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Effect of Architectural Components on the Dynamic Properties of a Long-Span Floor System

by G. Pernica

Reprinted from
Canadian Journal of Civil Engineering
Vol. 14, No. 4, Aug. 1987
p. 461-467
(IRC Paper No. 1518)

Price $3.00

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Effect of architectural components on the dynamic properties of a long-span floor system

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Received July 30, 1986
Revised manuscript accepted February 20, 1987

Vibration measurements were taken to determine the effects of architectural components on the dynamic properties (modal frequency, modal damping ratio, and mode shape) of a long-span floor system. The floor was located above a two-storey gymnasium in a recently constructed three-storey elementary school. The dynamic properties of the bare floor system were measured during the construction phase, immediately after the main structural components and the exterior masonry walls were in place. Six months later, with construction completed and the school ready for occupancy, the properties of the finished floor system, complete with internal partitions, mechanical ducts, furnishings, and carpeting, were again obtained.

A comparison of the results of the two test series indicated that the dynamic properties of the floor system were altered by the addition of the architectural components. The fundamental frequency rose by 3% and the frequencies of the higher modes by 23%, even though the static load on the floor increased by about 26%. The substantial stiffening of the floor system necessary to precipitate these increases in frequency was linked to the presence of the internal partitions. A full-span partition was also found to behave as a floor support, creating an additional set of modes which were not previously present. Except for the fundamental mode, damping ratios increased by about 2% of critical, from 1.5% to 3.5% of critical. For the fundamental mode, the negligible increase in damping from 4.1 to 4.2% of critical could not be explained.

Key words: floors, composite structures, vibration tests, spectrum analysis, resonant frequency, vibration damping.

Des mesures de vibration ont été prises afin de déterminer les effets des éléments architecturaux sur les propriétés dynamiques (fréquence modale, rapport modal d'amortissement et forme de mode) d'un plancher à grande portée situé au-dessus du gymnase d'une école élémentaire de trois étages construite récemment. Les propriétés dynamiques du plancher nu ont été mesurées durant la phase de construction, tout de suite après la mise en place des principaux éléments de construction et des murs de maçonnerie extérieurs. Six mois plus tard, lorsque la construction fut complétée et que l'école fut prête à être occupée, de nouvelles mesures des propriétés du plancher fini ont été prises, en tenant compte des cloisons intérieures, des conduits d'air, du mobilier et des moquettes.

Une comparaison des résultats des deux séries d'essais a indiqué que les propriétés dynamiques du plancher avaient été modifiées par l'addition des éléments architecturaux. La fréquence fondamentale s'est accrue de 3% et les fréquences des modes vibratoires supérieurs se sont accrues de 23%, même si la charge statique du plancher a augmenté d'environ 26%. Le raidissement substantiel du plancher responsable de ces augmentations de fréquence a été associé à la présence de cloisons intérieures. On a également constaté qu'une cloison pleine portée se comportait comme un appui de plancher, créant une série additionnelle de modes qui n'existait pas auparavant. Sauf pour le mode fondamental, les rapports d'amortissement ont augmenté d'environ 2% en fonction de l'amortissement critique, soit de 1,5% à 3,5%. Pour ce qui est du mode fondamental, l'accroissement négligeable de l'amortissement (4,1% à 4,2%) est demeuré inexpliqué.

Mots clés : planchers, structures composites, essais de vibration, analyse spectrale, fréquence de résonance, amortissement des vibrations.

[Traduit par la revue]

Can. J. Civ. Eng. **14**, 461–467 (1987)

Introduction

Over the past 15 years, a great deal of attention has been focused on the dynamic characteristics of long-span steel joist (beam), concrete-deck floor systems. These systems, generally lighter and more flexible than their predecessors, are also more susceptible to the dynamic forces produced by repetitive human activities such as walking, dancing, and exercising. To reduce the likelihood of annoying floor vibrations, design criteria for long-span floor systems have been developed for walking vibrations (Allen and Rainer 1976) and for vibrations produced by rhythmic activities (Allen *et al.* 1985). A requirement for using the criteria is the calculation of the fundamental frequency and estimation of the fundamental damping ratio of the floor system. For most long-span steel joist floor systems, there is little difficulty in estimating the two fundamental modal properties; the fundamental frequency is calculated from a beam formula for the appropriate set of end conditions (Timoshenko and Young 1955), and an estimate for the fundamental damping ratio is obtained from published results (Lenzen and Murray 1969). Although the effects of architectural components have been noted in the published estimates of fundamental modal damping (Canadian Standards Association 1984), only their mass is considered in the beam formula for the calculation of fundamental frequency. The effects of components such as movable partitions on the overall stiffness of the floor system are ignored simply because they are too difficult to consider.

This paper presents the measured effects of ductwork, furniture, and partitions on the modal frequencies, modal damping ratios, and mode shapes of a long-span open-web steel joist floor system. The floor is located above a two-storey gymnasium in a recently constructed three-storey elementary school. The three dynamic properties of the bare floor system were measured during the construction phase, immediately after the main structural components and exterior masonry walls of the building were in place. Six months later, with the building completed and ready for occupancy, the measure-

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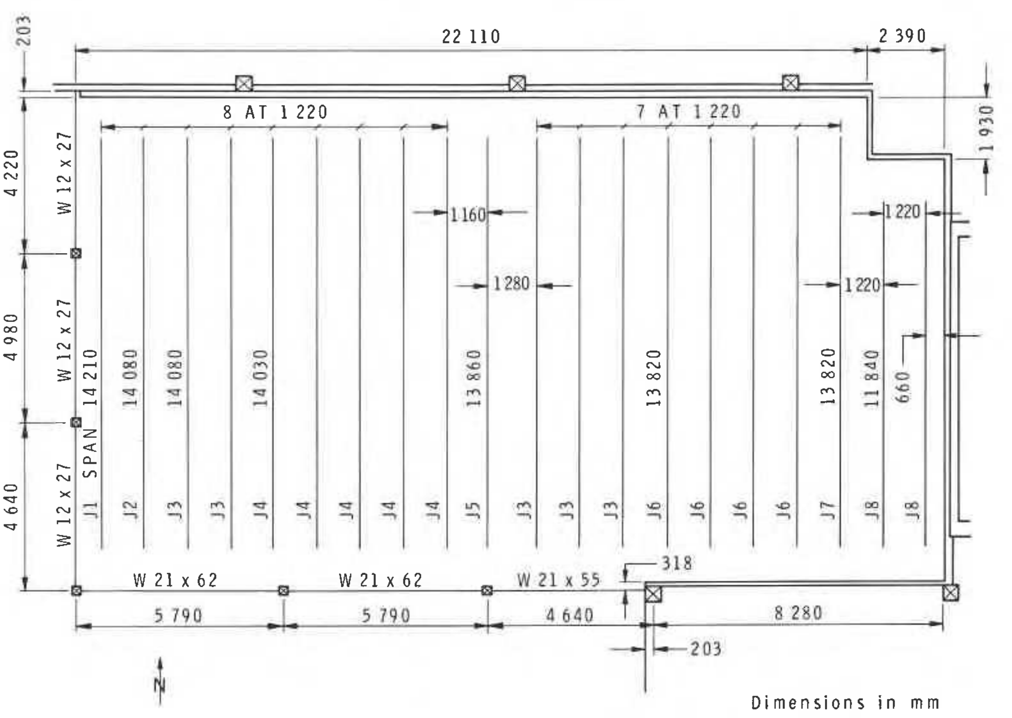

FIG. 1. Structural layout of floor.

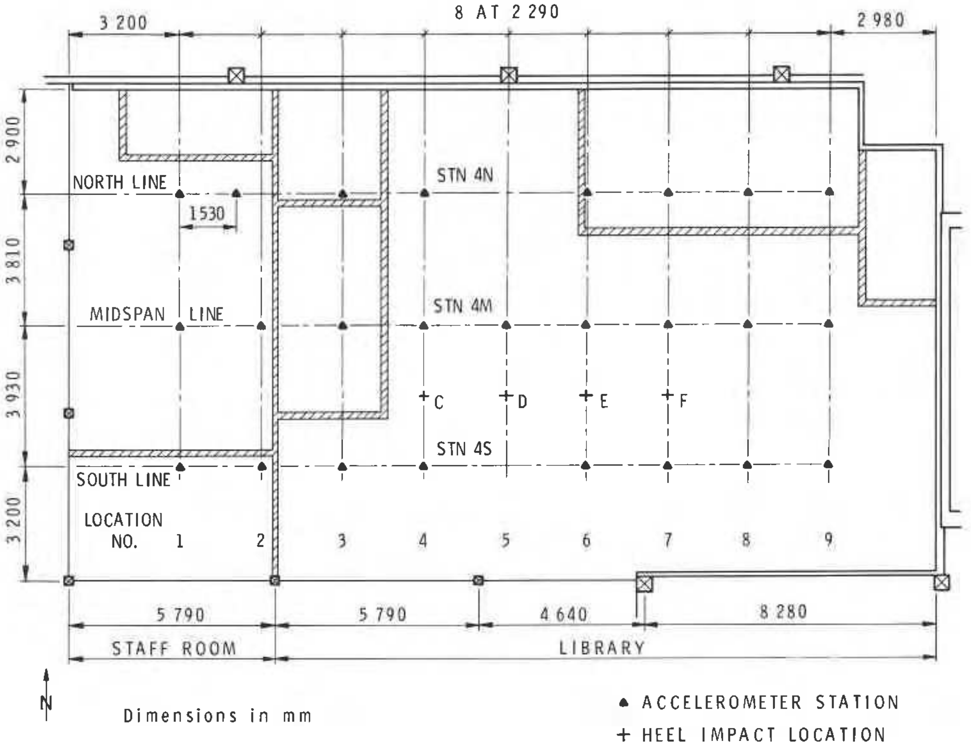

FIG. 2. Measurement locations and partition layout on finished floor.

ments were repeated on what was now the floor of the library and staff room.

Description of floor system

A plan view of the bare floor system is shown in Fig. 1. The floor consists of twenty 914-mm-deep open-web steel joists topped with a 127-mm-thick composite concrete deck. The joists are nominally at 1220 mm centres, have full spans ranging from 11.84 to 14.21 m, and have top and bottom chords constructed primarily from two 76 × 51 × 8 mm angles. The joists are simply supported at the ends and rest on either steel beams framing into steel columns, or concrete beams framing into either concrete columns or concrete shear walls.

An architectural plan view of the finished second-storey floor area is shown in Fig. 2. Internal partitions, comprising 90

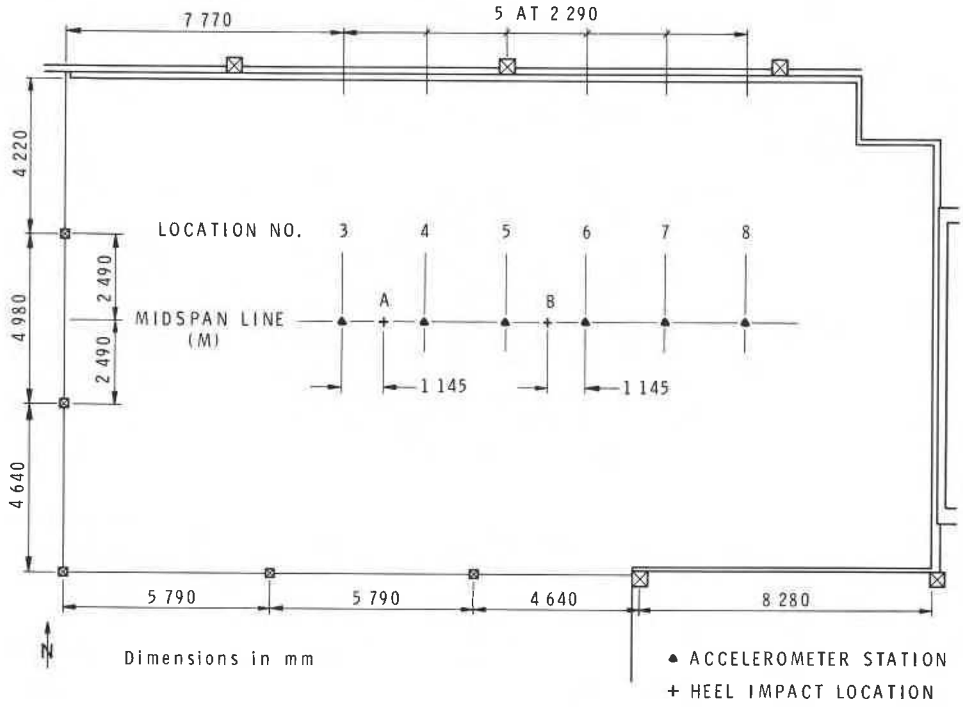

FIG. 3. Measurement locations on bare floor.

mm flexible steel channels and 12 mm drywall sheets screwed to both sides of the channels, divide the previously open floor area into two main rooms, a library and a teachers' staff room, and section off several smaller areas (offices, storage rooms, and closets) within each of the two rooms. The internal partitions reach from the floor level to the fire ceiling, a height of approximately 3050 mm. The fire ceiling is attached to the bottom chord of the roof joists and 150 mm below the fire ceiling is a standard suspended ceiling, consisting of metal tees and ceiling panels. The floor of the library is carpeted and that of the staff room tiled.

On the underside of the floor system is a two-storey gymnasium. The gymnasium is completely open, containing neither internal partitions nor an architectural ceiling.

Test procedure

The dynamic characteristics of the first six modes of the floor system, in its bare state and in its finished state, were investigated by measuring the vertical response of the floor to heel impacts. Six accelerometer stations (numbered 3 to 8 in Fig. 3) were chosen to monitor the dynamic response of the bare floor system. The stations were placed over the central portion of the floor area at 2290 mm intervals along a line at about the midspan of the floor joists. Additional stations at the east or west ends of the floor system or along the north or south sides were impractical because of ongoing construction.

The number of accelerometer stations on the finished floor system was substantially increased in order to obtain well-defined mode shapes for the first six modes (Fig. 2). The original midspan line was lengthened to contain nine accelerometer stations at 2290 mm spacing. Two additional lines of accelerometers, parallel to the midspan line on either side, replicated the number and spacing of stations on the midspan line. There was no difficulty in expanding the measuring system to 25 accelerometer stations, except at location line 5, where there is only a midspan accelerometer station (5M), since most of the central floor area of the library contained movable furnishings. Station 2N (north accelerometer line, location line 2) was placed about 760 mm west of its grid position because of a built-in wall cabinet.

Heel impacts were performed on the bare floor at two midspan locations (A and B in Fig. 3) by a man weighing approximately 930 N. At each location, eight impacts separated by approximately 30 s were made to excite the floor system. For the finished floor, eight impacts were again performed by the same man at each impact location. However, both the number and the position of the points of heel impact were changed to ensure that all modes were excited and to decrease the interference between closely spaced modes that was evident in the spectral results from the bare floor system. Consequently, four impact locations (C, D, E, and F in Fig. 2) were selected midway between the southern and midspan accelerometer lines at location lines 4, 5, 6, and 7.

Vibration measurements on the bare and the finished floor system were made at each station using servo-accelerometers with a sensitivity of $5V/g$ and a 0−500 Hz frequency range. The output from the accelerometers was appropriately amplified and low-pass filtered at 50 Hz before being recorded on a seven-channel FM tape recorder.

Measurements at the six accelerometer stations on the bare floor were recorded during two runs, one run for the set of floor impacts at each location. For the finished floor, 16 runs were necessary to record the vibrations at 25 accelerometer stations produced by heel impacts at four locations. For each of the 16 runs, the accelerometer at station 5M was paired with two location line sets of transducers symmetrically situated with respect to location line 5; e.g., signals from the three accelerometers at location line 4 (stations 4N, 4M, and 4S) were recorded simultaneously with those from the three accelerometers at location line 6 (stations 6N, 6M, and 6S).

TABLE 1. Dynamic properties of bare floor

Properties	Mode 1	2	3	4	5	6
Frequency (Hz)	6.6	7.0	8.0	9.2	11.2	13.6
Damping ratio (% Critical)	4.1	1.7	1.3	1.3	1.5	1.8
Mode shape at station						
3M	0.62	0.86	0.17	0.64	0.94	0.68
4M	0.78	0.42	−0.72	0.86	0.12	−0.88
5M	0.96	−0.47	−1.0	0.18	−0.90	−0.60
6M	1.0	−0.90	−0.61	−1.0	−0.30	0.84
7M	0.77	−1.0	0.39	−0.97	1.0	−0.14
8M	0.52	−0.84	0.93	0.30	0.45	−1.0

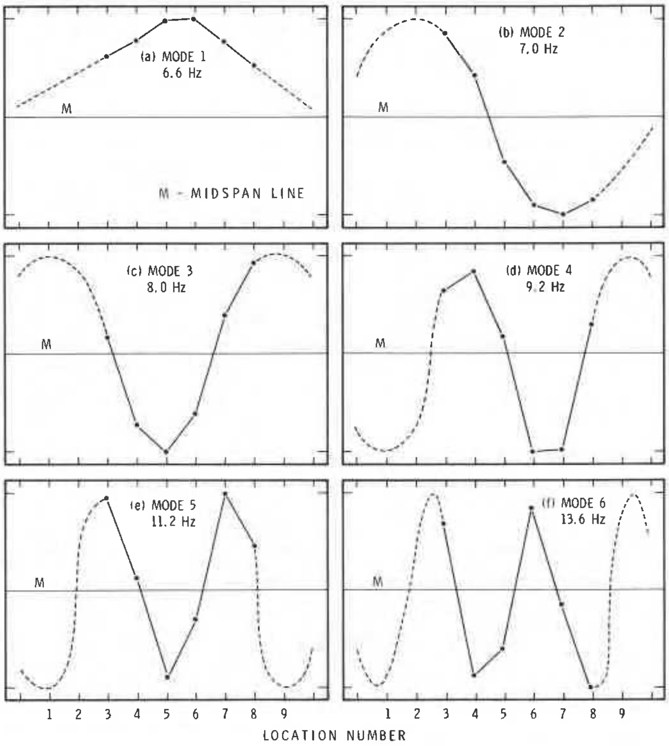

FIG. 4. Mode shapes of bare floor.

Signal analysis

The recorded accelerometer signals were analyzed on a two-channel, narrow-band spectrum analyser to obtain modal frequencies, modal damping ratios, and mode shapes of the two floor systems from the Fourier spectra of the induced free vibrations. The analysis was made using the 0–25 Hz frequency range and the uniform time window that has a frequency bandwidth of 0.2 Hz. Modal frequencies were identified from the location of the spectral peaks; modal damping ratios were calculated using the half-power point bandwidth method (assumes viscous damping); and mode shapes for each modal frequency were constructed from the spectral amplitudes at each accelerometer station and from the 0 or 180° phase relationship between accelerometer stations at each modal frequency. The phase between accelerometer stations was obtained directly from the analyser, which calculates transfer functions, or by comparing the spectral amplitudes of added and subtracted accelerometer signals.

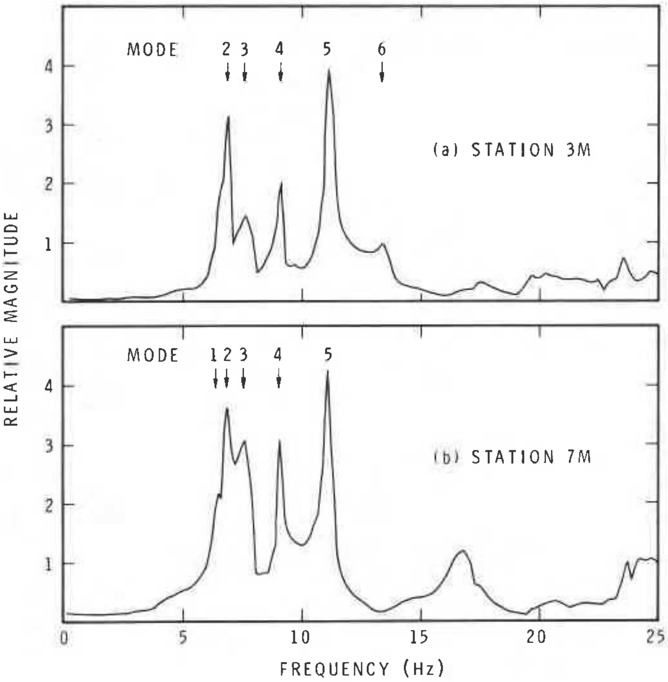

FIG. 5. Fourier spectra for heel impact on bare floor at location B.

Results

Bare floor

Modal frequencies, modal damping ratios, and mode shapes for the first six modes of the bare floor system are given in Table 1. Mode shapes are also plotted in Fig. 4 in ascending order of modal frequency. The dotted portions of the mode shapes are estimates for those sections of the floor system for which there is no measured data. They have been drawn so that both the nodal spacing and the modal amplitude of the lobes present in the measured portion of the mode shape are maintained along the midspan accelerometer line. As a result, the synthesized mode shapes follow the normal mode shape pattern for structural systems; that is, the number of nodal lines parallel to the joists increases by one with each increase in mode number. Nodal lines perpendicular to the span of the joists, i.e., points of inflection along the joists, do not appear to be present in the first six modes.

Mode shapes for the first three modes appear surprisingly well behaved, considering that their modal amplitudes were obtained from Fourier spectra in which modal interference between the three closely spaced modes was prevalent to varying degrees at all six accelerometer stations. This is illustrated in Fig. 5, which contains the Fourier spectra at stations 3M and 7M for heel impacts at location B. In Fig. 5*a* (Station 3M) the spectral peak at the fundmental frequency (6.6 Hz) is not noticeable because of the much larger floor response at the second natural frequency (7.0 Hz).

Modal damping ratios for modes 1–3, and in some instances modes 4–6, were calculated from the spectra of added or subtracted accelerometer signals, as this procedure enhanced the spectral peak of at least one of the first three modes by lessening the effects of the other closely spaced modes. Figure 6 contains the spectrum of the subtracted accel-

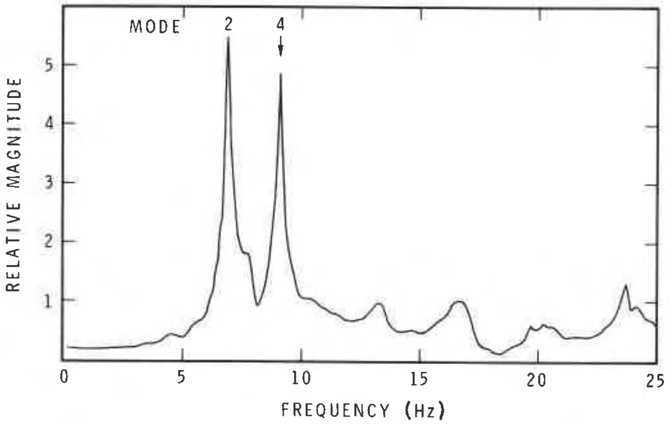

FIG. 6. Fourier spectrum, station 3M minus station 7M, for heel impact on bare floor at location B.

TABLE 2. Dynamic properties of finished floor

Properties	Mode 1	2	3	4	5	6
Frequency (Hz)	6.8	7.7	8.5	9.9	11.3	12.4
Damping ratio (% Critical)	4.2	3.9	3.6	2.7	3.4	
Mode shape at station						
1N	0.17	−0.04	−0.17	0.42	−0.48	
M	0.31	−0.08	−0.33	0.84	−1.0	
S	0.20	−0.06	−0.16	0.34	−0.32	
2N	0.21	0.08	−0.26	0.32	−0.19	
M	0.41	0.16	−0.50	0.63	−0.22	
S	0.24	0.08	−0.25	0.36	−0.10	
3N	0.30	0.20	−0.38	0.19	0.30	
M	0.53	0.37	−0.70	0.35	0.63	
S	0.40	0.26	−0.44	0.23	0.36	
4N	0.48	0.40	−0.37	−0.29	0.28	
M	0.86	0.79	−0.73	−0.58	0.54	
S	0.49	0.46	−0.47	−0.30	0.32	
5M	1.0	1.0	0.83	−0.65	−0.54	
6N	0.34	0.37	0.47	0.38	−0.20	
M	0.84	0.88	1.0	0.59	−0.50	
S	0.54	0.55	0.57	0.34	−0.27	
7N	0.23	0.26	0.43	0.51	0.31	
M	0.44	0.54	0.87	1.0	0.57	
S	0.29	0.33	0.50	0.53	0.28	
8N	0.12	0.09	0.21	0.30	0.26	
M	0.24	0.22	0.55	0.85	0.78	
S	0.12	0.09	0.23	0.32	0.28	
9N	0.05	0.02	0.05	0.09	0.11	
M	0.11	0.04	0.13	0.29	0.45	
S	0.05	0.02	0.04	0.13	0.27	

erometer signals from stations 3M and 7M; the individual spectra of these signals are those given in Fig. 5. The half-power bandwidth method was applied to this spectrum to obtain estimates of modal damping for modes 2 and 4.

Modal damping ratios for modes 2–6 are reasonable for a bare open-web, steel joist floor system, ranging from 1.3 to 1.8% of critical (Rainer and Pernica 1985). On the other hand, the damping ratio of 4.1% of critical for mode 1 seems high in comparison with the fundamental damping ratios measured on floors without partitions (Rainer and Allen 1973; Rainer 1984), and with the 3% suggested for design calculations in Appendix G of CAN3-S16.1-M84 (Canadian Standards Association 1984). There is apparently a major source of damping present in the bare floor system which is only effective for the fundamental mode. Unfortunately, the source of this damping is presently unknown.

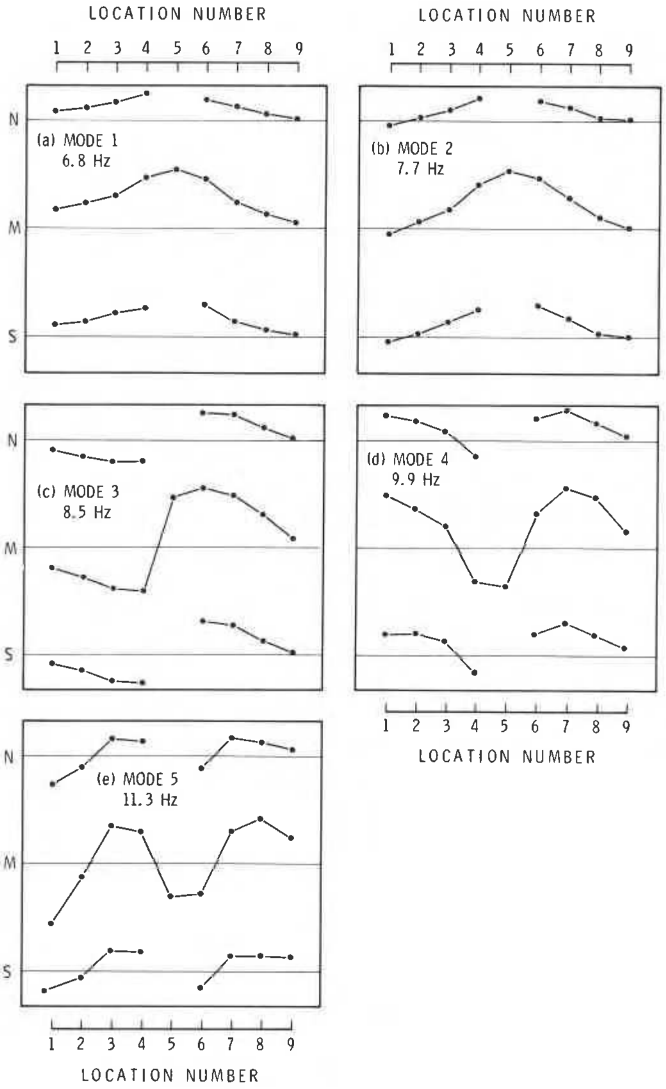

FIG. 7. Mode shapes of finished floor.

Finished floor

Modal frequencies, modal damping ratios, and mode shapes for the lowest five modes of the architecturally finished floor system are given in Table 2. Mode shapes for each of these modes are plotted in Fig. 7. The unmeasured east and west end portions of the mode shapes are not drawn as they were in Fig. 5 for the bare floor, since they could not be reasonably estimated from the measured central portions of the curves. There is no modal damping ratio or mode shape given for mode 6 (modal frequency 12.4 Hz), since these modal properties could not be accurately determined from the Fourier spectra.

Modal amplitudes for the first five modes were affected by the close spacing of their modal frequencies. This is illustrated in Fig. 8, which contains the Fourier spectra at station 7M (location line 7, midspan line) for the sets of heel impacts at

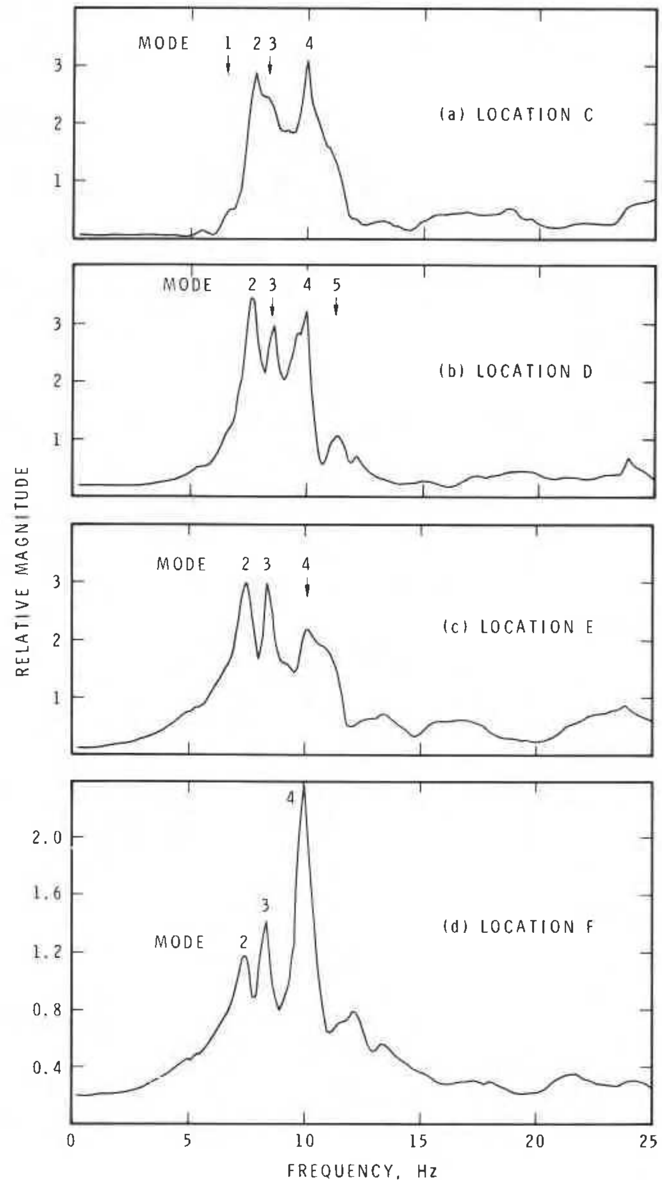

FIG. 8. Fourier spectra, station 7M, for heel impacts at locations C, D, E, and F on finished floor.

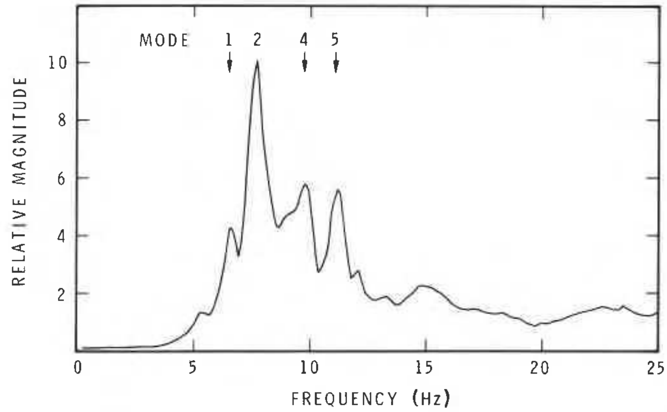

FIG. 9. Fourier spectrum, station 3M minus station 7M, for heel impact on finished floor at location D.

locations C, D, E, and F. Since none of the impact locations coincided with any of the modal nodes, spectral amplitudes of all modal frequencies in Fig. 8 were affected by one or more of their closely spaced modal neighbours. For mode 1, the interference from neighbouring modes was so great that its spectral peak is only just perceptible in Fig. 8*a*. For the other four modes, the amount of modal interference sustained by each varied widely with impact location. For mode 4 (9.9 Hz), the interference ranged from considerable for impacts at location E to negligible for impacts at location F (Fig. 8). Estimates of modal amplitudes for each of the modes were consequently obtained from those spectra in which modal interference from neighbouring modes was small.

Mode shapes for the first five modes contain no points of inflection in the direction of the joists. The modes in this direction are dish-shaped and for the most part symmetrical about the midspan line even though noticeable differences in the modal amplitudes on either side of the midspan line are present at one or two location lines (e.g., mode 1, location line 6). Perpendicular to the span of the joists, the five modes display shapes in which the regular pattern of increasing modal nodes with increasing mode number appears to be violated. However, if mode 2 is removed, the remaining four modes not only follow a normal nodal pattern, they also strongly resemble the first four modes of the bare floor. The major difference between the two sets of mode shapes is that those for the finished floor appear distorted, by comparison, as both the amplitudes of the lobes and the spacing of the nodes of this set vary across the width (direction perpendicular to the span of the joists) of the floor.

Mode 2, on the other hand, does not have the shape of a conventional second mode of a long-span floor system. Although it contains the same number of nodes as mode 3, it has a shape quite similar to mode 1. Because of this similarity and the noncentral position of the single nodal line, it has the appearance of a first mode of a floor system with an additional line support in the vicinity of location line 2. Since the full-span partition separating the library from the staff room is situated between location lines 2 and 3, the partition appears to be the structural support and mode 2 to be in fact mode 1 of a modified floor system.

Modal damping ratios were obtained in some cases from spectra of single accelerometer signals (as in Fig. 8*d*, mode 4) and in others from spectra of added or subtracted accelerometer signals (as in Fig. 9, mode 2). Modal damping ratios for the five modes ranged from 2.7% of critical for mode 4 to 4.2% of critical for mode 1. Suggested fundamental damping ratios for floors of composite construction are given in Appendix G of CAN3-S16.1-M84 (Canadian Standards Association 1984). The fundamental modal damping ratio of 4.2% is within the range stated for a finished floor (rugs, furnishings, fireproofing, and ducts) but well below the 12% suggested for a finished floor with partitions. As modal interference tends to exaggerate modal damping ratios that are calculated using the half-power band method, the damping present in this long-span floor system is significantly overestimated by the guide.

Discussion

The results obtained for the bare and the finished floor show that the dynamic properties of a long-span steel joist floor system can be altered by the presence of architectural components. Since measurements were not taken after the addition of each component, it is impossible to assess the contributions made by each to the three dynamic properties investigated.

However, it does appear that partitions had the most significant effect on modal frequencies and mode shapes. Modal frequencies of the finished floor were higher than those for the bare floor even though the total load (dead load plus live load) on the finished floor was approximately 960 N/m·m greater than that on the bare floor. The substantial increase in floor stiffness required to offset the large increase in floor load and raise modal frequencies has been primarily associated with the full-span partition separating the library from the staff room. In mode 2 of the finished floor, the partition was found to be a full-span line support for the floor system. This mode was considered to be the fundamental mode of a set of added or inserted modes associated with the structural support provided by this partition. The contributions of the office and closet partitions in the library and staff room to the stiffness of the floor system are reflected in the modifications to the mode shapes of the first four modes of the bare floor.

The smallest increase in modal frequency, although not necessarily the smallest in modal stiffness (changes in modal mass must also be considered), occurred in the fundamental mode (from 6.6 to 6.8 Hz). Theoretical calculations of the fundamental frequencies of the simply supported floor system (Canadian Standards Association 1984) yield the opposite result; 6.9 Hz for the bare floor with a joist load of 4.4 kN/m and 6.1 Hz for the finished floor with a joist load of 5.6kN/m. The effect of the partitions on floor stiffness is ignored in these calculations because it is extremely difficult to estimate.

The contributions of each architectural component (carpeting, furnishings, fireproofing, mechanical ducts, and partitions) to the increase in modal damping ratios of the floor system are, unfortunately, not known. For all but the fundamental mode, the increase in modal damping ratio between corresponding higher modes of the bare (modes 2–4) and finished floor (modes 3–5) was approximately 2% of critical (from 1.5 to 3.5% of critical). This increase is comparable to that stated in CAN3-S16.1-M84 for the increase in the fundamental damping ratio for finished floors without partitions.

The marginal increase in modal damping ratio of the fundamental mode from 4.1 to 4.2% of critical is unexplained, although the reasons for this infinitesimal increase appear to be strongly linked to the behaviour of the unknown damping mechanisms that produced the large (4.1%) fundamental damping ratio for the bare floor in the first place.

Summary

A comparison of the dynamic properties (modal frequency, modal damping ratio, and mode shape) of the lowest five modes of a long-span steel joist floor before and after the addition of architectural components indicated the following:

(1) The dynamic properties of all modes were affected by the addition of the components. The contribution of individual architectural components to the changes in the dynamic properties of the floor system could not be determined, since measurements were not taken after each component was added to the floor.

(2) The fundamental frequency rose by 3%, and the higher modal frequencies by about 23% even though the static load on the floor increased by approximately 26%. The substantial increase in the stiffness of the floor system required for this to occur was linked to the presence of the partitions.

(3) The full-span partition separating the library from the staff room and running parallel to the joists behaved as a floor support for mode 2 of the finished floor. Mode 2 appeared to be the fundamental mode of a set of additional modes for a partition-supported floor system.

(4) Mode shapes for modes 1, 3, 4, and 5 of the finished floor system, although similar to the corresponding shapes of modes 1–4 of the bare floor, were, by comparison, distorted and skewed as both the spacing of the nodes and the amplitudes of the lobes varied across the width (perpendicular to the span of the joists) of the floor system.

(5) Modal damping ratios of the higher modes increased by about 2% of critical (from 1.5 to 3.5%). The negligible increase in the fundamental damping ratio from 4.1% of critical (unusually high for a bare floor) to 4.2% of critical (a low ratio for a finished floor with partitions) could not be explained.

Acknowledgement

This paper is a contribution of the Institute for Research in Construction, National Research Council of Canada.

ALLEN, D. E., and RAINER, J. H. 1976. Vibration criteria for long-span floors. Canadian Journal of Civil Engineering, **3**: 165–173.

ALLEN, D. E., RAINER, J. H., and PERNICA, G. 1985. Vibration criteria for assembly occupancies. Canadian Journal of Civil Engineering, **12**: 617–623.

CANADIAN STANDARDS ASSOCIATION. 1984. Steel structures for buildings — limit states design, Appendix G (Guide for floor vibrations). CAN3-S16.1-M84, Rexdale, Ont., pp. 161–171.

LENZEN, K. H., and MURRAY, T. M. 1969. Vibrations of steel beam concrete slab floor systems. Report No. 29, University of Kansas, Lawrence, KS.

RAINER, J. H. 1984. Dynamic response of a gymnasium floor. Building Research Note 213, Division of Building Research, National Research Council of Canada, Ottawa, Ont.

RAINER, J. H., and ALLEN, D. E. 1973. Vibration characteristics of a dance floor. Technical Note 576, Division of Building Research, National Research Council of Canada, Ottawa, Ont.

RAINER, J. H., and PERNICA, G. 1985. Vibration characteristics of a floor sample. Division of Building Research Paper 1271, Division of Building Research, National Research Council of Canada, Ottawa, Ont.

TIMOSHENKO, S., and YOUNG, D. H. 1955. Vibration problems in engineering, 3rd ed. D. Van Nostrand Company, Toronto, Ont.