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ASPECTS REGARDING THE VIBRATIONS INDUCED BY HUMAN ACTIVITIES IN COMPOSITE STEEL FLOOR DECKS

SUMMARY

Composite steel floor decks are widely used in modern buildings. High resistance of the steel sections and conservation in time of the steel physico–mechanical characteristics make possible the execution of long-span floors. Due to the small stiffness and damping of the steel beams, human activities can induce vibrations in such floors. The paper presents the effect of human activities on building floors, some code provisions regarding the floor vibrations, and a case study of a composite steel floor deck with beams on two directions. The effect of the boundary conditions, load intensity, r.c. slab stiffness, and modeling itself on the dynamic response of the floor is examined.

Key words: floor vibrations, human activities, composite steel floor deck

1. EFFECT OF HUMAN ACTIVITIES ON BUILDING FLOORS

Educational or commercial areas, factories, etc., require long-span floors, which can be obtained by using light materials, with high strengths, but small damping. Disturbing vibrations can occur in these floors. Walk of people, dance, aerobics or malfunction of electro-mechanical equipments are dynamic actions that induce vibrations into the floors. Floor vibrations can be transitory, like those produced by bodies falling on the floors, or can be steady, like those produced by the walk of groups of people. Walk is equivalent to a harmonic excitation with the frequency of about 1.6 – 2.4 Hz, jogging corresponds to an excitation around 2.5 Hz, running produce excitations with frequencies around 3 Hz [1].

Generally, floor vibrations cause discomfort to the persons standing on the floors. If small vibrations are not perceived by the occupants, large floor vibrations can affect the occupants comfort or even the normal use of the building. In ordinary buildings, floors are made of reinforced concrete and have moderate spans. Their stiffness ensures natural frequencies of about 10 - 14 Hz that do not produce discomfort to the building occupants. 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 equal to 0.5% of the gravity acceleration produce discomfort for sitting or lying persons. People standing in commercial areas or sitting near a dance floor can accept accelerations of 2% of g. People doing aerobics can accept floor vibrations with accelerations up to 10% of g [1, 2]. 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 phenomenon of fatigue. Another undesirable effect of forced oscillations is the resonance, which occurs when the excitation frequency is equal to the natural frequency of the floor. When a group of persons 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 [1].

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2. VIBRATION LIMITATION IN CODE PROVISIONS

Due to the small weight and stiffness, the first natural frequency of the floors with large spans is small, the effect being disturbing oscillations even for normal walk of groups of people. The use on a large scale of floors in composite solution, with steel beams and r.c. slab, requires their check at serviceability limit state, in order to avoid the discomfort caused by the floor vibrations. Comfort criteria can be expressed in terms of oscillation accelerations, velocity and frequency. Some codes offer guidelines on the check conditions for floors in order to avoid the disturbing vibrations.

To prevent collapse caused by fatigue or by oscillation amplification due to resonance, the Canadian Code NBC (National Building Code) requires dynamic analysis of floors whose first natural frequency is smaller than 6 Hz [3].

The European Code Eurocode 5 requires special investigations for the floors with timber beams in residential buildings, which have the first natural frequency smaller than 8 Hz [4]. In order to avoid the occupant discomfort, the following lower limits for the first natural frequency of the floors used in public areas are provided in [5]: 3 Hz for floors with normal access and 5 Hz for gymnastics and dancing halls. Alternatively, the necessity of certain stiffness in order to obtain small deflections at the serviceability limit state is specified. An inferior limit of the first natural frequency of 7.5 Hz, for which no special dynamic analyses are required, is specified in [6].

The Standard ISO10137 defines a basic curve for the acceptable accelerations as function of the movement frequencies, as well as multiplying coefficients corresponding to the environment factors (homes, offices, commercial and educational areas, etc.) [7]. The oscillations of the floors in residential and office building should have peak accelerations smaller than 0.5% of g, according to [2].

3. CASE STUDY

The check of the comfort level offered by a composite steel floor deck is done. The r.c. slab of the floor works together with an orthogonal grid of steel beams that are fixed in the walls and with the perimeter beams (Fig. 1, a). The floor natural frequencies and the maximum deflections are determined. Since the check is done for the serviceability limit state (SLS), characteristic values of the dead and live loads are used in the analysis.

The general elements of the analysed floor are: spans of 14.0 x 14.0 m; beams HEA450 of steel S235, placed at a distance of 2.0 m between their axes on both directions; r.c. slab of 12 cm medium thickness, concrete C24/30 with E_C = 325 N/mm^2. The characteristic value of the dead load (including r.c. slab self weight, steel beams, floor, partition walls, false ceiling and ducts) is p_1 = 6.8 kN/m^2. The live load, p_2, has different values, of 3 kN/m^2 in the room area and 4 kN/m^2 in the corridor area.

Three models have been considered for the dynamic analysis of the floor, as follows. In the first model, M1, the composite floor is equalized with a grid of steel beams, as in Fig. 1, b, in two hypotheses. The first hypothesis is that the beams and the r.c. slab work together. In this case, the equivalent cross section of the beam is obtained by means of an equivalence coefficient corresponding to short-term actions, $n = E_S / E_C = 2100/325 = 6.46$. In the second hypothesis, when the beams and the slab do not work together, E_C = 0. In the model M2, the floor made of r.c. slab and steel beams, is fixed on the boundary (Fig. 1, c). In the model M3, the same floor from the model M2 is elastically supported by the perimeter beams and r.c. walls (Fig. 1, a).

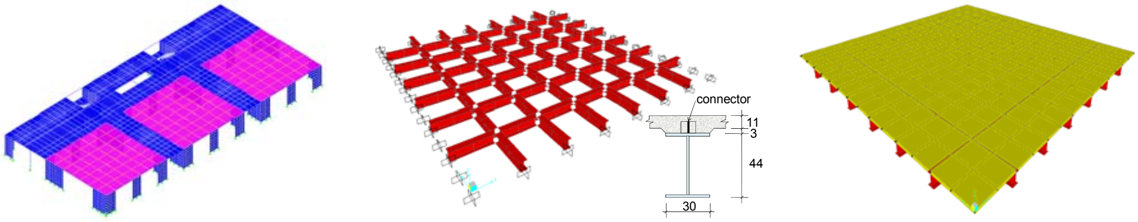
In the models M1 and M2, the floor is considered isolated from the structure and has rigid restraints on the boundary. In the model M3, a storey of the building is isolated, such as the floor dynamic characteristics and the deflections under gravity loads depend on the flexibility of the perimeter supporting members (beams and r.c. walls).

Each model is done in two variants regarding the concrete stiffness: non-degraded stiffness, by considering $\overline{E}_C = E_C$, and degraded stiffness, due to creep, shrinking and cracking, by reducing the Young modulus with 50% ($E_C^* = 0.5 E_C$).

The European Code for actions, Eurocode 1, gives the following formula for the load combinations:

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

where $G_{k,j}$ are dead loads with characteristic values, and $Q_{k,l}$ is the live load. The values of the coefficient $\psi_{1,1}$ can be smaller or at most equal to 1, depending on the nature of the live loading ($\psi_{1,1}$ = 0 if the load is not applied) [8].



a) b) c)

Fig. 1. Finite element models for the floor analysis

Since the natural frequencies of the floor depend on its mass and stiffness, the following load combinations have been considered, in accordance with Eurocode 1:

a) for the serviceability limit state (SLS):

LC1: the floor is acted only by the dead loads ($q_1 = p_1 = 6.8$ kN/m^2);

LC2: the floor is acted by the dead loads and 40% of the live load ($q_2 = p_1 + 0.4\, p_2$);

LC3: the floor is acted by the dead loads and the entire live load ($q_3 = p_1 + p_2$).

b) for the ultimate limit state (ULS):

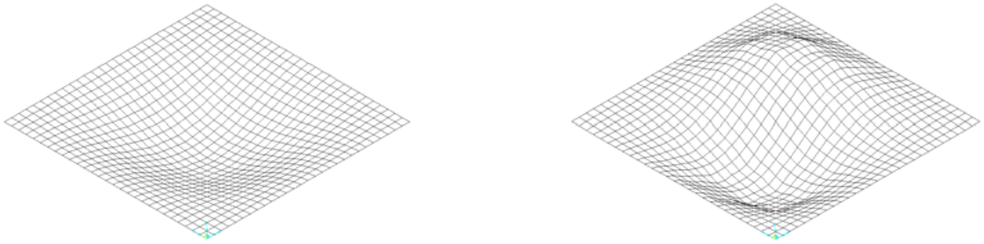
LC4: $q_4 = 1.35\, p_1 + 1.5\, p_2$

Natural frequencies and maximum deflections of the floor have been determined for each load combination. Figs. 2 – 3 show the first and the second vibration shapes of the floor in the models M1, M2, and M3, respectively. The values of the floor maximum deflections are given in *Table 1*, in each load combination and each hypothesis regarding the concrete stiffness.

(a) Mode 1, f_1 = 10.19 Hz

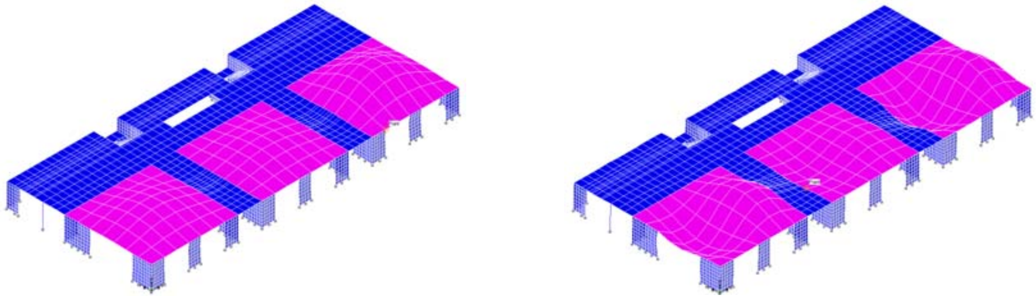
(b) Mode 2, f_2 = 19.44 Hz

Fig. 2. Floor modal shapes in model M1



(a) Mode 1, f_1 = 10.82 Hz (b) Mode 2, f_2 = 20.1 Hz

Fig. 3. Floor modal shapes in model M2



(a) Mode 1, f_1 = 7.69 Hz (b) Mode 2, f_2 = 14.84 Hz

Fig. 4. Floor modal shapes in model M3

LC		q_1	q_2	q_3	q_4
Model M1	$E_C = 0$	6.30	7.40	9.00	12.50
	$\overline{E}_C$	2.60	3.10	3.80	5.20
	E_C^*	3.00	3.60	4.30	6.10
Model M2	$\overline{E}_C$	2.40	2.79	3.50	4.80
	E_C^*	2.50	2.90	3.60	5.00
Model M3	$\overline{E}_C$	4.32	5.13	6.28	8.80
	E_C^*	5.52	6.50	7.95	11.15

Table 1. Maximum deflections of the floor, d_{max} [mm]

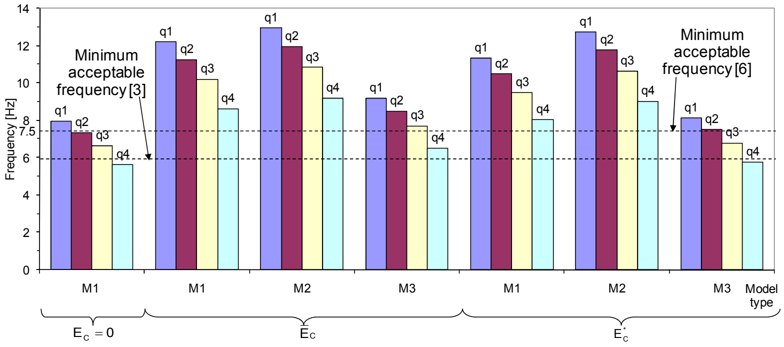


Fig. 5. First natural frequency of the floor, f_1 [Hz]

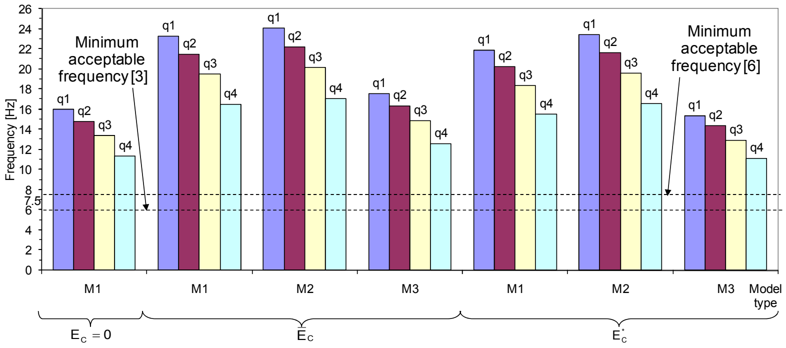


Fig. 6. Second natural frequency of the floor, f_2 [Hz]

Based on the frequency histograms presented in Fig. 5 and Fig. 6, the following remarks can be made:

- models M1 and M2 lead to close results;
- the results offered by the models M2 and M3 are significantly different, showing that neglecting the deformability of the perimeter members (beams, walls, columns) is unrealistic; 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 a lower limit case;
- the increase of the masses for the ULS (q_4) is an extreme, superior limit case;
- the check of the oscillations of large span floors, with possible large groups of people in movement, has to be done for the entire characteristic load (q_3);
- the first frequency of a composite floor can be approximately evaluated with the formula

$$f_1 = 20 / \sqrt{d_{max}}$$

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 first natural frequency becomes a condition much more restrictive than the deformability condition generally applied in floor designing, $d_{max} \le d_a = l/350$. For the analyzed floor, in the model M3 (with $E_C^* = 0.5 E_C$), $d_{max} = 8$ mm and $d_a = 14000/350 = 40$ mm. Therefore, $d_a / d_{max} = 5$.

4. CONCLUSIONS

The check of the dynamic characteristics of the floors with large span is mandatory. By using light materials with high strengths, light floors can be obtained, but generally these floors are flexible. The first natural frequency of the long span floors is thereby reduced and close to the frequency of the dynamic actions produced by groups of people walking or doing aerobics. The increase of the first natural frequency may be done by increasing the beam depth, thus reducing the storey clear height.

The correct evaluation of the natural frequencies depends on the floor modeling. Considering rigid supports gives large values of the frequencies, 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. On the other hand, the physico-mechanical characteristics of the materials, especially of the concrete, are different of those considered in analyses. That is why, experimental measurements in situ are absolutely necessary.

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