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Design of Stiff, Low-Vibration Floor Structures

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ABSTRACT

Many aspects must be considered in the design of low-vibration buildings. One major aspect is the floor supporting the vibration-sensitive equipment. This paper addresses the design of several types of floors for low vibration environments, drawing from some of the authors' design projects.

1. INTRODUCTION

Dynamic loading of a floor can excite vibrations that may adversely affect production or research activities using equipment supported on that floor. These loads may be caused by mechanical systems or personnel activities. One way to minimize vibrations is with a slab-on-grade floor, but often this is not possible due to constraints such as lot size or the requirement of a basement for mechanical equipment or piping.

This paper reviews the analysis and design of several types of floors for low-vibration environments. It addresses slab-on-grade floors as well as suspended floors made up of flat and waffle slabs, conventional steel-and-concrete composites, and long-span floors of concrete or steel primary members. The relative costs of several types of framing are examined.

2. VIBRATION CRITERIA

Several generic vibration criteria are in use for designing vibration-sensitive facilities in addition to a large collection of manufacturers' criteria for particular items of equipment. The authors have used the family of vibration criteria developed by BBN and Acentech, illustrated in Fig. 1 and summarized in Table 1.[1,2] They will be used when criteria are necessary for discussion in this paper. These criteria are specified in terms of velocity amplitude, as it has been shown that vibration sensitivity is, in general, a function of *vibration amplitude within a specific frequency range* rather than being a function of stiffness, frequency, or floor type alone. Typically, we assume a criterion of 250 microinch/sec for microelectronics facilities and others using high magnification devices like electron microscopes and one of 2000-4000 microinch/sec for research facilities using low-power optical microscopes.

3. TYPES OF FLOORS

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Floors can be divided into two generic categories:

- **Slab-on-grade:** Floor slab is supported directly on soil subgrade. Frequency content of response to vibratory loading is similar to that of the supporting soil.
- **Suspended:** Floor slab and supporting structure rest on a grid of columns. The most common styles are flat slab, waffle slab, and slab resting on a steel framework. Suspended floors typically exhibit a resonance frequency, which is excited by walkers as well as by broadband forces from turbulence in piping and ducting supported on the floor slab.

4. MODELS FOR FLOOR VIBRATIONS

The two most common sources of vibrations in a building are mechanical equipment and personnel activities. Gordon[2] has shown that in the case of a suspended floor the vibration velocity amplitudes can be calculated by Eqs. (1) and (2) for people walking on the floor and for the effects of turbulence in piping and ducting connected to the floor, respectively. Equation (1) is based upon the relationships developed by Ungar and White.[3]

$$V_{\mathrm{walker}} = \frac{C_w}{kf} \qquad (1)$$

$$V_{\mathrm{mech}} = \frac{C_m}{k} \qquad (2)$$

In these equations, k is the point stiffness (lb/in.) and f is the fundamental resonance frequency (Hz) of the floor at the point being considered. The coefficient C_w is based upon walker weight and speed following from the derivation by Ungar and White; Eq. (2) and C_m are empirical and are based upon statistical studies of one-third octave band vibration components of a number of floors.

It follows that reduction of these two kinds of vibrations can be achieved by increasing the point stiffness k; walker-induced vibrations will also be reduced by increasing the fundamental frequency. Since resonance frequency is proportional to the square root of stiffness divided by mass, the benefit of increasing stiffness is improved if mass increases as little as possible.

The dynamic behavior of slabs-on-grade is not as well documented as that of suspended floors; predictive models analogous to Eqs. (1) and (2) are not available. It might be assumed that velocity amplitudes due to walkers are inversely proportional to stiffness, so that one can compare improvements (but not predict actual amplitudes) when varying factors governing stiffness.

5. SIZING THE SLAB-ON-GRADE

It can be shown[4] that the point stiffness of a slab-on-grade is

$$k = 8\sqrt{SD} \tag{3}$$

where S is the subgrade modulus and D is the plate rigidity, commonly defined as

$$D = \frac{Dt^3}{12(1-n^2)} \tag{4}$$

The stiffness of a foundation[5] in simplified form is

$$k = SA \tag{5}$$

where S is the subgrade modulus and A is the area of the foundation.

If we compare Eqs. (3) and (5) for 3000 psi concrete and a good subgrade of 500 lb/in.,[3] we find that a slab of 9 in. thickness will provide the same stiffness as a massive square concrete foundation 6 ft on a side.

6. SIZING THE SUSPENDED FLOOR

Sizing the members of a suspended floor requires selection of a floor *type,* which will lead to assumption of an appropriate mathematical model, which can be as sophisticated as a finite element model or as simple as equations with appropriate coefficients.

6.1 Interaction of floor and columns

It is very important that the correct support conditions be assumed. In the situation where the column stiffness is considerably greater than the centerpoint stiffness of the floor (assuming rigid supports), one may assume with relatively small error that the floor can be modeled with rigid supports. However, in the case where the floor stiffness approaches or exceeds half of the column stiffness, a considerable error will arise from using rigid supports.

Figure 2 (from a not-yet-published study by the senior author) shows the fundamental plate resonance of a multispan slab floor as thickness is increased and column stiffness is held constant. When the plate fundamental resonance is less than the calculated column resonance, the column resonance is nonexistent and the plate resonance is the system fundamental. [It is the system fundamental that one uses in Eq. (1).] When the plate fundamental exceeds the column resonance, the latter appears and becomes the system fundamental. Figure 3 shows the effects of the ratio of plate stiffness (calculated assuming rigid supports) to support stiffness k_p / k_s on k, f, kf, and V_{walker}. When the ratio is less than 0.5, the error introduced by assuming rigid supports is slight; when it exceeds 0.5, support stiffness must be considered. When the stiffnesses are equal, the error is a factor of 2. (It should be noted that k_s should include both the column and footing stiffness.)

6.2 Waffle slab, grillage, or flat slab

Cast-in-place concrete floors are quite popular in a variety of applications. Generally, when high stiffness is desired for a vibration-resistant floor, designers have preferred to reduce span, increase depth, and minimize weight. The need for weight minimization has led to a preference for grillages and waffle slabs in microelectronics facilities requiring basements, although at least one facility has been built with a thick, solid slab about 1 meter thick.

If a multispan, square-bay-slab or waffle slab can be represented using plate rigidity [Eq. (4)], the stiffness and fundamental resonance frequency of the plate can be approximated for rigid supports by Eqs. (6) and (7), respectively.

$$k_p = f \frac{Et^3}{12(1-n^2)L^2} = f \frac{D}{L^2} \qquad (6)$$

$$f_p = \frac{l_i^2}{2pL^2}\left(\frac{Et^3 g}{12w(1-n^2)}\right)^{1/2} = \frac{l_i^2}{2pL^2}\left(\frac{Dg}{w}\right)^{1/2} \qquad (7)$$

where units are pounds and inches, $\phi = 64.2$, E is Young's modulus, t is slab thickness (or effective thickness), n is Poisson's ratio, L is the spacing between columns, l^2 is the frequency parameter (for this case $l^2 = 8.9$), g is the constant of gravity (386.4 in./sec^2 , and w is the sum of the distributed weight and effective applied load. The calculated plate stiffness k_p and the column stiffness k_s can be used with Fig. 2 to determine whether or not the calculated V_{walker} must be increased to account for column-plate interaction.

Figure 4 compares several measurements, including in-situ mobility, made on a waffle slab with column spacing of 16 x 16 ft, pan depth of 24 in., slab thickness of 4.5 in., and measured concrete strength of about f_c' = 6000 psi. The point stiffness is 5-6 x 10^6 lb/in. and a resonance frequency of 48 Hz. The floor was designed to meet BBN/Acentech criterion C (500 microinch/sec), but because of the increased concrete strength from 4000 psi specified, the floor is somewhat stiffer than intended and its performance is closer to 250 microinch/sec.

Figure 5 compares similar measurements made on a deep grillage with a high-strength concrete, column spacing of 12 x 12 ft, and depth of 36 in., designed to meet BBN/Acentech criterion E (125 microinch/sec). Its stiffness and resonance frequency are 7-8 x 10^6 lb/in. and 69 Hz, respectively. A thick mat foundation was used to achieve a very high stiffness at the base of the columns; these results would probably not have been possible with spread footings or piles.

The k_p / k_s of the floors represented by Figs. 4 and 5 equals or exceeds 1; both require consideration of column stiffness in calculation of dynamic properties.

6.3 **Steel/concrete composite**

It has become quite popular in the design of laboratories to use concrete slab with steel decking supported by a structural steel framework. The popular framing schemes are similar to those used for offices and other commercial buildings.

Calculation of stiffness and resonance frequency for composite floors is not as straightforward as for slab floors. Each member has a resonance frequency, and they are combined using Dunkerle's equation, shown in Eq. (8).

Stiffness is calculated for the assemblage as a whole taking into consideration how the members are connected, or using the methods of Murray.[6]

$$\frac{1}{f_{res}^2} = \frac{1}{f_{beams}^2} + \frac{1}{f_{purlins}^2} \tag{8}$$

The desires for maximum space utilization and economy lead to long spans and shallow, light steel sections. Long spans can be accommodated, but at the expense of depth and weight.

6.4 Long spans in steel

The authors have found that it is not practical to use standard rolled sections in spans longer than about 35 ft for vibration-sensitive facilities. Typical long spans require 36 in.-deep sections to achieve, and performance better than 2000 microinch/sec is generally not possible. Our preference is to stay with spans less than 30 ft.

The limiting span for 250 microinch/sec floors is much smaller, so much so that it usually isn't considered practical to put equipment of this sensitivity on upper floors in laboratories where open space is desirable. However, if floor-to-floor height or framing depth is not a limiting concern it is possible to achieve this environment using a steel truss. This scheme partially makes up for its depth by the ability to pass piping and ducting through the openings in the truss. If penetrations for large ducting is a concern, a Vierendeel truss may provide the most accommodating configuration. We have found that a 250 microinch/sec environment could be achieved in a 21'x 27.5' bay using a truss with 5 ft depth spanning the 27.5 ft direction and W24 members spanning the 21-ft direction.

7. Comparison of Costs

Figure 6 summarizes the results of a study relating dynamic properties and cost effectiveness of several structural approaches for a particular bay in a research building. Candidate schemes were steel framing laid out using several different depths, concrete waffle slabs with 20 and 24 in. pan depths, and a Vierendeel truss. In each depth of the steel sections, weight was being varied. In each depth of waffle pan, the topping slab thickness was being varied.

The concrete waffle slab quite clearly is the most economical approach to the problem. Pans of 24 in. depth are required if the criterion is to be less than 700 microinch/sec. All of the waffle slab options had unit costs less than $12/sq ft.

All of the steel options we examined had unit costs in excess of $14/sq ft. The most cost-effective composite environment meeting the design goal of 400 microinch/sec had a steel depth of 30 in. at a cost of about $17.50/sq ft. Surprisingly, the Vierendeel truss had a lower unit cost than even the W30 scheme--about $15/sq ft. Schemes employing W33 or W36 sections might be more cost-effective than the truss for obtaining 400 microinch/sec environments.

Table 1. Vibration Criteria

Facility Equipment or Use	Vibration (µin/sec)	Vibration (µm/sec)
Ordinary workshops Offices Residences,** computer systems	32,000 16,000 8,000	800 400 200
Operating rooms, surgery, bench microscopes at up to 100x magnification, laboratory robots	4,000	100
Bench microscopes at up to 400x magnification, optical and other precision balances, coordinate measuring machines, metrology laboratories, optical comparators, microelectronics manufacturing equipment - class A	2,000	50
Micro surgery, eye surgery, neurosurgery, bench microscopes at magnification more than 40x; optical equipment on isolation tables; microelectronics manufacturing equipment - class B	1,000	25
Electron microscopes at up to 30,000x magnification, microtomes, magnetic resonance imagers; microelectronics manufacturing equipment - class C	500	12.5
Electron microscopes at greater than 30,000x magnification, mass spectrometers, cell implant equipment, microelectronics manufacturing equipment - class D	250	6
Microelectronics manufacturing equipment - class E, unisolated laser and optical research systems	125	3

* Value of V for Fig. 1
** Criterion given by solid curve of Fig. 1 corresponds to a standard mean whole-body threshold of perception.

8. References

1. E. Ungar, D. H. Sturz, and H. Amick, "Vibration Control Design of High Technology Facilities," *Sound and Vibration*, July 1990.

2. C. G. Gordon, "The Design of Low-Vibration Buildings for Microelectronics and Other Occupancies," presented at the First International Conference on Vibration Control in Optics and Metrology, London, February 1987.

3. E. Ungar and R. White, "Footfall-Induced Vibration of Floors Supporting Sensitive Equipment," *Sound and Vibration*, October 1970, p. 10.

4. S. Timoshenko and S. Woinowsky-Krieger, *Theory of Plates and Shells*, 2nd ed., McGraw-Hill, NY, 1959.

5. B. M. Das, *Fundamentals of Soil Dynamics,* Elsevier, NY, 1983.

6. T. Murray, "Design to Prevent Floor Vibrations," *Engineering Journal,* American Institute of Steel Construction, Vol. 12, No. 3, 1975, p. 82.

Criterion A - Probe Test Equipment, 100x Microscopes
Criterion B - 500x Microscopes, Aligners, Steppers to 5 µm Geometries
Criterion C - 1000x Microscopes, Aligners, Steppers to 1.5 µm Geometries
Criterion D - Steppers, E-Beams to 0.3 µm Geometries, CD Inspection Equipment, Most SEMs to 50,000x
Criterion E - Anticipated Adequate for Future Fabrication and Test Equipment for Low Submicron Geometries

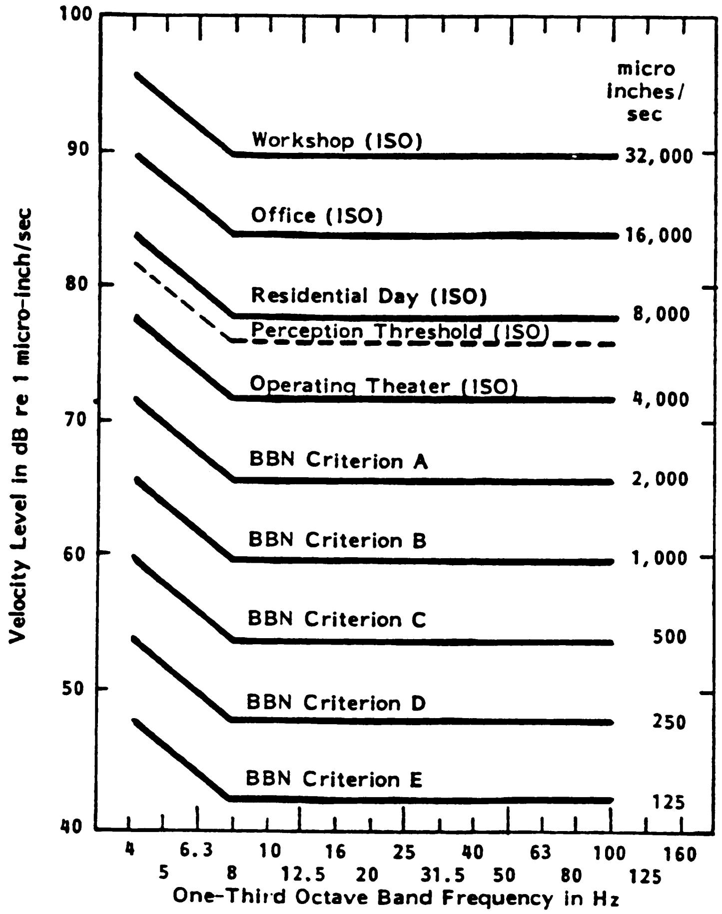

Figure 1. Floor vibration criteria for equipment used in the production of integrated circuits [Other curves represent criteria recommended by International Standards Organization (ISO)]

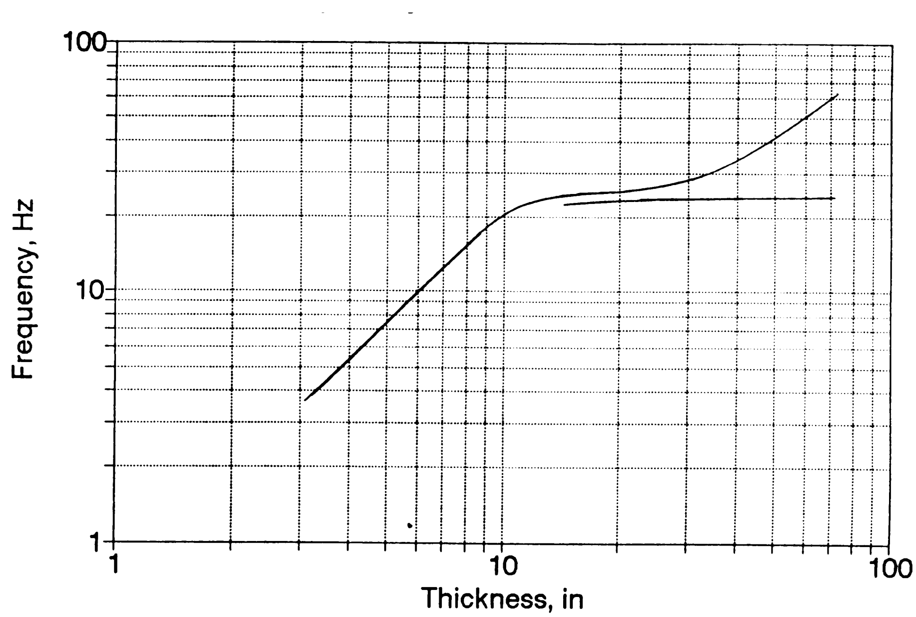

Figure 2. Frequency *vs* thickness for multibay floor supported on springs.

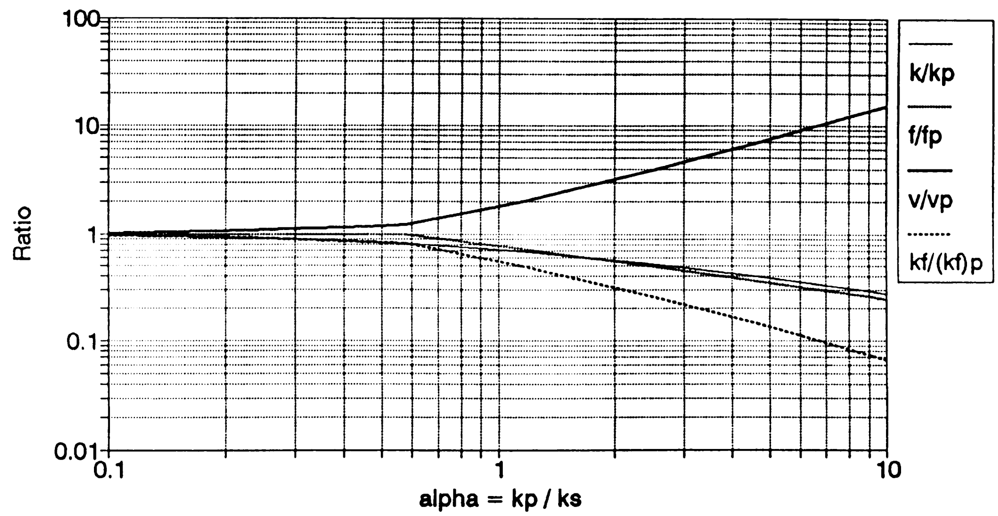

Figure 3. Dimensionless parameters for midpoint properties of multibay floor supported on springs.

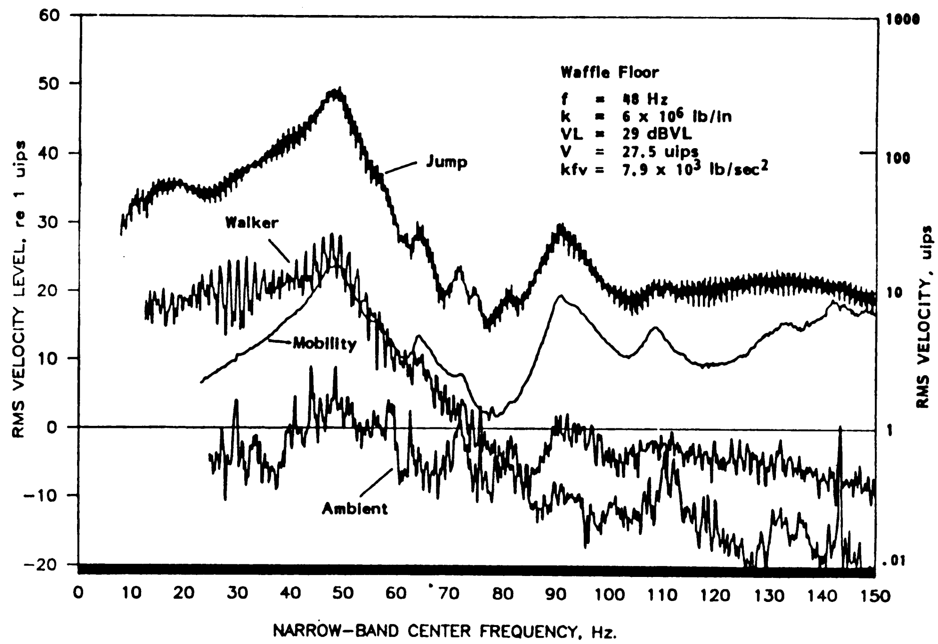

Figure 4. Vibration data measured on waffle floor.

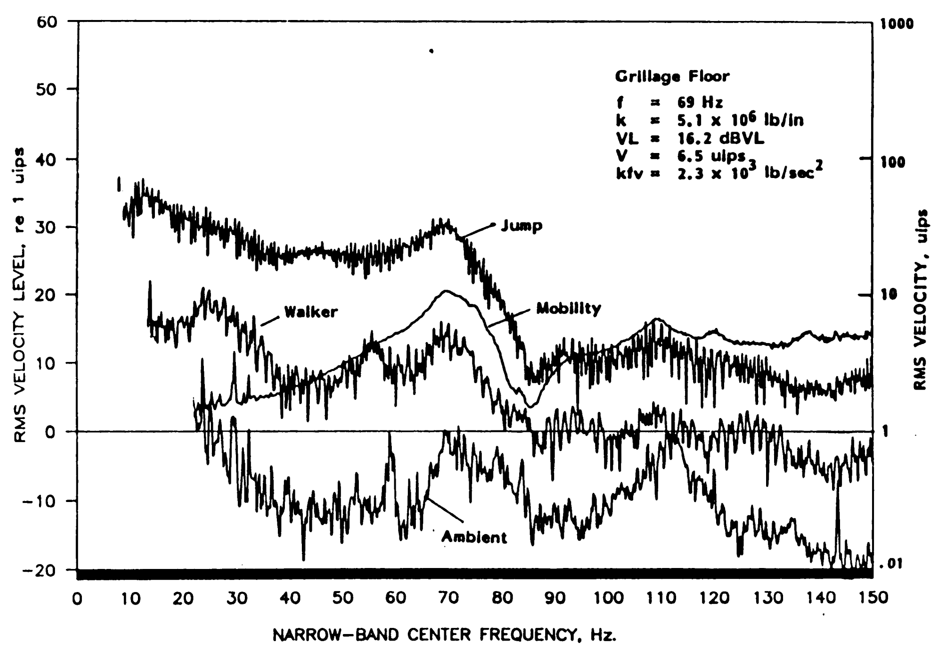

Figure 5. Vibration data measured on grillage floor.

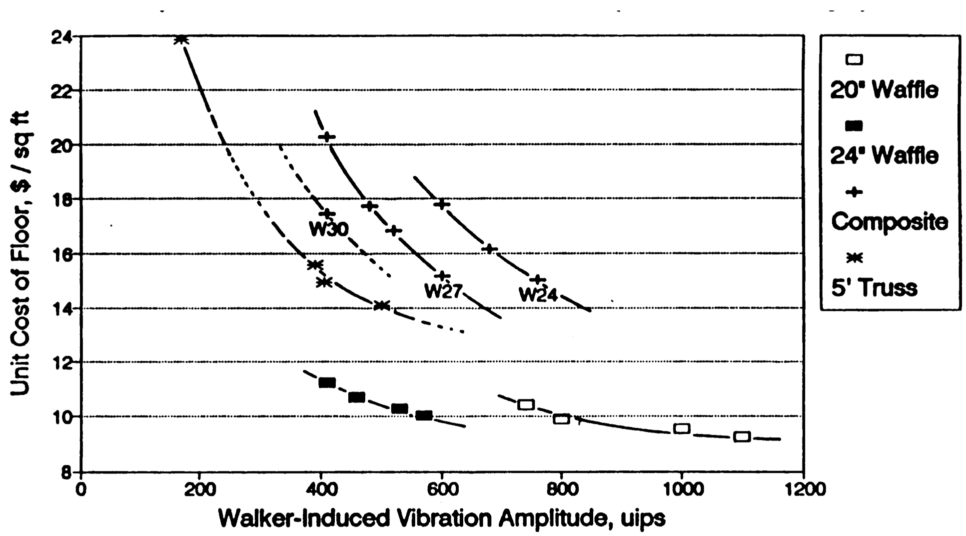

Figure 6. Comparison of the unit costs of several structural schemes as a function of walker-induced floor vibration performance.