponding frequency of the excited bay was actually the fourth mode of the floor, computed as 8.17 Hz, not as close as one may hope for with such detailed modeling techniques. The researchers chose to explicitly model the steel columns for the floor system, citing previous research they conducted with FE modeling of a concrete floor (El-Dardiry et al. 2002). However, the obvious differences between the column-floor boundary of a monolithically cast concrete floor plate-column system and steel column and composite floor system are quite substantial. It is this writer's opinion that the method for modeling the composite slab is too intricate for the degree of accuracy it provides, and it is not conducive for automation.

#### ***1.4 Need for Research***

The reviewed literature documents that dynamic testing of in-situ office building floors and development of FE model representations of their dynamic properties has been accomplished several times before. However, despite the numerous studies, there is an obvious lack of published cases involving the development of calibrated finite element models of in-situ steel composite floors based on extensive, high quality modal testing measurements. In some cases in the reviewed literature, limited unreferenced measurements became the cornerstone on which elaborate FE models and analyses were based, making huge leaps of faith with models validated

by only the most basic of the measured dynamic properties. Hanagan et al. (2003) succinctly summarized the need for the presented research:

“Fundamentally, modal analysis provides a basis for comparing analytical predictions of dynamic behavior to experimental results from actual in-place floors. A comparison might be used to evaluate the success of a finite-element model in predicting floor behavior. A successful analytical modeling approach, verified from experimental modal data, can be used to evaluate structures before they are built. Collecting high-quality experimental data on a floor is essential to developing better analytical techniques.”

As stated above, calibration of dynamic FE models to actual structures is best achieved using high quality modal data as well as a good understanding of the tested structure, which is why a large number of laboratory test floor cases are found in the literature.

The number of case studies involving in-situ floors are limited and the quality of measurements is questionable because opportunities to test large, in-situ, floor systems without the presence of occupants, construction materials, office furniture, or non-structural fit out are rare. Even rarer are studies that include testing in-situ floors using equipment with the capability to capture high-quality modal measurements. Experimental testing of relatively “clean” floor systems is part of the included research, as such floors serve as valuable test specimens when developing valid computational models under dynamic loadings.

Validated computational models of in-situ floors give researchers a method of predicting the response of the floor to dynamic loads, and consequently the ability to evaluate the performance due to human activities such as walking. If a set of general modeling techniques for steel composite floor systems can be developed from the calibrated FE models such that they adequately predict response to dynamic excitation, designers will have a better tool to evaluate proposed floor designs and avoid potential serviceability issues.