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FLOOR VIBRATION MEASUREMENTS IN A SHOPPING CENTRE

by G. Pernica and D.E. Allen

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Floor vibration measurements in a shopping centre

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Vibration measurements have been correlated on five long-span floors in a two-storey shopping centre. The floors are used primarily as walking areas and have been considered satisfactory with respect to floor vibrations. Three of the floors are steel beam composite concrete deck construction, and two are precast, prestressed, concrete beam construction.

Dynamic characteristics of the floors as determined by the heel impact test were compared with quiet occupancy criteria. Results suggest that quiet occupancy criteria can be increased by at least a factor of three for walking areas in shopping centres.

Calculations of fundamental frequency and initial peak acceleration from heel impact for the five floors are also presented and the results compared with measured values.

On a procédé à des mesures de vibrations sur cinq planchers de longue portée dans un centre d'achat de deux étages. Ces planchers, situés principalement dans des aires de circulation, étaient considérés comme satisfaisants à l'égard des vibrations. Trois des planchers sont du type mixte à dalle de béton sur poutrelles d'acier, et les deux autres sont composés de dalles préfabriquées en béton avec nervures précontraintes.

On a comparé les caractéristiques dynamiques des planchers déterminées par le test du coup de talon aux exigences anti-bruit relatives à ce genre de constructions. Ces résultats laissent voir que ces exigences pourraient être accrues par un facteur trois pour les aires de circulation des centres d'achat.

L'article présente, pour les cinq planchers, le calcul des fréquences fondamentales et des accélérations initiales de pointe créées par l'impact du talon, et en compare les résultats aux valeurs mesurées.

[Traduit par le revue]

Can. J. Civ. Eng., 9, 149-155 (1982)

Introduction

Annoyance criteria have been developed by Allen and Rainer (1976) for walking vibrations of long-span floors in residences, offices, and school rooms. Such occupancies are generally considered as quiet since noticeable floor vibrations are not anticipated under normal conditions. Occupancies such as arenas, stadiums, shopping centres, and dance floors in which there tends to be a great deal of activity can be classified as active occupancies (Allen *et al.* 1979). For these there are no annoyance criteria that can be used to check the suitability of the design. Those developed for quiet occupancies are probably too stringent; people in active occupancies, as the name suggests, are more involved with some physical activity and thus less likely to react to comparable levels of floor vibration. The need for annoyance criteria does exist, however, since unsatisfactory performance of floors in active occupancies has been encountered (J. H. Rainer, private communications, 1973, 1981).

Unfortunately, there are not at the present time sufficient data available for the development of active criteria. This paper is intended to provide more data by presenting the results of measurements made to ascertain the dynamic characteristics of five long-span floor systems used as public walking areas in a two-storey shopping centre. The study was undertaken when the authors' attention was drawn by several shoppers to

FIG. 1. Location of floor areas on second storey of shopping centre.

noticeable vibrations in a balcony area on the second floor of the centre. Although the vibrations were perceptible if one was standing on the balcony or seated along its edge, their amplitude was not sufficiently large to disturb these customers seriously. Measurements were taken on the balcony area and on four other floor areas that had not been mentioned. Two were indoors on the centre's second floor and two were outdoors on the upper level of a two-storey parking garage (Fig. 1). As for the reactions of other shoppers, it can only be said that none had complained to the management about vibrations of the balcony or any other area.

FIG. 2. Area A (balcony) structural layout and location of transducers and heel impacts.

FIG. 3. Area B structural layout and location of transducers and heel impacts.

Part I of this paper describes the five floor areas, discusses the method used to obtain their dynamic properties (namely, fundamental frequency, fundamental

damping ratio, and initial peak acceleration for the fundamental frequency from heel impact), and compares the results with quiet occupancy criteria. Part II presents in some detail the method used to calculate the fundamental frequency and initial peak acceleration due to heel impact for the five floor areas.

Part I. Experimental results

Floor areas

The three indoor floor areas are of the same composite construction. Each is a two-way, steel-beam floor system consisting of girders simply supported on steel columns or girder cantilevers and floor beams simply supported on girders or beam cantilevers. The $3\frac{1}{2}$ – $4\frac{1}{2}$ -in. (89–114 mm) composite concrete deck is covered by 2-in. (51 mm) terrazzo tile. A stucco-finished gypsum board ceiling is attached below. Structural layouts are shown in Figs. 2–4. The two-way steel beam system has cantilevered sections in both directions in area C and in one direction, along the girders, in area A (balcony).

The upper level of the parking garage consists of simply supported, precast, prestressed, double-T beams 6 ft 9 in. (2060 mm) wide by 26 in. (660 mm) deep, supported on precast girders and columns. The double-Ts are shear connected at their flanges. Figure 5 shows the two parking areas where vibration measurements were conducted. The double Ts have clear spans of 38 ft (11.58 m) and 58 ft (17.68 m).

Test procedure and data analysis

Each floor area was excited by (a) several heel impacts (up on toes, down on heels) at each impact location (Figs. 2–5), and (b) footsteps of a man weigh-

FIG. 4. Area C structural layout and location of transducers and heel impacts.

ing approximately 210 lb (95 kg) walking at a normal pace across the floor. For the two parking areas a compact car containing only the driver was driven across the floor at approximately 10 mph (16 km/h). At the time of the measurements the shopping centre was closed to the public.

Vertical acceleration was measured by means of accelerometers at several locations on each floor (Figs. 2–5). The output from each was appropriately amplified, low-pass filtered at 50 Hz, and then recorded on a four-channel tape recorder.

Accelerometer records from heel impacts were analysed on a Fourier spectrum analyser to determine the natural frequencies of each floor area. Each heel impact, walking, and driving record was then low-pass filtered at the fundamental floor frequency and displayed on photosensitive paper using an oscillograph. Initial peak acceleration at each transducer location and the fundamental damping ratio of each floor area were determined from the visual heel impact records. In area C (Fig. 4) it was difficult to obtain a good estimate of the damping ratio for the fundamental mode with this procedure because of its small amplitude in the filtered signal. Table 1 shows the fundamental floor frequency,

FIG. 5. Parking garage areas, structural layout, and location of transducers and heel impacts.

damping ratio, and initial peak accelerations¹ determined from each set of heel impact tests.

For the walking and driving tests, maximum peak and average peak acceleration amplitudes at each accelerometer location were determined from the filtered records. Only maximum peak acceleration amplitudes¹ are given in Table 1.

Comparison of test results with quiet criteria

Test results from heel impact are compared in Fig. 6 with annoyance criteria for quiet occupancies, using a damping ratio of 3%. Amplitudes from walking and driving tests are compared with criteria for continuous vibrations in Fig. 7. Figure 6 indicates that only area A and the 38-ft (11.58 m) span parking area would not be acceptable for quiet occupancies. Similarly, Fig. 7 indicates that walking vibrations in area A and the 38-ft (11.58 m) span parking area and car vibrations in both parking areas would be unacceptable for quiet occupancies. Interestingly, decreasing the clear span of the double Ts in the parking garage from 58 ft (17.68 m) to 38 ft (11.58 m), thereby substantially stiffening the floor system, actually reverses its acceptability, using quiet occupancy criteria.

Discussion

Although area A and the 38-ft (11.58 m) span parking area would not be acceptable as floors for quiet

¹Peak acceleration amplitudes given in Table 1 have been increased by 3 dB to compensate for the effect of low-pass filtering at the fundamental frequency.

TABLE 1. Results of floor vibration measurements

Location	Transducer setup (Figs. 2-5)	Test No.	Type of test	Peak acceleration ($10^{-3}g$) at Transducer location			Fundamental floor frequency f (Hz)	Fundamental damping ratio (%)
				(1)	(2)	(3)		
Area A (Fig. 2)	A	1	Heel impact at (1)	53	4.8	4.3	5.6	2.5
		2	Walking past (1) (2) (3)	14	2.6	1.6		
	B	3	Heel impact at (1)	45	14	3.7	5.6	2.5
		4	Heel impact at (2)	20	7.0	1.9	5.6	1.7
Area B (Fig. 3)	A	5	Heel impact at (1)	7.0	8.7	9.2	4.0	3.3
		6	Walking past (1) (2) (3)	2.6	3.0	3.2		
	B	7	Heel impact at (1)	7.7	3.1	1.5	4.0	3.1
		8	Walking past (1) (2) (3)	2.8	2.0	1.4		
Area C (Fig. 4)		9	Heel impact at (1)	8.9	1.2	6.3	5.2	~5
		10	Heel impact at (2)	1.0	14	1.4	5.2	
		11	Walking past (1) (2) (3)	2.9	4.0	2.6		
		12	Walking between (1) and (3)	2.1	0.8	3.2		
Parking garage 58 ft (17.68 m) span (Fig. 5)	A	13	Heel impact at (1)	14	8.6	14	3.8	2.1
		14	Walking past (1) (2) (3)	3.6	4.0	3.6		
	B	15	Heel impact at (1)	14	7.2	11	3.8	2.1
		16	Driving past (1) (2) (3)	14	15	17		
Parking garage 38 ft (11.58 m) span (Fig. 5)	A	17	Heel impact at (1)	28	16	18	8.4	2.2
	B	18	Heel impact at (1)	26	13	13	8.4	2.4
		19	Walking past (1) (2) (3)	7.2	8.0	8.8		
		20	Driving past (1) (2) (3)	32	34	27

FIG. 6. Peak accelerations from heel impact compared with criteria for walking vibrations for quiet occupancies; 1—area A (balcony); 2—area B; 3—area C; 4—parking garage, 17.68 m span; 5—parking garage, 11.58 m span.

occupancies (office, residential, etc.), they were considered acceptable as walking areas in a shopping center. This supports the hypothesis that criteria for quiet occupancies are conservative when applied to floors in active occupancies. Although quite limited, the information now reported suggests that quiet occupancy criteria can be increased by at least a factor of three for walking areas in shopping centres.

Part II. Calculation of dynamic properties of floors

The assumptions and equations used to calculate the fundamental frequencies and initial peak accelerations due to heel impact of the five floor areas are discussed in the following sections to illustrate the fact that the dynamic properties of complicated one and two-way cantilever systems (areas A and C) can be determined as easily and reasonably as can those of simple beam construction (area B and parking areas).

Fundamental frequency

The fundamental frequencies of area B, the two parking areas, and the beam portion of area A were calculated from [1] and are given in Table 2. These areas were assumed to behave essentially as one-way, simply-supported floor systems.

FIG. 7. Average peak accelerations from walking or driving compared with criteria for continuous vibrations for quiet occupancies. Walking: 1—area A (balcony); 2—area B; 3—area C; 4—parking garage 17.68 m span; 5—parking garage 11.58 m span. Driving: 6—parking garage, 17.68 m span; 7—parking garage, 11.58 m span.

$$\begin{aligned}
 [1] \quad f(\text{Hz}) &= 31 \sqrt{\frac{EI}{wL^4}} \\
 &= 156 \sqrt{\frac{EI}{wL^4}} \quad (\text{SI units})
 \end{aligned}$$

where E = modulus of elasticity in psi (MPa); I = moment of inertia in in.⁴ (mm⁴); L = span in in. (mm); and w = dead load in lb/in. (N/mm).

The frequencies of the cantilevered systems of areas A and C were also calculated using [1], as well as the properties of the suspended girders or floor beams. For area C the span L of the suspended members was taken as the full-span length. For area A the span L of the girder was taken as the average of the suspended span length and the full-span length. The reason for the difference in the span L of areas A and C is as follows. For continuous or cantilever construction, adjacent spans vibrate in opposite directions at the fundamental frequency. The full span was used to calculate the fundamental frequency for both the suspended beams and the girder in area C since, for either, the adjacent spans and the cantilevered and suspended member stiffnesses were approximately equal. For area A the spans were

TABLE 2. Dynamic properties of floor areas

Location	Fundamental floor frequency (Hz)		Initial peak acceleration from heel impact (%g)				Measured fundamental damping ratio (%)
			Calculated				
	Calculated	Measured	Panel width	f_{calc}	f_{meas}	Measured	
Area A							
Girder (18WF40)	5.3	5.6	w_t	3.2	3.4	4.9	2.5
Beam (10B11.5)	8.9		$60t_c$	4.6			
Area B							
Beam (24WF84)	3.8	4.0	$60t_c$	0.49	0.52	0.73	3.2
Area C							
Girder (24WF110)	4.7	5.2	w_t	1.0	1.1	0.89	~5
Beam (12B16.5)	6.3		$60t_c$	2.0			
Parking Garage							
58 ft (17.68 m) span	3.8	3.8	$60t_c$	0.77	0.77	1.4	2.1
38 ft (11.58 m) span	8.8	8.4	$60t_c$	2.7	2.6	2.7	2.3

not equal, and the stiffnesses of the cantilevered members were greater than that of the suspended member; a reduced span for the suspended member was therefore more appropriate.

The moments of inertia for the three indoor floor areas were calculated assuming full composite action. The thickness of the concrete slab (terrazzo tile included) and its strength were assumed to be $5\frac{1}{2}$ in. (140 mm) and 4 ksi (28 MPa), respectively. For the two parking areas the moments of inertia of the precast, prestressed double Ts were calculated using the beam's full cross-sectional area. The concrete strength of the double Ts was assumed to be 7 ksi (48 MPa).

The modulus of elasticity for concrete was determined from the following formula (Canadian Standards Association 1977):

$$[2] \quad E = 57\,000 \sqrt{\text{concrete strength in psi}} \quad (\text{psi})$$

$$= 5000 \sqrt{\text{concrete strength in MPa}} \quad (\text{MPa})$$

Calculated frequencies for the five floor areas are given in Table 2. Two frequencies were calculated for areas A and C, one considering only the girder as the stiffness element, the other only the floor beams. The calculated fundamental frequency of either floor area was assumed to be the smaller of the two values. Applying Dunkerley's formula² to obtain the fundamental frequency of either floor area from the girder and beam frequencies was considered to be an unnecessary refinement of this simple approach.

$$^2 \quad \frac{1}{f_A^2} = \frac{1}{f_G^2} + \frac{1}{f_B^2}$$

Initial peak acceleration

The initial peak acceleration, a_0 (in units of g), from heel impact for the fundamental mode was calculated for the five floor areas (Allen and Rainer 1976):

$$[3] \quad a_0 = \frac{2\pi f I(0.9)}{M}$$

$$= \frac{2\pi f I(0.9)}{9.81M} \quad (\text{SI units})$$

where f is the fundamental frequency (Hz), I is an impulse of 15 lb-s, (67 N·s) (Lenzen and Murray 1969), and M is an equivalent single-degree-of-freedom mass of the vibrating system. The mass M was calculated for the girder portions of areas A and C, using

$$[4a] \quad M = 0.405W$$

where W is the tributary load supported by the member (lb, kg). For the two parking areas, area B, and the beam portions of areas A and C, M was calculated using

$$[4b] \quad M = 0.405 \frac{60t_c}{w_t} W$$

where t_c is the effective thickness of the concrete slab (in., mm), and w_t is the tributary width of floor supported by the member (in., mm). For suspended members, W was determined using the span L employed in the calculation of fundamental frequency.

Equation [4a,b] assumes that for the calculation of mass the impacted floor member and neighbouring floor area form a vibrating two-way panel, with length L and width equal to the tributary width w_t for girders and $60t_c$ for joists or beams resting on girders (Galambos 1973). The factor 0.405 converts the mass

of this vibrating floor panel into the equivalent mass of a simple oscillator.

Calculated and measured fundamental frequencies of each floor area were used in [3] to calculate the initial peak accelerations given in Table 2.

Comparison of calculated and measured floor properties

Calculated values of fundamental frequency differed by less than 10% from measured values for the five floor areas, indicating that the method used to calculate the fundamental frequencies of the girder-beam cantilever systems in areas A and C was reasonable.

Calculated and measured values of a_0 did not agree as well as those of fundamental frequency. Measured values of a_0 ranged from 0.9 to 1.8 times calculated values. Possible reasons for this sizeable variation include: a varying heel impact, although performed by the same person; the use of an average impulse of 15 lb-s (67 N·s) for the 210-lb (95 kg) heel impactor; the location of the transducers with respect to the fundamental mode shape of the floor area; the effects of continuity produced by adjoining panels on the equivalent mass M ; and the contribution to the measured value of a_0 of other natural frequencies close to the fundamental.

For the 58-ft (17.68 m) span parking area and area B calculated values of a_0 were substantially smaller than those measured. This large discrepancy was caused mainly by the presence in the filtered accelerometer

records of other natural frequencies whose contributions to a_0 were significant even after filtering.

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- ALLEN, D. E., and RAINER, J. H. 1976. Vibration criteria for long-span floors. *Canadian Journal of Civil Engineering*, **3**, pp. 165–173.
- ALLEN, D. E., RAINER, J. H., and PERNICA, G. 1979. Vibration criteria for long-span concrete floors. *Proceedings, American Concrete Institute Symposium on Vibrations of Concrete Structures*, New Orleans, pp. 67–78.
- CANADIAN STANDARDS ASSOCIATION. 1977. Code for the design of concrete structures for buildings. National Standard of Canada CAN3-A23.3-M77, Rexdale, Ont.
- GALAMBOS, T. V. 1973. Vibration of steel joist-concrete slab floors. Technical Digest No. 5, Steel Joist Institute, Arlington, VA.
- LENZEN, K. H., and MURRAY, T. M. 1969. Vibration of steel beam concrete slab floor systems. Report No. 29, University of Kansas, Lawrence, KS.