Assessment of Hollow-Core Concrete Floors Against Human-Induced Vibration

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Abstract

Precast hollow-core concrete (HC) slabs are widely used in construction, especially in Nordic countries. The combination of prestressing and low self-weight due to the voids makes it possible to build long-span floors. However, this also makes the floors more sensitive to vibrations from human activities. In this paper, experimental and finite element (FE) analyses of a test HC slab and four in-situ experiments performed in three buildings are presented. For each case, the dynamic assessment is performed using two design guides: SCI P354 (2009) and the Concrete Center (2006). These analyses show that the proposed FE models give accurate results compared to experimental findings and that the Concrete Center design guide gives lower predictions than the SCI P354 guide. In addition, several recommendations can be derived from these studies for the dynamic assessment of HC floors in the design process. The most important is that for some structures, the accelerations calculated using the design guides are significantly higher with an FE model including the considered floor and the surrounding walls than with an FE model including also the lower and higher floors.

Keywords: hollow-core concrete floor; human-induced vibration; SCI P354 (2009); Concrete Center (2006); human walking; finite element (FE) models

Introduction

Precast hollow-core concrete (HC) slabs are widely used in the construction of floors for multi-storey buildings, high-rise apartments, shopping malls and parking garages, especially in Nordic countries. The combination of prestressing and low self-weight due to the voids makes it possible to build long-span floors. However, this also means that the floors become more sensitive to vibrations from human activities and dynamic analyses are often required in the design phase.

In previous works,1–3 the authors studied an experimental HC floor and proposed a method to implement an accurate model of the HC slab itself. The purpose of this paper is to extend the study to HC floors in real buildings and to propose recommendations for the assessment of HC floors using design guides.

To the authors' knowledge, there are three main sources of guidance with regard to floor vibration serviceability: SCI P354 (2009) Design of Floors for Vibration: A New Approach,4 the American Institute of Steel Construction (2016) A Design Guide for Footfall Induced Vibration of Structures5 and the Concrete Center (2006) A Design Guide for Footfall Induced Vibration of Structures6 and the American Institute of Steel Construction (2016) Design Guide Series 11: Vibrations of Steel-Frame Structural Systems Due to Human Activity.6 Many works on evaluating the serviceability of buildings based on these three norms can be found in the literature.7–13 In this paper, the SCI P354 (2009)4 and the Concrete Center (2006)5 design guides will be studied.

These design guides require that the natural frequencies and eigenmodes of the concrete floor are known which, in the design phase, are calculated using finite element (FE) analysis. The purpose of this paper is therefore to propose a method to implement accurate FE models of HC concrete floors and to investigate, evaluate and compare the responses predicted by the two design guides together with the developed FE models. The main objective is to derive specific recommendations that structural engineers can use to perform the dynamic assessment of HC floors.

To achieve these goals, an experimental HC floor1–3 and four other in-situ experiments performed in three buildings were used. SF1500 accelerometers were used. Their linear full acceleration range is ±3 g, with a corresponding sensitivity of 1.2 V/g. The sampling frequency was chosen at 2048 points per second. The natural frequencies and eigenmodes were obtained with two different tests: using an impact hammer and a shaker for the experimental HC floor, and using an impact hammer and the free-falling of a person from a height of 300 mm for the other floors. Experimental frequency response functions were then computed using fast Fourier transformations to extract the natural frequencies and eigenmodes. FE models were implemented for each structure and used to perform a dynamic assessment according to the two design guides. Some single-person walking tests were also performed for the experimental floor and for the two tested floors in the Segerstethuset. The experimental results were filtered at one-third octave bands and then processed using a running root mean square (RMS) method.

Summary of the Design Guides

The design guides from SCI P354 (2009)4 and the Concrete Center (2006)5 are considered in this section. Both of them are based on the same analyses but with different parameters for the Fourier load coefficients, the equivalent impulse load, the walking pace range, and the built-up and weighting factors. For low-frequency floors (i.e. floors with a fundamental frequency lower than 10 Hz), both steady-state and transient response analyses are required. For high-frequency floors (i.e. floors with a fundamental frequency higher than 10 Hz), only a transient
analyses is required. For both steady-state and transient analyses, the excitation point load should be applied at the maximum amplitude of the considered eigenmode and the response point is taken at the same position as the excitation point.

Steady-State Response

The excitation load is a sum of four harmonic components defined by

\[ f_h(t) = \alpha_h Q \sin(2\pi f_p t + \phi_h) \]  

where \( h \) is the number of the \( h \)th harmonic, \( \alpha_h \) is the Fourier coefficients of the \( h \)th harmonic, \( Q = 746\text{N} \) is static force, \( f_p \) is walking pace frequency, and \( \phi_h \) is the phase of the \( h \)th harmonic. The SCI P354 design guide recommends that all the modes of vibration up to 12 Hz should be taken into account, and the walking pace range is 1.8–2.2 Hz.

The steady-state response at a specific point is given by

\[ a_{w,rs,x,y} = \frac{\sum_{h=1}^{H} \sum_{n=1}^{N} \mu_{e,n} H_{r,n} \frac{\alpha_h Q}{M_n} D_{n,h} \sin(2\pi f_p t + \phi_h + \phi_{n,h}) W_h}{\sqrt{2}} \]  

with

\[ \tan \phi_{n,h} = \frac{-2h \xi \beta_n}{1 - (h \beta_n)^2} - \pi \leq \phi_{n,h} \leq 0 \]

where \( n \) is the number of the \( n \)th mode, \( H \) is the number of Fourier terms, \( N \) is the number of modes, the amplitudes \( \mu_{e,n} \) and \( \mu_{r,n} \) are the amplitudes of the \( n \)th mode at the excitation and response points, \( M_n \) is the modal mass, \( D_{n,h} \) is the dynamic magnification factor for the acceleration, \( W_h \) is the weighting factor for human perception of vibrations.\(^{14} \) \( \xi \) is the damping ratio, \( \beta_n \) is the frequency ratio (taken as \( f_p/f_n \)), and \( \phi_{n,h} \) is the phase of the response of the \( n \)th mode relative to the \( h \)th harmonic.

In the SCI P354 design guide, two ways to calculate the steady-state response are proposed. In Way 1, the exact response is calculated using Eq. (2). Then, the RMS acceleration of the total response is calculated with

\[ a_{w,rs,x,y} = \left( \frac{1}{T} \int_0^T a_{w,rs,x,y}(t)^2 \, dt \right)^{1/2} \]  

where \( T \) is the integration time, which is taken as 1/\( f_p \).

In Way 2 (Eq. 4), the modal superposition for each harmonic is performed without considering the phases of the modes. Then, the total response is obtained by the square root sum of squares (SRSS) of the amplitudes of the four harmonics.

\[ a_{w,rs,x,y} = \frac{1}{\sqrt{2}} \sum_{h=1}^{H} \sum_{n=1}^{N} \frac{\mu_{e,n} H_{r,n} F_h}{M_n} D_{n,h} W_h \]  

The responses obtained by Ways 1 and 2 will be compared in the numerical applications.

In the Concrete Center design guide, all the modes of vibration up to 15 Hz should be taken into account and the walking pace range is 1–2.8 Hz. The steady-state response is obtained by performing for each harmonic an exact modal superposition including the phase for each mode.

Transient Response

The transient response is dominated by a train of impulses, which rely on the heel impacts of human walking. Both norms recommend considering all the modes with frequencies up to twice the fundamental frequency. The impulse force is defined as

\[ F_I = 60F_{1,43}\frac{Q}{f_n^3} \]  

where \( f_n \) is the frequency of the mode under consideration.

In the SCI P354 design guide, the response is obtained by modal superposition according to

\[ a_{w,rs,x,y} = \sum_{n=1}^{N} 2\pi f_n \sqrt{1 - \xi_n^2} \mu_{e,n} H_{r,n} \frac{F_I}{M_n} \sin(2\pi f_n t - e^{-2\xi_n \pi f_n W_n}) \]  

Then, the RMS acceleration is calculated using Eq. (3).

In the Concrete Center design guide, the same approach is used, but by calculating velocities instead of accelerations.

Response Factors

The response factor \( R \) of a floor is the ratio between the weighted RMS acceleration (from either the steady-state response or the transient response) and the base value given in Ref. [15]. For the vertical vibrations, the base value is 0.005 m/s\(^2 \) for the acceleration and 0.0001 m/s for the velocity. In the Concrete Center design guide, and for the steady-state analysis, a response factor is calculated for each of the four harmonics. The total response factor is then obtained by the SRSS of the four values.

Finite Element Modelling

For the structures presented in the following sections, FE models were developed using ABAQUS. Following the work done by the authors in Ref. [2], an orthotropic shell model was used for the HC slabs. The optimal material parameters (see below) were obtained using a comprehensive numerical parametric analysis, ensuring that the difference between the numerical and experimental natural frequencies is less than 3% for the lowest mode and 5% for the second and third lowest modes.

\[ E_1 = \text{Elastic modulus of the HC concrete} \]
\[ E_2 = 0.45 \times E_1 \]
\[ G_{12} = 0.5 \times \sqrt{E_1 \times E_2} \]
\[ \nu = 0.2 \]
\[ G_{13} = 0.5 \times E_1 \]
\[ G_{23} = 0.5 \times E_2 \]

The surrounding horizontal steel beams and concrete walls were modelled using shell elements, whereas the steel columns were modelled using beam or shell elements. In all the models, two node shear flexible beam elements and four node doubly curved general-purpose shell elements were used. The typical mesh size for all the elements is 0.05 m, which gives converged results.

One key modelling aspect is related to the connections between the HC floor and the surrounding structure. These connections, which are specific for precast HC slabs, are shown in Fig. 1. For connections of types (a), (c) and (d), the void direction of the HC slab is perpendicular to the concrete wall.
or the steel beams, whereas for the connection of type (b), the void direction of the HC slab is parallel to the concrete wall. For the connection of type (a), the concrete wall consists of an external wall, insulation material and an internal wall. The up and down concrete walls are connected through a vertical reinforcing bar and mortar. A U-shaped steel bar bypasses the vertical reinforcing bar and is grouted into the keyway of the HC floor slabs so that the HC floor is rigidly connected (clamped) to the concrete wall. For the connection of type (b), there is no side bearing or connection. The gap between the HC floor and the concrete wall is just filled with concrete mortar. Consequently, the connection can only transmit a certain amount of the shear force. For the connections of type (c), there are two types of U-shaped steel bar: one steel bar bypasses the vertical reinforcing bar which is at the bottom flanges of the horizontal steel beam and is grouted into the keyway of the HC floor slabs, so that the HC floor is rigidly connected (clamped) to the horizontal steel beam; the other steel bar bypasses the reinforcement which is parallel to the horizontal steel beam and is also grouted into the keyway of the HC floor, to improve the shear resistance of the connection. For connections of type (d), the HC slab is fully connected to the steel beam through reinforcement and concrete mortar.

In the FE models, tie constraints were used to connect the HC floors to the steel beams or the concrete walls and the columns to the steel beams. Both displacements and rotations were constrained for connections of types (a), (c) and (d), whereas only displacements were constrained for the connection of type (b). Clamped boundary conditions were applied at the top or bottom edges of the concrete walls and at the ends of the columns.

To fit the recommendations of both design guides, the damping ratio for all modes is taken at 1.1% for the bare concrete floors in the experimental structure, Bobergsskolan school building and NCC’s head office building. For the furnished concrete floors in Segerstedthuset, the damping ratio is taken as 3%.

Experimental HC Slab

An experimental slab was built at the production plant of a leading supplier of precast concrete structures in Sweden. The slab consisted of six hollow-core elements of dimension $10 \times 1.2 \times 0.27$ m each, supported by horizontal and vertical steel beams (Fig. 2). A 50 mm height concrete topping was added on the slab 30 days after the casting of the joints. The strength class of the concrete was C45/55 for the hollow-core elements and the joints and C30/37 for the topping.

Ten accelerometers (Fig. 2) were used to record acceleration data. Accelerometers A1–A9 were installed at the typical points of one-quarter span, half span and three-quarters span of the slab to measure the vertical accelerations. Accelerometer A10 was

Fig. 2: Locations of accelerometers and loadings
installed on the side of one steel beam and registered the horizontal accelerations. The walking paths are also shown in Fig. 2.

The experimental tests were divided into two phases: in phase 1, HC slabs, concrete joints and the concrete topping were in place; in phase 2, all the intermediate steel columns were removed and the horizontal steel beams were then only supported at their ends. The walking tests were only performed in these two phases.

**Phase 1**

The FE model is shown in Fig. 3. The connection between the HC slab and the steel beam is of type (c) (see “Finite Element Modelling”, above), but the HC floor is only on one side. The concrete part was directly tied on the vertical surface of the two horizontal steel beams. Tie constraints were used to connect the steel columns to the horizontal steel beams and the steel columns to the diagonal steel bars. For all the tie constraints in the model, both rotations and displacements were constrained. The vertical steel columns were welded on to a 30 mm thick plate placed on the ground and clamped boundary conditions were applied at the bottom of the steel columns. The mesh size was taken as 0.05 m for both the concrete and steel parts.

**Natural Frequencies and Mode Shapes**

The obtained natural frequencies are shown in Table 1 and the mode shapes are shown in Fig. 4. Very good agreement between the numerical results and experimental results is obtained.

![Fig. 3: Finite element model](image)

| Model          | Mode 1 (Hz) | Mode 2 (Hz) | Mode 3 (Hz) |
|----------------|-------------|-------------|-------------|
| Experimental   | 6.89        | 13.4        | 22.7        |
| Finite element | 6.93        | 13.36       | 22.77       |

**Table 1: Natural frequencies**

| Mode          | Mode 1 (Hz) | Mode 2 (Hz) | Mode 3 (Hz) |
|---------------|-------------|-------------|-------------|
| Phase 2       |             |             |             |

**Human-Induced Vibration Evaluation**

The two first modes were used for the analysis. The highest calculated $R$ factors (Fig. 5) are obtained by applying the load at the maximum magnitude of mode 2 (near accelerometer 8), which is also a maximum amplitude point for mode 1. The walking tests were performed at a path frequency of 2.2 Hz. The maximum results, shown in Fig. 5 for three similar tests, are obtained at accelerometer 8 with walking path 2.

The two peaks in Fig. 5 correspond to the fourth and third harmonics of the walking pace frequency and resonance for mode 1. The results show that the SCI P354 design guide gives higher results than the Concrete Center for both steady-state and transient analyses. The experimental results at 2.2 Hz are higher than the transient ones predicted by the Concrete Center design guide but lower than the transient ones predicted by the SCI P354 guide.
These results also show that it can be problematic to limit the analysis to walking frequencies between 1.8 and 2.2 Hz (as suggested in the SCI P354 design guide), not because lower or higher path frequencies should necessarily be investigated but owing to a possible small inaccuracy in the FE model. The highest peak in Fig. 5 is obtained at a path frequency of 2.31 Hz and corresponds to the third harmonic for mode 1 (6.93 Hz). Consider that the real first natural frequency is instead 6.6 Hz, only 5% lower. Then, the resonance peak would be at a path frequency of 2.2 Hz. In other words, even if one considers that the walking frequency range should be limited to 1.8–2.2 Hz, it can be a good idea to increase this range to take into account that the calculated natural frequencies are only approximations of the real values.

Finally, it can be noted that Ways 1 and 2 give almost the same results at resonance but not otherwise. This is because, at resonance, only one mode (mode 1) contributes to the response.

### Phase 2

**Natural Frequencies and Mode Shapes**

In phase 2, the first four natural frequencies and mode shapes are shown in Table 2 and Fig. 6. Very good agreement between numerical results and experimental results is obtained.

| Model                  | Mode 1 (Hz) | Mode 2 (Hz) | Mode 3 (Hz) | Mode 4 (Hz) |
|------------------------|-------------|-------------|-------------|-------------|
| Experimental results   | 6.09        | 13.6        | 15.1        | 19          |
| Finite element model   | 6           | 13.15       | 15.5        | 18.2        |

Table 2: Natural frequencies

**Human-Induced Vibration Evaluation**

The three first modes were used for the analysis. The highest calculated $R$ factors (Fig. 7) are obtained by applying the load at the maximum magnitude of the mode 2 (near accelerometer 8), which is also a maximum amplitude point for mode 1. The walking tests were performed at a path frequency of 2 Hz. The maximum results, shown in Fig. 7 for three similar tests, are obtained at accelerometer 8 with walking path 2.

The two peaks in Fig. 7 correspond to the fourth and third harmonics of the walking pace frequency and resonance for mode 1. The results show that the SCI P354 design guide gives higher results than the Concrete Center guide and that the experimental results are lower than those predicted by the design guides. Finally, it can be noted that Ways 1 and 2 give the same results. In fact, if only mode 1, instead of modes 1, 2 and 3, is used to calculate the $R$ factors, almost the same curves (the differences are less than 1%) are obtained for the steady-state analyses.

**Bobergsskolan School Building**

Bobergsskolan is a new five-storey school building. The test region is on the fourth floor (the area in the red box area in Fig. 8a). It consists of 14 HC slabs, with a total dimension of 16.5 ×
10 × 0.27 m. A 40 mm deep concrete topping was cast. Concrete of strength class C45/55 was used for the HC slabs, the joints and the topping. The connections between the test region and the surrounding structure are of type (b) along the short sides and of types (a) and (c) for the long sides.

Nineteen accelerometers were used to record the acceleration data (Fig. 9). Accelerometers A1–A18 were installed on the floor. Accelerometer A19 was installed on the side concrete wall at a height of 1 m to measure the horizontal acceleration. The loads were applied at points P1 and P2.

**FE Models**

Two different FE models were developed (Fig. 10): (a) a “one floor” model including the structural members surrounding the floor; and (b) a “several floors” model including the higher and the lower level floors as well as the surrounding structural members connected to the additional floors.

**Natural Frequencies and Mode Shapes**

The obtained natural frequencies are shown in Table 3 and the mode shapes obtained with the “one floor” model are shown in Fig. 11. It was observed that the first three experimental modes have the same mode shape (first bending mode in the longitudinal direction).

The results in Table 3 show that the “one floor” model gives accurate results even though it is unable to reproduce the first three modes with the same longitudinal one-half wave bending mode shape. These additional two modes are due to the influence of the higher and the lower floors and are only obtained with the “several floors” model, as shown in Fig. 12.

**Human-Induced Vibration Evaluation**

Both the “one floor” model (with modes 2 and 4) and the “several floors” model (with modes 1–4) were used. The highest $R$ factors shown in Fig. 13 are obtained when the load is applied at point P1.
applied at the maximum magnitude of mode 2. The peak obtained with the “one floor” model corresponds to the fourth harmonic of the walking pace frequency and resonance for mode 2. This is due to the modal masses of the models (Table 4). These modal masses have been obtained by normalizing the eigen-modes with a maximum amplitude of 1. For mode 2, owing to the contribution of the higher and lower floors, the modal mass for the “several floors” model is twice that of the “one floor” model.

Finally, it can be observed that with the “several floors” model, the approximate Way 2 gives higher results at resonance compared to the exact Way 1. This is because, for this model, several modes are present at resonance and consequently some error is introduced if the modal superposition is performed without considering the phase between the different modes.

**Fig. 11: Mode shapes**

![Mode shapes](image)

**Fig. 12: First three modes of “several floors” model: (a) mode 1; (b) mode 2; (c) mode 3**

![Mode shapes](image)

| Mode mass | Mode 1 (kg) | Mode 2 (kg) | Mode 3 (kg) | Mode 4 (kg) |
|-----------|-------------|-------------|-------------|-------------|
| One floor | –           | 15 115      | –           | 15 008      |
| Several floors | 42 339     | 30 701      | 20 083      | 28 916      |

**Table 4: Modal mass**

lower (almost 50%) with the “several floors’ model than with the “one floor” model, although both peaks are obtained with the fourth harmonic of the walking pace frequency and resonance for mode 2. Here also, the SCI P354 design guide gives higher results than the Concrete Center guide. It can also be observed that the highest $R$ factor is much higher (around 35%)

**Fig. 13: Evaluation results**

![Evaluation results](image)
structure. The test region is on the seventh floor (Fig. 14a). It consists of 34 HC slabs with the largest span of 15.6 m and a thickness of 0.4 m, without concrete topping. However, since some equipment and building material were located on the left side, the accelerometers were only placed on the right side of the test region. Concrete of strength class C50/60 was used for HC slabs and joints. The connections between the test region and the surrounding structure are of type (d) along all the sides. The positions of the accelerometers and the excitation points are shown in Fig. 14b.

**FE Models**

Two FE models were developed (Fig. 15): (a) a “one floor” model including the surrounding steel beams and steel columns; and (b) a “several floors” model, also including the higher and the lower level floors and the surrounding elements.

**Natural Frequencies and Mode Shapes**

The first five natural frequencies up to 10 Hz were identified experimentally (Table 5, Fig. 16). The first three experimental modes have the same mode shapes and the largest amplitudes are obtained for mode 1. The “one floor” model gives very good agreement with experiments for modes 1, 4 and 5, regarding both natural frequencies and eigenmodes. However, only the “several floors” model is able to reproduce the three first modes with the same mode shapes (Fig. 17).

**Human-Induced Vibration Evaluation**

For the analysis with the “one floor” model, modes 1, 4 and 5 were considered, whereas for the analysis with the “several floors” model modes 1–5 were considered. The highest $R$ factors shown in Fig. 18 are obtained when the load is applied at the maximum magnitude of mode 1. For both models, the highest peak corresponds to the second harmonic of the walking pace frequency and resonance for mode 1.

It can be noted the highest peak for the “one floor” model is at 2 Hz, whereas the corresponding peak for the “several floors” model is at 1.75 Hz, i.e. outside the walking frequency range (1.8–2.2 Hz) proposed by the SCI P354 design guide. This is because, compared to the experimental results, the first natural frequency for the “several floors” model (3.59 Hz) is less accurate than the one for the “one floor” model (4.01 Hz). This shows that it can be a good idea to increase the range 1.8–2.2 Hz to take into account the possible approximation in the calculated natural frequencies.

As for Bobergsskolan, the highest $R$ factor is much lower (almost 50%) with the “several floors” model than with the “one floor” model. This can be explained by checking the modal masses of the models (Table 6). For mode 1, due to the contribution of the higher and lower floors, the modal mass for the “several floors” model is 70% higher than that for the “one floor” model.

With both models, Way 2 gives almost the same results as Way 1 at resonance but not at some of the other frequencies, especially for the “several floors” model between 1.8 and 2.2 Hz. As for the previous cases, the differences between the results with Ways 1 and 2 are due to the presence of several modes. In Fig. 19, the steady-state...
analyses have been performed by considering only mode 1. Comparison with Fig. 18 shows clearly that the highest peaks involve only mode 1, whereas for some other frequencies several modes are involved.

Segerstedthuset in Uppsala

Segerstedthuset is located in Uppsala University. It was completed in 2017. Two in-situ experiments were performed on two different floors. The walking paths and the positions of the accelerometers for each floor are shown in Fig. 20a, b. The first test region is on the second floor (Fig. 21a) and consists of 17 HC slabs with the largest span of 15.2 m and with a thickness of 0.38 m. The second test region is on the fourth floor (Fig. 21b)
and consists of 26 HC slabs with the largest span of 14.6 m and with a thickness of 0.38 m. For both floors, a 36 mm deep concrete topping was cast and a concrete of strength class C45/55 was used for the HC slabs, the joints and the topping. Here, it should be emphasized that there was no information about the internal walls (shown in red in Fig. 20) and, for this reason, the internal walls were not considered in the FE models, regarding either the stiffness or the mass.

### FE Models

Two different FE models were developed (Fig. 22): (a) a “one floor” model; and (b) a “several floors” model, also including the higher and the lower level floors and the surrounding elements. The connection near accelerometer A6 is of type (a), while other connections along the y-axis and near accelerometer A15 are of type (c). Along the x-axis, the connections are of type (d).

### Tests on the Second Floor

Natural Frequencies and Mode Shapes

In this test, only the first natural frequency was obtained experimentally. The results are shown in Table 7 and Fig. 23. Good agreement between the “one floor” model and experiments is obtained for both the first natural frequency and the corresponding mode shape. For the “several floors” model, three modes with the same mode shape for the test floor were obtained. But for this case, the vibrations of the lower and higher floors do not significantly affect the test floor, which can be shown in the mode shapes in Fig. 24 and in the values of the modal masses given in Table 8. This explains why only one eigenmode was obtained experimentally.

| Modal mass | Mode 1 (kg) | Mode 2 (kg) | Mode 3 (kg) | Mode 4 (kg) | Mode 5 (kg) |
|------------|-------------|-------------|-------------|-------------|-------------|
| One floor  | 55 462      | –           | –           | 67 045      | 130 610     |
| Several floors | 94 358    | 63 995      | 79 215      | 130 610     | 99 075      |

Table 6: Modal mass

Fig. 19: Comparison results

Fig. 20: Locations of accelerometers and loadings: (a) test region of second floor; (b) test region of fourth floor
Human-Induced Vibration Evaluation

Mode 2 was used for the analysis with the “one floor” model, whereas modes 1–3 were used for the analysis with the “several floors” model. For each model, the highest $R_f$ factors are obtained when the load is applied at the maximum magnitude of mode 2. The peaks shown in Fig. 25 correspond to the fourth and third harmonics of the walking pace frequency and resonance for mode 2.

For this case also, the Concrete Center design guide gives lower $R_f$ factors than the SCI P354 guide, for both the steady-state and transient responses. Both design guides also give higher results compared to the experimental walking tests obtained along walking path 2 with different walking ways. The experimental results shown in Fig. 25 are from accelerometer 8, which is very close to the maximum amplitude of mode 2 and which gives the highest accelerations.

In contrast to the previous cases, the two models give almost the same maximum $R_f$ factors. This was expected since the modal masses for mode 2 are of same magnitude for the two models (Table 8).

### Tests on the Fourth Floor

#### FE Models

Two different FE models were developed (Fig. 26): (a) a “one floor” model; and (b) a “several floors” model. The connections along the $x$-axle are of type (d) and other connections are of type (c).

#### Natural Frequencies and Mode Shapes

The first five natural frequencies were experimentally identified. As for the previous structures, almost identical mode shapes were obtained for different frequencies: for modes 2 and 3 and also for modes 4 and 5. The results presented in Table 9 and Fig. 27 show that both models give accurate results but that only the “several floors” model is able to reproduce the five experimental modes (Fig. 28).

| Model          | Mode 1 (Hz) | Mode 2 (Hz) | Mode 3 (Hz) |
|----------------|-------------|-------------|-------------|
| Experimental results | 8.2         |             |             |
| One floor       | –           | 7.76        | –           |
| Several floors  | 7.1         | 7.54        | 7.66        |

*Table 7: Natural frequencies*

![Fig. 21: Test regions: (a) second floor; (b) fourth floor](image)

![Fig. 22: Finite element models: (a) “one floor” model; (b) “several floors” model](image)

![Fig. 23: Mode shapes](image)
For the analysis with the “one floor” model, modes 1, 3 and 5 were considered, whereas for the analysis with the “several floors” model modes 1–5 were considered. The highest \( R \) factors shown in Fig. 29 are obtained when the load is applied at the maximum magnitude of mode 1. The peaks obtained with both models correspond to the fourth, third and second harmonics of the walking pace frequency and resonance for mode 1.

The results from the walking tests are taken at accelerometer 8, which gives the maximum accelerations and which is close to the maximum magnitude of mode 1. The three walking paths are shown in Fig. 20b. Two walking pace frequencies of 1.8 and 2.75 Hz were chosen for each walking path. For the pace frequencies of 1.8 and 2.75 Hz, the highest accelerations were obtained for walking paths 3 and 2, respectively. It can be observed in Fig. 29 that the results from the walking tests are lower than the values calculated by the two design guides.

The maximum \( R \) factors obtained with the “one floor” model are about 15% higher than those obtained with the “several floors” model. As before, this can be explained by the difference (15%) in the modal masses for mode 1 (Table 10).

### Conclusions and Recommendations

In this paper, six HC floors have been studied experimentally and numerically. For the floors in buildings, two FE models have been implemented and verified with experimental results. The “one floor” model includes only the considered floor with the surrounding walls and columns, whereas the “several floors” model includes also the lower and higher floors. Then, for each floor, the dynamic assessment against human-induced vibrations has been performed using two design guides (SCI P354 and Concrete Center). For some of the structures, comparisons between the results obtained from the design guides and experimental walking tests have also been made. Based on these six studies, the following conclusions and recommendations can be derived.

### Conclusions

For all the studied floors, good agreements with experiments regarding the lowest natural frequencies and eigen-modes are obtained with the “one floor” model.

With the exception of the first case study, both design guides give higher predictions than the experimental walking tests.

For all six studied floors, the SCI P354 design guide gives higher results than the Concrete Center guide, for both the steady-state and transient analyses. Besides, when resonance occurs along

| Model          | Mode 1 (Hz) | Mode 2 (Hz) | Mode 3 (Hz) | Mode 4 (Hz) | Mode 5 (Hz) |
|----------------|-------------|-------------|-------------|-------------|-------------|
| Experimental results | 5.45        | 7           | 7.8         | 9           | 11.14       |
| One floor      | 5.5         | –           | 8.43        | –           | 12.46       |
| Several floors | 5.43        | 7.62        | 8.35        | 11.4        | 12.34       |

Table 9: Natural frequencies
the walking pace range, the steady-state analyses give higher results than the transient ones. For the other pace frequencies, the steady-state analyses give lower results than the transient ones. Besides, and as expected, for the transient responses, the $R$ factors increase with the pace frequency. This applies for both design guides.

For several buildings, the predictions from the design guides are much higher with the “one floor” model than with the “several floors” model. The reason for this is that the higher and lower floors influence dynamically the considered floor and several fundamental frequencies with almost the same mode shape are then obtained. Consequently, the modal masses for the fundamental frequency are higher with the “several floors” model than with the “one floor” model.

In all the tested floors, the maximum $R$ factors predicted by both design guides are obtained by applying the force at the maximum amplitude of the lowest mode and are due to resonance with the lowest frequency of the floor.
Consequently, the two ways of performing the modal superposition proposed in the SCI P354 design guide (Way 1, an exact model superposition, and Way 2, an approximate modal superposition without considering the phase between the modes) give the same maximum $R$ factors with the “one floor” model. This is not necessarily the case with the “several floors” model, for which several modes can be involved at resonance.

As already mentioned, the maximum predicted $R$ factors with both design guides are due to resonance with the lowest frequency of the floor. Consequently, the accuracy of the walking frequency at which resonance occurs depends on the accuracy of the fundamental frequency obtained from the FE model. This can be a problem for the SCI P354 design guide, for which the proposed walking pace range is $1.8–2.2$ Hz. A small inaccuracy in the calculated fundamental frequency can result in a resonance peak outside, instead of inside, the walking pace range.

**Recommendations to Perform Dynamic Assessment**

An accurate “one floor” FE model of an HC floor can be implemented by using the proposed orthotropic shell formulation for the floor and by including the surrounding walls and columns. This model can be used for dynamic assessment during the design process.

If the “one floor” model gives too high predictions, then it can be worth implementing a “several floors” model by including also the lower and higher floors. Then, if this model presents several natural frequencies with the same lowest mode involving several floors as well as higher modal masses compared to the “one floor” model, this model can be expected to give lower predictions.

When the SCI P354 design guide is used, the walking pace range should be increased, not to investigate possible lower and higher walking frequencies, but to consider that the calculated natural frequencies are only approximate values of the real ones. If a resonance peak occurs just outside the walking pace range proposed by the SCI P354 design guide, then this peak should be considered for the dynamic assessment.

It is reasonable to expect that the maximum values predicted by the two design guides will be obtained by applying the point load at the maximum amplitude of the lowest mode and by taking the response at the same point. However, and as mentioned in the design guides, analyses must be performed by applying the point load at the maximum amplitude of all the considered modes.

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