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VIBRATIONS INDUCED BY HUMAN ACTIVITIES IN COMPOSITE STEEL FLOOR DECKS. CASE STUDY

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ABSTRACT
Composite steel floor decks are used in a large variety of constructions with long spans, like office buildings and hotels, shopping centres or bridges. The long-span floor resistance is ensured by the high strength capacity of the steel beams and the conservation in time of the steel physico-mechanical characteristics. Due to the reduced weight, stiffness and damping, problems related to the floor vibrations can occur. Floor decks with low frequencies may be in resonance with the vibrations induced by human activities, producing discomfort to the building occupants. The paper presents some provisions for composite steel floor decks from international codes and technical literature, a parametric study of the response in the frequency domain of a floor with steel beams on two directions and the floor vibration frequencies measured in situ. The dynamic response of the floor is obtained by considering different boundary conditions, load intensities and stiffnesses for the r.c. slab in the finite element models. The frequencies measured in situ are close to the frequencies obtained by numerical analysis, in the model considering the deformability of the floor perimeter supporting members and the floor slab with non-degraded concrete.
Keywords: composite steel floor deck, human activities, floor vibrations, numerical and in situ results

INTRODUCTION
Floors of buildings with moderate spans, made of r.c. slabs, have high stiffness and high natural frequencies, from 10 to 14 Hz, such as the vibrations produced by human activities are not disturbing for the building occupants. Buildings with long spans for educational or commercial areas, factories, etc. have composite steel floor decks, made of light materials, with high strength but small damping. Due to the small weight and stiffness, the natural frequency of these floors is low, between 3 and 10 Hz. Disturbing vibrations can be produced by dynamic actions like walk, dance, aerobics or functioning of electro-mechanical equipments that can affect the occupants comfort or even the normal use of the building.

EFFECT OF HUMAN ACTIVITIES ON BUILDING FLOORS
Walk, dance, aerobics are human activities that produce vibrations in the building floors. Ordinary walk of people on a floor is equivalent to a harmonic excitation with the frequency between 1.6 and 2.4 Hz, jogging corresponds to an excitation with the frequency of about 2.5 Hz and running to excitations with frequencies around 3 Hz (Saidi *et al.*, 2006). Floor vibrations can be transitory, like those produced by objects falling on the floors, or can be steady, like those produced by the walk of groups of people. Figure 1 shows the dynamic forces produced by a group of people dancing and jumping on a floor, respectively (Allen *et al.*, 1998).

a *b*

Figure 1. Dynamic Force produced on Floors by Dance (a) and Jumps (b) (Allen *et al.*, 1998)

The limit of the floor vibrations perceived by the occupants of a building depends on their position (standing, sitting or lying), as well as on their activities. Vibrations having accelerations of about 0.5% of g are unacceptable for sitting or lying persons. People doing aerobics can accept floor vibrations with accelerations up to 10% of g. People standing in commercial areas or dining near dancing floors can accept accelerations of about 2% of g. Since floor deflections and forces are generally small, there is no danger of floor collapse. But steady accelerations, greater than 20% of g can produce collapse, due to the fatigue phenomenon (Allen *et al.*, 1998).

Another undesirable effect of forced oscillations is the phenomenon of resonance, which occurs when the floor natural frequency is equal to the excitation frequency or is an integer multiple of the excitation frequency. When a group of people doing aerobics makes repeated jumps, resonance may occur not only at the frequency of the basic excitation (the step frequency), but also at the integer multiples of this frequency, associated to the superior harmonics (the second or the third harmonic). Usually, the lowest harmonic produces the greatest oscillations at resonance. The maximum accelerations depend also on the floor damping, as one can see in figure 2 (Allen *et al.*, 1998).

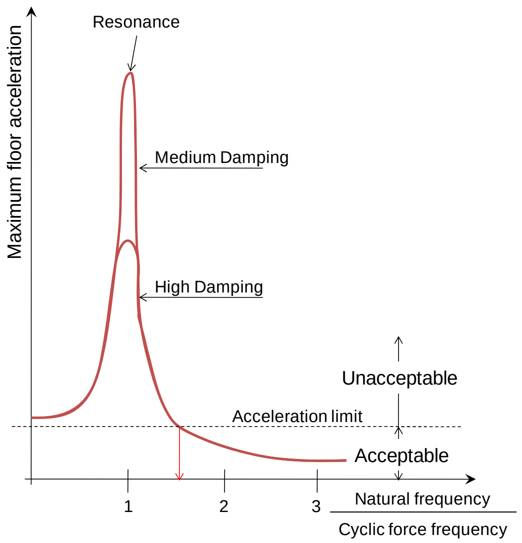

Figure 2. Floor Accelerations vs. Frequencies Ratio (Allen *et al.*, 1998)

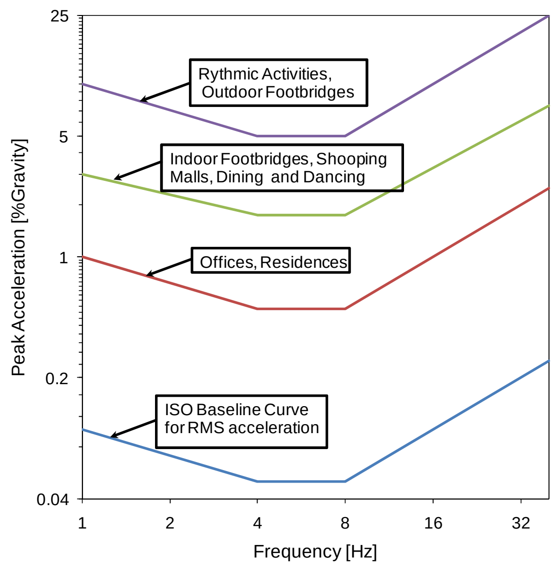

Figure 3. Curves Acceleration vs. Frequency for Different Environments (ISO10137, 1992)

VIBRATION LIMITATION IN CODE PROVISIONS

The use on a large scale of floors in composite solution, with steel beams and r.c. slab, requires their check at the serviceability limit state, in order to avoid the discomfort caused by the floor vibrations. Comfort criteria can be expressed in terms of oscillation accelerations, velocities and frequencies. Some codes give approximate indications about the conditions that floors must fulfill in order to avoid the disturbing vibrations.

To prevent collapse caused by fatigue or by oscillation amplification due to resonance, the National Buildings Code of Canada requires dynamic analysis of floors whose natural frequency is lower than 6 Hz (NBC, 1995). In the first part of the European Code “Design of timber structures”, special investigations are required for the floors with timber beams in residential buildings, which have the natural frequency lower than 8 Hz (EUROCODE 5, 2004). Related to the serviceability limit states of composite beams, Hanswille (2008) shows that dynamic analysis of floors with the natural frequency lower than 7.5 Hz is necessary. SSEDTA CD (2001) contains provisions for floors in public areas, in order to avoid the occupants discomfort. The following lower limits of the natural frequencies are provided: 3 Hz for floors with normal access and 5 Hz for gymnastics and dancing halls. It is also specified that the effect of the vibrations induced by human activities can be reduced by reducing the floor deflections at the serviceability limit state, that is by ensuring a certain stiffness of the floor. The Standard ISO10137 (1992) defines a basic curve for the acceptable accelerations as function of the dynamic activity frequency, as well as multiplying coefficients corresponding to the environment factors (homes, offices, commercial and educational areas, etc.). Figure 3 shows the curves corresponding to the amplification coefficients.

CASE STUDY

The floor analysed in the paper belongs to a university building with twelve levels – two basements and ten stories. The basements and the first nine stories have r.c. structure, while the tenth storey has steel structure. The building height above the ground level is 40.6 m and the current stories are 3.8 m high. The in plan dimensions of the building are 24.50 x 51.50 m, with unequal spans on longitudinal and transverse directions. The floors in the left transverse span are made in composite solution, on the whole length of the building (figure 4). It has been chosen this solution in order to reduce the storey height and the building self weight, as well as to reduce the creep effect in long-span reinforced concrete beams. At the second storey, sloped composite floors are built in the tiered lecture halls area (figures 4 and 5). The composite floors in the flat lecture rooms area from the stories 3 ÷ 9, as well as the other floors of the building, are horizontal (figures 4 and 6). The composite floor under analysis is horizontal and it is supported on the perimeter by r.c. beams and walls. The r.c. slab of about 12 cm thickness works together with the orthogonal grid of steel beams through rigid connectors placed at about 50 cm on longitudinal and transverse directions (figure 7). In the area of connection with the r.c. walls, the beams strength capacity has been reduced by reducing the flange width in the system “dog-bone”. No rigid connectors have been placed in the same area, in order to prevent the r.c. slab to work together with the steel beams. The beams are made of steel S235, with rolled sections HEA450, placed at a distance of 2.0 m between their axes on both directions. The r.c. slab is made of concrete C24/30 with E_C = 32500 N/mm^2.

The check of the comfort level offered by the composite steel floor deck is done for the serviceability limit state. Therefore, characteristic values of the dead and live loads are used in the analysis.

Figure 4. Building View

Figure 5. Steel Grid of the Sloped Floor

Figure 6. Steel Grid of the Horizontal Floor

Figure 7. Rigid Connectors and Slab Reinforcement

The characteristic value of the dead load, p_1, is determined as follows:

– r.c. slab (12 cm thick):	0.12 x 25 = 3.0 kN/m^2
– steel beams (1.4 kN/m)	≅ 1.2 kN/m^2
– flooring (5 cm thick)	0.05 x 22 = 1.1 kN/m^2
– partition walls	= 1.0 kN/m^2
– false ceiling and plumbing	= 0.5 kN/m^2
	p_1 = 6.8 kN/m^2

The live load, p_2, has different values, of 3 kN/m^2 in the lecture rooms area and 4 kN/m^2 in the corridors area.

Three models have been considered for the dynamic analysis of the floor. In the first two models, a floor area with the spans of 14.0 x 14.0 m long is considered isolated from the structure, having rigid restraints on the boundary. In the third model, the whole storey is considered, such as the floor dynamic characteristics and the deflections under gravity loads depend on the deformability of the perimeter supporting members. In the model M1, the isolated composite steel floor deck is equalised with a grid of steel beams, as shown in figure 8. The beam equivalent cross section is obtained by means of an equivalence coefficient corresponding to the short-term actions, $n = E_S / E_C = 2100/325 = 6.46$. The model M2 considers the isolated floor made of r.c. slab and steel beams fixed on the boundary (figure 9). In the model M3, the whole composite steel floor deck is elastically supported by the perimeter r.c. beams and walls (figure 10).

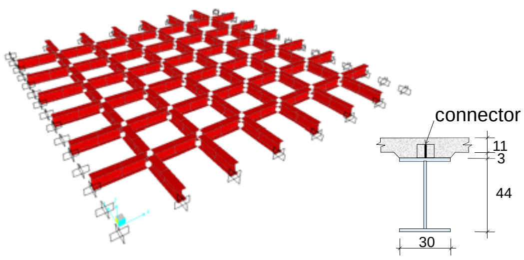

Figure 8. Equivalent Steel Grid for Model M1

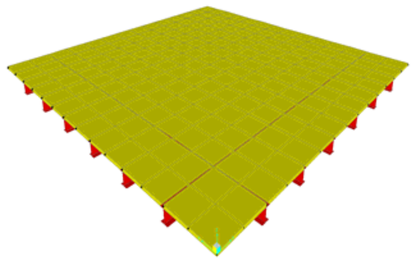

Figure 9. Isolated Floor in Model M2

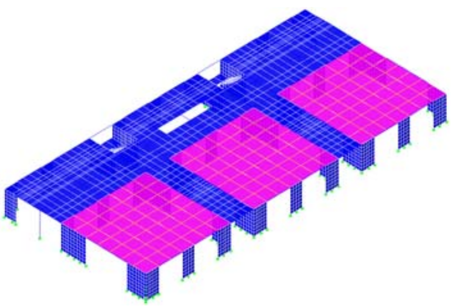

Figure 10. Composite Steel Floor Deck in Model M3

For each model, the concrete is considered non-degraded and degraded, respectively. In the first case, $\overline{E}_C = E_C$. In the second case, the degradation due to creep, shrinking and cracking is considered by reducing the Young modulus with 50%: $E_C^* = 0.5E_C$. In the model M1, the hypothesis that the r.c. slab do not work together with the beams is also considered, by taking $E_C = 0$.
The load combinations are done with the formula

$$\sum_{j=1}^{n} G_{k,j} + \psi_{1,1} Q_{k,1} \tag{1}$$

where $G_{k,j}$ and $Q_{k,1}$ are the characteristic values of the dead and live loads, respectively. The coefficient $\psi_{1,1}$ is smaller or equal to 1, depending on the nature of the live loading.

For the serviceability limit state (SLS), the floor is considered acted:
– only by the dead loads ($q_1 = p_1 = 6.8$ kN/m^2);
– by the dead loads and 40% of the live load ($q_2 = p_1 + 0.4\, p_2$);
– by the dead loads and the entire live load ($q_3 = p_1 + p_2$).
For the ultimate limit state (ULS), the floor is acted by $q_4 = 1.35\, p_1 + 1.5\, p_2$.

Natural frequencies and maximum deflections of the floor have been determined for each load combination. Figures 11, 12 and 13 show the floor first and second vibration shapes in the models M1, M2, and M3, respectively, for non-degraded concrete ($\overline{E}_C = E_C$) and the load q_3.

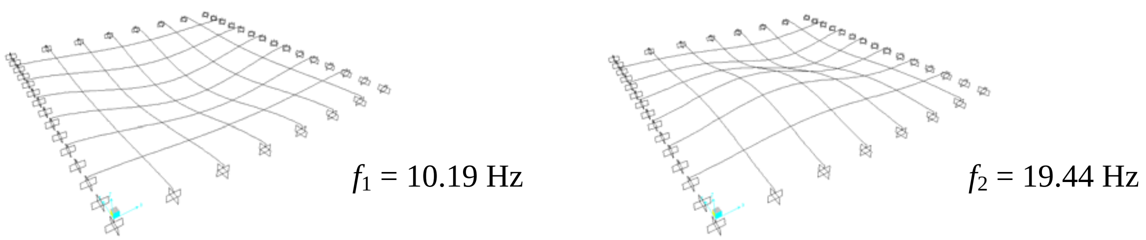

Figure 11. Modal Shapes in Model M1, for $\overline{E}_C = E_C$ and Load q_3

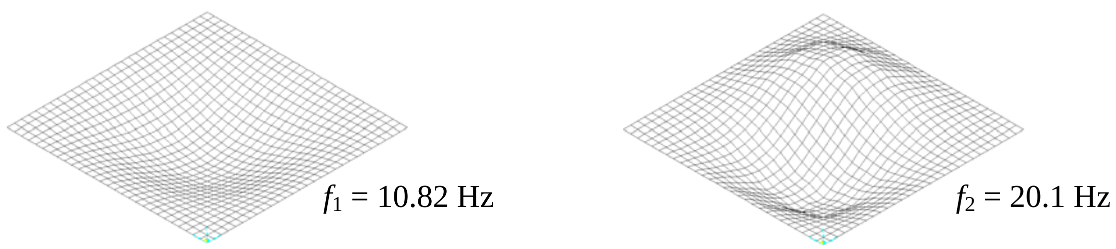

Figure 12. Modal Shapes in Model M2, for $\overline{E}_C = E_C$ and Load q_3

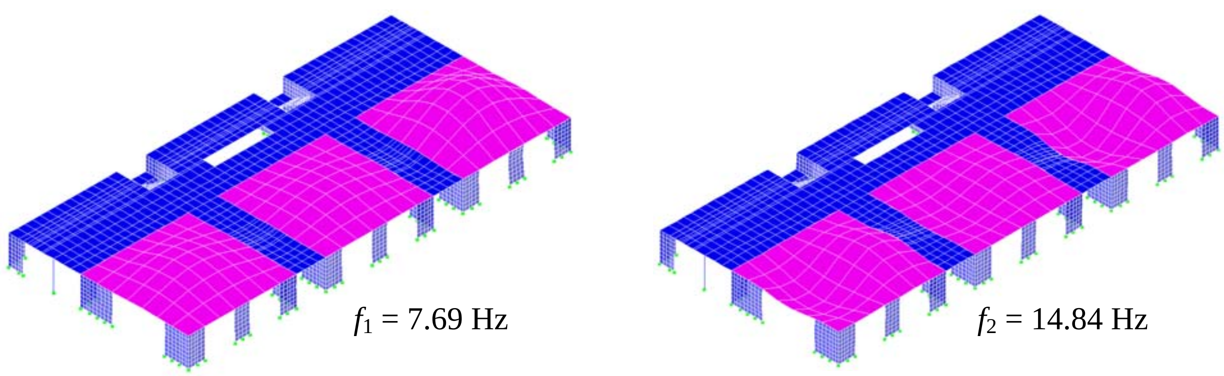

Figure 13. Modal Shapes in Model M3, for $\overline{E}_C = E_C$ and Load q_3

Table 1. Natural Frequencies and maximum Deflection of the Floor in Model M1

Load combination		q_1	q_2	q_3	q_4
f_1 (Hz)	$E_C = 0$	7.93	7.32	6.63	5.62
	$\overline{E}_C = E_C$	12.18	11.25	10.19	8.62
	$E_C^* = 0.5E_C$	11.32	10.47	9.48	8.03
f_2 (Hz)	$E_C = 0$	15.95	14.74	13.34	11.30
	$\overline{E}_C = E_C$	23.25	21.47	19.44	16.46
	$E_C^* = 0.5E_C$	21.87	20.21	18.31	15.50
d_{max} (mm)	$E_C = 0$	6.30	7.40	9.00	12.50
	$\overline{E}_C = E_C$	2.60	3.10	3.80	5.20
	$E_C^* = 0.5E_C$	3.00	3.60	4.30	6.10

Table 2. Natural Frequencies and maximum Deflection of the Floor in Models M2 and M3

Model		M2				M3			
Load combination		q_1	q_2	q_3	q_4	q_1	q_2	q_3	q_4
f_1 (Hz)	$\overline{E}_C = E_C$	12.93	11.94	10.82	9.16	9.18	8.48	7.69	6.51
	$E_C^* = 0.5E_C$	12.72	11.75	10.63	9.00	8.10	7.49	6.78	5.74
f_2 (Hz)	$\overline{E}_C = E_C$	24.04	22.20	20.10	17.02	17.54	16.32	14.84	12.55
	$E_C^* = 0.5E_C$	23.41	21.60	19.55	16.54	15.34	14.35	12.89	11.11
d_{max} (mm)	$\overline{E}_C = E_C$	2.40	2.79	3.50	4.80	4.32	5.13	6.28	8.80
	$E_C^* = 0.5E_C$	2.50	2.90	3.60	5.00	5.52	6.50	7.95	11.15

The values of the first and second natural frequencies and the maximum deflection are given in Table 1 for the model M1, in each hypothesis regarding the concrete behaviour and for each load combination. The same results are given for the models M2 and M3 in Table 2.

Figures 14 and 15 show the floor frequencies in the first two natural modes, obtained in the three models, in each hypothesis regarding the concrete stiffness and for each load combination. They can be compared with the minimum acceptable frequency for composite steel floor decks according to NBC (1995) and Hanswille (2008).

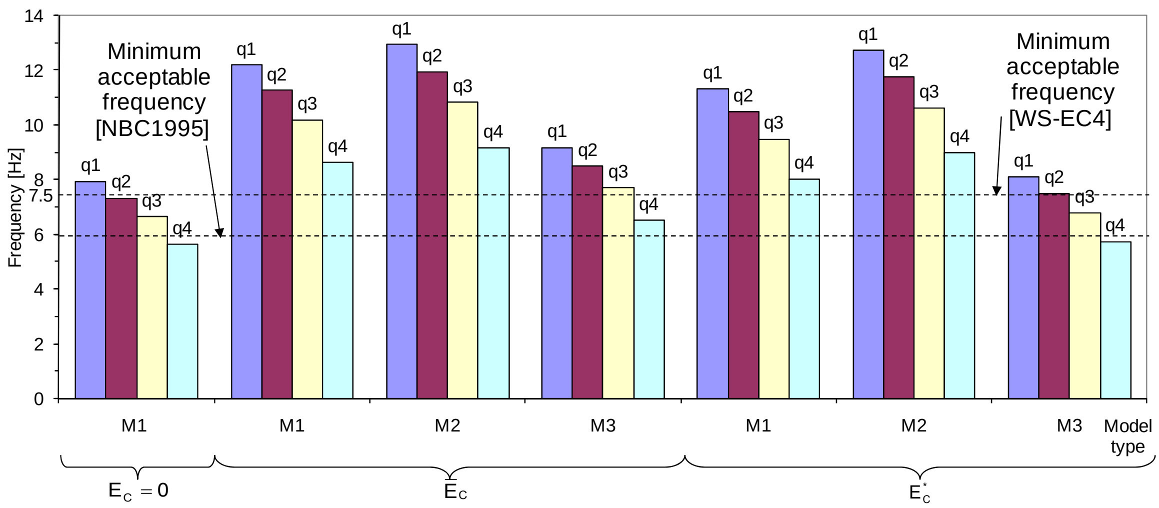

Figure 14. Floor Frequency in the First Natural Mode of Vibration, f_1 (Hz)

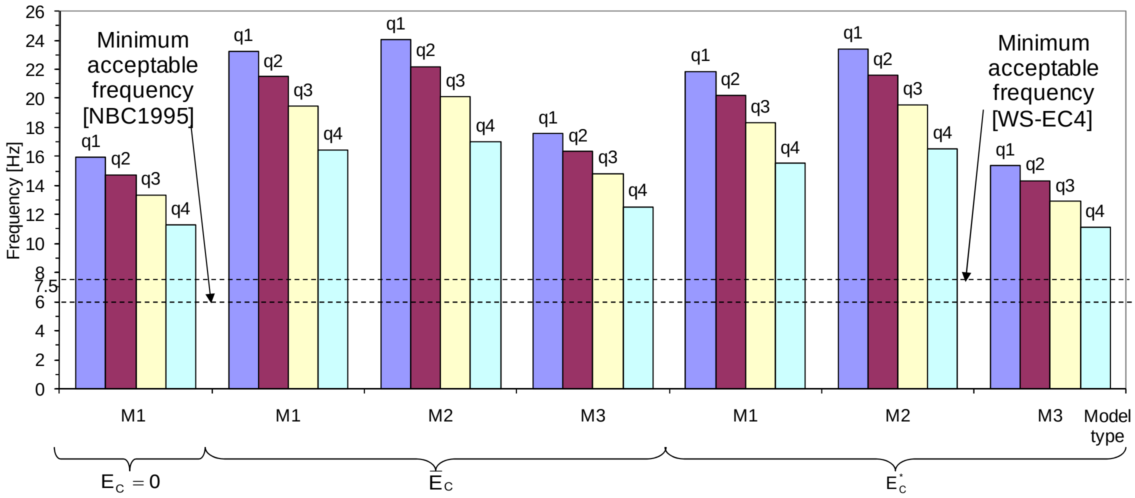

Figure 15. Floor Frequency in the Second Natural Mode of Vibration, f_2 (Hz)

By examining the frequencies histograms from figures 14 and 15, one can notice the followings:
– close results are obtained in models M1 and M2, in the hypothesis that the r.c. slab works together with the steel beams, for non-degraded or degraded concrete;
– the results obtained in the same conditions in models M2 and M3 are significantly different, showing that neglecting the deformability of the perimeter members is unrealistic, because the stiffness of the floor in model M2 is higher than in reality;
– by considering in the model M1 that the r.c. slab does not work together with the steel beams, reduced frequencies are obtained, this representing the lower limit case;
– the increase of the masses for the ULS (q_4) gives the lowest natural frequencies, representing the superior limit case;
– the check of the oscillations of long-span floors, with possible large groups of people in movement, has to be done for the entire characteristic load (q_3).

The following formula is proposed for the estimation of the fundamental frequency of a composite steel floor deck:

$$f_1 = \frac{20}{\sqrt{d_{\max}}} \tag{2}$$

where $d_{\max}$ is the maximum floor deflection under the considered characteristic loads, measured in mm.

In order to avoid disturbing oscillations, the limiting of the fundamental frequency becomes a condition much more restrictive than the limiting of the maximum deflection, which is the condition generally imposed at the floor designing. For the concert halls and stadia tiers, usually is required that $d_{\max} \le d_a = l/350$. In model M3, with $E_C^* = 0.5 E_C$ and for the load combination q_3, $d_{\max} = 7.95$ mm and $d_a = 14000/350 = 40$ mm. The maximum allowed deflection is about five times the maximum effective deflection. By using the formula (2), the first natural frequency is $f_1 = 20/\sqrt{7.95} \cong 7.1$ Hz, close to the value obtained by dynamic analysis.

Taranath (1998) recommends the following formula for the floor minimum acceptable frequency:

$$f_{\min} = f\sqrt{1 + \frac{1.3}{a_0/g}\frac{\alpha\, q_P}{q_t}}\,,\quad f_{\min} \le f_1 \tag{3}$$

where f is the excitation frequency, a_0/g is the ratio between the peak floor acceleration and g; α is the dynamic load factor; q_P is the characteristic load on the surface unit transmitted by the people doing rhythmic activity; q_t is the total characteristic load on the surface unit.

For an excitation with the frequency f = 2 Hz, one can take a_0/g = 0.05 and α = 1.5. Considering that the entire live load is applied (the load combination q_3), the value of the minimum acceptable frequency for the analysed floor is $f_{\min} = 2\sqrt{1+\frac{1.3}{0.05}\frac{1.5\times 3}{9.8}} = 7.2$ Hz, greater than f_1 = 6.78 Hz obtained in the model M3 by dynamic analysis and than f_1 = 7.1 Hz obtained with the approximate formula (2). If only 40% of the live load is applied (load combination q_2), $f_{\min}$ is 5.23 Hz, value smaller than f_1 = 7.49 Hz obtained by dynamic analysis and than f_1 = 7.84 Hz determined with the approximate formula (2).

IN SITU MEASUREMENTS

Natural vibrations and peak vertical accelerations have been measured when the building was still in construction. Therefore, the composite steel floor deck was acted only by the self weight and the slab concrete was not degraded.

The measurement device assembly is made of four capacitive accelerometers with four signal conditioners and an independent 8-channels data acquisition unit connected to a laptop with related software for real-time data storage, processing and representation (figure 16). The acceleration sensors have been placed in the central area of the floor from the fourth storey of the building superstructure. The free oscillations induced by impact, measured in one sensor location, are represented in figure 17. The first natural frequency $f_1 = 1/T_1$ = 12.5 Hz has been obtained by processing the record. For a better estimation of the natural frequencies, the Fourier spectra of the response acceleration amplitudes have been used. Figure 18 shows the Fourier spectrum for one of the accelerometers. The values of the natural frequencies for two sets of records made in the four measurement points, the average value of the frequencies for each set of records and the natural frequency obtained from the Fourier spectra are presented for comparison in figure 19.

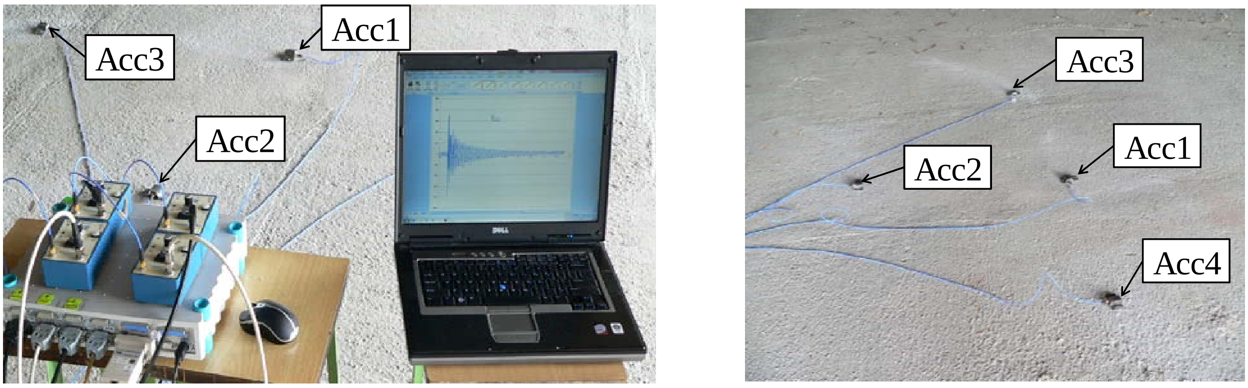

Figure 16. The Measurement Device Assembly

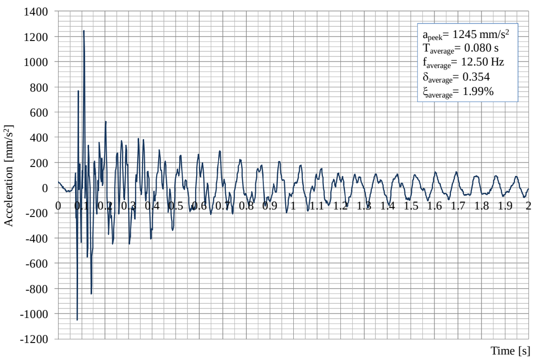

Figure 17. Floor Free Vibrations
(Set of Records 1, Accelerometer 2)

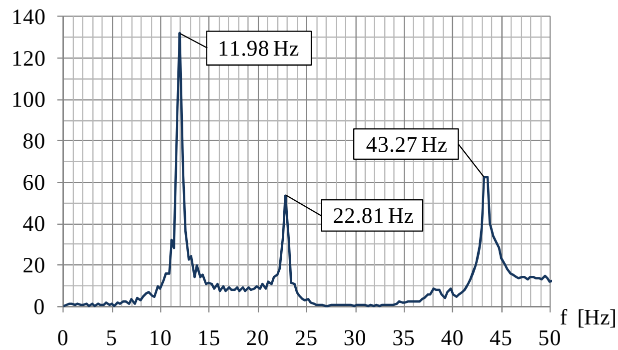

Figure 18. Fourier Spectrum for Response
Accelerations Amplitudes (Set 1, Acc 2)

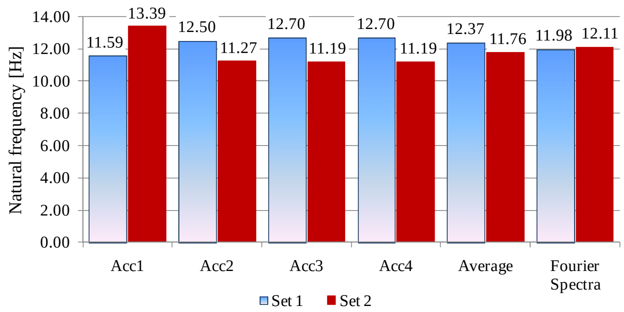

Figure 19. Floor Natural Frequencies

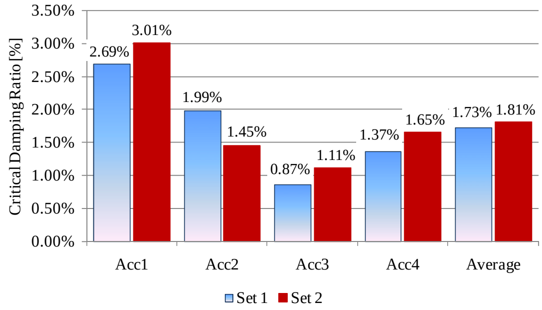

Figure 20. Floor Fractions of Critical Damping

The fraction of critical damping ξ can be calculated based on the logarithmic decrement δ,

$$\xi = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \tag{4}$$

For lightly damped systems, the fraction of critical damping is related to n cycles apart and the logarithmic decrement is determined with the relation

$$\delta = \frac{1}{n}\frac{u_i}{u_{i+n}} \tag{5}$$

where u_i and u_{i+n} are the amplitudes of the cycles i and $i+n$. The fractions of critical damping measured in the same locations in the two sets of records and their average values are shown in figure 20.

The comparison between the numerical results and the results obtained in situ must be done for the case of non-degraded concrete and for the fundamental frequency of the floor loaded with q_0, representing the r.c. slab and steel beams self weight. Since $f_1 = 2\pi\sqrt{k/m}$, the fundamental frequency for q_0 can be obtained from the fundamental frequency under the load combination q_1, by the transformation relation $f_{eff} = f_1\sqrt{m/m_0} = f_1\sqrt{q_1/q_0}$.

The fundamental frequency obtained in the model M3, for the dead load q_1 = 6.8 kN/m^2 and non-degraded concrete was 9.18 Hz. The self weight of the r.c. slab and steel beams is q_0 = 3.0 + 1.2 = 4.2 kN/m^2. The fundamental frequency of the bare floor will be $f_{eff} = 9.18\sqrt{6.8/4.2} = 11.68$ Hz, very close to the average value of the measured frequencies, $f_{1,med} \cong 12$ Hz (figure 19). Therefore, the in situ measurements confirm the numerical results obtained by considering the deformability of the supporting members.

The flooring, partition walls, false ceiling and plumbing actually increase the dynamic performances of the composite steel floor decks, since they increase the floor damping, so that the oscillations induced by human activities will rapidly decay.

According to Taranath (1998), the fraction of critical damping of a bare floor is increased from 3% to 6% when the false ceiling, the flooring and the furniture are added, and to 11.3% when the partition walls are added too.

CONCLUSIONS

Dynamic characteristics of the long-span floors must be checked, both by numerical analyses and in situ measurements. Composite steel floor decks are light, resistant, but flexible. They have low natural frequencies that can be close to the frequency of the dynamic actions produced by groups of people walking or doing rhythmic activities. The floor fundamental frequency can be increased by increasing the beam depth. This implies the reducing of the storey clear height and supplemental costs.

The correct evaluation of the natural frequencies depends on the floor modeling. By considering rigid supports, large values of the frequencies are obtained, situation that may be not conservative in reality. Even considering in the model the real geometrical and supporting conditions will not give the exact values of the natural frequencies, because the actual physico-mechanical characteristics of the materials, especially of the concrete, are different from those considered in the numerical analyses. That is why in situ measurements are absolutely necessary. For the floor analyzed in the paper, the experimental results confirmed the numerical results for the non-degraded concrete.

The paper authors suggest the addition of provisions in Eurocode 4 regarding the deformability conditions of the composite steel floor decks, in terms of vibration frequencies, accelerations and deflections.

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