CILAMCE
PANACM
RIO DE JANEIRO 2021

Steel-concrete composite floors subjected to mechanical equipment loads: dynamic analysis and fatigue assessment

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Abstract. This research work aims the study of the dynamic structural behavior and assesses the service life of steel-concrete composite floors when subjected to the vibrations induced by mechanical equipment. The development of this research becomes necessary due to the growing issues associated with excessive floors vibrations arising from dynamic loads, which are likely to cause human discomfort or even reduce the system service life. This way, the investigated structural design is based on a steel-concrete composite floor with dimensions of 5m x 5m and a total area of 25 m². The numerical modelling of the composite floor model was generated based on usual modelling techniques adopting the mesh refinement present in the Finite Element Method (FEM) and implemented in the ANSYS program. The applied loads were simulated based on harmonic forces related to the dynamic loadings imposed by the equipment on the concrete slab (generation unit: motor, gear unit and coupling). The investigated floor dynamic structural response was calculated by considering several types of equipment acting on the floor areas specified in the project, aiming to verify the occurrence of excessive vibrations and assess the steel-concrete composite floor service life, considering the recommended limits proposed in the traditional international design standards.

Keywords: Steel-concrete composite floors; Dynamic structural analysis; Fatigue assessment.

1 Introduction

Structural systems consisting of steel-concrete composite floors have been widely used to solve engineering problems regarding their use in large free spans, having in mind the utilisation of optimized structures. On the other hand, this type of structural system has been presenting problems associated with excessive vibrations, and it is recommended that the dynamic structural behavior of composite floors be rigorously investigated, mainly when submitted to the action of dynamic loads. (Alencar [1] and Menezes Junior [2, 3]).

Thus, aiming to contribute to the study of the current issue, an investigation was carried out on the dynamic structural response and fatigue assessment of a composite floor (steel-concrete), used as a technical pavement, when submitted to the action of dynamic loads from mechanical equipment.

The applied loads were simulated based on harmonic forces related to the dynamic loadings imposed by the motor generator (mechanical equipment). Regarding the evaluation of structural fatigue, the procedures recommended by the international design standard Eurocode 3 [4] were used.

The conclusions reached based on the development of this research work show the importance of evaluating the dynamic structural response and analyzing the fatigue life of composite floors (steel-concrete) when subjected to cyclic dynamic actions.

2 Modelling of the steel-concrete composite floor

2.1 Steel-concrete composite floor

The investigated structural model is based on a steel-concrete composite floor (steel-concrete), consisting of steel beams of material ASTM A572 Grau 50 (fy = 345 MPa) and reinforced concrete slab (fck = 25 MPa). The main beams and the secondary beams are composed of laminated W360 x 32.9 and W250 x 28.4, respectively. The concrete floor slab has a thickness of 10 cm and dimensions of 5m x 5m, and a total area of 25 m^2, as illustrated in Fig. 1.

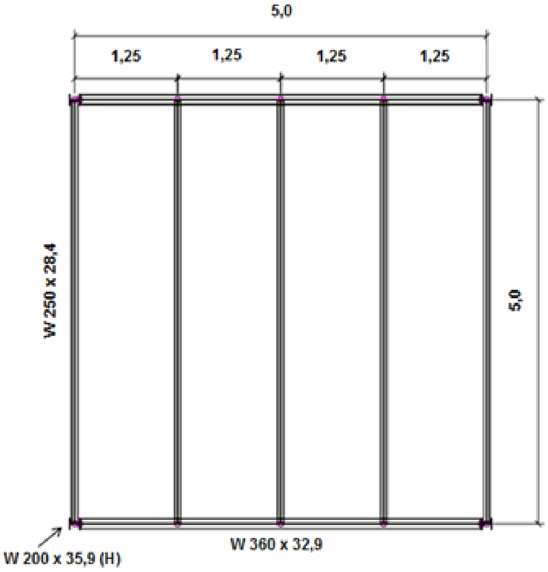


Figure 1. Composite floor (steel-concrete) analysed (dimensions in meters).

The composite floor (steel-concrete) investigated in this research work consists of an area destined to be a technical floor, where the allocation of large mechanical equipment is necessary. The equipment used in this research corresponds to motor-generator formed by a motor (rotor weight 1102 kg, with frequency 28.5 Hz) and a reducer (3822 Kg, 28.5 Hz frequency). The total mass of the equipment is 7115 kg (Menezes Junior[2]). The equipment is shown in Fig. 2.

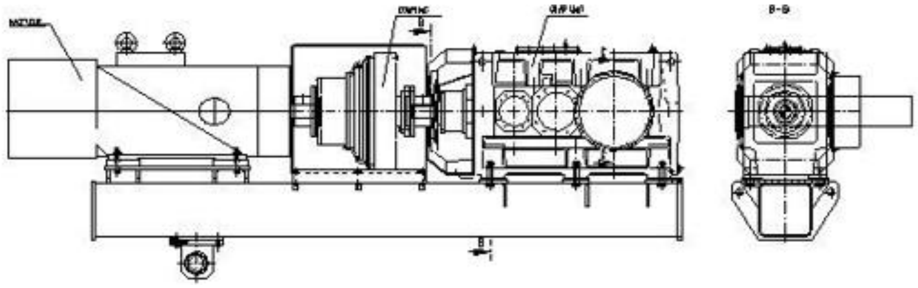


Figure 2. Researched Equipment: Engine generator (Menezes Junior [2])

The loads on the structural model under study are those used in the structural design; static loads and dynamic loads. Static loads are the weight of the structure itself, the coating on the concrete slab, and design overloads. On dynamic loading, was used a dynamic harmonic action from the equipment, variable over time, and simulated using eq. (1).

$$F(t) = F_0 \text{ sen } \omega t = M \omega^2 e \text{ sen } \omega t = M \omega (\omega e) \text{ sen } \omega t = M \omega R \text{ sen } \omega t \quad (1)$$

Equation. (1), "F_0" represents the amplitude of the sinusoidal harmonic load [$F_0 = M\omega^2 e$]; "M" is the rotor mass; ω concerns the frequency of excitation; "e" represents the eccentricity; "R" [$R = \omega e$] is associated with the quality of equipment balancing [R = 2,5 mm/s; [2, 5]], "t" is about time. Throughout the analyses, dynamic loads were simulated based on the use of one, two, and three generators, according to the geometry and usable area of the studied floor.

2.2 Modelling of finite element

The computational model developed for the dynamic analysis of the composite floor adopted the usual mesh refinement techniques present in the finite element method simulations implemented in the ANSYS program [6]. The steel beams (girder top and bottom flanges, the girder web) were represented by finite shell elements (SHELL63), which has four nodes with six degrees of freedom in each node, translations in the direction of the X, Y, and Z axes and rotations around the X, Y and Z axes. The floor concrete slab was simulated by solid finite elements (SOLID45) have eight nodes with three degrees of freedom per node, translations in the direction of the X, Y, and Z axes. The computational model adopted used 2677 SHELL63 elements, 3074 SOLID45 elements, and 8700 nodes that make up the mixed structural system (steel-concrete)

It is noteworthy that the numerical modeling considers the complete interaction between steel and concrete (total interaction). Then, Fig. 3 illustrates the finite element model developed in this investigation. The application of dynamic actions representative of the case where three pieces of equipment acting on the concrete slab are considered.

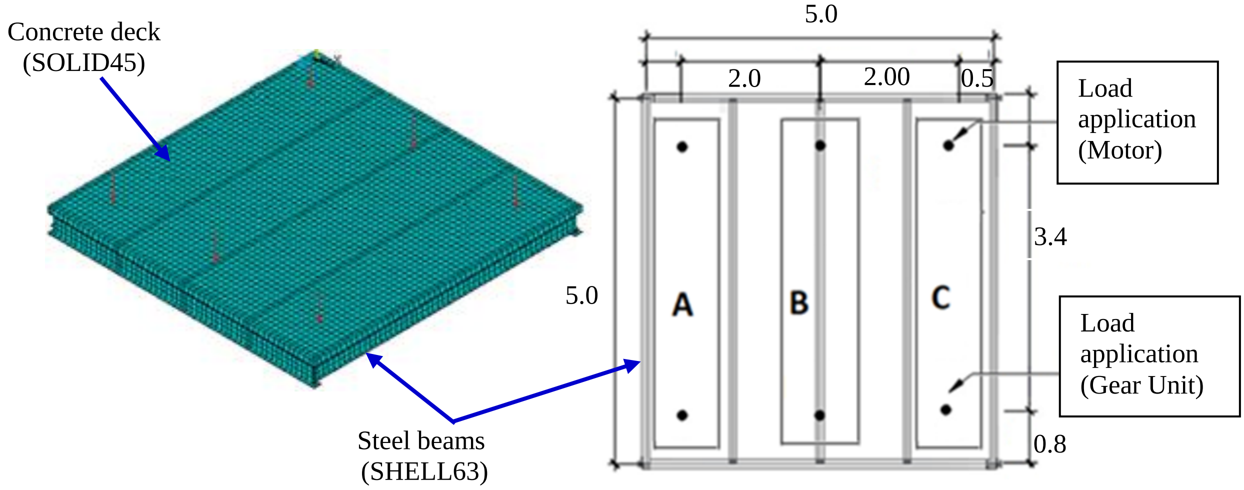


Figure 3. Investigated steel-concrete composite floor (units in meters)

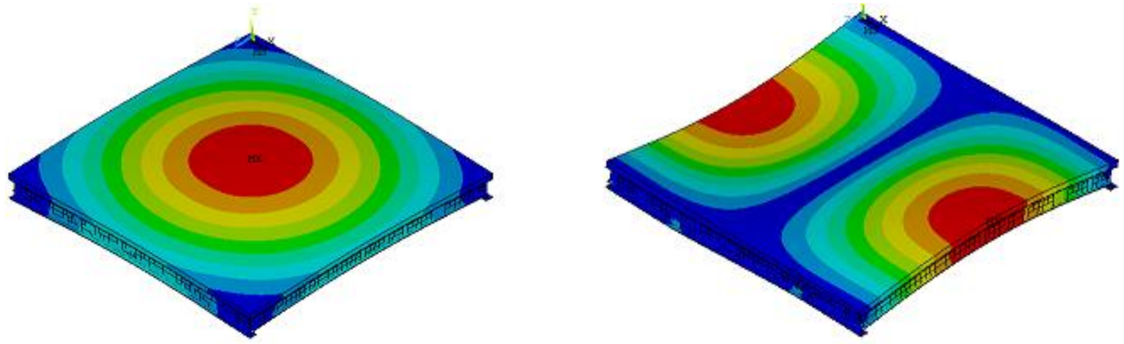
3 Dynamic structural analysis

The dynamic analysis was performed based on the finite element program, ANSYS (2012) program [6]. First, the values of the natural frequencies and the vibration modes of the structure were obtained. Then, forced vibration analyzes were carried out in the time domain, based on the development of a study on the position of the equipment wit 1, 2 or 3 generators, for better use of the floor.

The dynamic loads from the equipment were applied in the vertical direction on their support positions on the concrete slab. Fig. 3 illustrates the positioning of three pieces of equipment acting on the floor (most unfavorable situation). The dynamic loading from the equipment was simulated using eq. (1), and the Newmark method was used for the numerical integration of the dynamic equilibrium equations, with the temporal variation of up to 10 seconds and increment of $\Delta t = 10^{-3}$ s

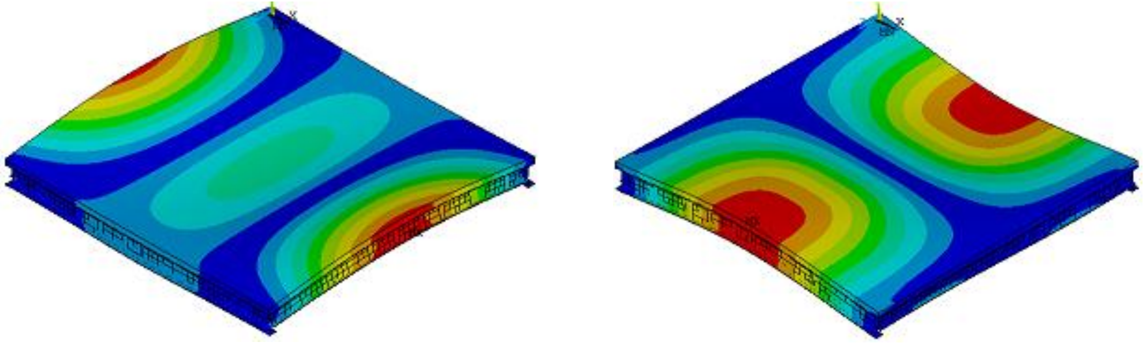
3.1 Natural frequencies and vibration modes

The natural frequencies (eigenvalues) and vibration modes (eigenvectors) of the composite floor (steel-concrete) were obtained from a free vibration analysis (modal analysis), using the ANSYS (2012) program. The associated composite floor main global vibration modes are shown in Fig. 4. By verifying the values of the structure's natural frequencies, it is highlighted that the equipment has an excitation frequency of 28.56 Hz for the motor, which is in resonance with the third natural frequency of floor bending and 0.94 Hz for the reducer, as shown in Fig. 4.



a) 1º vibration mode
f_{01} = 16.00 Hz

b) 2º vibration mode
f_{02} = 21.52 Hz



c) 3º vibration mode
f_{03} = 28.56 Hz

d) 4º vibration mode
f_{04} = 36.46 Hz

Figure 4. Main global vibration modes of the investigated structure obtained using the finite element modelling

3.2 Dynamic structural response of the composite floor (steel-concrete): forced vibration

The dynamic structural response of the floor was obtained by simultaneously applying the static loading and as dynamic actions from the equipment. Static loads were corresponding to the weight of the structure and the coating of the concrete slab (1.5 kN / m²), in addition to accidental overload (3.0 kN / m²). The dynamic actions from the capacitors were numerically simulated according to eq. (1).

The values of vertical translational displacements and stresses were obtained, in the time domain, considering a structural damping coefficient equal to 1.5% (ξ = 1.5% by Clough and Penzien [7]). The reference node chosen for the analysis of the dynamic floor response was the one where the maximum effects occurred, located in the middle of the central secondary beam (W250 x 28.4), Fig 1, at the meeting of the web with the lower flange from the beam. Fig. 5 and Fig. 6 and Tab. 1 show the dynamic response of the floor, in the steady-state phase of the response, in the section where the maximum values of Translational vertical displacement and stresses.

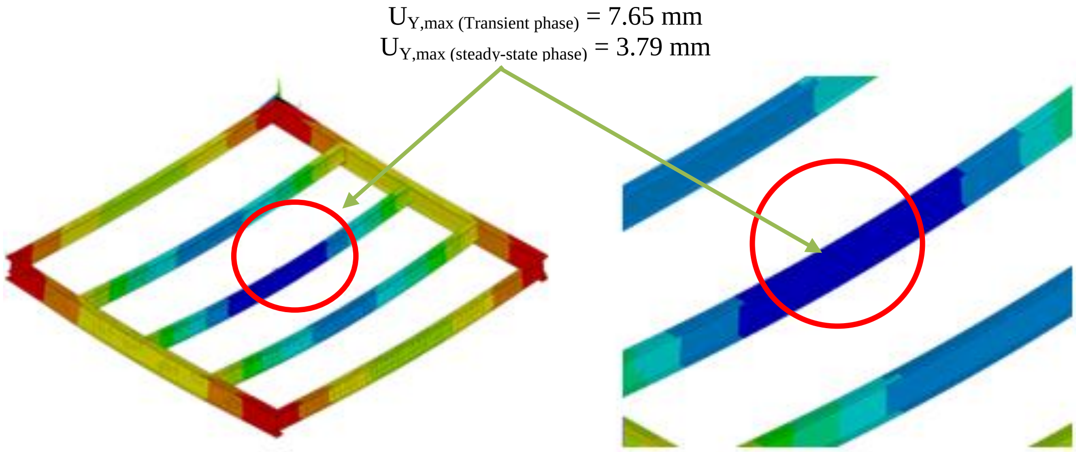


Figure 5. Translational vertical displacement values: 3 generators.

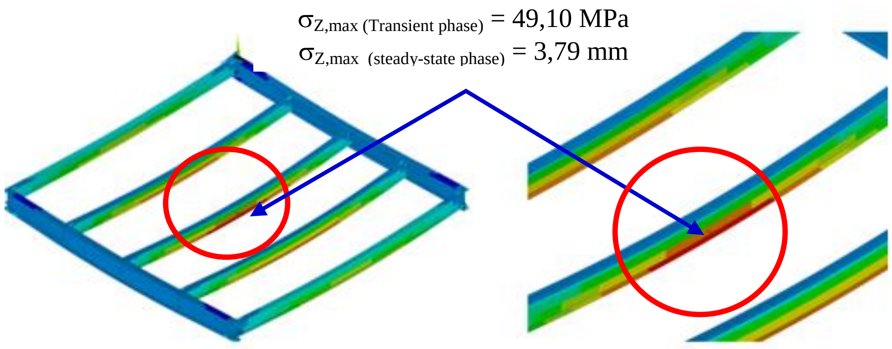


Figure 6. Maximum Stress σ_Z of the floor: 3 generators.

Table 1. Translational vertical displacement (U_Y) e Maximum Stress (σ_Z).

Dynamic loading cases	U_Y (mm)	σ_Z (MPa)
3 Generators	3.79 mm	49.10 MPa
2 Generators	3.84 mm	49.67 MPa
1 Generator	3.76 mm	48.77 MPa

In sequence, Fig. 7 and Fig 8 illustrate the general floor dynamic structural behaviour, considering the action of 3 generators, see Fig. 3, keeping in mind the amplitude of the harmonic dynamic load, see eq. (1). It is noteworthy that the stress values captured in the steady-state phase of the dynamic structural response will be used later for fatigue analysis, aiming to determine the service life of the composite floor (steel concrete).

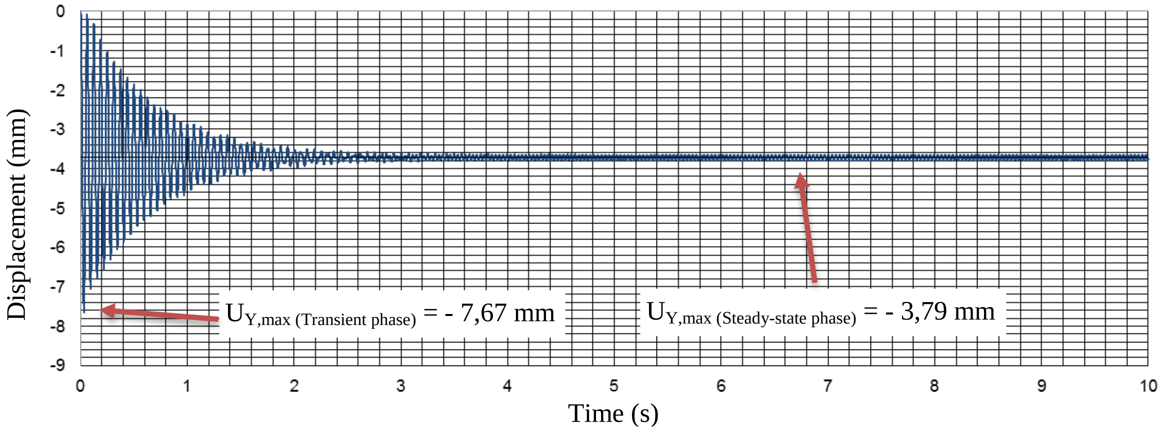


Figure 7. Translational vertical displacement U_Y (time domain): 3 generators

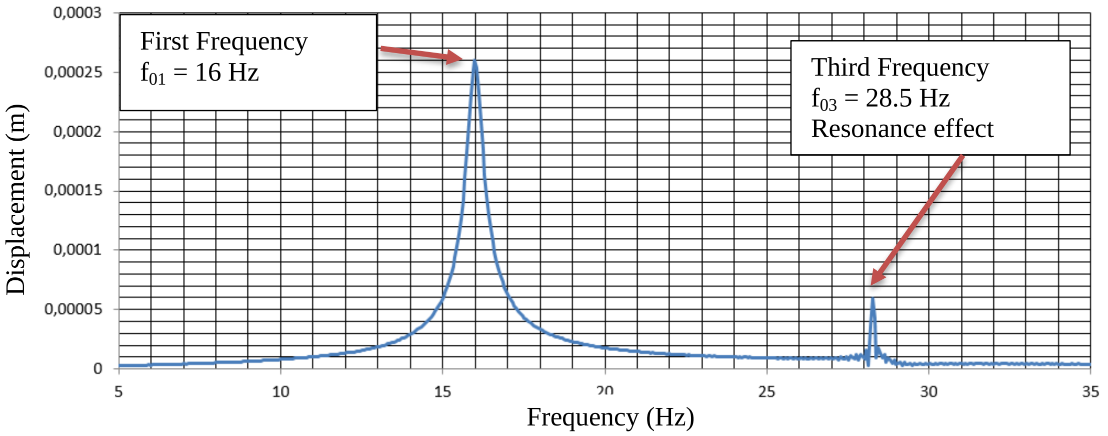


Figure 8. Translational vertical displacement U_Y (frequency domain): 3 generators.

4 Fatigue service life

Regarding the determination of the service life of fatigue and cumulative damage, it is necessary to obtain the range of stress variation that occurs on the structure during the use of the equipment. The maximum stress value was calculated based on the consideration of the usual design loads (own weight, coating, and accidental loads) and the dynamic load produced by the equipment.

The fatigue analysis was performed following the classical methodology for assessing fatigue damage in structures due to effects caused by loads of variable amplitude, based on the use of S-N curves, the Palmgren-Miner linear damage rule, and rainflow counting algorithm (Alencar [1]).

Then, Fig. 9 illustrates the stress history, over time, obtained to assess the fatigue service life associated with the floor section where the maximum effects occur. The stress history was obtained at the center of the intermediate secondary beam, consisting of profiles of the type W250 x 28.4, see Fig. 1 and Fig. 6. For this purpose, a structural detail of the contour weld type was considered, referring to class 63 of Eurocode [4].

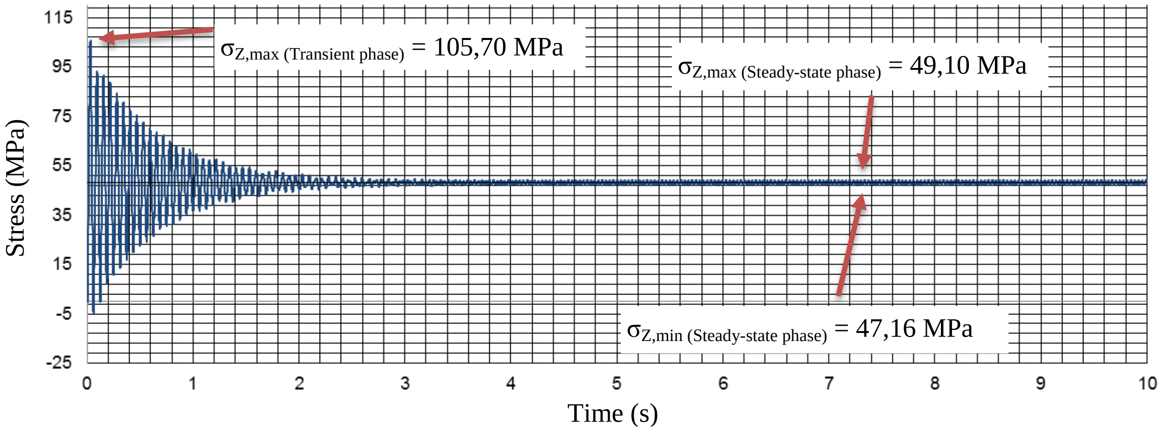


Figure 9. Stress σ_Z (time-domain): 3 generators

Regarding the calculation of the stress range values (cycle counting), the dynamic response in the steady-state phase was considered. Tab. 2 presents the useful life calculated for the investigated structural detail, highlighting that each stress cycle was proportionally associated with the value of 2 x 10^6 cycles for fatigue assessment (Eurocode 3[4]).

Table 2. Fatigue life of composite floor (steel-concrete)

Analysis	$\Delta\sigma_{max}$ (MPa)	Σ N^0 of cycles	Damage (D)	Fatigue life (years) [T = 1/D]
3 Generator	2.27	47.5	2.11x 10^{-5}	47367 (Infinite)
2 Generator	2.29	84.5	9.58x 10^{-5}	10431 (Infinite)
1 Generator	0.23	74	3.33x 10^{-8}	29953676 (Infinite)

Therefore, observing the service life values of the analysed steel-concrete composite floor, as presented in Tab. 2, it is crystal clear that the structural system don't surpass the design limit and fatigue verification proposed by Eurocode 3 [4]. On the other hand, when the investigated floor is subjected to the loads of 2 equipment, the service life is lower when compared with the two other studied situations (1 and 3 equipment).

5 Conclusions

Based on the development of this research work, a dynamic structural analysis of a composite floor (steel-concrete) with dimensions of 5m x 5m and a total area of 25m² was performed aimingoto verify the fatigue (service life), when subjected to dynamic loads (mechanical vibrations) produced by motor-generator sets.

Regarding the analysis of natural frequencies and vibration modes, it was found that the floor has high-frequency values, with the first natural bending frequencies equal to 16 Hz, 21.52 Hz, 28.56 Hz, and 36.45 Hz. Having in mind that the motor-generator excitation frequency is f = 28.50Hz, and this value is near of the the natural frequencies of the investigated structural system, the ressonance phenomenon can occur. This way, it is necessary to perform the dynamic analysis (forced vibration) and also verify the service life of the floor.

In this investigation, 3 simulations (3, 2 and 1 generator) were performed, based on the forced vibration analysis e the fatigue analysis. This way, the calculated floor fatigue service life values are much higher than those required by the Eurocode 3 [4], and the structure did not present problesm related to fatigue, considering the 3 dynamic loading hypotheses. A critical point verified along the analysis was that the dynamic response superposition effect was more significant for the case with 2 equipment when compared to the arrangement with 3 equipment on the floor. This way, the investigation has concluded that each loading situation, distribution, positioning, and operation of the equipment must be analysed as well.

Acknowledgments. The authors gratefully acknowledge the financial support for this research work provided by the Brazilian Science Foundation’s CNPq, CAPES and FAPERJ. The authors would like to thank the support from UERJ and IFB.

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