CHAPTER 4

DEVELOPMENT OF A FULL BAY FLOOR MODEL TO PREDICT FUNDAMENTAL NATURAL FREQUENCY

4.1 Overview

To extend the validity of the modeling techniques described in Sections 2.3.5 and 2.3.6, seven in-situ floors were modeled and the predicted frequencies compared to the measured frequencies. Three of the floors were single bay floors and one was a double bay floor, constructed for research purposes. The remaining three floors were located in occupied buildings. The first natural frequency, f_n, of each floor was obtained using either the "heel-drop" test or from experimental modal analysis. The floors were modeled using the techniques developed in Section 3.3.2 and analyzed using SAP2000.

The following sections describe the experimental measurement techniques, the structural aspects of the floors, the finite element models, and the results.

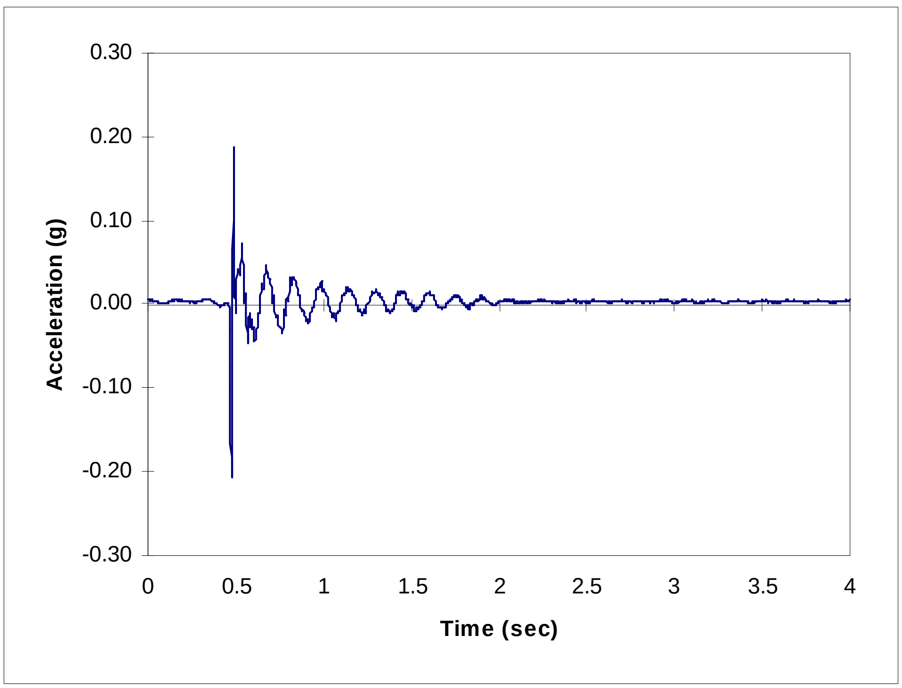
4.2 Experimental Methods for Determining Floor Frequency

Two experimental methods for determining the fundamental natural frequency were used on the floors in this study. The two methods are the "heel drop" test and modal analysis. Heel drop tests were performed on all seven floors, while only three floors were tested using modal analysis. The modal analyses were performed by another researcher, with help from the writer. Only the fundamental natural frequency found by the modal analysis was used in this study.

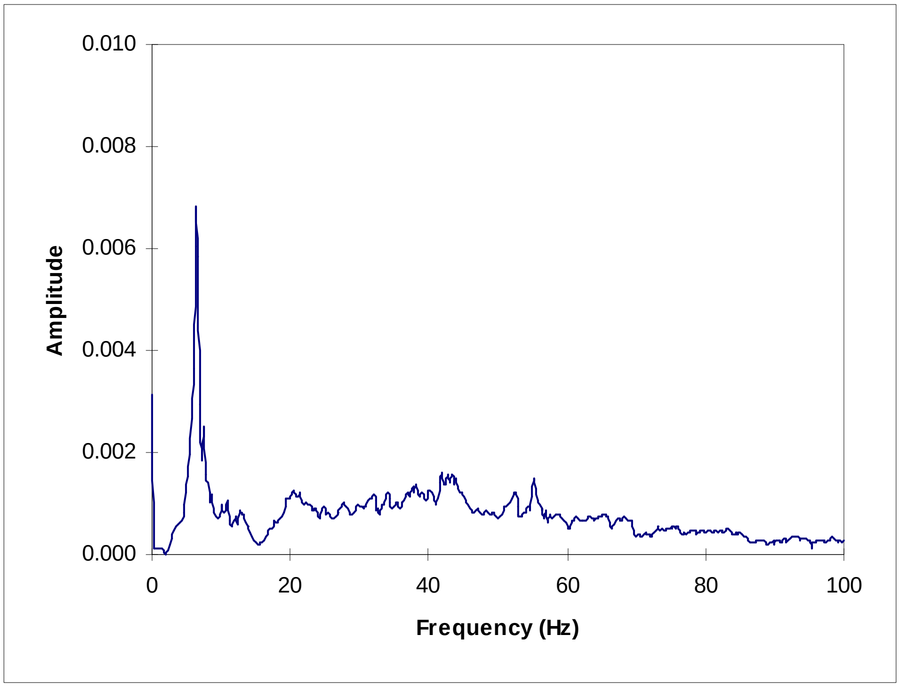
4.2.1 Description of a Heel Drop Test

A common method to model the excitation of a floor due to human occupancy is by way of the heel drop impact test. The heel drop impact is defined as the loading caused by a 190 lb. person, who stands on the balls of his feet with the heels approximately 2 ½ in. above the floor. The person suddenly relaxes and lets his heels fall to the floor, which results in an impact. This heel-drop loading function was first measured by Ohmart and Lenzen (1968) and is approximated by a linearly decreasing, 600 lb. ramp function lasting for 50 ms.

To measure the fundamental natural frequency of the test floors, heel drop tests were performed. The data was recorded using an Ono Sokki CF-1200 Handheld FFT Analyzer. The analyzer recorded the acceleration data picked up by a seismic accelerometer. The accelerometer used is manufactured by PCB Piezotronics as model 393C. From the acceleration data, the analyzer generates the frequency response function from a fast Fourier transform of the data. Figure 4.1 shows a typical acceleration trace and FFT for a heel drop impact.



a) Acceleration Trace of a Heel Drop Impact



b) FFT of a Heel Drop Impact

Figure 4.1 Typical Acceleration Trace and FFT for a Heel Drop Impact

4.2.2 Description of a Modal Analysis Test

For three of the floors a modal analysis was performed. The modal testing done on the three floors was performed by another researcher with assistance from the writer. Following is a brief description of the testing procedure. Analysis and interpretation of the data will not be discussed, for only the first natural frequency was used. All three of the floors had heel drop tests performed in addition to the modal analysis. The modal analysis gave results similar to the heel drop tests.

The basic principle in a modal test is to input energy into the system at a constant point and collect acceleration data from a grid of points on the floor. This data can then be manipulated to develop the mode shapes of the floor. The device used in this study to input energy into the system is an "Electro-Seis Model 400" shaker manufactured by APS Dynamics. This shaker has a reaction mass of 67 lbs. and can be controlled to produce any type of forcing function. The mass is moved by electromagnets and is then acted on by large rubber bands that provide the restoring force. The input function used for the modal test was a burst chirp, which causes the shaker to vibrate through a particular range of frequencies. For the three floor tests, this range of frequencies was usually 0 -50 Hz. The shaker rested on a force plate which was used to measure the excitation force imparted to the floor. This plate used four cantilever beam type load cells, Nikkei model NSB-500, each with a 500 lb. load capacity. A 12 in. x 12 in. x 3/8 in. bottom steel plate supported the four load cells. A 16 in. x 16 in. x 3/8 in. top steel plate was placed on the load cells, and the shaker rested on this plate. The load cells produce a voltage output proportional to the force measured. The four load cells are attached to a summing amplifier which adds the four voltages and produces a single output which is then read by the analyzer.

To collect the floor response data, a Wilcoxon Research seismic accelerometer, model 731, was used. Each floor was first divided into a reasonable sized grid of between 30 to 50 locations. The shaker was placed at a location usually one grid line in from the long edge and two grid lines in from the short edge. Several floor responses were obtained to determine if the shaker was located at a node of one of the first several modes of the floor. If this was the case, the shaker was moved. The shaker was controlled and data collected using a Hewlett Packard 35660A Dynamic Signal Analyzer. Once everything was set up, the data collection began. The accelerometer was placed on the first grid point, then the shaker went through its burst chirp. The floor response was recorded by the accelerometer, the data saved, and the accelerometer was then moved to the next position. This was repeated until all grid points on the floor had been tested. Finally, the data was analyzed and the first natural frequency was determined.

4.3 Description of Floors Used to Develop the Computer Model

Following is a description of the seven floors tested. The joists used in the floors are fully described with the geometry and individual members of the joist listed. The member list specifies the top chord, bottom chord, verticals (if any), and lists the web members. The total number of interior panels, P, are also given, each panel having the dimension given by L4. The geometry of the joists is described in Figure 2.1.

4.3.1 Floor 1 Description

This test floor is located near Blacksburg, Virginia at the Price's Fork Research Park of Virginia Tech. The overall dimensions of the floor are 372 in. by 384 in. There are 31 joists 368 in. in length, 8 in. in depth, spaced at 12 in. on center. For these joists, L1 is 13 in., L2 is 9 in., L3 is 9.5 in., L4 is 19 in., and P is 17. The joists do not have vertical members and were fabricated using round bar webs. The joist seats are 3 in. in depth. The joists are supported on masonry walls with steel plates imbedded in the top course of block. The joists were then welded to this plate. Table 4.1 lists the measured member sizes for this joist, and Figure 4.2 shows a plan view of the floor.

Table 4.1 Member Sizes for Floor 1 Joists

Member	Size (in.)
Top Chord	2L-1.75x1.75x0.143
Bottom Chord	2L-2.00x2.00x0.176
Web	RB 0.50 Dia.

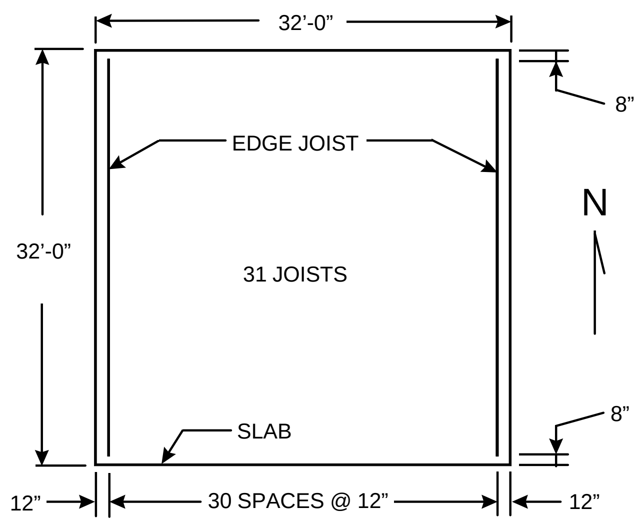


Figure 4.2 Plan of Floor 1

The concrete deck has a total thickness of 2.5 in., which is composed of a 0.6 in. steel deck and a 1.9 in. slab. The concrete used in this floor was assumed to be normal weight concrete, 150 pcf, with a compressive strength of 4000 psi. These parameters give an E_c of 3834 ksi. At the time of testing, there was no additional loading on the floor. The fundamental natural frequency of this floor as determined from a heel drop test was 6.25 Hz. A modal analysis done on this floor gave a frequency of 6.12 Hz.

4.3.2 Floor 2 Description

This test floor is located near Blacksburg, Virginia at the Price's Fork Research Park of Virginia Tech. The overall dimensions of the floor are 387 in. by 384 in. There are nine joists 364 in. in length, 28 in. in depth, spaced as shown on Figure 4.4. For the joist, L1 is 42 in., L2 is 32 in., L3 is 20 in., L4 is 48 in., and P is 5. These joists have vertical members and were fabricated of angle webs. The joist seats are 3.0 in. in depth. The joists are supported on joist girders which are 36 in. in depth. For the joist girders, L1 is 60 in., L2 is 38 in., L3 is 24 in., L4 is 48in., and P is 4. The joist girders have vertical members and were fabricated using angle webs. Table 4.2 lists the measured member sizes for the joists, Table 4.3 lists the measured member sizes for the joist girders, and Figure 4.3 shows a plan view of the floor.

Table 4.2 Member Sizes for Floor 2 Joists

Member	Size (in.)
Top Chord	2L-1.75x1.75x0.163
Bottom Chord	2L-1.50x1.50x0.163
Verticals	1L-1.25x1.25x0.125
W2	RB 0.935 Dia.
W3	1L-1.25x1.25x0.125
W4	2L-2.00x2.00x0.163
W5	1L-1.25x1.25x0.125
W6	1L-1.75x1.75x0.155
W7	1L-1.25x1.25x0.125
W8	1L-1.50x1.50x0.133
W9	1L-1.25x1.25x0.125

Table 4.3 Member Sizes for Floor 2 Joist Girders

Member	Size (in.)
Top Chord	2L-4.00x4.00x0.390
Bottom Chord	2L-4.00x4.00x0.390
Verticals	1L-1.50x1.50x0.155
W2	2L-3.50x3.50x0.375
W3	2L-1.75x1.75x0.155
W4	2L-2.50x3.50x0.260
W5	2L-1.75x1.75x0.155
W6	2L-1.75x1.75x0.155
W7	2L-2.00x2.00x0.187
W8	2L-1.75x1.75x0.155

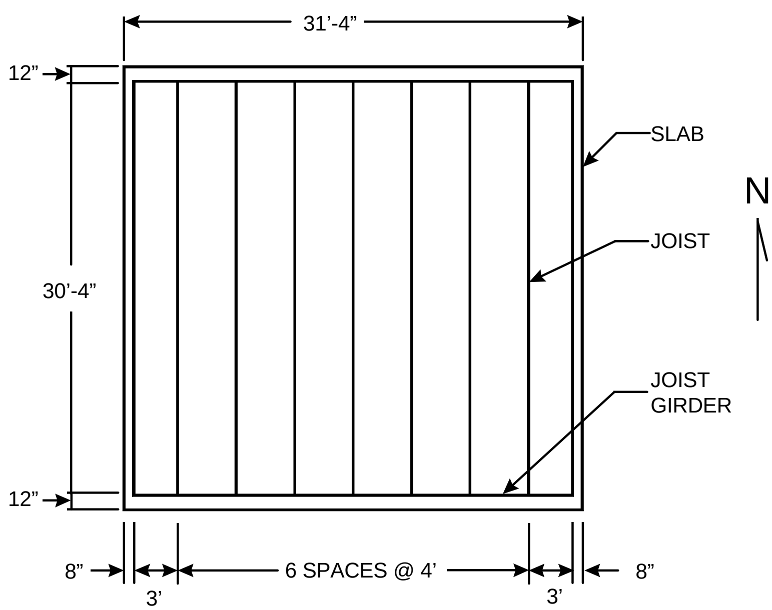


Figure 4.3 Plan of Floor 2

The concrete deck has a total thickness of 2.5 in., which is composed of a 1.0 in. steel deck and a 1.5 in. slab. The concrete used in this floor is lightweight concrete, 120 pcf, with a compressive strength of 4210 psi. These parameters give an E_c of 2815 ksi. At the time of testing, there was no additional loading on the floor. The fundamental natural frequency of this floor as determined from a heel drop test was 7.0 Hz.

4.3.3 Floor 3 Description

This small test floor is located near Eggleston, Virginia. The overall dimensions of the floor are 244 in. by 244 in. There are nine-20K4 joists 244 in. in length, 20 in. in depth, spaced approximately 30 in. on center. For the joist, L1 is 26 in., L2 is 14 in., L3 is 12 in., L4 is 24 in., and P is 7. The joists do not have vertical members and have round bar webs. The joist seat is 3 in. in depth. The joists are supported on 28G8N2.6K joist girders,. For the joist girders, L1 is 47 in., L2 is 32 in., L3 is 15 in., L4 is 60 in., and P is 2. The joist girders have vertical members and were fabricated using angle webs. Table 4.4 lists the measured member sizes for the joist, Table 4.5 lists the measured member sizes for the girder, and Figure 4.4 shows a plan view of the floor.

The concrete deck has a total average thickness of 3.0 in., which is composed of a 1.0 in. steel deck and a 2.0 in. slab. The concrete used in this floor is lightweight concrete, 112 pcf, with a compressive strength of 3860 psi. These parameters give an E_c of 2430 ksi. At the time of testing, there was no additional loading on the floor. The fundamental natural frequency of this floor as determined from a heel drop test was 9.25 Hz. A modal analysis done on this floor gave a frequency of 9.35 Hz.

Table 4.4 Member Sizes for Floor 3 Joists

Member	Size (in.)
Top Chord	2L-1.50x1.50x0.155
Bottom Chord	2L-1.50x1.50x0.113
W2	RB 0.75 Dia.
W3	RB 0.75 Dia.
W4	RB 0.75 Dia.
W5	RB 0.75 Dia.
W6	RB 0.75 Dia.
W7	RB 0.625 Dia.
W8	RB 0.625 Dia.
W9	RB 0.625 Dia.
W10	RB 0.625 Dia.
W11	RB 0.625 Dia.

Table 4.5 Member Sizes for Floor 3 Joist Girders

Member	Size (in.)
Top Chord	2L-2.50x3.50x0.212
Bottom Chord	2L-2.50x3.50x0.212
Verticals	1L-1.50x1.50x0.143
W2	2L-1.50x1.50x0.155
W3	1L-1.50x1.50x0.143
W4	1L-2.00x2.00x0.167
W5	1L-1.50x1.50x0.143
W6	1L-1.50x1.50x0.143

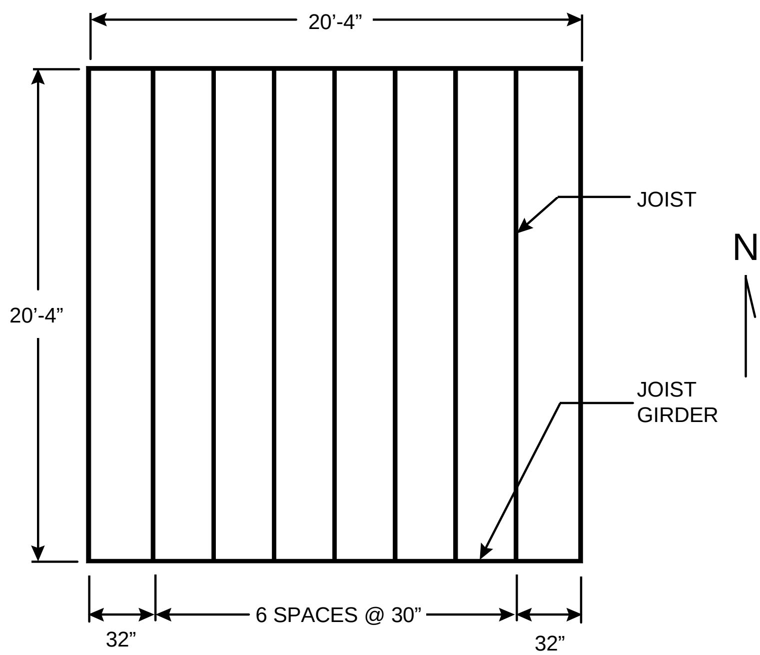


Figure 4.4 Plan of Floor 3

4.3.4 Floor 4 Description

This test floor is located near Blacksburg, Virginia at the Price's Fork Research Park of Virginia Tech. This floor has two bays with overall dimensions of 720 in. by 300 in. There are eleven joists 360 in. in length, 16 in. in depth, spaced 30 in. on center in each bay. For the joists, L1 is 48 in., L2 is 36 in., L3 is 12 in., L4 is 24 in., and P is 10.

The joists use round bar webs without vertical members. The joist seats are 3 in. in depth. The joists are supported on joist girders which are 20 in. in depth. For the girders, L1 is 26 in., L2 is 15 in., L3 is 4 in., L4 is 30 in., and P is 8. The joist girders have vertical members and angle web members. Table 4.6 lists the measured member sizes for the joists, Table 4.7 lists the measured member sizes for the joist girders, and Figure 4.5 shows a plan view of the floor.

The concrete deck has a total thickness of 2.5 in., which is composed of a 0.6 in. steel deck and a 1.9 in. slab. The concrete used in this floor is lightweight concrete, 110 pcf, with a compressive strength of 3000 psi. These parameters give an E_c of 2085 ksi. At the time of testing, there was no additional loading on the floor. The fundamental natural frequency of this floor as determined from a heel drop test was 5.25 Hz.

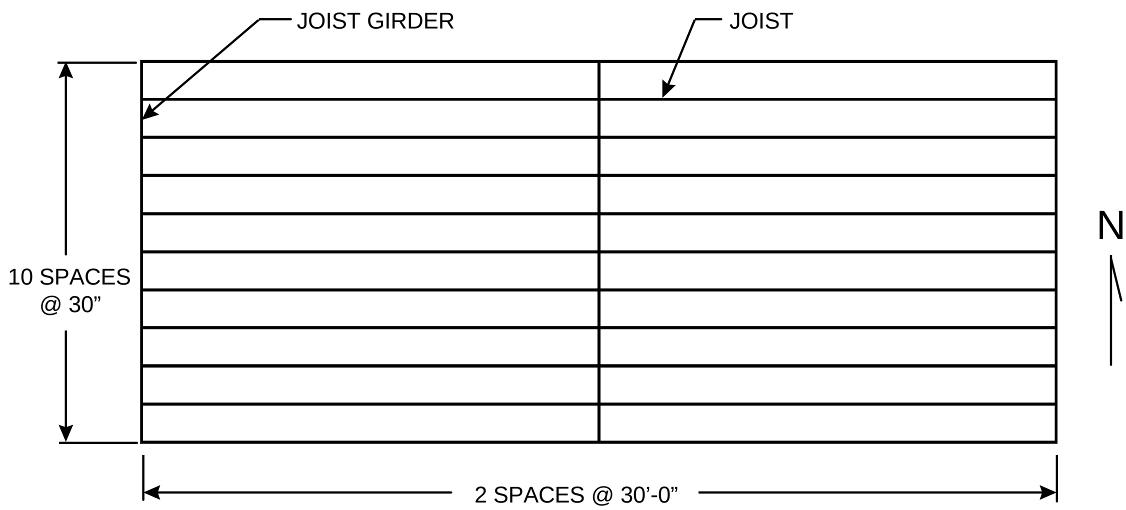


Figure 4.5 Plan of Floor 4

Table 4.6 Member Sizes for Floor 4 Joists

Member	Size (in.)
Top Chord	2L-1.50x1.50x0.133
Bottom Chord	2L-1.25x1.25x0.113
W2	RB 0.65 Dia.
W3	RB 0.57 Dia.
W4	RB 0.57 Dia.
W5	RB 0.57 Dia.
W6	RB 0.57 Dia.
W7	RB 0.57 Dia.
W8	RB 0.57 Dia.
W9	RB 0.57 Dia.
W10	RB 0.57 Dia.
W11	RB 0.57 Dia.
W12	RB 0.57 Dia.
W13	RB 0.57 Dia.
W14	RB 0.57 Dia.

Table 4.7 Member Sizes for Floor 4 Joist Girders

Member	Size (in.)
Top Chord	2L-3.50x3.50x0.313
Bottom Chord	2L-3.50x3.50x0.313
Verticals	1L-1.50x1.50x0.155
W2	2L-2.00x2.00x0.250
W3	1L-1.50x1.50x0.155
W4	2L-1.75x1.75x0.155
W5	2L-1.50x1.50x0.155
W6	2L-1.75x1.75x0.187
W7	2L-1.50x1.50x0.155
W8	2L-1.50x1.50x0.155
W9	1L-1.75x1.75x0.155
W10	1L-1.75x1.75x0.187
W11	1L-1.50x1.50x0.155
W12	1L-1.50x1.50x0.155

4.3.5 Floor 5 Description

This floor is located in a church building in Blacksburg, Virginia. The overall dimensions of the floor area tested are 600 in. by 336 in. There are 15-26K8 joists 600 in. in length, 26 in. in depth, spaced at 24 in. on center. For the joists, L1 is 48 in., L2 is 30 in., L3 is 12 in., L4 is 24 in., and P is 20. The joists were fabricated using round bar webs without vertical members. The joists are supported by stud framed walls. Table 4.8 lists the measured member sizes for the joists, and Figure 4.6 shows a plan view of the floor.

Table 4.8 Member Sizes for Floor 5 Joists

Member	Size (in.)
Top Chord	2L-1.50x1.50x0.193
Bottom Chord	2L-1.50x1.50x0.180
Web	RB 0.892 Dia.

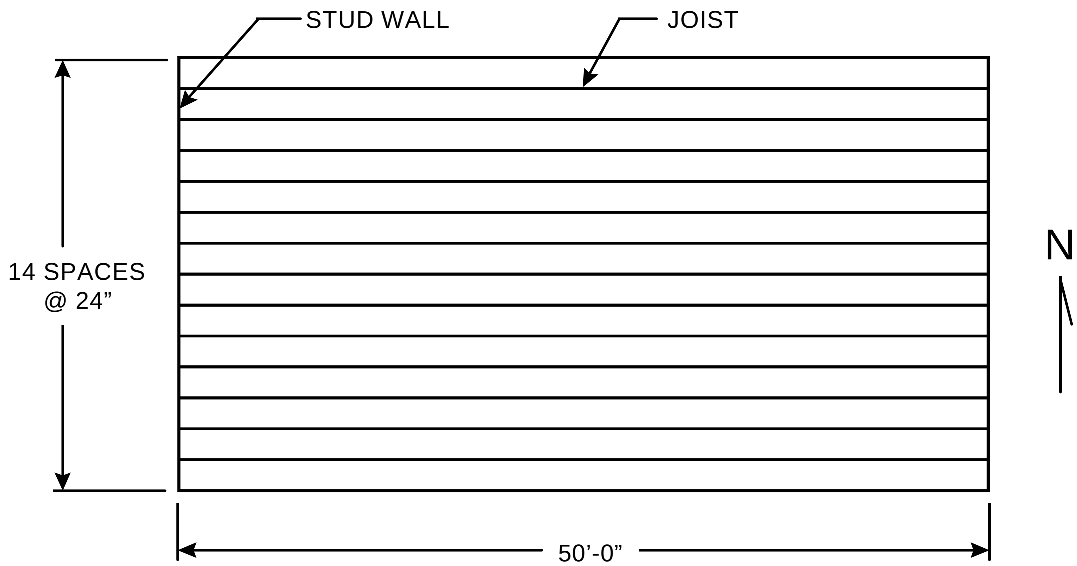


Figure 4.6 Plan of Floor 5

The concrete floor has a total thickness of 2.5 in., which is composed of a 1.0 in. steel deck and a 1.5 in. slab. The concrete used in this floor was assumed to be of normal weight concrete, 145 pcf, with a compressive strength of 3500 psi. These parameters give an E_c of 3410 ksi. At the time of the testing, there was no load on the floor, but the floor did support a hung ceiling, estimated to weigh 4 psf. The fundamental natural frequency of this floor as determined from a heel drop test was 5.25 Hz. A modal analysis done on this floor gave a frequency of 5.38 Hz.

4.3.6 Floor 6 Description

This floor is located in Maryville, Tennessee on the second floor of an office building. The overall dimensions of the floor area tested was 661 in. by 288 in., which is one bay. There are five joists 661 in. in length, 40 in. in depth, spaced at 72 in. on center in each bay. For these joists, L1 is 44 in., L2 is 0 in., L3 is 28.5 in., L4 is 86 in., and P is 6. The joists were fabricated using angle web members including verticals, and in these joists the W3 member shown in Figure 4.1 is a vertical member. The joist seat is 3 in. in depth. These joists are supported on hot rolled girders, W24x84. Table 4.9 lists the design member sizes for the joists, and Figure 4.7 shows a plan view of the floor.

Table 4.9 Member Sizes for Floor 6 Joists

Member	Size (in.)
Top Chord	2L-2.50x3.50x0.230
Bottom Chord	2L-3.00x3.00x0.297
Verticals	1L-1.50x1.50x0.113
W2	2L-1.75x1.75x0.143
W3	1L-1.50x1.50x0.138
W4	2L-2.00x2.00x0.205
W5	2L-1.50x1.50x0.138
W6	2L-1.75x1.75x0.155
W7	1L-2.00x2.00x0.155
W8	2L-1.50x1.50x0.138
W9	1L-1.75x1.75x0.143
W10	1L-2.00x2.00x0.187

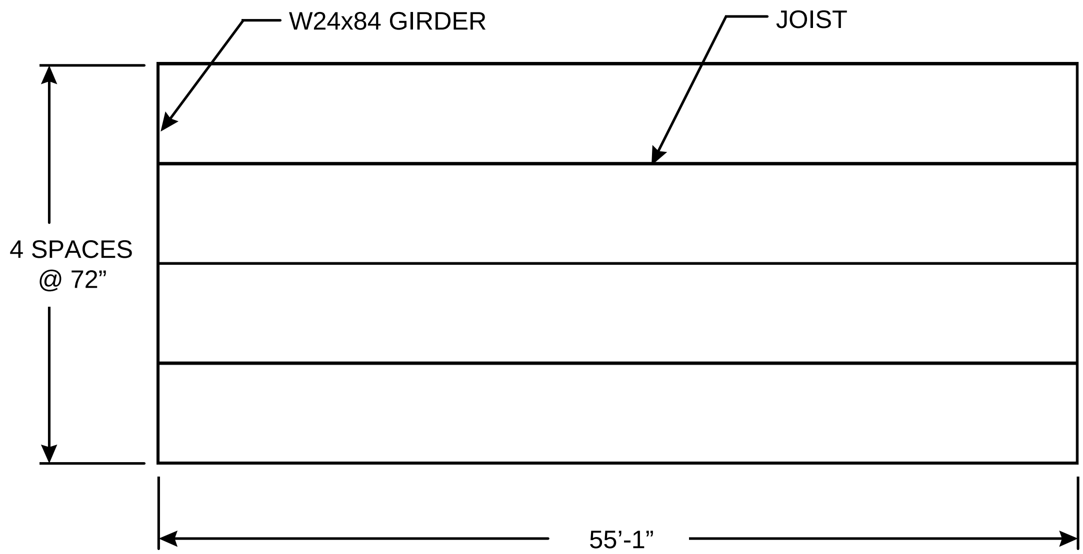


Figure 4.7 Plan of Floor 6

The concrete floor has a total thickness of 5.0 in., which is composed of a 1.5 in. steel deck and a 3.5 in. slab. The concrete used in this floor was assumed to be normal weight concrete, 145 pcf, with a compressive strength of 4000 psi. These parameters give an E_c of 3640 ksi. At the time of the testing, the building was under construction. The estimated load on the floor was 2 psf. The fundamental natural frequency of this floor as determined from a heel drop test was 4.25 Hz.

4.3.7 Floor 7 Description

This floor is located in Maryville, Tennessee on the third floor of the same office building as Floor 6. The overall dimensions of the floor area tested are 661 in. by 288 in., which is one bay of the floor. There are five joists 661 in. in length, 36 in. in depth, spaced at 72 in. on center in each bay. For these joists, L1 is 38 in., L2 is 35 in., L3 is 19.5 in., L4 is 78 in., and P is 7. The joists were fabricated using angle web members including verticals. The joist seat is 3 in. in depth. These joists are supported on hot rolled girders, W24x84. Table 4.10 lists the design member sizes for this joist, and the plan of the floor is the same as that shown in Figure 4.7.

Table 4.10 Member Sizes for Floor 7 Joists

Member	Size (in.)
Top Chord	2L-2.50x3.50x0.230
Bottom Chord	2L-3.00x3.00x0.250
Vertical	1L-1.50x1.50x0.113
W2	RB 1.1875 Dia.
W3	1L-1.50x1.50x0.113
W4	2L-2.00x2.00x0.155
W5	2L-1.50x1.50x0.143
W6	2L-1.75x1.75x0.155
W7	2L-1.50x1.50x0.113
W8	2L-1.50x1.50x0.138
W9	1L-1.50x1.50x0.155
W10	1L-2.00x2.00x0.187
W11	1L-1.50x1.50x0.155

The concrete floor has a total thickness of 5.0 in., which is composed of a 1.5 in. steel deck and a 3.5 in. slab. The concrete used in this floor was assumed to be normal weight concrete, 145 pcf, with a compressive strength of 4000 psi. These parameters give an E_c of 3640 ksi. At the time of the testing, the building was under construction. The estimated load on the floor was 2 psf. The fundamental natural frequency of this floor as determined from a heel drop test was 3.75 Hz.

4.4 Finite Element Modeling for the Tested Floors

Finite element models were developed and analyzed using SAP2000 for each of the tested floors. This model is a full three-dimensional representation of the floor. Each member of every joist was modeled using frame elements, and the concrete deck was modeled using shell elements. The modeling of these floors is described in detail in the following sections.

4.4.1 Description of the Joist Models

The modeling of the joists used Models C and D as defined in Section 2.5.1. Model C was used for joists fabricated with round bar webs, and Model D was used for joists fabricated with angle webs. The difference between these two models is the use of joint offsets in Model D, as described in Section 1.3.2 and shown in Figure 1.7. Since only one type of joist was used in each floor, one joist would be modeled and then copied as many times as needed and placed at the correct locations.

4.4.2 Description of the Concrete Deck Model

The concrete deck was modeled using shell elements. These elements had a thickness equal to that of the concrete above the ribs of the steel deck. The properties of the concrete were modified as described in Section 2.3.6. The dynamic modulus of elasticity was used as described in Section 3.3.2. The shell elements were generally square in shape and between one and two feet on a side. The layout of the shell elements was such that a line of nodes of an edge of shell elements were over each joist so that connections between the joist frame elements and the slab shell elements could be made.

4.4.3 Description of the Connection Between the Slab and the Joists

To model the composite action between the top chord of the floor joists and the concrete slab, a rigid link element, as described in Section 2.3.4, was used. These rigid links are placed between the top chord of the joists and the shell elements of the slab. Figure 1.6 shows a joist model with rigid links connecting the top chord to the beam elements modeling the slab. The locations of the rigid links are similar in this model to those shown in Figure 1.6. All of the rigid links are vertical, so nodes of the shell elements line up over positions on the joist where rigid links are placed. Rigid links are located to maintain a generally uniform spacing along the length of the floor beam. The spacing of these rigid links is the same on every joist within a floor model.

4.4.4 Description of the Girder Models

When joist girders supported the joists, they were modeled using Model D. No joist girders were fabricated using round bar webs in the floors of this study. Floors 6 and 7 used hot rolled sections to support the joist floor. These girders were modeled using a frame element located at the elevation of its centroidal axis. The frame element was divided several times to get acceptable behavior, as described in Section 2.4.

The girders were aligned perpendicular to the floor joists and located at both ends of the joists. The girders were located at the elevations determined by the centroidal axes of there components, either the chords of the joist girders or the center of a hot rolled section. Figure 4.8 shows details of a joist to joist girder connection. This figure also shows the relative elevations of the various components of the floor.

4.4.5 Description of the Joist Seat Connection

The joist seats were modeled using a different type of rigid link element. This element is called a rigid axial element. It is very stiff axially, but very soft in bending. The properties of this element are as follows: 100 in^2 for area and 0.001 in^4 for moment of inertia. All other properties are the same as the rigid bending element described in Section 4.4.3. These elements are used for the connection between the top chord at either end of the joist and the top chord of the girder.

The center joist is not connected to the girder using this rigid link. It uses the normal rigid link element for the joist seat connection. If this was not done, the joists have a tendency to drift to the side, causing the joist-slab system to move side to side relative to the girders. No other connections were made to the girder, such as a link between the girder top chord and the slab. If no girder was present, then these elements were not used.

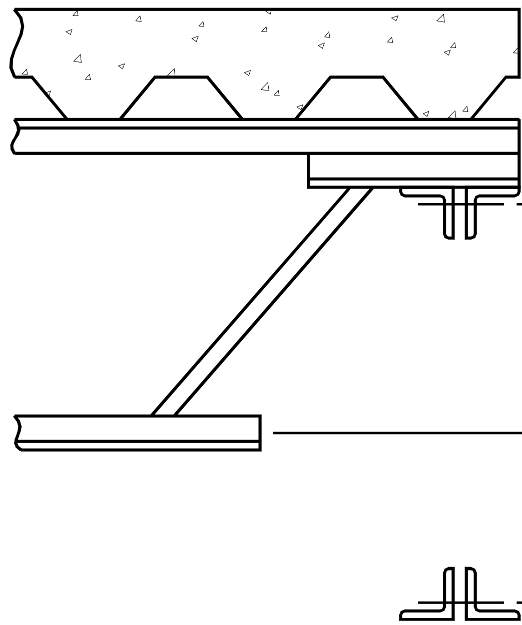


Figure 4.8 Cross Section of a Joist Floor

Originally, rigid bending elements were used to model the joist seats. However, it was determined that this was stiffening the model, due to the higher than expected frequency results from the model. This meant that the model was creating full composite action between the girder and the concrete slab, which, as discussed in Section 1.3.1, is not thought to be the true behavior of the girder. By using weak bending elements to model the joist seats, little composite action can form, thereby lowering the stiffness of the system and the frequency.

4.4.6 Description of the Joint Restraints

Once the joist, girder, and slab elements were defined, various joint restraints were applied. Since this is a three-dimensional model, there are six degrees of freedom at every joint. Originally, all of the joints were restrained similar to that of the single joist models in Chapter 3. However, this created a very stiff model which did not behave as expected. One main reason for this is that not all of the members are oriented in the same direction, such as the girders. Therefore, a system of restraints, as defined below, was developed. These restraints keep the behavior of the model consistent with that of the actual floor, while allowing enough degrees of freedom to prevent the model from being too stiff.

The first set of restraints is on the bottom chords of every joist or joist girder. Each joint was restrained in the one degree of freedom which is perpendicular to the plane of the joist or the girder. These restraints kept the joists or girders from moving out of plane. The next set of restraints model the support conditions for the girders. On one girder, a pin is modeled by restraining all of the translational degrees of freedom at one end. On the other end of the same girder, two degrees of freedom are restrained, which are the vertical and out of plane degrees of freedom. For the other girder, rollers are modeled by restraining only the vertical degree of freedom. This was done on both ends of the girder. For the Floors 1 and 5 which did not have girders, the above was done in a slightly different fashion. The first set of girder restraints was applied to an edge joist, and the second set of girder restraints was applied to all of the other joists.

In addition to the joist restraints, a set of restraints was applied to the slab. These restraints are similar to those of the first set of girder restraints described above, except the vertical degree of freedom was not restrained. The restraints are located on the extreme corners of the slab above the girder, which is pinned. On the slab above the pin, both of the horizontal degrees of freedom were restrained. On the slab above the other end of the pinned girder, the degree of freedom out of the plane of the girder was restrained. Figure 4.9 shows the slab and girder restraints described above. The solid boxes at the ends of the girders represent a roller support condition. The small lines on the right side of the figure represent a joint restraint in the direction of the line.

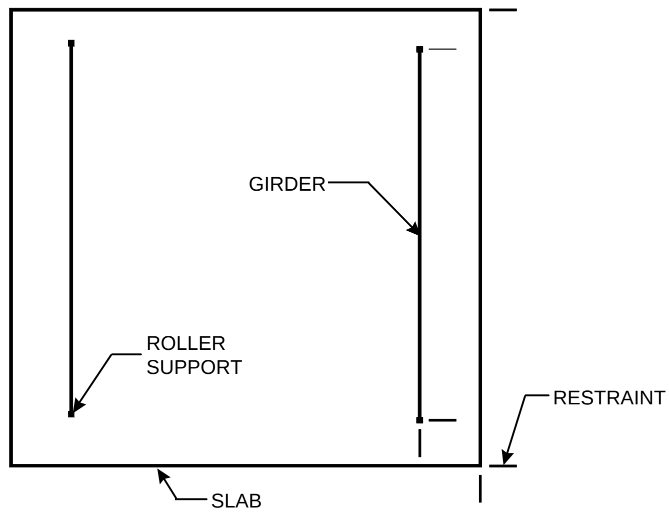


Figure 4.9 Definition of Slab and Girder Restraints

4.4.7 Description of Model Analysis and Output

Once the entire model was defined, an analysis was done to determine the first natural frequency, f_n, of the model. For these models, all degrees of freedom were active. Only f_n was determined from the models. No other analyses were done. To obtain f_n, an eigenvector analysis was performed by SAP2000. This is an option that is set by the user when defining the analysis settings, along with the number of modes desired. After several minutes of analyzing the model, SAP2000 provides the results of the dynamic analysis by giving the period of each mode requested. To obtain the frequency, the period is inverted.

Because the dynamic analysis in SAP2000 is mathematically driven, the mode of the first frequency of the system may not be the one that the actual floor experiences. The first mode desired is the first bending mode. Other modes, such as torsional ones, may be lower if the model was improperly defined. One of the reasons for the particular joint restraint scheme described in Section 4.4.6 was to prevent the torsional modes while still allowing the bending modes of the system. A feature of SAP2000 is that it can display the mode shape of a particular frequency, and it can animate this mode shape. Therefore, to make certain that the frequency obtained from the dynamic analysis was actually the first bending mode, the mode was animated. If the animation was consistent with the first bending mode, which is essentially an oscillating half sine wave, then the value for the frequency was accepted. If not, the model was checked to see if errors had occurred in its definition.

4.5 Results of the Finite Element Models

The seven floors described in Section 4.3 were analyzed using the modeling techniques described in Section 4.4 to determine the fundamental natural frequency. This model was consistently used for each floor without any specialization. The only difference in the overall definition of each floor was in its girder condition. By using a consistent model for all of the floors, the ability of the model to predict the first natural frequency of real floors could be investigated.

Each floor was experimentally tested to determine its fundamental natural frequency. Table 4.11 shows the first natural frequency, in Hz., from finite element analyses and the experimental result for each floor. Heel-drop impact results are shown for floors F2, F4, F6, and F7, while results from the experimental modal analysis are shown for floors F1, F3, and F5. Figure 4.10 graphically displays the data in Table 4.11. This graph plots the value of frequency obtained from the finite element model against the value obtained experimentally. The solid line on Figure 4.9 represents an exact match of the value for frequency obtained from the finite element model and the experimental value. The closer a data point is to this line, the better the agreement is between the finite element model and the experimentally obtained value.

Table 4.11 Finite Element and Experimental Floor Frequency Results

	Frequency, Hz.	
Floor	Finite Element	Exp.
F1	5.63	6.12
F2	7.60	7.00
F3	10.10	9.35
F4	5.06	5.25
F5	4.98	5.38
F6	4.44	4.25
F7	3.91	3.75

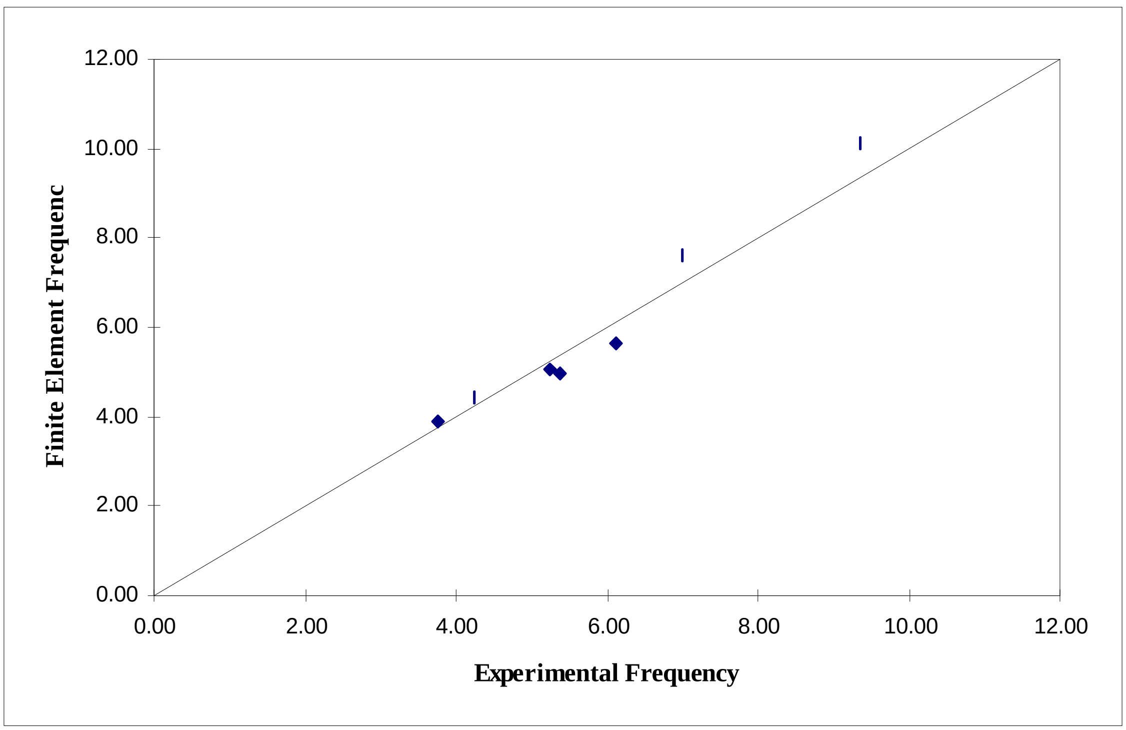


Figure 4.10 Finite Element vs. Experimental Floor Frequency, Hz.

4.6 Results of the Hand Calculations for the Floors

In addition to the finite element models generated for the seven floors, hand calculations were done using Equations (1.1), (1.2), and (1.7). Appendix D shows a sample calculation for a joist floor supported by joist girders. Table 4.12 shows the first natural frequency, in Hz., from the experimental results and hand calculations for each floor. Figure 4.11 graphically displays the data in Table 4.12. This graph plots the value of frequency obtained from the hand calculations against the value obtained experimentally. The solid line on Figure 4.10 represents an exact match of the value for frequency obtained from the finite element model and the experimental value.

Table 4.12 Hand Calculated and Experimental Floor Frequency Results

	Frequency, Hz.	
Floor	Hand	Exp.
F1	5.56	6.12
F2	7.86	7.00
F3	9.66	9.35
F4	5.22	5.25
F5	4.55	5.38
F6	4.47	4.25
F7	3.85	3.75

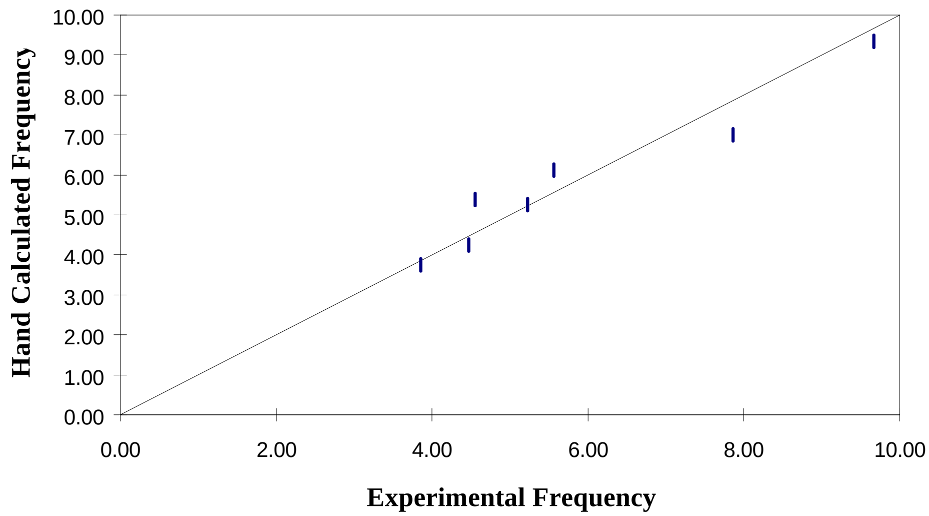


Figure 4.11 Hand Calculated vs. Experimental Floor Frequency, Hz.

4.7 Comparison of Finite Element, Hand Calculated, and Experimentally Determined Frequencies

The value of the finite element and the hand calculated freq uency was divided by the experimental value. A statistical analysis of each set of ratios was then performed to determine the average, standard deviation (SD), and the coefficient of variation. These results are presented in Table 4.13.

Table 4.13 Statistical Analyses of Floor Frequency Results

Floor	FE/Exp.	Hand/Exp.
F1	0.920	0.908
F2	1.086	1.123
F3	1.080	1.033
F4	0.964	0.994
F5	0.926	0.846
F6	1.045	1.052
F7	1.043	1.027
Average:	1.009	0.998
Std. Dev.:	0.071	0.093
Coeff. of Var., %:	7.042	9.310

From the data in Table 4.13, some observations can be made. First, the coefficient of variation of both sets of ratios is under 10%. Since the averages of both sets of ratios are very close to 1.0, the fact that the coefficient of variation is under 10% means that the finite element model and the hand calculations are predicting the first natural frequency of actual floors within 10%, on average. The finite element model is better at predicting the first natural frequency, with a coefficient of variation of 7%. The coefficient of variation for the hand calculations is 9.3%.

4.8 Conclusions

The results presented in Section 4.7 indicate that the finite element model is an accurate method to predict the first natural frequency of in-situ floors. The models were able to predict within 10%, on average, the measured value of f_n for all of the floors. Equations (1.1), (1.2), and (1.7) were also able to predict the value of f_n for the floors, but with slightly less agreement with the experimental values. Overall, both methods give good results in predicting f_n for the floors of this study.