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Final Report

EFFECT OF THE VARIATION OF STRUCTURAL PARAMETERS ON THE VIBRATIONAL CHARACTERISTICS OF STEEL JOIST-CONCRETE SLAB FLOOR SYSTEMS AND SUGGESTED DESIGNS

by Kenneth H. Lenzen and Lawrence P. Dorsett

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UNIVERSITY OF KANSAS CENTER FOR RESEARCH IN ENGINEERING SCIENCE Lawrence, Kansas

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Final Report

EFFECT OF THE VARIATION OF STRUCTURAL PARAMETERS ON THE VIBRATIONAL CHARACTERISTICS OF STEEL JOIST-CONCRETE SLAB FLOOR SYSTEMS AND SUGGESTED DESIGNS

INTRODUCTION

Background

In 1962, Dr. Kenneth Lenzen of the University of Kansas issued a final report ¹ summarizing therein all investigation completed at that time under sponsorship of the Research Committee of the Steel Joist Institute. That investigation set out to answer the questions: "How can annoying vibrations be eliminated in the initial design?" and "How can annoying vibrations be eliminated in a floor which is subject to them?" During the course of that investigation two test floors were constructed, various field investigations were conducted, human response was investigated, various damping means were designed and considered, and some analytical work on the general problem was completed. An appreciable store of information was gathered on floor vibrations.

However, for each question answered by that investigation new and important questions arose. As a result, several facets of the problem remained to be investigated more thoroughly. These included:

- 1. Verification or revision of the deflection formula;
- Verification that joists and slab act as a single unit during vibration (that is, substantiation of the "T" beam analogy for sections);
- Verification that bridging has little or no effect on the characteristics of floor vibration;

- Determination of the effect of a slab supported on all edges (plate action rather than beam action);
- 5. Substantiation or revision of the impact effect;
- Determination of the effect of the joist spacing and slab thickness on vibrational characteristics;
- Determination of the number of joists (that is, area of a particular floor) which undergo deflection on initial impact, and
- Determination of the distance between partitions that would cause the floor to act as an open floor rather than a partitioned one. (Previous tests had indicated that partitioned floors had no annoying vibrations).

Current Test Series

In order to further investigate these facets of the problem under controlled conditions a new test floor was constructed. This floor was much larger than either of the two previous floors and rested on a foundation which provided fixed support on three sides with a moveable wall supporting the fourth side. Bridging anchors were provided on the joists so that various bridging configurations could be installed. Also, the joists were installed in such a manner that they could be lowered or removed as desired. Thus, the new test floor lent itself both to the type of testing already completed and to the determination of essentially the complete set of fundamental properties of such floor systems.

Concurrent Analytical Developments

In the meantime, Dr. Marek Sokolowski of the Polish Academy of Sciences and Dr. Lenzen considered the analytical development of a more precise theory of steel joist-concrete slab floor systems. In their work they considered the problem of deflection and vibration of orthotropic plates, a generalization of the floor system. Rather than approaching the problem from the often used energy method (Ritz Method) they solved the deflection and vibrational problem from the more classical forceequilibrium viewpoint. As a result, a consistent theoretical background is available with which to predict the characteristics of any particular floor design.

Application of the Experimental and Analytical Developments

The overall objective of these investigations is, of course, to provide sufficient information to allow the design of better (less annoying) floor systems and to allow the elimination of annoying vibrations in present floor systems. This objective has been realized to a great extent by the application of the experimental and analytical developments by Mr. Ron Gibson² to both the calculation of the characteristics of the common floor systems which might be constructed with presently available joists and to the data already gathered on field installations by Mr. Joseph E. Keller.^{3,4} A wealth of information has been compiled in tabular and figure form which should prove very useful in the setting of future specifications for the construction of floor systems, and also in better understanding the problems evident in floors for which complaints have been made.

CURRENT TEST SERIES

General

The test floor (Figure 1) constructed for the current test series consisted of twenty-five thirty-two feet, nine-inch, open-webbed, steel joists at twenty-four-inch spacing supported by a three-sided, fixed, concrete block foundation which was forty inches high. This supporting foundation was fabricated using eight by eight by sixteen-inch concrete blocks. Lateral step supports were build at three positions along each of the long sections of the foundation. Each end of each joist rested on 4 two by four by eight-inch concrete bricks. These bricks could be removed to allow removal or lowering of any joist.

Standard Corruform centering was spot-welded to the top of the joists and a two-and-one-half inch thick (maximum thickness) concrete slab was cast on the centering. This slab was made of three thousand psi ready-mix concrete. It was reinforced with six by six-inch #6 wire mesh placed in the center of the slab. Casting the slab forced the wire mesh to the bottom and, although some effect was made to bring it back to the center, subsequent testing showed the wire to be just above the centering. The overall dimensions of the slab were thirty-two feet - nine inches by fifty-one feet.

To allow the active length of the floor to be varied, three angleiron stands (Figure 2) were constructed on top of which a section of eightinch, wide-flange I-beam was placed. The stands could be raised either by installed elevation screws or by placing hydraulic jacks under each end. The three sections spanned the entire width of the floor and could 4



Figure 1. Test Floor Constructed For and Used in Current Test Series.

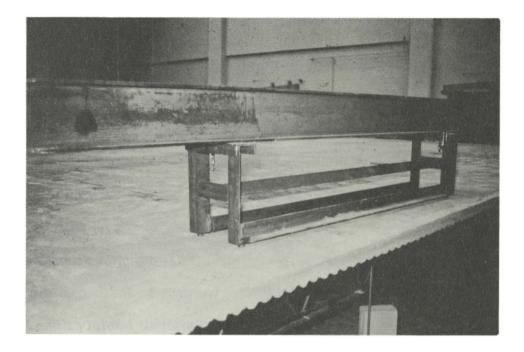


Figure 2. Moveable End Wall Stand with I-Beam in Position.

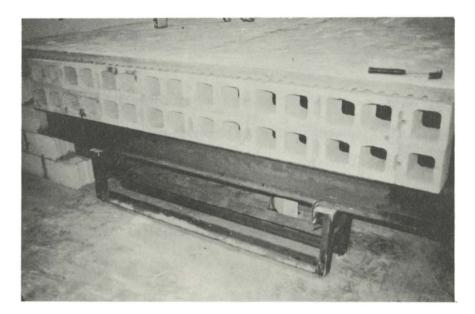


Figure 3. Moveable End Wall Section in Position at Extreme End of Floor for Test.

be moved beneath the floor, raised to come in contact with the bottom of the floor, and thereby, effectively shorten the length of the floor undergoing impact (Figure 3).

Three means of excitation were available. First, the floor could be continuously excited by a Calidyne Shaker. Secondly, a short duration impact could be applied by use of a mechanical impacter⁵ (Figure 4). This device consists of a weight which can be raised to varying heights (depending on the magnitude of impulse desired), released and caught on the rebound so that only one impulse is propagated. Finally, a relatively long duration impulse could be applied to the floor by the simple expedient of jumping. Each of these excitation methods were used and each yielded different facets of the overall problem.

Five means were available to measure the various parameters of interest in the tests. First of all, static deflection was measured by dial strain gauges installed beneath the floor. These were used only for calibration purposes. Static deflection during the test series was calculated from strain measurements by electrical resistance strain gauges (Figure 5) installed on the lower chords of the joists. The signals from these strain gauges were amplified and recorded by a Sanborn preamplifier-amplifier-recorder system (Figure 6). Dynamic deflection was calculated from measurements by accelerometers (Figures 7 and 8), the output of which was fed through integrating circuits into the Sanborn equipment. Dynamic deflection could also be calculated from measurements by the installed strain gauges or directly by a seismic type Sprengnether instrument (Figure 9). Finally, in some tests, the acceleration of the slab was measured by accelerometers feeding directly into the Sanborn equipment.

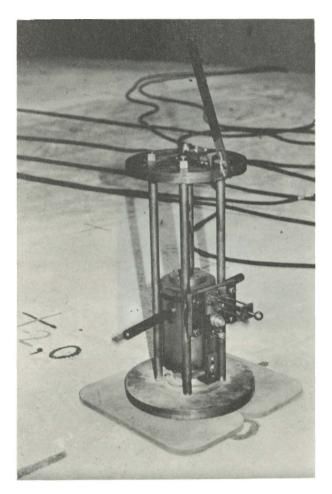


Figure 4. Mechanical Impacter.

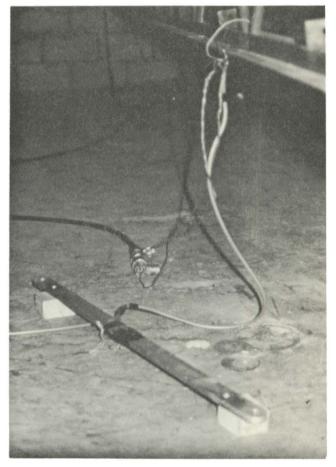


Figure 5. Strain Guage Installation.

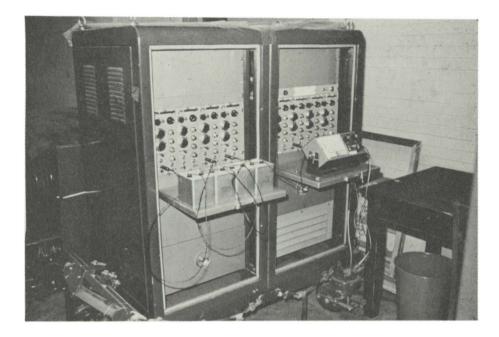


Figure 6. Sanborn Equipment.

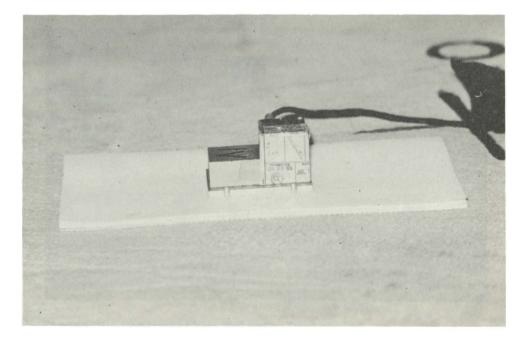


Figure 7. Accelerometer.

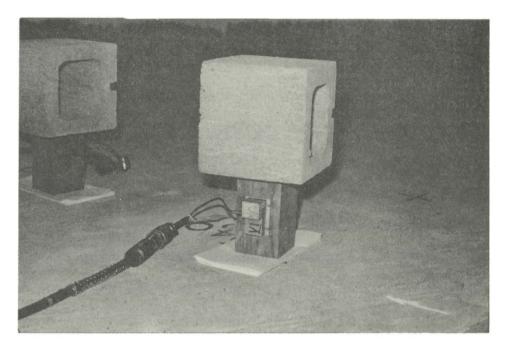


Figure 8. Accelerometer Positioned as for Testing.

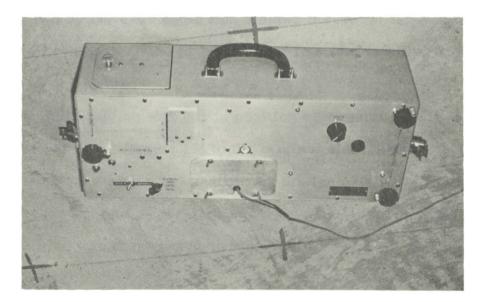


Figure 9. Sprengnether Seismic Instrument.

Floor Configurations Tested

When the test floor was built, single angle-iron bridging (Figure 10), one-eighth by one-and-one-quarter by one-and-one-quarter inch, was installed at the center and eight feet to either side of the center of the joists to properly space them and to provide some degree of stability during construction operations. After the slab was cast, tests were made with this particular bridging installed to develop the experimental techniques required, to check out the instrumentation, and to determine the nature of the characteristics to be measured. A full set of measurements were made with this configuration.

The single angle diagonal bridging (simple bridging) was then removed and measurements were taken of the floor with no bridging installed. There seemed to be no essential difference in the characteristics determined with and without simple bridging so the intermediate steps were bypassed and full bridging (Figure 11) was installed. The full bridging consisted of one-eighth by one-and-one-quarter by one-andone-quarter inch angle iron forming and "X" pattern with horizontal onequarter by two by two inch angle iron closing the "X" at top and bottom. It was placed in the center and at intervals of four feet to either side of the center of the joists.

The full bridging was left in position as an additional two inches of concrete were cast (Figure 13) to the original slab. Bonding between the two parts of the slab was enhanced by driving anchoring studs (Figure 12) into the bottom part at two-foot intervals with a stud gun (Figure 14). The bottom slab was then wetted and the additional concrete poured.

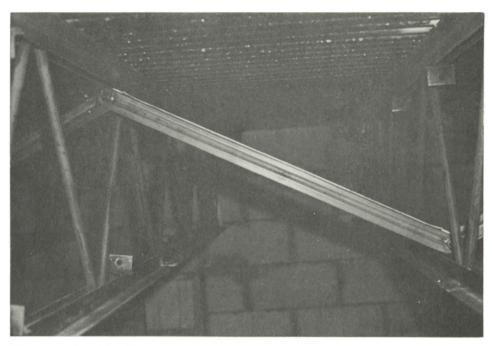


Figure 10. Simple Bridging.

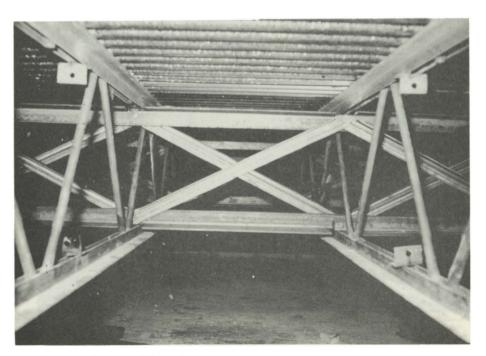


Figure 11. Full Bridging.

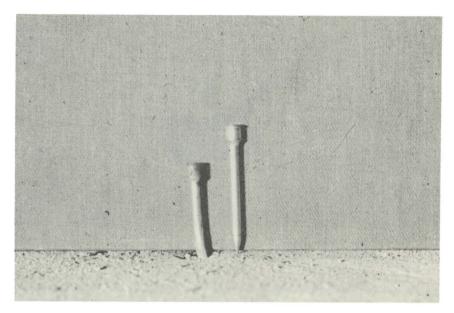


Figure 12. Anchoring Studs to Promote Bond Between Separate Slab Castings.



Figure 13. Addition of Two Inches of Concrete to Original Slab.

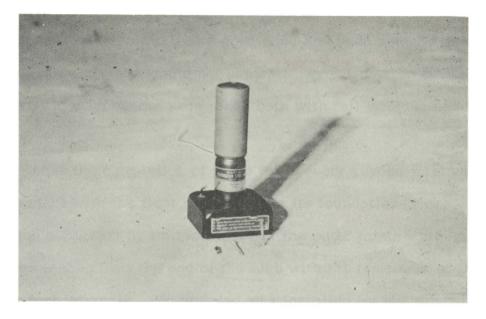


Figure 14. Stud Gun Used for Placing Slab Anchors.



Figure 15. Removal of Four Feet from both Long Edges of Slab.

Subsequent tests showed that a good bond had been secured and that, in fact, the two slabs would not separate, even when the floor was dismantled. Measurements were taken both with full bridging and without any bridging.

After the completion of these tests every second joist was lowered from contact with the floor by removal of its foundation bricks. The floor was then supported by thirteen joists. The outer joists were located eighteen inches from the end of the slab with the remainder of the joists at four foot intervals. No bridging was installed for the measurements made during this series.

Finally, the slab was cut (Figure 15) four feet from the edge of either long side (perpendicularly to the line of the joists) and the concrete outside the cuts removed. This step was taken to simulate the floor (Figure 16) which results when a portion of it has been removed for the installation of ventilation ducting. Again, no bridging was used while measurements were taken in this configuration.

Specific Measurements Taken

For each of the various floor configurations tested a recording was made of the deflection of the center of the active floor under impact. That is, for each thickness of concrete and arrangement of bridging, the moveable, end wall was positioned at intervals along the length of the full floor and at each position the center of the resultant floor section was impacted and the motion recorded. From these recordings the initial impact deflection, frequency of vibration, and damping characteristics were determined.

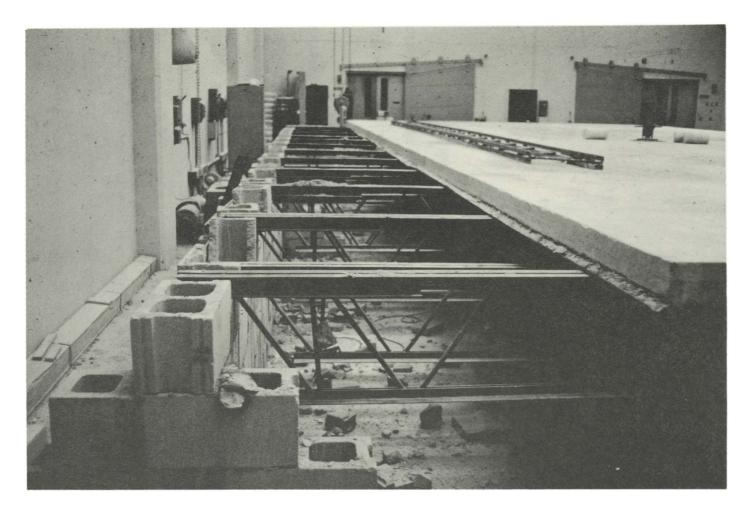


Figure 16. Test Floor with Four Feet of Slab Removed from Edge for Ventilation Duct Simulation.

For a few of the floor configurations the acceleration and the static deflection of the center of the active floor were measured. Acceleration was determined for the two modes of impact while the static deflection was determined for static point loading. In addition, for some floor configurations, the deflection profile under static point loading was determined. In this test the center of the full floor was loaded while the deflection of the floor was measured at two (or four--in configurations where half the joists were removed)-foot intervals along the center of the joists.

Finally, the original floor configuration was force vibrated by the Calidyne Shaker at the center of the full floor and at one-quarter of the length from the end. The shaker was operated at constant output over a range of frequencies from about one cps to ten cps in order to determine as accurately as possible the first few natural frequencies of vibration. Table 1 summarizes the tests made and measurements taken.

Floor Configuration	Impact Deflec- tion	Frequency	Damping	Static Deflec- tion Profile	Static Deflec- tion of Center	Acceleration
Two-inch floor, simple bridging	х	x				X
Two-inch floor, no bridging	х	X	x	х	x	
Two-inch floor, full bridging	X	X				
Four-inch floor, full bridging	х	х				
Four-inch floor, no bridging	x	х	x	x	х	
Four-inch floor, thirteen joists	X	x	x	x	x	·
Four-inch floor, thirteen joists, edges removed	X	X	X	x		

Table 1. Tests Made and Measurements Taken.

Note: Other tests were run and other measurements were, of course, taken. The above summary lists the set of tests considered most indicative of the characteristics to be investigated and, consequently, those tests for which sufficient readings were taken to allow a meaningful statistical average.

RESULTS OF THE TEST SERIES

Typical Recordings

Figure 17 shows a typical deflection-time recording after impact, whether by Sprengnether, accelerometer, or installed strain gauge, for the floor excited by the impacter. Indicated on the figure are the various measurements taken on each recording in order to gain the information necessary to make the plots that follow. As noted, each recording was analyzed for initial impact deflection, frequency of free vibration, logarithmic decrement, and the time required to establish the fundamental mode of vibration.

Figure 17 may be compared with Figure 18 which shows a typical deflection time recording after impact for the floor excited by a jump. Clearly apparent are beats which often occurred when the length of the active floor was more than thirty feet. The recordings of static deflection, whether for deflection profile or deflection of the center of the active floor, simply show a step discontinuity along the time axis. The ac-celeration recordings (recordings of accelerometer output with no integration) showed a rather high frequency signal superimposed on the basic floor vibration. These recordings were analyzed only for initial amplitude.

Composite Action of Slab and Joists

The instrumentation used for the current test series allowed the composite action of the slab and joists to be demonstrated. Perhaps the most clear demonstration is by Figure 19 where simultaneous recordings of the deflection of both the slab and joists after impact are depicted.

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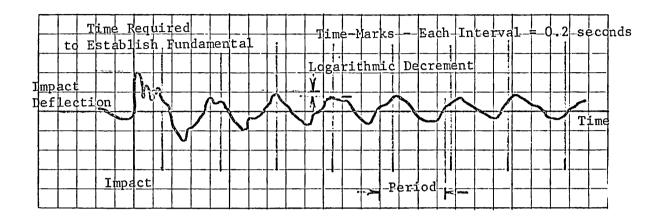


Figure 17. Typical Impact Deflection Recording Showing Measurements Taken on Recordings. Impacter Excited.

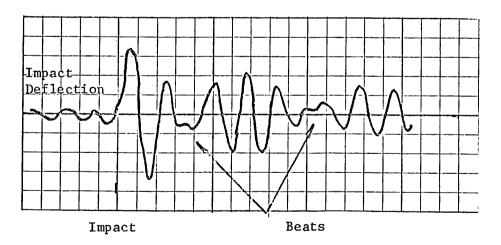
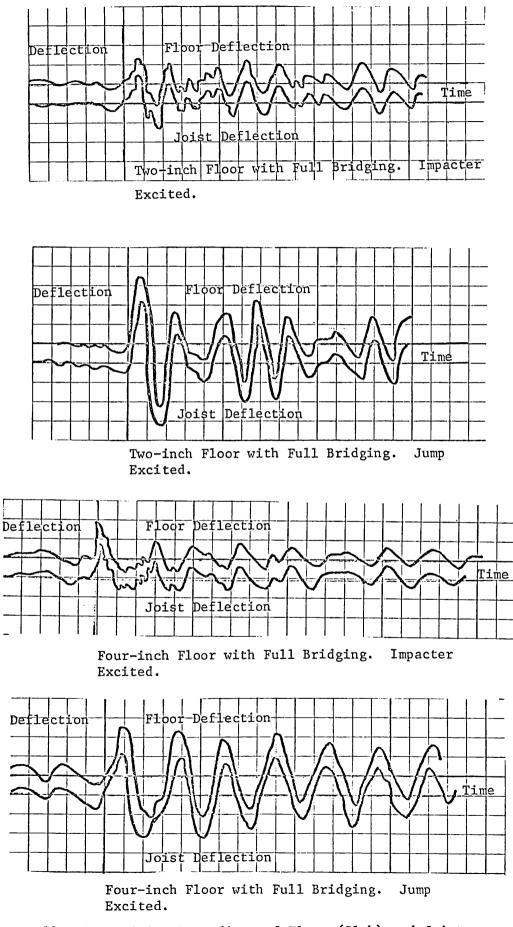
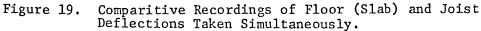


Figure 18. Typical Impact Deflection Recording Showing Beats. Jump Excited.





In each instance the upper recording is an actual recording made by the Sprengnether instrument positioned on top of the slab; the bottom recording is a recording made by installed instrumentation (that is, by strain gauges fastened to the bottom chords of the joists) reproduced with time and amplitude scale corresponding to that of the associated Sprengnether recording. These strain gauges measured joist deflection while the Sprengnether instrument measured slab deflection.

It is apparent that both the slab and joists moved with almost identical motions. The differences that do appear on the comparative recordings may reasonable be explained by the different characteristics of the two sensing devices.

The deflections shown are those in the vertical direction, which is, of course, the direction of maximum amplitude. Some attempt was made to measure deflection in the horizontal direction. This deflection was more difficult to measure accurately, but the results indicate that the top chords of the joists and the bottom of the slab move together while the bottom chords of the joists have a horizontal amplitude about twenty percent greater than the top chords (with no bridging). Still, these horizontal amplitudes are small in comparison with the vertical amplitudes, being less than one-fifth the corresponding vertical amplitude.

General Discussion

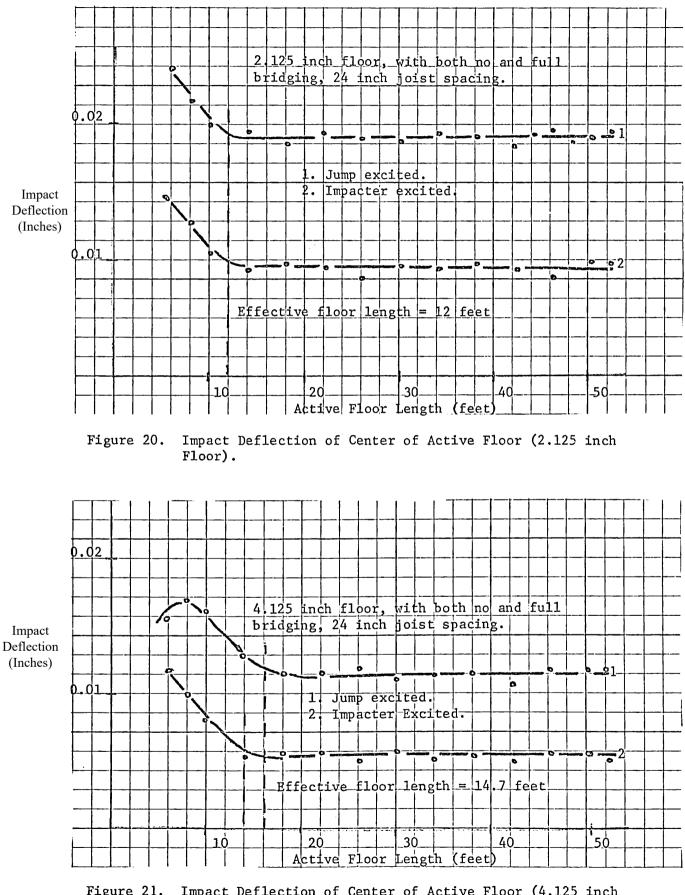
The figures that follow (Figures 20 through 31) summarize the results of the current test series, depicting in plots the information taken from the deflection-time recordings. The first set of figures (Figures 20 through 23) shows the deflection of the center of the active floor under impact as a function of the length of the active floor. In each case an attempt is made to indicate the point at which the curve undergoes a distinct change. The floor length at that point is referred to as the "effective floor length."

The second set of figures (Figures 24 and 25) shows the fundamental frequency of free vibration of the active floor as a function of the length of the active floor. The third set of figures (Figures 26 through 28) shows the damping characteristics of the floor configurations tested. The first figure is a plot of the logarithmic decrement of the fundamental mode as a function of the length of the active floor. Since the logarithmic decrement is related to the damping coefficient, the same information may be presented in terms of the percentage of critical damping as is done in the second figure. The last figure of the set is a rather arbitrary attempt to indicate the relative damping of higher order vibrations. It is a plot of the time required to clearly establish the fundamental mode of vibration as a function of the active floor length.

The fourth set of figures (Figure 29) shows the static deflection profile of the floor loaded at the center with a point load. The oscillatory nature of the deflection is clearly visible. The fifth set of figures (Figure 30) shows the static deflection of the center of the active floor as a function of the length of the active floor. Finally, the last set of figures (Figure 31) in this section shows the initial impact acceleration of the center of the active floor as a function of the length of the active floor.

Deflection of the Center of the Active Floor under Impact (Figures 20 through 23)

In all instances it may be noted that as the length of the active floor was decreased the impact deflection remained reasonably constant



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Figure 21. Impact Deflection of Center of Active Floor (4.125 inch Floor).

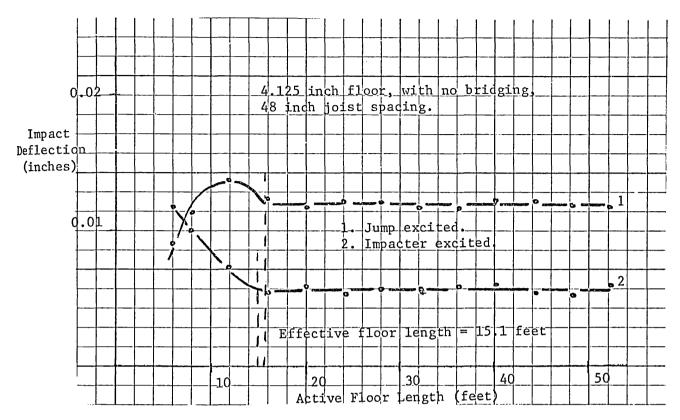


Figure 22. Impact Deflection of Center of Active Floor (4.125 inch Floor), 48 inch Joist Spacing.

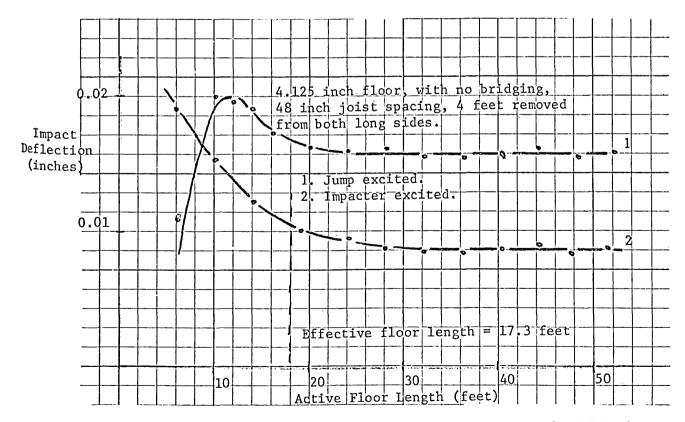


Figure 23. Impact Deflection of Center of Active Floor (4.125 inch Floor), 4 feet Removed from Both Long Sides.

until a readily apparent point was reached where the impact deflection sharply increased. This effect occurred both for the sharp impacts delivered by the impacter and for the longer duration impacts delivered by jumping. The point where these changes took place corresponds to a definite length of active floor referred to as the "effective floor length." For a given floor width the impact characteristics of a floor continuously change over floor lengths up to the effective floor length. For longer floors the characteristics are essentially constant.

Increasing the depth of the concrete added both flexural rigidity and weight to the system. As a result, the effective floor length increased somewhat while the impact amplitude decreased. It will be noted that the deflection excited by jumping decreases at an active floor length of about ten feet. This is due to the fact that the fundamental frequency of free vibration of the system becomes too high at that point to be effectively excited by the relatively long duration jump impact.

Removing half the joists naturally caused the effective floor length to increase with the change in flexural rigidity. Again, the impact amplitude increased, and the jump excited amplitude decreased at about twelve feet.

When four feet of the slab were removed from both long sides of the floor the general nature of the impact deflection curves remained the same but the point at which the characteristics changes became difficult to define. The effective floor length apparently increased again, although this observation is not certain. In any event, the impact deflection increased. It is apparent, then, from these results that increasing the depth of concrete in the slab decreases impact deflection, while increasing the effective floor length. Reducing the number of joists (or, equivalently, increasing the joist spacing) increases the impact deflection and also the effective floor length. As may be noted, bridging has no discernable effect, either on effective floor length or impact deflection. The data obtained both with no and full bridging yield the same impact deflection curve.

Frequency of Free Vibration of the Floor System (Figures 24 and 25)

For the 2.125 inch floor system two different frequency curves are shown. The upper curve of Figure 24 shows the variation of frequency with active floor length soon after the slab was cast. At that time very little cracking had occurred. During the testing the slab sustained a number of large cracks. These had the effect of reducing the rigidity of the system and the lower frequency curve resulted. It is interesting to note that the slab cracked in a way to quickly lower the rigidity to the point where the lower curve resulted, but, even though further cracking occurred, no measurable lowering of the flexural rigidity occurred.

Again, it may be noted that bridging had no discernable effect on the frequency characteristics of the floor. Indeed, if there was any real difference between the frequencies obtained with no bridging installed and those obtained with full bridging installed, that difference could be explained and accounted for by the weight the bridging added to the system. Very heavy bridging was used to attain the maximum effect on 27

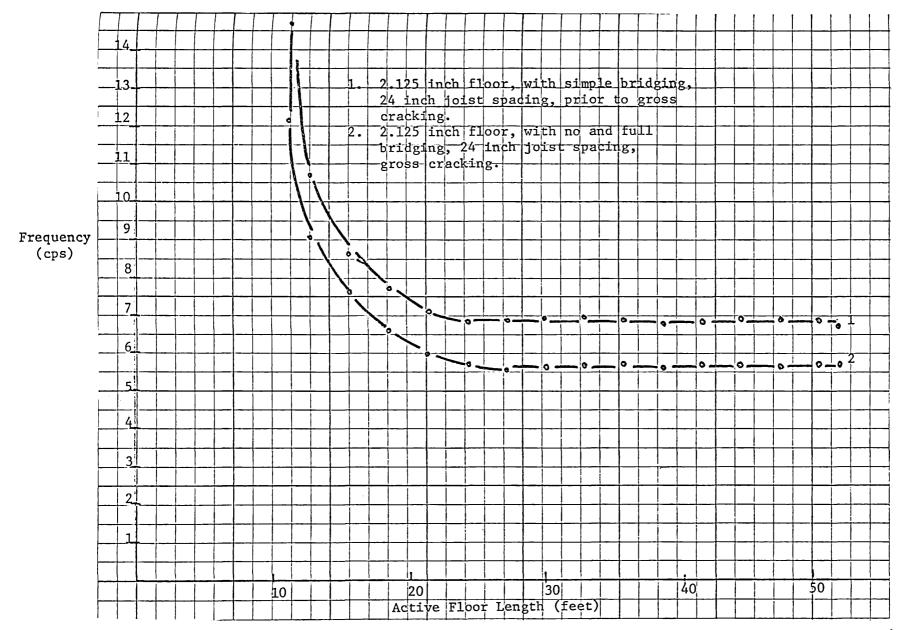


Figure 24. Experimentally Determined Fundamental Frequencies of Free Vibration (2.125 inch Floor).

14 ň 13 12 4.125 inch floor, with no and simple bridging. 11 24 inch joist spacing. 48 inch joist spacing. 1. 10 3. 48 inch joist spacing, 4 feet removed from both long sides. 9 (cps) 8 7 'n 0~ 6 0~ 5 1 -10-1 ά. 0~ 5 .2 4 ٥. 6-4 Ì. 1 0____0__ •3 0 0-3 2 1 40 20 Active Floor Length (feet) 30 50 10

Frequency

Figure 25. Experimentally Determined Frequencies of Free Vibration of Floor Configurations Tested (4.125 inch Floor).

rigidity that may be obtained by bridging. Calculations show that the weight of the bridging would decrease the fundamental frequency by about one percent. This difference was masked by the natural spread of the data.

Finally, the frequency of the fundamental mode changes very little for floors of length greater than the effective floor length, but increases for floors of smaller length because of increasing slab stiffness.

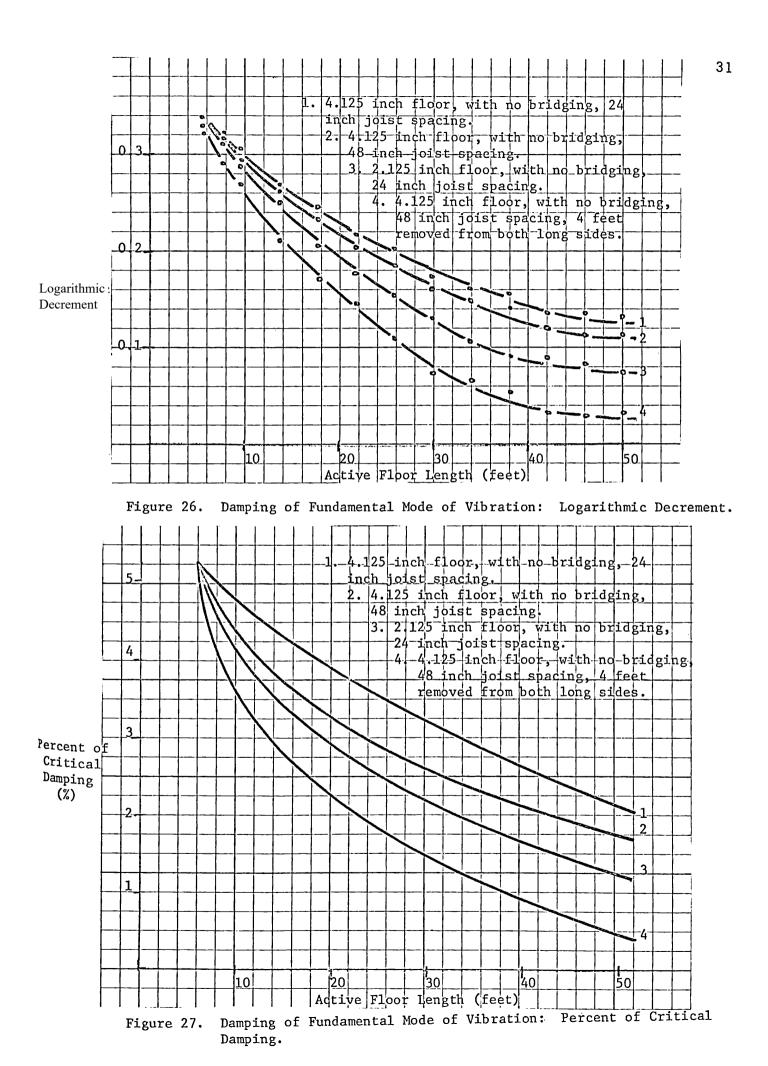
Damping Characteristics of the Floor System (Figures 26 through 28)

The damping of the fundamental mode of vibration, as evidenced in the change of the logarithmic decrement and the percentage of critical damping, decreased as the active floor length increased and as the rigidity of the system decreased (that is, thinner slab or more spacing between the joists). Especially noticeable is the low value of damping for the floor with four feet removed from both long sides of the slab.

Again, the damping of vibrational hormonics increases with an increase in the rigidity of the floor or a decrease in the active length of the floor. The time required to establish the fundamental mode of vibration, here used as a measure of the higher order damping, is not directly related to any particular parameter of the system. However, it seems to be the most convenient way to present the data.

Static Deflection Profile of Floor under Point Load at Center (Figure 29)

The static deflection profiles of the various floor configurations under point load at the center show the oscillatory nature of the floor deflection. The profile is quite similar to that of a beam on an elastic



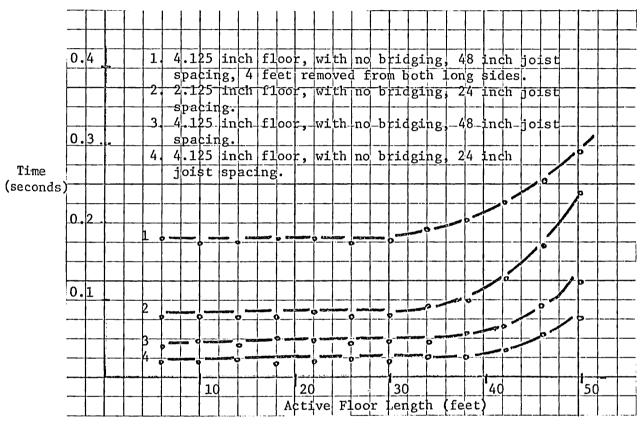


Figure 28. Damping of Vibration Harmonics: Time Required to Establish Fundamental Mode of Vibration.

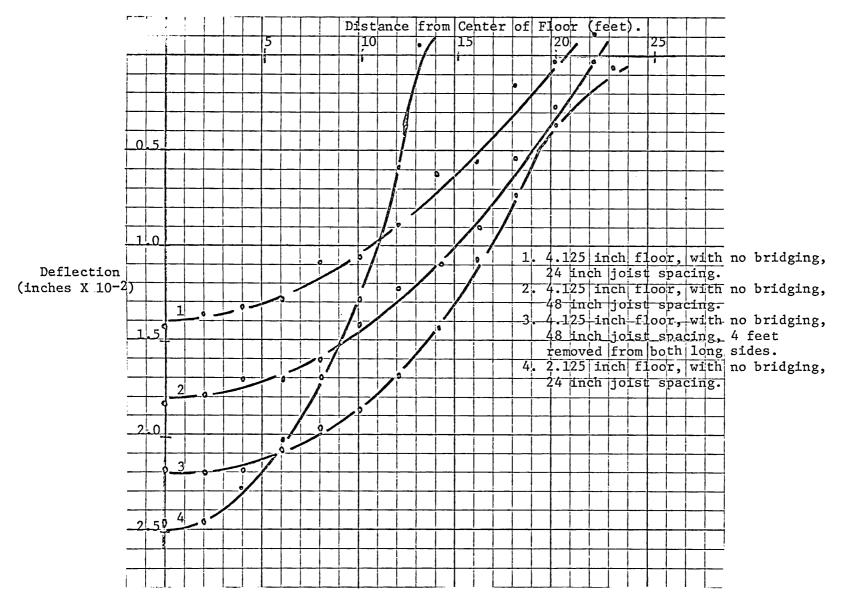


Figure 29. Experimentally Determined Static Deflection Profiles of Floor under Point Load at Center.

foundation. All floors showed some positive displacement (except that with four feet removed from both long sides), but, in general, it was very little, and the second reversal was never noted. The point at which the deflection changed signs occurred at greater distances from the load as the depth of concrete was increased and as the rigidity of the system in the direction of the joists was decreased.

The distance from the load to the point at which the deflection changes sign seems closely related to the effective floor size for a particular system. In fact, for the floors tested, the distance is approximately equal to the effective floor size. This suggests that such measurements may be used as an experimental measure of the effective floor size, at least on floors of greater length than the effective floor size for the particular system.

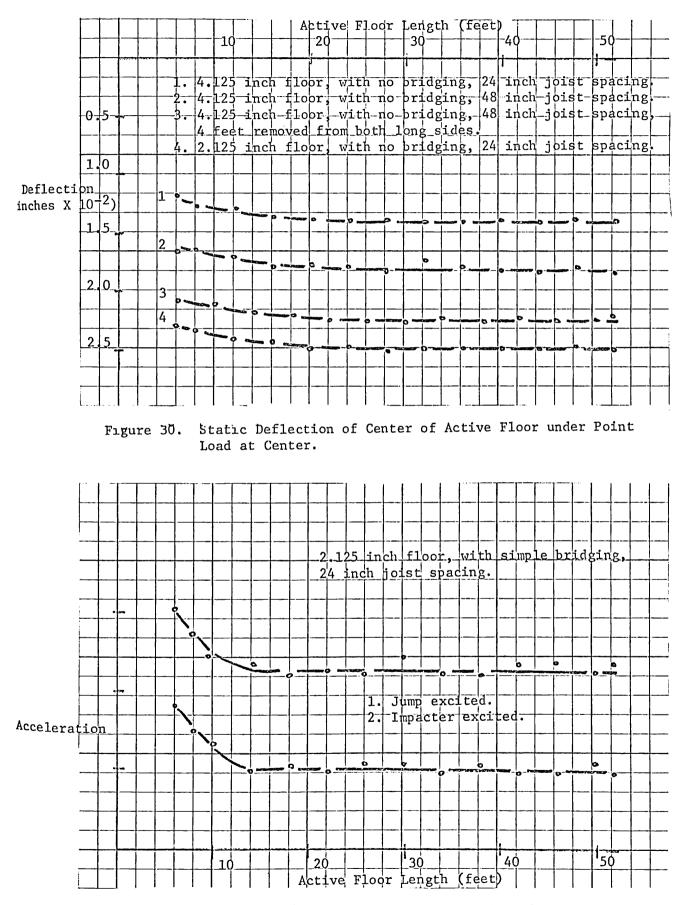
Finally, the total deflection of the center of the floor is inversely related to the rigidity as would be expected.

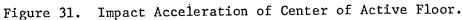
Static Deflection of the Center of the Active Floor under Point Load at the Center (Figure 30)

The static deflection of the center of the active floor under point load changed very little as the active floor length was varied. Only for short floor length was any significant difference noted. At these short lengths the deflection decreased somewhat. Again, the deflection was dependent on the rigidity of the system.

Acceleration of the Center of the Active Floor under Impact (Figure 31)

In the initial test runs recordings were made of the acceleration of the center of the active floor under impact. Since the acceleration is the





second time derivative of displacement, the acceleration is proportional to the displacement. Therefore, measurement of the impact acceleration is a means to measure impact displacement. However, the other means available to more directly measure the impact deflection were sufficiently effective that measurement of the acceleration was abandoned after the initial runs. It may be seen from the figure that the acceleration curve is of the same shape as the impact deflection curve and yields approximately the same value of the effective floor size.

CONCLUSIONS FROM THE TEST SERIES

General

The following general conclusions seem apparent from the results of the current test series:

- The slab and joists of a steel joist-concrete slab floor system act as a single unit during dynamic deflections. This conclusion is of particular importance as it verifies one of the fundamental assumptions of existing floor theory. As a result a floor system may be considered as an orthotropic plate (with less exact results as joist spacing increases), the bending rigidities of which are calculated by the standard "T" section analogy.
- 2. The basic characteristics of a steel joist-concrete slab floor system are almost completely unaffected by any of the commonly used forms of bridging. Bridging does, of course, give the joists some stability during construction operations, but it has no effect on the response of the floor other than that induced by its weight.
- 3. The basic characteristics of a steel joist-concrete slab floor system are almost invariant over a wide range of k (k = b/a, ratio of the dimensions of the slab). That is, for a given floor construction, the characteristics of any floor larger than one of the effective floor size for that construction are essentially identical. Floors smaller than the effective floor size exhibit a wide variation of parameters.

- 4. The addition of concrete to an existing floor reduces the vibrational amplitude and frequency. This result stems from the fact that the additional concrete has a greater effect on the weight of the system than it does on the flexural rigidity. The general effect is to improve the "feel" of the floor by reducing the amplitude of vibration, but it may not always be desirable to reduce the frequency of a particular system. Additional concrete also increases the damping of vibrational harmonics and the fundamental frequency.
- 5. Cracks in the slab of a floor system apparently have the effect of reducing the modulus of elasticity of the system. Considering the composite section as a whole, the modulus decreased about 20 percent.
- 6. It is highly undesirable to make the slab of a steel joistconcrete slab floor system discontinuous so as to accomodate ventilation ducting or wiring and plumbing lines. As may be seen from the information gained on the floor with four feet removed from both long sides, the frequencies of vibration and their associated amplitudes and damping characteristics are such as to make the floor very uncomfortable.
- 7. Use of the beam deflection formulas to calculate impact deflection formulas to calculate impact deflection of steel joist-concrete slab floor systems is reasonable although they seem to give about a ten percent higher deflection than is actually measured.

- 8. In large, light floors the phenomenon of "beating" occurs. That is, in addition to the natural frequency of the floor system, there can be felt a vibration of from one to three cycles per second. This very low frequency vibration is very noticeable and unpleasant.
- Open floors are those with partitions further apart than the effective floor length.

Effective Floor Size

For a particular choice of joist, joist spacing, and concrete thickness for a steel joist-concrete slab floor system there can be defined an effective floor size, or, more precisely, an effective k (k = b/a), the ratio of the lengths of the sides of the floor). The basic characteristics of a floor with a k less than k_{eff} are essentially the same as those for a floor with $k = k_{eff}$. In addition, on impact, a floor system reacts over the area of the effective floor size. That is, to all intents and purposes, it may be assumed for a floor larger than the effective floor, the impact is being borne by a subfloor equal to the size of the effective floor for the given construction.

There are several ways to determine the effective floor size. First of all, the effective floor length seems to be about equal to the length from the center of the floor at which the floor deflection becomes zero for a concentrated load at the center. This point may be determined experimentally by suitable measurements. Secondly, the effective floor length is equal to the length of the active floor at which the basic characteristics begin to markedly change. This point may be experimentally determined as has been done in the current test series. Finally, an empirical formula may be developed connecting the data points found in the test series. Defining ϵ^4 as the square root of the ratio of the flexural rigidity perpendicular to the joists to the flexural rigidity parallel to the joists (that is, $\epsilon^4 \boxed{D_x/D_y}$) leads to the formula

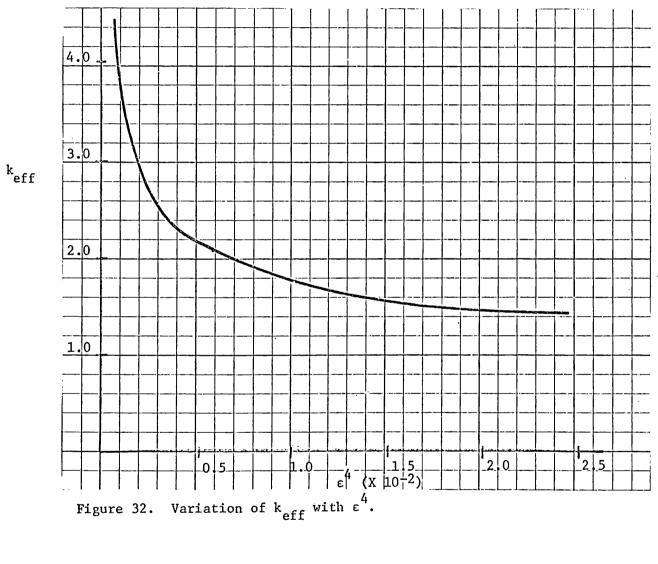
$$k_{eff}^{2} = -1 + 1 + \frac{1 \cdot 8}{\epsilon}$$
 (1)

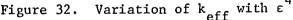
Figure 32 is a plot of k_{eff} as a function of ϵ^4 , derived on the basis of Eq. (1).

One of the most effective ways to eliminate undesirable vibrations is to subdivide a floor by office partitions or other means. This provides a mechanism for greater damping which often eliminates the undesirable effects. It might be thought possible to also subdivide a floor from below and achieve the same effect. This can be done so long as the subdivisions are all of smaller size than the effective floor size for the particular installation. Otherwise, no appreciable effect will be realized other than slightly greater damping.

Mechanical and Human Impact

Floors react very differently to human and mechanical impact. Mechanical impact is generally of short duration and excites not only the fundamental frequency of vibration but also some of the higher order harmonics. Human impact, on the other hand, excites only the fundamental frequency to any extent. Since mechanical vibration can be eliminated by other means, it is human impact which causes the most concern.





Earlier experimental figures show that at about a natural frequency of fourteen or fifteen cycles per second human impact is of too long a duration to appreciably excite a floor. Thus floors with natural frequencies above about fifteen cycles should exhibit little problem due to human impact.

CONCURRENT ANALYTICAL DEVELOPMENTS

Introduction

The analytical investigation and determination of the vibrational characteristics of anisotropic plates in general and of steel joist-concrete slab floors in particular have primarily been developed by use of the various energy methods. In 1960, Mr. James A. Wiley⁶, of the University of Kansas, considered such vibrations. This work, done as a part of the overall investigation for the Steel Joist Institute, produced a formula for the calculation of the frequencies of such systems. Frequencies calculated by this formula (and by energy methods in general) are somewhat higher than those measured in the laboratory because of the simplifying assumptions introduced into the general solution.

During the summer of 1966, Dr. Marek Sokolowski and Dr. Lenzen considered the problem on the basis of the more classical forceequilibrium method. Fewer assumptions need be made in deriving the solutions by this method so the results are, in general, more accurate.

Pertinent Formulas for the Calculation of Floor Characteristics

The detailed analysis of anisotropic plates will be contained in a forthcoming paper by Drs. Sokolowski and Lenzen. It is sufficient for the purposes of this report only to list the equations which apply to the characteristics of steel joist-concrete slab floor systems.

The natural frequencies of vibration of the floors is given by

$$\omega_{mn} = \sqrt{\frac{D_y}{\rho}} \frac{m^2 \pi^2}{b^2} \sqrt{\frac{1 + 2h\epsilon^2 n^2 k^2}{m^2} + \frac{n^4 k^4}{m^4}}$$
(2)

in which

$$\begin{split} D_{\mathbf{x}} &= \text{flexural rigidity of floor perpendicular to joists} \\ D_{\mathbf{y}} &= \text{flexural rigidity of floor parallel to joists} \\ \rho &= \text{surface density} \\ a &= \text{length of floor} \\ b &= \text{width of floor} \\ k &= b/a \\ h^{n} &= \epsilon^{2} \\ \epsilon^{4} &= \boxed{D_{\mathbf{x}}/D_{\mathbf{y}}} \end{split}$$

and m and n are integers indicating the mode of vibration of the plate. The fundamental frequency occurs when m = n = 1. Increasing m yields higher modes parallel to the joists whereas increasing n yields higher modes perpendicular to the joists. In practice it is difficult to excite modes other than m = 1, and n = 1, 2, 3, 4, 5.

Static deflection of the floor may be calculated by the formula

$$\omega(\mathbf{x},\mathbf{y}) = \frac{4P}{abD_{\mathbf{y}}} \sum_{\mathbf{y}} \sum_{\mathbf{y}} \frac{\sin \frac{m\pi}{2} \sin \frac{n\pi}{2} \sin \alpha_{n} \sin \beta_{n} \mathbf{y}}{\frac{2}{4} (m^{4} + 2h\epsilon^{2}n^{2}m^{2}k^{2} + \epsilon^{4}m^{4}k^{4})}$$
(3)

in which

$$P = load$$

 $\alpha_n = n\pi/a$, $\beta_n = n\pi/b$

This formula reduces, for deflections at the center, to

$$w(\frac{a}{2}, \frac{b}{2}) = \frac{Pb^2}{\sqrt{2}\pi D_y} \sqrt{\frac{D_y}{D_x}}$$
(4)

The deflection profile of the system is given by

$$w(x,y) = \frac{Pb^2}{\pi^3 \epsilon} \mathop{\rm e}\limits_{y} e^{\frac{\beta_1 x}{\epsilon \sqrt{2}}} \sin\left(\frac{\pi}{4} + \frac{\beta_1 x}{\epsilon \sqrt{2}}\right)$$
(5)

into which is substituted y = b/2 to yield the deflection profile at the center. The first zero point of the deflection is obtained by substituting w(x,b/2) = 0 into Eq. (5) and solving for x. The resulting expression is

$$\mathbf{x}_{0} = \frac{3}{4}\sqrt{2} \quad \boldsymbol{\epsilon} \mathbf{b} \tag{6}$$

Mr. Leslie D. Meyer derives a formula for the impact deflection generated by the impacter he designed. This formula has been revised somewhat by Dr. Robert D. Ohmart.⁶ The formula is

$$A_{o} = \frac{4P_{o}b^{3}}{\pi^{2}EI} \quad \sin\left(\frac{\omega_{11}\gamma}{2}\right)$$
(7)

in which

 $A_o = initial impact deflection$ $P_o = value of experimentally determined force developed by impacter$

 γ = duration of impact force

When the constants are evaluated, the computational form of the formula

$$A_{o} = 2.41 \times 10^{-6} \frac{b^{3}}{1} \sin \left[(1.57 \times 10^{-2}) F_{11} \right]$$
(8)

COMPARISON OF THE RESULTS OF THE ANALYTICAL DEVELOPMENTS AND CURRENT TEST SERIES

Basic Characteristics

The results obtained by applying the formulas from the analytical developments are compared with the experimental results. Figure 33 compares the experimental and analytical frequencies, Figure 34 the static deflections at the center of the active floor, and Figure 35 the static deflection profiles.

Figure 33 is of prime importance. There is essentially no difference between the calculated curve and the experimentally determined curve. This figure, in itself, is strong substantiation for the analytical developments and thereby provides a second verification for the composite action of the slab and joists. That is, since the analytical developments are based on the supposition that slab and joists act as a single unit and the experimental results substantiate analytical predictions, then it may be assumed that the slab and joists do, in fact, act as a single unit.

The frequencies are predicted almost as closely for the 4.125 inch floor as well. The curve shown for the 2.125 inch floor represents data obtained prior to any substantial cracking of the slab. As the slab cracked the effect was to reduce the modulus of elasticity. In the course of the test series, the modulus dropped about 20%. When this correction is substituted into the analytical formulas the experimental frequencies are predicted almost exactly. Viest, Fountain, and Singleton in <u>Composite</u> <u>Construction in Steel and Concrete</u> note this change in the modulus with age and cracking although they appear to be considering less extensive cracking than encountered in this system.

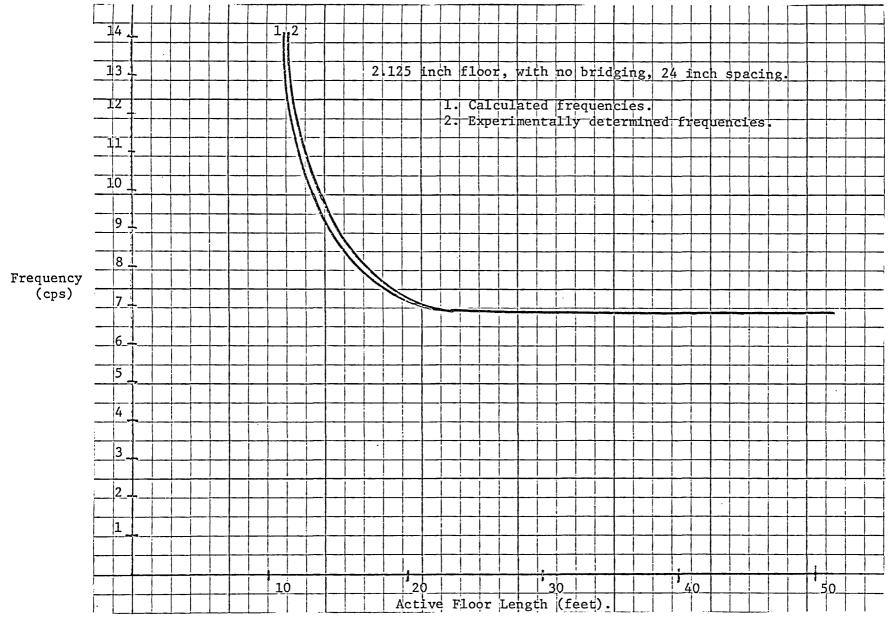


Figure 33. Comparison of Experimentally Determined and Analytically Calculated Frequencies of Vibration.

Figure 34 shows that the static deflections of the center of the active floor are also quite closely predicted. It may be seen that the experimental deflections decrease at short floor lengths. This is due primarily to the method of effecting a "point" load. For convenience, a cart was loaded with concrete test specimens and positioned at the center of the active floor. As a result, the loading was somewhat distributed rather than concentrated. This distributed effect was proportionately greater at shorter floor lengths and so the deflection decreased somewhat.

It may be noted that the curve for the 4.125-inch floor with fortyeight-inch joist spacing shows the most marked difference between theory and experiment. It is a possibility that this difference is an indication that the orthotropic assumption is not as good for the forty-eight inch joist spacing as for other floors.

The static deflection profiles shown in Figure 33 indicate again that the analytical developments closely predict the experimental results. There is some difference, of course, but in all instances the point of zero deflection is predicted within 10 percent. It should also be noted that it is difficult to precisely determine the experimental point of zero deflection. In no instance was the positive deflection very large (although it was readily apparent in all floors except the one with four feet removed from both long sides) and curve fitting introduced some uncertainty.

Impact Deflections

The actual impact deflections of the floor configurations tested were actually about 0.91 times the predicted values. This suggests a revision of the factor in the formula to 2.01×10^{-6} to allow prediction

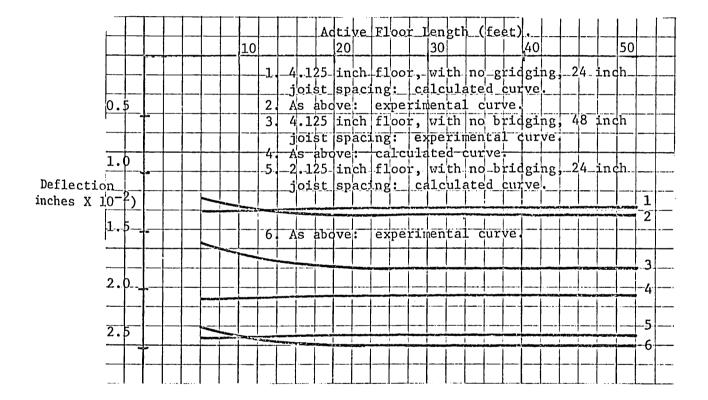


Figure 34. Comparison of Experimentally Determined and Analytically Calculated Deflections of Center of Active Floor under Point Load at Center.

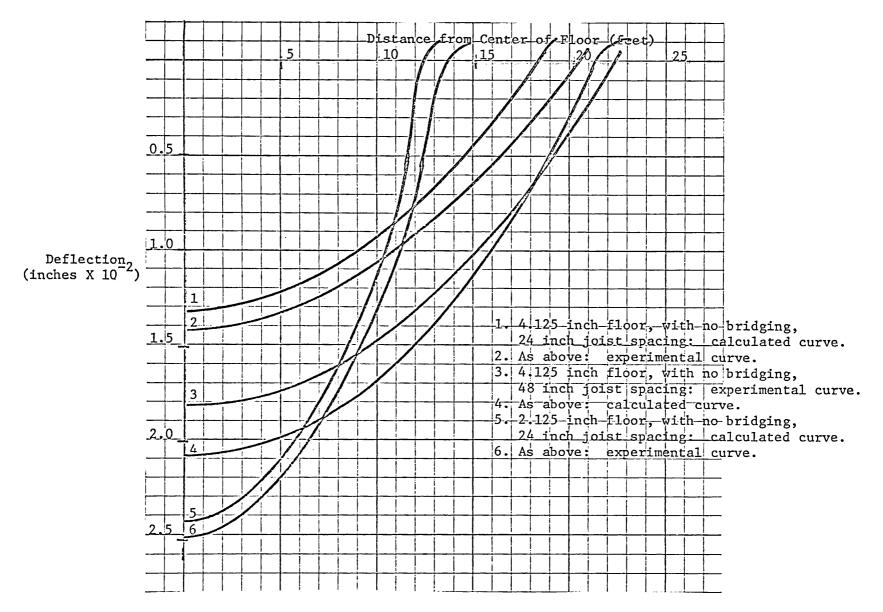


Figure 35. Comparison of Experimentally Determined and Analytically Calculated Static Deflection Profiles of Floors under Point Load at Center.

of the impact deflection of steel joist-concrete slab floor systems tested with the impacter. It should be noted that the constant given was not calculated specifically for this type of construction so that some revision might be expected. Further, the modulus of elasticity of the concrete was assumed to be 3,000,000 psi. A minor revision here would allow a calculation that would check the measured value. This is also true in the other calculations.

Conclusions

In view of the close agreement between the analytical and experimental results, it may be assumed that the analytical formulas presented may be used to predict the characteristics of steel joist-concrete slab floor systems. Applications indicate that use of these formulas yield results within about five percent of actual values.

Consideration of the frequency formula, Eq. (2) indicates the probable origin of "beats." In any application where the value of ϵ is very small the first two expected frequencies, ω_{11} , and ω_{13} will be very close to the same value (within one to three cycles per second). This proximity will yield the "beats" which will, in turn give the floor an uncomfortable feeling. Any design of a large floor should take this possibility into consideration.

APPLICATION OF EXPERIMENTAL AND ANALYTICAL DEVELOPMENTS

General

On the assumption of the validity of the analytical developments (as indicated by the experimental developments) a computerized study was made of the standard floor constructions that are now used. Rather than work with the concept of an effective floor size an effective number of joists was calculated for each particular construction. That is, the joist directly under the impact was assumed to be totally effective and each joist moving in a direction perpendicular to the joist and away from the impacted one is in some proportion less effective.

In actual application the deflection shape generated by Eq. (5) was approximated by a sine curve between the two points of zero deflection. The joist spacing for the particular construction is known and can be superimposed on the approximation. Then, the joist at the center is considered to be totally effective and those to either side are effective in proportion to the value of the sine function at their individual position. When all contributions from the joists within the approximation are added the result is known as the effective number of joists.

Figure 36 shows a typical deflection surface with a sine wave approximation. The effective number of joists is given by

$$N = 1 + 2 \sum \cos \pi x / 2x$$
(9)

A sample calculation based on this figure is given in Appendix I. The other parameters of the system, fundamental frequency and impact deflection, are calculated directly from the formulas given earlier.

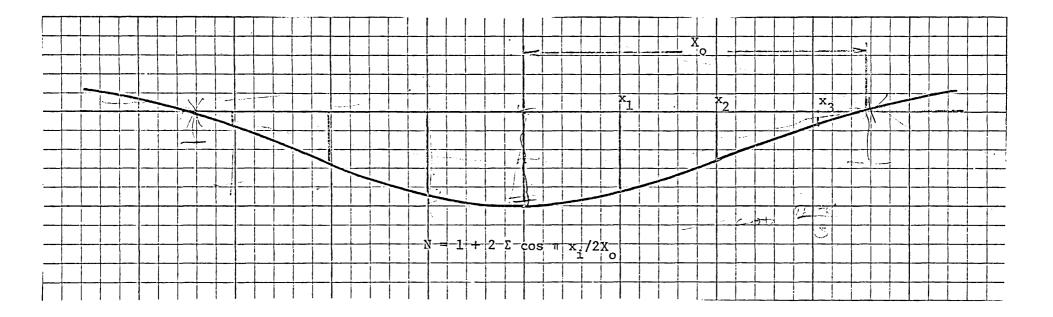


Figure 36. Sine Curve Approximation

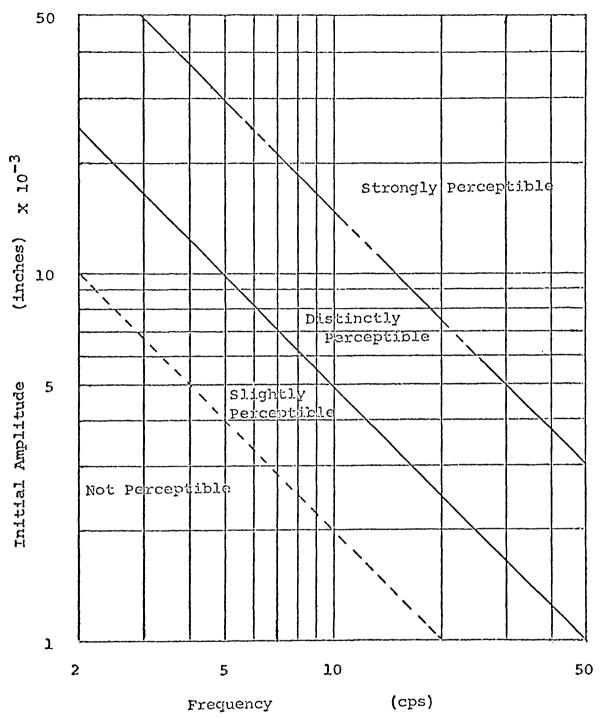
In order to predict the occurrance of unpleasant vibration in design the natural frequency is plotted versus initial amplitude. The results thus obtained may be compared with existing response curves. These curves include those of Reiher and Meister, Figure 37, and Goldman, Figure 38. Goldman's curve may be further simplified with a straight line approximation which is superimposed on Reiher's and Meister's response curves in Figure 39.

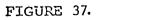
It must be noted that these response curves are based on steady state vibration. Investigations in the laboratory and field (with some forth-six floors tested in the Kansas City area) were based primarily on transient vibration induced by a single impact. Therefore, the amplitude scale has been multiplied by a factor of ten in order to account for the difference in the number of times the vibration occurs.

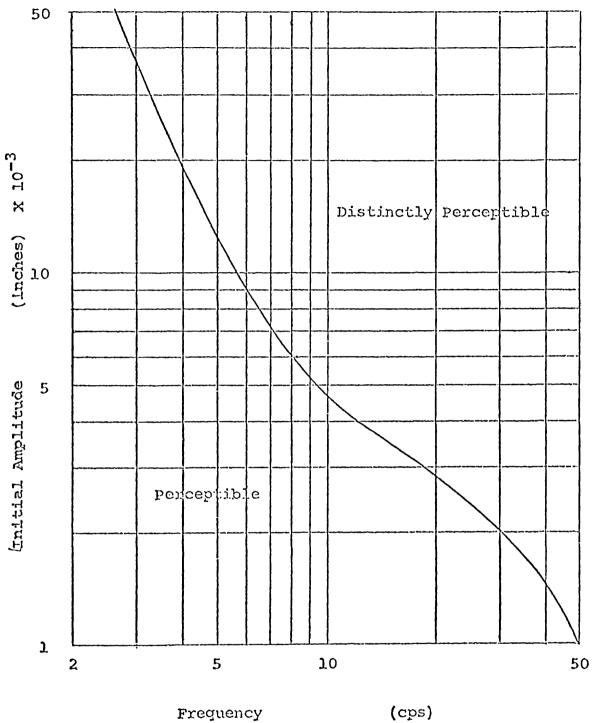
Characteristics of Generally Used Floor Constructions

Direct application of the formulas developed during the investigation to the standard joists now available yields the characteristics to be expected from the floors in which they are used. To complete the calculations it is necessary to assume a joist spacing and floor thickness. A complete catalog of the characteristics of existing joists in floors with twenty-four, thirty-six, and forty-eight inch joist spacing with concrete thicknesses of two-and-a-half, three-and-a-half, and four-and-a-half inches is given in Appendix III of this report.

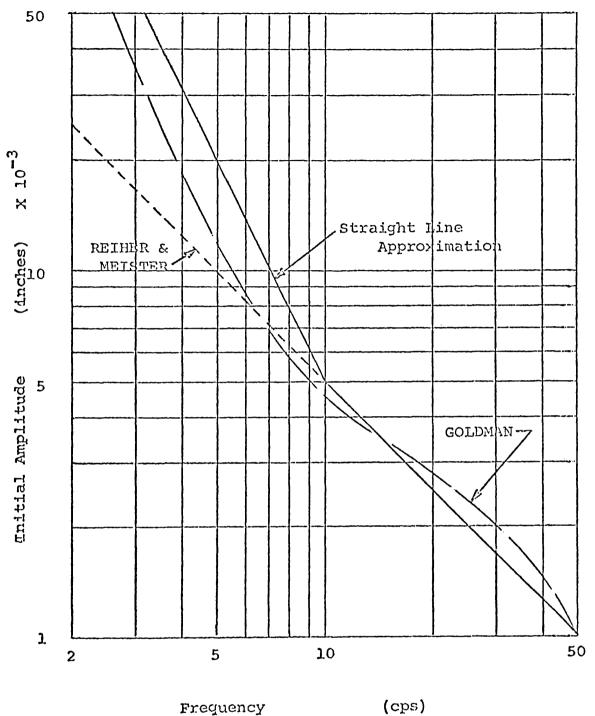
Careful consideration of the information available in this catalog yields certain trends as various of the structural parameters are changed. For instance, when the length of the joists increases (that is, floor width













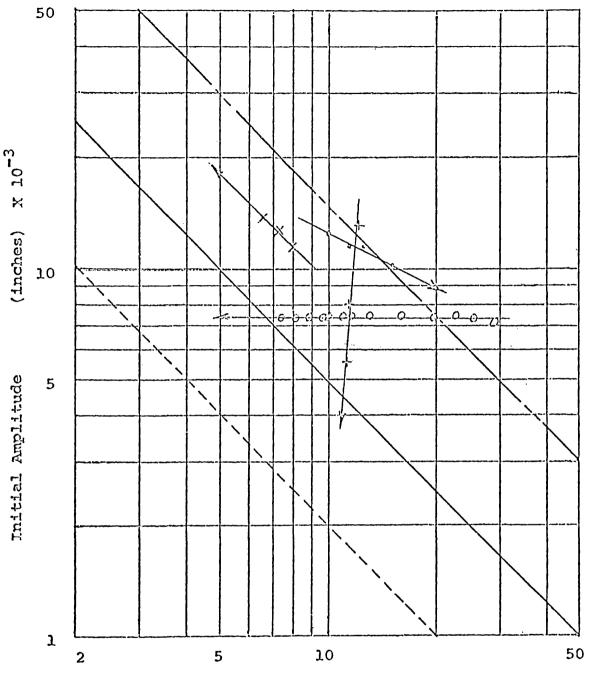
increased) for a given concrete thickness and joist spacing, the number of effective joists increases while the impact amplitude remains almost constant. Further, if the length of the joists and their spacing remain constant while the depth of concrete is increased, the number of effective joists increases while the amplitude decreases very rapidly. Finally, by increasing the spacing between the joists the number of effective joists decreases accompanied by a distinct increase in impact amplitude.

Figures 40 through 42 indicate these trends. Figure 40 shows the effects of parameters on the response curve. That is, it shows the effect on initial amplitude and frequency of changes in span, joist depth, center to center spacing, and concrete thickness. Figure 41 shows the effect of stiffness on amplitude and Figure 42 the effect of joist spacing on impact amplitude.

If the effective stiffness (NK) is multiplied by the square of the concrete thickness and divided by the spacing between joists and the resulting value plotted versus impact amplitude the data reduces to a limiting curve. This curve is shown in Figure 43.

Application to Existing Floor Systems

The analysis thus far considered has been applied to the forty-six floors tested in the field.⁴ Complete information is not available on the test data taken for these floors since at that time it was not known exactly what information was needed. However, as much information as possible has been taken from that data and compared with the predicted results.



Frequency

(cps)

- o = Increase in span from 12' to 24' for 12J4 with 3.5"x24"
 concrete.
- Increase in joist depth with 2.5"x24"x20'concrete using 10j4, 12j4, 14j4, 16j4.
- x = Increase in center to center spacing for 12J4 with 2.5" concrete and 23' span.
- + = Increase in concrete thickness for 12J4 with 36"c.c. concrete and 18' span.

FIGURE 40. Effects of Parameters on the Response Curves.

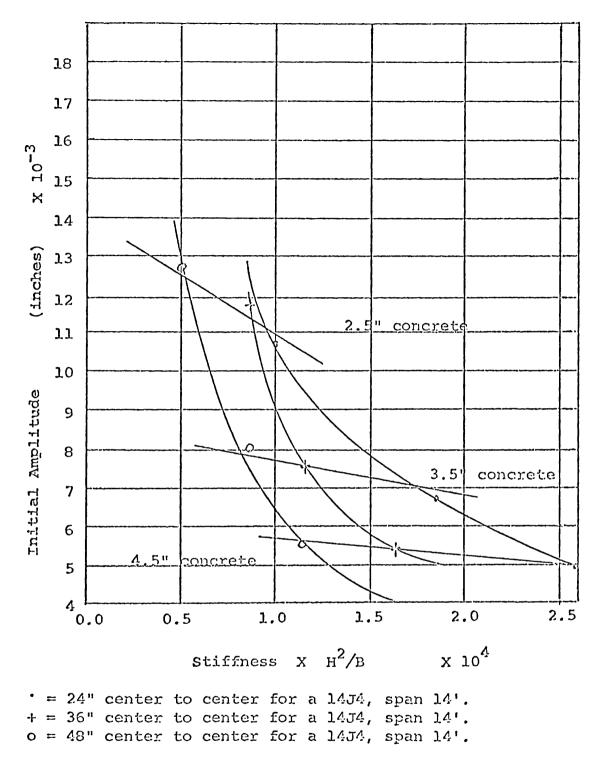
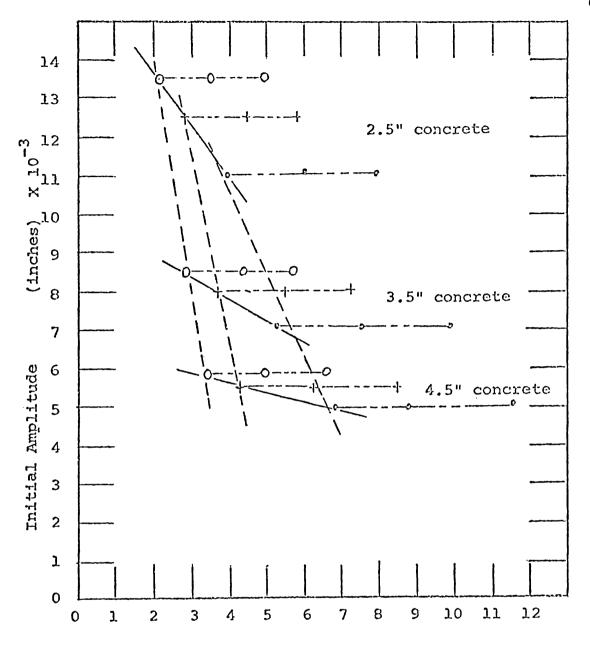


FIGURE 41. Stiffness - Amplitude Plot



Number of Effective Joist

• = 24" center to center for a 14J3. + = 36" center to center for a 14J3. \circ = 48" center to center for a 14J3.

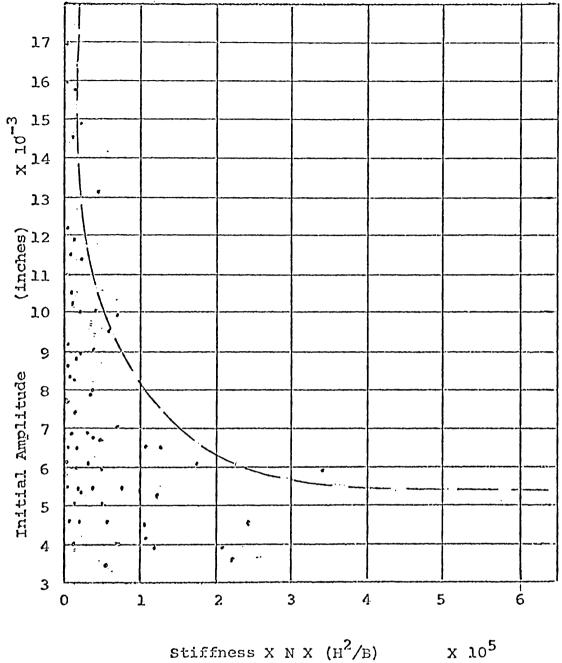
FIGURE 42.

Effect of Parameters on Amplitude

Included in Appendix IV are the characteristics calculated for the buildings tested given both in terms of human and mechanical impact. This data, plotted against field test data yields the scatter shown in Figure 44. If the information were complete and the theory exact a fortyfive degree line should result. However, it must be remembered that these tests were taken under field conditions and information such as partitioning and distributed loading were not noted so the data points show appreciable scatter. Despite this all the data points except two lie on or below the forty-five degree line. One of these two was a building subject to difficulties other than floor design and the other was tested in a narrow corridor where there were fewer joists than the number of effective joists for that particular construction. Thus, the data does show that the theory represents a limiting value. More complete data should only verify this conclusion.

Floors without Annoying Vibration

The basic purpose of this testing and research has been to aid in the design of floor systems not subject to annoying vibration. It is now possible to accurately predict the characteristics to expect from any open (non-partitioned) floor system. For instance, the set of figures 45 through 50 contained in Appendix II indicate the human response for J-series joist spans from twenty-four to forty-four feet, concrete thicknesses of two-and-a-half, three-and-a-half, and four-and-a-half inches for all depth joists from twelve to twenty-four inches. These curves are plotted from information contained in Appendix III and similar plots could be made at leisure from that information as desired.



Stiffness X N X (H²/B)



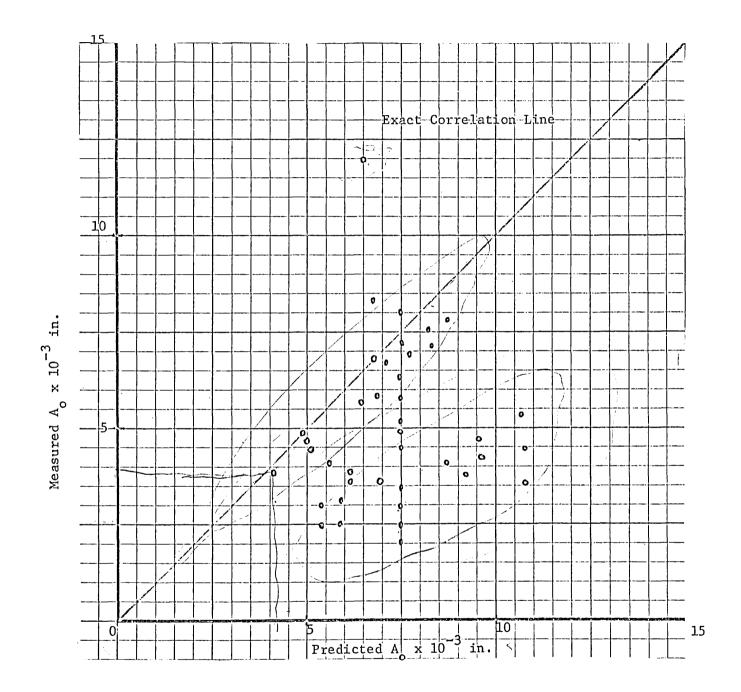


Figure. 44. Comparison of Measured and Predicted Impact Amplitude of Field Tests.

The fundamental difficulty, however, in designing floors without annoying vibration is the difficulty of defining just what constitutes annoying vibration. At present the response curves of Reiher and Meister and of Goldman are available. But these have been determined for steady-state vibrations. They still may be used if it is appreciated that they constitute a limiting case. That is, they represent the effect of the response of a system after a single impact with no damping. Damping is always present as evidenced by the experimental data. Therefore, the response curves represent very conservative limits for the design of floor systems.

It is still possible to define joist acceptability in terms of the curves. For instance, Tables 2, 3, and 4 list all available joists in various spans with two-and-a-half, three-and-a-half, and four-and-a-half inch concrete thicknesses and twenty-four, thirty-six, and forty-eight inch joist spacings. Blocked portions of the table indicate systems vibrationally acceptable (it is possible that a system vibrationally acceptable is not strong enough for the anticipated load, but there are other tables available for this determination) on the basis of Reiher and Meister's curves with the allowable amplitude increased by a factor of 10. Table 2 sets acceptance at the perceptable level, Table 3 at ten perceptable level. This range is recommended since laboratory floor damping was used to set the limits. Field floors have higher damping and the added thickness would introduce additional damping. Thus it is felt that these are still conservative.

Just exactly what criteria will be chosen to determine acceptance of a system and under what conditions those criteria will be applied must be set by the industry. It is apparent, even though much remains to be learned of floor vibration, that such criteria may be established on the basis herein described. It may be appreciated that such criteria are likely to be conservative because of the limitations of knowledge now existent. Tabulation of Vibrationally Acceptable Concrete Slab-Steel Joist Floor Systems Based on 0% Deviation from Reiher & Meister's Perceptible Curve.

Joist	Clear	2.5"	3.5"	4.5"	2.5"	3.51	4.5"	2.5"	3.5"	4.5"
Type No.	Span	× 24"	× 24"	× 24"	× 36"	× 36"	x 36"	× 48''	× 48"	× 48"
2J2 2J3 2J4 2J5 2J6	24'-0"									
4J3 4J4 4J5 4J6 4J7										
6J4 6J5 6J6 6J7 6J8							IIII IIII			
18J5 18J6 18J7 18J8										
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
4J3 4J4 4J5 4J6 4J7	25'-0"									

Joist Type No.	Clear Span	2.5" × 24"	3.5" × 24"	4.5" × 24"	2.5" × 36"	3.5" × 36"	4.5" × 36"	2.5" × 48"	3.5" × 48"	4.5" × 48"	
16J4 16J5 16J6 16J7 16J8	25'-0"										
8J5 8J6 8J7 8J8											
20J5 20J6 20J7 20J8											
22J6 22J7 22J8											
24J6 24J7 24J8											
4J3 4J4 4J5 4J6 4J7	26'-0"										
16J4 16J5 16J6 16J7 16J8											
18J5 18J6 18J7 18J8											
20J5 20J6 20J7											

Joist Type No:	Clear Span	2.5" × .24"	3.5" × 24"	4.5" × 24"	2.5" × 36"	3.5" × 36"	4.5" × 36"	2.5" × 48"	3.5" × 48"	4.5" × 48"
20J8	26'-0"			<u>IIII</u>			17777			<i>11111</i>
22J6 22J7 22J8										
24J6 24J7 24J8										
4J3 4J4 4J5 4J6 4J7	27'-0"									
16J4 16J5 16J6 16J7 16J8										
18J5 18J6 18J7 18J8						-				
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
4J3 4J4 4J5	28'-0"									

Joist Type	Clear Span	2.5" × 24"	3.5" × 24"	4.5" × 24"	2,5" × 36"	3.5" × 36"	4.5" × 36"	2.5" × 48"	3.5" × 48"	4.5" × 48"
No.		·	24	24	20		20	48"	40	48.
4J6 4J7	28'-0"									
16J4				, IIIII						
16J5 16J6										
6J7 6J8							UIIII			
18J5 18J6				IIIII						
18J7 18J8										
20J5				117777				ĺ		2111
20J5 20J6 20J7										
20J8										
22J6 22J7				IIII						
22J8]]]]]]			01111			
24J6 24J7			ļ	IIIII						
24J8				<u>]]]]]]</u>			[]]]]]			
16J4 16J5	29'-0"			IIIII	l					
16J6 16J7										
1618										
18J5 18J6				IIII						
18J7 18J8										
20J5		i.		11111			111171			1111
20J6 20J7										
2018				011111			011111			

Jois† Type	Clear Span	2.5" x	3.5" x	×	2.5" ×	3.5" ×	4.5" ×	x	×	4.5" ×
No		24"	24"	24"	36"	36"	36"	48''	48"	48"
22J6 22J7 22J8	29'-0"									
24J6 24J7 24J8										
16J4 16J5 16J6 16J7 16J8	30'-0"								77777	
8J5 8J6 8J7 8J8										
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
16J4 16J5 16J6 16J7 16J8	31'~0'									
18J5 18J6 18J7 18J8									<i>11111</i>	
20J5			I	<i>71111</i>	ļ		2002			<u>IIII</u>

Joist Type <u>Na</u>	Clear Span	2.5" × 24"	3.5" × 24"	4.5" × 24"	2.5" × 36"	3.5" × _36"	4.5" × 36"	2.5" × 48"	3.5" × <u>18</u> "	4.5" × 48"
20J6 20J7 20J8	31'-0"									
22J6 22J7 22J8										
24J6 24J7 24J8										
16J4 16J5 16J6 16J7 16J8	32'-0"									
18J5 18J6 18J7 18J8			7,1111			<u>IIIII</u>				
20J5 20J6 20J7 20J8									<u>11111</u>	
22J6 22J7 22J8										
24J6 24J7 24J8										
18J5 18J6 18J7 18J8	33'-0"									
20J5 20J6 20J7										

Joist Type	Clear Span	2.5" × 24"	3.5" × 24"	4.5" × 24"	2.5" × 36"	3.5" × 36"	4.5" × 36"	2.5" × 48"	3.5" × 43"	4.5" × 48"
<u>No.</u> 20J8	33!-0"			<u>IIIII</u>	WE - Connec					
22J6 22J7 22J8						<u>IIII</u> I				
24J6 24J7 24J8										
18J5 18J6 18J7 18J8	34'-0"									
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
18J5 18J6 18J7 18J8	35'-0"									
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7									11111	

Joist Type Clear Span 2.5^n 3.5^n 4.5^n 2.5^n 3.5^n 4.5^n x											
No. 24^n 24^n 36^n 36^n 36^n 48^n 48^n 44^n 24J8 $35^1 - 0^n$ 55^{10} 5				,					1	1	1 1
2418 35'-0" 35'100 35'100 1815 36'-0" 35'100 35'100 1815 36'-0" 35'100 35'100 2015 35'100 35'100 35'100 2016 35'100 35'100 35'100 2017 35'100 35'100 35'100 2016 37'100 35'100 35'100 2017 35'100 35'100 35'100 2016 37'100 35'100 35'100 2016 37'100 35'100 35'100 2017 35'100 35'100 35'100 2016 35'100 35'100 35'100 2016 38'100 35'100 35'100 2016 38'100 35'100 35'100 2016 38'100 35'100 35'100 2016 38'100 35'100 35'100 2016 38'100 35'100 35'100 2017 35'100 35'100 35'100 2016 38'100 35'100 35'100 2016		Span	× 24"		X 24"	X 3611	X' 36''	X 36"	X 48''		
18J5 36'-0" 18J6 36'-0" 18J7 18J8 20J5 20J6 20J7 1 20J8 1 22J6 1 22J7 1 22J8 1 24J6 1 24J7 1 20J8 1 20J5 37'-0" 20J6 1 20J7 1 20J8 1 20J5 37'-0" 20J6 1 20J7 1 20J8 1 20J5 37'-0" 20J6 1 20J7 1 20J8 1 20J5 38'-0" 20J5 38'-0" 20J5 38'-0" 20J5 38'-0" 20J7 1 20J8 1 22J6 1 2J7 1 2J7 1 2J7 1 2J7 1 2J7		-VORTO THE LEE	The order	and and second	- Lardav-arus	~~~~~~~~~	1		(1	
18J6 18J7 18J8 20J5 20J7 20J8 22J6 22J7 22J8 24J6 24J7 24J8 20J5 20J7 20J8 22J6 22J7 22J8 24J6 24J7 24J8 20J5 37'-0" 20J8 22J6 22J7 22J6 20J7 20J8 20J5 37'-0" 20J8 20J7 20J8 2107 2108 2109 2109 21016 2017 2016 2017 2018 2109 21016 2017 21016 21017 21018 21019 21016 21017	24J8	35'-0"		<u>THI</u>	TIIIIII		TITIT	IIIII	Į.	<u>IIII</u>	<u>IIII</u>
18J6 18J7 18J8 20J5 20J7 20J8 22J6 22J7 22J8 24J6 24J7 24J8 20J5 20J7 20J8 22J6 22J7 22J8 24J6 24J7 24J8 20J5 37'-0" 20J8 22J6 22J7 22J6 20J7 20J8 20J5 37'-0" 20J8 20J7 20J8 2107 2108 2109 2109 21016 2017 2016 2017 2018 2109 21016 2017 21016 21017 21018 21019 21016 21017	1815	361-0"		11111	111111		71777	TTITI	ļ	71177	ann
18J7 18J8 20J5 20J6 20J7 20J8 22J6 22J7 2J8 24J6 24J7 24J8 20J5 2017 2018 24J6 24J7 24J8 20J5 271-0" 20J8 20J5 271-0" 20J8 20J5 271-0" 20J5 271-0" 20J5 271-0" 20J8 20J7 20J8 217 22J6 22J7 22J8 20J5 38'-0" 20J5 38'-0" 22J6 22J7 22J6 22J7 22J6 22J7 22J6 22J6 22J7 2J7 2J8 </td <td></td> <td>50 -0</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>illilli i</td>		50 -0									illilli i
20J5 2016 20J8 22J6 22J7 22J8 24J6 24J7 24J8 2017 2015 37'-0" 2016 2017 2017 2018 2015 37'-0" 2016 2017 2018 2016 2017 2018 21018 211 2116 211 2117 211 2116 211 2117 211 2116 211 2117 211 2116 211 2117 211 2118 38'-0" 2015 38'-0" 216 217 217 218 216 217 217 218 216 217 217 218 216 217 217 218 216 217 217 218 217 219 217 217	18J7							illilli i			HIII.
20.06 20.17 20.18 22.06 22.17 22.18 24.16 24.17 24.18 37'-0" 20.15 37'-0" 20.16 20.17 20.16 20.17 20.15 37'-0" 20.16 20.17 20.18 20.16 20.17 20.18 22.16 21.16 22.16 21.16 22.16 21.16 20.15 38'-0" 20.15 38'-0" 20.15 38'-0" 20.15 28'-0" 20.15 28'-0" 20.15 28'-0" 20.15 28'-0" 20.16 20.17 20.18 21.16 20.15 28'-0" 20.16 20.17 20.18 21.16 22.16 21.16 22.16 21.16 22.16 21.16 22.16 21.16 22.16 21.16 22.17 21.16	18J8			11111			VIIIII			77777	ZTTTT
20.06 20.17 20.18 22.06 22.17 22.18 24.16 24.17 24.18 37'-0" 20.15 37'-0" 20.16 20.17 20.16 20.17 20.15 37'-0" 20.16 20.17 20.18 20.16 20.17 20.18 22.16 21.16 22.16 21.16 22.16 21.16 20.15 38'-0" 20.15 38'-0" 20.15 38'-0" 20.15 28'-0" 20.15 28'-0" 20.15 28'-0" 20.15 28'-0" 20.16 20.17 20.18 21.16 20.15 28'-0" 20.16 20.17 20.18 21.16 22.16 21.16 22.16 21.16 22.16 21.16 22.16 21.16 22.16 21.16 22.17 21.16	20.15				mm		11111			11111	777772
2017 2018 2216 217 2218 2416 2416 2417 2418 2015 2015 37'-0" 2018 2015 2017 2016 2017 2016 2015 37'-0" 2018 2016 2017 2018 2216 217 2218 2116 2015 38'-0" 2015 38'-0" 2015 38'-0" 2016 2017 2018 2015 2015 38'-0" 2015 38'-0" 2018 216 2116 217 21216 217 2138 216 21406 217 216 217 217 218 216 217 217 218 216 217 217 218 216 217 217 218 216 <		}									
22.16 22.17 22.18		{ · · ·							j		
22.17 22.18 24.16 24.17 24.18 37'-0" 20.15 37'-0" 20.16 37'-0" 20.17 300 20.18 37'-0" 22.16 38'-0" 24.18 38'-0" 20.15 38'-0" 20.15 38'-0" 20.15 38'-0" 20.15 38'-0" 22.16 38'-0" 20.15 38'-0" 20.15 38'-0" 20.16 38'-0" 20.17 38 20.18 38'-0" 22.16 38'-0" 22.16 38'-0" 22.16 38'-0" 22.16 38'-0" 22.16 38'-0" 22.16 38'-0" 22.16 38'-0" 22.17 38 22.18 3000000000000000000000000000000000000	20J8			01111			<u>//////</u> /	liiiii		11111	20000
22.17 22.18 24.16 24.17 24.18 37'-0" 20.15 37'-0" 20.16 37'-0" 20.17 300 20.18 37'-0" 22.16 38'-0" 24.18 38'-0" 20.15 38'-0" 20.15 38'-0" 20.15 38'-0" 20.15 38'-0" 22.16 38'-0" 20.15 38'-0" 20.15 38'-0" 20.16 38'-0" 20.17 38 20.18 38'-0" 22.16 38'-0" 22.16 38'-0" 22.16 38'-0" 22.16 38'-0" 22.16 38'-0" 22.16 38'-0" 22.16 38'-0" 22.17 38 22.18 3000000000000000000000000000000000000	2216			77777	771771				Į	1777	timit.
22J8 24J6 24J7 24J8 20J5 37'-0" 20J6 37'-0" 20J7 38' 22J6 38'-0" 24J8 38'-0" 20J5 38'-0" 20J5 38'-0" 22J6 38'-0" 24J8 38'-0" 20J5 38'-0" 20J6 38'-0" 20J7 38'-0" 20J5 38'-0" 20J5 38'-0" 20J6 38'-0" 20J7 38'-0" 20J8 38'-0" 20J5 38'-0" 20J6 38'-0" 20J7 38'-0" 20J8 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J7 38'-0" 22J8 38'-0" 24J6 38'-0"									1		
24J7 24J8 20J5 37'-0" 20J6 20J7 20J8 37'-0" 22J6 38'-0" 24J8 38'-0" 20J5 38'-0" 20J5 38'-0" 22J6 38'-0" 20J5 38'-0" 20J5 38'-0" 20J8 38'-0" 20J8 38'-0" 22J6 38'-0" 20J5 38'-0" 20J8 38'-0" 20J8 38'-0" 20J5 38'-0" 20J6 38'-0" 20J7 38'-0" 20J8 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J7 38' 24J6 38'-0"		Į					<u>UIIII</u>	İIIIII		$\nabla U U U$	
24J7 24J8 20J5 37'-0" 20J6 20J7 20J8 37'-0" 22J6 38'-0" 24J8 38'-0" 20J5 38'-0" 20J5 38'-0" 22J6 38'-0" 20J5 38'-0" 20J5 38'-0" 20J8 38'-0" 20J8 38'-0" 22J6 38'-0" 20J5 38'-0" 20J8 38'-0" 20J8 38'-0" 20J5 38'-0" 20J6 38'-0" 20J7 38'-0" 20J8 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J6 38'-0" 22J7 38' 24J6 38'-0"							1			CONT	
24J8 20J5 37'-0" 20J6 37'-0" 20J7 20J8 22J6 22J7 22J8 24J6 24J4 24J6 24J5 38'-0" 20J7 20J8 22J6 22J7 24J8 24J6 20J5 38'-0" 20J7 20J8 22J6 22J7 20J5 38'-0" 20J8 22J6 22J6 22J7 22J8 22J6 22J7 22J8 24J6 22J7 22J6 22J7 22J8 22J6 22J6 22J7 22J8 22J6 24J6 24J6									j		
20.J5 37'-0" 20.J6 37'-0" 20.J7 37'-0" 20.J8 38'-0" 24.J6 38'-0" 24.J8 38'-0" 20.J5 38'-0" 22.J6 38'-0" 22.J6 38'-0" 22.J6 38'-0" 22.J6 38'-0" 22.J8 38'-0" 22.J6 38'-0" 32.J7 38'-0" 32.J8 38'-0" 32.J9 38'-0" 32.J1 38'-0" 33.100 38'-0" 33.100 38'-0" 33.100 38'-0" 33.100 38'-0" 33.100 38'-0" 34.100 38'-											
20.16 20.17 20.18	2.00	•						[]		
20J7 20J8 22J6 22J7 22J8 1 24J6 1 24J7 1 24J8 1 2015 38'-0' 2017 1 2018 1 2015 38'-0' 2016 1 2017 1 2018 1 22J6 1 22J7 1 2018 1 22J6 1 22J7 1 22J8 1 24J6 1		37'-0"		(1111)							illilli.
20J8 22J6 22J7 22J8 24J6 24J7 24J8 20J5 38'-0' 20J8 22J6 20J7 20J5 20J5 20J5 20J6 20J7 20J8 22J6 22J7 22J8 24J6									3		
22J6 22J7 22J8 24J6 24J7 24J8 20J5 38'-0" 20J5 20J6 20J7 20J8 22J6 22J7 22J8 24J8											
22J7 22J8 24J6 1 24J7 1 24J8 1 20J5 38'-0' 20J5 38'-0' 20J8 1 22J6 1 22J7 1 22J8 1 24J6 1	2000							- deside a final a	1		
22J8 24J6 24J7 24J8 20J5 38'-0' 20J6 38'-0' 20J7 20J8 22J6 22J6 22J7 22J8 24J6 1000000000000000000000000000000000000				TITT	IIIII		TITTI I			IIIII	ann)
24.16 24.17 24.18 20.15 38'-0' 20.16 20.17 20.18 22.16 22.16 22.17 22.18 24.16									3		
24J7 24J8 20J5 38'-0' 20J6 20J7 20J8 22J6 22J7 22J8 24J6	2238			7777777	///////////////////////////////////////		777777			77777	177777
24J7 24J8 20J5 38'-0' 20J6 20J7 20J8 22J6 22J7 22J8 24J6	24J6			711111	innn.		11111	iiiiii	1	11111	TIIII)
20J5 38'-0' 20J6 20J7 20J8 1 22J6 1 22J7 1 22J8 1 24J6 1											
20J6 20J7 20J8 22J6 22J7 22J8 24J6	24J8			<i>[[]]</i>			VIIII	111111			hnni
20J6 20J7 20J8 22J6 22J7 22J8 24J6	20.15	381_0		harren	111111		77777	77777		17777	anna
20J7 20J8 22J6 22J7 22J8 11111111		0- 00									
22J6 22J7 22J8 24J6											
22J7 22J8 24J6 111111111111111111111111111111111111	20J8			tanni	.111111		711171	(11111)		VIIII	7777777
22J7 22J8 24J6 111111111111111111111111111111111111	2216			17777	11111	Į	11111	TYTTT:	1	1000	
22J8 24J6 2110/00000 2110/00000 2110/000000 2110/0000000000								illilli		(IIII)	AIIII)
				<u>VIIII</u>	<u>IIIIII</u>		UIIII	JIIIII			VIIII
						ł					
	24J6 24J7	i 1			IIIIII	{ S		illilli.	N N		

Joist	Clear	2.5"	3.5"	4.5"	2.5"	3.5"	4.5 ^m	2.5"	3.5"	74.517
Type No.	Span	× 24"	× 24"	× 24"	× 36"	× 36"	× 36"	× 48''	× 48''	× 48''
2.4J8	38'-0"		<u>IIIII</u>	IIIII	analit Parke in Co.	<u> (1111)</u>				[[]]]
20J5 20J6 20J7 20J8	39'-0''									
22J6 22J7 22J8										
24J6 24J7 24J8										
20J5 20J6 20J7 20J8	40'-0'									
22J6 22J7 22J8										
24J6 24J7 24J8		1								
22J6 22J7 22J8	41'-0'									
24J6 24J7 24J8										
22J6 22J7 22J8	42'-0'									
24J6 24J7 24J8										

Joist	Clear	2.5"	3.5	4.5"	2.5	3.5	4.5"	2.5	3.5	4.5
Туре	Span	×	×	×	×	×	×	×	×	X
No.		24"	. 24''	24"	36"	36"	36"	48"	48"	48"
22J6	43'-0'		777777	177777		TTTT	111111		111111	7777
22J7		Į		illilli.	}	//////	AIIIIIA		111111	HHH.
22J8		1	[]]]/////	IIIIIX		111111	(IIIII)		()/////	IIII
2230			777773	997777			1999 5 7 1)
24J6			iIIII	mm		11111	IIIII		11111	1111
24J7	1		111/1/		1	()))))	illilli		VIIIII	<u>())))</u>
24J8	l		UIIII	<u>UIIII</u>		IIIII	jIIIII		UIIIII	
22J6	44'-0'	Į	77777			777771	17/17/1		imm	inn
22J7	44 -0		A/////	illllik	1	()))))			//////	AIII
	Į	ł	()))))	illilli]	()))))	AIIIIIA		(())))	ANN:
22J8	ł	-	σm	(11111)	Ì	0777775	())))))		11117) 1) } } } } }
24J6			717777	IIIII	ļ	717711	innn		111111	inn
24J7		ł	111112		1		illllir.		(//////	AIII
24J8	1	1	VIIII	AIIII	1.	χ	<u> </u>		\overline{UUUU}	IIII
	1									
24J6	45'-0'	[THIIT	IIIII		777777	IIIII)	TITTI)	IIIII	IIII
24J7							illilli:	ann	illilli i	11117
24J8			<u> </u>	IIIII		VIIIII			711111	/////
24J6	46'-0'	Į	111111					11111	177777	19777
24J0 24J7	40 -0				mm	IIIIIi	illilli	HHH:	HHHH.	IIII
			ΛΠΠΛ		1	//////3		illilli.	HHHE	IIII
24J8	ļ		777777	///////	1	777777	[(77777)	777777	 }}}
24J6	47'-0'	IIIII	inn	IIIII	IIII	TITTI'	inni.	mm	inn:	m
24J7	1		111111	illilli.		illlli				ANN.
24J8		TIIII	, un de la competencia de la compe	IIIII	, illilli	IIIII	,111111	illlli	, IIIIII	,IIII,
24J6	48'-0'	TTTTT	177777		ma		and the second	TITTI		in the
	400	AIIII		IIIII	111111	IIIIII.		111111.	IIIIIi	
24J7	Į	AIIII			illlli:	HHHI.		illlii.		11111
24J8		777777	///////	, innn,		//////	, 777 / 777) 	777777		10000
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			ł						1	1
					}		1		1	1
							{		1	1
]	1	1	1	1
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	1					}	1		1	

TABLE III

Tabulation of Vibrationally Acceptable Concrete Slab-Steel Joist Floor Systems Based on 10% Deviation from Reiher & Meister's Perceptible Curve.

Joist Type	Clear Span	2.5 ^m ×	3.5" ×	4.5" ×		×	4.5" ×	2.5" ×	3.5" ×	4.5" ×
No.		24"	× 24"	24"	× 36"	36"	× 36"	48"	48"	× 48"
12J2 12J3 12J4 12J5 12J6	24'-0"									
14J3 14J4 14J5 14J6 14J7										
16J4 16J5 16J6 16J7 16J8										
18J5 18J6 18J7 18J8										
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
4J3 4J4 4J5 4J6 4J7	25'-0"									

Joist Type No.	Clear Span	2.5" × 24"	3. <u>5</u> " × 24"	4.5" × 24"	2.5" × 36"	3.5" × 36"	4.5" × 36"	2.5" × 48"	3,5" × 48"	4.5" × 48"
16J4 16J5 16J6 16J7 16J8	25'-0"									
18J5 18J6 18J7 18J8										
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
4J3 4J4 4J5 4J6 4J7	26'-0"								<u>IIII</u>	
16J4 16J5 16J6 16J7 16J8										
18J5 18J6 18J7 18J8										
20J5 20J6 20J7										

Joist	Clear	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"
Type No:	Span	× 24"	× 24"	× 	× 36''	× 36''	X 36''	× 48"	× 48''	× 48''
20J8	26'-0"			<u>11017</u>			<u>11111</u>			<u> 717</u>
22J6 22J7 22J8										
24J6 24J7 24J8										
4J3 4J4 4J5 4J6 4J7	27'-0"		<u>1</u> 7777							
6J4 6J5 6J6 6J7 6J8										
8J5 8J6 8J7 8J8										
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8			<u>11111</u>							
4J3 4J4 4J5	28'-0"									

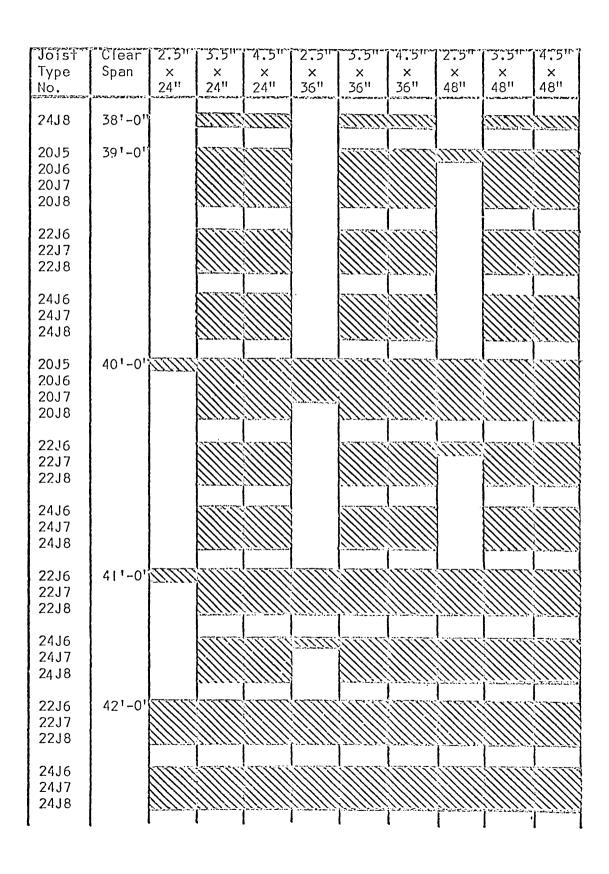
Joist Type No.	Clear Span	2.5" × 24"	3.5" × 24"	4.5" × 24"	2.5" × 36"	3.5" × 36"	4.5" x 36"	2.5" × 48"	3.5" × 48"	4.5" × 48"
4J6 4J7	28'-0"									
6J4 6J5 6J6 6J7 6J8										
8J5 8J6 8J7 8J8			<u>TITI</u>			11112				
20J5 20J6 20J7 20J8									<u>111112</u>	
22J6 22J7 22J8										
24J6 24J7 24J8										
6J4 6J5 6J6 6J7 6J8	29'-0"									
8J5 8J6 8J7 8J8										
20J5 20J6 20J7 20J8										

Joist	Clear	2.5"	1	4.5	2.5"	3.5"				4.5"
Туре	Span	× 24"	× 24"	× 24"	x 36.''	× 36"	× 36"	× 48''	× 48"	× 48''
No	107-107-107-107-107-107-107-107-107-107-							****		
22J6 22J7	29'-0"									IIII)
22J8						<u>AIIII</u>	IIII			
2416			XXXXX	Classic at		COURSES.	2			
24J6 24J7										
24J8				jilli		<u>IIIII</u>	IIIII			<u>UIIII</u>
16J4	30'-0''		77777	111111		iniere	7777777		17777	17775
16J5	20 0									
1616							illili;			
16J7 16J8								1		
			777777			277777	3.3.5 <u>13</u> .2.5.		ANNANA.	
18J5 18J6				IIIII		IIIII			IIIII	IIII
18J7										
18J8			777777			TIIII	ann		<u> //////</u>	
20J5			77777			11111	717777		777777	TITTI I
20J6										
20J7 20J8										
			177712	\		777777	Sara Sara Sara Sara	ĺ	Darke De Nadar	1.2.2.2.2.2.2
22J6 22J7			<u>IIIII</u>			IIIII	IIIII			
22J7 22J8										
0.114										
24J6 24J7										
24J8			<u>AIIII</u>	اللللة		TIII	JIIII			<u>illlli</u>
16J4	31'-0'		11111			177577	inne.	ļ	777777	181777
16J5	51 0									
16J6										
16J7 16J8										
					1	- 2020 (1997)	· · · · · · · · · · · · · · · · · · ·			
18J5 18J6			(IIII)	IIIII.			IIIII.			
18J7					i }					illlii
18J8			71111	<u>IIIII</u>		VIIII	<u>IIIII</u>			i IIII.
20J5						<u>ann</u>	mm		11111	

Joist	Clear	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"
Type <u>No.</u>	Span	× 24"	× _24''	× 24"	× _36"	× _36''	× 36"	× 48''	× 48''	× 48''
20J6 20J7 20J8	3 '-0''	·						-4.9		
22J6 22J7 22J8										
24J6 24J7 24J8										
16J4 16J5 16J6 16J7 16J8	32'-0"									
18J5 18J6 18J7 18J8										
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
18J5 18J6 18J7 18J8	33'-0'									
20J5 20J6 20J7					9					

Joist	Clear	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"	2.5"	1	4.5"
Type No.	Span	× .24''	× 24''	× · 24"	× _36''	× .36"	× 36"	× 48''	× 45"	× 48''
20J8	33'-0"		<u>11111</u>		· • • • • • • • • • • • • • • • • • • •	1]]]]]]]		na alt i Bat prand.		
22J6 22J7 22J8										
24J6 24J7 24J8										
18J5 18J6 18J7 18J8	34'-0"									
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
18J5 18J6 18J7 18J8	35'-0"									
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7					5]]]]]]				

Joist	Clear	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"
Туре	Span	× 24"	× _24"	× _24"	× 36"	× _36''	x 36"	× 48"	× 48''	× 48''
NQuestie	******				29		20	40	40	40
24J8	35'-0"		<u>77777</u>			<u> 177777</u>	11111		01200	<u>IIII</u> I
18J5 18J6 18J7 18J8	36'-0"									
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
20J5 20J6 20J7 20J8	37'-0"									
22J6 22J7 22J8										
24J6 24J7 24J8										
20J5 20J6 20J7 20J8	38'-0'									
22J6 22J7 22J8										
24J6 24J7										



Joist	Clear	2.5"	3.5	4.5	2.5"	3.5	4.5	2.5	3.5"	4.5"
Type No.	Span	× 24"	× 24''	× 24"	× 36"	× 36''	× 36"	× 48"	× 48"	× 48''
									SALENDING BALLY	
22J6 22J7	43'-0'		IIIII:					iIIII:		
22J8		IIIII	<u>illlli</u>	IIIII	<u>IIIII</u>	IIIII	<u>IIIII</u>	IIIII	iIIIII	
24J6		IIIII				innni innni		TITT	11111	
24J7 24J8										
				//////	777777	777777	.777777 	177777	111111	777777
22J6 22J7	44'-0'				IIIII			IIIII		
22J8		UIII	jIIII	<u>IIIII</u>	IIII		IIIII			
24J6		11111		111111		771777		111111		
24J7										
24J8		711111	97777	777777	711777	111111]]]]]]]]	(JIIII)]]]]]]]]]	
24J6	45'-0'	IIIII	IIIII	illIII	<u>IIIII</u>	IIIII	IIIII.	IIII	IIIII	
24J7 24J8			<u>IIIII</u>		JIIII					
2 4J6	46'-0'		177777			anter	THEFT.	STANK.	www	
24J0 24J7	400									
24J8	l	UNN,	IIIII		<u>IIIII</u>	, ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,		,11111, 		<u>()))))</u>
24J6	47'-0'	IIIII		illilli	IIIII	711111		TITTI I		mm
24J7 24J8	{									
		77777		177777	/777777	,177171 	177777	17777) }///////	13.3.3.X.X.X
24J6 24J7	48'-0'		IIIII						TIIII	IIIII
24J8		<u> ())))</u>			IIIII	IIIII	IIIII	IIIII	<u>IIIII</u>	<u>illlli</u>
	}									
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			1			}				
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TABLE IV

Tabulation of Vibrationally Acceptable Concrete Slab-Steel Joist Floor Systems Based on 20% Deviation from Reiher & Meister's Perceptible Curve.

Jois† Type No.	Clear Span	2.5" × 24"	3.5" × 24"	4.5" × 24"	2.5" × 36"	3.5" × 36"	4.5" × 36"	2.5" × 48"	3.5" × 48"	4.5" × 48"
12J2 12J3 12J4 12J5 12J6	24'-0"				<u> </u>			40		
4J3 4J4 4J5 4J6 4J7			11772							
6J4 6J5 6J6 6J7 6J8										
!8J5 18J6 18J7 18J8										
20J5 20J6 20J7 20J8						<u>77777</u>				
22J6 22J7 22J8						<u>71117</u>				
24J6 24J7 24J8									<u>27777</u>	
4J3 4J4 4J5 4J6 4J7	25'-0"									

TABLE 3	٤V
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Joist Type No.	Clear Span	2.5" × 24"	3.5" × 24"	4.5" × 24"	2.5" × 36"	3.5" × 36"	4.5" × 36"	2.5" × 48"	3.5" × 48"	4.5" × 48"
16J4 16J5 16J6 16J7 16J8	25'-0"									
8J5 8J6 8J7 8J8						<u>1997</u> 1997				
20J5 20J6 20J7 20J8									<u>([[[</u>]]	
22J6 22J7 22J8									<u>, 1111,</u>	
24J6 24J7 24J8										
14J3 14J4 14J5 14J6 14J7	26'-0"									
16J4 16J5 16J6 16J7 16J8										
18J5 18J6 18J7 18J8										
20J5 20J6 20J7										

Joist	Clear	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"
Type No:	Span	X 2/11	× 24"	× _24''	X 36''	X 36"	X 36"	× 48"	X 49"	X 48''
20J8	26'-0"		777221	712/12		<u>777777</u>	<u>11111</u>		711217	
22J6 22J7 22J8										
24J6 24J7 24J8										
14J3 14J4 14J5 14J6 14J7	27'-0"									
6J4 6J5 6J6 6J7 6J8										
18J5 18J6 18J7 18J8										
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
4J3 4J4 4J5	28'-0"									

Joist Type No.	Clear Span	2.5" × 24"	3.5" × 24"	4.5" × 24"	2.5" × 36"	3.5" × 36"	4.5" × 36"	2.5" × 48"	3.5" × 48"	4.5" × 48"
4J6 4J7	28'-0"									
16J4 16J5 16J6 16J7 16J8										
18J5 18J6 18J7 18J8										
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
6J4 6J5 6J6 6J7 6J8	29'-0"									
18J5 18J6 18J7 18J8										
20J5 20J6 20J7 20J8										

Joist Type	Clear Span	2.5" ×	3.5 ⁿ ×	4.5" ×	2.5 ¹¹⁻ ×	3.5" ×	~4.5"~ ×	2.5" x	'3.5'''' x	(4.5"" ×
No		24"	24"	24"	36!"	36"	36"	48"	48''	48"
22J6	29'-0"		11111	TITI	. The BF (*) is 'tools flage ()	11111	TITIT	7997 <i>64</i> , 3,4977473	17777	1117
22J7 22J8										
24J6 24J7 24J8										
	30'-0"		141447 1.1111	777777		777777	(S.		7777777 7777777	1211210 1777713
16J4 16J5	500									
16J6 16J7 16J8										
18J5			11111	TTTTT		IIIII				
18J6 18J7 18J8										
20J5			177777			11111			77777	
2035 20J6 20J7										
20J8			JIIII]]]]]]]					011111]]]]]]]
22J6 22J7										
22J8]]]]]]]]]]]]]		<u>777117</u>	<u>illll</u> l		(11111)	
24J6 24J7										
24J8			71111			711111				
16J4 16J5	31'-0'									
16J6 16J7										
16J8			11111]]]]]]]]		711111				
18J5 18J6										
18J7 18J8										
20J5			[[]]]]	[[]]]]		77777	<u>(IIII)</u>		17777	<u>, 11777</u>

No. 24" 24" 24" 36" 36" 36" 48" 18" 48" 2016 31'-0" 31'-0" 31''' 31'''' 31''''' 31''''''''''''''''''''''''''''''''''''	Joist	Clear	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"
20.16 20.17 20.18 31'-0" 31'-0" 31'-0" 22.16 22.17 22.18 32'-0" 31'-0" 31'-0" 16.14 16.15 16.16 16.17 16.18 32'-0" 31''-0" 31''-0" 16.15 18.16 18.17 18.18 32''-0" 31''-0" 31''-0" 22.16 22.17 22.18 31''-0" 31''-0" 31''-0" 21.15 20.16 20.17 20.18 33''-0" 31''-0" 31''-0" 18.15 18.16 20.17 20.18 33''-0" 31''-0" 31''-0" 18.15 18.16 20.15 20.16 33''-0" 31''-0" 31''-0" 20.15 20.16 31''-0" 31''-0" 31''-0" 21.17 22.18 31''-0" 31''-0" 31''-0" 18.15 20.15 31''-0" 31''-0" 31''-0"	Туре	Span	X 2411	X	X	X	X	X 7611	X		X
20.17 20.8 22.16 22.17 22.18 24.16 24.16 24.17 24.18 32'-0'' 16.14 32'-0'' 16.15 16.16 16.16 16.17 16.18 10.11 18.15 18.16 18.17 18.18 20.15 20.16 20.15 22.16 22.16 22.16 22.16 22.16 22.16 22.16 22.16 22.16 22.16 23.11 18.15 33'-0' 18.15 33'-0' 18.18 20.15 20.15 20.16 20.15 20.15	- LLOsterener	NESTIGATION OF		- State way			<u></u>		40	1. Quarter	40
20.18 22.16 22.17 22.18 24.16 24.17 24.18 32'-0'' 16.14 32'-0'' 16.15 16.16 16.16 16.17 16.18 16.17 18.15 18.16 18.17 18.16 18.18 18.17 18.18 18.16 22.16 19.10 22.16 19.10 22.16 19.10 22.16 19.10 24.16 19.10 24.16 19.10 24.16 19.10 24.16 19.10 24.16 19.10 24.18 18.15 18.15 13.5'-0'' 18.15 13.5'-0'' 18.15 13.5'-0'' 18.15 13.5'-0'' 18.15 13.5'-0'' 18.16 19.10 18.17 19.10 18.18 19.10 20.15 10.10 20.16 10.10 <td></td> <td>31'-0"</td> <td></td> <td>71117</td> <td>innn</td> <td></td> <td>IIIII</td> <td></td> <td></td> <td>TITTI I</td> <td>iiiii.</td>		31'-0"		71117	innn		IIIII			TITTI I	iiiii.
22.16 22.17 22.17 22.18 24.16 24.17 24.18 32'-0'' 16.14 32'-0'' 16.15 16.16 16.16 16.16 16.17 16.16 16.18 1000000000000000000000000000000000000											
22.17 22.18 24.16 24.17 24.18 32'-0' 16.14 32'-0' 16.15 16.16 16.16 16.17 16.18 16.18 18.15 18.16 18.17 18.18 20.15 20.16 20.17 20.18 22.16 22.17 22.18 11.11 18.15 13.1 18.15 13.1 18.15 13.1 18.15 13.1 21.16 11.1 22.16 11.1 22.17 11.1 22.18 11.1 18.15 13.1 18.15 13.1 18.15 13.1 18.16 18.17 18.18 11.1 18.18 11.1 18.18 11.1 20.15 11.1 20.15 11.1 20.15 11.1	2018			777777			7177777	$\sigma m m$		77777.	-777777
22.18 24.16 24.17 24.17 24.18 32'-0' 16.15 16.15 16.16 16.17 16.18 10.11 18.15 18.16 18.17 10.11 20.15 10.11 20.15 10.11 20.16 10.11 24.16 24.17 24.18 10.11 18.15 13.11 18.15 13.11 20.15 10.11 20.15 10.11 20.16 10.11 21.17 10.11 22.16 10.11 22.17 10.11 24.16 10.11 24.16 10.11 24.17 10.11 18.15 13.11 18.16 11.11 18.17 18.16 18.17 18.16 18.17 18.16 18.17 18.16 18.17 18.16 18.17 18.16 18.16 10.11 1				11111			illilli	ann		11111	IIIII
24.16 32'-0' 16.14 32'-0' 16.15 16.17 16.16 16.17 16.18 16.17 16.18 16.17 18.15 18.16 18.17 18.18 20.15 16.14 20.15 16.14 21.17 16.14 22.16 16.14 24.16 16.14 24.16 16.14 20.15 16.14 21.16 16.14 22.17 16.14 22.18 16.14 24.16 16.14 24.16 16.14 24.15 16.14 24.16 16.14 21.15 16.14 18.15 133'-0' 18.16 18.17 18.18 16.14 18.17 18.18 18.17 18.18 18.18 16.14 18.17 18.16 18.18 16.14 18.15 17.14 18.16 17.14 <t< td=""><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></t<>											
24J7 24J8 16J4 32'-0' 16J5 16J6 16J7 16J8 16J8 16J7 18J5 16J7 22J6 16J7 22J7 16J7 22J8 16J7 24J6 16J7 24J6 16J7 18J5 33'-0' 18J5 13J'-0' 18J6 16J7 18J8 16J7 18	2218			71111	711777		777777	11111		States 1	(]]]][]]
24J8 32'-0" 16J4 32'-0" 16J5 16J5 16J6 16J7 16J8 16J7 16J8 16J7 16J8 18J5 18J6 18J7 18J8 18J7 18J8 20J5 16J8 16J7 20J7 16J8 16J7 20J8 16J7 16J8 22J6 16J7 16J8 24J6 16J7 16J8 24J8 18J5 33'-0" 18J5 131'-0" 16J8 18J5 131'-0" 16J8 18J8 16J7 16J8 18J8 16J7 16J8 18J8 16J9 16J9 18J9 <td>24J6</td> <td></td> <td></td> <td>IIIII</td> <td>illilli</td> <td></td> <td>IIIII</td> <td>TITT</td> <td></td> <td>TITT</td> <td>m</td>	24J6			IIIII	illilli		IIIII	TITT		TITT	m
16J4 32'-0' 16J5 6J6 16J7 1 16J8 1 18J5 1 18J5 1 18J7 1 18J8 1 20J5 1 20J7 1 20J8 1 22J6 1 22J7 1 2J8 1 24J6 1 24J7 1 24J8 33'-0' 18J7 1 18J7 1 18J5 33'-0' 18J8 1 20J5 1 20J5 1 18J7 1 18J8 1 18J5 33'-0' 18J8 1 20J5 1 <td></td>											
16J5 16J6 16J7 16J8 18J5 18J6 18J7 18J8 20J5 20J6 20J7 20J8 22J6 22J7 22J8 1000000000000000000000000000000000000	24J8			71111	//////		71111	711111		677777	177777
16J6 16J7 16J8 18J5 18J5 18J6 18J7 18J8 20J5 18J8 20J5 18J8 20J5 18J8 20J5 18J8 20J7 18J8 22J6 18J5 24J6 18J7 24J8 18J5 18J7 18J8 18J7 18J8 20J5 18J6 18J7 18J8 20J5 18J8	16J4	32'-0"		mm	inni)		11111	mm		inni i	m
16J7 16J8 18J5 18J5 18J6 18J7 18J8 18J8 20J5 18J8 20J5 18J8 20J6 18J8 20J7 18J8 22J6 18J7 22J7 18J8 24J6 18J5 24J7 18J8 18J5 33'-0' 18J7 18J8 20J5 18J6 18J7 18J8 20J5 18J7 18J8 18J7 18J8 18J7 20J5 18J8 20J5 18J6 20J5 18J5 20J5 <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>()))))</td> <td></td>										()))))	
16J8											
18J5 18J6 18J7 18J8 20J5 20J6 20J7 20J8 22J6 22J7 22J8 18J5 24J6 18J7 24J8 18J5 18J7 18J8 18J5 33'-0' 18J7 18J8 20J5 18J6 18J7 18J8 20J5 18J7 18J8 18J7 20J5 18J8 20J5 18J8 20J5 18J8 20J5 18J8								HHH.			
18J6 18J7 18J8 18J8 20J5 20J6 20J7 18J8 20J8 18J7 22J6 18J7 22J8 18J5 24J6 18J5 24J8 18J5 18J5 33'-0' 18J8 18J7 20J5 18J8 20J5 18J7 20J5 18J7 20J5 18J7 20J5 18J7 20J5 18J5 20J5 18J5 20J5 18J5 20J5 18J7 20J5 18J7 20J5 18J7 20J5 18J7 20J5 18J7				#21.202-D2	1.2.2.3.5.7.3.		12 (P P P No. 1	(1.7.1). (2.1). (1.7.1)	1	1	
18J7 18J8 20J5 20J6 20J7 20J8 22J6 22J7 22J8 24J6 24J7 24J8 18J5 33'-0' 18J8 20J5 20J5 20J6				IIIII I	IIIII		IIIII	IIIII	1	111112	<u>IIIII</u>
18J8 18J8 18J8 1100000000000000000000000000000000000		i									
20J5 20J6 20J7 20J8 22J6 22J7 22J8 1000000000000000000000000000000000000											
20J6 20J7 20J8 Image: Constraint of the second						•					
20J7 20J8 22J6 22J7 22J8 1000000000000000000000000000000000000				IIIII)				IIIII			
20J8 22J6 22J7 22J8 24J6 24J7 24J8 18J5 18J5 33'-0' 18J7 18J8 20J5 20J5 20J5 20J5								illilli.			IIIII.
22J7 22J8 24J6 24J7 24J8 18J5 33'-0' 18J6 18J7 18J8 20J5 20J6				<u>VIII</u>	IIIII		\overline{UUU}	IIIII			IIII
22J7 22J8 24J6 24J7 24J8 18J5 33'-0' 18J6 18J7 18J8 20J5 20J6							FFFFFF				
22J8 24J6 24J7 24J8 18J5 33'-0' 18J6 18J7 18J8 20J5 20J6											
24J7 24J8 18J5 33'-0' 18J6 18J7 18J8 20J5 20J6				<u> ()))))</u>							
24J7 24J8 18J5 33'-0' 18J6 18J7 18J8 20J5 20J6									ł		
24J8 18J5 33'-0' 18J6 18J7 18J8 20J5 20J6				<u>IIII</u>	illili.			<u>IIIII</u>		IIIII	
18J5 33'-0' 18J6 18J7 18J8 20J5 20J6											
18J6 18J7 18J8 20J5 20J6				-Strictore							
18J7 18J8 20J5 20J6		33'-0'		IIIIA						IIIIA	IIIII)
18J8 20J5 20J6 300000000000000000000000000000000000											
20J5 20J6				<u>IIIII</u>						<u>IIIIA</u>	IIIII
			i								
				IIIII)					1		
	2016 2017			TIIII	IIIII						IIII

Joist	Clear	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"
Type <u>No</u>	Span	× _24''	× _24''	× 24"	× _36"	× 36"	× 36"	× 48''	× 43''	× 48"
20J8	33'-0"		71772		WE LY THE ALL.	TITTI I		and Same		
22J6 22J7 22J8										
24J6 24J7 24J8										
18J5 18J6 18J7 18J8	34'-0"									
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7 24J8										
18J5 18J6 18J7 18J8	35'-0"									
20J5 20J6 20J7 20J8										
22J6 22J7 22J8										
24J6 24J7]]]]]]							

Joist [.] Type	Clear Span	2.5"	3.5" x	4.5"	2.5"	3.5"	4.5"	2.5"	3.5"	4.5"
No.	opun	× 24''	24"	× _24''	× 36"	X 	× 36"	× 48''_	× 48''	× 48''
24J8	35'-0"		<u>11110</u>	111111 1		<u> 11111</u>	71177		11111	(1 <u>1111</u> 7
18J5 18J6	36'-C"		IIII							
18J7 18J8										
20J5 20J6										
2030 20J7 20J8										
22J6				illilli.		11111				
22J7 22J8										
24J6 24J7									IIII)	
24J8			01111							
20J5 20J6	37'-0"									
20J7 20J8										
22J6 22J7			IIII							
22J8		[[[[]]		[[[]]]				1		
24J6 24J7		177777						<u>(DIU)</u>		
24J8 20J5	38'-0'	11111. 11111.	/11111 }							
20J6 20J7	50 0									
20J8							//////////////////////////////////////			
22J6 22J7 22J8										
22J0 24J6		TTTTT								
24J7		<u>UIIII</u>	MM	mm	'IIIII	<u>'IIIII</u>	'IIIII	illlli	imm	, IIIII

Joist	Clear	2.5	3.5"	4. 5"~	2.5"	-"3.5"	4.5"	2.5"	3.5"	7475"-7
Туре	Span	× 24''	X	X	X	X	X	X	X	X
No.	200-1017-07-04-00-04-0-	24	24"	24"	36"	36"	36"	48"	48"	48"
2.4J8	38'-0'		am	<u>IIIII</u>	iIIII	TIIII	IIIII	IIIII	IIIII	<u>(1111)</u>
20J5	391-01	11111	117777	TITT	177777	mm	177777	1171771	111111	
2035 20J6	590									
20J7										
20J8		TIIII	7777777		JITTU	//////	,111111	TIIII	///////	i]]]]]]
22J6		inni	111111	m		IIIII	IIIII	11111	IIIII	ann
22J7										
22J8		UHHI]	[]]]]]]]	,111111	mm		177777	01111	[[]]]]
24J6			mm	IIIII	IIIII	TIIII	nnn i	IIIII	inni	11111
24J7										
24J8		777777		(11111)	71111.	1171777	711777	//////		
20J5	40'-0"	iIIIIi	11111	IIIII	IIIII	IIIII	TIIII)	illilli	mm	illilli
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		ميناريز <u>ليواريزا. وال</u>	1.22.22.22.22.22.	2.43×31.3.4×			a (in a she a brid a an in	22,5 24,7 24,0		(***to*a + Aprilant ar
22J6		<u>IIIIi</u>	<u> </u>							
22J7 22J8								IIIII.		
		2- 3-1-3- 3-3-3			Salt 2. Salt 2.					
24J6		IIIII	IIIII	IIIII						
24J7 24J8										
22J6 22J7	41'-0'	<u> </u>		IIIII.						
22J8					<u>IIIIi</u>		IIIII			
							TUEFE		l.	arrers
24J6 24J7										
24J7 24J8		<u>VIIII</u>	IIII			<u>IIIII</u>			IIIII	
					-					
22J6 22J7	42'-0'									
22J8		<u>IIIII</u>			IIIII			jIIII	<u>IIIII</u>	
24J6 24J7										
24J8		UIIII	IIIII		,IIIII				jIIIII	<u>IIIII</u>
. 1		l	i	ł	ł	l	l	I	1	1

Joist Type	Clear Span	2.5" x	3.5" ×	4.5" ×	2.5" ×	3.5" x	4.5" ×	2.5" ×	3.5" x	4.: ×
No.	anna	24"	24"	24"	36"	36"	36"	48"	48"	48
22J6	43'-0'					linni				
22J7 22J8										
24J6 24J7										
24J8		<u> (</u>				<u>illilli</u>			711111	
22J6 22J7	44'-0'									
22J8									, 111111	Ŵ
24J6 24J7									IIIII	
24J7 24J8			jIIII							
24J6	45'-0'									
24J7 24J8			IIII					JIIII		
24J6	46'-0'						illilli			
24J7 24J8		<u>UIII</u>								
24J6	47'-0'									
24J7 24J8										
24J6	48'-0']					
24J7 24J8						jIIII				
		ļ								
	l		l	l	l	1	ł	l		1

SUGGESTIONS FOR FURTHER INVESTIGATION

In is readily apparent that a more difinite definition of annoying transient vibration must be made. Existing information deals almost entirely with steady-state vibrations. Furthermore, information (probably of a field installation nature) must be gathered to determine the damping effect of partitions, piping, and other structural additions. No clear picture of the relative effect of damping means now exists. Thus floors are designed to the open space layout which tends to be quite conservative in practice. Finally, there is little experimental and no theoretical information available to indicate the effect of partial floors (for instance, a floor partially removed to allow ventilation installation). It is clear that such floors are generally undesirable, but in some instances it may be practical to make such a design. However, without further information no reasonable prediction may be made of the characteristics of such a floor.

This type of an analysis can be extended to the long-span and the new intermediate span series. Same tests should be made to confirm values and to obtain same feeling of minimum damping.

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Lawrence P. Dorsett, Lt. J. G., USN, Co-Author, is assigned to the University for graduate study. The Navy's foresightedness in allowing men of this caliber to proceed through graduate training under the NESEP and post-graduate programs should be recognized. Much of this research was done by him and is recorded in his M.S. thesis.⁸

Ronnie W. Gibson made many of the calculations for the authors and contributed much to the project.

The contributions of the graduate students working on earlier portions of this problem are recognized. Most of their contributions are summarized in reference one. They include Joseph Keller, Gerald Barr, James Wiley, and William Lyons.

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APPENDIX I

Sample Calculation of the Number of Effective Joists

The simplest demonstration of the calculation of the number of effective joists is by the graphical method. Suppose Figure 36 in the text represents the static deflection surface obtained for Raytown Jr. High School, data set no. 2. The joist spacing for this set is 23.5 inches. Substitution of the construction parameters into Equation (6) yields an x_0 of about 84 inches (see Appendix IV). This means that a total of seven joists are located within the zeros of static deflection.

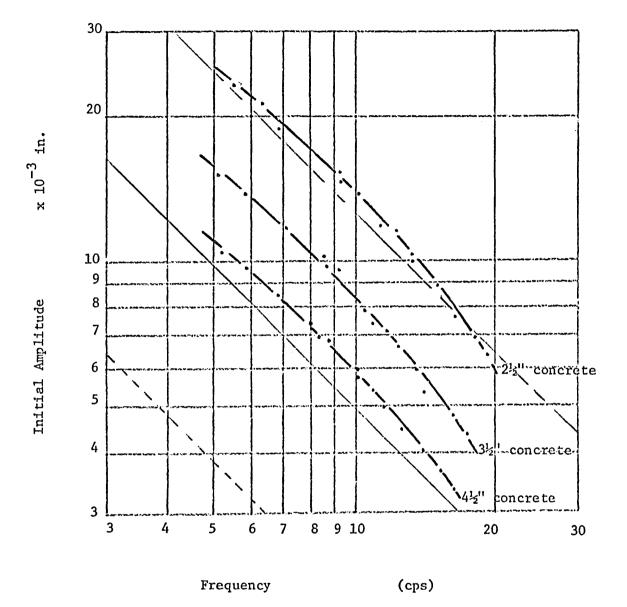
First assume that the center joist is totally effective. Then its contribution is 1.0. At a distance to either side or the center joist equal to the joist spacing the value of the sine approximation is about 0.9. Thus the contribution of the joists at these positions is taken to be 0.90. Similarly, the joists two spacings removed from the center each contribute about 0.6 and those at a distance of three spacings from the center each contribute about 0.2. Thus the total contributions are

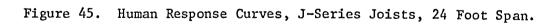
	Total		4.4	effective joists
joists at 70.5 in. from center	2×0.2	=	0.4	
joists at 47.0 in. from center	2×0.6	=	1.2	
joists at 23.5 in. from center	2×0.9	=	1.8	
center joist		=	1.0	

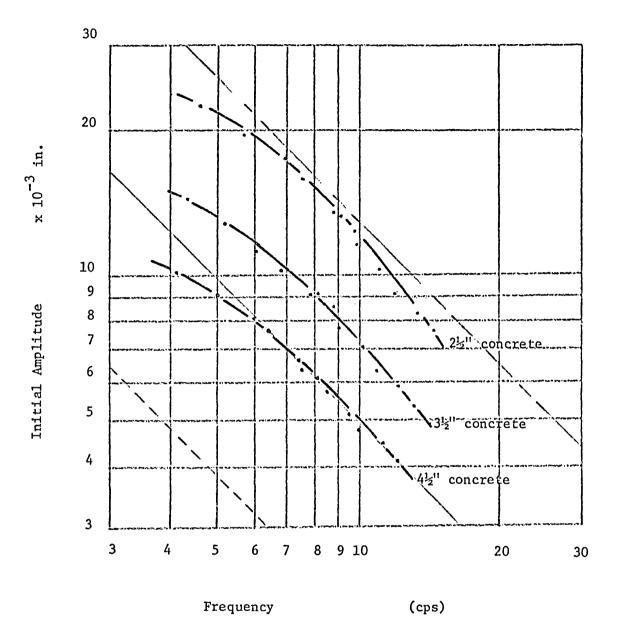
This number compares favorably with the more exact computer calculation of 4.587 as listed in Appendix IV.

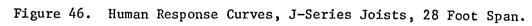
APPENDIX II

The following six figures (figures 45 through 50) illustrate the human response for J-series joist spans from twenty-four to forty-four feet, concrete thicknesses of two-and-a-half, three-and-a-half-, and four-and-a-half inches for all depth joists from twelve to twenty-four inches. These curves are plotted directly from information contained in Appendix III.









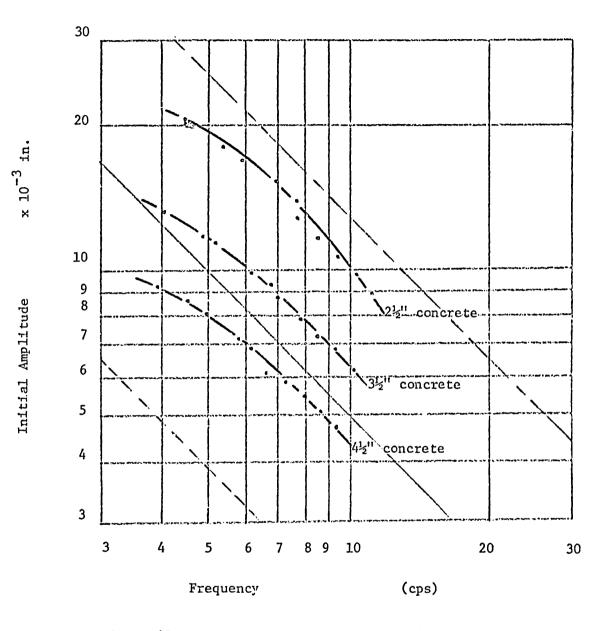
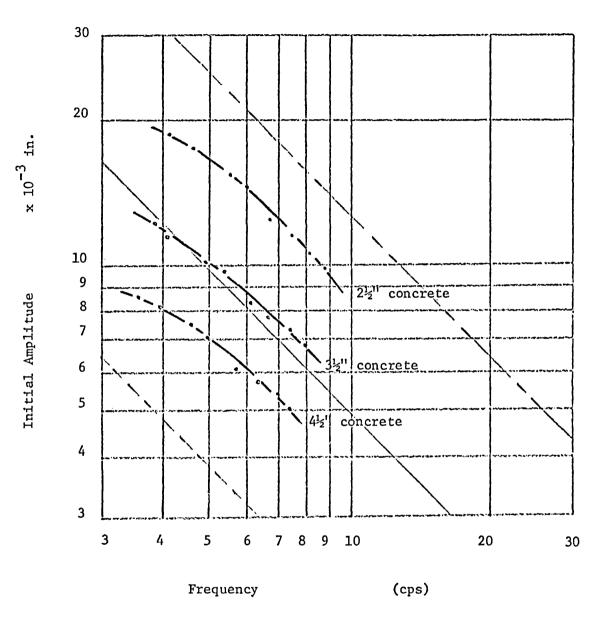
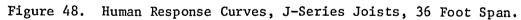


Figure 47. Human Response Curves, J-Series Joists, 32 Foot Span.





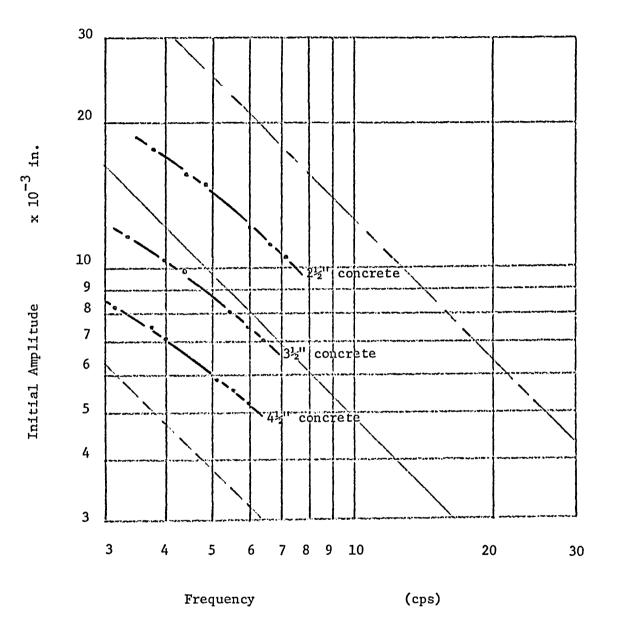
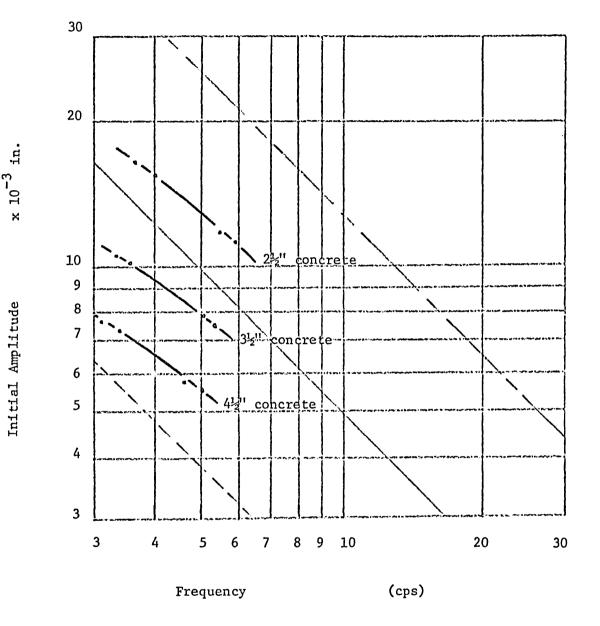


Figure 49. Human Response Curves, J-Series Joists, 40 Foot Span.





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