

## Građevinski materijali i konstrukcije Building Materials and Structures

journal homepage: [www.dimk.rs](http://www.dimk.rs)

doi: 10.5937/GRMK2101045G UDK: 692.53.072.2

Technical Paper



# Numerical parametric study on steel-concrete composite floor beams vibrations due to pedestrian traffic

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### Article history

Received: 29 January 2021

Received in revised form:

23 February 2021

Accepted: 27 February 2021

Available online: 30 March 2021

### Keywords

pedestrian traffic,  
composite structures,  
deflection,  
structure serviceability,  
floor vibration

### ABSTRACT

Human perception of floor vibrations and uncompromised serviceability of equipment are two most important acceptability criteria considering floor vibrations. While verification of deflection is a simple and well-known procedure in structures' design for serviceability limit state, the fulfilment of floor vibrations acceptability criteria are presented in different standards in the form of various calculation procedures. Results achieved through those calculation procedures are presented in the form of various classification of floor structures. Classification of composite floor structures due to vibrations is inconsistent considering different calculation procedures. Comparison of various calculation procedures for the definition of composite floor vibrations is presented in this paper. In addition, a parametric analysis is performed on the wide range of steel-concrete composite floor structures, through analysis of various composite floor layouts and a wide range of imposed loads values. The analysis of the relation between deflection, vertical vibrations and accelerations of steel-concrete composite floor beams is presented in this paper. The results of the parametric analysis are given through direct relation between deflections of composite beams and achieved floor class for the fulfilment of vibrations acceptability criteria due to the pedestrian walking.

## 1 Introduction

Pedestrian traffic is the most common internal source of floor vibrations, resulting in vertical oscillatory movement of structure parts with certain amplitude and frequency. On the other hand, wind actions, road and rail traffic, seismic actions and impact on the structure members, are the most common external source of structure vibrations. Vibrations are mostly vertical or horizontal. While seismic and wind actions result in horizontal vibrations of structures, walking of pedestrians is the most usual source of vertical vibrations.

Two most important acceptability criteria of floor vibrations are human perception and uncompromised serviceability of equipment for different floor occupancies. Human response to floor motion is a very complex phenomenon and it is often related to the combination of different factors such as the magnitude of motion, the surrounding environment and the type of human activity which takes place at that moment. Although the vibrations of a floor structure can cause a feeling of uncertainty and significantly decrease human comfort and quality of life

inside the building, their occurrence does not necessarily lead to less structure safety.

Various floor occupancies inside of buildings, such as hospitals, surgeries, schools, laboratories, offices, residential buildings, hotels or sport and industry facilities require different acceptability criteria of floor vibrations. Increased floor vibrations can compromise the building functionality and operation of the equipment inside the building, which further emphasizes the importance of acceptance criteria definition at the early stage of structure design. Improvement of an existing structure to reduce its susceptibility to vibrations is a very difficult and expensive process that requires significant modifications of structure mass, stiffness or increase of structure damping, often using special devices.

The first step in structure dynamic analysis is modelling dynamic loads induced by human activities and subsequent determination of acceptance criteria of floor vibrations. These loads can be separated in two groups: periodic dynamic loads induced by rhythmic body motion such as walking, running, dancing and stochastic dynamic loads

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induced by single body motions such as heel impact, jumping off impact or landing impact after jumping from an elevated position [1]. The dynamic loads of one or more pedestrians vary with time and position and can be classified as impulsive loads (usually in situ loads) caused by persons who jump from the objects or sudden standing of a crowd and periodic (moving loads) caused by walking, marching or running [2], [3].

Appearance and magnitude of floor structure vibrations depend on type and layout of vertical and horizontal constructive elements, the arrangement of interior walls and type of floor structures, suspended ceilings and floor finishing. Aforementioned characteristics of the building structure affect not only the natural frequencies of different fundamental mode shapes but also structural damping ratio which present important characteristic for dynamic analysis of the structure. In addition, analysis of floor structure vibrations becomes more complicated considering the nature of dynamic excitation caused by pedestrian traffic. In common engineering practice, the complexity of floor structures vibrations caused by pedestrian traffic is explained through simplified design procedures in which continuous structural systems are replaced with discrete systems with a single degree of freedom and the complex function of pedestrian walk is broken down into a series of sinusoidal functions based on the Fourier transformation. These simplified design procedures are given in different standards, technical guidelines and design recommendations [1], [3], [4], [6] - [8].

The description of the dynamic loads generated by pedestrian traffic is not a simple task. Numerous investigations were made aiming to establish parameters to describe such dynamic actions. The vertical accelerations of the body mass are associated with reactions on the floor and they are closely periodic, at the pace frequency [6]. This dynamic loading model is most commonly represented by the load static parcel, related to the individual's weight, and combination of harmonic forces with frequencies that are multiples or harmonics of the basic frequency of the force repetition [2], [4], [6], [8]. For the analysis of the dynamic performance of composite steel-concrete floors, different authors developed various dynamic load models of pedestrian traffic [9], [10], [11].

The latest research significantly moves towards a more realistic estimation of the vibration response through new design methods to account the variability of each pedestrian, their interaction and statistical evaluation of obtained results. In addition, the latest researches highlighted the importance of human structure interaction, i.e. the effects of the human body on the dynamic properties of the occupied structure [12], [13]. The new modelling approach describes a human body as a mechanical system often composed of masses connected with springs and dampers. These new modelling approaches are more complex and lead to the more realistic prediction of structure vibration response, but it remains to be seen how they will be reflected on the simplified design procedures given in aforementioned design guidelines and how they can be used in common design procedures.

Determination of dynamic properties of floor structures, such as natural frequency, modal mass and damping of the structure is important for the definition of acceptable levels of floor vibrations. The fundamental natural frequency of floor

structures can be defined using simplified design procedures given in different literature [4], [8], [14], [15], [16] or using FEM analysis in the appropriate software.

Design recommendations for structures considering fulfilment of vibrations acceptance criteria can be found in different standards, design manuals and other specialized literature. Historically, many designers considered that fundamental natural frequency is the main structure characteristic and that sufficiently high fundamental natural frequency provides appropriate performance of the structure due to floor vibrations [4]. According to Eurocode, serviceability criteria for floor vibrations should be considered for each project or should be defined within National Annex. According to EN 1990, Annex A1 [17] a comfort of user and functionality of structure or its structural members should be considered in order to display acceptable behaviour regarding vibrations of floor structures. In addition, EN 1990 [17] defines that for the further guidance EN 1991-1-1 [18], EN 1991-1-4 [19] and ISO 10137 [3] should be used. EN 1990, Annex A2 [17] gives recommended maximum values for accelerations of any part of the floor structures as  $0.7 \text{ m/s}^2$  for vertical vibrations and  $0.2 \text{ m/s}^2$  for horizontal vibrations. ISO 2631-2 [5] defines acceptability criteria of floor vibrations in the function of human perceptibility curves for various floor accelerations. The same acceptability criteria are also adopted in BS 6472-1 [20] through base acceptability curves and multiplying factors  $R$  of different floor occupancies for horizontal and vertical vibrations. New design recommendations for acceptability criteria of composite steel-concrete floors exposed to vibrations induced by human activities are defined based on the results of the extensive investigation within ECCS (research project JRC55118 [15]). Three main parameters that influence the floor vibrations are fundamental natural frequency  $f_0$ , structural damping  $D$  and modal mass  $M_{\text{mod}}$ . Determination of  $OS\text{-}RMS_{90}$  variable is a part of the general procedure for the determination of acceptable floor response to excitation induced by walking persons. Variable  $OS\text{-}RMS$  represents the root mean square velocity for significant one step, which is associated with a certain probability of body mass and step frequency. Variable  $OS\text{-}RMS_{90}$  is introduced in the purpose of comfort estimation and definition of vibrations acceptance criteria presenting velocity (or acceleration) for a significant single step that is larger than 90% fractile of people walking steps. This variable is defined as a single representative response parameter and is suitable for being compared with response requirements depending on the type of building and its use, according to JRC55118 [15]. The direct relation between two different variables given in BS 6472-1 [20] and JRC55118 [15] (multiplying factor  $R$  and  $OS\text{-}RMS_{90}$  variable, respectively) is defined through  $OS\text{-}RMS_{90}$  equivalent given in JRC55118 [15].

Current design recommendations for floor vibrations recognize peak or root mean square accelerations as main criteria for fulfilment of acceptability demands, as explained previously. However, it was shown that this procedure can be complex for the usual engineering practice. Therefore, the definition of the direct relation between composite beam deflection and achieved floor class for the fulfilment of vibrations acceptability criteria could facilitate the design procedure. Firstly, the numerical analysis of composite steel-concrete beams and floor structures with the dynamic model

of pedestrian loading is presented in this paper. In this framework, the difference of the acceptability criteria achieved using simplified design procedures given in BS 6472-1 [20] and JRC55118 [15] and through numerical analysis performed in Sofistik FE software (see <https://www.sofistik.com> [21]) is shown. Afterwards, the parametric study of composite steel-concrete beams is presented in this framework. The relationship between the overall deflections of composite beam and vibrations acceptability criteria for different floor occupancies according to JRC55118 [15] is presented as a result of the parametric study.

## 2 Classification of composite floor structures based on numerical analysis

### 2.1 Geometrical properties and natural frequencies

In this framework, vertical vibrations assessment of composite steel-concrete beams and their comparison with acceptance levels given in BS 6472-1 [20] and JRC55118 [15] is performed for six composite beams with 8, 10, 12 and

15 m span and 4 m spacing between beams, denoted from CB 1 to CB 4. The shape and dimensions of profiled steel sheeting, composite concrete slab, headed studs and structural steel with mechanical properties of adopted materials are shown in Figure 1 and Table 1.

Composite steel-concrete beams are made with standard hot-rolled steel sections and composite slab with profiled steel sheeting CF70. The direction of profiling (perpendicular to the beam axis) and detailed dimensions of profiled steel sheeting with 1 mm thickness are shown in Figure 1a. The total height of the composite slab is 150 mm with concrete C30/37. Steel sections and profiled steel sheeting are made from steel grade S235 and S355, respectively. Composite action between the steel beam and composite slab is achieved with headed studs - 22 mm in diameter and 120 mm height.

Composite beams CB 2-1 and CB 3-1 are variant solutions of composite beams CB 2 and CB 3 with larger structural steel cross-section and up to four times higher second moment of area of composite beam cross-section. Numerical models of composite beams are developed in Sofistik FE software [21]. The calculated second moment of area of composite beams cross-sections and those obtained

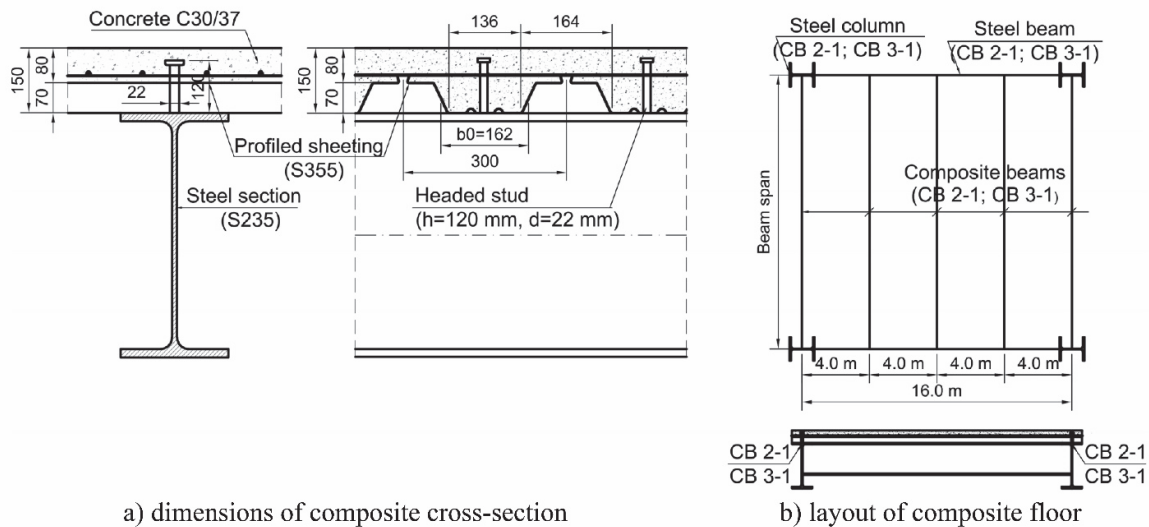


Figure 1. Layout and geometry of composite beam and floor

Table 1. Cross-section properties of composite beams

Beam	Steel section	Span (m)	Second moment of area of composite slab (cm <sup>4</sup> /m)	Second moment of area of composite beam (cm <sup>4</sup> )	Second moment of area of composite beam - Sofistik (cm <sup>4</sup> )	Difference (%)
CB 1	IPE 360	8.0	881	71980	71990	0.01
CB 2	IPE 450	10.0		130723	130700	0.02
CB 2-1	HEA 600	10.0		387122	387100	0.01
CB 3	IPE 550	12.0		232923	233300	0.16
CB 3-1	HEB 800	12.0		877235	877200	0.00
CB 4	IPE 600	15.0		313391	313400	0.00

from Sofistik FE software [21] are shown in Table 1. It can be seen that close agreement was achieved between individual parameters with a difference of less than 1 %. This difference is the consequence of concrete volume embedded in profiled steel sheeting which is modelled in Sofistik FE software [21] as a concrete part of the cross-section with the reduced modulus of elasticity and height which represent the height of profiled steel sheeting. However, this difference is taken as a small calculation error which is common for software analysis and satisfactory small for further numerical analysis.

Loads adopted for all numerical examples are 5.0 kN/m<sup>2</sup> of imposed load, 0.75 kN/m<sup>2</sup> of loads during construction and 1.0 kN/m<sup>2</sup> of floor finishing and installations. Calculation of ultimate and serviceability limit states is performed according to recommendations given in EN 1994-1-1 [22]. Composite beams are designed as unpropped during construction, except floor beam with 15 m span which is calculated as propped beam during construction in a third of the span. For all analysed composite beams, precamber of the steel section is predicted for the value of beam vertical deflection which is reached before composite action is envisaged. Adopted structural damping for all analysed composite beams is 3 % as total damping which consists of structural damping, damping due to furniture and damping due to finishes, according to JRC55118 [15]. The fundamental natural frequency of composite beams is calculated using the self-weight approach [20], as shown in Eq.1:

$$f_0 = \frac{17.8}{\sqrt{\delta_m}} \quad (1)$$

$$\delta_m = \frac{5}{384} \left( \frac{q_{swb} L^4}{E_a I_{i0}} \right) \quad (2)$$

where  $L$  is the composite beam span;  $\delta_m$  vertical deflection of the composite beam in millimetres (mm);  $q_{swb}$  is the composite beam weight per unit length (kN/m);  $E_a$  is the modulus of elasticity of structural steel and  $I_{i0}$  is the second moment of area of composite cross-section. In addition, the fundamental natural frequency of composite floor structure, composed of composite beams with arrangement presented in Figure 1b, is determined for orthotropic floor structure [14], using Eq.3, Eq.4 and Eq.5, respectively:

$$\frac{1}{f_0^2} = \frac{1}{f_{0s}^2} + \frac{1}{f_{0b}^2} \quad (3)$$

$$f_{0s} = 3.56 \sqrt{\frac{E_a I_s}{m_s b^4}} \quad (4)$$

$$f_{0b} = \frac{\pi}{2} \sqrt{\frac{E_a I_{i0}}{m_b b L^4}} \quad (5)$$

where  $f_0$ ,  $f_{0b}$  and  $f_{0s}$  are fundamental natural frequencies of the composite floor, composite beam and composite slab, respectively;  $m_s$  and  $m_b$  is the composite slab and beam vibrating mass per unit area (kg/m<sup>2</sup>) respectively [14];  $I_s$  is the second moment of area of the composite slab;  $b$  is the spacing between composite beams and other variables which have the same definition as in the Eq.1 and Eq.2. In addition, 10% of imposed loads were used for determination of natural frequencies based on two different approaches, [15] and [20]. Determination of composite floor fundamental natural frequency  $f_0$  using Eq.3 is based on Dunkerley's approach [15]. Based on the Dunkerley's approach, expected mode shape of the composite floor is divided into two independent single-mode shapes, composite slab and composite beam mode shape, with their natural frequencies. This approach is used when expected mode shape is complex and estimates its lower natural frequency limit. In addition, in Eq.4 and Eq.5 coefficient 3.56 and  $\pi/2$  are used for simple supports and both fixed supports against rotation, respectively and values for other end conditions are given by Wyatt [6]. Eq. (1) and (5) are derived from the same equation and represent fundamental natural frequency for simply supported beams. Eq. (1) gives satisfactory results for beams when analysed alone. Dunkerley's approach presented in Eq. (3) to (5) is used for the whole composite floor. Moreover, the fundamental natural frequency of analysed composite beams and composite floors is calculated in Sofistik FE software [21]. Results of natural frequencies calculation using different approaches and their comparison with the results of numerical analysis in Sofistik FE software [21] are presented in Table 2.

Minimal utilization level of plastic resistance moment of the composite cross-section for beams CB 1, 2, 3 and 4 is 75 %. The same utilization level for composite beams CB 2-1 and CB 3-1 is approximately 35 %, considering that these beams are the variant solution with larger structural steel cross-sections. The results presented in Table 2 indicate that difference between natural frequencies of composite beam and orthotropic floor structure for composite beams CB 1, 2, 3 and 4 with higher utilization level is less than 10 %. Lowering the level of utilization with larger structural steel cross sections for composite beams CB 2-1 and CB 3-1 resulted in a higher difference between natural frequencies for two individual calculation procedures, which approximately amounts 20 %. This is attributed to the higher fundamental natural frequency of composite beams CB 2-1 and CB 3-1 which exceeds 7 Hz, calculated according to self-weight approach [20] due to lower vertical deflection  $\delta_m$ . Composite beams CB 1, 2, 3 and 4 which have fundamental natural frequency lower than 7 Hz are classified as beams with low frequency according to BS 6472-1 [20]. Their natural frequency show close agreement with the frequency of the same orthotropic floor structure.

Table 2. Fundamental natural frequency of composite beam and floor

Beam	Self-weight approach - composite beam [20]			Orthotropic floor structure (steel beam + concrete slab) [15]					Sofistik [21]	
	$q_{swb}$ (kN/m)	$\delta_m$ (mm)	$f_{0b}$ (Hz)	$m_s$ (kg/m <sup>2</sup> )	$m_b$ (kg/m <sup>2</sup> )	$f_{0s}$ (Hz)	$f_{0b}$ (Hz)	$f_0$ (Hz)	Beam $f_{0b}$ (Hz)	Floor $f_0$ (Hz)
CB 1	19.51	8.13	6.24	482.67	497.22	13.78	6.23	5.67	6.11	5.67
CB 2	19.72	10.86	5.40		502.45		5.39	5.02	5.26	5.16
CB 2-1	20.72	3.88	9.04		528.03		9.02	7.54	8.67	7.50
CB 3	20.00	12.68	5.00		509.68		4.99	4.69	4.84	4.78
CB 3-1	21.56	3.66	9.31		549.44		9.29	7.70	8.85	7.98
CB 4	20.16	23.00	3.71		513.76		3.70	3.58	3.60	3.51

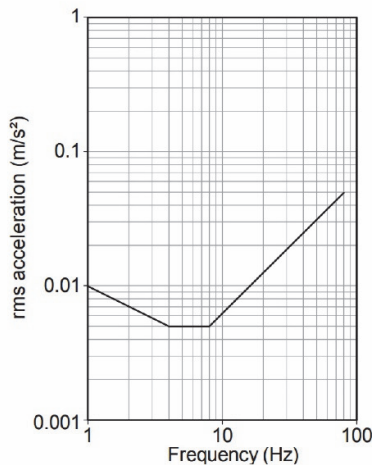
Numerical models are developed in Sofistik FE software [21] in order to compare natural frequencies obtained from the software with those obtained from the literature. Numerical models for composite beams are developed using beam structural element with composite cross-section, which is defined for every composite beam with belonging effective width. Dimensions of the composite cross-section are given in Figure 1a. Concrete volume embedded in profiled steel sheeting is modelled in Sofistik FE software [21] as a concrete part of the cross-section with the reduced modulus of elasticity and reduced self-weight in order to represent real self-weight of the composite beam. All analysed composite beams are simply supported. Numerical models for composite floor structure are developed using composite beams with cross-sections and spans defined in Table 1. The composite slab is defined with equivalent height in order to realistically present composite cross-section, shown in Figure 1a. The concrete plate is connected to steel beams with rigid links, defining the one-way composite slab. The general layout of composite floor structure is presented in Figure 1b. All composite beams (primary beams) are connected to steel beams (secondary beams) and columns with simple joints. The analysed composite beam (primary beam) / steel beam (secondary beams) span ratio is between

1.0 and 1.5 (1.0 for CB 1, 1.25 for CB 2 and CB 4 and 1.5 for CB 3). Solid finite elements are used for numerical analysis of composite floor structure in Sofistik FE software [21].

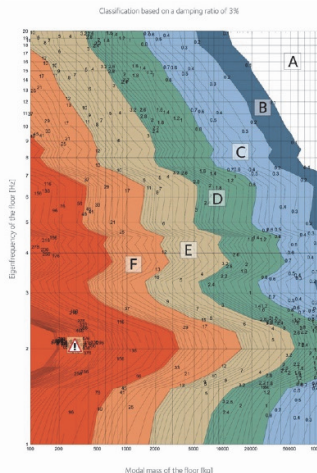
Natural frequency in Sofistik FE software [21] is calculated including structure self-weight with floor finishing and installations and 10% of imposed loads, according to recommendations given in JRC55118 [15]. As shown in Table 2, close agreement between natural frequencies of developed numerical models obtained from software and recommendations given in BS 6472-1 [20] and JRC55118 [15] is achieved.

2.2 Vibrations of composite floor structures induced by pedestrian loading

Figure 2 presents acceptance levels diagrams of floor vibrations according to BS 6472-1 [20] and JRC55118 [15] and their comparison through the direct relationship between multiplying factor  $R$  and  $OS-RMS_{90}$  equivalent. BS 6472-1 [20] defines acceptance levels of floor vibrations for different floor occupancies in the form of the base curve shown in Figure 2a and multiplying factors  $R$ , as shown in Figure 2c.



a) base curve for vertical accelerations [20]



b) classification of floor response [15]

Intended use of the structure	Multiplying factor $R$	$OS-RMS_{90}$ equivalent
Critical working area	1	0.1
Residential	2 to 4	0.2 to 0.4
Quiet office	2	0.2
General office	4	0.4
Workshops	8	0.8

c) vibration limits specified in [3], [20] and equivalent  $OS-RMS_{90}$  [15]

Figure 2. Floor vibrations acceptance criteria

Multiplying factor  $R$  can be calculated using Eq.6 for structures with fundamental natural frequency lower than 7 Hz:

$$R = \frac{68000C_f}{m_b S_{\text{eff}} L \zeta} \quad (6)$$

$$S_{\text{eff}} = 4.5 \left( \frac{E_a I_s}{m_b f_0^2} \right)^{\frac{1}{4}} \quad (7)$$

where  $C_f$  is the coefficient which depends upon the natural frequency and should be adopted as 0.4 if  $f_0$  is between 3 Hz and 4 Hz, as 0.2 if  $f_0$  is higher than 4.8 Hz or should be calculated as  $1.4-0.25 \cdot f_0$  if  $f_0$  is between 4 Hz and 4.8 Hz, as defined in BS 6472-1 [20];  $\zeta$  is the structure damping ratio;  $S_{\text{eff}}$  is composite floor effective width (m) [6] and other variables have the same definition as in previous equations. Fourier component factor  $C_f$  should be taken as a function of the floor fundamental natural frequency but is also related to the type of excitation. Precise recommendations for values of coefficient  $C_f$  for fundamental natural frequency lower than

3 Hz are not given in current literature. Therefore, it can be concluded that the nature of excitation of vertical accelerations does not significantly influence the structure response and adoption of value 0.4 for this coefficient gives safe side prediction. Multiplying factor  $R$  can be calculated using Eq.8 for structures with the fundamental natural frequency which exceeds 7 Hz:

$$R = \frac{30000}{m_b b_e L} \quad (8)$$

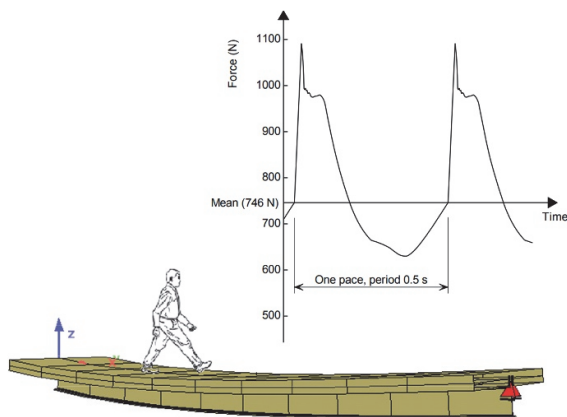
$$b_e = \min(b, 40h_p) \quad (9)$$

where  $h_p$  is the height of concrete slab and other variables have the same definition as in previous equations.

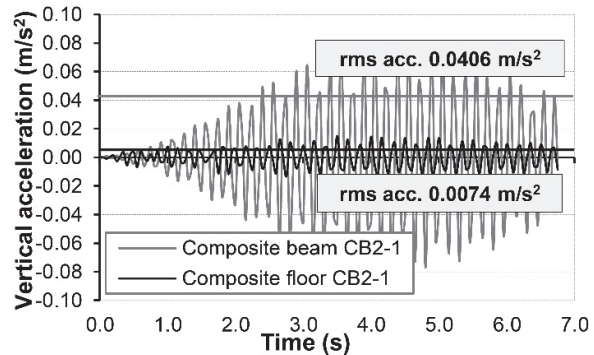
Multiplying factors  $R$  calculated according to Eq.6 and Eq.8 based on natural frequencies given in Table 2 are presented in Table 3. Calculated multiplying factors  $R$  for all numerical examples are used for drawing new acceptability curves based on the Figure 2a and calculation of root mean square accelerations  $a_{\text{rms}}$  for certain fundamental natural frequency. These results are also presented in Table 3.

Table 3. Acceptance levels according to BS 6472-1 [20]

Beam	Self-weight approach [20]						Sofistik [21]	
	Composite beam			Orthotropic floor			Beam	Floor
	$C_f$	$R$	$a_{\text{rms}}$ (m/s <sup>2</sup> )	$C_f$	$R$	$a_{\text{rms}}$ (m/s <sup>2</sup> )	$a_{\text{rms}}$ (m/s <sup>2</sup> )	$a_{\text{rms}}$ (m/s <sup>2</sup> )
CB 1	0.20	7.724	0.03862	0.20	7.724	0.03862	0.01167	0.00431
CB 2	0.20	5.765	0.02883	0.20	5.765	0.02883	0.01136	0.00221
CB 2-1	0.20	1.810	0.00905	0.20	1.775	0.00888	0.04062	0.00738
CB 3	0.20	4.681	0.02341	0.23	4.687	0.02344	0.01688	0.00285
CB 3-1	0.20	1.449	0.00725	0.20	1.422	0.00711	0.02489	0.00559
CB 4	0.40	6.381	0.03191	0.40	6.503	0.03252	0.00885	0.00907



a) numerical model of pedestrian loading according to Bachmann [1]



b) vertical accelerations of composite beam and floor CB2-1

Figure 3. Numerical analysis in Sofistik FE software [21]

To calculate structure vertical acceleration due to pedestrian loading, dynamic analysis is performed in Sofistik FE software [21]. Dynamic load function for continuous excitation due to pedestrian traffic is shown in Figure 3a, and explained in detail in numerous publications [1], [4], [6]. Figure 3a presents contact force from a single footfall and basic pace frequency is presented with the second Fourier component [6]. This type of dynamic loading can be broken down into a series of sinusoidal functions based on Fourier transformation. Fourier transformation for dynamic load function of human walking is explained also in [23] and short review of dynamic load factors for each harmonic and different type of human activities is given in [24].

The numerical model of pedestrian traffic is analysed in Sofistik FE software [21], using DYNA module for dynamic analysis which is incorporated in this software. Sofistik FE software [21] offers direct implementation of pedestrian traffic according to Bachmann [1], which function is presented in Figure 3a. Using DYNA module for dynamic analysis pedestrian traffic is implemented with a total weight of one person of 800 N, which is moving over composite beams or composite floor structures with pacing width of 0.7 m and pace frequency of 2.10 Hz. Results of numerical analysis performed in Sofistik FE software [21] in the form of root mean square vertical accelerations in the middle of the beam span are given in Table 3. Root mean square accelerations are calculated based on the accelerations of the beam in the middle of the span (Figure 3b) obtained through dynamic analysis in Sofistik FE software [21]. The results shown in Table 3 indicate that numerical model of composite beams CB 2-1 and CB 3-1 gives higher values of root mean square accelerations  $a_{rms}$  in comparison with the same values obtained from multiplying factor  $R$  and base curve, but the close agreement between two parameters for the same composite floor structure. These results also indicate that FE analysis of composite beams with a fundamental natural frequency lower than 7 Hz gives

sufficiently accurate results, excluding the necessity for modelling of the whole composite floor structure. However, this approach could not be adopted for composite beams with a fundamental natural frequency higher than 7 Hz. Their behaviour can be observed only through the numerical model of the whole composite floor structure. In addition, vertical accelerations obtained from numerical analysis for composite beams CB 1, 2, 3 and 4 and all composite floor structures have lower values in comparison with the same values obtained from literature, as shown in Table 3.

Classification of analysed composite floor structures according to recommendations given in JRC55118 [15] is shown in Table 4. Graphical presentation of floor classification for adopted natural damping of 3 % is shown in Figure 2b. To define composite floor class it is necessary to define its fundamental natural frequency and modal mass using Eq. 3 and Eq. 10, respectively:

$$M_{mod} = M_{total} \left( \frac{\delta_x^2 + \delta_y^2}{2\delta^2} + \frac{8}{\pi^2} \frac{\delta_x \delta_y}{\delta_{total}^2} \right) \quad (10)$$

$$\delta_x = \frac{5}{384} \left( \frac{m_s g b^4}{E_a I_s} \right) \quad (11)$$

$$\delta_y = \frac{5}{384} \left( \frac{m_b g b L^4}{E_a I_{i0}} \right) \quad (12)$$

where  $\delta_x$  is the vertical deflection of a composite slab, as defined in Eq.2;  $\delta_y$  is the vertical deflection of the composite beam;  $\delta_{total}$  is the sum of vertical deflections of composite beam and composite slab and other variables have the same definition as in previous equations.

Table 4. Acceptance levels according to JRC55118 [15]

Beam	Orthotropic floor structure (steel beam + concrete slab) [15]							Sofistik [21]	
	$\delta_y$ (mm)	$\delta_x$ (mm)	$\delta_{total}$ (mm)	$M_{mod}$ (kg)	Class	OS-RMS <sub>90</sub> equivalent	R	Beam Class	Floor Class
CB 1	8.128	8.531	16.659	7202.5	D	0.8	8.000	C	A
CB 2	10.859		19.309	9110.9	D	0.8	8.000	C	A
CB 2-1	3.877		12.408	9701.1	C	0.2	2.000	D	B
CB 3	12.683		21.214	11118.2	D	0.8	8.000	C	A
CB 3-1	3.655		12.186	12137.6	C	0.2	2.000	C	B
CB 4	23.003		31.534	14260.5	D	0.8	8.000	B	A
Class A – recommended for all floor occupancies; Class B – critical for critical areas and recommended for all other occupancies; Class C – not recommended for critical areas and recommended for all other occupancies; Class D – not recommended for critical areas, critical for use in hospitals, surgeries, schools and training centres, recommended for all other occupancies; Class E – not recommended for critical areas, hospitals, surgeries, schools and training centres, critical for residential buildings, office buildings, meeting rooms, senior citizens residential buildings and hotels, recommended only for industrial workshops and sports facilities; Class F – critical for industrial workshops and sports facilities and not recommended for any other floor occupancies.									



Classification of the composite floor structure is later used for definition of  $OS-RMS_{90}$  coefficient, according to JRC55118 [15] and determination of multiplying factor  $R$ . As shown in Table 4, multiplying factor  $R$  which is determined based on the  $OS-RMS_{90}$  equivalent shows good agreement with the same values presented in Table 3. Moreover, results of numerical analysis in Sofistik FE software [21] are used for determination of multiplying factor  $R$  and  $OS-RMS_{90}$  equivalent in order to define the relationship between root mean square accelerations obtained from numerical analysis and floor structure classification given in JRC55118 [15]. In addition, results given in Table 3 indicate that detail numerical analysis of pedestrian loading in FE software gives lower vertical accelerations and lower class of the floor structure in comparison with the results obtained from design recommendations given in JRC55118 [15].

Lower vertical accelerations and lower floor structure class provide that considered floor structure can be used for a wider range of floor occupancies. As defined in JRC55118 [15] and presented in Table 4, floor structure can be classified from A (recommended for usage for different occupancies from critical areas and hospitals to the sports facilities) to F (critical for usage for industrial workshops and sports facilities and not recommended for other occupancies).

### 2.3 Discussion of numerical analysis results

According to the results of numerical analysis, the following remarks can be stated:

1) BS 6472-1 [20] and JRC55118 [15] provide a relatively simple calculation procedure of composite floor vibrations. In addition, the results obtained from two individual design procedures show good agreement (see Table 3 and Table 4). Moreover, JRC55118 [15] defines the relationship between multiplying factor  $R$  given in BS 6472-1 [20] and similar  $OS-RMS_{90}$  factor used for classification of composite floor structures. JRC55118 [15] gives more detail partitioning between floor occupancies than BS 6472-1 [20], which can be helpful for structure design.

2) Numerical analysis of composite beams in FE software with a fundamental natural frequency higher than 7 Hz gives inappropriate results. Root mean square accelerations for these beams obtained from FE software have higher values than the same values obtained from BS 6472-1 [20] (see

Table 3). In addition, numerical analysis of composite floor structures gives lower values of floor accelerations.

3) Accelerations of composite beams and floor structures which are the result of numerical analysis are lower than the same results obtained using the design recommendations given in BS 6472-1 [20] and JRC55118 [15]. Lower accelerations of floor structures are more favourable and enable the usage of these structures for a wider range of floor occupancies. In addition, detail numerical analysis of floor vibrations is of high importance for the design of complex structures or structures occupied with high precision equipment or specific working processes.

### 3 Parametric study of vibrations of composite steel-concrete beams

#### 3.1 Analysis method

Parametric study of vibrations of composite steel-concrete beams, which is presented in this chapter is conducted using design recommendations for ultimate and serviceability limit state given in EN 1994-1-1 [22] and JRC55118 [15]. The aim of the parametric study was to define the relationship between vibrations of composite beams and their deflection. While verification of deflection is a well known and relatively simple procedure, calculation of floor vibrations caused by pedestrian traffic is defined in different literature and still causes certain design difficulties. In addition, meeting the requirements of floor vibrations is directly related to the envisaged floor occupancies. Classification of composite floor structures due to vibrations according to JRC55118 [15], which is shown in the previous chapter, is used in this parametric study. The parametric study included composite beams with span from 7 m to 15 m and span of the composite slab (spacing between composite beams) which is analysed is 3 m and 4 m. Composite beams are performed with three types of hot-rolled steel sections (IPE, HEA and HEB). The main properties of composite floor structures analysed in this parametric study are given in Table 5. Three main composite structure types (CS 1, CS 2, CS 3) are analysed with 0.75 kN/m<sup>2</sup> of loads during construction and for imposed load from 2.0 to 5.0 kN/m<sup>2</sup> which comprise a wide range of floor occupancies according to JRC55118 [15] and EN 1991-1-1 [18]. Composite structures CS 1 and CS 3 are analysed for 2.0 kN/m<sup>2</sup> and CS 2 for 1.0 kN/m<sup>2</sup> of additional permanent load due to floor

Table 5. Analysis parameters

	Composite floor				Second moment of area of composite slab (cm <sup>4</sup> /m)	Load (kN/m <sup>2</sup> )		
	Span (m)	Profiled steel sheeting				During construction	Additional permanent	Imposed
		Thickness (mm)	Height (mm)	Concrete height (mm)				
CS 1	3.0	1.20	60	60	0.75	2.0	2.0 – 5.0	
CS 2	4.0	1.00	70	80		1.0	2.0 – 5.0	
CS 3	4.0	1.20	80	60		784	2.0	2.0
				70		944		3.0
				80		1127		4.0
				90		1333		5.0
Adopted material properties in the parametric study: structural steel - S235, concrete class - C30/37, reinforcement - B500, profiled steel sheeting - S355.								



finishing and installations. Every composite structure is analysed for each value of imposed load with three types of hot-rolled steel sections IPE, HEA and HEB. Therefore, the presented parametric study included 324 composite beams overall.

The same design procedure was performed for every composite structure and specific values of loads, shown in Table 5. Firstly, for every type of steel section (IPE, HEA and HEB) and for each composite beam span, design procedure given in EN 1994-1-1 [22] is followed in order to acquire required resistance of cross-section and shear connection. Hereafter, it was tried to find a specific steel section from a range of analysed cross-sections which satisfies recommendations of vibrations for each composite floor class according to JRC55118 [15], and in the same time acquire required resistance of cross-section and shear connection according to EN 1994-1-1 [22]. At last, for specified cross-section total vertical deflection of composite beam  $\delta_{total}$  is determined as summation of vertical deflection of steel beam during construction and vertical deflection of the composite steel-concrete beam after the shear connection is achieved. The results of the parametric study are presented in the form of beam span ( $L$ ) vs. beam span/total deflection ( $L/\delta_{total}$ ). To achieve the evenness of the parametric analysis for every composite beam span, every beam is analysed as unpropped during construction. Considering that the serviceability limit state is authoritative criteria for this analysis, the variation of steel grade for

structural steel is irrelevant. Therefore, structural steel for all composite beams is made from steel grade S235, as given in Table 5.

Composite floor structures with lower class are more favourable for a wide range of floor occupancies, as given in Table 4. Concrete slab and profiled steel sheeting height of composite slab shown in Table 5 are adopted as minimal values in order to accomplish required design resistance for adopted load value and which offers a safe prediction to the floor vibration vs. deflection.

The main result of the parametric study is the direct relation between vertical deflection of composite beams and achieved floor class, according to floor vibrations classification given in JRC55118 [15]. Therefore, according to the results of this parametric study, verification of floor deflection can lead directly to the classification of floor vibrations.

### 3.2 Results of the parametric study

Results of parametric analysis for composite beam spacing of 3 m of composite structure CS 1 which dimensions are shown in Table 5 and imposed load of 2.0 kN/m<sup>2</sup> are shown in Figure 4. For analysed composite beam total vertical deflection is determined for achieved composite floor class due to vibrations, as explained in the previous chapter. Beam span/total deflection ( $L/\delta_{total}$ ) is plotted versus the span of the analysed composite beam (Figure 4).

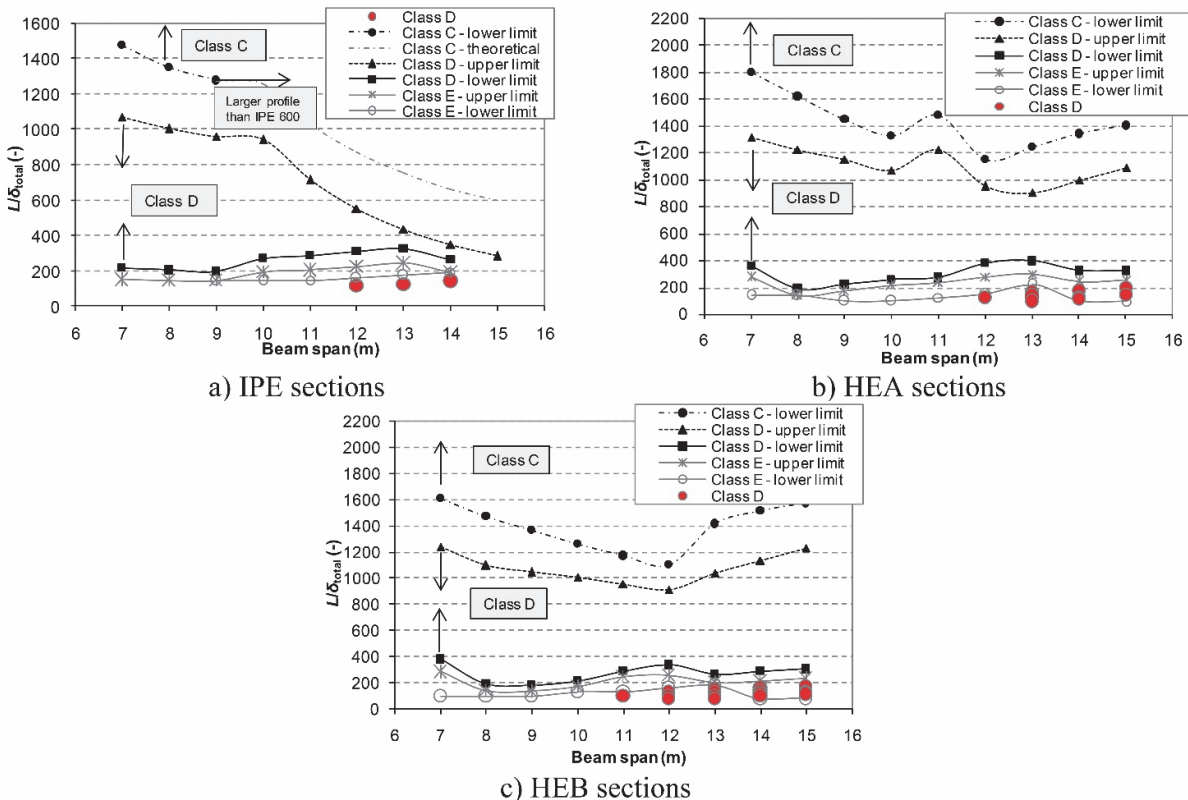


Figure 4. Deflection of composite beam for beam spacing of 3 m and imposed load of 2 kN/m<sup>2</sup> - CS 1

For composite structure CS 1, class A and B with analysed hot-rolled steel sections could not be accomplished, as shown in Figure 4. The same behaviour is obtained for two other composite structures CS 2 and CS 3. In additional, similar behaviour is achieved for HEA and HEB steel sections of composite beams, while IPE sections show somehow different behaviour. Moreover, for composite beam span higher than 9 m, floor class C could not be accomplished even with the larger IPE section (IPE 600). The theoretical extension of the curve which represents vertical deflection for class C is derived based on the results for class D, as shown in Figure 4a. Difference between vertical deflection for the lower limit of class C and the upper limit of class D is the result of different geometrical properties of two consecutive cross-sections. In addition, with standard IPE, HEA and HEB cross-sections composite floor class E can be accomplished, but with very high values of vertical deflection.

The widest range of cross-sections lead to the composite floor class D, and class C is achieved for beam span/total deflection values higher than 1400 for IPE sections and 1800 and 1600 for HEA and HEB sections, respectively. It can be concluded that for composite structure CS 1 the higher efficiency considering floor vibrations can be achieved for beam span of 12 m, using HEA and HEB steel sections. In addition, using the consecutive cross-sections from lower to the largest, higher floor class can be achieved with a smaller cross-section and for larger cross-section lower floor class, which is presented in form of red dots on the plots in Figure 4. This is the outcome of the composite floor class diagrams presented in Figure 2b which are not given in form of linear relation between modal mass  $M_{mod}$  and fundamental natural frequency  $f_0$ , especially for fundamental natural floor frequencies of 2 Hz and 4 Hz, which present the range of frequency of pedestrian walk.

Comparison of cross-section design resistance utilization level for composite structure CS 1 with imposed load of 2 kN/m<sup>2</sup> is given in Figure 5. It is shown that the achievement of class C for three different steel sections can be accomplished with cross-section design resistance utilization level amounting approximately 20 %. The lower limit of composite floor class D which beam span/total deflection ( $L/\delta_{total}$ ) ratio is in the range from L/200 to L/400 (Figure 4) is

achieved with a cross-section which utilization level is from 50% to 70% for IPE sections and relatively equally for HEA and HEB sections (40 % to 50 %). The analysis presented in Figure 5 is accomplished for various cross-sections, aiming to achieve different composite floor classes with lowest possible cross-section dimension, but also accomplishing design procedure for the ultimate limit state.

Comparison of beam span ( $L$ ) vs. beam span/total deflection ( $L/\delta_{total}$ ) plots for composite structure CS 1 and different values of imposed loads are given in Figure 6. The higher value of imposed load leads in the achievement of designated floor class with smaller steel section, higher value of vertical deflection and lower beam span/total deflection ( $L/\delta_{total}$ ) ratio. The same trend is noticed for three analysed steel section IPE, HEA and HEB, as shown in Figure 6. The lower limit of floor class D for three analysed steel sections have similar values for four analysed imposed loads values. The same behaviour is noticed for other analysed composite structures CS 2 and CS 3.

The parametric study presented in this paper included a wide range of composite beam spans, with most common composite floor spans. In addition, analysed loads included usual values of additional permanent loads and whole range imposed loads which are defined according to EN 1991-1-1 [18]. Results of three analysed composite structures (Table 5) are compared in order to define unique beam span ( $L$ ) vs. beam span/total deflection ( $L/\delta_{total}$ ) plots for three different types of hot-rolled steel sections (Figure 7). The results presented in Figure 7 offers the safe (conservative) prediction of composite floor class due to vibrations. Values of beam span/total deflection ( $L/\delta_{total}$ ) which are higher than values given with red curve presented in Figure 7 gives a safe (conservative) prediction for class C composite floor, and values which are between black curves (upper and lower limit for class D) gives a safe (conservative) prediction for class D. For values which are between curves which present upper and lower limit for specified class, the design procedure for composite floor classification given in JRC55118 [15] should be performed in order to confirm composite floor class. In addition, it is important to highlight that the values of total vertical deflection  $\delta_{total}$  presented on plots in Figure 4, Figure 6 and Figure 7 are obtained through the summation of vertical deflection through all construction

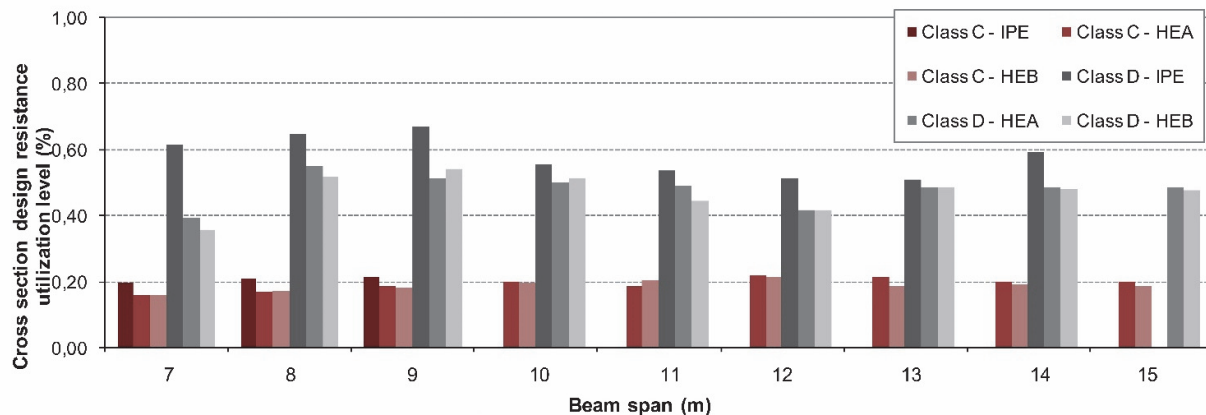


Figure 5. Design resistance of composite steel-concrete cross section - CS 1

phases without support within the span of the steel beam during construction or precamber of the steel section. In order to accomplish vertical deflection limitation according to

EN 1994-1-1 [22] precamber of steel sections for the value of the deflection during construction can be performed.

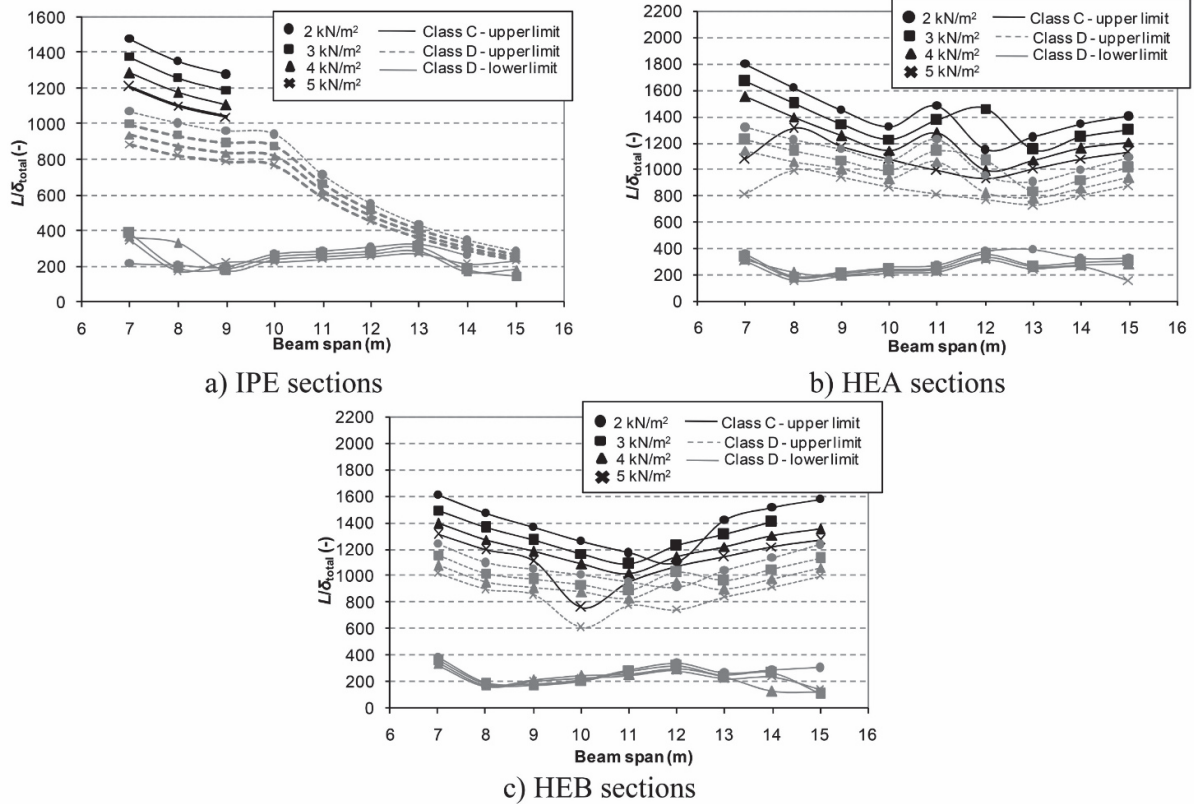
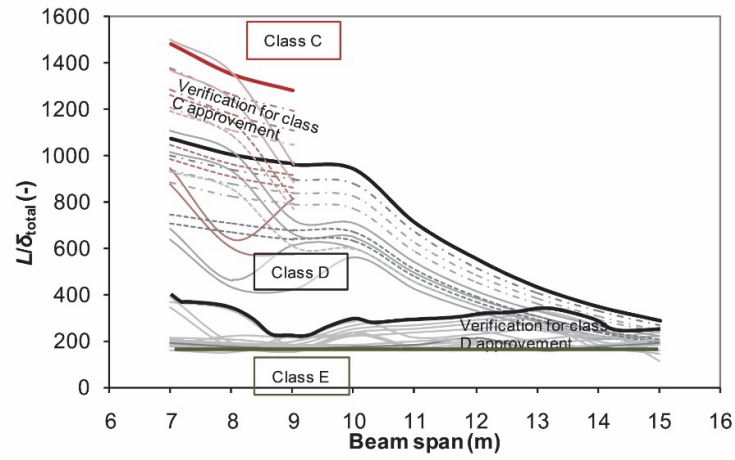
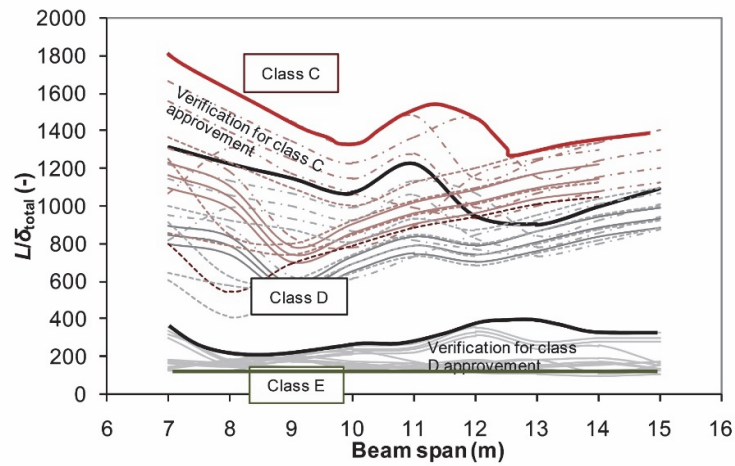


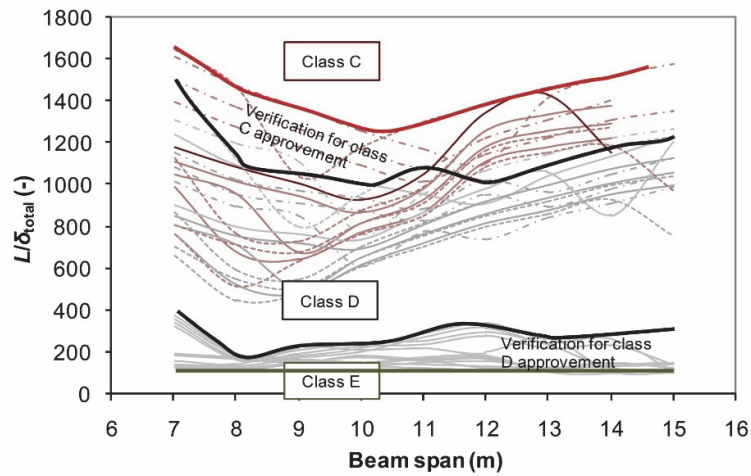
Figure 6. Comparison of vertical deflections for different values of imposed loads – CS 1



a) IPE sections



b) HEA sections



c) HEB sections

Figure 7. Composite floor class vs. beam deflection

### 3.3 Discussion of parametric study results

According to the results of the parametric study, the following remarks can be stated:

1) Even the largest steel sections from the range of IPE, HEA and HEB hot-rolled steel sections used in the parametric study presented in this paper cannot lead to the achievement of composite floor class A and B due to floor vibrations according to JRC55118 [15]. Moreover, the lowest floor class F is not accomplished, considering that small structural steel sections would not satisfy cross-section design resistance.

2) IPE steel sections are favourable for beams with larger spans for the achievement of designated composite floor class due to vibrations. HEA and HEB steel sections showed relatively similar behaviour, and this type of steel sections shows the best achievement of designated composite floor class for spans between 10 and 12 m for three analysed composite structures.

3) The widest range of adopted steel sections and composite beam and floor class results in the achievement of composite floor class D. Composite floor class D is not recommended for the usage in critical working areas, hospitals, surgeries, schools and training centres

## 4 Conclusions

Architectural trends towards slender structural design and using modern high-strength construction materials often result in low natural frequencies of the structure. Therefore special attention should be given to serviceability limit states verification, which can often be authoritative criteria for structures design. Subsequent re-design of structures which fail to satisfy vibrations acceptance criteria for the intended use of the structure is very difficult, not economical and often unfeasible. Design recommendations dealing with composite floor vibrations are given through different technical guidelines or recommended procedures which are not mandatory for the structural design. Moreover, Eurocode defines only rough (indicative) recommendations for evaluation of acceptance criteria regarding vibrations of floor structures and fails to provide more precise recommendations for calculation of floor structures exposed to vibrations.

In this paper, the results of numerical analysis and parametric study of composite beams due to vibrations induced by pedestrian loading are presented. The following conclusions are obtained:

1) Vertical root mean square accelerations obtained from numerical analysis using FE software are significantly lower than the same values obtained from simplified design procedures. Lower vertical accelerations lead to lower composite floor class due to vibrations which are favourable for different floor occupancies.

2) Composite floor beams which are designed in order to accomplish recommendations for the ultimate limit state with high level of utilization most often leads to the floor classes due to vibrations which are between class D and E. Safe prediction of composite floor class D leads to the utilization level from 50% to 70% for IPE sections and from 40% to 60%

for HEA and HEB hot-rolled steel sections, according to JRC55118 [15]. Composite floor class D can be used for residential buildings, office buildings, meeting rooms, senior citizens residential buildings, hotels, industrial workshops and sports facilities.

3) Lowering the level of utilization of composite cross-section resistance to 20%, leads to the composite floor class C, according to JRC55118 [15]. Composite floor structures of class C are not recommended only for critical working areas and can be used for all other occupancies.

4) Composite floor classes A and B cannot be accomplished with standard hot-rolled steel sections and achievement of high floor classes can be reached only with specifically built-up steel members, according to design recommendations given in JRC55118 [15]. The main difference between these floor classes and composite floor class C is that floors with class C cannot be used in critical working areas where specific working activities are envisaged or installation of equipment with high precision. These types of floor occupancies are very specific and detailed composite floor verification based on the precise numerical analysis of vertical vibrations should be performed.

5) The results of the parametric study presented in this paper can be used for safe (conservative) prediction of composite floor class against vertical floor vibrations, based on the determination of composite beam vertical deflection.

## Acknowledgement

This investigation is supported by the Serbian Ministry of Education, Science and Technological Development through the TR-36048 project.

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