Structural Design

design issues for structural engineers

Vibration of Reinforced Concrete Floor Systems

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It is generally perceived that vibration is not an issue for reinforced concrete floor systems. Because of the inherent mass and stiffness of such systems, this perception is generally true. However, there can be situations where the effects of vibration are one of the main design issues that need to be addressed. In this general overview, simplified methods are provided that can be used in a preliminary analysis to determine approximate fundamental vibration characteristics, which can help in choosing a suitable floor system for a given set of conditions.

Acceptance Criteria for Human Comfort

Human response to floor vibration is very complex. The magnitude of the motion and what a person is doing are two of the factors that have an impact on perception and acceptability. Floor systems that can "dampen out" the effects of vibration in a relatively short period of time are likely to be perceived as less annoying than those systems that cannot dampen vibration as quickly.

Many criteria have been proposed through the years related to vibration and human comfort. To date, no universally accepted criteria exist. A discussion on walking and rhythmic excitation follows.

Vibrations can be caused by a person or persons walking on a floor system. Depending on a number of factors, this vibration can be annoying, or worse, for the people that are occupying the area affected by the vibration. Recommended acceleration limits for human comfort due to specific human activities were developed by the International Standards Organization and have been successfully implemented in a wide variety of situations (ISO 2631-2). This standard provides limits for different occupancies in terms of root-mean-square acceleration as a multiple of a baseline curve.

For vibrations due to walking to be acceptable, the peak acceleration of the floor system should be less than or equal to the recommended acceleration for a particular occupancy. The natural frequency (f_n), the effective weight, and the inherent damping of the floor system are all related to peak acceleration. It is common to find that the acceptance criterion for walking is satisfied for all types of reinforced concrete floor systems, including flat plates.

The same conclusion is not necessarily true for reinforced concrete floor systems subjected to rhythmic excitations. Activities in health clubs, gymnasiums, and dance halls, to name a few, can produce significant vibrations. Because the dynamic forces and accompanying vibration associated with rhythmic activities is generally large, it is usually not practical to mitigate vibration by increasing the mass or damping of the system. The acceptance criterion for rhythmic excitations is satisfied when f_n is greater than the frequency of the highest harmonic that can cause resonant vibration.

While the acceptance criterion for walking excitations is easily satisfied for a flat plate system, it is unlikely that the appropriate criterion will be satisfied when the flat plate is subjected to aerobics or jumping. In such cases, it would probably be more economical to use a two-way joist (waffle) system or a grillage system, the latter of which consists of evenly spaced concrete beams in two orthogonal directions. For less demanding activities such as dancing, a concert, or a sporting event, a wide-module joist or a voided slab system can usually be utilized (a voided slab system is similar to a flat plate, except it contains regularly-spaced voids that are created using hollow recycled plastic void formers; see Mota 2010 for more information).

Acceptance Criteria for Sensitive Equipment

Manufacturers of sensitive equipment will generally provide vibration acceptance criteria for their equipment. The limits are usually given as a vibrational velocity, which has the units of micro-inches per second. The criterion for sensitive equipment is satisfied when the expected maximum velocity, which is a function of the walking pace of the occupant or occupants near the equipment, is less than or equal to the limiting value given by the manufacturer. The smaller the limiting value, the more challenging it is to satisfy the acceptance criteria.

In the preliminary design stage, the equipment is usually known only in general terms and no information on the specific model or type is available. In such cases, generic acceptance criteria can be utilized to arrive at a suitable floor system. This system can be subsequently checked once specific information on the equipment becomes available.

The type of reinforced concrete floor system to use when supporting sensitive equipment depends for the most part on the limiting value of the vibrational velocity and the bay sizes. For example, a flat plate system supporting computer equipment, which has a relatively large vibrational velocity limit, may work for slow and moderate walking paces but may not work for a fast walking pace. It is unlikely that a flat plate would satisfy the criteria for a facility where eye surgery is performed, except possibly for a slow walking pace. Two-way joist or grillage reinforced concrete systems are typically

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utilized to support equipment where the spans are long and/or the vibrational velocity limits are small.

Vibration Characteristics

Stiffness, damping, and natural frequency are parameters that are needed in the vibration analysis of any reinforced concrete floor system. The following recommendations and approximate procedures can be utilized in the preliminary design stage to quickly ascertain the types of floor systems that are best suited to satisfy the required vibration criteria.

Stiffness. The stiffness of the floor system has a direct effect on natural frequency: the greater the stiffness of the floor, the greater the natural frequency, which translates to a likely decrease in adverse effects caused by vibration.

For typical reinforced concrete floor systems of usual proportions, the major component of the deflection of the system is due to flexure. Thus, only the flexural stiffness of the floor E_cI_e needs to be considered. The quantity E_c is the modulus of elasticity of the concrete. Because the strains in the concrete are small when subjected to dynamic loading, it is appropriate to use a value of E_c that is 20 to 30 percent larger than the code-prescribed value. The term I_e is the effective moment of inertia. It is recommended to include the effects of cracking when initially determining the stiffness of a non-prestressed floor system because the natural frequency may be overestimated if it is not considered. A more refined cracking analysis can always be performed later, if desired.

Damping. Damping is a measure of how quickly vibration will subside and eventually stop. It is greatly dependent on the nonstructural items that are supported on the floor, such as people, partitions, file cabinets, bookshelves, and furniture, to name a few.

The amount of damping is usually expressed as a percentage of critical damping and is commonly referred to as the damping ratio. A damping ratio of 0.02 is recommended for floors with few nonstructural components (like electronic offices), while a ratio of 0.05 can be used where full-height partitions are present between floors (ATC 1999). A value of 0.03 is commonly used for office spaces with partial height partitions. Additional information on how to choose an appropriate damping ratio can be found in Hewitt and Murray, 2004.

Natural frequency. Natural frequency is a measure of how the floor system will respond to the sources that can cause vibration, and is related to how occupants will perceive such vibrations. Numerous resources and methods are available to determine this property. It is usually convenient to obtain this and other vibration characteristics from a commercial computer program. Like all software, it is very important to understand the methodologies that are used to calculate this parameter.

The equations in the *Table* give approximate values of the natural frequency for various reinforced concrete floor systems. They have been developed using fundamental principles of dynamics. More information on their use, including worked-out design examples for commonly used reinforced concrete floor systems, can be found in the *Design Guide for Vibrations of Reinforced Concrete Floor Systems* (Fanella and Mota, 2014).▪

Approximate equations for natural frequency of reinforced concrete floor systems.

System	Natural Frequency
Wide-module Joist	$f_n = \dfrac{3.54}{\sqrt{(\Delta_j + \Delta_g)}}$ Δ_j = instantaneous mid-span deflection of the joists Δ_g = instantaneous mid-span deflection of the girders
Flat Plate and Voided Slab Systems	$f_n = \dfrac{k_2\lambda_1^2}{2\pi\ell_1^2}\left[\dfrac{k_1E_ch^3}{12\gamma(1-v^2)}\right]^{1/2}$ $k_1 = I_e/I_g$ $k_2 = \begin{cases} 1.9 \text{ for } c_1 \leq 24 \text{ in.} \\ 2.1 \text{ for } c_1 > 24 \text{ in.} \end{cases}$ c_1 = column dimension h = thickness of slab ℓ_1 = longer of the two center-to-center span lengths of the plate panel ℓ_2 = shorter of the two center-to-center span lengths of the plate panel γ = mass per unit area of the plate v = Poisson's ratio $\begin{array}{cc} \ell_1/\ell_2 & \lambda_1^2 \\ \hline 1.0 & 7.12 \\ 1.5 & 8.92 \\ 2.0 & 9.29 \end{array}$
Two-way Joist	$f_{ij} = \dfrac{\lambda_{ij}^2}{2\pi\ell_1^2}\left[\dfrac{k_1E_ch_e^3}{12\gamma(1-v^2)}\right]^{1/2}$ $k_1 = I_e/I_g$ h_e = equivalent slab thickness ℓ_1 = longer of the two center-to-center span lengths of the panel γ = mass per unit area of the plate v = Poisson's ratio $\lambda_{ij}^2 = \pi^2\left[i^2 + j^2\left(\dfrac{\ell_1}{\ell_2}\right)^2\right]$ i,j = mode indices
Grillage	$f_{11} = \dfrac{\pi}{2\gamma^{1/2}}\left[\dfrac{D_x}{\ell_1^4} + \dfrac{D_y}{\ell_2^4} + \dfrac{2D_{xy}}{\ell_1^2\ell_2^2}\right]^{1/2}$ $D_x = D_y = \dfrac{k_1E_ch_s^3}{12(1-v^2)} + \dfrac{k_1E_cI_r}{s}$ $D_{xy} = \dfrac{k_1E_ch_s^3}{12(1-v^2)}$ $k_1 = I_e/I_g$ h_s = slab thickness I_r = moment of inertia of rib s = center-to-center spacing of ribs ℓ_1 = longer of the two center-to-center span lengths of the plate panel ℓ_2 = shorter of the two center-to-center span lengths of the plate panel γ = mass per unit area of the plate v = Poisson's ratio

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