SP 60-1

Introduction and Background: Vibrations of Concrete Structures

By Gajanan M. Sabnis

Synopsis: Various aspects of vibrations of concrete structures are presented to set the stage for the rest of the symposium. These include, complexity of vibrations, structural problem, human response, approach for their evaluation and elimination and code provisions. It is hoped that the information provided in this paper will stimulate the thinking of designer concerning the potential problem that he might be faced with.

Keywords: building codes; dynamic characteristics; evaluation; human factors engineering; prestressed concrete; reinforced concrete; structures; vibrations.

Dr. Gajanan M. Sabnis, F ACI is an active member of ACI, and has been until recently chairman of ACI committee 435, Deflections of Concrete Structures and also is a member of ACI Committees 116, 444, 549. He is also active locally in ACI activities and presently is Director of the National Capital Chapter, of which he was a co-founder and past President. Dr. Sabnis obtained his Ph.D. from Cornell University and is registered engineer in the States of California and Maryland. He is currently associate professor in Civil Engineering at Howard University and is editor of Handbook of Composite Construction Engineering to be published by Van Nostrand Reinhold.

INTRODUCTION

When this symposium was planned, the ACI committee 435 had just begun to think in terms of the effect of dynamic action of forces on concrete structures from the deflections point of view. For many years, engineers have faced this problem and looked for assistance to those who may know a little bit more about it and possibly the solution. The committee started looking seriously into this topic and especially having just completed the task of 'state-of-the-art' on static deflections(1), came up with the excellent idea of doing likewise in the case of dynamic deflections(2).

It is the express purpose of this paper to touch upon various background items in order to set a stage for the symposium.

The remaining papers of this symposium deal with specific problems and occasionally with recommendations as to how a solution might be reached. In some instances, research background is presented which should be helpful to designer.

Various aspects of vibrations in concrete structures are:

1. existence and complexity of vibration
2. structural problem of vibration
3. human response to vibration
4. approach for evaluation and remedies of the problem
5. some code provisions

EXISTENCE AND COMPLEXITY

Vibrations in a structure occur due to a multitude of causes. They are commonly caused by walking (as inside a building) or by wind or other loading (external to the building). Other forms of loading causing vibrations are considered in several of the papers in this symposium that follow. They include blast loading (3,4), seismic vibrations (5), construction loading (6) and so on. The main reason for importance of vibration in a structure is attributed to the concern for the serviceability due to use of higher strength materials and the use of strength theories which in turn results lower thickness of floors and hence may accentuate the deflections due to vibratory loading.

Floor vibrations is an oscillatory motion of the floor about a position of rest. When a panel vibrates it may create vibration of opposite nature in the adjacent panel. This may cause discomfort to the occupants of the adjacent panel. The original vibration and the translated vibration will cease with the passage of time as shown in Fig. 1 (6) depending on the damping characteristics of the floor. The higher the stiffness, and the higher the damping, the faster will be this decay and the less discomfort will be experienced by the occupants. This figure also shows that higher frequency modes can be neglected since they alternate quickly and do not cause serious discomfort. The effect of vibration is further complicated by the fact that different people will react differently, depending on their ability of perception and on many other factors.

THE STRUCTURAL PROBLEM

The term "structural problem" refers to that which the structure itself will be faced with in the event of vibrations. The problem has been recognized for many years. In 1828, Tredgold wrote (9):

> "Girders should always, for long bearings, be made as deep as they can be got; an inch or two taken from the height of a room is of little consequences compared with a ceiling disfigured with cracks, besides the inconvenience of not being able to move on the floor without shaking everything in the room."

The above quotation clearly signifies the problems, which have been recognized by the codes with our simplified provisions for depth/span ratio and for deflection limits under equivalent static loading. It is now recognized, however, that the designer must calculate certain dynamic characteristics, such as frequency and damping of the structure in order to prevent or minimize potential problems.

Frequency (f) of a simply supported, one way system (9) is given by:

$$f = 31\sqrt{\frac{E}{\omega L^4}} \quad (1)$$

in which the terms are

E = Modulus of Elasticity
I = Moment of Inertia
ω = load per unit length of span
L = span

(ALL units are in pounds and inches)

The values for other support conditions can be found using different coefficients as shown by Blume and Honda (5). Proper considerations must be given to account for other attached members in the above expression.

Fig. 2 shows how the natural frequency of reinforced concrete can be determined. The details were developed using following frequency expressions

$$f = \frac{\pi}{2}\left\{\frac{1}{\ell_x^2}+\frac{1}{\ell_y^2}\right\}\sqrt{\frac{D}{\rho t}} \quad (2)$$

where, $D = E t^4/12(1-\nu^2)$ (3)

in which the terms have the usual meaning. Both the simply supported and built-in edges are considered. It is recommended (10) that the thickness should be adequate to have a frequency value of higher than 15 Hz.

Damping in a floor system must be estimated. A range of values for damping is suggested (9). This range may vary between 2 per cent for bare concrete floors to 10 per cent for finished floors with concrete deck and partitions in place.

Damping will absorb the vibrations in a certain frequency range and will reduce resonance and in turn any potential damage to the structure. The relation between damping expressed in percent of critical damping and decay of free vibration is shown in Fig. 3.

HUMAN RESPONSE

There are basically three kinds of human exposure to vibration, namely:

(a) Vibrations transmitted simultaneously to the whole body surface or substantial parts of it. e.g. when high intensity sound in air or water excites vibrations of the body.

(b) Vibrations transmitted to the body as a whole through the supporting surface, namely, the feet of a standing man, the bottom of a seated man or the supporting area of a reclining man. This kind of vibration is usual in vehicles, in vibrating buildings and in the vicinity of working machinery.

(c) Vibrations applied to particular parts of the body such as the head or limbs; for example, by vibrating handles, pedals, or head-rests, or by the wide variety of powered tools and appliances held in the hand.

It is also possible to recognize the condition in which an indirect vibration nuisance can be caused by the vibration of external objects in the visual field (for example, an instrument panel).

Human response in these conditions will depend on many factors as listed below:

1. Type of excitation (e.g. impulsive shock, machinery vibration, etc.)
2. Type of property (e.g. residential, office, hospital, etc.)
3. Time of day
4. Limit of acceptance

The first two characterize the structural problem as was mentioned in the last section. The last two depend on an individual's position, when subjected to vibration and the effect will accordingly change. Examples are shown by three positions as shown in Figure 4 to determine such a response (11). Since the effect will differ, suitable weighting factors are recommended to set up the proper criteria for the type of occupancy.

APPROACH TO EVALUATION AND REMEDY

For a given structure and occupancy the dynamic characteristics may be evaluated as mentioned before and suitable structural deficiency made up. On the other hand, other remedial measures for continuous vibrations (9) can be:

(a) Relocation of vibrating source
(b) Removal of source
(c) Vibration isolation

Sources, such as machinery or potentially usable areas for dancing or gathering, should be isolated from sleeping quarters or office areas. Structures should be designed (or altered) to avoid resonance by making the floor frequency of the sensitive occupancy different from that of the floor directly vibrated. Equipment should be balanced to reduce eccentric forces or connected to the structure with large mass to increase inertial resistance to movement. Often, vibration sources can be founded on isolated pads or soft springs to reduce transmission of vibrating to the structure. It must be recognized that isolation will only succeed if it is less than the forcing frequency. e.g. if it is 1/3 of the forcing frequency, the transmitted frequency is reduced approximately 80 per cent. On the other hand, if the two are about the same, the transmitted vibration is greatly enhanced due to resonance.

Structural properties mentioned before can be used to avoid resonance and to provide suitable damping to reduce the duration of vibrations.

CODE CONSIDERATIONS

As mentioned before the problem of vibrations has drawn more attention of professional engineers in the last decade due to the use of higher strength and lighter materials leading to economical but shallower structures. It is hoped that based on ISO* standards, codes will be able to recommend provisions for vibration standards. These criteria should consider:

(a) human response to vibrations
(b) limitation of structural stiffness

ISO specifies exposure limits for vibration transmitted to human body from solid surfaces in the range of 1 to 80 Hz. These standards should be specified in terms of vibration frequency, acceleration magnitude, exposure time and the direction of vibration relative to the torso.

The basic rating (Hz) is given for the most stringent conditions and proper weighting factors applied for other conditions depending on the type of structure and occupancy.

The stiffness of a floor should be such that maximum deflection shall not exceed certain limits. According to ISO (11), this limit with a standard 150 lb. static line load distributed over a floor width is taken as:

$$\Delta_v \leq \frac{2}{3f} \qquad (4)$$

in which Δ_v = maximum deflection, in inches

f = lowest natural frequency of the structure in Hz.

Canadian Standards Association (CSA) (12) recommends that proper corrective measure should be taken to reduce the annoying vibrations, if they exist. The effective way is to increase damping by adding partitions or damper posts in the floor below. If these methods are not suitable, special devices to absorb vibrations or damping materials should be incorporated into the floor system. Even a simple measure of using a rug is effective in reducing walking impact as well as in cushioning the sway of china cabinets.

DIN 4150 (13) takes slightly different approach and provides with equations to calculate maximum stress in a structure subjected vibration velocities, which in turn are related to human exposure. Gasch and Klippel (4) have discussed this in detail. Fig. 5 shows relationship between the various quantities as contained in the German provisions.

Although currently no provisions exist in the ACI code, it is felt that based on what is presented in this symposium and the material available to the profession, ACI Committee 435 will eventually make recommendations to ACI Committee 318 for inclusion in future building codes.

---

*International Standards Organization

REFERENCES

1. Deflection of Concrete Structures, SP-43, American Concrete Institute, Detroit, 1974, 637 pp.

2. Vibrations of Concrete Structures, SP-60, American Concrete Institute, Detroit, 1979, 308 pp.

3. Jeary, A. P., and Sparks, P. R., "Some Observations on the Dynamic Sway Characteristics of Concrete Structure" (part of Reference 2).

4. Gasch, R., and Klippel, P., "Estimation of Dynamic Stressing of Floors and Other Structural Parts of Building Due to Shocks and Blasting" (part of Reference 2).

5. Blume, J. A., and Honda, K. K., "Dynamic Characteristics of Reinforced Concrete Buildings" (part of Reference 2).

6. Akins, K. P., and Dixon, D. E., "Concrete Structures and Construction Vibrations" (part of Reference 2).

7. Fowler, T. J., and Karabinis, A. H., "Vibration Performance of Industrial Structures" (part of Reference 2).

8. Warwaruk, J., "Deflection Requirements--History and Background Related to Vibrations" (part of Reference 2).

9. Allen, D. E., Rainer, J. H., and Pernica, G., "Vibration Criteria for Long Span Concrete Floors" (part of Reference 2).

10. Ichikawa, K., personal communication, 1977.

11. ISO 2631, "Guide for the Evaluation of Human Exposure to Whole-Body Vibration," September 1974.

12. CSA Standard S16.1-1974, "Steel Structures for Buildings-Limit States Design," 1974.

13. DIN 4150, "Erschutterungen in Bauwesen," 1975 (Vibrations in Structural Engineering) (Preliminary Standard 1975).

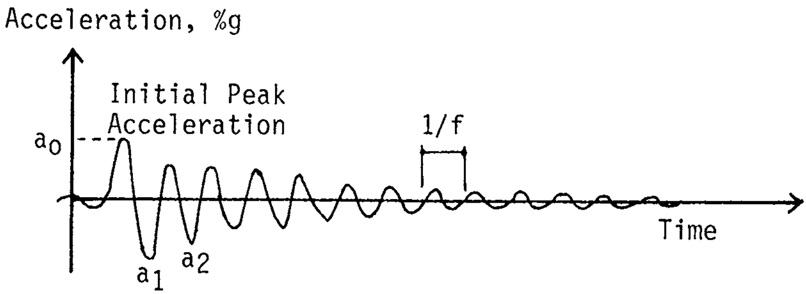

Figure 1 Typical Transient Vibration from Heel Drop (High Frequencies Filtered out) (From Ref 12)

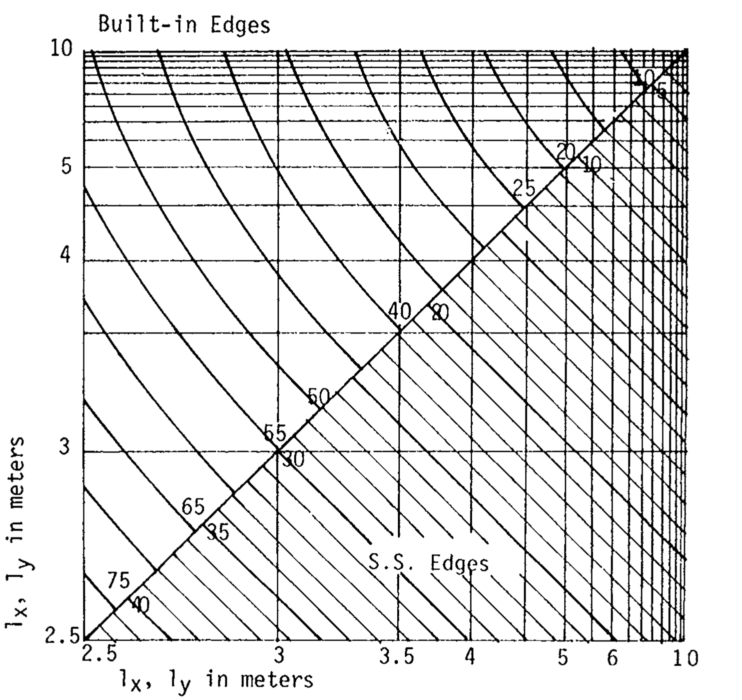

Figure 2 Relation between Natural Frequencies and Spans for Reinforced Concrete Slabs (From Ref. 10) (t= 10 cm)

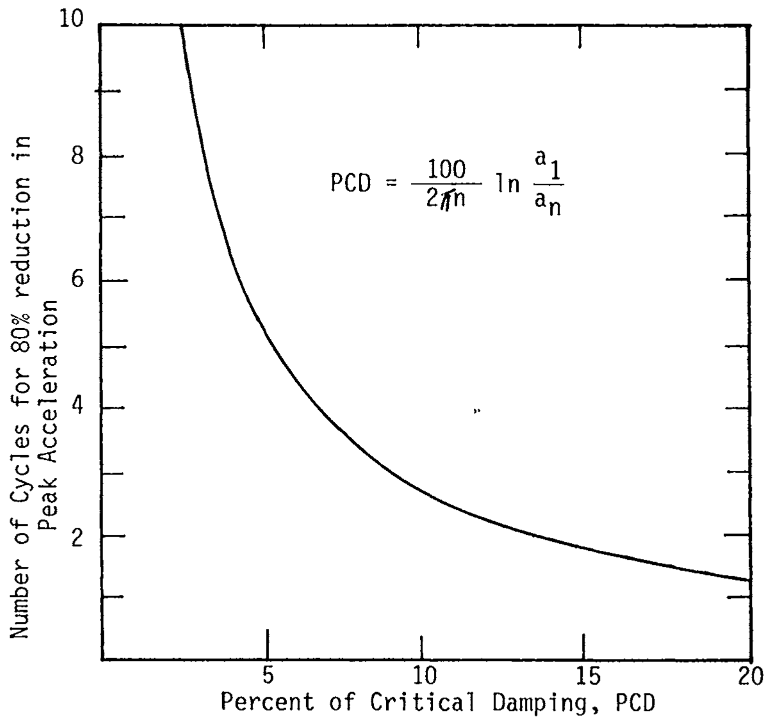

Figure 3 Relation between Damping and Decay (From Ref.12)