# Chapter 6

## Summary, Conclusions, and Recommendations for Future Research

### 6.1 Summary

The objective of this research was to develop relatively simple, experimentally verified methods for evaluating low frequency floors (natural frequencies not exceeding approximately 10 Hz) for vibration serviceability due to walking. Several methods currently exist for evaluating this limit state—some are based on simple SDOF approximations and some are very complex. The methods proposed in this research were developed to be generally applicable, but no more difficult or complex than necessary considering the current ability to predict modal properties using finite element analysis. The writer believes that all three methods presented herein individually accomplish this goal.

In summary, the first method uses linear response history (time history) analysis to predict the response to a series of footstep forces applied as individual waveforms. The footsteps were selected from a set of footsteps measured using an instrumented force plate to have specific frequency contents in the first four harmonics. In the model, they are applied to nodes at spacing approximately equal to the average human stride length. The footsteps are timed to match a subharmonic of the dominant frequency, which is the natural frequency that provides the maximum response in the bay under consideration. The result is a prediction of the maximum acceleration that can be reasonably expected due to an individual walking along the walking path chosen by the engineer.

The second method also uses response history analysis, but with a different representation of the load: a four term Fourier series. This is a traditional representation of the applied load due to a series of footsteps and has the advantage of being easier to apply in most structural analysis programs. Again, the result is a prediction of the acceleration waveform that results from walking in the bay under consideration.

The third method uses a simple frequency domain formulation and is the fastest and easiest to apply if the available software can compute the FRF magnitude. It takes advantage of the fact that the vast majority of the response to walking at resonance is due to the harmonic that matches the dominant frequency. The dominant mode's FRF peak magnitude is simply multiplied by the harmonic walking force and then reduced to account for imperfect resonant build-up. Because all three methods tend to over-predict the response, adjustment factors are recommended.

An experimental program was completed to provide measured modal properties and responses to walking for comparison with analytical predictions made using the proposed methods. Six floors were tested: two open-web steel joist laboratory specimens, a long-span composite slab specimen, a full-scale mockup of a long-span composite slab floor system, a conventionally framed composite floor, and a light non-composite floor system supported by open-web steel joists, providing a good sample of the various steel-framed floor systems used in North America.

Detailed modal tests were performed on all floors to provide estimates of the accelerance FRF magnitudes which were then used to estimate natural frequencies, mode shapes, and damping ratios. An electrodynamic shaker was used to provide burst chirp excitation at the centers of several bays while roving accelerometers were used to measure accelerations at enough key locations to allow estimation of the mode shapes. Whenever possible, to reduce the errors associated with force dropoffs that inevitably occur as the chirp signal passes through resonance, an instrumented force plate was used to measure the force applied by the shaker.

Subsequent walking tests were performed, during which individual walkers traversed each tested bay several times using a metronome to encourage walking at a subharmonic of the dominant frequency. The results of these tests, which included four individuals, were numerous measured waveforms, with the maximum response being useful for comparison to analytical predictions.

Numerous individual footstep forces were measured to provide loading functions for the first of the three proposed response prediction methods. These were processed to determine the frequency content of a series of steps. It was found that footsteps that appeared almost identical in the time domain often had extremely different frequency contents and therefore produced very different responses when used in the models. Therefore, "design" footsteps were selected based on an approximately 25% probability of exceedance according to a very large footstep force database (Kerr 1998).

Finite element models were created of each structure using SAP2000 (CSi 2005), largely following the modeling techniques recommended by Barrett (2006) and the SCI DG (Smith et al. 2007). These models were used to predict the natural frequencies, mode shapes, accelerance FRF magnitudes (computed using measured damping ratios), and responses to walking which were then compared to the corresponding measurements.

The modeling techniques were found to accurately predict natural frequencies in general, with all but one comparable mode (matching measured and predicted mode shapes) predictions within 10%. However, the FRF peaks were so narrow that small errors place the predicted peak mostly or completely off the measured peak.

The models inconsistently predicted the mode shapes and therefore the FRF peak magnitudes. (The peak magnitude depends on the effective mass which is directly related to the mode shape.) Indeed, at the two building floors, several of the measured and predicted mode shapes did not correspond—the model predicted some shapes that were not measured and vice versa. The accelerance FRF peak magnitudes are directly related to mode shapes, so they were not predicted as accurately as were the frequencies. On average, they were over-predicted by 50% with predicted-to-measured ratios ranging from 0.665 to 2.84. These are noteworthy because FRF peak magnitudes directly relate to acceleration response to walking on low frequency floors. The fairly detailed models simply did not have the ability to consistently predict the modes, which is consistent with the research of Pavic et al. (2007). This, in the writer's opinion, casts serious doubt on the current usefulness of attempts to quantify the response from multiple modes.

One very surprising finding is that most of the poor FRF peak magnitudes predictions were due to the model predicting almost all of the movement to be isolated to small areas whereas the tests indicated that far-away portions of the structures almost always move significantly.

The maximum responses to walking were predicted using the three proposed methods with actual walker weights and measured modal damping ratios. The individual footsteps method average ratio of predicted-to-measured acceleration is 1.47 (COV = 38.6%) if all tests were included, with ratios varying between 0.818 and 2.88. Four tests in particular, were affected by inaccurate mode shape predictions leading to over-prediction of response to walking. If these are excluded, the average ratio of predicted-to-measured acceleration is 1.18 (COV = 23.8%). The second proposed method, response history using a Fourier series representation of the load, produced more conservative results. The average ratio of predicted-to-measured response was 1.84 (COV = 27.2%), ranging between 0.952 and 2.79. If the four tests mentioned above are excluded, the ratio is 1.71 (COV = 28.1%). The Fourier series approach was also examined using only the term that matched the natural frequency. In this case, the comparisons were actually slightly better than if all four terms were used, simply because the responses were slightly less. This method over-predicted the response regardless of whether one term or four terms were used. The simplified frequency domain method produced similar results, with predicted-to-measured responses averaging 1.71 (COV = 29.2%) and ranging from 0.952 and 2.66.

Design methods were recommended in Chapter 5, based on the predictions described in the previous paragraph with modeling recommendations mostly adopted from others (Murray et al. 1997, Barrett 2006, Smith et al. 2007). One notable conclusion of this research is that a large portion, if not all of a floor should be modeled. Models created of smaller portions of the structure did a poor job of predicting the FRF peak magnitudes and therefore the acceleration due to walking. (All floors were bare slabs, so it is not known if this holds true for floors with substantial partitions.) The design methods are identical to the methods used to generate the test floor predictions except that assumed damping values are used, reduction factors are required, and some of the walking loads are simplified slightly. Damping ratios are adopted from DG11 (Murray et al. 1997) or the SCI DG (Smith et al. 2007) except for bare slab structures such as those tested—0.5% of critical damping is recommended for bare slabs. Because all three prediction methods over-predicted the response by a somewhat predictable amount, reduction factors were used to increase the accuracy of the predictions. This is not unconservative partially because the walking forces are 75th percentile forces rather than average forces—therefore retaining some conservatism. The walking loads are somewhat simplified also, without sacrificing significant accuracy, by observing that the harmonic loads do not vary appreciably over the frequency ranges that they can be applied. Therefore, average design-level forces are recommended.

Predictions from the three methods were made in a "blind" manner to assess how well they would have performed as design tools for the tested bays. The individual footsteps method reasonably accurately predicted the response, with an average predicted-to-measured ratio of 1.30 (COV = 54.3%). The ratios ranged between 0.657 and 3.34 with only two predictions being incorrect by more than 100%. Without exception, very inaccurate predictions were produced by poor FRF peak magnitude predictions which resulted from poor mode shape predictions. Even so, only two predictions were incorrect by more than 71%, which the writer considers to be very encouraging. A plot of the predicted and measured accelerations is shown in Figure 6.1.

Similar results were obtained using response history analysis using Fourier series representation of the load with DLFs computed using the proposed equations. The average ratio of predicted-to-measured acceleration was 1.19 (COV = 47.4%), with ratios ranging from 0.538 to 2.80. Only one prediction was incorrect by more than 57% and it was caused by poor FRF peak magnitude prediction. Figure 6.2 summarizes the comparisons made using this method. The comparisons were repeated with a four term Fourier series using average design DLFs rather than computed ones. The results were slightly better than when using the computed DLFs, with the predicted-to-measured ratio averaging 1.16 (COV = 46.4%).

Finally, blind comparisons were made using the simplified frequency domain method, with results shown in Figure 6.3. The average predicted-to-measured response was 1.16 (COV = 44.4%), with ratios ranging between 0.549 and 2.51. Only two predictions were incorrect by more than 100%. One of these was due to an inaccurate peak FRF prediction.

In summary, the three methods were shown to produce response predictions sufficiently accurate for design use. The simplified frequency domain method is the most efficient of the three, so is recommended for general design usage.

Chapter 5 contains a discussion of parameters that contain at least some degree of variability and the extent that the variability affects predictions of FRF magnitude predictions and response to walking. Concrete cracking is shown to have an insignificant effect on some mode shapes, but not others. Specifically, mode shapes with adjacent bays moving the same direction have significant curvature at the crack location, so are significantly affected. Damping has a significant effect on prediction of response to walking, but not as much as would be indicated by its effect on steady-state response. For one example case, the response was predicted to change by only a modest amount for moderate errors in damping prediction.

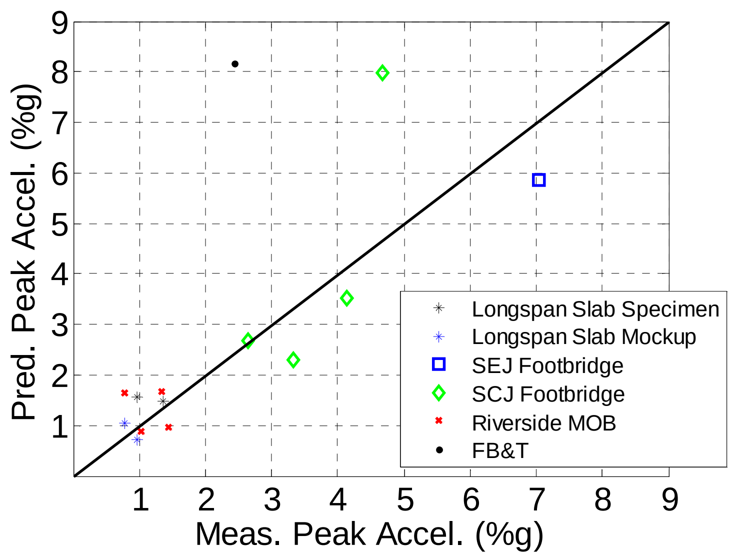


**Figure 6.1: Measured and Predicted Accelerations – Individual Footsteps Method**

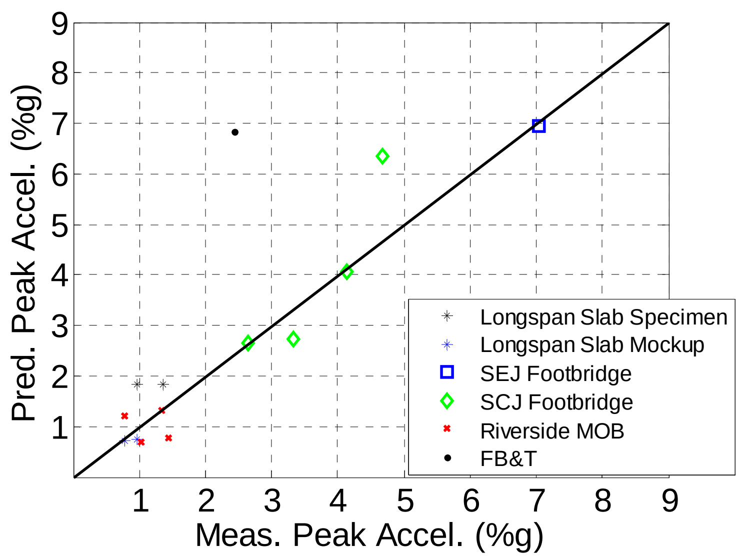


**Figure 6.2: Measured and Predicted Peak Accelerations—4-Term Fourier Series, Using Computed DLFs**

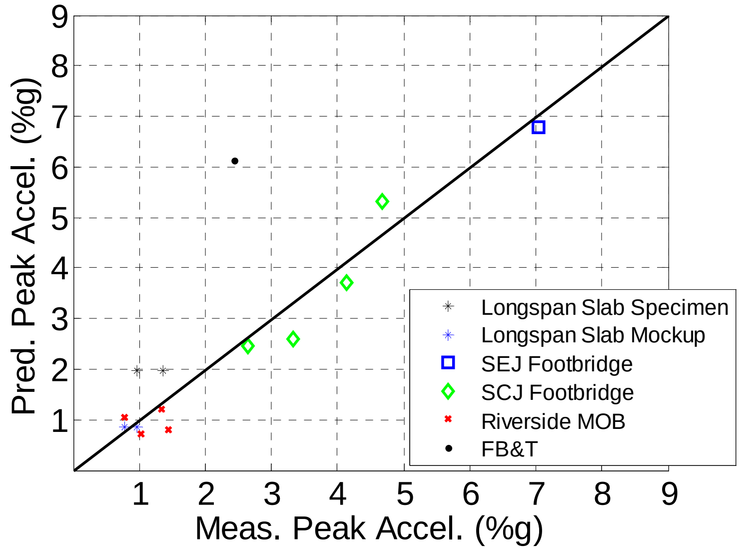


**Figure 6.3: Measured and Predicted Peak Accelerations—Simplified Frequency Domain Procedure**

## 6.2 Conclusions

Numerous conclusions are made in the preceding paragraphs and summarized below.

Modal Testing

- An instrumented force plate should be used whenever practical. Force measurements using an armature accelerometer only can incorrectly miss so-called "force glitches" in the frequency domain which are associated with force dropoffs in the time domain.
- Force should be applied at locations with high effective mass to decrease force glitch size even when using a force plate.

Footstep Force Measurement

- Footstep waveforms that look very similar in the time domain can have extremely different frequency content. Footsteps used as loading functions for low frequency floors must be selected based on frequency content.

Modeling and Modal Property Prediction

- The floor system model should encompass a large area of floor, if not the entire floor. Models including limited areas were shown to produce more severe FRF peak magnitude over-predictions.

- Current finite element analysis methods can predict natural frequencies that are very accurate for relatively simple specimens. For building floors, the methods can predict frequencies that are in the generally correct frequency range, but cannot predict multiple modes with the correct shapes and at the correct frequency spacing.
- Current finite element analysis methods can only predict FRF peak magnitudes with a moderate amount of reliability. Peaks are often very severely over-predicted when the modeling techniques predict that a small area of floor is moving whereas much larger areas experience significant movement in reality.

Prediction of Response to Walking

- Response history analysis using individual footsteps as the loading function conservatively predicted the response. Using measured damping and bodyweight, this method was 47% on the conservative side with a COV of 38.6%. Blind predictions, including an adjustment factor to reduce conservatism associated with imperfect cadence, were 30% on the conservative side with a COV of 54.3%.
- Response history analysis using Fourier series loading conservatively predicted the response. Using measured damping and bodyweight, this method was 84% on the conservative side with a COV of 27.2%. Blind predictions were 19% on the conservative side with a COV of 47.4%.
- The simplified frequency domain method also conservatively predicted the response. Using measured damping and bodyweight, this method was 71% on the conservative side with a COV of 29.2%. Blind predictions using this method were 16% on the conservative side with a COV of 44.4%.

## 6.3 Recommendations for Future Research

There are numerous potential topics that are in need of research toward the goal of improving prediction of floor vibration response, not only to walking, but to other types of human induced loads.

First and foremost should be research to improve the prediction of basic modal properties. As mentioned numerous times in this dissertation, poor response predictions very often stem from poor prediction of mode shapes which directly affect the effective mass. These accounted for *all* of the very large predictions errors encountered in this research. Experimental programs such as the one performed by Barrett (2006) will be the most useful in the writer's opinion. His work should be extended, especially to finished buildings.

Research to improve the prediction of damping ratios would also be very helpful. Currently, the best design option is to use the values recommended in the established publications. As shown in this research and in others (Barrett 2006), damping can be highly variable, even within a bare floor system. The effects of cladding, partitions, ductwork, and occupants need to be verified and could be directly determined using modal tests similar to those used in this research.

Research on footstep and other forces (running, swaying, etc.) due to human activity, which is a strong focus of international research at the time of this writing, should be continued.