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METHODS TO IMPROVE THE VIBRATION CHARACTERISTICS OF JOIST SUPPORTED FLOOR SYSTEMS

by

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(ABSTRACT)

The development of high strength, light weight materials has generated more efficient designs of steel joist-concrete slab floor systems. Though the structural integrity is rarely compromised, these floor systems are more susceptible to human-induced vibrations which may be annoying to the occupants of the structure.

The purpose of this investigation was to develop methods of improving the vibration characteristics of joist-supported floor systems. The frequency and first maximum amplitude of vibration can be altered by redesigning the cross-section of the floor system in order to improve its acceptability. However, damping has the greatest effect on the perceptibility of occupant-induced floor vibrations. Therefore, this study focussed on devising methods of increasing damping in joist supported floor systems.

Steel joist-metal deck-concrete slab test floors were constructed for the purpose of this investigation. In addition, a two-bay building was constructed so that the developments of this research could be field tested. The experimental results were presented and recommendations were made for future work in this field.

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INTRODUCTION AND LITERATURE REVIEW

1.1 Scope

The increased use of high strength, light-weight building materials has been accompanied by a greater awareness of occupant-induced floor vibrations. Designers are recognizing that even though floor systems constructed with these materials are generally structurally sound, such floors are more susceptible to annoying vibrations caused by human footfalls. These vibrations can often be severe enough to discomfort the occupants, drastically affecting the intended use of the building. Realizing the magnitude of this serviceability problem, occupant-induced floor vibrations are receiving greater attention from both design and research engineers.

1.2 Review of Previous Research

Previous research has shown that human perceptibility of these transient floor motions is dependent upon three vibration parameters: frequency, maximum amplitude, and damping [Lenzen and Murray 1969]. Several scales have been introduced which gauge the human perceptibility of steady-state vibrations [Pool and Murray 1972]. These scales show how relationships between frequency and maximum amplitude affect the human sensitivity to floor vibrations. However, it has been determined that damping plays a vital role and should be included in acceptability analyses of systems susceptible to occupant-induced floor vibrations.

Damping is implicitly considered in the commonly-used modified Reiher-Meister scale (Figure 1.1). The original version of this scale was developed for steady-state vibrations [Reiher and Meister 1931]. Lenzen [1966] determined from experimental tests that damping could be accounted for by increasing the amplitude axis by a factor of ten. This adjustment is reflected in the modified scale.

Studies by Murray [1981] have shown that the modified Reiher-Meister and other scales are inconsistent in their incorporation of damping into acceptability criteria. These scales underestimate the effect of damping and yield conservative appraisals of the acceptability of floor systems. Murray developed a new criterion after experimentally studying over 90 floor systems. This guideline is represented by:

$$D > 35A_o f + 2.5 \qquad (1.1)$$

where D = damping in percent of critical, A_o = maximum amplitude of motion in inches resulting from a heel-drop impact, and f = first natural frequency of the floor system in hertz. If the inequality is satisfied, occupants of the structure will not be disturbed by floor vibrations resulting from normal human activity. Murray also concluded that if the damping required for acceptability based on Equation 1.1 is less than 3.0 to 3.5%, the system will be acceptable regardless of the provided damping [1982].

The frequency and maximum amplitude of vibration must first be determined before the modified Reiher-Meister scale or Murray's criterion can be employed. It has been shown that the first natural frequency of a steel beam- or steel joist-concrete slab floor system can be calculated using a single T-beam model [Ohmart 1968, Lenzen and Murray 1969]. The simply-supported T-beam is

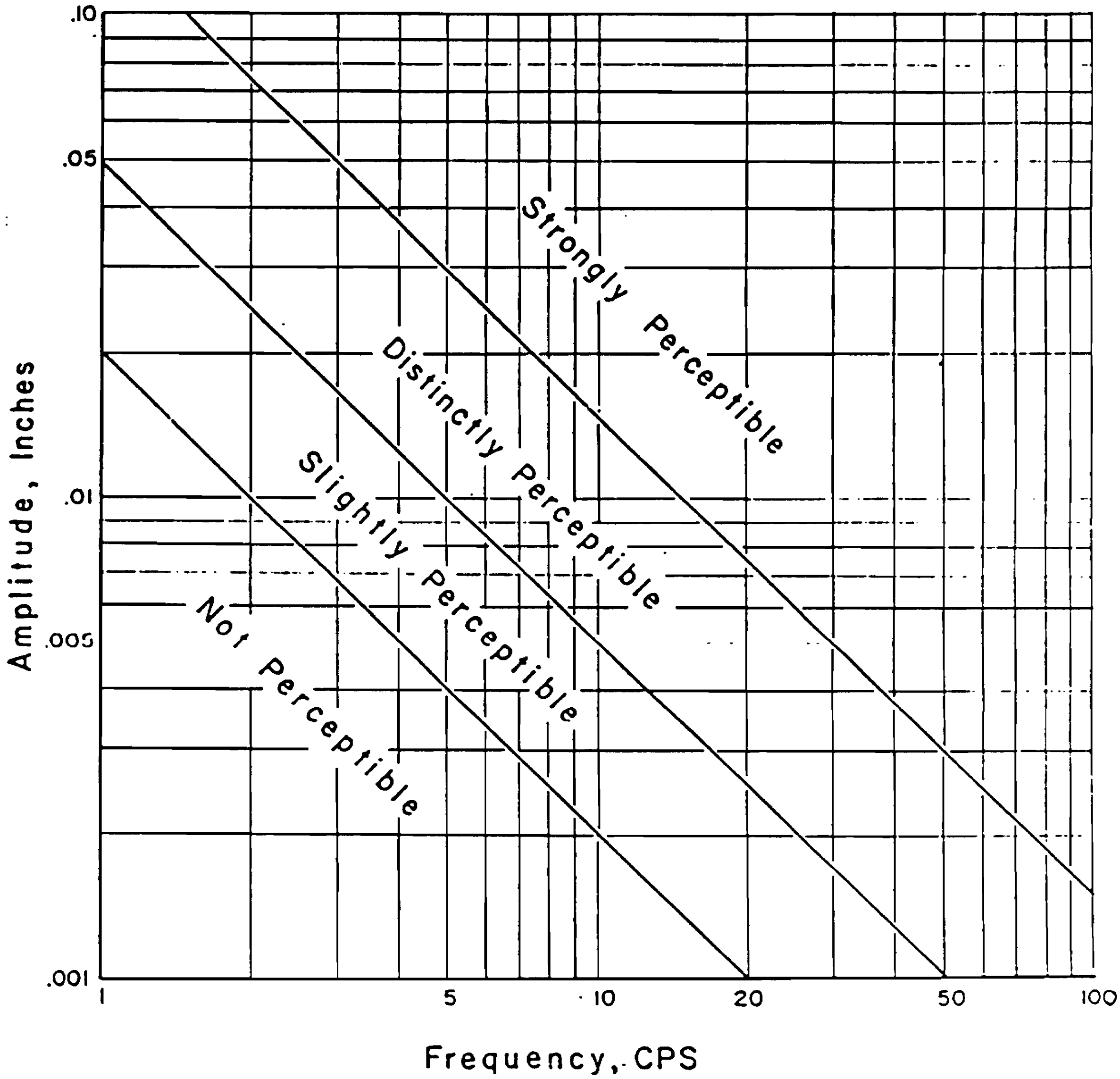


Figure 1.1. Modified Reiher-Meister Scale

comprised of the beam or joist and a section of the slab equal to the beam or joist spacing. This procedure assumes composite action of the system even if the slab is not structurally connected to the supporting beams or joists. Studies have shown that the impacting force is not significant enough to overcome the friction force between the components of the floor [Murray 1989]. With this assumption, the frequency can be predicted by:

$$f = 1.57\sqrt{\frac{gEI_t}{WL^3}} \tag{1.2}$$

where g = 386.4 in/sec, E = modulus of elasticity in ksi, I_t = transformed moment of inertia in in^4, W = total weight supported by the T-beam in kips, and L = T-beam span in inches. The weight contribution of the slab is calculated using an effective slab depth, d_e. This depth is defined as that which produces the same weight of the actual slab including concrete in the ribs of the deck and the weight of the deck for the given slab width. The total weight, W, should include all dead load as well as an estimate of the live load normally present on the floor (11% of the design live load). Without the inclusion of live load, frequencies predicted by Equation 1.2 would be conservative for vibration analyses.

In some systems, the T-beams will vibrate with the supporting girders as a unit. This usually occurs when the girders are flexible relative to the floor beams or joists. If this be the case, the system frequency can be approximated using Dunkerley's equation:

$$\frac{1}{f_s^2} = \frac{1}{f_b^2} + \frac{1}{f_g^2} \tag{1.3}$$

where f_s = system frequency, f_b = T-beam frequency, and f_g = girder frequency.

The maximum amplitude results from a standard "heel-drop" impact on the floor. The heel-drop is characterized by a 190-lb man standing relaxed with his heels approximately one and one-half inches off the floor then suddenly dropping his heels and allowing his weight to impact the floor. The force vs. time relationship of the actual heel-drop can be approximated by a 600 lb force linearly decreasing to zero force after 50 milliseconds (Figure 1.2).

The T-beam maximum amplitude, in inches, resulting from a heel-drop can be calculated by:

$$A_{ot} = (DLF)_{max}\, d_s \tag{1.4}$$

where $(DLF)_{max}$ = maximum dynamic load factor (Table 1.1) and d_s = static deflection in inches resulting from a 600 lb concentrated force at midspan. For the simply supported case:

$$d_s = 600L^3/48EI_t \tag{1.5}$$

where L, E, and I_t are as described for Equation 1.2. The maximum amplitude of a single T-beam often overestimates the maximum amplitude of the entire floor system. This is because the floor system acts as an orthotropic plate that is stiffer than a single T-beam of the system. To account for this, the system maximum amplitude is determined by:

$$A_o = A_{ot}/N_{eff} \tag{1.6}$$

where N_{eff} = number of effective T-beams of the system that act to resist the heel-drop impact. Several equations exist for calculating N_{eff} for steel beam- or

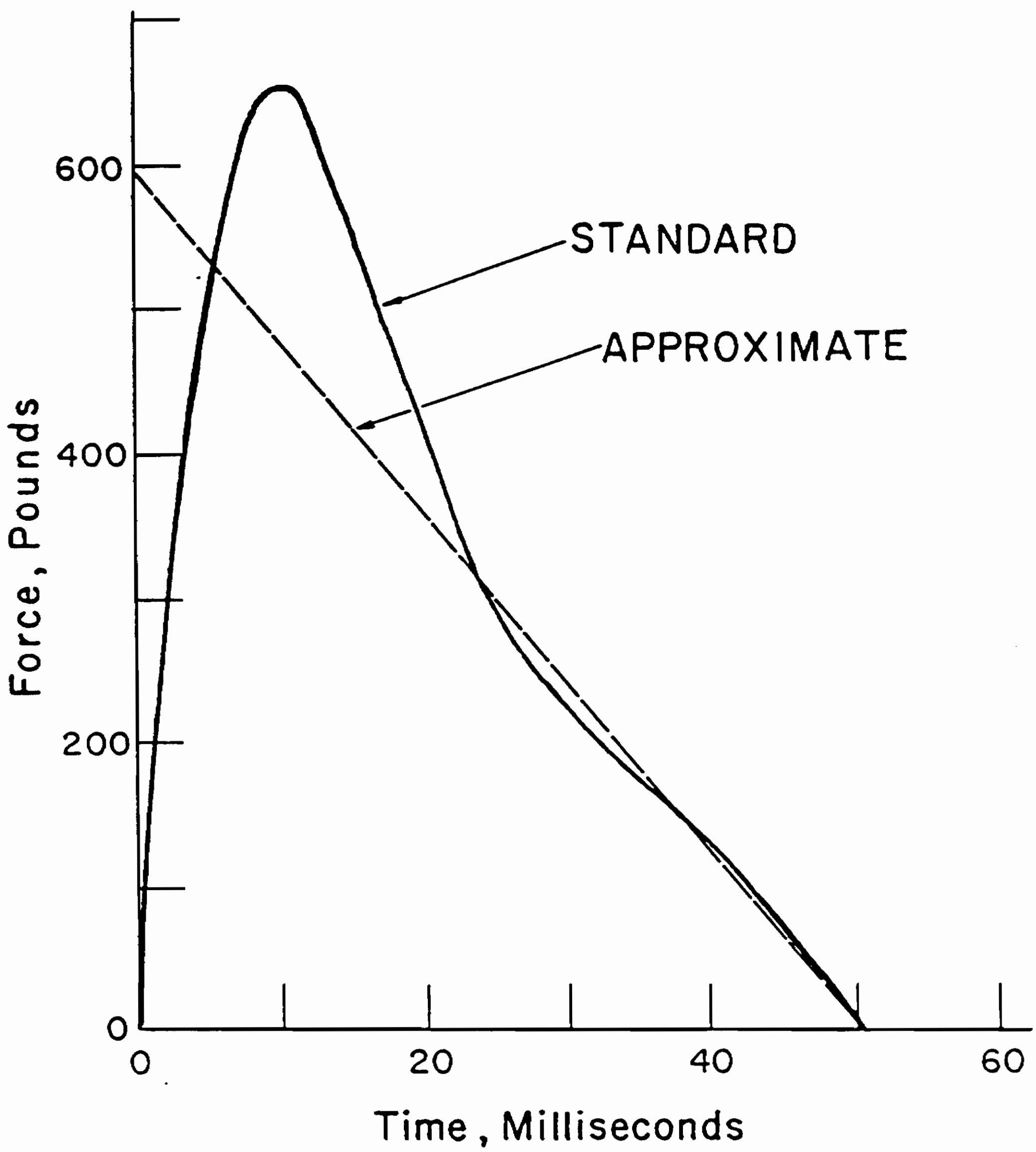


Figure 1.2 Heel-Drop Impact

Table 1.1 Dynamic Load Factors for Heel-Drop Impact

f,Hz	DLF	f,Hz	DLF	f,Hz	DLF
1.00	0.1541	5.50	0.7819	10.00	1.1770
1.10	0.1695	5.60	0.7937	10.10	1.1831
1.20	0.1847	5.70	0.8053	10.20	1.1891
1.30	0.2000	5.80	0.8168	10.30	1.1949
1.40	0.2152	5.90	0.8282	10.40	1.2007
1.50	0.2304	6.00	0.8394	10.50	1.2065
1.60	0.2456	6.10	0.8505	10.60	1.2121
1.70	0.2607	6.20	0.8615	10.70	1.2177
1.80	0.2758	6.30	0.8723	10.80	1.2231
1.90	0.2908	6.40	0.8830	10.90	1.2285
2.00	0.3058	6.50	0.8936	11.00	1.2339
2.10	0.3207	6.60	0.9040	11.10	1.2391
2.20	0.3356	6.70	0.9143	11.20	1.2443
2.30	0.3504	6.80	0.9244	11.30	1.2494
2.40	0.3651	6.90	0.9344	11.40	1.2545
2.50	0.3798	7.00	0.9443	11.50	1.2594
2.60	0.3945	7.10	0.9540	11.60	1.2643
2.70	0.4091	7.20	0.9635	11.70	1.2692
2.80	0.4236	7.30	0.9729	11.80	1.2740
2.90	0.4380	7.40	0.9821	11.90	1.2787
3.00	0.4524	7.50	0.9912	12.00	1.2834
3.10	0.4667	7.60	1.0002	12.10	1.2879
3.20	0.4809	7.70	1.0090	12.20	1.2925
3.30	0.4950	7.80	1.0176	12.30	1.2970
3.40	0.5091	7.90	1.0261	12.40	1.3014
3.50	0.5231	8.00	1.0345	12.50	1.3058
3.60	0.5369	8.10	1.0428	12.60	1.3101
3.70	0.5507	8.20	1.0509	12.70	1.3143
3.80	0.5645	8.30	1.0588	12.80	1.3185
3.90	0.5781	8.40	1.0667	12.90	1.3227
4.00	0.5916	8.50	1.0744	13.00	1.3268
4.10	0.6050	8.60	1.0820	13.10	1.3308
4.20	0.6184	8.70	1.0895	13.20	1.3348
4.30	0.6316	8.80	1.0969	13.30	1.3388
4.40	0.6448	8.90	1.1041	13.40	1.3427
4.50	0.6578	9.00	1.1113	13.50	1.3466
4.60	0.6707	9.10	1.1183	13.60	1.3504
4.70	0.6835	9.20	1.1252	13.70	1.3541
4.80	0.6962	9.30	1.1321	13.80	1.3579
4.90	0.7088	9.40	1.1388	13.90	1.3615
5.00	0.7213	9.50	1.1434	14.00	1.3652
5.10	0.7337	9.60	1.1519	14.10	1.3688
5.20	0.7459	9.70	1.1583	14.20	1.3723
5.30	0.7580	9.80	1.1647	14.30	1.3758
5.40	0.7700	9.90	1.1709	14.40	1.3793

steel joist-concrete slab floor systems; however, one equation has been developed that is applicable to both types of construction [Shamblin 1989]. Based on a study of 240 floor systems, the number of effective T-beams is calculated by:

$$N_{eff} = 31.4506\frac{d_e}{S} + 0.2777\frac{L^4}{EI_t} + 0.2370\frac{L}{S} \tag{1.7}$$

where S = beam or joist spacing in inches and d_e, L, E, and I_t are as previously stated.

If the T-beams and supporting girders vibrate as a unit as previously described, the system amplitude can be approximated by:

$$A_{os} = A_{ob} + A_{og}/2 \tag{1.8}$$

where A_{os} = system amplitude, A_{ob} = T-beam amplitude, and A_{og} = girder amplitude (with N_{eff} = 1.0). Once f and A_o have been determined, the required damping based on Equation 1.1 can be calculated.

Damping, or the removal of energy from a vibrating system, is to some degree present in all dynamic structures. Unless there is a driving force which will maintain a constant amplitude of vibration, energy will leave the system, and the motion will eventually stop. There are three forms of energy dissipation, and each will be briefly discussed. Complete explanations of the types of damping should be available in any good structural dynamics text.

A velocity dependent form is viscous damping. In hydraulic shock absorbers, dashpots, or when masses move on or in fluids, a resisting force is produced which is proportional to the velocity of motion. This resisting force promotes the energy dissipation from the system and reduces the oscillatory motion.

Coulomb friction-damping is another form of energy dissipation. This occurs when bodies slide on dry surfaces. Coulomb damping is attractive because the resisting force, simple friction, is constant. The only factors affecting the damping are the normal force and the coefficient of kinetic friction. Several concepts in this investigation dealt with the use of friction to increase the damping of floor systems and will be introduced later.

The third type of energy dissipation is hysteresis, or structural, damping. This form results when internal frictional resistance is produced by molecular slip in the structural material. When structural members are deformed, energy is dissipated in the form of heat created by the internal movements. Although many factors can affect this form of damping [Lazan and Goodman 1961], it has been determined that hysteresis damping is proportional to the displacement amplitude and independent of the frequency of motion. Several concepts of this study focussed on structural damping as a means of improving the vibration characteristics of joist supported floors.

There is no means of accurately predicting the inherent damping of a particular floor system; however, estimates of the damping contributions of various building components have been suggested [Murray 1975]. If the vibration analysis is being conducted during the pre-construction (design) stage, a reasonable forecast of the damping must be made to determine the acceptability of the floor system based on Equation 1.1. If the provided damping is greater than required, no occupant-induced vibration problem should exist. If the inequality is not satisfied, then redesign may be necessary and can result in a significant increase in the cost of the structure. When redesign is not successful or not economical, the damping may be artificially increased to satisfy Murray's criterion [Murray 1989]. For post-construction analyses, the actual damping can be experimentally measured and calculated. Once the vibration response has been recorded, the damping in percent of critical can be obtained from:

$$D = \frac{230.3}{2\pi(m-n)} \log \frac{A_n}{A_m} \tag{1.9}$$

where A_n = amplitude of the n^{th} peak, A_m = amplitude of the m^{th} peak, and m−n = number of peaks. If the measured damping is less than required by Equation 1.1, artificial methods of damping may be necessary.

Attempts to artificially increase the energy dissipation from floor systems have been described in previous studies; however, the methods can be expensive, impractical, and/or unsuccessful depending on the floor system. Dynamic vibration absorbers were successfully used by Lenzen [1966] on a test floor. However, reports of effective installations of such devices in actual buildings are unknown.

Viscoelastic materials have great potential for increasing the energy dissipation from vibrating structures. The variety of materials available provide a broad spectrum of dynamic properties to match the design application. Viscoelastic materials have been used as damping mechanisms in automobiles, aircraft, ships, computer hard disk drives, office copiers, and building floor systems. Damping posts using viscoelastic material were installed in an office floor and studied by Allen and Swallow [1975]. The posts were successful in reducing the perceptibility of motion, but they interfered with the use of the floor space. Nelson [1968] investigated the use of viscoelastic material attached to the bottom flanges of beams in a building to reduce annoying floor vibrations. The improvements were marginal, and similar installations are often costly [Murray 1989].

Even though dampers have been developed which incorporate Coulomb friction [Crede 1961], only one study to date has investigated damping annoying floor vibrations with a friction device. In an unpublished investigation, dampers were constructed so that when the test floor vibrated, steel plates in contact produced friction forces which enhanced the energy dissipation from the system. Laboratory simulations with this device were effective, but field installations were not successful [Murray 1989a].

Of the three vibration parameters, damping is the most important to human perceptibility of occupant-induced floor motions. Frequency and maximum amplitude depend upon the stiffness of the system. However, as the cross-section of the floor is altered, improvements in one usually result in offsetting changes in the other and no significant reductions in perceptibility are obtained. Therefore, this investigation will focus on improving the vibration characteristics of joist supported floor systems by developing artificial methods of increasing damping.

1.3 Method of Evaluation

To evaluate the concepts derived in this investigation, six two-joist floor systems were constructed and dynamically tested. The vibration parameters of these floors were measured, and improvements in these parameters produced by the developments of this study were determined.

In addition, field tests were conducted to study the performance of one of these concepts installed in an actual building, constructed for the purpose of this investigation. The framing plan and elevation of this "vibration test facility" is illustrated in Figure 1.3. Six braced columns support three joist girders and two bays of eleven floor joists, spaced as shown. Metal deck was attached to the top

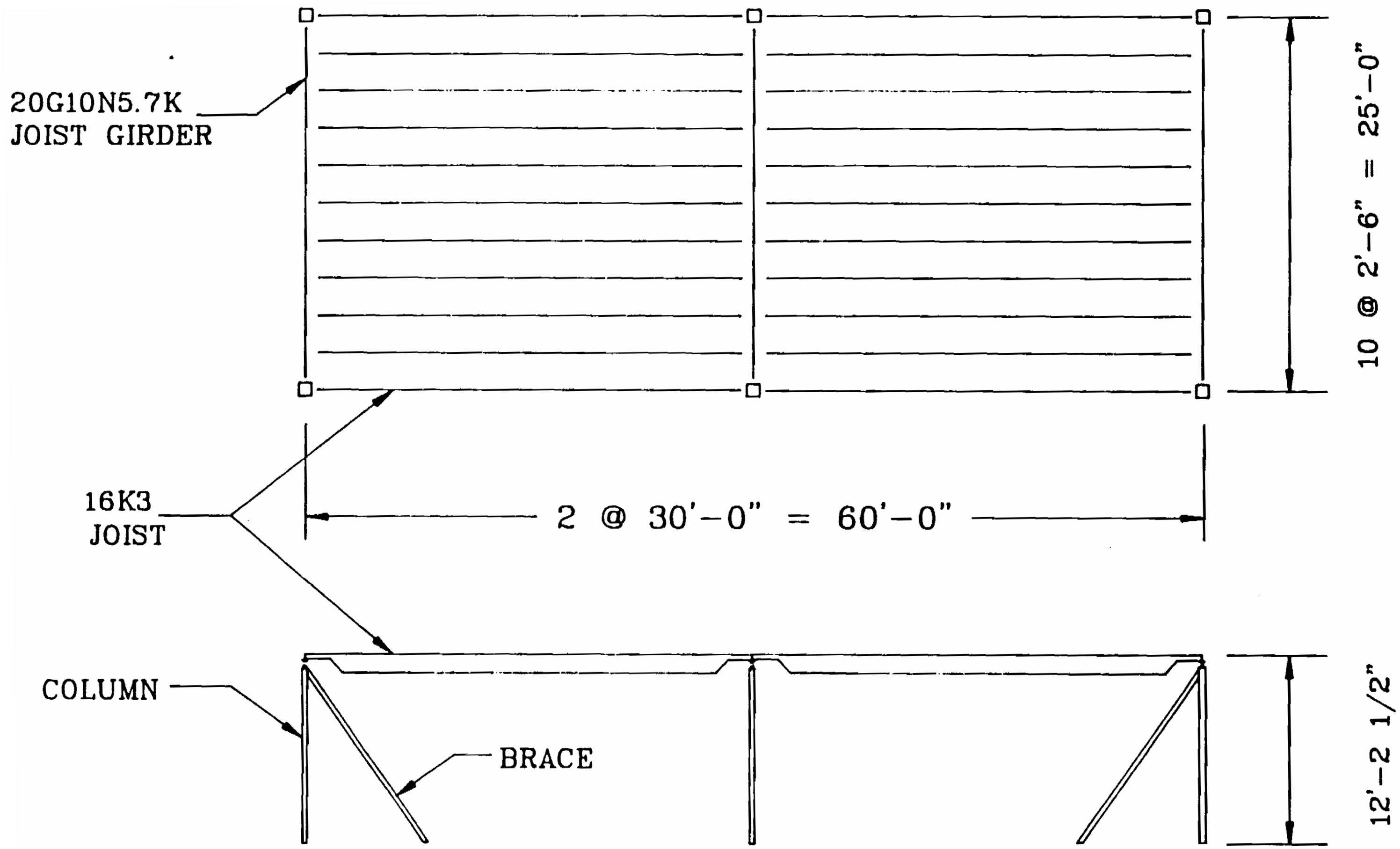


Figure 1.3 Two-Bay "Vibration Test Facility"

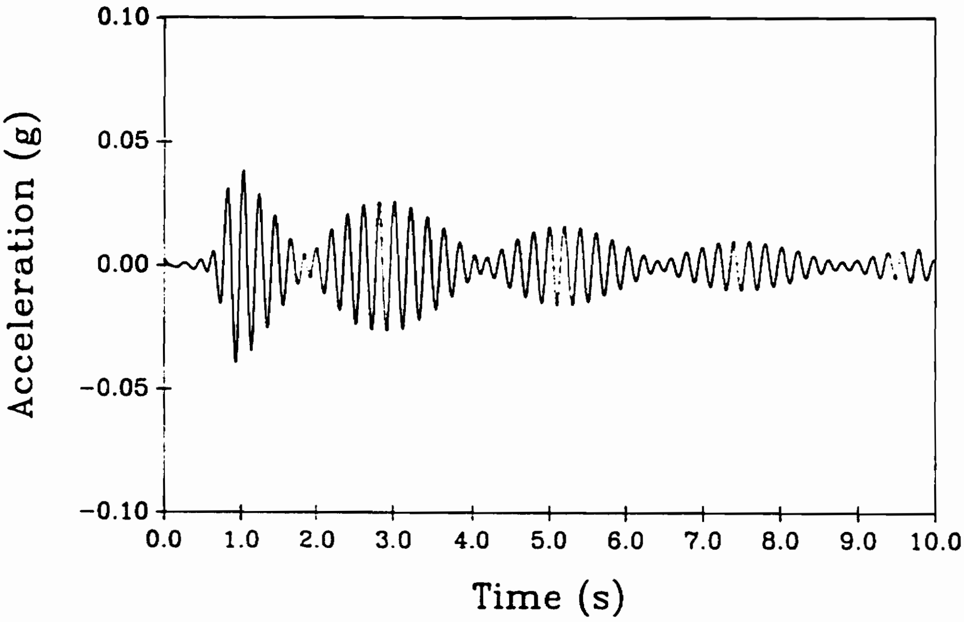
chord of the floor joists, and a 2 1/2" normal weight concrete slab was placed on top to complete the floor.

The two-bay building is structurally safe; however, the floor was designed so that the occupant-induced vibrations would be annoying. The predicted natural frequency and maximum amplitude due to a human heel-drop in the center of a bay of this floor is 5.0 hz and 0.0240 inches respectively. Based on Murray's criteria using these values, the damping required for this to be an acceptable floor system is 6.7 percent of critical.

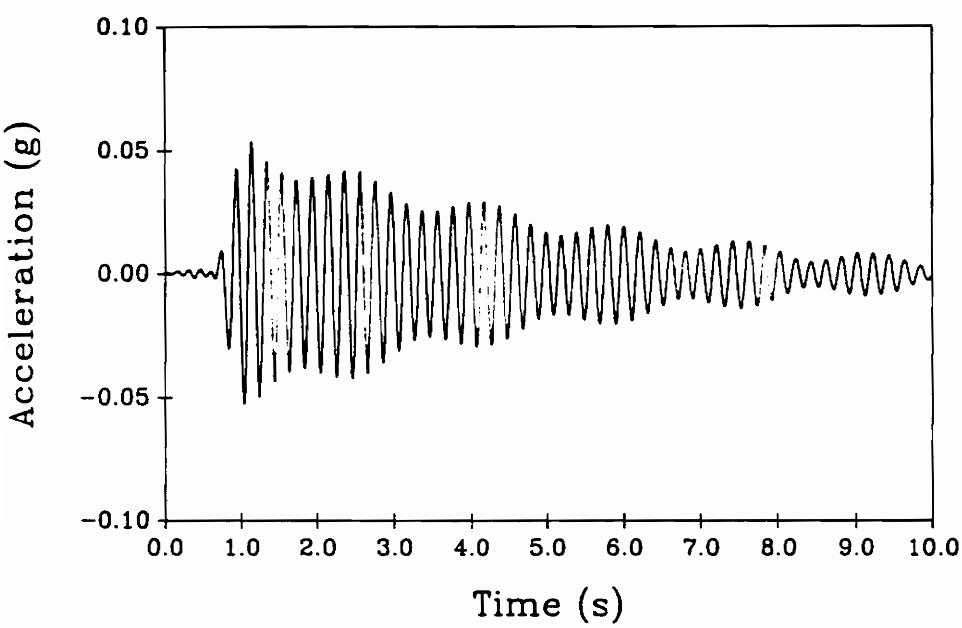
In addition to the annoyance of the primary vibrations, a disturbing "beating" effect existed in this structure. Figure 1.4(a) shows a response from a heel-drop impact in the center of one bay. The vibration energy momentarily leaves the impacted bay then returns. This wave of energy oscillates between bays for several "cycles" before finally dampening out. This behavior may not be typical in all buildings and is not accounted for in acceptability criteria; however, it did magnify the annoyance of the distinctly perceptible, fundamental floor vibrations. In an attempt to diminish the affect of the vibration transmissibility between bays, one bay was loaded with approximately 70 psf of concrete blocks. Figure 1.4(b) shows the heel-drop response of the building after this dead load addition. Even though the beating effect was still present, it was not as perceptible after the 70 psf was added. The additional dead load was present in one bay for all experimental work involving this building.

For all floor systems tested, the vibration characteristics were extracted by performing a human heel-drop. In each test, this impact was conducted at the middle of the floor. Heel-drops on the vibration test facility were executed in the middle of the bay without the additional dead load.

The heel-drop responses were measured by a seismic accelerometer [Wilcoxon Research Model 731] and amplifier [Model P31]. The digital signals



a) Without 70 psf



b) With 70 psf in One Bay

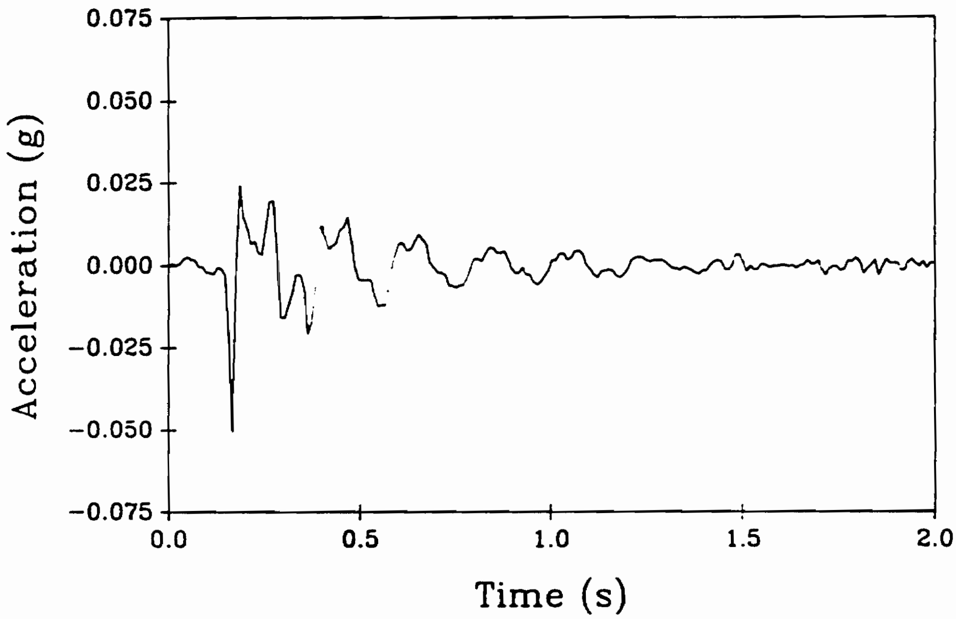
Figure 1.4 Heel-Drop Response of the "Vibration Test Facility"

from these units were then recorded by a portable computer [Zenith Model ZW-189-93] equipped with a data acquisition card [Metrabyte DASH-8]. Software was previously developed to record and store the acceleration versus time data and plot the responses on the computer monitor.

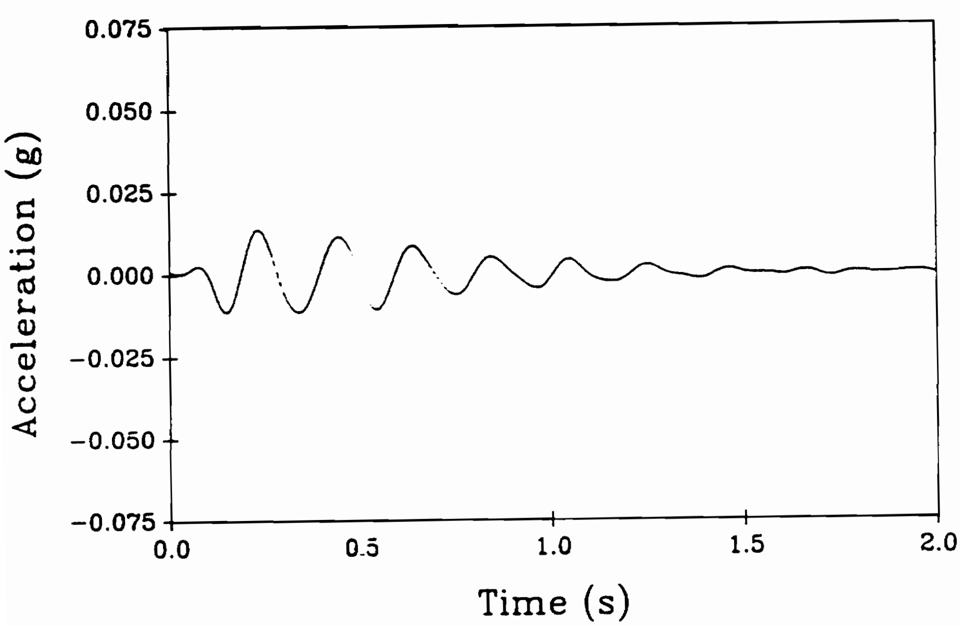
Due to the extreme sensitivity of the accelerometer, software was created to filter out signals not inherent to the floor systems. This extraneous noise was present in the floor; however, it did not affect the human perceptibility of the vibrations. Therefore to improve the accuracy of the data reduction, a Fast Fourier Transform [FFT] algorithm, coupled with other subroutines, removed the foreign frequencies from the responses.

The FFT also mathematically determined the natural frequency of each heel-drop response. If the signal was naturally void of any extraneous noise, the frequency could be determined by simply dividing the number of cycles over a given time period by that time period. However, the traces were often not clear enough to accurately calculate the frequency by this method. Therefore, the data was passed through the FFT to determine the natural frequency. The predicted frequencies were compared to values from the FFT, and it was concluded that the FFT consistently identified the natural frequencies with an acceptable degree of accuracy.

Figure 1.5(a) shows an example of an unfiltered response due to a heel-drop impact. It would be difficult to reliably determine the maximum amplitude and damping of this signal. These parameters could be clearly calculated once the trace had been passed through the FFT and filtered as illustrated in Figure 1.5(b). The difference in amplitudes of the two signals for a given peak was due to the contribution of the signals not inherent to the floor motion. The maximum amplitudes of the filtered responses sufficiently verfied the predicted values of the floors tested.



a) Unfiltered



b) Filtered

Figure 1.5 Typical Floor Response to a Heel-Drop Impact

Since the responses were in the form of acceleration versus time, the maximum amplitudes were converted to displacements so that the previously described acceptability criteria could be used to analyze the data. Although these floor vibrations were transient, steady-state sinusiodal responses were assumed for the purpose of calculating displacements. By this assumption, the floor motions of interest are described by:

$$\ddot{x} = \ddot{X} \sin[(2\pi f)t] \tag{1.10}$$

where $\ddot{x}$ = acceleration at t, $\ddot{X}$ = peak acceleration, f = natural frequency, and t = time. The expression for displacement:

$$x = \frac{-\ddot{X}}{(2\pi f)^2} \sin[(2\pi f)t] \tag{1.11}$$

where x = displacement at t, results from double integration of Equation 1.10. From these equations, the relationship between displacement and acceleration:

$$x = \frac{-\ddot{x}}{(2\pi f)^2} \tag{1.12}$$

is obtained. This equation was used to convert the first maximum amplitude in acceleration (g) to displacement (in.) without compromising any degree of accuracy.

For each heel-drop response, data was recorded for ten seconds, beginning just before the impact. In each individual investigation of this study, at least three heel-drop responses were recorded. The tabulated vibration parameters in this report represent average values of the series of responses for each particular investigation. The values were averaged to eliminate the effects of testing inconsistencies.

The natural frequency of each response was determined by the FFT, and the maximum amplitude (inches) was calculated as previously described. The damping was calculated using Equation 1.9. Consistency in the calculations was maintained by determining the damping after one second of the signal (for example, from A_0 to A_5 for a 5 hz vibration).

Since the objective of this study was to develop methods of improving the vibration characteristics of joist supported floor systems, a consistent means of comparing floors with different values of f, A_0 and D was necessary. One distinct characteristic of a floor is the damping required for acceptability based on Murray's criteria. This expression states a relationship that is necessary between two of the parameters and the third in order for a floor system to be judged acceptable. In most cases for a particular floor, the measured natural frequency and maximum amplitude correspond well with the predicted values. Therefore, little or no difference in required damping values is noted if calculated using predicted and measured values of f and A_0. For the purpose of this investigation, required damping values were based on predicted frequencies and maximum amplitudes unless otherwise stated. The measured damping is also essential in ultimately describing the acceptability of a floor, unless valid estimates of damping in the system exceed the required value.

For the purpose of this study, the ratio of the measured damping over the required damping, based on predicted values of f and A_0, was introduced to describe the acceptability of a floor system. For ratios less than unity, the measured damping is less than the required damping. For ratios equal to or greater than one, the measured damping is equal to or greater than required, and the floor would be acceptable to the occupants. Referred to as the Acceptability

Ratio (A.R.), this is a measure of how well Murray's criteria is satisfied for a particular floor. The A.R. allows floors with different vibration parameter values to be compared based on acceptability. In addition, by considering A.R.'s instead of just measured or required damping, improvements in floor vibration characteristics produced by the concepts of this study were consistently quantified. An example of the described data reduction techniques is given in the Appendix.

1.4 Overview of Thesis

The purpose of this study is to develop methods of improving the vibration characteristics of joist supported floor systems. To achieve this, seven floor systems were constructed and implemented with the concepts derived during this study. In Chapter II, the methods of improving the vibration characteristics are described, and the laboratory results are presented. In addition, basic conclusions are drawn from each set of results. Cost and performance comparisons of selected methods as well as final conclusions are presented in Chapter III. Finally, recommendations are made for future work involving the promising results of this study.

CHAPTER II

METHODS OF IMPROVING VIBRATION CHARACTERISTICS

2.1 Friction Methods

As briefly discussed in Section 1.2, Coulomb friction-damping is one of three main forms of energy dissipation. For simple idealized models, the friction damping can be described by Coulomb theory. However, in most real cases, geometric factors and surface conditions of the friction mechanism can affect the energy dissipation. In such instances, the topic of interface physics is essential in dealing with damping provided by actual friction surface conditions.

Brown [1968] gives a concise explanation of interface mechanics as it pertains to the damping of steel plates in contact. It was determined that the damping in a lap joint can be maximized by optimizing several of the factors. His results are available and will not be repeated here. The results obtained by Brown were not used to develop the concepts in the following sections but were used as a basis for suggesting modifications to improve the performance of the device described in Section 2.1.1.

2.1.1 Modified Friction Devices

An unpublished study [Murray 1989a] investigated increasing the damping in joist supported floors with a patented friction device. This device utilizes the relative motion of floor system components to develop friction-damping forces between contact surfaces. Laboratory tests were conducted with various contact surfaces: metal-to-metal, metal-to-metal with abrasive grit on the surfaces, metal-to-rubber, and metal-to-leather. Different locations in the floor system were equipped with the devices to determine the most effective installation. Normal force was provided in the devices by tightening the assemblies of bolts and spring washers to a specified torque. However, no correlation between torque and normal force was determined.

Once the successful laboratory work was completed, these devices were field tested in an actual building. This installation relied upon the relative movement between the joist bottom chords and the supporting girders for the success of the devices. It was found that when the floor vibrated, the girders twisted out-of-plane and negated the relative movement of the bottom chords. Therefore, the devices were ineffective in this building. Other configurations of this device rely upon the relative movement between the joists and columns, walls, or adjacent floors. Such installations may also be ineffective or may obstruct the intended use of the building.

Realizing the potential for friction-damping devices in floors susceptible to occupant-induced vibrations, modifications were made, during this study, to the original device to improve the performance and standardize the configuration for any installation. The modified device was designed to rely solely on the relative movement between the joist seat and bottom chord; making the device independent of the movement of other framing components (i.e. girders, columns, adjacent floors, etc).

Preliminary testing of this device was conducted on a two-joist floor that is illustrated in Figure 2.1. The simply supported 12K1 joists spanned 24 ft. 0 in. and were spaced at 2 ft. 0 in. on center. Metal deck was attached to the top chord of the joists with self-drilling screws. A 4 ft. 0 in. wide 2 3/4 in. thick normal weight concrete slab was placed on the deck.

The friction devices, as installed on the joists, are shown in Figure 2.2. Figure 2.3 illustrates the components of the device. A double angle extension

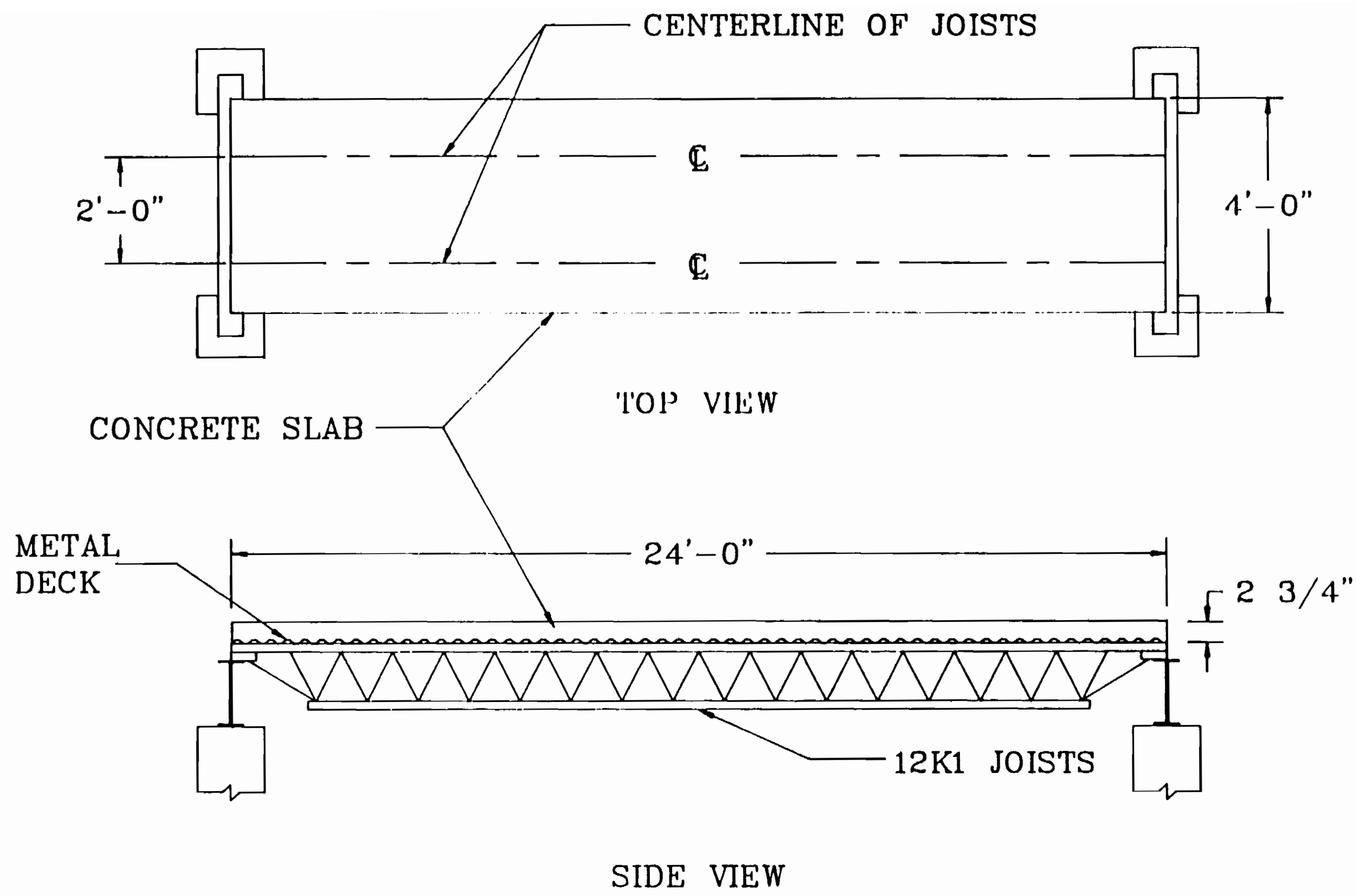


Figure 2.1 Modified Friction Device Test Floor

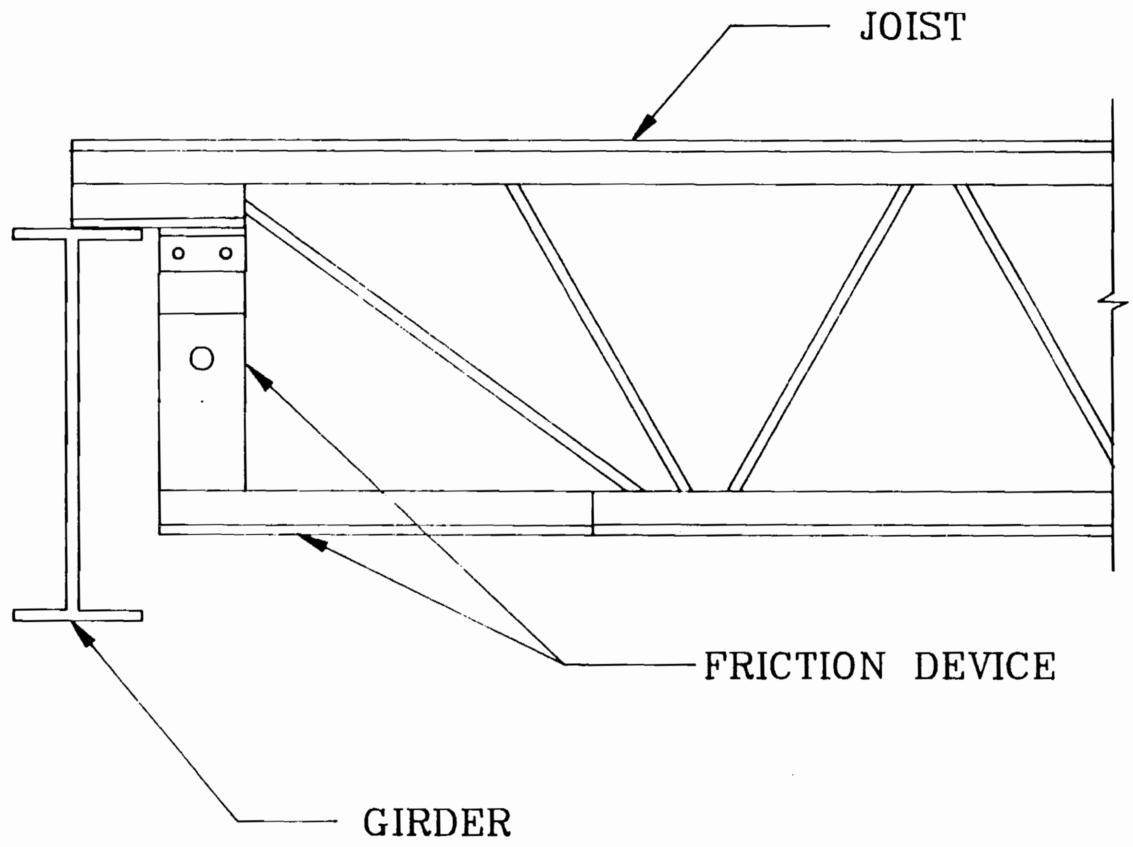


Figure 2.2 Modified Friction Device Installed on a Floor Joist

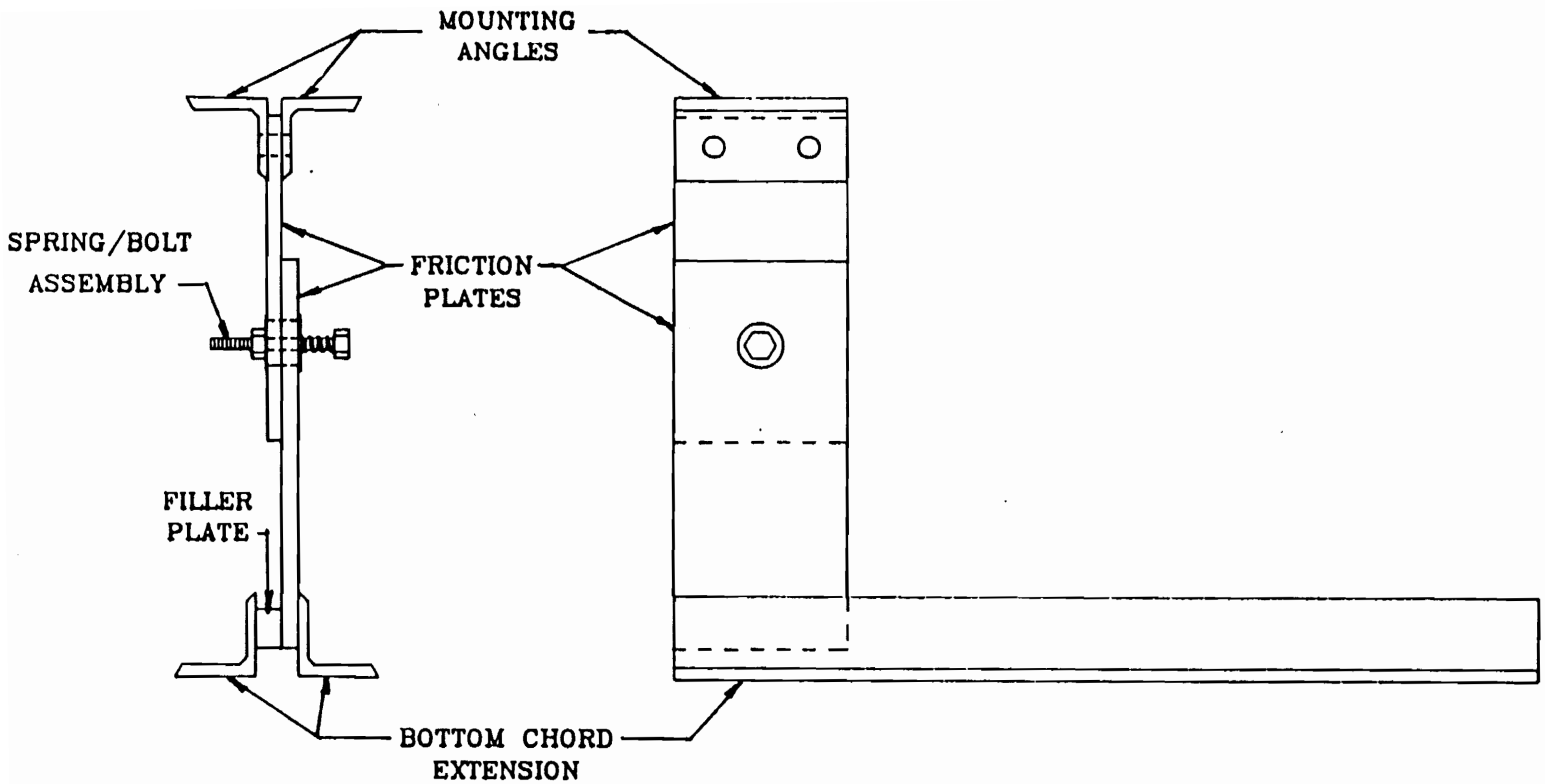


Figure 2.3 Components of the Modified Friction Devices

was welded to the bottom chord at each end of both joists. A filler plate was welded between the angles to maintain the same spacing at each end of the extensions. The contact faces of the friction plates were prepared with a grinder to remove any inconsistencies from the surfaces. One friction plate was welded to one angle at the end of each extension. Two holes were drilled in one leg of each mounting angle. Then, a pair of mounting angles was welded to the bottom of each joist seat so that the legs with holes extended down. The remaining friction plates were then bolted between the mounting angles.

The required normal force was provided by spring-bolt mechanisms placed through pre-drilled holes in the friction plates. Each assembly consisted of a 3/8 in. diameter bolt and nut with a compression spring sandwiched between the bolt head and a washer placed over the hole. The holes were oversized so that the bolts did not restrict the movement of the friction plates. The stiffness of the springs was obtained from the manufacturer.

Once testing of the modified device on the two-joist floor was completed, similar devices were installed on the joists of the two-bay test facility to evaluate their performance in an actual building. These devices were like those previously described except three friction plates were used to create two friction surfaces in this assembly. Only the exterior joist ends of the bay without the additional dead load were equipped with the devices. Due to the design of the building, devices could not be mounted on the exterior joist on both sides of the bay.

In order to obtain vertical alignment of the friction plates beneath the mounting angles, longer bottom chord extensions were required. Angles were welded on top of the extensions and joist bottom chords for additional stiffness. These modifications were not believed to affect the performance of the devices.

2.1.1.1 Testing Procedure

Heel-drop responses of the two-joist floor were first recorded without any normal force applied to the devices. These responses revealed the vibration characteristics of this floor without the effects of the friction devices and served as base data. Tests were then conducted with varying normal forces on the friction plates. The normal forces were produced by tightening the bolts and thereby compressing the springs. The spring-bolt assemblies were adjusted so that equal spring compressions were measured for each device. The normal force was determined by multiplying the measured displacement of the spring by its stiffness. The forces were applied in increments of 1.35 lbs ranging from 0.00 to 13.50 lbs.

Testing of the devices in the two-bay building consisted of six phases. Each phase investigated varying normal forces on a given number of devices. For example in the first phase, a data base was established by recording heel-drop responses of this floor with no normal force in any of the devices. Then in the second phase, heel-drops were performed with different normal forces on just the device installed on the middle joist. For the third phase, tests were run with varying but equal normal forces on only the middle three devices. Tests were performed with the middle five and middle seven devices employed over a range of normal forces, and the sixth phase was run with all nine devices operative. The range and increments of normal force were the same as used for the preliminary testing on the two-joist floor. By incrementally testing the devices, the results would indicate any optimal combination of normal force and number of devices.

2.1.1.2 Results

Table 2.1 lists the results from the tests on the two-joist floor. As expected, the measured frequencies and maximum amplitudes did not vary with changes in the applied normal force and, for that reason, are not tabulated. The normal

Table 2.1 Results from the Modified Friction Devices on the Two-Joist Floor

Normal Force (lbs)	Measured Damping (% critical)	A.R.
0.00	5.8	0.290
1.35	6.3	0.315
2.70	6.6	0.330
4.05	6.7	0.335
5.40	6.5	0.325
6.75	7.0	0.350
8.10	6.7	0.335
9.45	6.9	0.345
10.80	7.1	0.355
12.15	6.7	0.335
13.50	6.9	0.345

Predicted Values:

f = 6.9 hz A_o = 0.0724 in D_{req} = 20.0% critical forces and corresponding changes in damping were of main concern in this study. Although there is some irregularity in the data, Figure 2.4 indicates the increasing trend in measured damping with growing normal forces in the devices. The largest increase (1.3 % of critical) was measured when the normal force was approximately 10.8 lbs. Larger normal forces produced declining values of damping. This is explained by the work of Lazan, Brown, Gannett, Kimser, and Klumpp [1952].

They determined that the damping depends on the clamping pressure on the contact surfaces, and an optimum value can be obtained. The energy dissipation is proportional to the product of the friction force and the relative movement of the contact surfaces. With this in mind, the relationship between damping and normal force clear. For high clamping pressures, the relative motion is small, and under low normal forces the friction force is negligible. The damping is maximized at a point between the two extreme conditions. In this investigation, the optimum clamping force seems to be approximately 10.8 lbs.

Since increasing the normal force in the devices had no effect on the floor stiffness, the required damping remained constant. Therefore, the changes in the A.R. are equivalent to the changes in measured damping. For all tested values of normal force, the A.R. is greater than that corresponding to zero normal force; indicating improvements in the vibration characteristics of the test floor.

As with the two-joist floor, the friction devices had no effect on the measured frequencies and maximum amplitudes of the vibration test facility. The measured damping of the two-bay building with no friction devices was 1.6 % of critical. With a required damping of 6.5 % of critical, the A.R. of this floor is 0.246. Unfortunately, no significant increases in damping were produced by the friction devices installed in this structure. A maximum increase of only 0.3 % of critical damping was provided when 9.45 lbs normal force existed in seven devices.

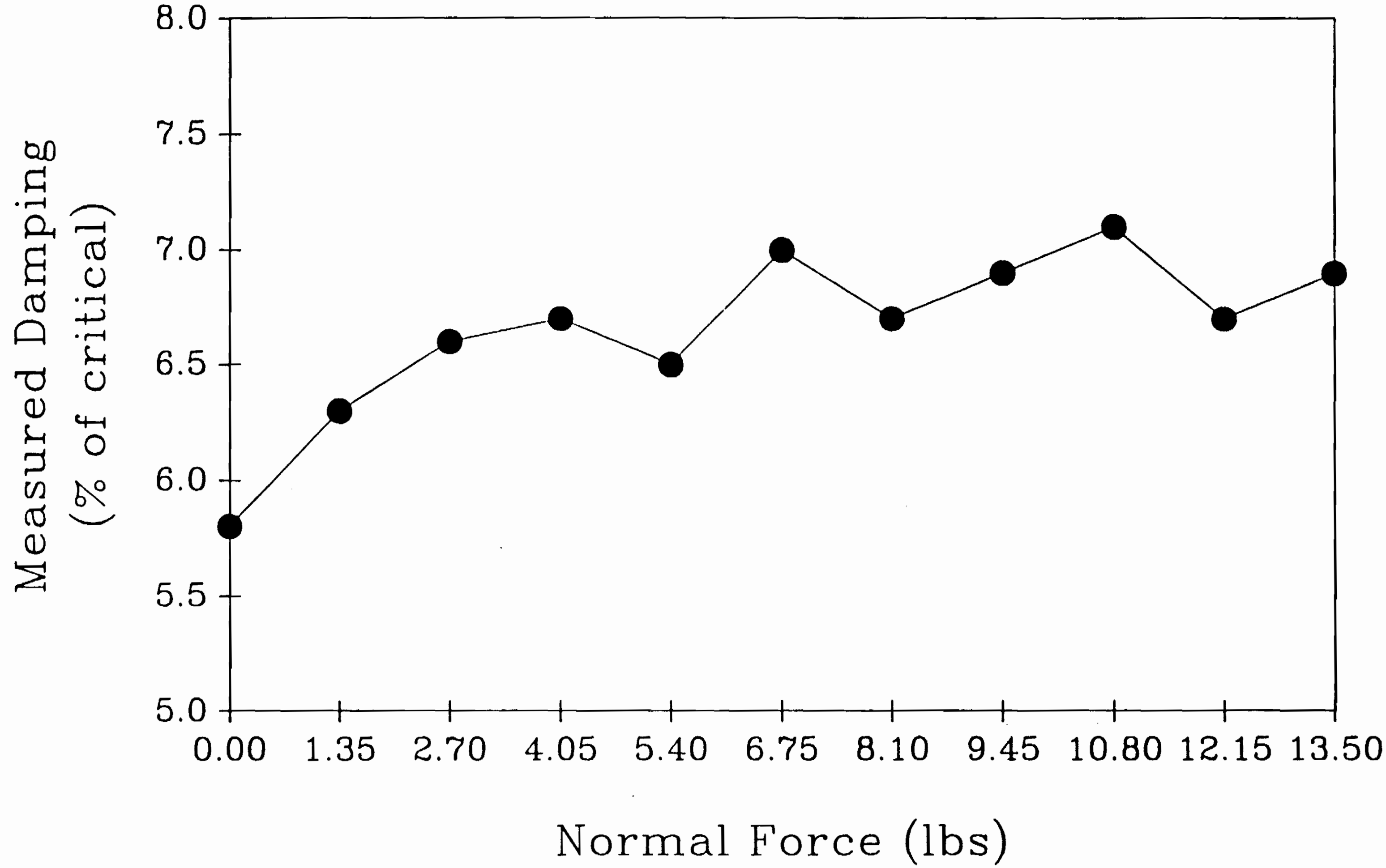


Figure 2.4 Plot of Normal Force on Modified Friction Devices vs. Measured Damping

Other combinations of normal force and number of devices produced more negligible changes in damping. No significant increases in the A.R. of this floor evolved, hence the devices were ineffective in this installation.

2.1.2 Cellular Deck

Friction-damping was incorporated into a concept of creating a friction surface within the floor system itself. By adding a second layer of deck to the system, a friction surface was produced at the interface of the sheets of deck. The normal force necessary to create the friction force was provided by the weight of the slab.

A single-span floor system was constructed to study this concept. This floor is shown in Figure 2.5. Two 12K1 joists, simply supported on steel beams, spanned 24 ft. 0 in. and were spaced at 2 ft. 0 in. on center to support a 4 ft. 0 in. wide 2 1/2 in. thick normal weight concrete slab on the "cellular" deck.

The cellular deck consisted of two layers of metal deck. The first layer was fastened to the top chord of the joists using self-drilling screws in every fifth or sixth rib of the deck. The second layer was then placed on the first but was shifted so that the two layers formed cells along the deck. Self-drilling screws connected the two layers of deck together in every rib in which the first layer was attached to the joists. Once the cellular deck was assembled, the slab was placed on top of the second layer to complete the cross-section that is shown in Figure 2.6.

By creating a cellular deck, the ribs of the bottom layer remained void of any material. Thus, when the floor system vibrated, the ribs of this layer were more free to expand and contract. This movement enhanced the relative slip desired between the layers of deck for increasing the energy dissipation from the

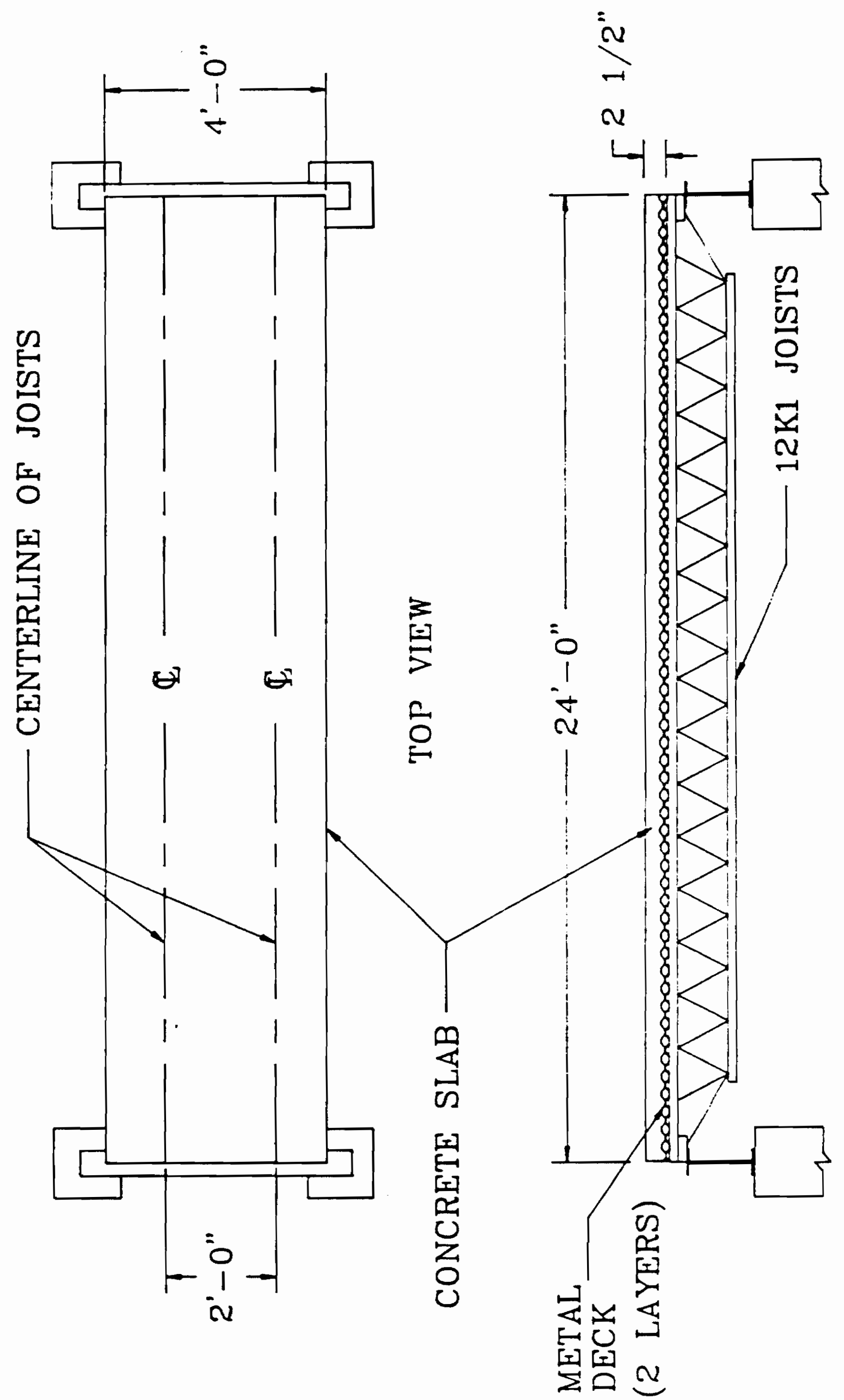


Figure 2.5 Cellular Deck Floor System

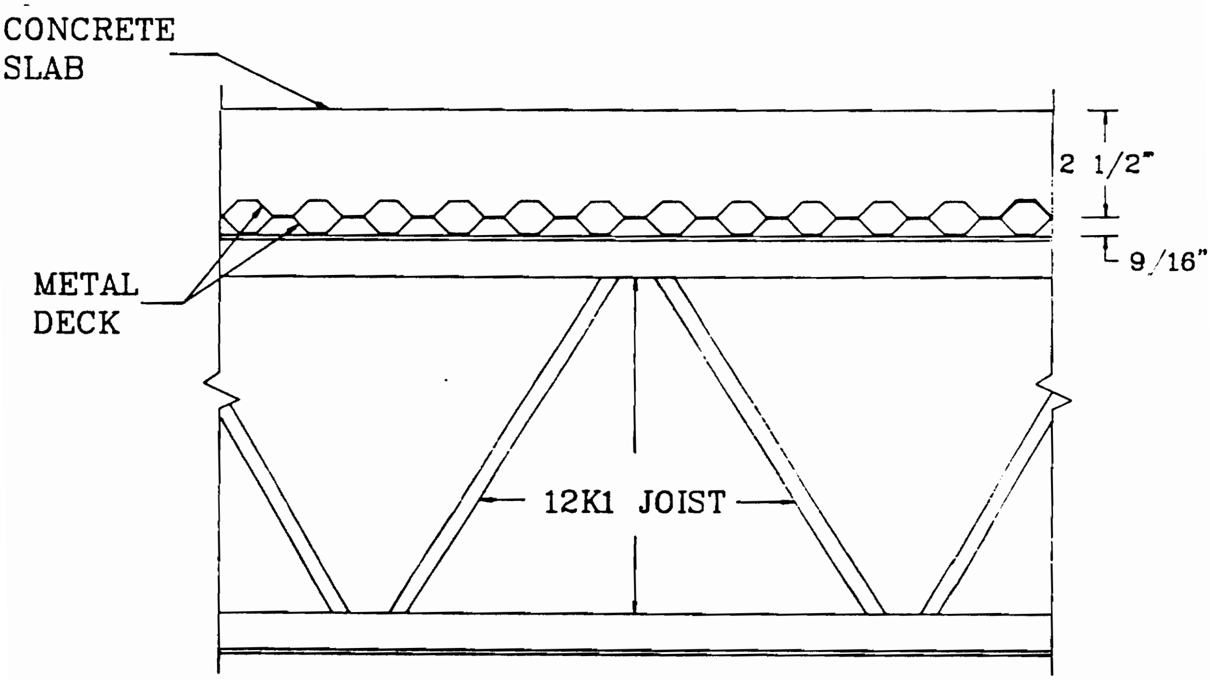


Figure 2.6 Section of Cellular Deck Floor

floor. In addition, this less restricted deck movement further developed the inherent damping potential of the metal deck as discussed in Section 2.3.

2.1.2.1 Testing Procedure

The construction of this floor seemed to provide sufficient shear transfer throughout the cross-section to assume composite action during the dynamic testing. However, the floor's measured vibration response did not concur with the predicted values; indicating that the floor did not behave compositely. Therefore to determine its stiffness, the floor was incrementally loaded at midspan, and the corresponding displacements were recorded. From these values, the stiffness of the floor was calculated by:

$$EI = \frac{PL^3}{48d} \tag{2.1}$$

where EI = the stiffness in lbs-in^2, P = the load in lbs, L = the span of the floor in inches, and d = the static midspan deflection in inches. Once the stiffness of the floor was determined, the expected natural frequency and maximum amplitude were calculated.

Three sets of heel-drop impacts were performed on this floor. The first set was performed on the system as constructed. Once all of these responses were recorded, every other screw holding the layers of deck together was removed in an attempt to increase the damping by increasing the slip between layers. In doing so, the system stiffness was reduced. The previously described procedure for determining the floor stiffness was repeated, now with a screw connecting every tenth or twelfth rib of the two layers of deck. The responses from a second set of heel-drops on this floor were recorded before this process was repeated a final time. With a screw spacing of twenty to twenty-four ribs, the stiffness of the floor was calculated, and the third set of heel-drop responses was recorded.

2.1.2.2 Results

For each screw spacing, the floor's predicted and measured heel-drop responses are listed in Table 2.2. Even though the stiffness of the floor (Table 2.2) was reduced as screws were removed from the cellular deck, the measured frequencies remained at 5.7 hz. The measured maximum amplitudes were essentially consistent with the predicted values. The largest damping (8.8 % of critical) was measured when there was a screw connecting every fifth or sixth rib of the two layers of deck. The spacing of ribs per connector did not have the anticipated affect on the measured damping. Actually, lower damping was measured when the stiffness was reduced by removing screws from the cellular deck.

The responses of the cellular deck floor were compared to the vibration characteristics of a similar but conventionally constructed floor system. This base floor was the same as the cellular deck floor except only one layer of deck was used to support the slab. The predicted frequency and maximum amplitude of this floor were 7.1 hz and 0.0786 inches, respectively, and the required damping based on Equation 1.1 is 22.0 % of critical. The measured frequency and maximum amplitude were 7.1 hz and 0.0816 inches, respectively. The measured damping was 6.5 % of critical. Based on these values, the A.R. of the base floor is 0.295.

For all tests, the A.R. of the cellular deck floor is greater than that of the base floor. When the two layers of deck were connected at every fifth or sixth rib, the A.R. is 0.415. For screw spacings of every ten to twelve and twenty to twenty-four ribs, the A.R. is 0.377 and 0.372, respectively. These values indicate a

Table 2.2 Results from Cellular Deck Floor

Ribs/Screw	Experimental EI (lbs. in^2)	f (hz)		A_o (in)		D (% critical)		A.R.
		Predicted	Measured	Predicted	Measured	Required	Measured	
5-6	2.62×10^9	5.8	5.7	0.0923	0.1083	21.2	8.8	0.415
10-12	2.58×10^9	5.8	5.7	0.0937	0.0982	21.5	8.1	0.377
20-24	2.45×10^9	5.6	5.7	0.0987	0.1037	21.8	8.1	0.372

Notes:

1. The predicted frequencies and amplitudes include the contributions of the supporting girders.
2. The required damping values are based upon the predicted values of f and A_o.

significant improvement in the floor vibration characteristics when the slab was supported by cellular deck instead of a single layer of deck.

2.1.3 Conclusions

Based on the test results, the modified friction-damping device and the cellular deck produced improvements in the vibration characteristics of the two-joist floors. Unfortunately, the modified friction-damping devices had no beneficial affect when installed in an actual building.

Measured damping of the two-joist floor was increased by 1.3 % of critical when assisted by the modified friction devices. There was an obvious correlation between normal force in the devices and the measured increases in damping. Explanations for similar friction-damping applications have been suggested but require information about the energy dissipation mechanism that was not obtained during this study [Brown 1968]. Therefore, attempting to mathematically rationalize the performance of the modified devices would only be speculation.

The intent of this investigation was to determine if the modified device would measurably increase the damping of a joist supported floor. No attempts were made to optimize the performance of the device, but it is probable that these devices could be improved. Three of Brown's four suggestions for maximizing damping in a lap joint seem applicable to improving the damping efficiency of the modified device. The justifications for these conclusions have been presented by Brown and will not be repeated here. First, he determined that the width, or the dimension of the contact surfaces transverse to the primary direction of movement, of the lap joint should be minimized. Since the friction device does not serve as a load-carrying mechanism, the floor system strength will not control this aspect. Space limitations and practicality should be the only controlling factors in minimizing the width of the friction surfaces. Second, Brown concluded that the interfaces should be as smooth as possible. Due to machining costs, creating smoother surfaces could be expensive. Therefore, the degree of smoothness will be a question of cost versus performance. And finally, it was also determined that the interface should possess a low modulus of elasticity and shear strength. This may be accomplished by one of two options. One possibility is to coat the steel friction surfaces with materials having lower quantities of these properties than the steel. The other alternative is to construct the devices with friction plates made entirely of such materials. Again, these remedies may depend upon an acceptable trade-off between cost and performance.

Another possible improvement in the modified device is to increase the number of friction surfaces. By adding more plates to the mechanism, the energy dissipation capacity will be increased without changing the normal force. The additional plates will increase the cost of the device, but an optimal number could be determined.

The reason for the unsuccessful performance of the modified friction devices in the two-bay building is not exactly known. A possible explanation is that the vibration energy in the bays could not be efficiently dissipated by the limited number of devices. Recall that devices were only installed on one end of the joists in one bay. Based on the total possible number of devices in this building, only 25 % were installed. If the building were completely equipped with devices, the measured damping may have significantly increased. Unfortunately, such extensive testing was not possible during this investigation. The previously discussed modifications may also enhance the performance of these friction-damping devices in actual buildings.

From comparison of the A.R.'s, the accomplishments of the cellular deck were greater than those of the modified friction devices. The required damping of the cellular deck floor was sightly less than that of the base floor and the floor with the modified devices. Differences in the A.R.'s were mostly due to differences in the measured damping values. The cellular deck yielded significantly greater energy dissipation (8.8 % of critical) than produced by the base floor (6.5 % of critical) or the two-joist floor equipped with the modified devices (7.1 % of critical).

The cellular deck floor was constructed with the assumption that the slip between layers would create a beneficial friction-damping force. In addition, the amplified deck movement was presumed to further develop the material damping potential of the deck and improve the energy dissipation of the system. It is believed that these assumptions actually occurred during testing. However, as with the modified friction devices, the cellular deck was not experimentally monitored. Therefore, no data exists to correlate the hypotheses with the floor behavior, and no attempts at this will be made in this study. The fact still remains that the vibration characteristics of the cellular deck floor were more acceptable than those of the conventionally constructed base floor.

2.2 Viscoelastic Methods

Building components (i.e. beams or joists, deck, slab, etc) can provide some damping for floor systems, but these elastic materials cannot efficiently convert the applied mechanical energy of vibrations to heat [Johansson 1982]. There are materials which have strong capacities for storing mechanical energy and converting it to heat; thus, increasing the damping of a dynamic system. These materials possess both viscous and elastic properties and for that reason are referred to as viscoelastic.

Viscoelastic materials, under certain conditions, can dissipate energy more efficiently than typical construction materials, such as steel and concrete. This occurs because of a phase shift between stress and strain in the viscoelastic material. The offset between stress and strain is a measure of the energy dissipation capacity and is referred to as the loss factor. Greater damping results from materials with larger loss factors. Elastic materials such as steel possess negligible loss factors.

Since these highly efficient damping materials are not simply elastic, their properties cannot be described solely by the modulus of elasticity. Instead, a complex modulus of elasticity is used to express the elastic and viscous nature of these materials. The complex modulus, E^* is comprised of a storage modulus, E', and a loss modulus, E". The relationship of these quantities is expressed by:

$$E^* = E' + E'' \tag{2.2}$$

The loss factor can then be defined as the ratio of the loss modulus over the storage modulus.

These material properties are dramatically affected by the temperature and frequency under which they perform. Figure 2.7 illustrates these relationships for a particular viscoelastic material. These relationships limit the optimal damping of the material to a specific range of temperatures and frequencies, depending upon the application.

Viscoelastic materials have been used as damping devices in a wide variety of environments, including floor systems. Studies have been conducted with viscoelastic materials constrained on the flanges of floor beams. As the floor system vibrated, shear stresses were induced in the materials which in turn increased the system damping. Floors have also been equipped with devices which utilized shear produced in viscoelastic materials to increase energy dissipation [Allen and Swallow 1975 and Mahmoodi 1969]. Similar devices were investigated and will be introduced in Section 2.2.2.

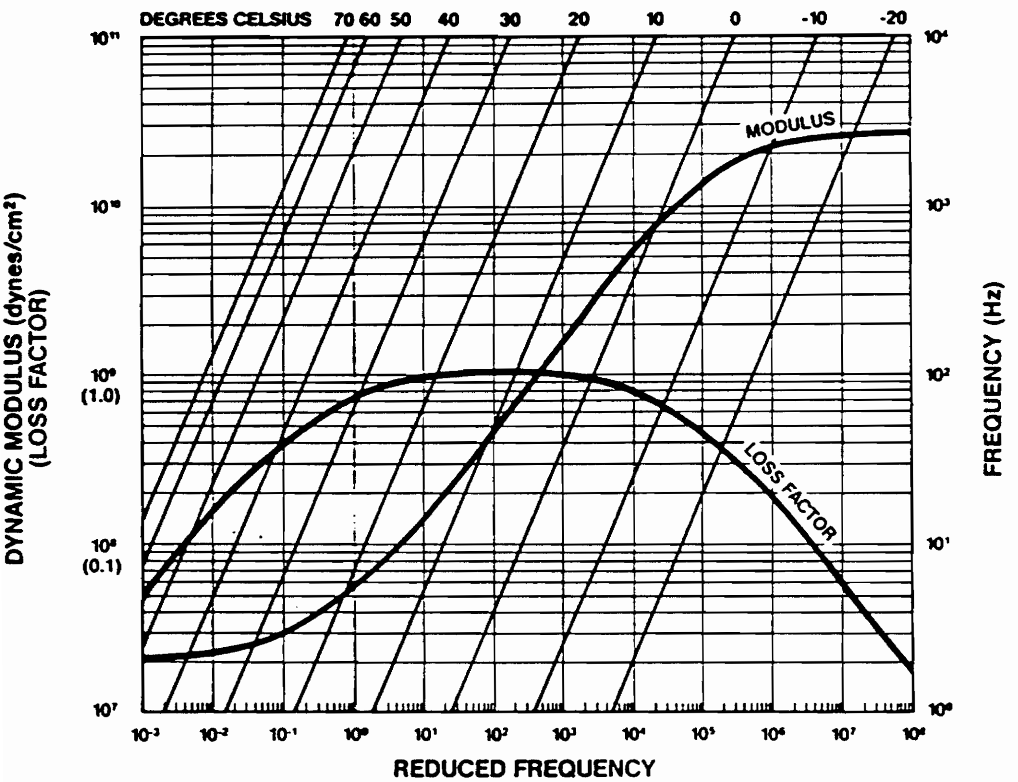


Figure 2.7 Example of a Viscoelastic Material Properties Nomogram

Energy dissipation can be greatly enhanced by properly selected viscoelastic materials. Previous studies have concluded that viscoelastic material can, in some instances, successfully reduce annoying floor vibrations. In this investigation, two independent concepts of using viscoelastic materials to improve the vibration characteristics of joist supported floors were studied.

2.2.1 Joist Seat Pads

Viscoelastic materials are used to isolate buildings or floor systems from annoying or damaging vibrations. Machine-generated vibration problems are sometimes solved by viscoelastic materials. Such vibrations are often disturbing to occupants of the building and can sometimes be hazardous to the structural integrity. To eliminate these dilemas, machines are supported by viscoelastic pads. The pads are not intended to dampen the machine vibrations but serve to dissipate the energy before it is transmitted to the supporting floor. Similarly, building are supported on rubber pads to protect the structure from damaging external vibrations such as earthquakes, trains, or automobiles.

Although it would not be possible to isolate the source of occupant-induced vibrations in this manner, it is believed that these materials can, as an integral part of a floor system, increase the system damping. One phase of this study investigated increasing the damping of a floor system by installing viscoelastic materials between the joist seats and the flanges of the supporting girders. Tests were conducted with various materials to examine the effects of different viscoelastic properties.

A two-joist floor was constructed to investigate the use of damping pads between the joist seats and supporting structure (Figure 2.8). The 28K6 joists were spaced at 2 ft. 0 in. on centers. They spanned 25 ft. 3 in. and were simply-supported on steel girders. Metal deck was attached to the top chord of the

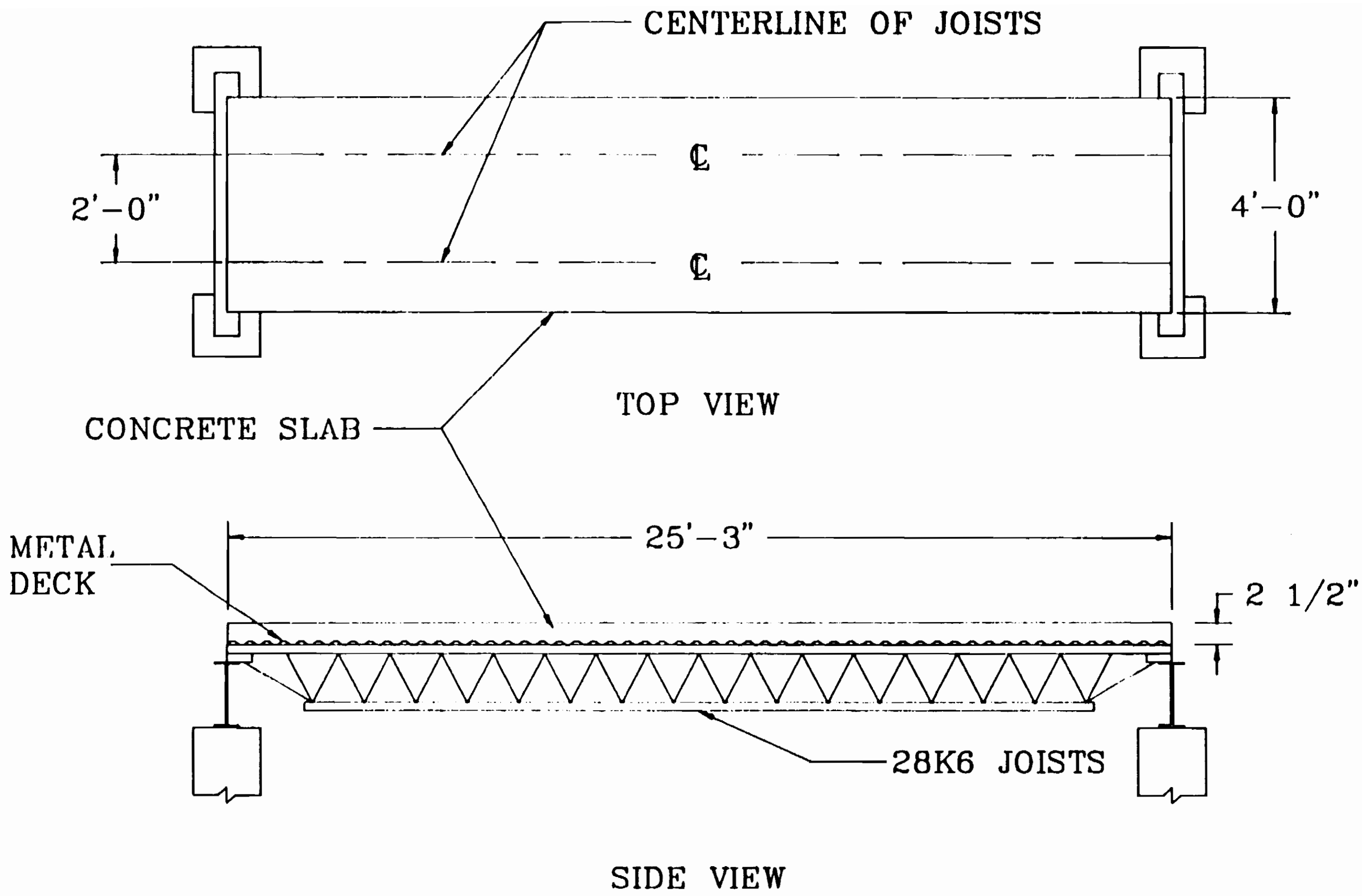


Figure 2.8 Viscoelastic Damping Pads Test Floor

joists, and a 4 ft. 0 in. wide, 2 1/2 in. thick normal weight concrete slab was placed on the deck.

2.2.1.1 Testing Procedure

Heel-drop responses were first recorded without any pads under the joist seats of the test floor. This data served as a base so that improvements from the pads could be identified. Each end of the floor was then jacked off the supporting girder, and a pad was placed under each joist seat. Cover plates were placed on top of the pads to help distribute the loads from the floor uniformly over the pads. The floor was then lowered onto the plates until the system returned to equilibrium. Heel-drop responses were obtained, then the pads in-place were replaced with another set. This process was repeated until all of the pads had been tested.

2.2.1.2 Results

The results from the testing described in Section 2.2.1.1 are given in Table 2.3. The pads are described in Table 2.4. In many cases, the measured frequency and maximum amplitude are significantly different than the same quantities of the floor without any pads. This is explained by the fact that the pads have distinct stiffnesses under given loads and tend to behave as springs during dynamic testing. The additional springs in the floor system change the stiffness, resulting in an altered system frequency and system maximum amplitude. Since there was no means of predicting the frequency and maximum amplitude of the floor with pads in place, required damping values were based on measured values of f and A_o. Depending on the relative changes in f and A_o for a particular set of pads, a change in the required damping may have resulted. Such variations are reflected in Table 2.3.

Table 2.3 Results from Viscoelastic Pads Beneath the Joist Seats

Pad	f (hz)	A_o (in)	Damping (% critical) Required	Measured	A.R.
0	12.3	0.0277	14.4	4.4	0.306
1	7.0	0.0501	14.8	10.9	0.736
2	5.8	0.0687	16.4	7.0	0.427
3	12.9	0.0250	14.7	3.7	0.252
4	11.9	0.0285	14.4	4.9	0.340
5	12.4	0.0261	13.8	5.4	0.391
6	12.4	0.0282	14.5	5.9	0.407
7	12.2	0.0271	14.0	6.9	0.493
8	12.1	0.0262	13.7	6.1	0.445
9	12.0	0.0268	13.8	5.2	0.377
10	12.4	0.0264	14.0	4.9	0.350

Table 2.4 Descriptions of Viscoelastic Pads

Pad	Manufacturer	Description
0	--	No pads under joist seats
1	Rogers Corp.	Endur-C 100-25 cellular foam; 3 in. x 6 in. x 2 in. thick
2	Lord Corp.	J-5425-1 sandwich mount; natural rubber; 3 in. thick, 3.12 in. diameter
3	Home Rubber Co.	60 Durometer natural rubber; 4 in. x 5 in. x 1/4 in. thick
4	Home Rubber Co.	40 Durometer natural rubber; 4 in. x 5 in. x 5/16 in. thick
5	E. A. R.	Isodamp C-1002; 4 in. x 6 in. x 1/2 in. thick
6	E. A. R.	Isodamp C-1002; 4 in. x 6 in. x 1/4 in. thick
7	E. A. R.	Isodamp C-1002; 4 in. x 6 in. x 1/8 in. thick
8	E. A. R.	Isoloss HD; 4 in. x 4 in. x 1/4 in. thick
9	E. A. R.	Isoloss HD; 4 in. x 4 in. x 1/8 in. thick
10	Unknown	Neoprene; 4 in. x 5 in. x 1/2 in. thick

The measured damping values, also listed in Table 2.3, were used with the tabulated required values to calculate the A.R.'s produced by the various pads in the floor system. The Endur-C cellular foam pads seem to be the most effective. These pads produced the largest increases in both the A.R. and measured damping. Other materials increased the damping from the base value, but none of the improvements matched the performance of the foam pads.

2.2.2 Viscoelastic Shear Devices

Damping posts were briefly discussed in Section 1.2. These devices consisted of layers of viscoelastic material sandwiched between steel plates. The assemblies were installed so that when occupant-induced vibrations were produced, the floor motion induced shear stresses in the material and greater damping resulted. The damping posts, however, obstructed the intended use of the floor space.

This concept of using viscoelastic material placed in shear to increase floor system damping was modified during this investigation. The modification was similar to that of the friction device described in Section 2.1.1. Mechanisms were designed to work independently of building components other than the floor joists. These devices were constructed so that when the floor system vibrated, the relative movement of the bottom chords and seats of the joists would induce shear in the viscoelastic materials. Due to the inherent damping potential of these materials, this would result in increased energy dissipation from the floor system.

For the purpose of this investigation, a simple-span two-joist floor was constructed. The 12K1 joists were spaced at 2 ft. 0 in. on centers and spanned 24 ft. 0 in.. Metal deck was attached to the joists with self-drilling screws and a 4 ft. 0 in. wide 2 1/2 in. thick normal weight concrete slab was placed on top. A schematic of this floor is shown in Figure 2.9.

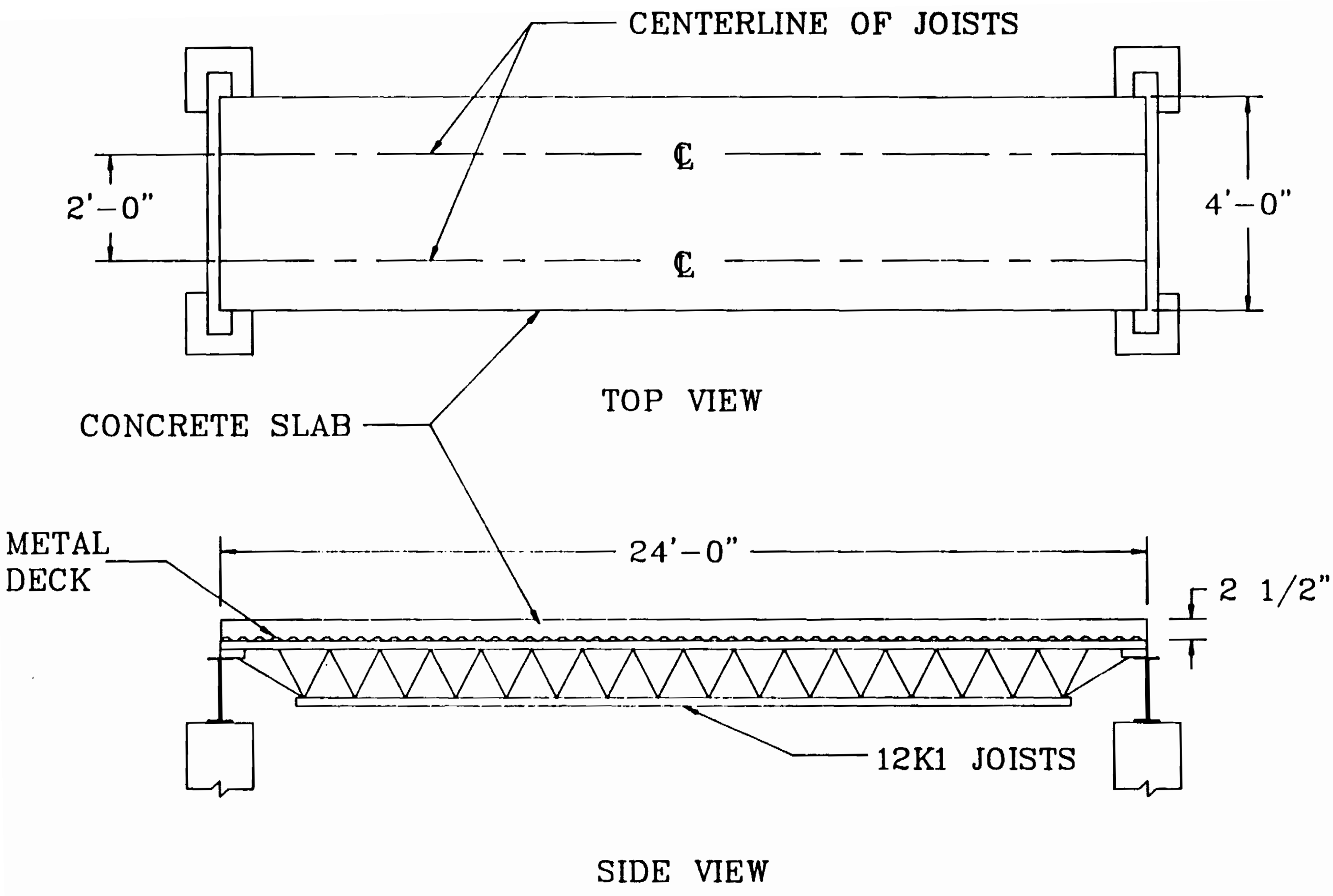


Figure 2.9 Viscoelastic Shear Device Test Floor

Figure 2.10 shows a side view of the shear devices installed on the joists. A double angle extension was welded on the ends of the bottom chord of both joists. The bottom of the shear device was bolted to a plate which had been welded between the ends of the angles of each extension. The top of the shear device was was bolted to the oustanding legs of a pre-drilled double angle assembly which was welded to the bottom of each joist seat.

Each shear device consisted of two pieces of viscoelastic material sandwiched between three steel plates as shown in Figure 2.11. The viscoelastic material was 2 in. high, 4 in. long and either 1/8 in. or 1/4 in. thick. These pieces were bonded between the steel plates with a commercial construction adhesive. The faces of the plates in contact with the viscoelastic material were roughened with a grinder so that the adhesive would properly bond to the metal surfaces. Each sandwich was assembled then firmly clamped together for approximately 24 hours to assure a secure connection. Four sandwiches of each material were constructed.

2.2.2.1 Testing Procedure

Before the sandwiches were installed, heel-drop impacts were performed on the floor to determine its natural vibration parameters. Once the data base was established, a set of sandwiches was bolted in place and a series of heel-drops was performed. The responses were recorded then the sandwiches were removed and replaced by another set. This process was repeated until all of the viscoelastic materials had been tested.

2.2.2.2 Results

Table 2.5 lists the results from the tests conducted on this floor system. As expected, the measured frequency and maximum amplitude did not significantly change in any of the tests; hence, they are not tabulated. Changes in damping

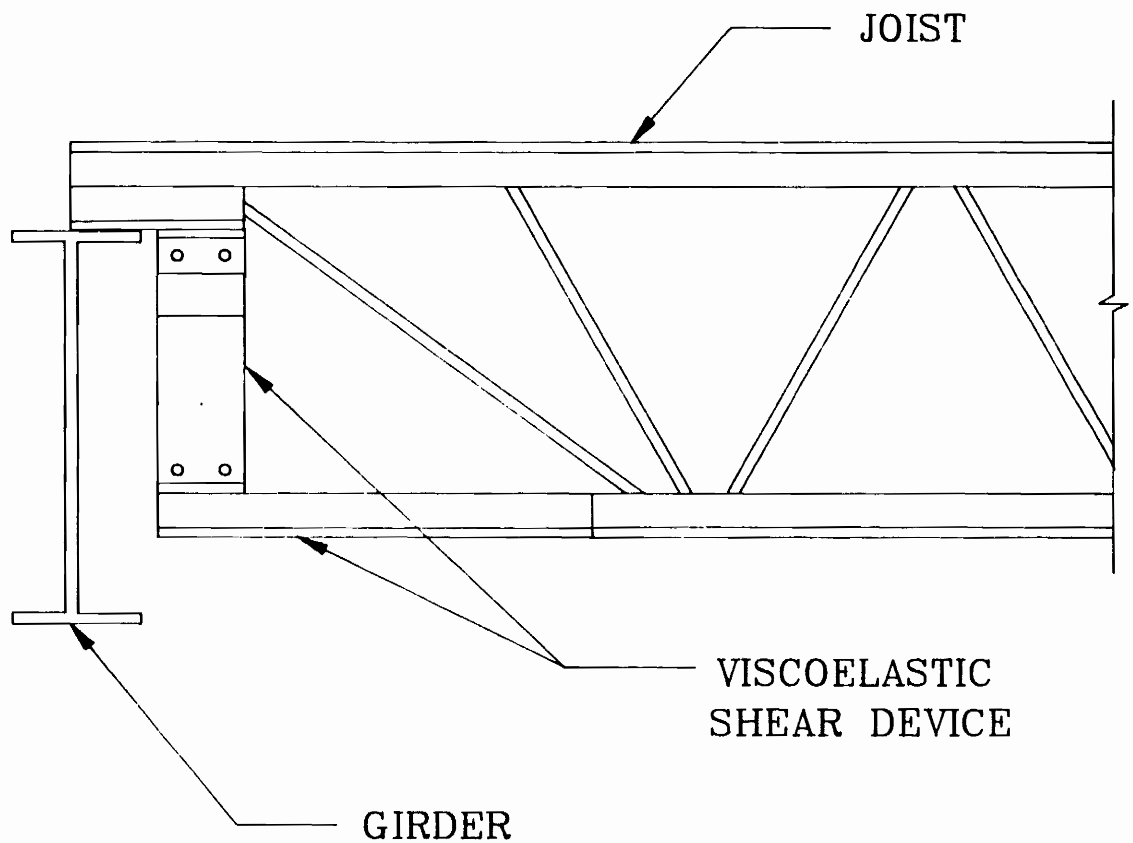


Figure 2.10 Viscoelastic Shear Device Installed on a Floor Joist

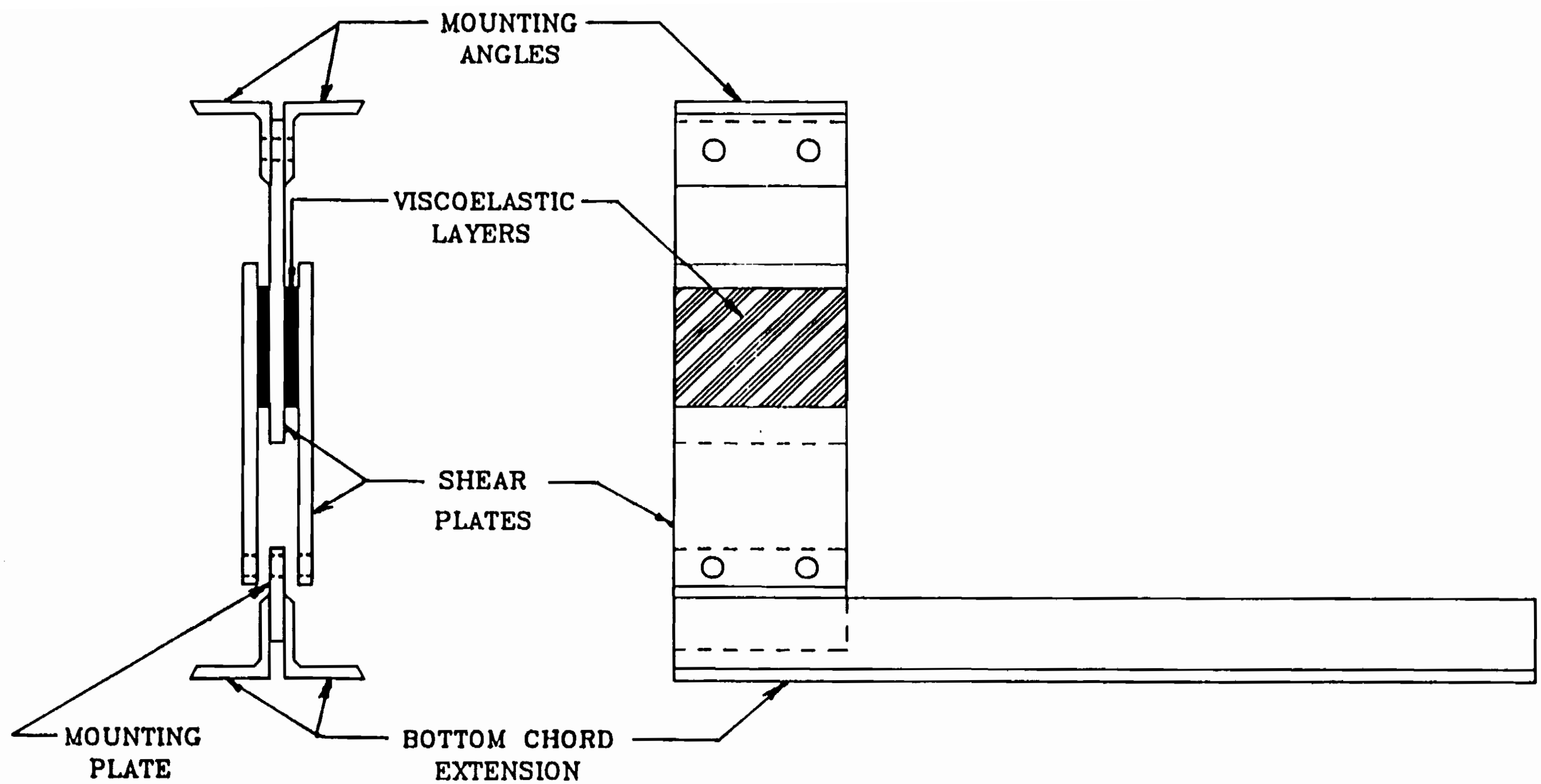


Figure 2.11 Components of the Viscoelastic Shear Device

Table 2.5 Results from Viscoelastic Shear Devices on Test Floor

Material	Thickness (in.)	Measured Damping (% critical)	A.R.
None	--	6.5	0.295
Isoloss	0.125	6.4	0.291
Isoloss	0.250	6.8	0.309
C-1002	0.125	6.7	0.305
C-1002	0.250	6.3	0.286

Predicted Values:

$F = 7.1$ hz $\quad A_o = 0.0786$ in $\quad D_{req} = 22.0\%$ critical provided by the shear devices were the primary interest of this investigation. The 1/8 in. thick ISOLOSS and the 1/4 in. thick C1002 material did not increase the energy dissipation from this floor system. The increase in damping provided by the 1/4 in. thick ISOLOSS and the 1/8 in. thick C1002 material was approximately equal but not substantial.

2.2.3 Conclusions

Recognizing the potential for increased damping, two concepts involving viscoelastic materials were developed and investigated. The experimental results of each were presented and improvements in the floor system vibration characteristics were identified.

The viscoelastic shear devices did not produce any improvements in the vibration charactersitics of the test floor. Increases in measured damping were anticipated but none resulted. No deficiencies in the devices were detected. Since similar devices from other studies have worked successfully, the only explanation for their poor performance is that the tested viscoelastic materials were not suitable for this application.

The installation of viscoelastic pads beneath the joist seats of the two-joist floor produced substantial improvements in the floor's vibration characteristics. Comparison of the test results indicates that proper selection of the viscoelastic material may be crucial to the effectiveness of the pads. In this utilization of the viscoelastic materials, there are several factors which can affect the performance of the damping pads. They include: frequency, temperature, pad area and volume, and static load. Frequency and temperature are the most important as they directly affect the viscoelastic properties of the material (Section 2.2). The pad dimensions and loading in conjunction with the material properties determine the energy dissipation capacity. The pads tested were samples randomly obtained from manufacturers. No attempts were made to optimize the performance of a particular material or maximize the damping by obtaining the ideal material. This will be left to future studies.

The purpose of this study was to determine if viscoelastic pads between the joist seats and supporting girders would improve the vibration characteristics of the test floor. Mathematical verification, using viscoelastic theory, of the performance of these pads is beyond the scope of this work. From examination of the A.R.'s, some pads produced significant improvements in the vibration characteristics of the test floor. It can be concluded that properly selected viscoelastic materials installed beneath the joist seats can effectively improve the vibration characteristics of joist supported floors.

2.3 Alternative Slab/Deck Configurations

If a floor system is determined to be unacceptable at the time of design, the engineer may choose to redesign the cross-section to improve the vibration characteristics. Several options may exist. Often, the most effective solution is to increase the slab thickness. Although the system stiffness will increase, the added mass will overcome this effect and a reduced frequency and maximum amplitude will result. Another alternative is to reduce the beam spacing. This will significantly affect the number of T-beams and lower the maximum amplitude [Murray 1987]. The result of both options will be an improvement in acceptability but at an added cost to the structure. The thicker slab will increase the weight of the floor; requiring larger beams, columns, and foundations. Reducing the beam spacing will increase the required number of beams and lead to an increased cost in connections. Therefore, it is difficult to effectively and cost-efficiently improve the vibration characteristics of a floor by redesigning the cross-section.

However, the vibration characteristics of joist supported floors may be improved by altering the slab/deck relationship and utilizing the structural damping properities of the components of the floors. An unpublished study determined that the major contributor of damping to an open, empty floor is the deck [Murray 1989a]. As a floor vibrates, the deck bends and the ribs expand and contract. In conventionally constructed floors, this deck movement is usually restricted by the concrete in the ribs. If a floor was constructed without concrete in the ribs, the deck movement would increase and greater displacements would be produced in the floor system.

The floor displacements are the accumulation of the internal displacements of the structural materials. The molecular slipping in the floor components creates frictional resistance which dissipates the vibration energy in the form of heat. Hysteresis damping can be affected by many factors but primarily depends upon the amplitude of motion [Harris and Crede 1961]. By constructing floors without concrete in the ribs of the deck, the ribs would be more free to expand and contract and greater energy dissipation from the floor system may result.

2.3.1 Sand Floor

A single span, two-joist floor system was constructed to study how the floor vibration characteristics were affected when the ribs of the deck were void of concrete. A plan of this floor system is seen in Figure 2.12.

The 12K1 joists, spaced at 2 ft. 0 in., were simply supported on steel girders. Metal deck, 4 ft. 0 in. wide, was attached to the top chord of the joists with self-drilling screws. The ribs of the deck were then filled with fine sand and a sheet of polyethylene was laid over the deck to prevent the 2 1/2 in. normal weight concrete slab from mixing with the sand. The purpose of the sand was to

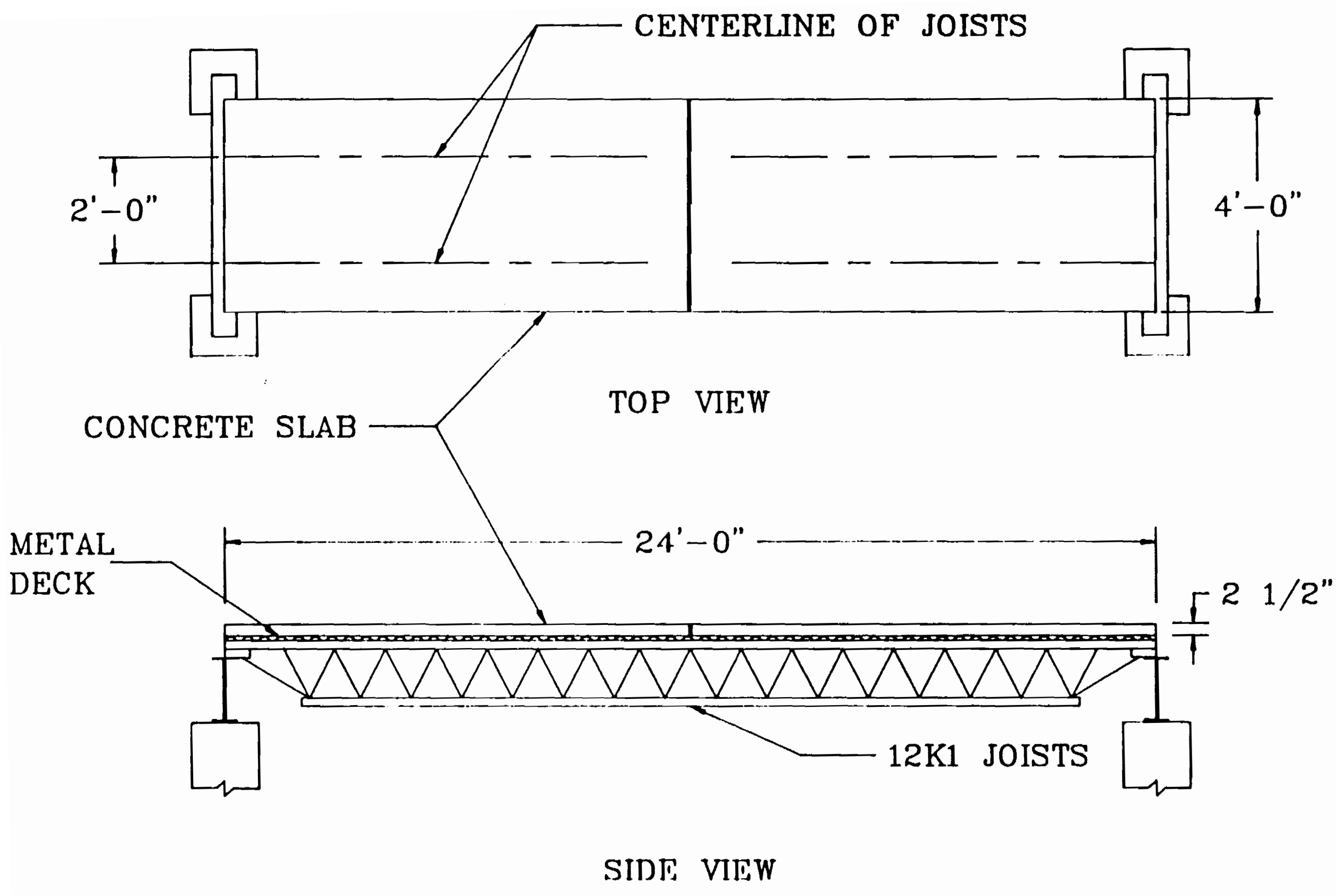


Figure 2.12 Test Floor with Sand Between the Deck and Slab

prohibit concrete from settling in the ribs yet still allow the deck to expand and contract as the floor vibrated. Increased damping was anticipated from this amplified movement of the deck. At midspan across the width of the slab, a 3/8 in. thick strip of plywood was inserted before the concrete was poured to maintain consistent stiffness along the floor but allow for installation of an asphalt expansion joint after the concrete cured. Figure 2.13 shows a section of this floor at midspan.

2.3.1.1 Testing Procedure

A series of heel-drop impacts was performed on the floor with the plywood strip in-place and removed from the slab. In addition, several heel-drop responses were recorded after the plywood was replaced with an asphalt expansion joint that fit snugly in the 3/8 in. gap. This modification to the floor was made to investigate the how the presence of this compressible material in the slab affected the vibration characteristics of the floor. For all tests, the floor was impacted and the vibrations were recorded at the center of the slab.

The presence of sand in the ribs prevented full composite action of this cross-section since there was not sufficient shear transfer between the slab and the deck. Therefore, the frequency and amplitude of this system could not be accurately predicted by the same equations used for typically constructed floor systems. The stiffness of this system was determined by the method described in Section 2.1.2.1 and the expected frequency and maximum amplitude were then calculated. This procedure was repeated to predict f and A_O for both without the plywood and with the expansion joint.

2.3.1.2 Results

Table 2.6 lists the stiffnesses and the predicted and measured vibration parameters of this floor. The changes in measured frequency and maximum

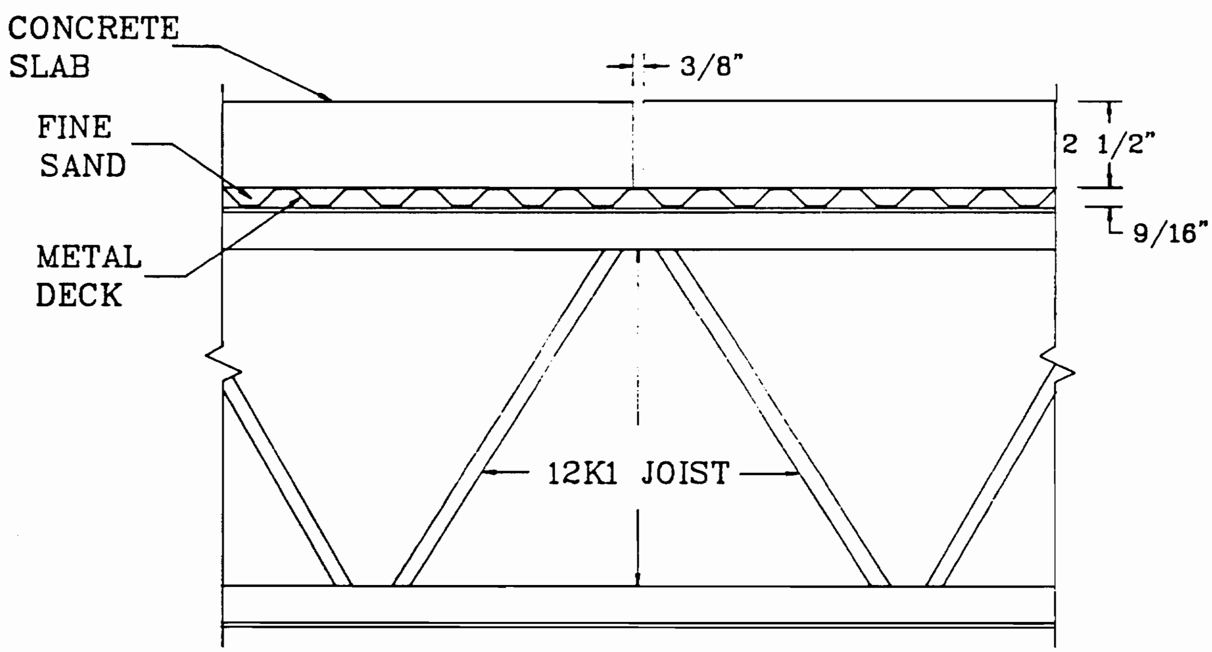


Figure 2.13 Midspan Section of Sand Floor

Table 2.6 Results from Sand Floor

Description	Experimental EI (lbs. in^2)	f (hz)		A_O (in)		D (% critical)		A.R.
		Predicted	Measured	Predicted	Measured	Required	Measured	
Plywood installed	1.92×10^9	5.1	5.1	0.1155	0.1062	23.1	7.0	0.303
Plywood removed	1.79×10^9	4.9	4.7	0.1195	0.1400	23.0	6.1	0.265
Expansion joint installed	1.85×10^9	5.0	4.8	0.1175	0.1346	23.1	6.6	0.286

Notes:

1. The predicted frequencies and amplitudes include the contributions of the supporting girders.
2. The required damping values are based upon the predicted values of f and A_O.

amplitude indicate the reduction in stiffness of this floor when the plywood was removed. The measured damping decreased as well. The asphalt expansion joint did not significantly affect the frequency or maximum amplitude, and the damping was still slightly less than when the plywood was still in place.

The results obtained from these tests were compared to the measured heel-drop responses of a similar but conventionally constructed floor system, described in Section 2.1.2.2. This base floor was the same as the floor described above except no material was placed in the ribs of the deck before the concrete was placed and the slab was continuous (i.e. no gap) across its width at midspan. The responses of this floor served as base data to verify any improvements yielded by the test floors.

As expected and observed, the sand floor was considerably less stiff than the base floor. This is reflected in comparison of the measured frequencies and maximum amplitudes of the two floors. The base floor was constructed such that composite action of the cross-section would occur during the dynamic testing. The measured damping of the sand floor after the plywood was removed was less than that of the base floor. Slightly larger damping values were measured with the plywood in place and with the expansion joint in place compared to the base floor.

With the plywood in place, the A.R. is 0.303. The A.R.'s of the sand floor without the plywood and with the expansion joint are 0.265 and 0.286, respectively. The A.R. of the base floor is 0.295. These values indicate a slight improvement in the vibration characteristics when the floor was constructed with sand in the ribs of the deck compared to the conventionally constructed floor. The removal of the plywood or the addition of the expansion joint in the slab at midspan did not improve the acceptability of the system.

2.3.2 Celotex Floor

A second floor system without concrete in the ribs of the deck was constructed and is illustrated in Figure 2.14. This floor was the same as the one described in Section 2.3.1 except for two differences. First, no sand was spread in the ribs of the deck. Instead, to prohibit concrete in the ribs, sheets of 1/2 in. thick Celotex (foil-back Styrofoam) were laid over the entire deck before the concrete was placed. This allowed the uninhibited movement of the deck as previously described. Second, a 3/8 in. thick piece of plywood was placed in the concrete across the width of the slab at midspan but not with the intentions of replacing it with an asphalt expansion joint. Instead, the plywood was later removed, and the gap was filled with silicone caulking. Figure 2.15 shows a section of this floor system at midspan.

2.3.2.1 Testing Procedure

The testing procedure for this floor was identical to that used for the "sand" floor. Heel-drop impacts were performed on this floor with the plywood strip in-place and removed and with the gap filled with caulking. Again, there was lack of sufficient shear transfer between the slab and deck of this floor to enable this cross-section to behave compositely. Therefore, the stiffnesses, frequencies, and maximum amplitudes of this floor system were determined in the same manner used for the "sand" floor.

2.3.2.2 Results

Table 2.7 lists the predicted parameters and the measured heel-drop responses of this floor. The stiffness of the floor was noticeably reduced when the plywood was removed. The increase in measured damping when the plywood was removed was unexpected since similar tests on the sand floor did not yield equivalent results. The addition of silicone caulking in the gap at

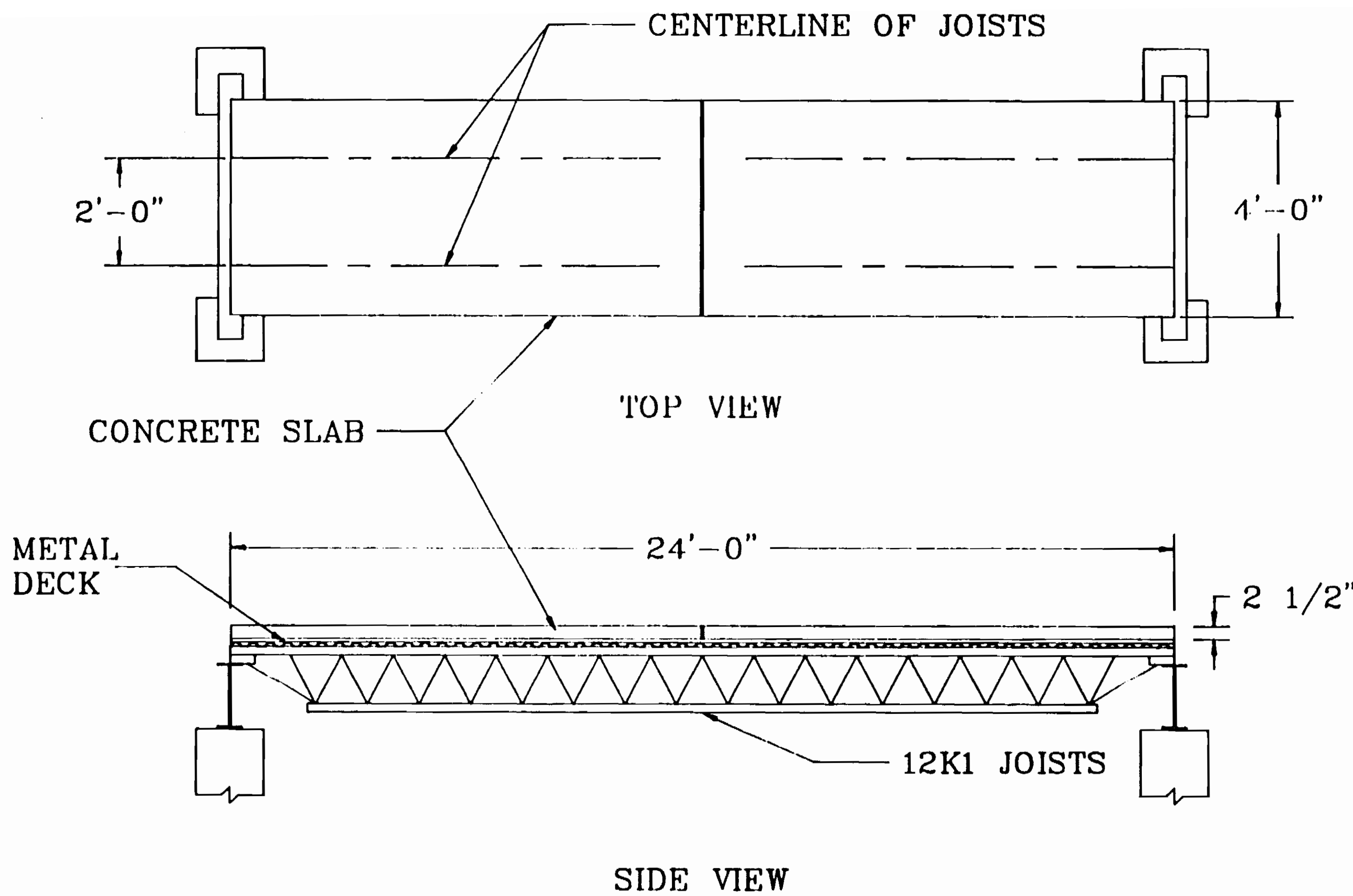


Figure 2.14 Test Floor with Celotex Between the Deck and Slab

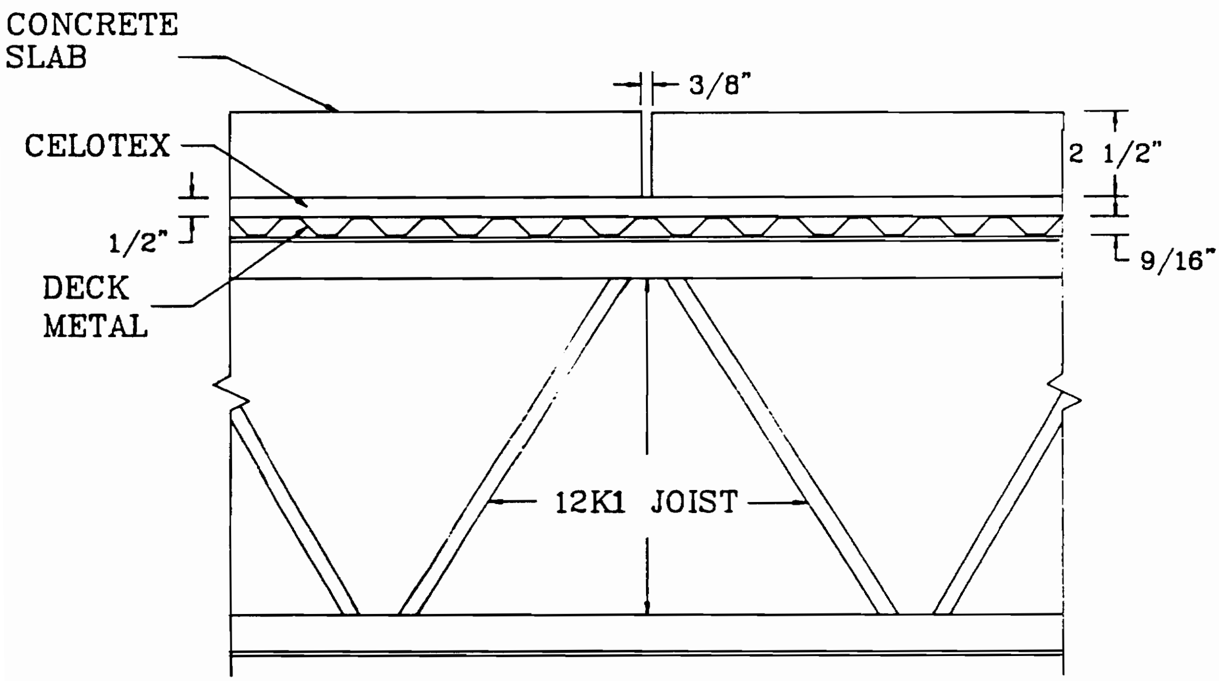


Figure 2.15 Midspan Section of Celotex Floor

Table 2.7 Results from Celotex Floor

Description	Experimental EI (lbs. in^2)	f (hz)		A_o (in)		D (% critical)		A.R.
		Predicted	Measured	Predicted	Measured	Required	Measured	
Plywood installed	2.363×10^9	5.7	6.0	0.1040	0.0915	23.2	7.6	0.328
Plywood removed	1.97×10^9	5.2	5.2	0.1150	0.1644	23.4	8.8	0.376
Caulking installed	2.11×10^9	5.5	5.5	0.1080	0.1469	23.3	7.5	0.322

Notes:

1. The predicted frequencies and amplitudes include the contributions of the supporting girders.
2. The required damping values are based upon the predicted values of f and A_o.

midspan slightly altered the frequency and maximum amplitude, but the measured damping was essentially the same as when the plywood was in place.

The results from the tests conducted on this floor were compared to the vibration parameters of the base floor described in Section 2.1.2.2. The Celotex floor was not as stiff as the base floor which behaved compositely. This is evident in comparison of the frequencies and maximum amplitudes of the two floors. The measured damping for all tests on the Celotex floor was greater than measured on the standard floor.

The A.R.'s of the floors are used to determine if any improvement resulted from constructing the floor with Celotex between the deck and slab. For all tests, the A.R. of the Celotex floor is greater than the A.R. (0.295) of the standard floor. With the plywood in place, the A.R. is 0.328. An A.R. of 0.376 results when the plywood was removed, and with the gap at midspan filled with silicone caulking, the A.R. is 0.322. These A.R.'s indicate that the vibration characteristics were improved when the floor was constructed with Celotex between the deck and slab. The greatest improvement resulted when the plywood was removed and the gap remained void of any material.

2.3.3 Conclusions

Two floors were constructed to determine if the addition of materials between the slab and deck would improve the floors' vibration characteristics. The heel-drop responses of these floors were compared to those of a similar, but conventionally constructed, floor. Improvements were verified by comparing the A.R.'s of the floors.

The presence of sand or Celotex prevented the interaction between the slab and deck which normally occurs in conventionally constructued floor systems. The sand and Celotex floors behaved non-compositely under dynamic testing. Consequently, these floors were less stiff and possessed lower frequencies and higher maximum amplitudes than the base floor. However, the floors with these materials exhibited higher values of measured damping than the base floor. The increased damping usually offset the adverse changes in f and A_O, resulting in improved acceptability.

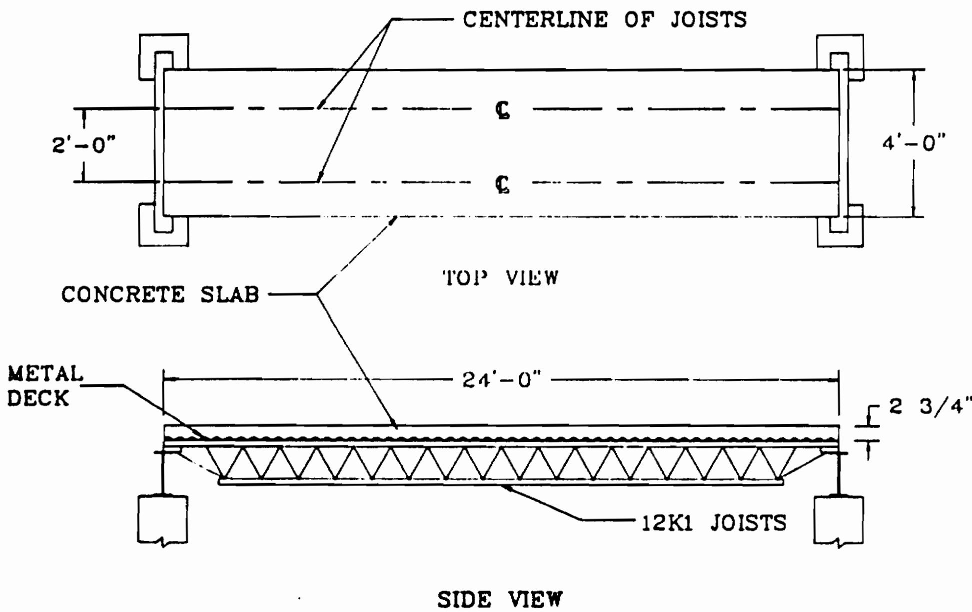
The improvements yielded by the Celotex floor surpassed those of the sand floor. Of the two test floors, the increases in damping were smaller with the sand floor. The amplified motion of the deck in the sand floor exploited the material damping characteristics of the deck. This deck movement was further enhanced in construction of the Celotex floor. The Celotex prohibited concrete in the ribs but also allowed the ribs to remain void of any material; whereas the sand was slightly restrictive of the deck contraction. Increases in the measured damping of this floor were greater than of the sand floor.

Although there is no definitive explanation for this improvement over the sand floor, several hypotheses exist. One is that the increased deck motion led to the measured increases in damping. By ensuring the ribs were void of restraining material and thereby allowing larger deck movements, the inherent damping potential of the metal deck was further developed. Another explanation is that a friction surface existed between the deck and the foil face of the Celotex. Although this may have also occurred between the deck and polyethylene in the sand floor, the evidence was more convincing with the Celotex floor. As the floor vibrated, noise was produced between the slab and top chords of the joists. When this floor was dismantled by lifting the slab off the deck, the Celotex clung to the concrete but easily separated from the deck. This along with the noise suggests that slip between these surfaces occurred under normal dynamic conditions. Similar to the cellular deck concept, the friction developed between the deck and Celotex when the floor vibrated increased the measured damping of the system. The final theory is that the Celotex possesses inherent energy dissipation properties that were employed much like a constrained viscoelastic layer is when the floor vibrated. This is supported by the increase in damping that resulted when the plywood at midspan was removed. By allowing more flexibility, the bending stresses of the Celotex were amplified when the floor vibrated; resulting in increased damping.

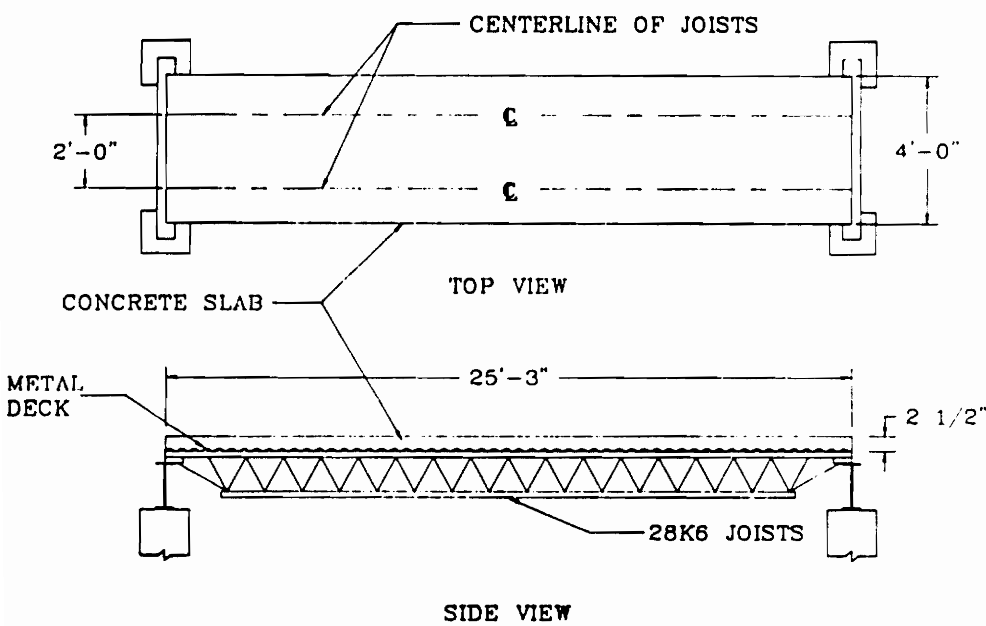
The improvements from this floor may have resulted from one or a combination of all of these hypotheses. However, since the behavior of the components of these floors was not experimentally monitored, no data is available to verify these explanations. Regardless of the reason, the results indicate that the vibrations characteristics of these joist supported floors were improved by the addition of selected materials between the deck and slab.

2.4 Presence of the Human Body

Lenzen [1966] indicated that normal human occupancy significantly increases the damping compared to that of an empty floor. But he determined that non-human loads (i.e. concrete cylinders on a floor) did not improve the floor damping. The damping effects of the human body were observed when heel-drop impacts were performed on the two-bay floor system with a man present in each bay. Both men hung relaxed by their arms from the bottom chord of the middle joist at midspan while a third person impacted the floor at the center of one bay. The perceptibility of motion during these tests was noticeably less than when the floor was impacted without anyone suspended from the joists. The measured frequencies and maximum amplitudes were essentially unchanged from values previously recorded. However, the damping was significantly increased and the beating effect (Section 1.3) was noticeably diminished when the men were hanging below the floor.



a) Floor A



b) Floor B

Figure 2.16 Human Body Damping Test Floors

To further substantiate the human body contribution to damping, impact tests were performed on other floor systems using both human heel-drop and mechanical impacts. Mechanical impactors have been substituted for human heel-drops in previous floor vibration studies [Lenzen 1963]; however the human heel-drop impact can be consistently reproduced with an acceptable degree of accuracy [Murray 1989a]. The measured frequencies and amplitudes were approximately equal for both types of impacts; however, there was a noticeable difference in the perceived and measured damping. The damping was significantly greater when the impact was a human heel-drop.

Both of these findings led to a further investigation of the effect the presence of the human body has on the damping of a floor system.

2.4.1 Testing Procedure

Preliminary tests indicated that the damping associated with the human heel-drop depended upon how the impact was performed. The standard method is with the knees in a relatively straight but relaxed position during and after impact. However, if the knees were "locked" straight or significantly bent when the heel-drop was performed, the damping varied from the standard impact. This indicated that not only did the presence of a human body effect the damping but how the body impacted the floor altered the energy dissipation from the system.

A series of tests were conducted on the two floor systems shown in Figure 2.16. In all tests, the impacts were performed and data was recorded at the center of the floor. Three different people performed the heel-drop tests. Tester 1 was a female approximately 5 ft. 3 in. tall and 120 lbs. Tester 2 and Tester 3 were males 5 ft. 9 in. tall and 190 lbs and 5 ft. 10 in. tall and 240 lbs, respectively. Each tester performed nine heel-drops on each floor; three with knees stiff, three with knees relaxed (standard position) and three with knees bent as if preparing to sit.

In addition, three impacts were performed on each floor with a mechanical impactor. This impactor consisted of a metal frame that suspended a leather bag filled with lead shot weighing 25 lbs. The bag was released from approximately 30 inches, allowing it to impact the floors. Although this impact did not precisely model the standard heel-drop, it was effective in extracting the natural frequency and damping of both floors without a human body present.

The same conditions existed when Testers 1 and 2 impacted the floors. Unfortunately, when Tester 3 performed the heel-drops, a sheet of ice approximately 1/4 in. thick was present on Floor B.

2.4.2 Results

The measured vibration parameters due to the various impacts on Floors A and B are listed in Tables 2.8 and 2.9. As expected for Floor A, the frequency did not significantly vary in the tests. The only variable in the frequency equation that changed was the mass, due to the difference in weight of the testers. However the deviation was not great enough to significantly alter the frequency. The measured frequencies of Floor B were essentially the same when Testers 1 and 2 performed the heel-drops. The increase in frequency measured when Tester 3 impacted the floor may have resulted from the additional stiffness provided by the sheet of ice present on the slab.

A variance in maximum amplitudes for each type of heel-drop was expected from tester to tester since their weights produced different impacting forces. For each tester, the maximum amplitudes of motion varied for each heel-drop for two reasons. First, the testers were inexperienced in performing consistent heel-drops. Second, the impacting force varied as the position of the knees were changed. Although this force was not experimentally monitored, it was evident to the testers and observers that a larger heel-drop force was exerted

Table 2.8 Heel-Drop Responses of Floor A

Impactor	Knees	f (hz)	A_o (in.)	D (% critical)
Mechanical	--	7.0	0.0176	1.6
Tester 1	Stiff	6.9	0.0475	4.9
	Relaxed	7.0	0.0456	3.9
	Bent	7.0	0.0350	2.2
Tester 2	Stiff	6.8	0.0832	8.6
	Relaxed	6.8	0.0629	5.1
	Bent	7.0	0.0488	2.4
Tester 3	Stiff	6.7	0.0668	7.7
	Relaxed	7.1	0.0381	4.1
	Bent	7.2	0.0362	2.1

Predicted Values:

$F = 6.9$ hz $A_o = 0.0740$ in $D_{req} = 20.4\%$ critical

Table 2.9 Heel-Drop Responses of Floor B

Impactor	Knees	f (hz)	A_o (in.)	D (% critical)
Mechanical	--	11.9	0.0103	2.3
Tester 1	Stiff	12.2	0.0150	4.4
	Relaxed	12.2	0.0136	3.2
	Bent	12.2	0.0110	2.1
Tester 2	Stiff	12.2	0.0224	5.1
	Relaxed	12.3	0.0209	4.9
	Bent	12.2	0.0175	2.8
Tester 3	Stiff	12.8	0.0172	5.0
	Relaxed	12.7	0.0173	4.0
	Bent	12.8	0.0137	2.5

Predicted Values:

F = 12.0 hz A_o = 0.0190 in D_{req} = 10.5% critical on the floors when the knees were stiff as opposed to relaxed and relaxed compared to bent. In addition, the added stiffness provided by the sheet of ice on Floor B when impacted by Tester 3 contributed to the reduced maximum amplitudes.

The frequency and maximum amplitude results were expected; however, the purpose of this study was to determine if the presence of a human body effects the damping of a floor system. A variance in measured damping for both floors is evident in Tables 2.8 and 2.9. For each tester, the damping was greatest when the heel-drop was performed with stiff knees and lowest when knees were bent. For both floors, the damping measured when the mechanical impactor was used was approximately equal to the damping that resulted when the testers heel-dropped with their knees bent.

The measured damping of Floors A and B for the three types of heel-drops was plotted versus the weights of the testers. Figure 2.17 shows the change in damping resulting from the different testers impacting the floors with knees stiff. Significant changes in damping are observable for Floor A from tester to tester. The changes in measured damping for Floor B were not as distinct for this type of impact. In Figure 2.18, the changes in measured damping from tester to tester impacting the floors with knees relaxed is seen as essentially the same for A and B. The damping of Floor A was slightly greater than that of Floor B. Similar changes from impacting with knees bent are shown in Figure 2.19.

For all types of heel-drops on both test floors, the damping asssociated with Tester 2 was greater than generated by Testers 1 and 3. In most cases, the damping measured when Tester 3 impacted the floors was slightly higher than when Tester 1 produced the heel-drops.

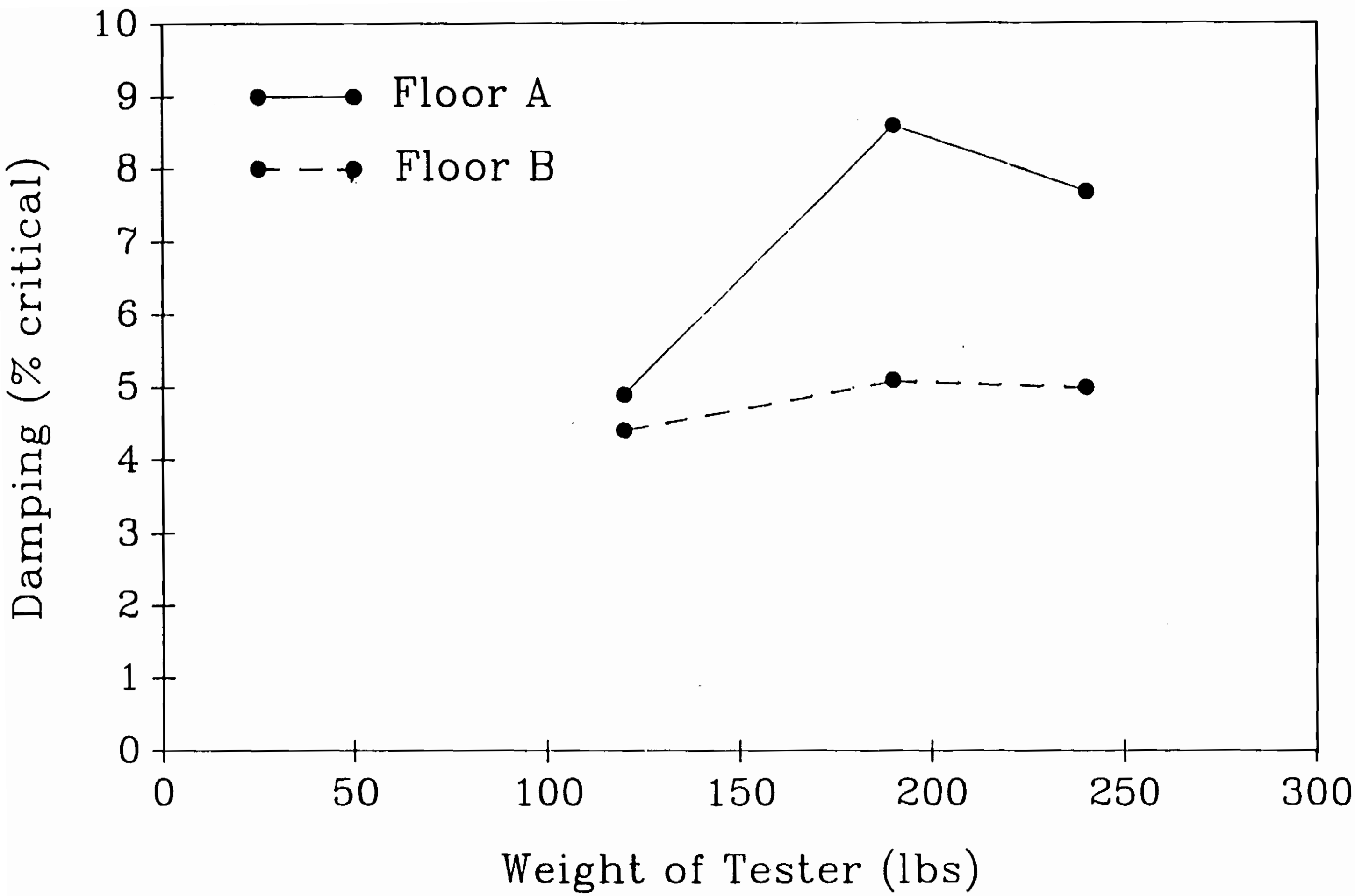


Figure 2.17 Plot of Weight of Tester with Knees Stiff vs. Measured Damping

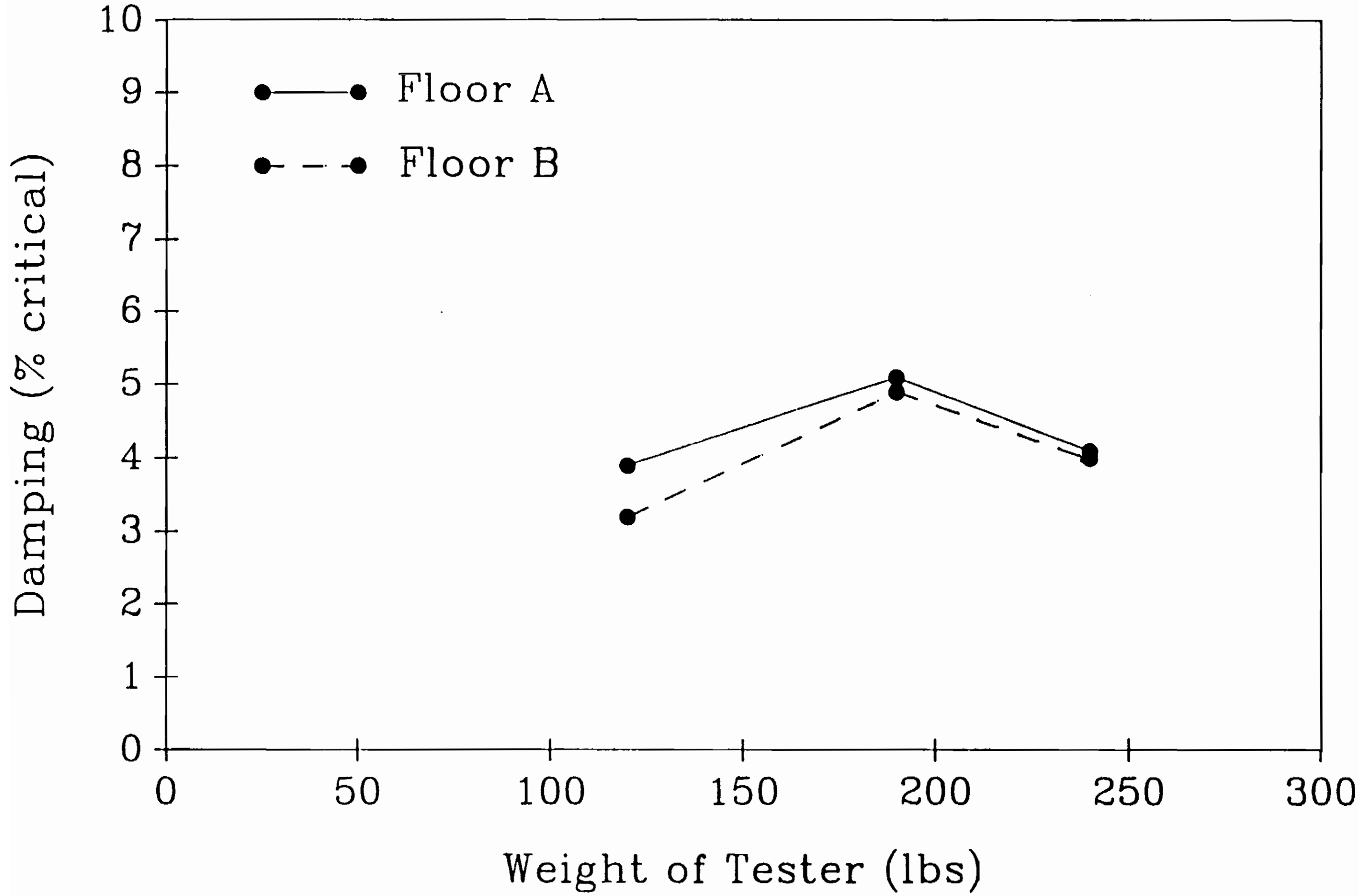


Figure 2.18 Plot of Weight of Tester with Knees Relaxed vs. Measured Damping

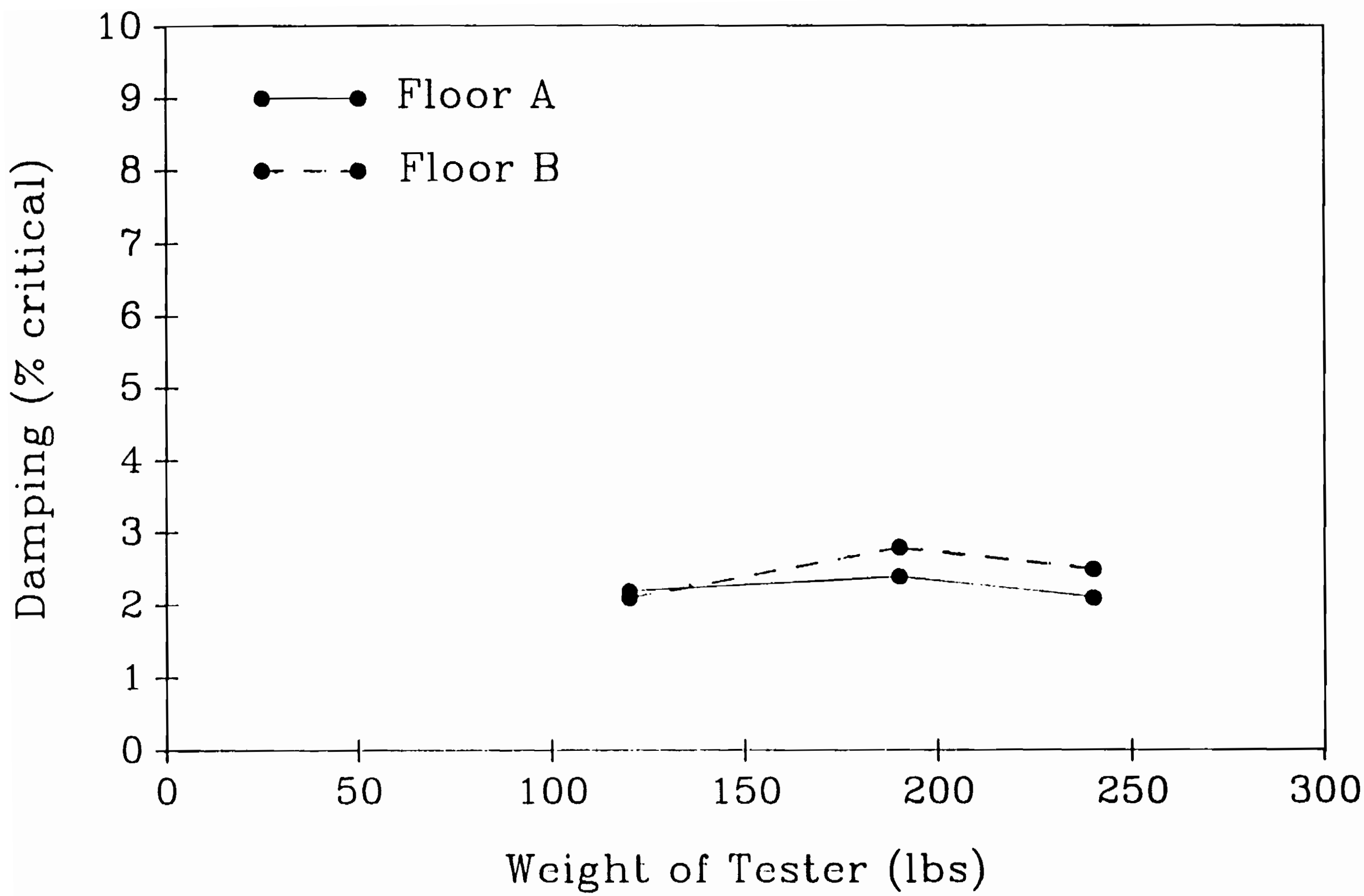


Figure 2.19 Plot of Weight of Tester with Knees Bent vs. Measured Damping

2.4.3 Conclusions

It is evident from comparison of the results that the human body improved the damping of these floor systems. The measured damping associated with the mechanical impactor was less than the damping measured when any of the testers performed the heel-drop with either stiff or relaxed knees. This indicates that a mechanical impact simulating a human heel-drop may result in a conservative assessment of the human preceptibility of floor motion. Since the sources and sensors of the annoying vibrations are humans, the measured damping associated with the standard human heel-drop best represents the damping of the occupied floor system.

Comparison of the results from the different testers reveals that the size of the person performing the heel-drop can affect the measured damping. The largest damping values were recorded when Tester 2 (190 lbs) impacted the floors. The testing was not extensive enough to provide a reliable estimate of the damping expected when a floor system is occupied, however these results show that damping depends on the mass of human body present on the floor.

The change in damping due to the change in position of the knees of the testers indicates that the damping effect of the human body is not simply a function of the body mass alone. Instead, it is believed that the body tends to act as a second mass damper, sometimes referred to as a tuned mass damper. Components of the body serve as the mass, spring, and dashpot of the damper. The mass of the damper is the mass of the body itself. It is not known exactly which body parts act as the spring and dashpot. A theory is that the internal organs and tissue serve as the spring element, and the organs and bodily fluids act as a viscous dashpot.

For each tester, the mass remained constant as the position of the knees changed, however the spring and dashpot elements of the damper were affected by the variation in knee positions. When the floors were impacted with stiff knees, the damper components of the body were employed and worked at increasing the vibration energy dissipation from the systems. The efficiency of the second mass damper was reduced when the knees were relaxed. In this position, the knees absorbed some of the floor motion before it reached the spring and dashpot elements of the body. By doing so, the dashpot component of the damper is not as efficient and the damping is less. When the heel-drops were performed with bent knees, the measured damping was equivalent to when the mechanical impactor was used, indicating that the damping effects of the body were essentially eliminated. The knees absorbed even more of the floor vibration. Therefore, the spring and dashpost elements no longer worked to dissipate energy from the system.

The results of these tests show that the human body can act as an artificial damping device for occupant-induced floor vibrations. Although the exact reason for this behavior is not given, similar artificial devices could work in the same fashion. If designed and installed properly based on tuned mass damper theory, bladder dampers may work as well or better than the human body at increasing the damping of floor systems.

CHAPTER III

COMPARISON OF RESULTS AND CONCLUSIONS

3.1 Results of Selected Methods

Chapter II included the results from all of the concepts investigated during this study. It has been concluded that some of methods did not effectively improve the vibration characteristics of the test floors. The modified friction devices were ineffective in the two-bay building (Section 2.1.1.2). Increases in measured damping produced by the viscoelastic shear devices (Section 2.2.2) were negligible. Some of the tests involving the cellular deck (Section 2.1.2.2) and the floors with sand and Celotex (Sections 2.3.1.2 and 2.3.2.2) resulted in no appreciable improvements in the vibration characteristics of the floors. The studies in Section 2.4 were conducted to determine the damping contribution of the human body and not with the intention of using the human body as an artificial damping remedy.

Therefore, comparisons of the various methods will be limited to several which produced significant improvements in the vibration characteristics of the joist supported floors. The specific concepts which will be compared are: the modified friction devices with a normal force of 10.8 lbs, the cellular deck with screws in every fifth or sixth rib, the Endur-C foam pads beneath the joist seats, and the Celotex floor without the plywood. The A.R.'s as well as the costs involved in obtaining the improvements of the floors will be compared.

3.2 Comparison of Results

For the selected methods listed above, the required damping values were based on the actual number of T-beams. Recall that the system maximum amplitude depends upon the effective number of T-beams which resist the heel-drop impact. For the laboratory floors, only two T-beams were available to resist the impact. Similar structures with such a small number of T-beams are pedestrian bridges. In these structures, required damping values may be as high as some of the values presented in Chapter II. However, two-joist floors are not commonly found in building systems.

As the number of effective T-beams increases, the system maximum amplitude as well as the required damping decreases. Therefore, the required damping values presented in Chapter II tend to overestimate the required damping associated with typical building floor systems. To estimate the performance of these methods in a typical building floor system, the number of effective T-beams of the test floors were calculated based on Equation 1.7 and are listed in Table 3.1. From these values, the system maximum amplitudes and corresponding A.R.'s were determined. There is a significant difference in the A.R.'s of each method depending on the number of effective T-beams used to calculate the required damping (Table 3.1). The A.R.'s based on the actual two T-beams are all less than unity; indicating that Equation 1.1 is not satisfied. These floors would be unacceptable based on Murray's criteria. However, when the effective number of T-beams is used, the A.R.'s approach and often exceed 1.000.

Assuming that the cross-sections of typical building floors were the same as the tests floors corresponding to these methods, Equation 1.1 may be satisfied. The A.R.'s based on N_{eff} T-beams presume that the appropriate test floor cross-sections are used. For example, a floor equivalent to the one

Table 3.1 Acceptability Ratios of Selected Methods

Method	N_{eff}	A. R. 2 T-Beams	A. R. N_{eff} T-Beams
Modified Friction Device	7.04	0.355	0.950
Cellular Deck	7.58	0.415	1.183
Endur-C Pads	6.49	0.736	1.735
Celotex Floor	8.06	0.376	1.101

described in Section 2.2.1 with approximately 6.5 effective T-beams and with Endur-C pads beneath the joist seats easily satisfies Murray's criteria. If the cellular deck floor (Section 2.1.2) were constructed with N_{eff} = 7.58, the measured damping would exceed the required damping. Similarly, a Celotex floor (Section 2.3.2) with N_{eff} = 8.06 would also be acceptable. These floors are representative of actual building systems and would not present annoying occupant-induced floor vibration problems.

The performances of the selected methods were evaluated by comparing the corresponding A.R.'s to those of conventionally constructed base floors. Table 3.2 lists the increases in A.R.'s produced by these methods. For example, the A.R. with the Endur-C pads beneath the joist seats was 0.736. This is 0.430 more than of the same floor without any pads and is the largest increase of the four methods. The A.R.'s indicate the effectiveness of the methods, but cost may be a factor. Estimates were made of the material costs involved with each method. The costs per plan square foot of floor area are listed in Table 3.2. The cost per square foot of the modified friction device reflects an estimate of $1.00/lb for steel and fabrication and $5.00 for hardware. The total weight of the four friction devices was approximately 50 lbs. Other labor costs are not included in any of the estimates. By calculating the ratios of cost per floor area per increase in A.R., the efficiencies of the methods can be compared.

Even though the Endur-C pads cost more per square foot than the other methods, this was still the most efficient means of improving the floor vibration characteristics. The Celotex floor was the least expensive and ranked second in efficiency. Although the cellular deck produced the second largest increase in A.R., the cost was relatively high. The modified friction device was the most expensive and produced the smallest increase in A.R. of these four effective methods; hence, this method ranked fourth in efficiency.

Table 3.2 Cost Comparison of Selected Methods

Method	Δ A.R.	Cost/Floor Area ($/ft^2)	Cost/Floor Area /Δ A.R. ($/ft^2)
Modified Friction Device	0.065	0.57	8.77
Cellular Deck	0.120	0.52	4.33
Endur-C Pads	0.430	0.80	1.86
Celotex Floor	0.081	0.24	2.96

3.3 Conclusions

All comparisons indicate that the Endur-C pads beneath the joist seats performed better than any other concept. The cellular deck followed in effectiveness, but the Celotex floor ranked second in efficiency. The performance of the modified friction devices on the two-joist floor was noteworthy and indicated that similar devices may have potential in floor system applications. Even though not all of the concepts of this study were successful, the methods discussed in this chapter indicate that the vibration characteristics of joist supported floors systems can be effectively improved.

CHAPTER IV

RECOMMENDATIONS

The results from this investigation show that the vibration characteristics of joist supported floors can be improved by several methods. In this chapter, recommendations will be made for further related work. It is anticipated that the results along with the recommendations of this study will initiate research to further develop these methods towards accepted use.

The first method discussed in Chapter II was the use of friction as a damping mechanism. Laboratory as well as field tests were conducted on the modified friction device. In Section 2.1.3, recommendations were proposed for improving this device and its performance in actual buildings. Before such a damping mechanism is deemed impractical, more extensive tests should be conducted after the improvements are made. Complete field tests should then determine the potential of this device. Although this method was not as effective as others studied, it may be installed in existing buildings to remedy floor vibration problems.

The cellular deck concept produced significant improvements in the floor vibration characteristics. It is suggested that more extensive testing be conducted so that the performance of this method can be verified. Tests should be run with a variety of deck configurations, experimentally monitoring the deck behavior.

Viscoelastic methods of damping were also discussed. The most effective and efficient concept of this investigation was the use of Endur-C pads between the joist seats and supporting girders. Other viscoelastic pads were studied, but their performances were not as impressive. It is strongly recommended that this concept be pursued. Other viscoelastic materials should be investigated and field tests should be performed. Guidelines are needed for proper selection and installation of the damping pads. This method has vast potential for solving occupant-induced floor vibration problems.

The viscoelastic shear devices were ineffective. If this concept is considered as a potential retrofit for existing floor vibration problems, studies should be conducted with other viscoelastic materials better suited for this application. It is not known at this time which materials would improve the performance of this method; however, material data is often available from the manufacturer.

Alternative slab/deck configurations, in some instances, resulted in improved floor vibration characteristics. It is understood that these systems may not be practical for building floors, but the results show that concepts were successful. With modifications, equivalently effective floors may be acceptable for use in building floor systems.

Finally, the damping contributions of the human body were studied. It was found that the human body tends to increase the energy dissipation from a floor system. Further work may result in a damping device similar to and as effective as the human body. Comparisons were made between the damping associated with a mechanical impactor and a human heel-drop. Impact tests revealed that the human heel-drop better represents the condition of a floor system when perceptibility of motion is of concern. For this reason, it is recommended that human heel-drops, rather than mechanical impacts, be used when measuring the actual vibration parameters of a floor system.

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APPENDIX

DATA REDUCTION EXAMPLE

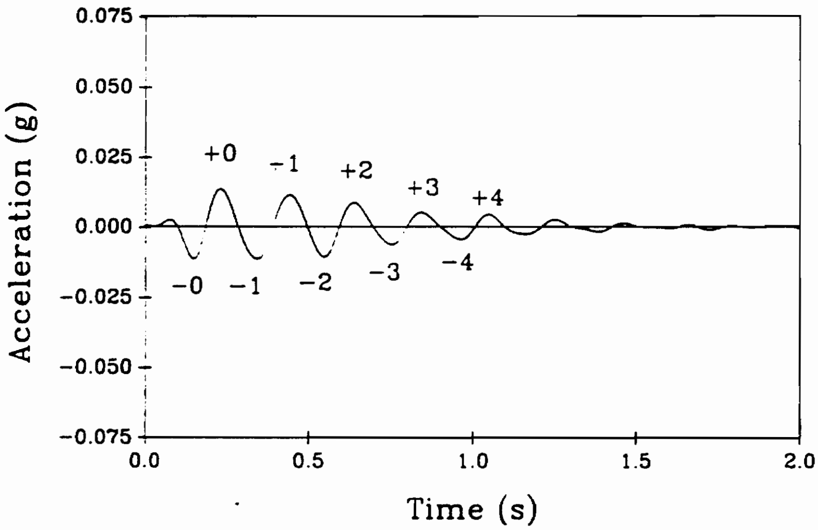

Figure A.1 Sample Heel-Drop Response

Peak Number	Peak Acceleration (g) +	−	Avg
0	0.0120	0.0130	0.0125
1	0.0120	0.0100	0.0110
2	0.0080	0.0065	0.0073
3	0.0005	0.0040	0.0048
4	0.0040	0.0030	0.0035

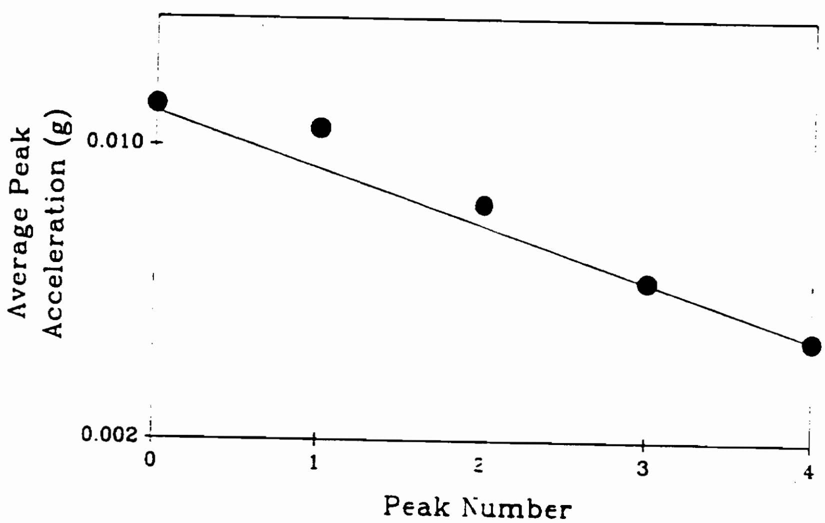

Figure A.2 Semi-Log Plot of Peak Number vs. Average Peak Acceleration

FREQUENCY

f = <u>4.8 hz</u> (from FFT software)

MAXIMUM AMPLITUDE

$$A_o = \frac{a_o g}{(2\pi f)^2} = \frac{0.0125(386.4)}{(2\pi x 4.8)^2}$$

$$= \underline{0.0053 \text{ in.}}$$

REQUIRED DAMPING

$$D_{req} = 35A_o f + 2.5 = 35(0.0053)(4.8) + 2.5$$

$$= \underline{3.4 \text{ \% of critical}}$$

MEASURED DAMPING

$$D = \frac{230.3}{2\pi(m\text{-}n)} \log(\frac{A_n}{A_m}) = \frac{230.3}{2\pi(5\text{-}0)} \log(\frac{0.0125}{0.0035})$$

$$= \underline{5.1 \text{ \% of critical}}$$

ACCEPTABILITY

$$A.R. = \frac{D}{D_{req}} = \frac{5.1}{3.4}$$

$$= \underline{1.5} > 1.0 \text{ Acceptable}$$

VITA

Christopher R. Cook was born in Dayton, Ohio on February 18, 1965. He graduated from Central High School in Woodstock, Virginia. In May, 1988 he received his Bachelor of Science degree in Civil Engineering from Virginia Polytechnic Institute and State University. He enrolled in the graduate program at VPI & SU in August, 1988.