COMPOSITE FLOORS UNDER HUMAN-INDUCED VIBRATIONS

Konstantinos Bakalis
Postdoctoral Researcher
ETH Zurich
Zurich, Switzerland
e-mail: kbakalis@ethz.ch

Athanasia Kazantzi
Adjunct Lecturer
International Hellenic University
Serres, Greece
e-mail : kazantzi@ihu.gr

1. ABSTRACT

Composite steel-concrete floor systems are widely used in modern construction for achieving long-spans with a low number of intermediate columns. The design of such slender and lightweight floor systems is typically governed by the serviceability limit state requirements, associated with deformations, human comfort perception, and vibration tolerances. To guide designers through the process of delivering floors that are not prone to human-induced vibrations, and hence imposing a feeling of discomfort to their users, a number of design guidelines of variable complexity have been developed in the past few decades [1,2]. In their simplest form, such guidelines adopt several deterministic assumptions regarding the floor damping, the imposed loads, the connection rigidity under service loads, the step frequency, the footpath and the human weight. In this study, sources of uncertainty are discussed. A numerical grillage-based floor model is also presented, that could be utilised for extracting the needed engineering demand parameters for undertaking an assessment of such floor systems when subjected to walking-induced vibrations.

2. INTRODUCTION

Composite steel-concrete floors are characterised by low self-weights and damping ratios compared to ordinary reinforced concrete ones. Hence, in view of these distinct properties, contemporary composite steel-concrete floors are more prone to human-induced vibrations that could cause discomfort to their users (i.e., vibration serviceability issues). Discomfort, as well as the perception of annoying vibrations in general, is a rather complex and subjective matter. For instance, the tolerance to vibrations is affected by the type of the environment, with the acceptable limits being higher for more active places (e.g., shopping malls) and lower for less active ones (e.g., hospitals, offices). This condition is reflected in the acceleration limits that are defined in the AISC/CISC Design Guide 11 [1] and are herein reproduced in Fig. 1.

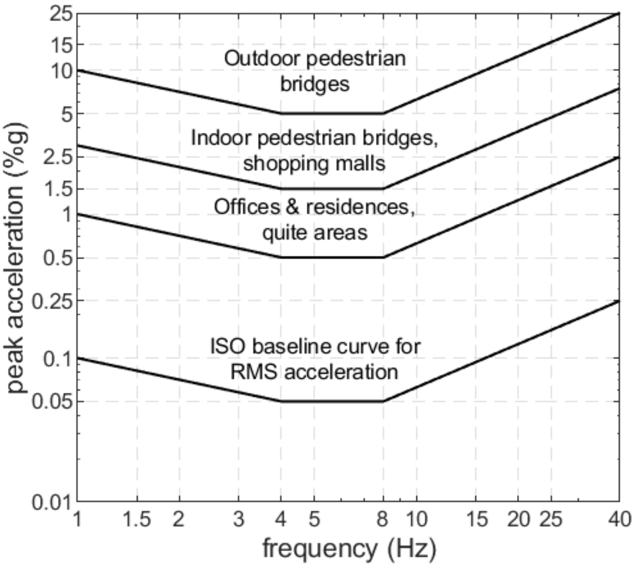

Fig. 1: Recommended acceleration tolerance limits for human comfort [1]

In general, based on the magnitude of their fundamental frequency, floors are characterised as either low- or high-frequency ones. Although the exact frequency threshold for characterising a floor as low- or high-frequency varies in the literature, floors with first mode natural frequencies in excess of 10Hz are typically characterised as high-frequency ones [3]. The implications of such a classification are not restricted to the realm of theory, but are rather directly reflected to the anticipated vibration response under human-induced excitations. In particular, low-frequency floors are prone to resonant build-up, a condition that occurs when the step frequency or a multiple of the latter (i.e., harmonic) matches the eigenfrequency of a floor mode and especially that of the floor's natural frequency. By contrast, high-frequency floors are not prone to resonant build-up since no frequency matching can practically occur, and thus, they exhibit an impulsive response.

2.1 Sources of uncertainty

The vibration performance of steel-concrete composite floors under human walking is affected by a variety of factors, such as the dynamic properties of the floor, its damping ratio, the weight of the individual that was assumed to walk on the floor, the step frequency and the step length, among others (e.g., walking path, load model). One of the major causes of annoying vibrations due to human activity refers to the case where the beat of a harmonic of a certain activity is close to or matches one of the modal frequencies of the floor.

The load imposed on a floor due to a human walking, comprises three components in the associated lateral, longitudinal and vertical direction. However, the first two components are disregarded in this study, and only the most important (at least for the case of floors) vertical one was considered. This study is also restricted in the realm of a single person excitation, which is deemed to be the standard design scenario in the case of office floors [4]. Yet, even for this simple case, the actual step frequency, step length and human weight are highly variable parameters across a population of different individuals. For instance, by means of walking load experiments on 61 test subjects and 2204 records, Chen and Zhang [5] found that the walking step frequency f_s of normal walk approximately follows a normal distribution, with a mean value of 1.937Hz and a standard deviation of 0.296Hz. The mean of the aforementioned distribution complies well with the 2.0Hz pacing rate reported before by Bachmann and Ammann [6] for normal walking conditions. Other researchers, such as for instance Matsumoto *et al.* [7], proposed similar normal distributions for normal walking (with a pacing rate 2.0Hz and a standard deviation of 0.18Hz). Similarly, on account of measurements conducted in an office building at Delft, the walking frequency was approximated with a lognormal distribution having a mean of 2.0Hz and a CoV of 8.5% [2]. The SCI Publication P354 [2] states that although the pace frequencies of walking activities may range from 1.5Hz to 2.5Hz the most probable range is between 1.8Hz to 2.2Hz.

Damping is another factor that plays a determinant role in the vibration assessment of floors, as it defines to a large extent the magnitude of the response in low frequency floors. In high frequency floors damping was found not to affect the initial peak response due to the footfall impact [8]; yet, in both type of floors (i.e., low and high frequency ones) it affects the decay of the motion. Apart from the material type, damping varies substantially between floors having connections with different rigidity, partition walls, equipment or furnishing, suspended ceilings as well as stationary humans [9]. In general, compared to ordinary concrete floors, steel-concrete composite ones are characterised by lower damping levels, that consequently could lead to more severe vibrations and hence discomfort to their users. Hewitt and Murray [10] also indicated the lack of paperwork in modern offices as a reason for the lower damping levels. The methodology that is presented by Feldmann *et al.* [11] for the design of floors against human-induced vibrations defines the system damping as the sum of the contribution of three individual factors, that are the structural damping which varies for different construction materials, the damping due to furniture as well as the damping due to finishes. In fact, the importance of damping in the floor vibration response is also further highlighted by the fact that the increase of damping is among the most important retrofit measures against annoying human-induced floor vibrations. This can be attained by, e.g., changing the position of the non-structural elements or through utilising tuned mass dampers [2].

This study proposes a numerical grillage-based model that is suitable for conducting a probabilistic floor vibration assessment. The focus is on low-frequency floors that are prone to resonance phenomena, in particular composite steel-concrete floor systems that are commonly used in modern construction, yet they often have relatively low natural frequencies that lie within the frequency range likely to be affected by ordinary human activities (e.g., walking, running, dancing).

3. CASE STUDY

A single-unit steel-concrete composite floors is examined herein [12]. A generic drawing of the floor considered, is illustrated in Fig. 2. It comprises two steel girders having a span of L_g, four girders with a span of L_j and a $h_c = 150$mm thick concrete slab. All cross-section properties for both beams and columns are summarised in Table 1. The case study floor is borderline acceptable according to the AISC design guide [1,12].

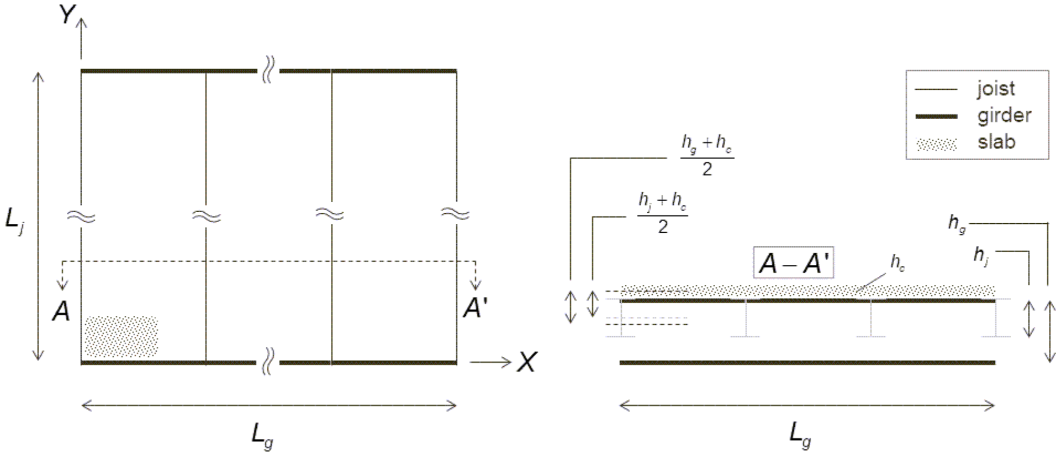

Fig. 2: Generic drawing of an $L_g \times L_j$ steel-concrete composite slab; (left) plan view; (right) A-A' cut view

Member	Cross section	Height (mm)	Flange width (mm)	Flange thickness (mm)	Web thickness (mm)	Length (m)
Girders	VS I 550×64	550	250	9.5	6.3	9.0
Joists	VS I 450×51	450	200	9.5	6.3	6.5
Columns	CS I 300×62	300	300	9.5	8.0	5.0

Table 1: Member properties of the case study floor [9,12]

4. STEP FORCE MODELLING

Several different options are available in the literature for modelling the step forces that are induced to the floor by a walking individual. One of the earliest models assumes the step force as perfectly periodic, thus allowing the respective loading function $F(t)$ to be expressed through the following Fourier series [6]:

$$F(t) = W\left[1 + \sum_{i=1}^{n} a_i \sin\left(2\pi i f_s t + \varphi_i\right)\right] \tag{1}$$

In Equation (1), W is the weight of the individual (often assumed between 700N and 800N), i is the harmonic component, t is the time in seconds, f_s is the step frequency in Hz, α_i is the dynamic coefficient of the i^{th} harmonic and φ_i is the phase angle of the i^{th} harmonic.

An alternative walking load model is proposed by Feldmann *et al*. [11]. In this model, the load of a person walking on a floor, is approximated by a series of steps, with the contact force of each step estimated via the following formula:

$$F(t) = W\sum_{i=1}^{8} K_i t^i \tag{2}$$

The coefficients K_i that are used to evaluate Equation (2) are summarised in Table 2.

	$f_s \leq 1.75\text{Hz}$	$1.75\text{Hz} < f_s < 2.00\text{Hz}$	$f_s \geq 2.00\text{Hz}$
K_1	$-8\cdot f_s + 38$	$24\cdot f_s - 18$	$75\cdot f_s - 120.4$
K_2	$376\cdot f_s - 844$	$-404\cdot f_s + 521$	$-1720\cdot f_s + 3153$
K_3	$-2804\cdot f_s + 6025$	$4224\cdot f_s - 6274$	$17055\cdot f_s - 31936$
K_4	$6308\cdot f_s - 16573$	$-29144\cdot f_s + 45468$	$-94265\cdot f_s + 175710$
K_5	$1732\cdot f_s + 13619$	$109976\cdot f_s - 175808$	$298940\cdot f_s - 553736$
K_6	$-24648\cdot f_s + 16045$	$-217424\cdot f_s + 353403$	$-529390\cdot f_s + 977335$
K_7	$31836\cdot f_s - 33614$	$212776\cdot f_s - 350259$	$481665\cdot f_s - 888037$
K_8	$-12948\cdot f_s + 15532$	$-81572\cdot f_s + 135624$	$-174265\cdot f_s + 321008$

Table 2. K_i coefficients for the Feldmann et al. [11,13] *load model*

In this study, to undertake the numerical analyses for determining the response of the investigated composite floor, the load model proposed by Feldmann *et al*. [11] is adopted and the load duration of a single footfall (t_s) is computed as:

$$t_s = 2.6606 - 1.757\cdot f_s + 0.3844\cdot f_s^2 \tag{3}$$

The length of each step (L_s) can be estimated as [14]:

$$L_s = \frac{v_s}{f_s} \tag{4}$$

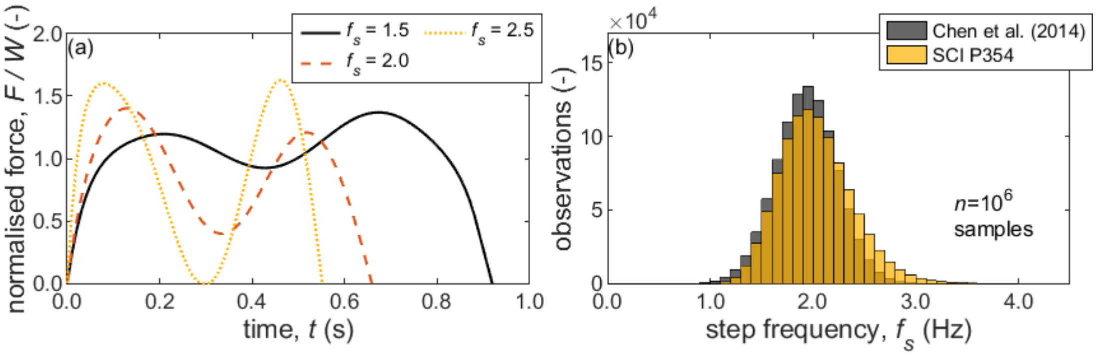

Fig. 3: (a) Single-step load functions for step frequencies of 1.5Hz, 2.0Hz and 2.5Hz [11]*; (b) step frequency distributions* [2,5]

In Equation (4) v_s is the velocity of the individual walking on the floor, which can be evaluated according to the following relationship [15]:

$$v_s = 1.67\cdot f_s^2 - 4.83\cdot f_s + 4.5 \tag{5}$$

Fig. 3 (a) presents the normalised load timeseries functions for a single footstep and three indicative step frequencies. It is provided side by side with two step frequency histograms that are generated according to distributions of the step frequencies that are available in the literature by Chen et al. [5] and Smith et al. [2].

5. MODELLING

The numerical investigation of the case study steel-concrete composite floors is carried out using the OpenSees software platform [16]. In the adopted computational model, girders (i.e., primary steel beams), joists (i.e., secondary steel beams) and steel columns are modelled with elastic beam-column elements that are readily available in the OpenSees element library. The composite slab is modelled by means of a grillage of interconnected elastic beams. Each grillage node is assigned a mass that is calculated based on the respective tributary area. As the girders, joists and grillage beam elements have their centroids at different elevations (Fig. 5), vertical rigid links are used to connect the nodes of the concrete slab with those of either the girders or the joists that are in the same position but at a different elevation (Fig. 5). Both girders and joists are discretised following the mesh size that was finally adopted for the slab grillage, in view of the outcomes of a sensitivity study, that are presented later on in this manuscript. A Rayleigh

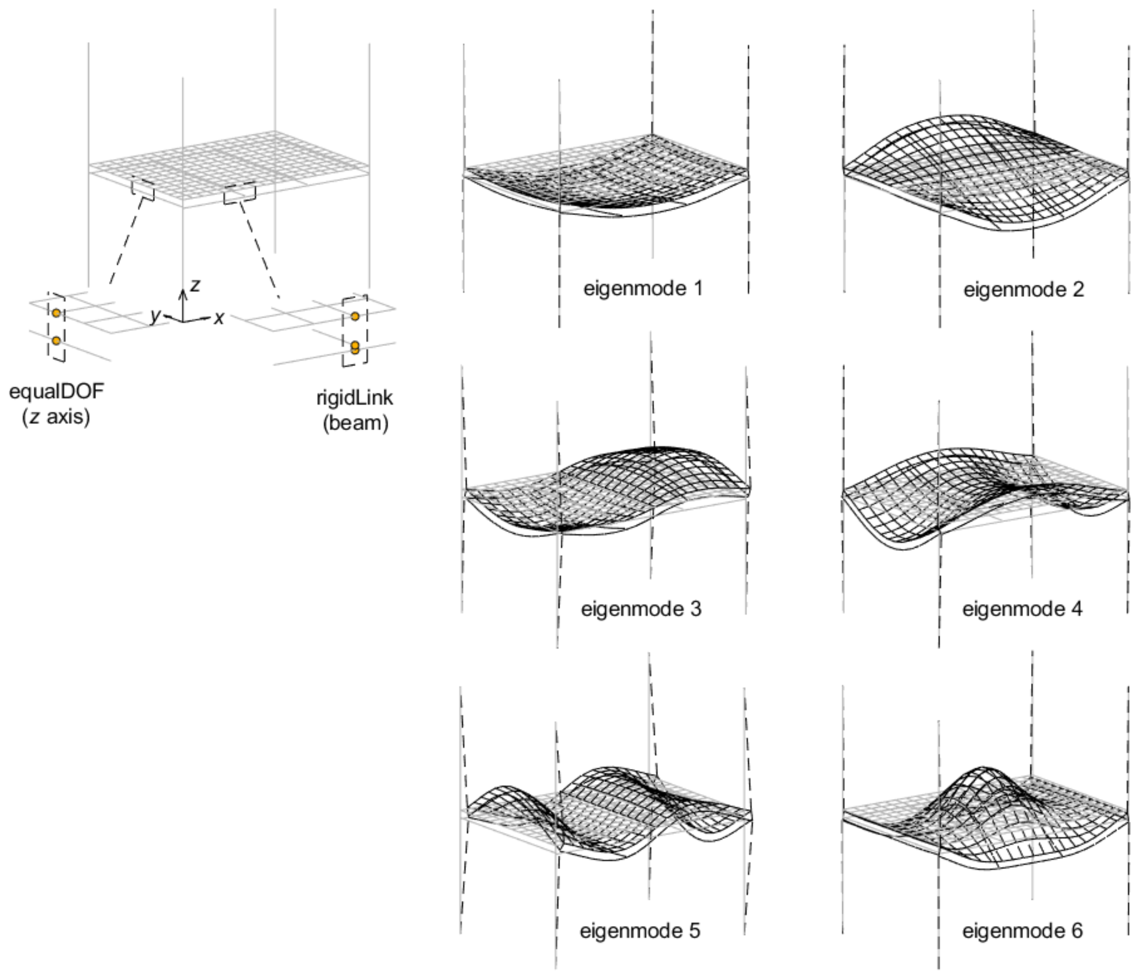

Fig. 4: 3D floor model and mode shapes 1-6 of the case study floor; figure shows the mode shapes of the 0.5m×0.5m mesh density model

damping approach is adopted, assigning a damping ratio of 3% in the first and second vibration modes.

5.1 Modal analysis

To determine the dynamic properties of the case study steel-concrete composite floors (natural frequencies and mode shapes) modal analysis is performed. The mode shapes of the case study floor are presented in Fig. 5. A parametric analysis is undertaken for this floor configuration to determine the optimum refinement for the rectangular mesh that is used for modelling the slab. Using a 1:1 element aspect ratio for the grillage (and thus girders and joists), the mesh size sensitivity study employs models with element sizes varying from 1.0m×1.0m to 0.04m×0.04m. According to the results shown in Fig. 6, a mesh size of 0.1m×0.1m is fine enough to yield robust estimates for the modal frequencies of the investigated floor, in the sense that further refinement does not result in any notable difference in the frequency estimates. Hence, a grillage size of 0.1m×0.1m is adopted, which also serves well the requirements that stem from the need to apply the footfalls across a walking path at certain distances [15,17]. The frequencies of the first six modes for the investigated floors are summarised in Table 3.

Mode	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**
	7.86	14.99	15.95	22.51	31.96	33.78

Table 3: Eigen-frequencies 1-6 of the case study floor

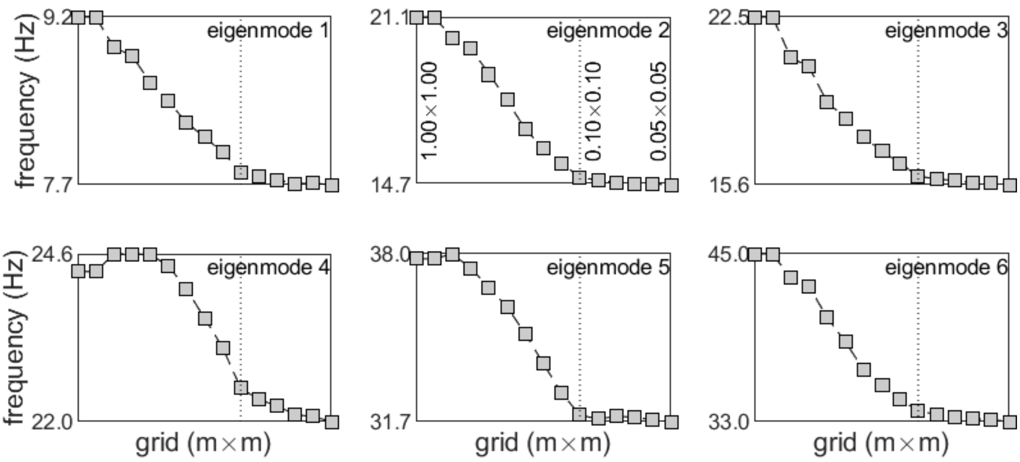

Fig. 5: Mesh density sensitivity for the first six eigenmodes of the case study floor

5.2 Response history analysis

To evaluate the dynamic response of the case study floor, response history analysis is employed utilising the Newmark time integration algorithm. To properly simulate each footfall on the composite slab, the force timeseries are evaluated using Equation (2) and are then applied on the grillage nodes of the 3D floor model shown in Fig. 5. For a certain footpath (e.g., along the X axis of the floor), a lateral distance of footfalls (D_s) is considered, using a value of 0.2m [15]. Moreover, the overlap t_0 between two consecutive footsteps [14] is also taken into account as:

$$t_0 = t_s - \frac{1}{f_s} \tag{6}$$

An illustrative description of the aforementioned procedure is offered through Fig. 6, where consecutive force functions are presented versus time in Fig. 6 (a) and the nodes of the entire footpath on the 3D floor model, where force functions are applied, in Fig. 6 (b). The integration time of the transient analysis is 10s, which includes the duration of the footsteps plus a few extra seconds for free vibration. Indicative response histories for floor acceleration and displacement are also provided in Fig. 6(c, d) at the locations where the maximum response is recorded.

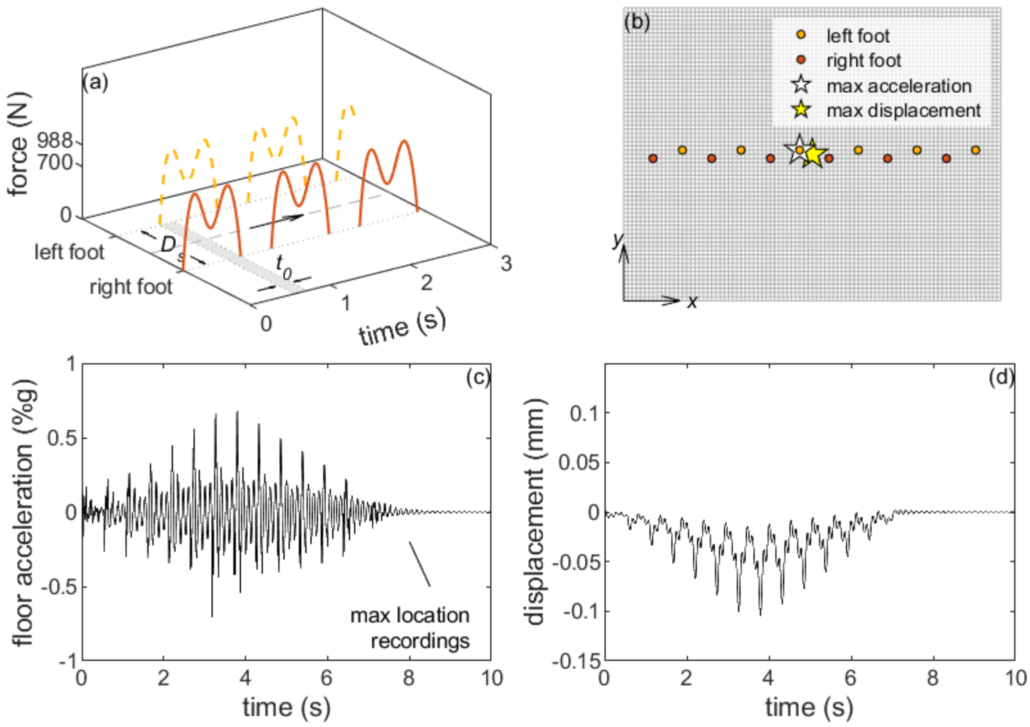

Fig. 6: (a) Loading input; (b) plan view of the 3D floor model featuring the footpath along the x-axis and the maximum acceleration and displacement locations; (c) maximum acceleration time history at the location of the maximum response; (d) displacement time history at the location of the maximum response

6. CONCLUSIONS

A numerical model has been presented to evaluate the serviceability performance of single-unit steel-concrete composite floors designed to AISC under human-induced walking excitations. The model relies on the grillage technique and can provide explicit information on floor acceleration and displacement demands. The proposed model can be employed to accommodate different uncertainty sources that are deemed to be important (e.g., step frequency, damping, human weight, etc.), to eventually provide the full picture of what one should expect regarding the level of discomfort that is likely to be encountered in a floor that conforms to contemporary design guidelines.

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ΣΥΜΠΕΡΙΦΟΡΑ ΣΥΜΙΚΤΩΝ ΔΑΠΕΔΩΝ ΥΠΟ ΑΝΘΡΩΠΟΓΕΝΕΙΣ ΤΑΛΑΝΤΩΣΕΙΣ

Κωνσταντίνος Μπακάλης
Μεταδιδακτορικός Ερευνητής
ETH Zurich
Ζυρίχη, Ελβετία
e-mail: kbakalis@ethz.ch

Αθανασία Καζαντζή
Ακαδημαϊκή Υπότροφος
Διεθνές Πανεπιστήμιο της Ελλάδος
Σέρρες, Ελλάδα
e-mail: kazantzi@ihu.gr

ΠΕΡΙΛΗΨΗ

Τα σύμμικτα δάπεδα από χάλυβα και σκυρόδεμα χρησιμοποιούνται ευρέως στις σύγχρονες κατασκευές για την επίτευξη μεγάλων ανοιγμάτων με μικρό αριθμό ενδιάμεσων υποστυλωμάτων. Ο σχεδιασμός τέτοιων εύκαμπτων και συνάμα ελαφρών συστημάτων διέπεται από τις απαιτήσεις της οριακής κατάστασης λειτουργικότητας, που σχετίζονται με τις αναπτυσσόμενες παραμορφώσεις, την ανθρώπινη άνεση και τις ανοχές έναντι κραδασμών. Οι σχετικές κανονιστικές διατάξεις στοχεύουν στην καθοδήγηση των μηχανικών με απώτερο στόχο το σχεδιασμό πατωμάτων τα οποία δεν είναι επιρρεπή σε ταλαντώσεις που συχνά προκαλούν ένα αίσθημα δυσφορίας στους χρήστες τους. Στην απλούστερη μορφή τους, τέτοιες διατάξεις υιοθετούν αρκετές ντετερμινιστικές υποθέσεις αναφορικά με την απόσβεση, τα επιβαλλόμενα φορτία, τη δυσκαμψία των συνδέσεων υπό τα φορτία λειτουργικότητας, τη συχνότητα του βηματισμού, τη διαδρομή που ακολουθεί το άτομο, καθώς και το βάρος του. Στην παρούσα εργασία, γίνεται μία αναφορά στις αβεβαιότητες που διέπουν τη συμπεριφορά των σύμμικτων δαπέδων. Παρουσιάζεται επίσης ένα αριθμητικό μοντέλο δαπέδου, μέσω του οποίου δύναται να εξαχθούν διάφορες παράμετροι απόκρισης που είναι κρίσιμες για την αξιολόγηση τέτοιων συστημάτων που υπόκεινται σε ταλαντώσεις λόγω βαδίσματος.