CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusions

The purpose of this research was to examine the dynamic behavior of in-situ steel composite floors and present a set of fundamental modeling techniques for generating finite element models for steel composite floor systems such that the resulting dynamic analysis yields an adequate prediction of response for evaluation of vibration serviceability. Briefly, the desired goals of the research were:

- Identify and summarize the best and recommended practices in dynamic testing of in-situ floor systems. Develop a classification system for floor vibration testing based on equipment and techniques employed, as well as the information available from each class of testing.
- Conduct extensive dynamic testing of in-situ multi-bay steel composite office floors to estimate dynamic parameters/response and to identify trends in dynamic behavior.
- Generate a set of fundamental FE modeling techniques to represent 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 evaluation of vibration serviceability using the finite element method.

The measurement, characterization, analysis, and computation of a floor's accelerance frequency response function (FRF, the acceleration response at one location of the floor per unit of input force at another location) is the core premise linking all areas of the presented research. Chapter 2 describes best practice techniques for testing in-situ floors and acquiring high quality dynamic measurements in the form of the accelerance FRF. Chapter 3 describes the characteristics of in-situ floor behavior as a result of the experimental testing and acquisition of high quality measurements for three in-situ steel composite office floors. Chapter 4 provides recommended modeling techniques for steel composite floors based on the high quality measured data and proposes a method for evaluation of vibration serviceability based on the computed accelerance

FRF. The present chapter briefly summarizes the presented research including the notable conclusions in each of the areas of study and provides recommendations for future research in this field.

5.1.1 Dynamic Testing of In-Floor Systems

Multi-bay in-situ floors are large structures that present their own unique challenges for dynamic testing. Virtually all aspects of in-situ floor testing require compromise, and limited time available to test a floor is the leading factor in the quality and extent of test measurements. Best practice techniques for testing in-situ floors were presented that stressed efficient test methods and techniques to ensure quality measurements. The recommended approach to floor testing and best practice techniques is valid for virtually any type of in-situ floor, not just the steel composite floors of the presented research. The notable findings from this area of study are as follows:

- Various methods of excitation were described in this research, including chirp signals, instrumented heel drop, steady state sinusoid, and unreferenced measurements. The burst chirp signal using an electrodynamic shaker is recommended as the most accurate and consistent source of excitation for high quality measurements that are suitable for use in parameter estimation, operating deflection shape animation, and calibration of FE models. An instrumented heel drop may provide an inexpensive alternative to generate an accelerance FRF, however the controlled excitation and quality of measurement using an electrodynamic shaker is unparalleled.
- It is recommended to use a force transducer to measure the input force from an electrodynamic shaker rather than an accelerometer mounted to its armature, which can underestimate the measured response at its most critical values, the resonant peaks of the accelerance FRFs.
- Several methods for estimating damping were presented, including the half power bandwidth of chirp derived accelerance FRFs and sinusoidally derived accelerance FRFs, MDOF frequency domain curve fitting of the accelerance FRF using modal analysis software, and decay from resonance time domain curve fitting. All methods were in general agreement with one another, however MDOF curve fitting of the driving point accelerance FRF is recommended for its ability to deal directly with closely spaced

modes. MDOF curve fitting is the most reliable, but it still requires a fair amount of engineering judgment to confirm the validity of estimated parameters in the modal analysis software. The half power bandwidth method is very consistent; however the presence of closely spaced modes can lead to overestimation of damping. Time domain curve fitting decay from resonance is consistent for clearly dominant modes; however estimates may be misinterpreted if there are closely spaced modes with significant participation. Damping is the dynamic parameter most affected by poor frequency domain resolution, as truncated peaks in the accelerance FRF can lead to overestimates of damping.

- Although all levels of dynamic testing have various degrees of usefulness, only certain types of dynamic measurements are suitable for tasks that require high quality modal data, such as FE model calibration or detailed parameter estimation of damping and mode shapes. Section 2.5 describes a classification of floor vibration testing expressed in terms of the methods/equipment used (or required) for testing and the extent of the useful information that can be extracted from the tests. Establishing a common ***Class of Floor Testing*** helps prevent false expectations in the capabilities of measured data and identifies the equipment, time, and cost (in terms of analysis/testing effort) required to obtain the desired results.

5.1.2 Dynamic Behavior of In-Situ Floor Systems

Three in-situ steel composite office floors were tested in this research (NOC VII-24, NOC VII-18, and VTK2), including two nominally identical floors within the same building (identical framing, nearly identical partition wall layout). The extent of testing varied for each of the three tested floors; however accelerance FRFs were measured with an electrodynamic shaker located within 26 unique bays, providing the largest survey high-quality modal measurements on in-situ floors known to be available in the current literature. The notable findings and recommendations from this area of study are:

Frequency

- Mid-bay driving point accelerance FRFs are the most valuable and descriptive measurements from testing an in-situ floor. The driving point accelerance FRF provides immediate feedback on dominant and significantly participating frequencies within the bay, an estimate of damping can be performed using the half power bandwidth method on the peaks, and the magnitudes of the peaks relative to other measured portions of the floor provide immediate feedback on response intensity (and indirectly the mode shape).

- The dominant frequencies of the 26 bays on the three tested floors ranged from 4.85 Hz to 9 Hz, all within the range of frequencies where humans have the lowest threshold of tolerance. The term “dominant frequency” is used to describe the frequency of the largest magnitude peak on the mid-bay accelerance FRF because it is the frequency that will generate the greatest response per unit of input force (such as from walking excitation). This term is used in lieu of “fundamental frequency,” which is typically reserved to describe the lowest frequency. When two peaks of nearly identical magnitude are present, the lower frequency peak is generally considered to be the dominant frequency because of its susceptibility to a lower harmonic of walking frequency (which translates to a larger applied force).
- The accelerance FRF measurements were consistent between the two identically framed floors tested in NOC VII (with only slightly different interior partition layout), which validates assumed consistent behavior of similarly framed floors. This consistency is a fundamental assumption for developing tools to accurately predict floor behavior, such as FE modeling.
- Because multi-bay floors generally consist of bays of similar or identical framing, they result in a narrow frequency band of the dominant frequencies. The nine exterior (similarly framed) bays of NOC VII had dominant frequencies within a 0.5 Hz band, and the seven exterior bays of VTK2 were within a 1.0 Hz band.

Damping

- Measured damping values were low (less than 2.5% of critical, many less than 1%), but the values are reasonable considering the bare condition of the tested floors.
- The measured estimates of damping varied considerably, ranging from 0.6% to 2.4% of critical for NOC VII (0.65-1.15% was typical), and 0.44% to 1.33% for VTK2 (0.5-1.0% was typical). The wide range of damping values makes it difficult to establish recommended values for damping to incorporate into FE models; however, a designer has no other choice but to used assumed damping values for forced response analysis.

- Although there was no definitive trend, some indications showed that proximity to boundaries affects the level of damping (e.g. corner bays with multiple exterior boundaries or interior bays adjacent to areas with interior partitions), which seems reasonable.
- Overall, NOC VII had higher levels of damping than VTK2, which is likely a result of spray on fireproofing, finished interior partition walls, and finished exterior boundaries.

Mode Shapes and Operating Deflection Shapes

- Because ODSs are measured forced-response shapes and vibration serviceability is a forced-response phenomenon, displaying an ODS at the dominant frequency visually illustrates the floor's potential vulnerability to walking excitation. At resonance, the ODS closely *approximates* the mode shape provided it is dominated by a single mode.
- ODSs are animated directly from measured accelerance FRFs, thus the validity of the displayed shape is a direct result of the quality of the measurements. The mode shapes are not measured; they are *estimated* from measured accelerance FRF data. Because the mode shapes are estimated from these measurements, the quality of the mode shape is also a direct result of the measurement quality. It is from this demand for quality measurements that the recommended best practice techniques were derived.
- Several measured shapes on the floors were localized to just a few bays and occasionally there was very little response in immediately adjacent bays. To investigate this phenomenon, sets of measurements were taken with the shaker in multiple locations for coverage areas in both NOC VII and VTK2. Because of the localized response, not all modes were adequately excited by forcing at a single mid-bay location. Gathering sets of measurements with the shaker at multiple locations allowed estimates of modal parameters from the set of measurements that most strongly excited a particular mode. The quality of the estimated mode shapes (and strength of the visually displayed ODSs) was significantly improved using multi-reference testing, and this approach is highly suggested if well defined mode shapes are of interest.

General Response Behavior

- The shape of a bay excited at its dominant frequency is characterized by single curvature.

- The mid-bay location is the best point for excitation because it roughly corresponds to the anti-node (point of maximum response) of the bay when driving at its dominant frequency. It was demonstrated that this location was also almost always the anti-node of response for the *whole floor* when excited at its dominant frequency, essentially making the mid-bay driving point accelerance FRF the upper bound response for the entire floor.
    - The observed upper bound response behavior validates current methods of evaluation of vibration serviceability, which compute the mid-bay response to a mid-bay excitation for comparison with acceptability criteria.
    - Additionally, it allows more efficient testing because a collection of mid-bay driving point measurements (rather than full modal testing) may be adequate to define the dominant frequencies and upper bound response for excitation within each tested bay of a floor.
- The displayed operating deflection shapes of the tested floors revealed there is generally more response in bays that are adjacent to the bay of excitation in the direction of the composite deck span than in the perpendicular direction (parallel to the floor beams).
- Significant response was measured at spandrel members of the exterior boundaries of the floor. Magnitudes of response ranged from 9-26% of the mid-bay response for both of the tested buildings, which is significant considering that such a boundary is typically assumed to be rigid.

Measurement Consistency and Linearity

- For all measurements, one or more accelerometers were located with the shaker and force plate to record redundant driving point measurements. Theoretically, these measurements should be identical, and they were very consistent in the presented research. However, slight variations can occur (due to changing environmental conditions like temperature), and redundant measurements allow the ability to recognize and account for them.
- Although the driving point measurements were very consistent in this study, it is suggested to perform a modal sweep over a coverage area as quickly as time allows, avoiding any potential changes in the condition of the floor or test set up.

- No significant nonlinearity was identified in the tested floor systems, although a larger input force (and response amplitude) had the tendency to slightly shift the dominant frequency to the left (decrease in frequency by one or two spectral lines). This can be interpreted as a tendency for the floor to become slightly more flexible at higher levels of excitation.
- There was excellent agreement between reciprocal FRFs of bays immediately adjacent to the bay of excitation, but the agreement deteriorated at locations further away (more than two bays). Rather than a gross nonlinearity in the system, this poor agreement is more likely a function of poor signal strength at the longer distances.

Mid-Bay Floor Evaluation

- A reduced mid-bay testing scheme is recommended as a time-saving alternative to modal testing over a full coverage area, provided the only desired estimates of dynamic parameters are frequencies, damping, and mid-bay acceleration response. The evaluation method requires multiple sets of accelerance FRFs to be measured with the shaker and roving accelerometers located at the centers of each of the surveyed bays.
- Forcing at the mid-bay of each of the surveyed bays ensures that all bays' dominant frequencies are adequately excited for estimates of frequency and damping. The peak accelerance of the mid-bay driving point FRF also provides the upper bound acceleration response of the floor from excitation within that bay.
- A limited description of the shape of the floor's response can be made through comparison of the relative mid-bay accelerance FRF magnitudes and phase.
- Multiple sets of measurements from different forcing locations allows multi-reference MDOF curve fitting of a small but representative set of accelerance FRFs, instilling a higher confidence in the estimated modal parameters.

5.1.3 Fundamental Modeling Techniques for Composite Floors

Using the measured in-situ behavior of the tested floors for reference, finite element (FE) models were developed for the NOC VII and VTK2 floors. The FE models for both floors were developed in parallel using a shared set of simplified FE modeling techniques. Manual FE model updating was performed to bring the computed results into agreement with the experimentally measured results. A summary of notable results is listed here.

- Recommended fundamental FE modeling techniques for steel composite floors were presented in Section 4.1.
- The FE models for the two tested floors developed using the recommended FE modeling techniques were presented in Section 4.2.
- An abbreviated summary of the recommended techniques was presented in Section 4.3.
    - The described techniques provide recommendations for modeling mass, stiffness, and boundary conditions of steel composite floors.
    - Also included are recommendations for dynamic analysis for the purpose of evaluation of vibration serviceability. These techniques include modal analysis, representing damping in the FE model, and forced response steady state analysis over a frequency range of interest.
- Performing a steady state analysis using a *unit* point load at a single location on the FE model is the computational equivalent of measuring the accelerance FRFs for the entirety of a floor from forcing at a single driving point location with an electrodynamic shaker. Using this advantageous property, unit point loads were placed at the mid-bay locations (corresponding to experimental excitation locations) for steady state analysis. The *computed* mid-bay driving point accelerance FRFs were used for comparison with *measured* mid-bay driving point accelerance FRFs.
- Two FE models were generated for NOC VII, a full floor model and partial floor model.
    - The first FE model for NOC VII represented the entire floor and successfully captured the behavior in four of the eleven analyzed bays, but struggled to adequately represent the behavior of the floor along the long exterior strip of bays.
    - A reduced floor model containing just the ten bays along the long exterior strip was much more successful in representing the behavior of these bays. The success of a partial floor model was a particularly encouraging result as developing an FE model of an entire floor system can be costly.
    - It is likely the over-constraint of the interior bays of the floor (which was not a part of the reduced floor model) was a factor in the poor agreement of the full floor model. In these areas, vertical restraints were added to interior slab and

framing members to represent full-height partition framing, elevator cores, stairwells, etc. The exact layout within these interior bays was not known, thus engineering judgment was exercised on their placement.

- VTK2 was represented with a full floor model, although commentary and comparison of frequencies and mode shapes were not made for the portions of the floor that were not tested.
    - The VTK2 floor contains several areas of irregular framing and consequently has some unique (and non-intuitive) mode shapes. The applied FE modeling techniques were very successful in capturing the unique mode shapes at their corresponding frequencies. Predicted dominant frequencies from all twelve analyzed bays were within 5% of measured values.
- Although there is room for refinement of the techniques with further testing/modeling of in-situ floors, the presented fundamental FE modeling techniques were shown to provide adequate representations of measured floor behavior for the purposes of serviceability evaluation.
- An advantage of the recommended FE modeling techniques and method of dynamic analysis are their simplicity, making them very conducive to automation. Depending on the FE program used for modeling, the recommended techniques leave room for alternative approaches of specifying damping for forced response analysis.

5.1.4 Evaluation of Vibration Serviceability of Floor Systems

This research proposed a method for evaluating vibration serviceability of floor systems using the finite element method, which has the potential to be just as applicable to the evaluation of in-situ floors through experimental testing. The proposed method was presented in Section 4.4 and is summarized here.

- A *design accelerance curve* is proposed to represent a response threshold in the frequency domain that can be used in comparison with an acceleration response in the frequency domain (an accelerance FRF).
- Using the FE method, the proposed method of evaluation uses the *computed* mid-bay accelerance FRF as the evaluation parameter.

- Existing floors can also be evaluated through comparison of the *measured* mid-bay accelerance FRF with the design accelerance curve.
- As a proposed method, the final form of the design accelerance curve was not finalized; however, an example design accelerance curve is presented based on current serviceability guidelines, specifically DG11 limits of acceptability and effective harmonic forces due to human activities such as walking.
- Because the recommended method of evaluation is based on the mid-bay driving point accelerance FRF, it is also very conducive to automation within a FE program.
- Mid-bay driving point accelerance is a directly measured quantity (unlike walking forces), thus the final form of a design accelerance curve may be directly developed from a survey of in-situ measurements of both acceptable floors and floors with known serviceability problems.

5.2 Recommendations for Future Research

The recommended areas of future research presented in this section address several aspects of floor vibrations, including additional in-situ floor testing and refinement of FE modeling techniques. Also presented are recommendations for the calibration of the proposed *design accelerance curve* method of evaluation through further FE modeling and experimental testing of in-situ floors.

In-Situ Floor Testing

- Additional high-quality modal testing of in-situ floors fit out to all conditions of occupancy (bare floor, open office, etc.) is recommended. This includes a full modal survey over the floor area using multiple references to ensure the dominant modes of all surveyed bays are adequately excited for the purposes of MDOF curve fitting and FE model calibration.
- If the time required for a full modal sweep of the in-situ floor is not available, implement a mid-bay testing scheme as a minimum measurement survey. At the very least, this survey adds to the database of measured mid-bay accelerance FRFs.

- Perform high quality modal testing of *the same* in-situ floor at different stages of fit out, at minimum testing a floor in a bare condition and again at an occupied fit out condition to examine the change in dynamic behavior.
- In addition to mid-bay driving point measurements, test floors with the shaker located at quarter points of a bay to validate second bending mode frequencies/shapes (and confirm that these frequencies are typically out of range of the harmonics of interest and at smaller magnitudes than their mid-bay counterparts).
- Directly test specific floor components such as members between columns by placing a shaker on these areas for certain measurements. For different fixity conditions, this may give insight into their level of fixity when compared to theoretical values based on composite moment of inertia and degree of fixity (and thus frequency).
- Combine high-quality modal testing with walking tests to establish the correlation between peak accelerance values and unreferenced response-only walking tests at resonance and off resonance. Try to determine if it is possible to determine a quasi-FRF using off-resonance walking, a similar approach to stepped sine testing at frequencies near resonance.

Finite Element Modeling of In-Situ Floors

- Conduct further refinement of recommended (simplified) modeling techniques by applying automated FE model updating procedures. Potential variable parameters for iteration in the automatic update algorithms may include the partial fixity values at beam-to-girder and beam/girder-to-column web/flange connections (which, if expressed as a fraction of *EI/L*, provides a much more conducive variable for iteration) and/or the baseline property modifier multiplier for spandrel members.
- Conduct further investigation of reduced models of portions of a floor. Determine parameters to adequately represent the missing portion of the floor, or only consider the mode shapes localized away from these artificial boundaries as valid for the reduced models.
- Apply recommended (or refined) modeling techniques to blind testing of floors. Model an in-situ floor prior to testing using an assumed level of damping. Compute the mid-bay accelerance FRFs for the areas to be tested for immediate comparison of measurements.

Calibration of Proposed Method of Evaluation Using In-Situ Floor Accelerance FRFs

- Obtain high quality modal measurements of in-situ floors with known serviceability problems. Compare with high quality modal measurements of floors without problems and examine the data for trends in peak accelerance values. This database of measured peak accelerance values coupled with subjective serviceability evaluation should be the basis of the final form of the design accelerance curve.
- Generate FE models of the existing database of problem floors with known serviceability issues and look for trends in computed peak accelerance values.