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Vibration Analysis of Orthotropic Composite Floors for Human Rhythmic Activities

Competitive world market trends have long been forcing structural engineers to develop minimum weight and labour cost solutions. A direct consequence of this design philosophy is a considerable increase in problems related to unwanted floor vibrations. This phenomenon is very frequent in a wide range of structures subjected to dynamical loads. The main objective of this paper is to evaluate an orthotropic solution for composite floors subjected to dynamical actions such as rhythmical activities arising from gymnastics, musical and sports events and ballroom dances. The proposed analysis methodology considers the investigation of the dynamic behaviour of a building floor made with a composite slab system with steel beams and an incorporated steel deck. The results indicated that the investigated composite floor violates the vibration serviceability limit state, but satisfied the human comfort criteria.

Keywords*: dynamic, vibrations, steel structures, composite floors, human comfort, dynamic structural design, rhythmic dynamical loads, human rhythmic activities*

Introduction

Structural designers have long been trying to develop minimum cost solutions, as well as to increase the construction speed. This procedure has produced slender structural solutions, modifying the ultimate and serviceability limit states that govern their structural behaviour. A direct consequence of this design trend is a considerable increase in the problems related to unwanted floor vibrations. This phenomenon is becoming very frequent in a wide range of structures subjected to dynamical actions. These load actions are generally caused by human activities such as: sporting events, dance or even gymnastics (Bachmann and Ammann 1987, Ellis and Ji 1994, Murray and Howard 1998, Silva et al. 2003, Stephenson and Humpreys 1998, Vecci et al. 1999).

This significant growth in building floors subjected to unwanted vibrations is caused by the fact that a significant number of structural engineers disregard, or even do not know how to incorporate the dynamical actions in the structural analysis. This procedure limits current structural designs to a simple static analysis that can, in extreme cases, demand a structure redesign or even a structure retrofitting.

Proper consideration of all the aspects earlier mentioned calls for an investigation of the structural behaviour of composite floors subjected to dynamical load actions. The main objective of this paper is to evaluate the dynamic behaviour composite slabs with an incorporated steel deck. This investigation is focused on the possible occurrence of unwanted vibrations that could cause human discomfort or, in extreme cases, structural failure.

The evaluation of the structural system vibration serviceability limit state implies in the knowledge of the structure dynamical response. Alternatively, simple procedures for the evaluation of the system vibration levels are found in design standards (Canadian Standard 1995, CEB 1991, DIN 4150-2 2000, ISO 2631-2 2003). These recommendations are based on parameters like: structure and excitation frequencies, peak accelerations, velocities and displacements.

This paper presents and discusses results related to the characterization of the structure natural frequencies, followed by a comparison of the excitation frequencies. Afterwards, results of an extensive computational analysis performed to obtain the structure dynamic response, based on accelerations, velocities and displacements, are depicted.

When a composite floor incorporates a steel deck the isotropy of the structural system is a hypothesis that can be at least considered questionable. One of the most commonly used solutions to better represent the composite floor is to consider it an orthotropic system where the major direction is parallel to the steel deck ribs span.

A usual design assumption considers the major direction stiffness as the addition of the portion related to the concrete slab above the steel deck ribs plus an extra term that incorporates an “effective width” based on the ratio of concrete area present in the ribs over the overall area (ribs + voids). In the minor direction, only the first part is considered i.e. the concrete cover slab, above the concrete slab ribs. This simple hypothesis can be easily incorporated to any design model and the results strongly depend on the steel deck geometry.

Previous investigations (Silva et al. 2003), based on the isotropic analysis demonstrated that the level of dynamical effects (displacements, velocities and accelerations), on composite floors subjected to rhythmic dynamical load actions is quite high. The level of these dynamic effects could induce excessive vibrations, causing human discomfort and even compromising the structural system safety.

This investigation continued with a parametric study using the orthotropic model for the concrete slabs. It focused the use of different steel deck geometries and their influence on the dynamical response of commonly used composite floors with steel decks. The main geometrical parameters evaluated were the concrete/voids-rib ratio, the ribs height and the effective concrete slab thickness (Silva et al. 2002).

The investigated structural system response, obtained from finite element method isotropic and orthotropic simulations, were compared to current experimental evidence and theoretical results available in the literature. The structural system response, obtained numerically with the aid of the proposed finite element model, was also compared to the limiting values proposed by several authors (Bachmann and Ammann 1987, Canadian Standard 1995, CEB

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1991, DIN 4150-2 2000, ISO 2631-2 2003, Ellis and Ji 1994, Murray and Howard 1998).

Nomenclature

A_{rib} = *area of an individual rib,* m^2
A_{void} = *area of an individual void between the ribs,* m^2
$F(t)$ = *dynamical loading, N*
$F(t)_{max}$= *maximum amplitude of the sinusoidal function, N*
FA = *amplification factor, dimensionless*
P = *individual weight, N*
T_p = *step period defined by the relationship* $1/f_p$*, s*
$(b_{eff})_l$ = *effective width on the left of the steel component, m*
$(b_{eff})_r$ = *effective width on the right of the steel component, m*
f = *excitation frequency, Hz*
f_{01} = *composite floor first natural frequency, Hz*
f_p = *frequency of the human step, Hz*
g = *gravity acceleration* ($g=9{,}81 m/s^2$), m/s^2
h_{rib} = *height of the rib, m*
h_{solid} = *height of the solid part of the concrete slab, m*
k_p = *defined by the expression* $F(t)_{max}/P$*, dimensionless*
l_p = *human's step size, m*
t = *time, s*
t_p = *human step duration, s*
v = *displacements obtained in the dynamic analysis, m*
v_{est} = *displacements obtained in the static analysis, m*
w_{eff} = *effective width of the section, m*

Greek Symbols

β = *frequency parameter, dimensionless*
υ = *human's walking velocity. m/s*
θ = *angle between the ribs and composite beam span, rad*
ΔP_i = *harmonic amplitudes, N*
ϕ_i = *harmonic phase angles, dimensionless*

Composite Structures

Composite steel-concrete structures are widely used in modern bridge and building construction. A composite member is formed when a steel component, such as an I-section beam, is attached to a concrete element, such as a floor slab or bridge deck. In such a composite T-beam the comparatively high concrete compression resistance complements the high strength of the steel in tension (Oehlers and Bradford 1999).

The fact that each material, steel and concrete, is used to take advantage of its best attributes makes composite steel-concrete construction very efficient, economical, competitive and attractive. However, the real attraction of composite construction is based on the development of an efficient steel to concrete connection. To perform this task, shear connectors like stud bolts, channel sections or "perfobond" plates are currently used.

Nowadays, most modern flooring systems in buildings use a concrete slab with a 0.8mm thick cold formed profiled steel sheeting element. This is a special form of composite member where the steel provides permanent and integral formwork for the concrete component, and the composite action is achieved by embossments in the sheeting and by some chemical bonding between the concrete and steel sheeting.

When the steel component acts compositely with the concrete, the composite slab cross-sectional shape, to be used in the structural analysis, depends on the relative direction of the span of the concrete slab ribs to the steel component span.

The composite floor analysed in this paper presents a cross-section in which the profile ribs span are in the same direction as the composite beam, as shown in Fig. 1, where $(b_{eff})_l$ and $(b_{eff})_r$ are the effective widths on the left and right of the steel component, h_{solid} is the height of the solid part of the concrete slab component or cover-slab, h_{rib} is the rib height, A_{rib} is the area of an individual rib, A_{void} is the area of an individual void between the ribs and $\theta=0^0$, where θ is the angle in degrees between the direction of the ribs span and the composite beam span.

The structural system cross-section can be analysed as illustrated in Fig. 1, where the area of the haunch is equal to the areas of the individual ribs ΣA_{rib} over the effective width w_{eff} of the section. When $\theta=90^0$ the ribs are transverse to the composite beam span direction leading to the use, in the structural analysis, of the weakest cross-section, see Fig. 1.

Dynamic Loading Induced by Human Activities

The type of dynamic loading considered in this paper is induced by human activities. This type of dynamic action basically occurs in structures like: footbridges, gymnasiums and floors submitted to rhythmic human activities, such as dance, aerobic activities and so forth.

Some experimental evidence should be considered in the analysis of structures submitted to human induced dynamic excitations. One of the difficulties in analysing heavily loaded slabs regards how to consider the human mass, since it controls important characteristics of the structural system, such as the fundamental frequency. If this parameter is not properly considered the structure dynamic response can be substantially changed.

A criterion usually adopted is to consider the humans as a mass added to the global structure mass, which implies in a mass increase and a fundamental frequency reduction.

Based on several works published on this subject, it can be verified that in the case of people jumping with the two feet simultaneously, or during activities in which the contact of people with the structure is relatively short, the humans mass is not vibrating together with the structural system mass. In addition, the human involvement, in these cases, is restricted to the induction of loads not including any additional mass to the system (Ellis and Ji 1994).

The results of the present investigation considered the response of composite slabs submitted to rhythmic dynamic excitations. One example of human induced dynamic excitations is the jumping movements on the structural system. When this case was simulated, the human involvement was only considered as a load action disregarding any mass increase.

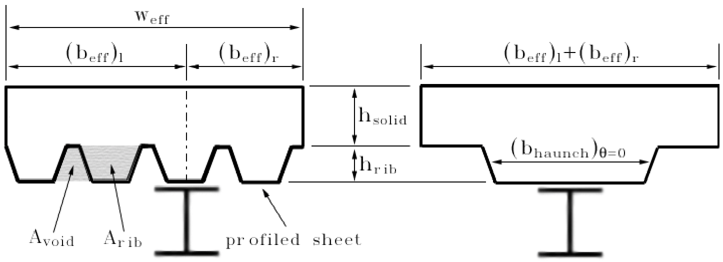
The first step of a dynamic analysis concerns the identification and distinction of the various load frequencies induced by humans. Initially the load frequencies induced by people walking and running are considered. These load types are frequent in footbridge structures. Previous investigations demonstrated the interdependency of parameters like: human's walking velocity, υ, the step size, l_p, and its frequency, f_p. Some of these mean values are presented in Table 1 (Bachmann and Ammann 1987).

The Canadian Steel Buildings Design Standard (Canadian Standard 1995), specifies that individuals or human groups can generate periodic forces with associated frequency ranging from 1.0Hz to 4.0Hz, approximately. It is clearly noticed, that the specified Canadian Standard human induced frequencies (Canadian Standard 1995) are covered in Table 1 (Bachmann and Ammann 1987).

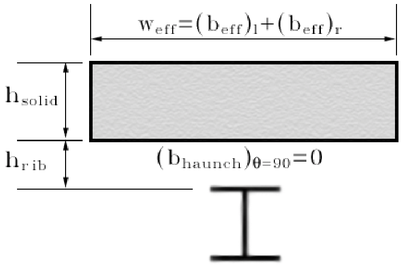
In this paper the mathematical modelling of two cases of these dynamical loading are investigated. The first named "walking" is the case in which the individual maintains a continuous contact with the structural system surface, while the second denominated "running" occurs when that contact is discontinuous.

In the case of a continuous surface contact, it is common to use a general expression for the excitation produced by an individual throughout time. These loads are produced with both feet, as function of a static part associated to the individual weight and three harmonic loading components parcels, Eq. (1) (Bachmann & Ammann 1987, Ellis & Ji 1994).

$$F(t)=P+\Delta P_1 \sin(2\pi f_p t)+\Delta P_2 \sin(4\pi f_p t-\phi_1)+\Delta P_3 \sin(6\pi f_p t-\phi_2) \quad (1)$$



(a) Section



(b) Equivalent section

Figure 1. Longitudinal ribs ($\theta = 0^0$) and transverse ribs ($\theta = 90^0$).

Table 1. Load frequencies induced by humans.

Type of Human Induced Dynamic Loads	Velocity υ (m/s)	Step Size l_p (m)	Frequency f_p (Hz)
Slow Walk	1.10	0.60	1.70
Standard Walk	**1.50**	**0.75**	**2.00**
Fast Walk	**2.20**	1.00	2.30
Standard Run	3.30	1.30	2.50
Fast Run	5.50	1.75	3.20

In Eq. (1), P represents the load static part, corresponding to the individual weight. The magnitudes ΔP_1, ΔP_2 and ΔP_3 are associated with harmonic amplitudes, and f_p, ϕ_1 and ϕ_2 refers, respectively, to the frequency of the human step and to the harmonic phase angles. The present investigation assumed the human weight, P, to be equal to 800kN. The first harmonic amplitude, ΔP_1, is equal to 0.4P for f_p equal to 2.0Hz and 0.5P for f_p equal to 2.4Hz. A simple interpolation between these two values was used in intermediate cases. The second and third harmonic amplitudes, ΔP_2 e ΔP_3, were assumed to be equal to 0.1P for f_p equal to 2.0Hz (Bachmann and Ammann 1987). The phase angles ϕ_1 and ϕ_2 depend on various other factors and should represent the most favourable used load combinations. In the present study the phase angles ϕ_1 and ϕ_2 were assumed to be equal to $\pi/2$.

A discontinuous contact dynamic excitation is represented by a half sinusoidal curve during the contact, while presenting a zero load value when the contact is lost, as presented in Eq. (2) (Bachmann and Ammann 1987, Ellis and Ji 1994). In Eq. (2), tp represents the human step duration, T_p is the step period defined by the relationship $1/f_p$ and the variable k_p defined by the expression $F(t)_{max}/P$. In this expression, $F(t)_{max}$ is the maximum amplitude of the sinusoidal function and P is the individual weight.

$$F(t) = k_p P \sin(\pi f_p t), \text{ for } t < t_p \text{ and } F(t) = 0, \text{ for } t_p < t < T_p \quad (2)$$

Another case regarding dynamic excitations induced by man is the dance, very common in rock concerts. For design purposes, a frequency band ranging from 1.60Hz to 3.00Hz for the exciting frequency is generally considered, often governed by the music rhythm. Another more conservative frequency band can be adopted i.e. between 1.50Hz and 3.50Hz (Bachmann and Ammann 1987, Ellis and Ji 1994). The same mathematical modelling adopted for the continuous loading is recommended for this case, Eq. (1).

Another kind of human induced dynamic loading is associated with jumping. This excitation usually happens in gymnasiums, stadiums, ballrooms or even gymnastic rooms. For design purposes, a frequency range from 1.80Hz to 3.40Hz is generally considered for the excitation frequency, frequently governed by the music rhythm. The mathematical modelling used for the discontinuous loading is recommended for this situation, Eq. (2).

Structural System

The main objective of this paper is to incorporate the orthotropic solution for the composite slabs subjected to human dynamic excitations such as jumping in gymnastics. A detailed definition of this type of dynamic loading was described in sections 3 and 4 of the present paper. Those dynamic actions were imposed to the composite slab.

The composite floor studied in the present paper, spanning 14.0m by 43.7m, is currently used for gymnastics (Vecci et al. 1999). The structural system is constituted of composite girders. The 150mm thick composite slab uses a steel deck with the following geometrical characteristics: 0.80mm thickness, and 75mm flute height, see Figs. 2 and 3, respectively.

The steel sections used were welded wide flanges (WWF) made with a 300MPa yield stress steel grade. The isotropic and orthotropic systems adopted a 2.05x10^5 MPa Young's modulus for the steel beams and deck.

The concrete slab possesses a 20MPa specified compression strength and a 2.35x10^{4}MPa Young's modulus (Vecci et al. 1999). However, according to Murray (Murray et al. 1997), in such situations where the composite slab is submitted to dynamic excitations the concrete becomes stiffer than that case when it is submitted to pure static loads. Due to this fact, according to the authors is suggested a 35% increase in the conventional concrete Young's modulus (Murray et al. 1997), value used in the isotropic system.

The structure permanent load and the gymnastics live load were equal to 3.5kN/m^2 and 0.2kN/m^2 respectively. The model assumed the columns as rigid supports in the primary beam system while adopted simple steel connections in the secondary beam system (Vecci et al. 1999). Future steps of the present investigation will incorporate the effects of the columns stiffness in the structural model response.

Table 2 depicts the geometrical characteristics of all the steel sections used in the structural model, presented in Figs. 2 and 3. It is important to emphasize that there was a haunch present in the extreme spans of V1 to V4 girders. The minimum height of the steel sections near the supports was equal to 460.0mm (Vecci et al. 1999).

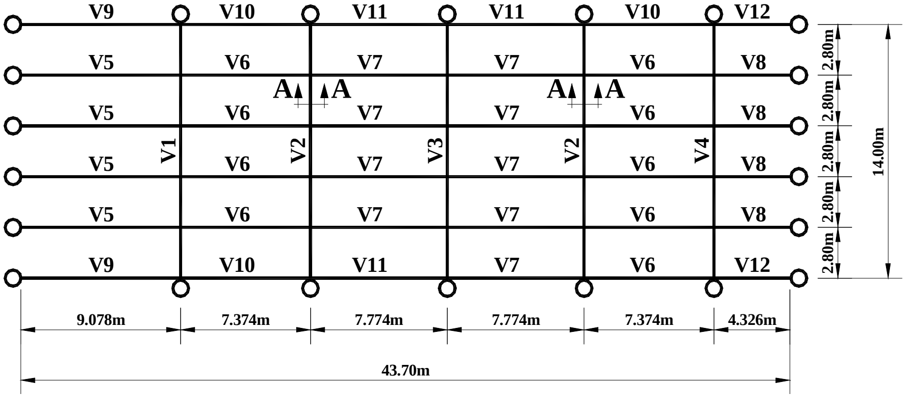


Figure 2. The structural model.

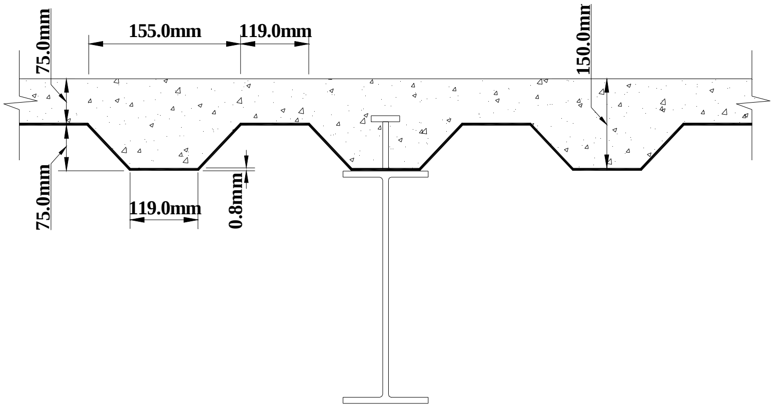


Figure 3. Typical composite slab cross-section: Section AA.

Table 2. Geometrical characteristics of the beam steel sections.

Beams	Height (mm)	Flange Width (mm)	Top Flange Thickness (mm)	Bottom Flange Thickness (mm)	Web Thickness (mm)
V1-V4	1400	350	12.5	12.5	12.5
V5	700	200	8.0	8.0	8.0
V6-V7	600	150	6.3	6.3	6.3
V8-V12	250	130	6.3	6.3	4.75
V9	400	200	6.3	6.3	4.75
V10-V11	400	150	6.3	6.3	4.75

Computational Model

The proposed computational model, developed for the composite slab dynamic analysis, adopted the usual mesh refinement techniques present in finite element method simulations implemented in the ANSYS program (ANSYS 1998).

In the developed finite element model, floor steel girders are represented by three-dimensional beam elements, where flexural and torsion effects are considered. The composite slab is represented by shell finite elements.

The combined actions of floor slab and steel beams were considered in the present investigation. The eccentricities of the floor slab and the steel beams were considered and clearly enlarge the floor system stiffness significantly, according to the existing structures. The computational model was developed taking into account this effect associated to the eccentricities of the floor slab and the steel beams. The ANSYS program (ANSYS 1998) has provided all the procedures related to the locations of the neutral axes of the effective widths of the plates using basic concepts of structural analysis.

When a composite floor incorporates a steel deck, the isotropy of the structural system is a hypothesis that can be at least considered questionable. One of the most commonly used solutions to better represent the composite floor is to consider it as an orthotropic model (Silva et al. 2002).

In this paper, the major direction was considered parallel to the span of the slab ribs, as presented in Fig. 1. The proposed computational model considers the major direction inertia as the addition of the part related to the concrete slab above the steel deck ribs plus an extra term that incorporates an effective width based on the ratio of concrete area present in the ribs over the overall area (ribs + voids). The minor direction only considers the first part i.e. the concrete slab above the concrete slab ribs, the so-called cover slab, as shown in Fig. 1.

In this analysis, the orthotropic simulation considers that the ratio between the area of an individual rib, A_{rib}, and the area of an individual void between the ribs, A_{void}, is varied from 0.1 up to 0.5 ($A_{rib}/(A_{rib}+A_{void})$ = 0.1 up to 0.5).

In order to emulate the orthotropic system, different longitudinal and transverse Young’s modulus, as well as Poisson ratios, for the concrete slab were used in the major/minor concrete slab plane directions, as well as in a direction perpendicular to this plane, according to the system orthotropic inertia characteristics, Table 3. These values were calculated based on the simple idea of modifying the Longitudinal Young’s Modulus. Since the concrete inertia was kept constant in both directions to simplify the model geometry, the Young’s modulus, in the direction parallel to the deck ribs, was increased. This was made to compensate for the extra area, and consequently, inertia provided by the concrete present in the deck ribs. With these results in hand, the Transverse Young’s modulus, as well as the Poisson ratios, were also re-evaluated. This was made accordingly to simple elasticity formulae for orthotropic materials. The increase in stiffness/resistance provided by the profiled steel sheet was not considered in the computational model.

The final computational model used 3366 nodes, 726 three-dimensional beam elements, BEAM44, and 3264 shell elements, SHELL63, leading to a numeric model with 18012 degrees of freedom. The BEAM44 rigid offset capability was explored to incorporate, in the structural model, the combined floor beam section eccentricity due to the steel deck.

Dynamic Behaviour of the Composite Slab System

This section presents the evaluation of the structural system vibration levels when submitted to dynamic excitations produced by gymnastics, based on the load model presented in Eq. (1). The composite floor dynamic response was determined through an analysis of its natural frequencies, displacements, velocities and accelerations.

The live load considered in this analysis considered the present of one human for each 4.0m^2, corresponding to 0.25 human/m^2. It is also assumed that an individual human weight was equal to 800N (Bachmann and Ammann 1987). A critical damping ratio of 1% was considered to model the composite floor while a constant damping ratio was assumed for all vibration modes. The dynamic analysis results were obtained from an extensive numeric analysis, based on the finite element method utilising the ANSYS program (ANSYS 1998).

Response spectra were obtained, according to the proposed methodology for the considered frequency range, in accordance to the composite floor dynamic characteristics. This was done by varying of a frequency parameter, β. This parameter is defined by the f/f_{01} ratio, where f represents the excitation frequency, regarding the gymnastics human induction, and f_{01} is the composite floor first natural frequency.

The response spectrum was obtained for representation of the composite floor dynamic response under the action of the dynamic loadings. This spectrum is related to the vertical displacements, and to the amplification factor, FA. The amplification factor, FA, is defined by the relationship v/v_{est}, in which v and v_{est} represent the vertical displacements obtained in the dynamic and static analysis, respectively.

This section finalizes with the determination of the composite floor velocities and accelerations. These values were then compared to those specified in current design standards (Bachmann and Ammann 1987, Canadian Standard 1995, CEB 1991, DIN 4150-2 2000, ISO 2631-2 2003, Ravara 1969), to evaluate a possible occurrence of excessive vibrations and human discomfort.

Natural Frequencies of the OrthoTropic Model

The composite floor natural frequencies were determined with the aid of the numerical simulations, Table 4. The natural frequencies here presented are related to the orthotropic system with 18012 degrees of freedom ($A_{rib}/(A_{rib}+A_{void})$ from 0.1 up to 0.5). These natural frequencies were compared to values obtained on the isotropic analysis (Silva et al. 2003).

The natural frequencies obtained based on the isotropic analysis are higher than the experimental test frequencies. However, it can be clearly noticed from Table 4 results, that there is a very good agreement between the orthotropic system fundamental frequency value, f_{01}=9.60Hz ($A_{rib}/(A_{rib}+A_{void})$ = 0.5), and the experimental test frequency, f_{01}=9.50Hz (Vecci et al. 1999). Such fact validates the numeric model here presented, as well as the results and conclusions obtained throughout this work.

It can be observed from Table 4 results that the composite floor fundamental frequency depends of the ratio $A_{rib}/(A_{rib}+A_{void})$. When the ratio $A_{rib}/(A_{rib}+A_{void})$ increases, the fundamental frequency value decreases. Such fact is explained by the slab rib mass increase.

Figures 8 and 9 illustrate the vibration mode corresponding to the fundamental frequency of the studied structural system considering different ratios between the area of an individual rib, A_{rib}, and the area of an individual void between the ribs, A_{void}. These figures are important to emphasize the different computational models developed in this work. Small differences are observed in the vibration modes final configuration obtained for different ratios $A_{rib}/(A_{rib}+A_{void})$, as depicted in Figs. 4 and 5.

Table 3. Material characteristics of the orthotropic system.

Young's Modulus, E (MPa)	Isotropic Model	Orthotropic Model				
		$A_{rib}/(A_{rib}+A_{void})$				
		0.10	0.20	0.30	0.40	0.50
E_x (parallel to deck ribs)	3.05×10^4	6.68×10^4	9.76×10^4	12.41×10^4	14.72×10^4	16.78×10^4
E_y (perpendicular to deck ribs) E_z (perpendicular to concrete slab plane)		3.05×10^4				

Table 4. Natural frequencies of the composite floor.

Natural Frequencies f_{0i} (Hz)	Isotropic Model [6]	Orthotropic Model					Measured Frequency (Vecci et al. 1999) f_{01} (Hz)
		$A_{rib}/(A_{rib}+A_{void})$					
		0.10	0.20	0.30	0.40	0.50	
f_{01}	10.80	10.75	10.50	10.19	9.89	9.60	9.50
f_{02}	11.27	11.24	10.96	10.63	10.30	10.00	
f_{03}	11.96	11.88	11.55	11.19	10.83	10.49	
f_{04}	11.97	12.45	12.25	11.93	11.59	11.25	
f_{05}	12.56	12.81	12.50	12.12	11.73	11.37	

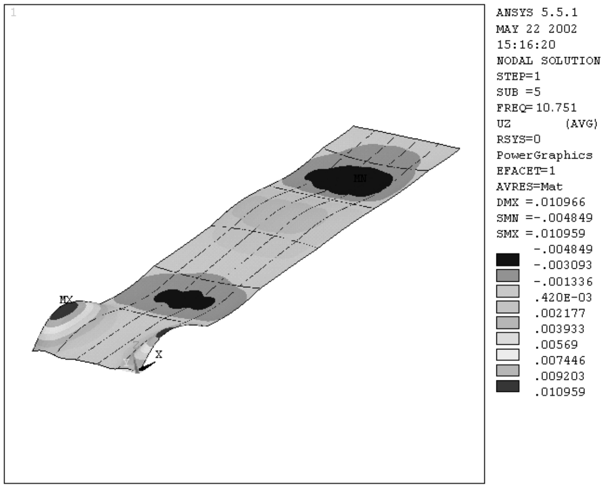


Figure 4. Vibration mode associated with the 1st natural frequency: f_{01}=10.75Hz. Orthotropic simulation: ($A_{rib}/(A_{rib}+A_{void})$ = 0.10).

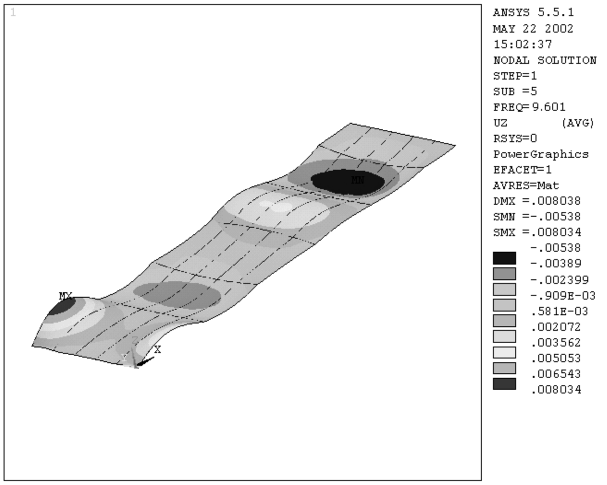


Figure 5. Vibration mode associated with the 1st natural frequency: f_{01}=9.60Hz. Orthotropic simulation: ($A_{rib}/(A_{rib}+A_{void})$ = 0.50).

Analysis of the Displacements Response Spectra

The dynamical analysis proceeded with the evaluation of the composite floor response spectrum. This response spectrum, Fig. 6, depicts the dynamic response of the composite floor submitted to gymnastics dynamic excitations for a wide frequency range (up to 30Hz). The response spectra here presented is related to the orthotropic model ($A_{rib}/(A_{rib}+A_{void})$ = 0.5).

The displacements response spectrum, Fig. 6, presents peak dynamic effects associated with the frequency parameter, β, ranging from 0.7 to 1.5. This spectrum frequency range corresponds to values of the frequency parameter, β, close to unity. This fact can be explained if the excitation frequency, f, associated, for instance with multiple of the first harmonic of the dynamic loading (1.80Hz to 3.40Hz) (Bachmann and Ammann 1987, Ellis and Ji 1994), and the composite floor fundamental frequency, f_{01}, equal to 9.60Hz, coincides. An extra peak on the response spectrum was observed for high natural frequencies associated to the frequency parameter, β, ranging from 1.2 to 1.5.

In the case of systems with several degrees of freedom, the resonance physical phenomenon can happen when one of the structure natural frequencies is equal, or is very close to the excitation frequency. Bachmann and Ammann (1987) describe a situation in which a footbridge with a fundamental frequency of 8.0Hz presented the resonance phenomenon for a human induced frequency of 3.70Hz. Such phenomenon is due to the fact that the third dynamic loading harmonic frequency, 11.10Hz, excited the structure second natural frequency, 11.10Hz.

The level of the dynamic effects on the studied structural system can be considered very small when the excitation frequency range of the response spectrum located between 1.0Hz and 5.0Hz (β<0.5), is considered. It is also observed that the maximum value of the amplification factor, FA, equal in this case to 50.0, occurs for the peak dynamical effects corresponding to values of the frequency parameter, β, close to unity, as illustrated in Fig. 6. This maximum amplification value leads to vertical displacements that could induce excessive vibrations, compromising human comfort conditions and even jeopardising the structural system integrity.

Human Comfort and Vibration Serviceability Limit State

The present study proceeds with the evaluation of the composite floor performance in terms of human comfort and vibration serviceability limit states. The first step of this procedure concerns the determination of the composite floor maximum velocities and accelerations. These values were obtained numerically with the aid of the proposed orthotropic model, with 18012 degrees of freedom, assuming that the ratio between the area of an individual rib, A_{rib}, and the area of an individual void between the ribs, A_{void}, equal to 0.5 ($A_{rib}/(A_{rib}+A_{void}) = 0.5$).

In sequence the maximum velocities and accelerations were then compared to the limiting values proposed by several authors (Bachmann and Ammann 1987, Canadian Standard 1995, CEB 1991, DIN 4150-2 2000, ISO 2631-2 2003, Ravara 1969). The most representative values of the composite floor velocities and accelerations are presented in Figs. 7 to 12 for excitation frequencies of 3.0Hz, 4.0Hz and 5.0Hz, respectively. These excitations frequencies are relevant because the computational model used in the present paper considered that individuals or human groups generating periodic forces with associated frequency ranging approximately from 1.0Hz to 4.0Hz.

The German Standard DIN 4150-2 (DIN 4150-2 2000), described in Bachmann and Ammann (1987), limits the composite floor velocities up to values of 10.0mm/s not to violate the acceptable vibration levels for structural safety, although, in the limit cases, small wall cracking can appear. When this criterion is applied to the composite floor maximum velocity values of the studied structural system, equal to 5.16mm/s (f=3.0Hz), Fig. 7, 7.59mm/s (f=4.0Hz), Fig. 8, and 10.42mm/s (f=5.0Hz), Fig. 9, it can be concluded that the composite floor presented excessive vibrations for the excitation frequency of 5.0Hz (f=5.0Hz).

Another less conservative criterion recommends that the velocities should be limited to 15.0mm/s (Ravara 1969). In this case, the dynamic analysis velocities are significantly lower than this limiting value, disregarding the occurrence of unwanted excessive vibrations.

The next step concerns the evaluation of the composite floor maximum accelerations values induced by gymnastics dynamic loads. These acceleration values are depicted in Figs. 10, 11 and 12, respectively.

The Canadian Standard (1995), CEB (1991) specified limiting accelerations values for human comfort, without considering their associated natural vibration frequencies. Those values are expressed exclusively in terms of the gravity acceleration ($g=9.81m/s^2$), in percentage. The referred standard recommends a limiting value for the composite floor accelerations used for: gymnastics, music halls and sports arenas to a value of 5%g (Canadian Standard 1995, CEB 1991). On the other hand, the acceleration limit values recommended by the International Standard Organization ISO 2631-2 (ISO 2631-2 2003) can also be considered. The ISO Standard suggests limits in terms of rms (root mean square) acceleration as a multiple of the baseline line curve shown in the Fig. 13. The multipliers for the proposed design criteria, expressed in terms of peak acceleration, are equal to 10 for offices, 30 for shopping malls and indoors footbridges, and 100 for outdoors footbridges, Fig. 13. For design proposes, these limits can be considered to range between 0.8 and 1.5 times the recommended values, depending on the duration and frequency of the vibration events (ISO 25631-2 2003).

In the present investigation the composite floor maximum accelerations values were equal to 1.0%g (f=3Hz), Fig. 10, 1.92%g (f=4.0Hz), Fig. 11, and 3.45%g (f=5.0Hz), Fig. 12. These values indicated that the floor did not present problems related with human comfort when the limiting accelerations for human comfort related to Canadian Standard (1995), CEB (1991) and ISO 2631-2 (2003), see Fig. 13, were considered.

Other author recommendations for accelerations limiting values are suggested and should be used with caution as stated in specific design standards (Bachmann and Ammann 1987). According to Bachmann and Ammann (1987), a limiting value of 10%g could be accepted for slabs designed for sport practice, music concerts and dance. This limiting value assures that the composite floor satisfies its purpose without presenting any human discomfort.

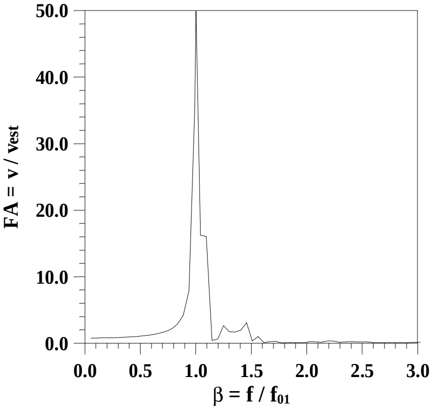


Figure 6. Composite floor response spectrum: ($A_{rib}/(A_{rib}+A_{void}) = 0.50$).

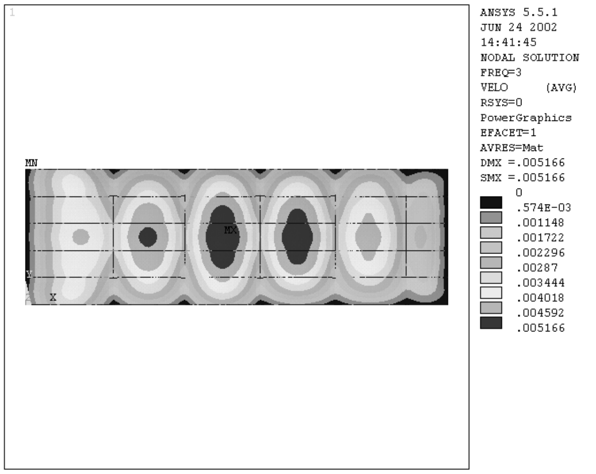


Figure 7. Composite floor maximum velocities: f=3.0Hz.

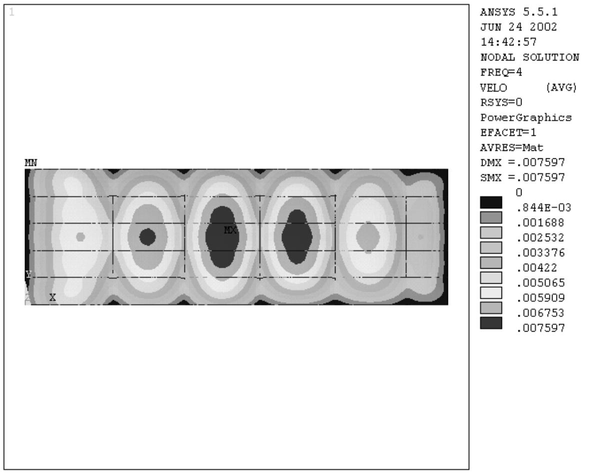


Figure 8. Composite floor maximum velocities: f=4.0Hz.

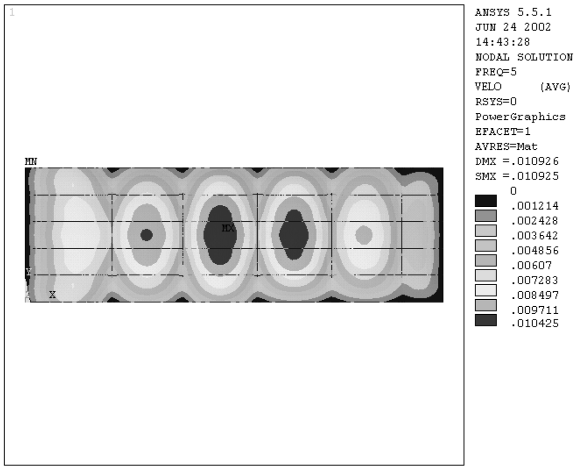


Figure 9. Composite floor maximum velocities: f=5.0Hz.

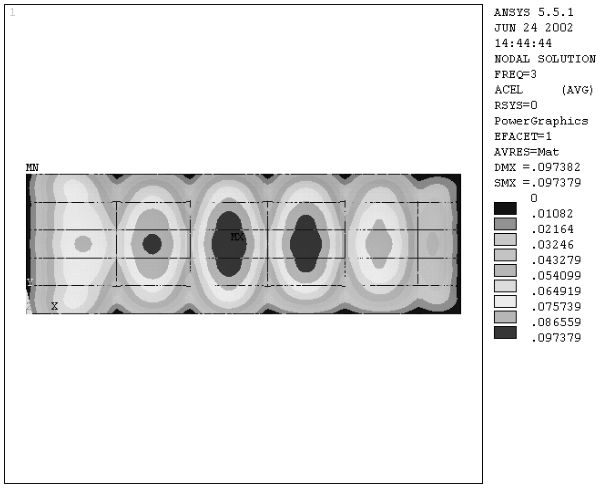


Figure 10. Composite floor maximum accelerations: f=3.0Hz.

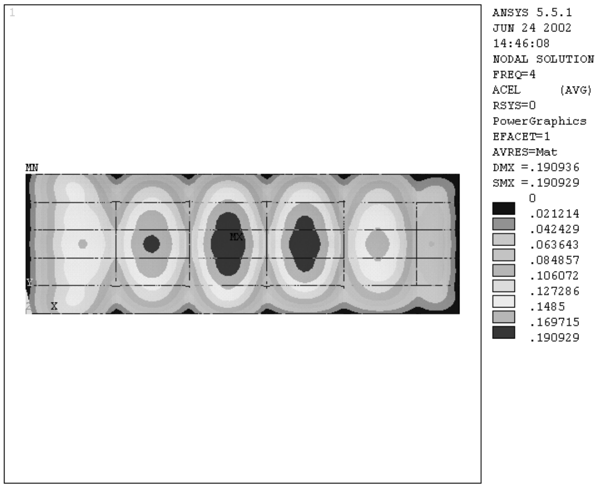


Figure 11. Composite floor maximum accelerations: f=4.0Hz.

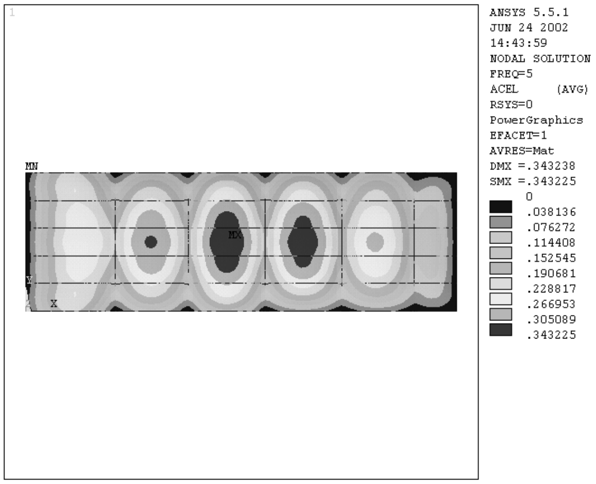


Figure 12. Composite floor maximum accelerations: f=5.0Hz.

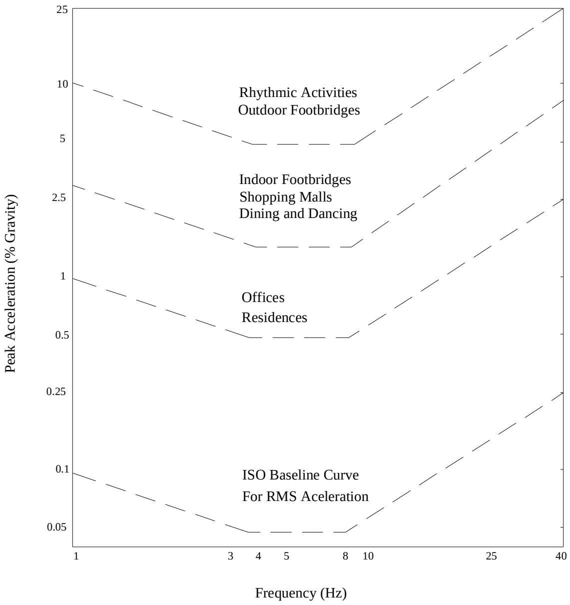


Figure 13. Recommended peak acceleration for human comfort related to vibrations due to human activities (ISO 2631-2 2003).

Comparison of Results: Orthotropic and Isotropic Simulations

A dynamical response comparison of the composite floor based on isotropic (Silva et al. 2003) and orthotropic simulations is presented in Tables 5 to 8. In this work, the orthotropic simulation considers that the ratio between the area of an individual rib, A_{rib}, and the area of an individual void between the ribs, A_{void}, is varied from 0.1 to 0.5 ($A_{rib}/(A_{rib}+A_{void})$ = 0.1 up to 0.5). The investigated structural system was evaluated in terms of human comfort and vibration serviceability limit states.

The maximum values of velocities and accelerations based on the orthotropic model are lower than those obtained on the isotropic simulation. Such fact can be explained by the favourable influence of the slab ribs related to the composite slab major direction, inherent to the own nature of the modelled orthotropic system.

Based on the results presented in Tables 5 and 6, it is noticed that a slightly variation exists between the maximum velocities and maximum accelerations values when the ratio $A_{rib}/(A_{rib}+A_{void})$ is changed. However, it can be observed that the maximum velocities values in both models, orthotropic and isotropic, violate the acceptable vibration levels for structural safety recommended by the German Standard DIN 4150 (DIN 4150-2 2000), described in Bachmann and Ammann (1987), for a 5.0Hz excitation frequency, as presented in Table 5.

It can be concluded that the composite floor presented excessive vibrations for the loading frequency equal to 5.0Hz, as illustrated in Table 5. With reference to the maximum accelerations values it is clearly noticed, that the human comfort of the investigated structural system is guaranteed, according to the limiting values proposed by several authors (Bachmann and Ammann 1987, CEB 1991, Canadian Standard 1995, ISO 2631-2 2003), as shown in Table 6.

Finally, it is also clearly noticed that the maximum velocities and accelerations values related to the resonance physical phenomenon, based on isotropic and orthotropic simulations, would induce excessive vibrations, compromising human comfort conditions and even jeopardising the composite slab system integrity, as depicted in Tables 7 and 8.

Table 5. Composite floor maximum velocities for excitation frequencies of 2.0Hz to 5.0Hz based on isotropic and orthotropic simulations.

Excitation Frequency (Hz)	Velocity (mm/s) - Limiting Value: 10.0mm/s (DIN 4150-2 2000)					
	Orthotropic Model					Isotropic Model (Silva et al. 2003)
	$A_{rib}/(A_{rib}+A_{void})$					
	0.50	0.40	0.30	0.20	0.10	
2.0	3.23	3.23	3.23	3.28	3.39	3.82
3.0	5.15	5.15	5.15	5.19	5.34	6.02
4.0	7.50	7.50	7.50	7.52	7.68	8.67
5.0	10.40	10.40	10.40	10.45	10.70	12.05

Table 6. Composite floor maximum accelerations for excitation frequencies of 2.0Hz to 5.0Hz based on isotropic and orthotropic simulations.

Excitation Frequency (Hz)	Acceleration (%g) - Limiting Value: 5%g (CEB 1991, Canadian Standard 1995, ISO 2631-2 2003)					
	Orthotropic Model					Isotropic Model (Silva et al. 2003)
	$A_{rib}/(A_{rib}+A_{void})$					
	0.50	0.40	0.30	0.20	0.10	
2.0	0.41	0.41	0.41	0.42	0.43	0.49
3.0	0.99	0.99	0.99	1.00	1.02	1.16
4.0	1.92	1.92	1.92	1.93	1.97	2.22
5.0	3.45	3.45	3.45	3.46	3.51	3.90

Table 7. Composite floor maximum velocities corresponding to the resonance physical phenomenon based on isotropic and orthotropic simulations.

Excitation Frequency Corresponding to the Resonance Physical Phenomenon (Hz)	Velocity (mm/s) - Limiting Value: 10.0mm/s (DIN 4150 2000)		
	Orthotropic Model		Isotropic Model (Silva et al. 2003)
9.60	$A_{rib}/(A_{rib}+A_{void}) = 0.50$	967.03	1295.70
9.89	$A_{rib}/(A_{rib}+A_{void}) = 0.40$	999.49	
10.19	$A_{rib}/(A_{rib}+A_{void}) = 0.30$	1037.51	
10.50	$A_{rib}/(A_{rib}+A_{void}) = 0.20$	1083.85	
10.76	$A_{rib}/(A_{rib}+A_{void}) = 0.10$	1148.02	

Table 5. Composite floor maximum accelerations corresponding to the resonance physical phenomenon based on isotropic and orthotropic simulations.

Excitation Frequency Corresponding to the Resonance Physical Phenomenon (Hz)	Acceleration (%g) - Limiting Value: 5%g (CEB 1991, Canadian Standard 1995, ISO 2631-2 2003)		
	Orthotropic Model		Isotropic Model (Silva et al. 2003)
9.60	$A_{rib}/(A_{rib}+A_{void}) = 0.50$	594.64	894.18
9.89	$A_{rib}/(A_{rib}+A_{void}) = 0.40$	633.18	
10.19	$A_{rib}/(A_{rib}+A_{void}) = 0.30$	677.67	
10.50	$A_{rib}/(A_{rib}+A_{void}) = 0.20$	729.31	
10.76	$A_{rib}/(A_{rib}+A_{void}) = 0.10$	791.47	

Final Remarks

This paper presents the evaluation of the structural dynamical behaviour of composite floors. The developed analysis methodology incorporates the orthotropic solution for the concrete slabs subjected to human induced dynamic loadings, such as rhythmical activities arising from gymnastics, musical and sports events and ballroom dances. This investigation focused the use of different steel deck geometries and their influence in the dynamical response of the commonly used composite floors.

The proposed analysis methodology considers the investigation of the linear dynamic behaviour, in terms of serviceability limit states, of a building floor made with a composite slab system with welded wide flange (WWF), steel beams and a incorporated steel deck.

A finite element computational model was developed using the ANSYS program. The model enabled a complete dynamical evaluation of the investigated composite floor system especially in terms of human comfort and its vibration serviceability limit states.

The system dynamic response in terms of displacement amplitudes, velocities and accelerations, was obtained and compared to the limiting values proposed by several authors and design standards. The maximum amplification factor displacement value presented in this work was equal to 50.0, related to a resonance condition. The maximum values found for the velocity and acceleration were equal to 10.40mm/s and 3.45%g, respectively, while the maximum accepted values for the velocity and acceleration were 10.0mm/s and 5%g, respectively. The results obtained throughout the investigation indicated that the composite floor analysed in this work violates the vibration serviceability limit state, but satisfied the human comfort criteria.

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