VIBRATIONS OF A HOLLOW CORE CONCRETE FLOOR INDUCED BY HAMMER-IMPACT LOAD AND SINGLE PEDESTRIAN WALKING

Fangzhou Liu, Jean-Marc Battini and Costin Pacoste

KTH, Division of Structural Engineering and Bridges, Stockholm, Sweden

e-mail: fangzhou@kth.se

Precast and prestressed hollow core concrete slabs, that combine low self-weight and high strength, are often used for long span floors. However, this implies that the slabs are also confronted with the issue of human induced floor vibration serviceability. In this paper, experimental results from both hammer-impact and walking tests of a slab consisting of 6 hollow core concrete elements and of dimension 10 m × 1.2 m are presented. Comparisons with results Finite element results are performed. Three different walking paths and four numerical models taken from the literature for the single pedestrian load are considered. The results show that with transversal and diagonal walking paths, the vibrations due to the torsional mode of the slab can be higher than the ones due to the lowest bending mode. They show also that the four pedestrian loads give rather different numerical results.

Keywords: Experiments, vibration, FE models, Simulation.

1. Introduction

Precast and prestressed hollow core slab are often used, particularly in Sweden, in the construction of floors for high-rise apartments, multi-story buildings, shopping malls, offices or parking garages. The main advantage of these slabs is that the combination of low self-weight and high strength makes it possible to design floors with long spans. Therefore, this implies that the slabs are also confronted with the issue of floor vibration serviceability, particularly the vibration from human activity. In fact, many practical cases in Sweden have shown that the length of the span is often limited by dynamic consideration and not by static criteria.

To the authors’ knowledge, there are only a few research works in the literature concerning the dynamic response of hollow core floors. Natural frequencies of a solid slab and a hollow core slab have been compared by Jendzelovsky and Vrablova [1]. Marcos et al. [2] presented a parametric study on the vibration sensitivity of hollow core slabs. They found that the most important parameter for the first natural frequency is the span. However, these two studies were only numerical and the results were not confirmed by experimental investigations.

The main purpose of the present work is to study experimentally and numerically the dynamic response of a built hollow core concrete slab due to a single pedestrian. Three different walking paths and four numerical models taken from the literature for the single pedestrian load are considered. The numerical results are filtered at 1/3 octave band and then processed by using a running RMS method. A complete description of the experimental tests and results can be found in [3]. The finite element shell model of the concrete slab has been presented in a previous work [4].

2. Experimental tests

2.1. Hollow core concrete slabs
The experimental structure was built at the production plant of the company Contiga, a leading supplier of precast concrete structures in Sweden. The slab consisted of 6 hollow core elements of dimension $10\, \text{m} \times 1.2\, \text{m} \times 0.27\, \text{m}$ each, see Fig. 1(a and d). The connections (joints) between the slabs were poured with grouted concrete. A 50 mm height concrete topping was added on the slab thirty 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.

The connection between the concrete floor and the horizontal steel beams was performed through steel connectors welded to the horizontal steel beam and anchor steel bars casted on the concrete floors, see Fig. 1(b-c). The space of about 5 cm between the concrete floor and the horizontal steel beams were then poured with grouted concrete. The horizontal steel beams were supported by a set of hot formed hollow steel columns, see Fig. 1(a), with the following cross-sections: $180\, \text{mm} \times 180\, \text{mm} \times 8\, \text{mm}$ at the four corners; $100\, \text{mm} \times 100\, \text{mm} \times 6.3\, \text{mm}$ for the ten intermediate columns; $100\, \text{mm} \times 50\, \text{mm} \times 8\, \text{mm}$ for the diagonal bars. The ground was horizontal below the steel beams but not along the direction of the voids. Consequently, the length of the steel columns was 0.45 m on one side and 0.75 m on the other side. Finally, the vertical columns were welded on each side on a steel plate of thickness 30 mm that was simply placed on the ground.

Ten accelerometers, see Fig. 1(d), were used to record acceleration data. As shown in Fig. 1(d), accelerometers A1 to A9 were installed at the typical points of $\frac{1}{4}$ span, $\frac{1}{2}$ span and $\frac{3}{4}$ span of the slab in order to measure the vertical accelerations. Accelerometer A10 was installed on the side of one steel beam and registered the horizontal accelerations. The sampling frequency was chosen at 2048 points per second.

The experimental tests were divided in three phases: in phase 1, the joints were casted but not the topping; in phase 2, the concrete topping was in place; in phase 3, all the intermediate steel columns were removed and the horizontal steel beams were then only supported at their ends.

![Experimental structure](image)

![Cross-section of horizontal steel beams and steel connector](image)

![Grout concrete, steel connectors and steel bars](image)

![Location of accelerometers A1 to A10 and exciting loads](image)
2.2. **Harmonic vibration tests**

A sinusoidal force with a peak amplitude of 25N and a frequency range from 4 Hz to 35 Hz has been applied to the structure. This test, which is described in [3], was then used to calibrate the finite element model of the slab in [3,4].

2.3. **Hammer-impact tests**

The slab was subjected to an impact force applied using a heavy-duty impact hammer (see Fig. 2(a)) of Type 8208 [5]. The impact loading was applied at position H1, see Fig. 1(d). The hammer has built-in electronics and is designed to excite and measure impact forces on medium to very large structures. It gives an impulse load of very short duration and consequently, frequencies up to 50Hz can be excited. The imposed signals both in time domain and frequency domain are shown in Fig. 2(b).

![Hammer-impact tests](image)

**Figure 2:** Heavy-duty impact hammer (Type 8208) (a) and time and frequency response of impact force (b)

2.4. **Single pedestrian walking**

The tests of a single pedestrian (85 kg) walking on the slab were conducted for phases 2 and 3, i.e. after the casting of the topping. Three different paths were considered, see Fig. 3. The walking frequency was 2.2Hz in phase 2 and 2Hz in phase 3 so that it corresponds to 1/3 of the lowest natural frequencies.

![Single pedestrian walking](image)

**Figure 3:** Single pedestrian walking paths

3. **Natural frequencies and mode shapes**

The experimental results were processed using Matlab and Fast Fourier Transforms, without numerical filtering. Natural frequencies and mode shapes for phases 2 and 3 are shown in Table 1 as well as in Fig. 4.
Table 1: Natural frequencies Hz in phase2 and phase3

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mode 1 exciter</th>
<th>Mode 2 exciter</th>
<th>Mode 3 exciter</th>
<th>Mode 4 exciter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hammer</td>
<td>hammer</td>
<td>hammer</td>
<td>hammer</td>
</tr>
<tr>
<td>Phase 2</td>
<td>6.82</td>
<td>6.89</td>
<td>13.2</td>
<td>22.7</td>
</tr>
<tr>
<td>Phase 3</td>
<td>6.09</td>
<td>6.14</td>
<td>13.6</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>22.7</td>
<td>22.7</td>
<td>15.1</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>19</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: First three mode shapes in phase 2 (a) and first four modes in phase 3 (b)

4. Finite element modelling

4.1. Structure

A FE model of the structure was developed using the finite element programme ABAQUS, see Fig. 5. The concrete part was modelled as one homogeneous plane using orthotropic shell elements whereas the steel parts were modelled using isotropic shell elements. 4-node doubly curved shell elements S4 were used. A convergence study was carried out and an optimised element size of 0.05 m was chosen for both of concrete and steel parts. Tie constraints were used to connect the steel columns to the horizontal steel beams and the steel columns to the diagonal steel bars. The concrete part was directly tied on the vertical surface of the two horizontal steel beams. The reinforcement and the prestressing were not considered. As a matter of fact, the vibrations induced by human activities do not induce damage or cracking and consequently, the reinforcement does not contribute significantly to the dynamic behaviour.

Figure 5: 3D finite element model

One important aspect regarding the modelling of the concrete floor is the determination of the thickness of the shell. For that, the moment of inertia of the cross-section of the concrete slab in the voids direction were calculated by using ABAQUS and 4-node bilinear two-dimensional warping elements WARP2D4, see Fig. 6. A very fine mesh of 0.01 m was chosen. The same elastic modulus for the hollow core elements, the topping and the joints was taken. The thickness of shell elements can then be calculated from Eq. (1):
\[ h = \sqrt{\frac{12 \times 1}{b}} \]  

(1)

Where \( h \) is the thickness of shell elements; \( b \) is the width of shell elements; \( I \) is the moment of inertia.

A thickness \( h = 0.300 \) m was obtained. In order to generate a shell model that has the same mass as the real slab, the density of the concrete has been taken as \( \rho = 1603.6 \) kg/m\(^3\). The material properties of the steel were taken as: \( E = 210 \) GPa, \( \nu = 0.3 \), \( \rho = 7850 \) kg/m\(^3\). For the concrete slab, orthotropic shell elements with a lamina material have been used. The following parameters have been taken: \( E_1 = 36 \) GPa, \( E_2 = 16.2 \) GPa, \( \nu_{12} = 0.2 \), \( G_{12} = 12.1 \) GPa, \( G_{13} = 18 \) GPa and \( G_{23} = 8.1 \) GPa. Direction 1 is along the voids and direction 2 is perpendicular to direction 1. The optimal values of these parameters have been determined in [4] through comprehensive numerical parametric studies and by calibrating the finite element model against the experimental results obtained with the harmonic excitation. For that, the relative error between measured and numerical natural frequencies has been minimized.

4.2. Single pedestrian walking loads

Four types of single pedestrian walking loads (see Fig. 7(b)) of pace frequency 2Hz were taken from the literature (EU project [6], Setra [7], Chen [8] and Pan [9]) and applied in phase 3. In order to fit the pace frequency of 2.2Hz used in phase 2, the walking load history of the second step (right foot) was moved forward 0.05s, see Fig. 7(a). These frequencies were calculated so that they correspond to 1/3 of the lowest measured natural frequencies, see Table 1.

Single footfall forces (walking load time histories of right or left foot) were applied at the nodal points of the FE mode as proposed in Pan [9]. The distance between adjacent nodal points was taken as the average stride length of each walking test.

5. Comparison between experimental and numerical results

The experimental tests were analysed numerically using a modal superposition procedure including the 10 lowest modes. Both the experimental results and numerical results were processed using Fast Fourier Transforms. An alternative processing method was also used. This involved filtering.
the signal in 1/3 octave bands. Further, the filtered signals were processed again using a running r.m.s. method [10]. The running r.m.s. method takes into account occasional shocks and transient vibration by using a short integration time constant. The equation was defined by Eq. (2):

$$a_w(t_0) = \sqrt{\frac{1}{\tau} \int_{t_0}^{t_0-\tau} [a_w(t)]^2 dt}$$

(2)

As recommended in ISO 2631-1 [10] and ISO 10137 [11], the value $\tau = 1$ s was taken.

5.1. Hammer-impact test

The numerical analysis was performed by importing the registered experimental impact load time history in the FE model. The results are presented in Figs. 8 and 9. A very good agreement between numerical and experimental results is obtained. This shows that the numerical model of the slab is accurate.

5.2. Single pedestrian walking tests

Experimental and numerical results for single pedestrian walking tests are presented in Fig. 10 for Phase 2 and Fig. 11 for Phase 3. The experimental results (green lines) show, as expected, that the first mode (bending) is excited for each walking path. They show also that the second mode (torsion) is excited for walking paths 2 and 3. Moreover, in phase 2, the amplitudes of the acceleration are higher for the torsional mode than for the bending mode.

The numerical results show that the four single pedestrian walking load models excite the first two modes. However, a large difference between the four models regarding the amplitude of the accelerations can be observed. In particular, the load model EU project [6] overestimates the amplitudes of the first bending mode in all the analyses. In Phase 2, the results obtained with the load models Setra [7] and Pan [9] are also very high compared to the experimental results for mode 1. In Phase 3, the three load models Pan [9], Chen [8] and Setra [7] give lower results compared to experiments for the first mode. None of the load model gives good results in both Phases 2 and 3. However, acceptable results were obtained using the load model Chen [8] in Phase 2 and the load model Pan [9] in Phase 3.

In the authors’ opinion the high acceleration level for the torsional mode in Phase 2 is due to the fact that the 6th order harmonic of the footstep (2.2 Hz) coincides with the experimental natural frequency in torsion (13.2 Hz). In order to validate this hypothesis, the parameters $E_2$ and $G_{12}$ of the concrete slab have been changed so that the numerical frequency for the torsional mode in Phase 2 matches exactly the experimental one. As a matter of fact, the optimal material parameters given in Section 4.1 were obtained in [4] by considering both Phases 2 and 3 and also higher modes. One of the results is shown in Fig. 12 for the load model Chen [8]. With the new values for the material parameters, the amplitude of acceleration increases significantly for the second mode (torsion). With this load model, very good agreements between experimental and numerical results are obtained for the torsional mode.
Figure 8: Phase2: FFT accelerations and RMS accelerations at centre frequencies of 1/3 octave bands

Figure 9: Phase3: FFT accelerations and RMS accelerations at centre frequencies of 1/3 octave bands

Figure 10: Phase2: RMS accelerations of single pedestrian walking at each path

Figure 11: Phase3: RMS accelerations of single pedestrian walking at each path
6. Conclusion

In this paper, experimental and numerical results of a concrete slab consisting of 6 hollow core elements and excited by hammer-impact and single pedestrian walking loads have been presented.

For the hammer-impact test, very good agreement between experimental and numerical finite element results is obtained.

For the single pedestrian walking tests, three different walking paths have been considered. The most interesting experimental result is that in Phase 2 and for walking paths 2 and 3 the amplitudes of acceleration are higher for the second mode (torsion) than for the first mode (bending). Additional numerical analyses have shown that this is probably due to the fact that the 6th order harmonic of the footprint (2.2 Hz) coincides with the natural frequency in torsion (13.2 Hz).

Four single pedestrian walking load models taken from the literature have been implemented. All the four models excite the two lowest modes but large differences regarding the amplitude of the accelerations can be observed. None of the load model gives accurate results in both Phases 2 and 3. However, acceptable results compared to experiments are obtained with the load model Chen [8] in Phase 2 and the load model Pan [9] in Phase 3.

References

5 Product Data: Heavy-duty Impact Hammers Types 8207, 8208 and 8210 - Brüel & Kjær.