# Vibration of Steel Joist-Concrete Slab Floors

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DEVELOPMENTS IN MATERIALS and technology have led to lighter types of construction in floors with little decrease in factors of safety. These economical methods of construction have resulted in occasional floors with insufficient stiffness to prevent noticeable vibration induced by human impact. This problem has not been limited to any type of construction or construction material.

The Steel Joist Institute, in order to acquire basic knowledge and test data in the field of floor vibration, initiated and sponsored a research program at The University of Kansas. Copies of the final report can be obtained from either The University of Kansas or from the Steel Joist Institute at Washington, D. C.

The program consisted of analytical and experimental work both in the field and laboratory. Two floors were built in the laboratory for control purposes, and to obtain floors which were subject to annoying vibrations. These floors were at the limit of the acceptable design range. Figure 1 shows the first floor loaded with dead weight to design load.

In addition, measurements were taken on 46 different floors in the Kansas City area. The floors were designed for many different usages; offices, churches, schoolrooms, halls, and assembly rooms. The floors were in buildings in use for years as well as buildings under construction. The condition of the supported concrete slabs was a large variable. Some floors had badly cracked concrete, and others were in excellent condition. The thickness of the concrete varied as much as 2 in. from that indicated on the drawing. In only three floors of those investigated, would the disagreement between the predicted and measured frequency have been of any consequence if a vibration problem were present.

### COMPUTATION OF NATURAL FREQUENCY

In all of the floors it was found that full interaction occurred between the steel joists and the concrete slabs in defining the natural frequency of the system. The natural

Kenneth H. Lenzen is Professor, Dept. of Mechanics and Aerospace Engineering, The University of Kansas, Lawrence, Kansas. frequency f of these floors could be closely approximated by the equation,

$$f = 1.57 \sqrt{\frac{gEI_t}{w_d l^4}}$$

in which

- g = acceleration due to gravity, 386.4 in./sec<sup>2</sup>
- $I_t$  = the moment of inertia of the composite section multiplied by the number of joists
- E = the modulus of elasticity of the composite section. (Usually it is easier to work in terms of the steel joist and equate the concrete to an equivalent area of steel.)
- $w_d$  = dead load is lbs/in. of the floor system

l = effective length of joist in inches

A more exact method for computing the natural frequency of floor systems was derived in which the stiffness of the slab perpendicular to the joist could be taken into account. Since this refinement made the computations cumbersome, it was not used. Those floor systems with appreciable stiffness perpendicular to the joists had a large natural frequency, a small amplitude, and no objectional vibrations.



Fig. 1. First test loaded to design load

## HUMAN RESPONSE TO VIBRATIONS

The determination of human sensitivity to vibrations is of prime importance. In 1911 research was being conducted on this subject; it is continuing today. Reliable curves are available from several sources for the human reaction to steady-state vibrations. Probably the one of most use is that one published by Reiher and Meister in 1946. It is of the same form as that shown in Fig. 3 except that the amplitude scale is displaced downward by a factor of 10, i.e., the distinctly perceptible range is from an amplitude of 0.006 in. to 0.018 in. The difference between the scales is due to the difference in human sensitivity to transient vibrations as compared to steady state vibrations.

In originally deriving the graph, and in all of the checks of it, a steady-state vibration was used. In checking the floors, a transient vibration induced by impact was used. The difference was, therefore, the time or number of cycles to which the human was exposed to the vibrations. Additional tests on the test floor substantiated this conclusion.

A normal floor is not subjected to a steady-state vibration induced by machinery of any nature. If such is the case, the machinery can be easily isolated from the floor system and, thus, the vibrations eliminated. The main source of vibration is from the occupants themselves impacting the floor through normal usage. The problem is then reduced to the elimination of vibrations induced by this source.

The search of literature gave no indication of how the human responded to transient vibrations. To substantiate the ideas formed from the various tests, a platform was designed on which the natural frequency, amplitude, and damping characteristics could be varied. Tests on students and staff indicated that variation in frequency and amplitude within the range measured in the field had a minor effect. The main factor influencing the



Fig. 2. Detail view of dynamic vibration absorber

effect of vibrations on the human was the damping. If the floor was damped to a small amplitude prior to five cycles of oscillation, the occupant felt only the initial impact, no vibration. If the vibration persisted above 12 complete cycles, the occupant responded to the vibration just as to a steady-state vibration. The response to the vibrations between these ranges was a function of the number of cycles before the amplitude became negligible. Reanalysis of the Kansas City floors substantiated these conclusions. The three floors on which the vibrations were definitely perceptible all had amplitudes after five cycles of vibration above 0.4 of the initial amplitude. All other floors had much lower amplitudes after five cycles. Those above 0.2 but below 0.4 of the initial amplitude after five cycles were between the perceptible and barely perceptible range of sensitivity. Amplitudes after five cycles below these values were barely or not at all perceptible. The main problem then is not one of frequency and amplitude such as encountered in steady-state vibrations but of damping. If floors can be damped before 12 cycles of oscillation the effect of the oscillatory motion is reduced.

#### DAMPING FROM NORMAL CONSTRUCTION AND OCCUPANCY

What provides damping? Again, in reviewing the floors tested in Kansas City it was found that almost everything provided damping.

Human occupants provided excellent damping. The human frame will absorb a large amount of energy. Four people increased the damping on the test floor 300 percent above that without them. In a school building annoying vibrations were reported by school teachers working after classes. Tests made in the empty classroom indicated an initial amplitude of about 0.007 in. with a frequency of nine cycles per second. After five cycles, the amplitude was 41.7 percent of the initial value. Later, the tests were repeated when the class was present. With a full classroom, the initial amplitude remained 0.007 in. but the frequency decreased slightly to 8.75 cycles per second. The amplitude after five seconds was 8.7 percent of the initial value. The vibrations were not perceptible by the students or teacher even when looking for them when the room was full. The same vibrations but with much less damping were annoying when the room was empty. This also demonstrated the large effect of damping.

Simple loads other than humans do not increase the damping values. A floor loaded with concrete cylinders had much less damping than when unloaded. The activation of the dead load provided more energy which had to be absorbed before the vibrations would decrease.

On the building floors investigated, it was found that most structural components contributed to the damping.



Suggested design curve for steel joist-concrete slab floors due to dampened vibrations caused by impact-type loads.
$I_t$ = the moment of inertia of the composite T-section multiplied by the number of joists g = acceleration due to gravity, 386.4 in/sec <sup>2</sup> $w_d$ = dead load in lbs/in of the floor system l = effective length of joist in inches

Especially efficient were partitions of all types including the small wooden temporary partitions. The flooring, rugs, and ceilings assisted to a reduced extent. The three floors recorded earlier as having definite to annoying vibrations all had large open areas with no partitions and were in school buildings and a church. Normal construction provides the damping necessary to absorb the energy of the floor and, thus, remove any annoying sensation. Only when these normal values are totally absent is the vibration noticeable as in the situation in which no partitions are present above or below the floor.

### ARTIFICIAL DAMPING

Although annoying vibrations would not usually be expected in a normal design, it is sometimes necessary to provide damping in a floor which has excessive vibrations. Also, since it seemed inadvisable to penalize all floors for the few that would be encountered with no partitions and consequently the possibility of insufficient damping, damping would have to be provided artificially if annoying vibrations resulted. Several methods have been tried but only one has been successful in this study.

A design of a dynamic vibration absorber was optimized to provide maximum damping with a minimum of weight. It was found that a device weighing 0.02 of the weight of the floor would dampen any floor in less than five cycles if it were mounted on springs which provided a natural frequency of the unit of about one cycle per second less than that of the floor to be damped. A dash pot must be provided to absorb the energy of the floor and must provide the damping unit with a damping equivalent to 7.5 percent of the critical value. A unit is shown in Fig. 2.

Another test floor was designed and built to evaluate the dynamic damping units and other methods of eliminating annoying vibrations from floor systems.

It was found that the damping units were effective. The test floor which was designed to have annoying vibration characteristics became entirely satisfactory when the dynamic damping units were attached to it. The damping units succeeded in damping the floor in less than four complete cycles.

Since typical installations normally provided sufficient internal damping to avoid annoying conditions, the damping provided by ceilings was investigated. It was found that attached ceilings provided more damping than hung ceilings. The amount of energy which either would absorb was not significant as compared to that needed for a floor with so little damping as to be annoying. If the vibration is in the low perceptible range, a ceiling probably will damp the vibrations sufficiently.

An attempt was made to damp vibrations by various methods such as providing insulation of various types between the bridging members and the joists, providing cross bridging, prestressing the top and bottom chords of the joists, and providing a variety of cable installations which would cause interaction between members with a resulting absorption of energy. No effective damping method was found, due largely to the fact that the motion of a floor is small, (0.003 in. to 0.010 in.).

#### SUMMARY OF TEST RESULTS

If steady-state vibration is encountered in a building, the source usually can and should be insulated, thus removing the vibrations. Therefore, it is assumed that steadystate vibration is not a factor in the design of buildings. With this assumption, the results of the investigation indicates the following:

1. Transient vibrations are those which must be

counteracted and these are important only if the vibrations induced persist more than five cycles.

2. Human response to transient vibrations is influenced primarily by the damping. If damping reduces the vibration to a negligible quantity in five cycles, the human will not respond. If it persists beyond 12 cycles, he will respond as if to steady-state vibrations.

3. Normal construction provides sufficient damping through such construction features as walls, partitions, flooring, and ceilings so that the transient vibrations are usually in the non-perceptible or barely perceptible range.

4. In large open areas such as schoolrooms, department stores, and churches, insufficient damping will usually result. For such areas the design curves (Fig. 3) seem satisfactory for steel joist-concrete slab floors in which the span does not exceed 24 ft. (See later discussion for spans above 24 ft.)

5. The human being was one of the best energy absorbers found.

#### **DESIGN THOUGHTS**

Although damping is inherent with even the worst design, it would be possible to design a floor satisfactory to the human occupants even if the structure had no damping. Such a design is possible because the natural frequency of vibration of the floor increases as the square root of the moment of inertia while the deflection decreases directly with the moment of inertia. Actually, such a design will only remove the vibration from the perceptible range of the occupants and would require a natural frequency which would probably be at least 30 cycles per second. To comply with such a design requirement would necessitate a ridiculous size of joist and slab. It should be realized that all floors will have some inherent damping.

In the design of large open areas encountered in churches and school buildings, sufficient damping to avoid the vibration problem may usually not be realized. Increased stiffness may be used in combination with the inherent damping to insure that the vibrations are, at worst, in the low perceptible ranges. A graph is presented in Fig. 3 which can be used for such designs. In general, the curve will require a stiffer floor structure than that usually used. The moment of inertia can be increased most efficiently by increasing the depth of the joist. Increasing the thickness of the concrete slab is not as efficient as increasing the joist size. The required stiffness or moment of inertia may be obtained by a small increase in weight by using a deeper joist, or, if headroom is important, a heavier joist of the same depth with added slab thickness can accomplish the same purpose.

The curve in Fig. 3 appears to be reasonable for the design of typical floors like those from which test data were obtained. It has been found that the impulse factor used to compute deflection (300 lbs in Fig. 3) is only approximately correct for spans under 24 feet. The value of the correct impulse factor is being determined in a continuation of the research project by SJI. Until such time that a correct value be given, it is recommended that this factor be  $L^2/d$ , in which L is the span of the joists in feet and d is the depth of the joist in feet. This is not theoretically correct but seems to result in an acceptable value.

Also, included as an objective in the present investigation is determination of the effective number of joists. For a floor with a great number of joists, the normal  $2\frac{1}{2}$ in. slab may have insufficient sheet stiffness to transmit the load to all of the joists. It is recommended that the total number of joists be used if they number less than 12. For floors with more than 10 joists, it is recommended that only 10 be used. These recommendations are made on the assumption of a 2-ft spacing of joists and a  $2\frac{1}{2}$ -in. concrete slab.

### DESIGN CRITERIA

An insufficient number of floors have been designed under the ideas presented in this paper to arrive at firm conclusions on the vibratory action of floors that would result. More experimental work is necessary before these concepts can be included in specifications, but the following seems indicated by this project:

1. All floors designed under present specifications in which higher stresses are allowed are as sound structurally as those designed according to previously used rules.

2. Since the mass and stiffness of the floors have been reduced in many cases, there is an increasing possibility of annoying vibrations.

3. Whenever sufficient damping has been present, which seems best provided by partitioning above or below the floor area, no vibration annoying to the occupants has been found. Subdividing the area by partitions is common to most designs.

4. If the area is not partitioned, the curves in Fig. 3 should be used but the impulse factor for deflection should be  $L^2/d$  (in feet) rather than 300.

5. If more than 10 normally spaced joists are used in an individual span of a section of floor, it is recommended that only 10 be considered as effective when calculating anticipated vibration response.

6. No studies have been made on the vibration effects for continuous or fixed-ended floors.