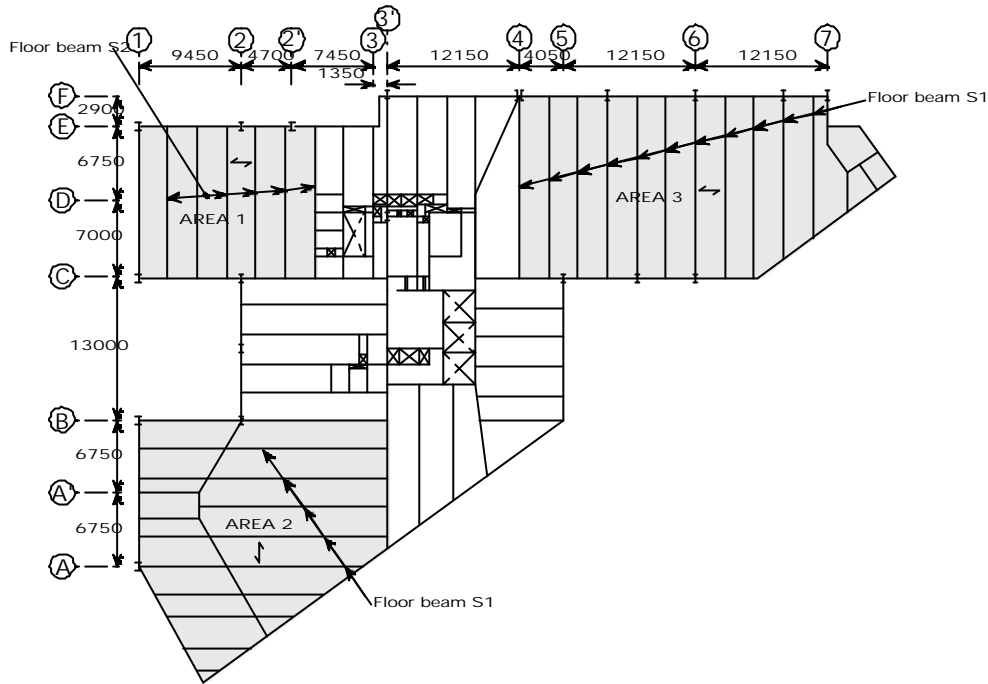


Paris Office

The floor arrangement at the Paris Office project is an excellent example of a steel framed building using modern long-span construction techniques. In order to minimise the floor zone, as well as providing long uninterrupted areas of office space, the structural solution adopted shallow cellular beams acting compositely through Hilti HVB shear connectors.

On plan, the building is triangular in shape, with primary beams typically comprising of HEA 450 sections. These beams have the dual purpose of supporting the long-span secondary beams, as well as the external cladding loads. The secondary beams, comprising of asymmetric cellular sections (which were propped during construction), span from front-to-back of the building, with their spacing dictated by the spanning capabilities of the composite slab. The composite floor slab consists of 120 mm deep normal weight concrete on 0.88 mm gauge Haircol 59S trapezoidal decking. A general plan arrangement of the building is shown in Figure 1 below.

In attempting to identify a critical area on the floor plan, through impact tests using instrumented hammer excitation, it was found that the 'noisy' atmosphere occasioned from site processes, caused inaccuracy within the measured results. Therefore, it was decided to divide the building plan into three areas for forced vibration tests, where the loading was amplified to counteract any disruption due to site activities. Also, the coherence of the results was constantly monitored throughout the testing, in order to investigate for the effects of external excitations. Although this caused the experimental work to take considerably longer to complete, it was thought that the quality, and the amount of experimental information gained from this investigation warranted the extra effort.



Floor beam S1 459 mm deep cellular beam 356 × 171UB67 top/HEB 340 bottom with 269 mm diameter cells at 431 mm centres.

Floor beam S2 459 mm deep cellular beam 406 × 140UB46 top/HEA 280 bottom with 278 mm diameter cells at 408 mm centres.

Figure 1 General arrangement of the Paris Office

As expected, from an analysis of the floor areas using the principles given within the SCI design guide (see report of Design for Vibrations of Long Span Composite Floors), it was predicted that the vibration mode, which gave the lowest natural frequency, arose from the motion of the secondary beams. The main reason for this was that the primary beams were located around the periphery of the building, which meant that the full height external cladding provided a stiffening effect to these members: thereby causing them to behave as nodal lines. The vibration performance of each of these three areas is considered on an individual basis, in each of the following sub-sections.

Area 1

At the time of testing, non-structural components were still being installed at the lower floor levels within the building. This meant that information on the dynamic characteristics could be obtained for the floor in both its bare, and finished state. For both cases, no partitions, furniture or personnel were present on the floor during the tests. Services had been installed at each level within the ceiling zone, but the loading from these components was not significant.

Fifth floor

At this level in the building, the floor was still in its bare state. From a hand analysis of this area, using the permanent loads that were present at the time of testing, a fundamental frequency of 5.31 Hz was estimated. In addition, by assuming a damping value of 1.5%, a response factor of 13.8 was calculated (equivalent to an $a_{\text{rms}} = 0.069 \text{ m/s}^2$). Thus, in its bare state, the floor would only just be unacceptable for a 'busy office' classification, in terms of table 2.3 of section 2.2.3 of report of Design for Vibrations of Long Span Composite Floors.

On subjecting the floor to sine-sweep loading, it was found from the transfer function that three closely spaced modes of vibration existed at 4.1, 4.3 and 4.6 Hz (see Appendix B of report of Design for Vibrations of Long Span Composite Floors). In addition, some higher modes were identified at 5.7, 6.2 and 8.1 Hz. By constructing a best-fit SDOF curve through the experimental data, the damping and stiffness for these six modes was found. These results are summarised in Table 1.

Table 1 Summary of forced vibration tests using sine-sweep loading on the bare floor within Area 1

Frequency (Hz)	Average Overall Damping %	Lowest Stiffness (N/m)
4.1	1.28	3.8×10^6
4.3	1.62	2.4×10^6
4.6	1.60	2.7×10^6
5.7	1.58	7.1×10^6
6.2	1.78	4.6×10^6
8.1	1.14	3.8×10^7

In order to give an independent estimate on the level of damping, the floor within Area 1 was also subjected to a continuous single sine-wave loading, at one of the frequencies identified by the earlier tests, prior to the generator being suddenly stopped to monitor the decay of oscillation. Although every attempt was made to excite the floor at the six frequencies identified by the transfer function, not all of the monitored results produced a smooth curve (particularly at the closely spaced modes). Nevertheless, when a smooth decay was recorded, the damping values compared fairly well with those derived from the transfer function (see Appendix B of report of Design for Vibrations of Long Span Composite Floors).

Due to the lower modes of vibration being closely spaced together, in addition to the fact that the second, third and fourth harmonic of a typical walking frequency might also excite three vibration modes (e.g. $2 \times 2.05 \text{ Hz} = 4.1 \text{ Hz}$, $3 \times 2.05 \text{ Hz} \approx 6.2 \text{ Hz}$ and $4 \times 2.05 \text{ Hz} \approx 8.1 \text{ Hz}$), it was expected that the lower effective mass arising from these effects would cause the floor to exhibit a high response when subjected to walking excitation. A total number of ten walking tests were undertaken over Area 1, but only three are of particular interest, see below.

Test 2

For walking test 2, an individual paced at a low frequency of 1.3 Hz along grid-line D (Figure 1). Thus, it was hoped that the third harmonic of the pace frequency would excite the first three closely spaced modes, and the fourth harmonic would excite the 5.7 Hz mode. This design scenario was achieved, which resulted in a peak acceleration of 0.039 m/s². In this project, the rms acceleration was derived directly from the raw electronic data, and had a value of 0.008 m/s², giving a response factor of only 1.6.

Test 3 & 4

For walking tests 3 and 4, the walking frequency was increased to 2.0 Hz. This meant that it would be expected that the second, third and fourth harmonic of the walking force would excite three modes of vibration (see above). Indeed, this situation was created and, for Test 3 (where the walking path was along grid-line 2), this resulted in the highest recorded response for the area, with a peak acceleration of 0.040 m/s². The rms acceleration was 0.009 m/s²; equivalent to a response factor of 1.8.

From the tests on this floor level, it can be concluded that the value of damping taken from the SCI guide was close to that established from the investigation. However, the measured floor response was quite different to that predicted using the same guide. Although it might be expected that the closely spaced modes would reduce the effective mass participating in the motion (and hence increase the acceleration), the measured response factor was approximately eight times less than that predicted by hand calculations. Therefore, this bare floor would be acceptable for all of the classifications, in terms of table 2.3 of section 2.2.3 of report of Design for Vibrations of Long Span Composite Floors, rather than the 'busy office' category.

Third floor

At this floor level, 20 mm thick timber raised flooring had been installed, providing a 200 mm void for electrical cables and other services. By repeating the hand analysis with the additional load applied to the floor, the fundamental frequency was reduced by 5% to a value of 5.05 Hz. In addition, by adopting a damping value of 3% (assuming that the presence of the false floor effectively increased the damping by a factor of 2), a response factor of 6.3 was calculated (equivalent to an $a_{\text{rms}} = 0.031 \text{ m/s}^2$). Thus, in its finished state, the floor would be acceptable for a 'general office' classification, in terms of table 2.3 of section 2.2.3 of report of Design for Vibrations of Long Span Composite Floors.

In a similar way as before, Area 1 at this floor level was subjected to sine-sweep loading. From the transfer function, it was apparent that the additional loading from the false flooring caused the closely spaced modes to disappear and resulted in four distinct vibration modes to be observed at 4.1, 4.8, 5.7 and 8.4 Hz. From a best-fit SDOF curve through this experimental data, the damping and stiffness for these four modes were found. These results are summarised in Table 2.

Table 2 Summary of forced vibration tests using sine-sweep loading on the finished floor within Area 1

Frequency (Hz)	Average Overall Damping %	Lowest Stiffness (N/m)
4.1	1.55	4.4×10^6
4.8	1.74	3.0×10^6
5.7	1.47	4.1×10^6
8.4	1.03	1.7×10^6

In a similar way to the investigation conducted on the bare floor, the damping derived from a decay of vibration, due to continuous single sine-wave loading, produced values which agreed fairly well with those calculated from the transfer function (see Appendix B of report of Design for Vibrations of Long Span Composite Floors). It is interesting to note that by comparing Table 1 with Table 2, the presence of the raised flooring did not increase the damping to any significant degree. This result broadly agrees with the observations made by Osborne and Ellis¹.

Three walking tests were carried out on the finished floor of Area 1. Although it was expected that the extra mass on this area would reduce the floor response, two of the walking tests provided the highest peak accelerations. Details of these two tests are discussed below.

Test 11

In this test, an individual walked quickly at a frequency of 2.0 Hz along grid-line D (see Figure 1). Although it was expected that this pacing rate would excite at least three of the floor frequencies identified by the forced vibration tests, for this case, only the highest mode of 8.4 Hz was the dominant response frequency. The peak acceleration measured was approximately double that measured on the bare fifth floor with a value of 0.076 m/s². However, the directly derived rms acceleration increased by only 20% to a value of 0.011 m/s²: equivalent to a response factor of 2.2.

Test 12

For this final test, a rapid walk was conducted at a frequency of 2.5 Hz along grid-line D (see Figure 1). This test was carried out in an attempt to excite some of the lower frequencies identified in the earlier forced vibration tests. This design situation was achieved, and resulted in a peak acceleration 25% greater than that measured in the companion test, with a value of 0.095 m/s². The rms acceleration showed a smaller increase, with a value of 0.013 m/s², resulting in a response factor of 2.5. As can be observed from Appendix B of report of Design for Vibrations of Long Span Composite Floors, one of the reasons for this higher acceleration was due to five frequency modes being excited by the walking force at 4.7, 5.1, 5.6, 7.7 and 8.4 Hz. Coupled with this, the heel strikes arising from an individual walking at the very rapid frequency of 2.5 Hz, may have caused quite high local accelerations.

From the investigation on Area 1, it is concluded that the presence of the raised flooring did not contribute significantly to the overall damping of the floor. Even though it would be thought that the extra mass from the raised flooring would reduce the floor response, the worst-case design scenario was created when the floor was in

this finished condition. A possible reason for this result was that the higher harmonics from the walking force excited five frequency modes (rather than the single, fundamental mode assumed in the SCI guidance), resulting in a lower effective mass participating in the motion.

From the measured floor behaviour, the response factor of 2.5 in Test 12, means that Area 1 was acceptable for all of the classifications, in terms of table 2.3 of section 2.2.3 of report of Design for Vibrations of Long Span Composite Floors. This value is about a third of that calculated using the SCI design guide. However, this estimation was based on a higher damping value than that actually measured ($\zeta = 3\%$). By recalculating the response factor with the level of damping consistent with a bare floor ($\zeta = 1.5\%$), a value of 12.5 is obtained. Thus, for this particular floor, it can be seen that a high degree of conservatism exists in the present SCI guidance.

It is interesting to note that qualitative measures of the floor response were also recorded whilst the walking tests were underway. In no case did these subjective ratings suggest that the floor vibrations were in any way annoying. The only exception to this rule was when the forcing function comprised of an individual jumping on the spot at 2.0 Hz (comparable to a loading which would be expected on an aerobics, or dance floor (see section 2.2 of report of Design for Vibrations of Long Span Composite Floors). For these cases, the most annoying response occurred when a single frequency mode was excited, which corresponded to a peak acceleration of 0.266 m/s^2 (the rms acceleration was 0.110 m/s^2 ; equivalent to a response factor of 22.0).

Area 2

In a similar way to Area 1, due to the sequence of installing the non-structural components to the building, the dynamic characteristics of this floor area, in both its bare and finished state, could be established.

Fifth floor

At this level in the building, the floor was still in its bare state. From a hand analysis of this area, and using the appropriate level of permanent loads that were present at the time of testing, a fundamental frequency of 5.69 Hz was estimated. In addition, by assuming a damping value of 1.5%, a response factor of 16.7 was calculated (equivalent to an $a_{\text{rms}} = 0.083 \text{ m/s}^2$). Thus, in its bare state, the floor would be unacceptable for all of the classifications, given within table 2.3 of section 2.2.3 of report of Design for Vibrations of Long Span Composite Floors.

After subjecting the floor to sine-sweep loading, the transfer function identified three distinct modes of vibration at 4.4, 7.6 and 8.8 Hz (see Appendix B report of Design for Vibrations of Long Span Composite Floors). By constructing a best-fit SDOF curve through this experimental data, the damping and stiffness for these three modes was found. These results are summarised in Table 3.

Table 3 Summary of forced vibration tests using sine-sweep loading on the bare floor within Area 2

Frequency (Hz)	Average Overall Damping %	Lowest Stiffness (N/m)
4.4	1.37	1.1×10^6
7.6	1.18	3.2×10^6
8.8	1.10	4.7×10^6

In order to give an independent estimate of the damping, the floor within Area 2 was also subjected to a continuous single sine-wave loading at the frequencies identified by the earlier tests, prior to the generator being suddenly stopped, to monitor the ensuing decay. Although every attempt was made to excite the floor at the three frequencies identified by the transfer function, only one of the monitored results produced a smooth decay. In a similar way to Area 1, this damping value compared fairly well with that derived from the transfer function (see Appendix B of report of Design for Vibrations of Long Span Composite Floors).

A total number of ten walking tests were undertaken over Area 2, but only four of them are of particular interest, see below.

Test 1 & 2

For walking test 2, an individual paced at a comfortable frequency of 1.5 Hz along grid-line A' (see Figure 1). It was therefore hoped that the third, fourth and fifth harmonic of the pace frequency would excite all three modes identified by the transfer function. The principal frequencies excited by this walking test were 4.4 and 5.1 Hz, which resulted in a peak acceleration of 0.025 m/s^2 . In a similar way as Area 1, the rms acceleration was derived directly from the raw electronic data, and had a value of 0.008 m/s^2 ; equivalent to a response factor of only 1.6.

Test 3 & 4

For walking tests 3 and 4, the frequency of the walking pace was increased to 2.0 Hz. This meant that it would be expected that the second and fourth harmonic of the walking force would excite the first two modes of vibration (see above). Indeed, this situation was created and, for both walking tests, this resulted in the highest recorded response for the area, with a peak acceleration of 0.042 m/s^2 . The increase in rms acceleration was much less for these tests, with a value of 0.010 m/s^2 ; equivalent to a response factor of 2.

From the tests on this floor level, it can be seen that the measured damping was only slightly less than the value given within the SCI guide for a bare floor. However, the calculated response factor of 16.7 overestimated the actual measured response by, approximately, a factor of eight.

Fourth floor

In a similar way to Area 1, 20 mm thick raised flooring had been installed at this floor level. By repeating the hand analysis with the additional load applied to the floor, the estimated fundamental frequency reduced by approximately 5% to a value of 5.43 Hz. In addition, by adopting a damping value of 3%, a response factor of 7.6 was calculated (equivalent to an $a_{\text{rms}} = 0.038 \text{ m/s}^2$). Therefore, with the increase of mass and damping due to the applied finishes, the floor would just be acceptable for the ‘general office’ classification, given within table 2.3 of section 2.2.3 of report of Design for Vibrations of Long Span Composite Floors.

At this floor level, Area 2 was subjected to sine-sweep loading. From the transfer function, it was apparent that the additional loading from the false flooring caused two additional modes to appear at 5.0 and 6.3 Hz (see Appendix B of report of Design for Vibrations of Long Span Composite Floors). From a best-fit SDOF curve through this experimental data, the damping and stiffness for all five modes was found. These results are summarised in Table 4.

Table 4 Summary of forced vibration tests using sine-sweep loading on the finished floor within Area 2

Frequency (Hz)	Average Overall Damping %	Lowest Stiffness (N/m)
4.1	1.60	1.7×10^6
5.0	1.31	8.0×10^6
6.3	1.77	1.9×10^7
7.4	1.20	2.9×10^7
8.0	1.33	4.8×10^7

In a similar way to the investigation conducted on the bare floor, the area was subjected to a continuous single sine-wave loading in order to give an independent assessment on the damping derived from the transfer function. These tests met with more success compared to those conducted on the bare floor, with a smooth decay of oscillation measured for three frequencies (see Appendix B of report of Design for Vibrations of Long Span Composite Floors). The damping derived from these measurements produced values that agreed fairly well with those calculated from the transfer function.

It is interesting to note that, in a similar way as Area 1, the presence of the raised flooring did not increase the damping to any significant degree (Table 3 cf. Table 4 Table 4 Summary of forced vibration tests using sine-sweep loading on the finished floor within Area 2). This result broadly agrees with the observations made by Osborne and Ellisⁱ.

Three walking tests were carried out on the finished floor of Area 2, all of which at a pace frequency of 2.0 Hz. Although it was expected that the extra mass on this area would reduce the floor response, one of the walking tests (Test 12) provided the highest peak acceleration by exciting the single frequency mode of 4.0 Hz. The peak

acceleration measured had a value of 0.123 m/s². The rms acceleration also increased, but to a lesser extent, with a value of 0.013 m/s², resulting in a response factor of 2.6.

The measured response factor of 2.6 is about three times less than the predicted response factor of 7.6, calculated from the SCI design guide. However, this estimated value is based on a higher damping value than that actually measured ($\zeta = 3\%$). Thus, by recalculating the response factor with the level of damping consistent with a bare floor ($\zeta = 1.5\%$), a value of 15.2 is obtained, which is about six times greater than that measured on the fourth floor, indicating a high conservatism within the present SCI guide.

Area 3

For this area, 20 mm thick raised flooring had been installed at all of the floor levels. Thus, only the dynamic performance of the floor in its finished condition could be established for this area. Since the largest spanning section of the whole floor occurred in this zone, it was expected that Area 3 would provide the worst-case design scenario for the building (see Figure 1).

All of the vibration tests described here were carried out at the fourth floor level. From a hand analysis of the response in this area, and using the appropriate level of permanent loads that were present at the time of testing, a fundamental frequency of 4.33 Hz was estimated. In addition, by assuming a damping value of 3%, a response factor of 6.9 was calculated (equivalent to an $a_{\text{rms}} = 0.034 \text{ m/s}^2$). Thus, in term of table 2.3 of section 2.2.3 of report of Design for Vibrations of Long Span Composite Floors, the floor would be acceptable for a 'general office' classification.

By subjecting the floor to sine-sweep loading, it was found from the transfer function that three closely spaced modes of vibration existed at 4.5, 4.8 and 5.9 Hz (see Appendix C of report of Design for Vibrations of Long Span Composite Floors). In addition, some higher modes were identified at 7.2 and 8.8 Hz. By constructing a best fit SDOF curve through the experimental data, the damping and stiffness for these five modes was found. These results are summarised in Table 5.

Table 5 Summary of forced vibration tests using sine-sweep loading on the finished floor within Area 3

Frequency (Hz)	Average Overall Damping %	Lowest Stiffness (N/m)
4.5	1.32	9.1×10^6
4.8	1.87	1.0×10^6
5.9	1.71	1.4×10^7
7.2	1.06	2.6×10^7
8.8	0.97	3.9×10^7

In order to give an independent assessment of the damping, the floor within Area 3 was then subjected to a continuous single sine-wave loading at the frequencies identified by the earlier tests, prior to the generator being suddenly stopped, to monitor the ensuing decay. From these tests the average damping agreed reasonably well with those derived from the transfer function with 2.3% at 4.8 Hz, and 0.9% at 7.2 Hz (see Appendix C of report of Design for Vibrations of Long Span Composite Floors).

Prior to undertaking the walking tests, qualitative measures of the floor response were also recorded whilst the floor was put into resonance by a continuous single sine-wave loading. Thus, from a consensus of opinion from five people present on the floor, crude subjective ratings were noted and graded on a scale of 1 to 5; 5 being the most annoying. The most annoying case occurred at a loading frequency of 7.2 Hz, with the second most annoying occurring at 4.8 Hz. Conversely, when the structure was put into resonance with a fundamental frequency of 4.5 Hz, the consensus of opinion was that the response could hardly be felt. This result is interesting, as, with reference to baseline curve given within figure 2.14 of section 2.2.3 of report of Design for Vibrations of Long Span Composite Floors, it would be expected that the tolerance to annoying vibrations would start to increase near a frequency of 7.2 Hz.

A total number of twelve walking tests were undertaken over Area 3, but only four are of particular interest, see below.

Test 1 & 2

For walking test 1, an individual paced at a comfortable frequency of 1.6 Hz along grid-line D (see Figure 1). Therefore, it was hoped that the third harmonic of the pace frequency would excite the 4.8 Hz mode identified by the transfer function. In fact, five frequencies were excited by this walking test at 4.8, 5.0, 5.9, 6.7 and 8.6 Hz; which resulted in a peak acceleration of 0.029 m/s². The directly derived rms acceleration had a value of 0.007 m/s², giving a very low response factor of 1.4. Very little reduction in the peak acceleration was measured in walking test 2 (and no change, at all, in terms of the rms acceleration), where the cushioning effect to heel-strikes, from the presence of carpet tiles positioned along grid-line D, was investigated.

Test 3 & 4

For walking test 4, the carpet tiles were still positioned along grid-line D, but the frequency of the walking pace was increased to 2.5 Hz. This meant that it would be expected that the second and third harmonic of the walking force would excite the second and fifth mode of vibration (see above). Indeed, this situation was created, and also excited the 7.3 Hz mode of vibration (see Appendix C of report of Design for Vibrations of Long Span Composite Floors). This particular test produced the highest recorded response for the area with a peak acceleration of 0.059 m/s². The rms acceleration also increased by a factor of two, to a value of 0.014 m/s²; equivalent to a response factor of 2.7.

The measured response factor of 2.7 is about two-fifths of that predicted using the SCI design guide. However, the estimated value is based on a higher damping than that actually measured ($\zeta = 3\%$). By recalculating the response factor with the level of damping consistent with a bare floor ($\zeta = 1.5\%$), a value of 13.7 is obtained; about five-times as great as that measured on the floor.

It is interesting to note that, when considering the results from the walking tests which were carried out on the three floor areas, a significant disparity exists between the directly derived rms acceleration, compared to that which would have been calculated, had the peak acceleration been simply divided by $\sqrt{2}$. This shows that the assumption that the acceleration response is sinusoidal, made in the development SCI equations, is not entirely appropriate. Further evidence of this can be seen graphically when considering the acceleration-time plots obtained from the walking tests (see Appendix B and C of report of Design for Vibrations of Long Span Composite Floors). For the floors at the Paris Office, the ratio between the rms acceleration and the peak acceleration ranged from 0.10 to 0.35, which is much less compared to the factor of 0.71 ($\approx 1 / \sqrt{2}$).

ⁱ Osborne, K.P. & Ellis, B.R.: 'Vibration design and testing of a long-span lightweight floor', *The Structural Engineer*, **68**, No. 10, May 1990, pp.181-186