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Vibration Analysis and Fatigue Assessment of Floors. Part I: Human Rhythmic Activities

Ana C. S. da Silva[1], Elisângela A. R. Santos[1], Leandro A. Deus[1], Mayara M. Martins[1] and José G. S. da Silva[1,2]

1. State University of Rio de Janeiro (UERJ), Rio de Janeiro/RJ 20550-900, Brazil

2. Structural Engineering Department (ESTR), State University of Rio de Janeiro (UERJ), Rio de Janeiro/RJ 20550-900, Brazil

Abstract: Structural problems associated with excessive vibration of building floor systems when subjected to human rhythmic activities have been frequent. In this context, this research work aims to develop an analysis methodology to evaluate the human comfort and assess the fatigue performance of steel-concrete composite floors when subjected to human rhythmic activities (aerobics). The investigated structural model corresponds to a steel-concrete floor with dimensions of 10 m × 10 m and a total area of 100 m^2. The numerical model developed for the dynamic analysis of the floor adopted the usual mesh refinement techniques present in finite element method (FEM) simulations implemented in the ANSYS program. The investigated floor dynamic response was calculated through the consideration of people practicing rhythmic activities on the structure, in order to verify the occurrence of excessive vibration and to assess the human comfort. The fatigue assessment is based on a linear cumulative damage rule through the use of the Rainflow-counting algorithm and S-N curves from traditional design codes. The results indicated that, in several analysed situations, the investigated floor presents excessive vibration and user's discomfort. On the other hand, the structure service life values were higher than those proposed by the design codes, ensuring that the members, connections and joints will not fail by fatigue cracking.

Key words: Steel-concrete composite floors, human rhythmic activities, vibration analysis, human comfort, fatigue assessment.

1. Introduction

The current steel-concrete composite floors design might be susceptible to the resonance phenomenon causing undesirable vibrations in the frequency range that is the most noticeable to human perception, i.e. 4 Hz to 8 Hz [1].

This way, this work aims to study the dynamic behaviour and evaluate the human comfort of a composite floor, when subjected to human rhythmic activities. The investigated structural model is related to a composite floor presenting dimensions of 10 m by 10 m, and total area of 100 m^2. The dynamic loads representing the human rhythmic activities applied on the floor were obtained based on the use of the traditional "only-force" model proposed by Faisca [2].

The finite element model, developed for the steel-concrete composite floor dynamic analysis, adopted the usual mesh refinement techniques present in finite element method (FEM) simulations implemented in the ANSYS program [3].

Thus, after the dynamic structural analysis the human comfort was evaluated, based on the comparisons between the floor dynamic structural response and the recommended limits from the design standard AISC [4].

The fatigue analysis performed in this research work is based on a linear cumulative damage rule through the use of the Rainflow-counting algorithm and S-N curves from traditional design codes EUROCODE 3 [5], AASTHO [6] and NBR 8800 [7].

The main conclusions of this investigation focused on alerting to the importance of evaluating the dynamic structural behaviour, the human comfort and the fatigue service life of steel-concrete composite floors when subjected to dynamic loadings.

Corresponding author: José Guilherme Santos da Silva, D.Sc., full professor, research fields: dynamic analysis, steel-concrete composite structures, finite element modelling.

2. Human Rhythmic Activities Modelling

The rhythmic dynamic loading function is described in this investigation by the experimental approach proposed by Faisca [2], based on the use of the mathematical Hanning function.

Eq. (1) presents the "only-force" mathematical model developed based on experimental tests [2]. In Eq. (1), $F(t)$ is the dynamic force (N); CD is the phase coefficient; K_p is the impact coefficient; P is the person's weight (N); T_c is the activity contact period (s); T is the activity period (s) and t is the time (s).

$$F(t) = CD\left\{K_p P\left[0.5 - 0.5\cos\left(\frac{2\pi}{T_c}t\right)\right]\right\} \qquad t \le T_c \tag{1}$$

$$F(t) = 0 \qquad T_c \le t \le T$$

3. Finite Element Modelling of the Floor

The finite element model was constructed based on a steel-concrete composite floor spanning 10 m by 10 m, with a total area of 100 m^2. The floor is made of steel beams and a 100 mm thick concrete slab (see Fig. 1). The steel sections used were made from a 345 MPa yield stress steel grade (ASTM A572) and the concrete slab presents compression strength of 20 MPa.

The numerical model developed for the composite floor dynamic analysis adopted the usual mesh

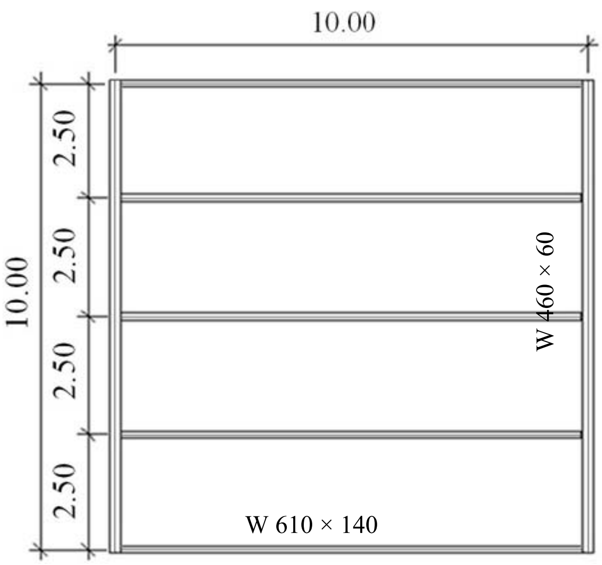


Fig. 1 Investigated structural model (units in m).

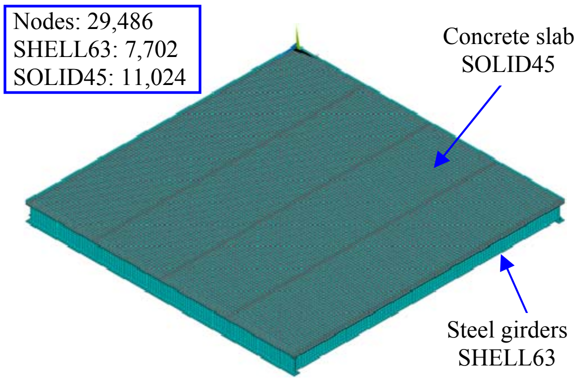


Fig. 2 Composite floor finite element model.

refinement techniques present in FEM simulations implemented in the ANSYS program [3]

The steel girders were represented by shell finite elements (SHELL63), and the floor concrete slabs were simulated based on the use of solid finite elements (SOLID45), see Fig. 2. The final developed computational model presents 29,486 nodes, 18,726 elements and 113,532 degrees of freedom.

4. Natural Frequencies and Vibration Modes

The modal analysis was performed and it was verified that the first two natural frequencies of the studied composite floor, varying from 6.01 Hz to 7.39 Hz (Table 1), are close to the excitation frequency range associated to aerobics.

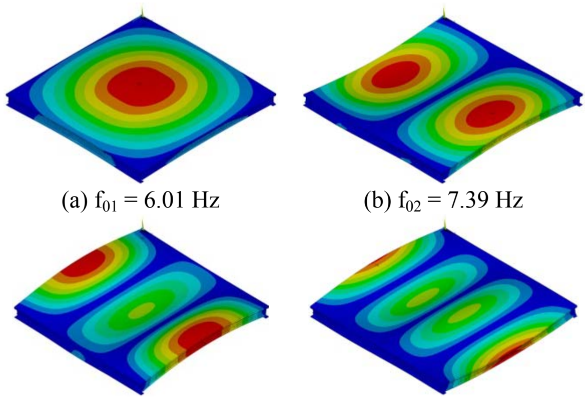
In this situation, the frequency of the third harmonic of the dynamic loading may match these natural frequencies and therefore lead the composite floor to a resonant motion. Therefore, such situation might result in undesirable vibrations and thus human discomfort.

In sequence, Fig. 3 presents the main global vibration modes of the steel-concrete composite floor.

It must be emphasized that all investigated steel-concrete composite floor vibration modes have presented a predominant flexural behaviour.

Table 1 Natural frequencies and modal masses.

Vibration modes	Composite floor frequencies (Hz)	Modal mass/structure mass Mass ratio (%)
f_{01}	6.01	96.58
f_{02}	7.39	73.96
f_{03}	9.27	32.44
f_{04}	12.20	26.72



(a) f_{01} = 6.01 Hz (b) f_{02} = 7.39 Hz

(c) f_{03} = 9.27 Hz (d) f_{04} = 12.20 Hz

Fig. 3 Vibration modes of the investigated floor.

5. Human Comfort Analysis

In this study, the simulation of rhythmic human actions (aerobics) was represented by the dynamic loading model developed by Faisca [2].

The excitation frequency of 2 Hz was considered, which corresponds to the first harmonic range (aerobics) [4]. It is also assumed that a single person's weight is equal to 800 N and the structural damping is taken as ξ = 1% (ξ = 0.01) according to ISO10137 [8]. This way, the floor dynamic response was investigated based on the structural sections A to C, see Fig. 4.

The composite floor structural response was determined based on the use of the dynamic loadings associated to 12, 16 and 20 people practicing aerobics on the concrete slab (0.25 people/m^2), see Fig. 5.

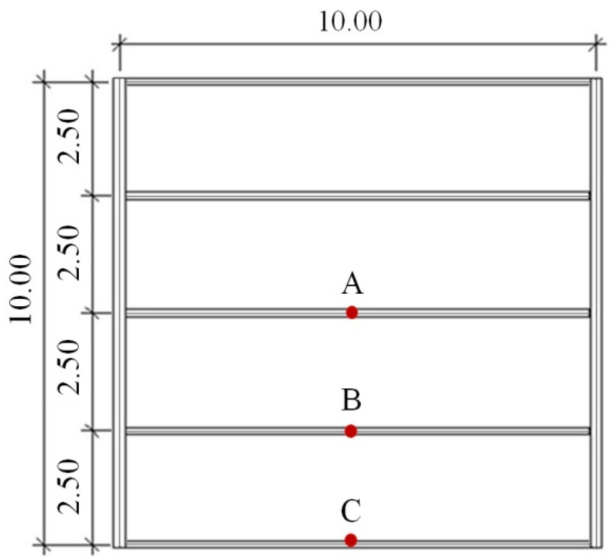
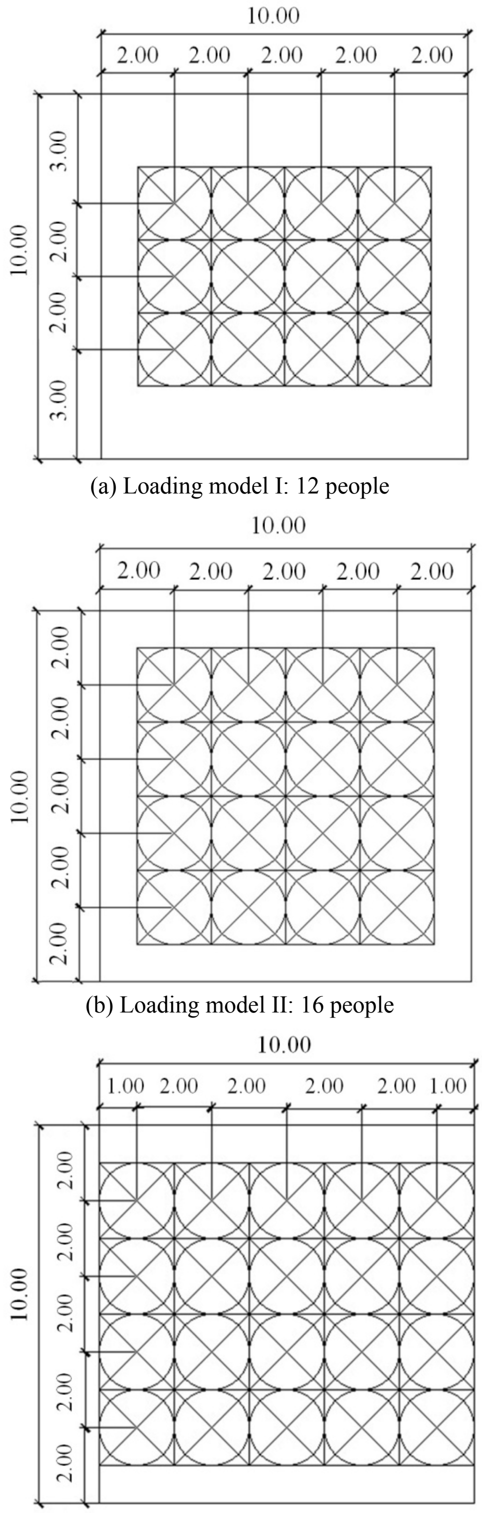


Fig. 4 Investigated structural sections: A to C (units in m).



(a) Loading model I: 12 people

(b) Loading model II: 16 people

(c) Loading model III: 20 people

Fig. 5 Dynamic loads on the composite floor (units in m).

Thus, after the analysis, it was possible to verify the high values of the dynamic response in several design situations (loading models I to III), see Tables 2 and 3.

Table 2 Dynamic structural response: displacements.

Loading model	Displacement (mm)		
	Section A	Section B	Section C
12 people	1.87	1.48E-03	2.32E-04
16 people	2.24	1.77E-03	2.64E-04
20 people	2.31	6.32E-04	3.11E-04

Table 3 Dynamic structural response: accelerations.

Loading model	a_{peak} (m/s^2)		
	Section A	Section B	Section C
12 people	0.48	0.37	0.074
16 people	0.58	0.44	0.085
20 people	0.59	0.16	0.031

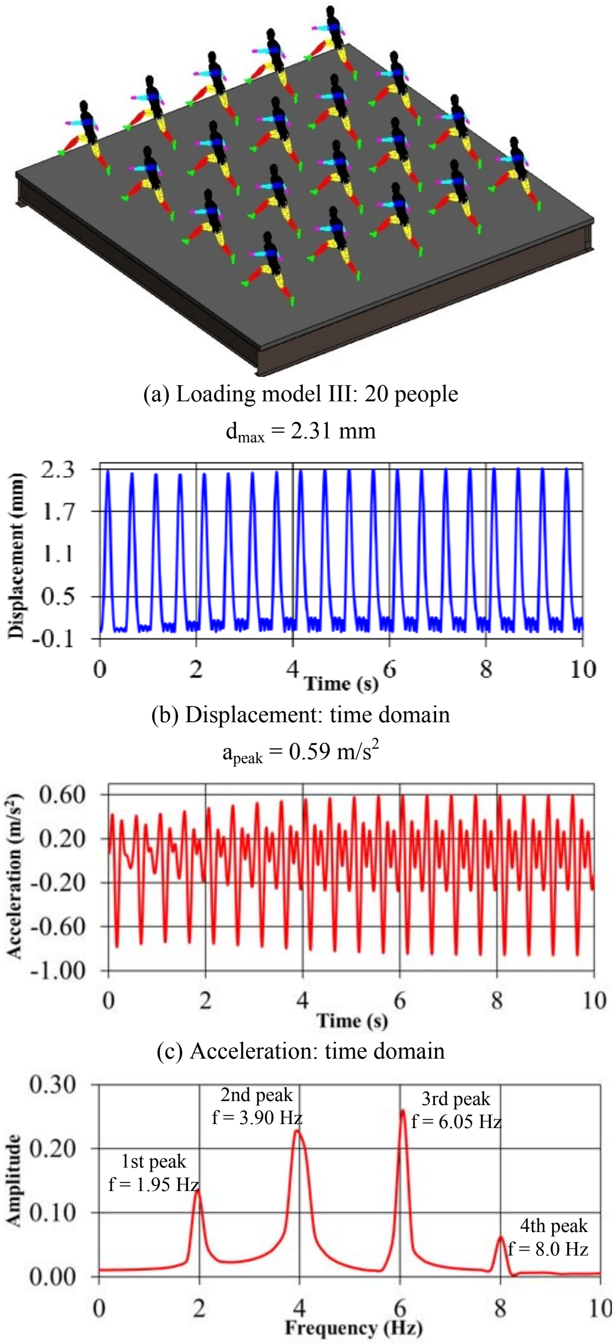
The results shown in Tables 2 and 3 pointed out that Section A presented the highest displacements and accelerations values, when compared to the other investigated structural sections (B and C), considering the analysed loading models (12, 16 and 20 people).

Therefore, considering the most design unfavourable situation (Section A), it is also observed that only the first loading model (12 people) did not exceed the recommended limit proposed by AISC [4] (a_{peak} < a_{lim} = 0.50 m/s^2). On the other hand, the loadings models II and III have generated peak accelerations values higher than the limit proposed by AISC [4], resulting in discomfort for the users (a_{peak} > a_{lim} = 0.50 m/s^2). When the floor sections B and C are investigated, it is clear that the loadings models did not cause undesirable vibrations on the structure (see Table 3).

In order to illustrate these analyses, Fig. 6 shows the composite floor dynamic structural response, in time and frequency domain, considering the dynamic loadings related to 20 people practising aerobics, evaluated as the worst design case scenario.

It must be emphasized that the results indicated that, in several situations, the investigated steel-concrete composite floor presents excessive vibration and user's discomfort (see Table 3).

It is important to point out that the stress values calculated in the floor dynamic structural response will be used later for the fatigue analysis.



(a) Loading model III: 20 people

d_{max} = 2.31 mm

(b) Displacement: time domain

a_{peak} = 0.59 m/s^2

(c) Acceleration: time domain

(d) Acceleration: frequency domain

Fig. 6 Floor dynamic structural response (Section A).

6. Fatigue Assessment

Dynamic impacts due to rhythmic human activities can induce significant increase of the displacements and stresses values. These dynamic actions can generate the nucleation of fractures or even their propagation on the floor structure.

The proposed analysis methodology evaluates the fatigue performance (nominal stress) of steel-concrete composite floors subjected to rhythmic human activities. The developed methodology is based on a linear cumulative damage rule and Rainflow counting method is used to calculate the stress range magnitudes. A flowchart of the overall process applied for a typical fatigue assessment on steel-concrete composite floors details is presented in Fig. 7.

Then, Fig. 8 illustrates the stress history, over time, obtained to assess the fatigue service life associated with the floor section where the maximum effects occur (Section A) for the dynamic loadings related to 20 people practising aerobics (Fig. 5c), evaluated as the worst design case scenario.

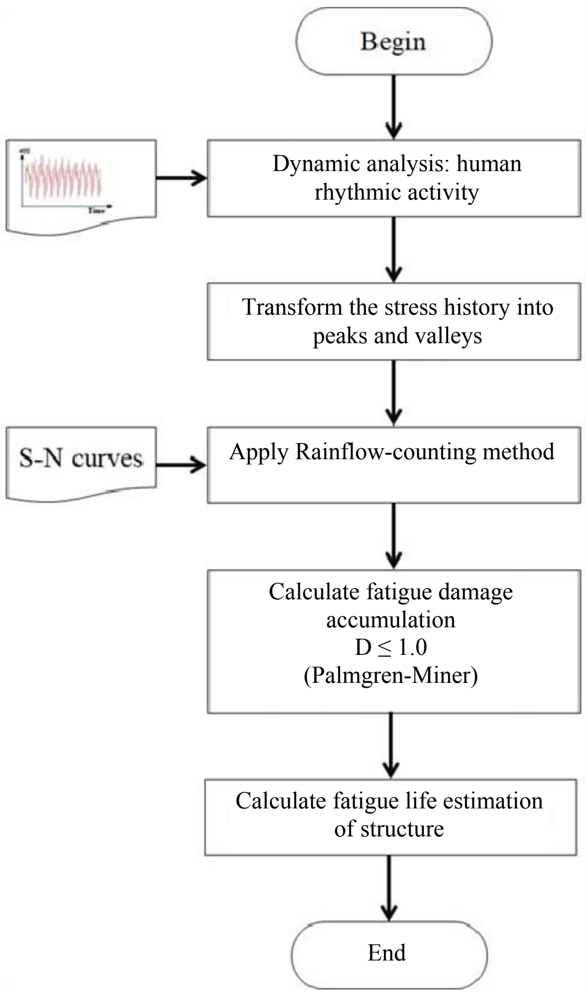


Fig. 7 Fatigue assessment analysis methodology.

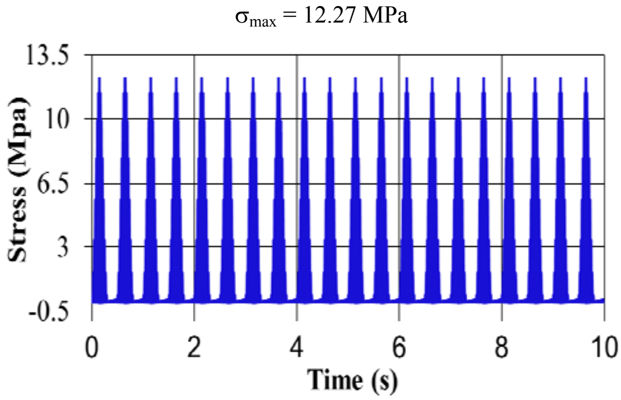
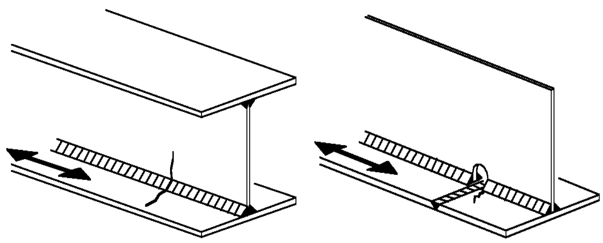


Fig. 8 Loading model III: stress history (Section A).

The investigated structural details (Details I and II) are in accordance with EUROCODE 3 [5], AASTHO [6] and NBR 8800 [7] (see Fig. 9 and Table 4). In this analysis it is also assumed a number of cycles equal to 2 million per year ($2 \times 10^{+6}$ cycles).

Fatigue life calculations based on Palmgren-Miner's rule were performed considering the Details I and II (Fig. 9). Tables 5 and 6 show the calculated fatigue life estimation in years for each analysed structural detail, respectively (Details I and II). Under these conditions, and considering the most unfavourable design situation (loading model III: Fig. 5c), and the first investigated structural detail (Detail I: Fig. 9a), the calculated fatigue life was equal to 825.5 years, 813.04 years and 805.86 years, respectively, when EUROCODE 3 [5], AASTHO [6] and NBR 8800 [7] recommendations were used (Table 5).



(a) Detail I (b) Detail II

Fig. 9 Investigated structural details I and II.

Table 4 Structural details for each design standard.

Detail	EUROCODE 3 [5]	AASHTO [6]	NBR 8800 [7]
I	125	B	B
II	71	D	D

Table 5 Fatigue assessment: Detail I (service life in years).

Loading model	$\Delta\sigma_{max}$ (MPa)	EUROCODE 3 [5]	AASHTO [6]	NBR 8800 [7]
12 people	7.36	4,031	3,970	3,942
16 people	9.82	1,462	1,440	1,428
20 people	12.27	825	813	805

Table 6 Fatigue assessment: Detail II (service life in years).

Loading model	$\Delta\sigma_{max}$ (MPa)	EUROCODE 3 [5]	AASHTO [6]	NBR 8800 [7]
12 people	7.36	716.95	728.49	722.71
16 people	9.82	260.08	264.27	261.9
20 people	12.27	148.8	149.16	147.74

On the other hand, considering the same unfavourable situation (loading model III: Fig. 5c), for the Detail II (Fig. 9b), the fatigue life was equal to 148.8 years, 149.16 years and 147.74 years, respectively, when EUROCODE 3 [5], AASTHO [6] and NBR 8800 [7] rules were used (Table 6).

Therefore, analysing the service life values of the investigated steel-concrete composite floor (see Tables 5 and 6), it must be emphasized that the structure service life values were higher than those proposed by the design codes (EUROCODE 3 [5]: 120 years; AASTHO [6]: 75 years), ensuring that the members, connections and joints will not fail by fatigue cracking.

7. Conclusions

This paper investigated the dynamic behaviour of a steel-concrete composite floor spanning 10 m by 10 m, when subjected to the dynamic actions coming from human rhythmic activities (aerobics). The developed analysis methodology enabled a complete evaluation of the floor in terms of human comfort and fatigue assessment. This way, the following conclusions can be drawn from the results presented in this investigation:

(1) It was verified that the first two natural frequencies of the studied steel-concrete composite floor are close to the excitation frequency range related to the aerobics.

(2) Based on the floor dynamic structural analysis it was concluded that in several situations, associated to the most unfavourable situation (Section A), the floor peak accelerations values surpass the recommended limits (a_{peak} > 0.50 m/s^2 [4]), provoking excessive vibrations and user's discomfort.

(3) On the other hand, considering the fatigue limits proposed by EUROCODE 3 [5] (120 years) and by AASTHO [6] (75 years), it is crystal clear that the investigated composite floor meets the standard's recommendations for the analysed structural details.

Acknowledgments

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