2019 SECED Conference
Earthquake risk and engineering towards a resilient world
9-10 September 2019, Greenwich, London

PARAMETRIC ANALYSIS OF COMPOSITE FLOOR SYSTEMS UNDER FOOTFALL-INDUCED VIBRATIONS

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***Abstract**: Structural engineers face the challenge of designing composite steel floors that are safe, material efficient and meet serviceability requirements. The design of composite floors is very often driven by the need of meeting desired vibration characteristics, and it requires complex analyses of footfall-induced vibrations. Designing a floor system that minimizes the use of materials and meets vibration serviceability requirements is a non-trivial exercise and the design optimization generally involves a large number of iterations. This manuscript describes some of the results of a parametric study performed to characterize the dynamic response of typical composite steel floors under footfall-induced vibrations. In particular, the influence of different design variables on the vibration response of composite floors has been investigated. These variables include the floor span, beam section, beam spacing, inherent damping, point of loading and support conditions. Results of this study are plotted in easy to use design charts, which can be adopted for the schematic design of composite floors.*

Introduction

Modern construction materials and structural analysis tools offer the possibility of designing aesthetically pleasing floor systems with long spans and slenderer elements. Many of these floors, despite meeting strength requirements, are prone to serviceability issues including excessive vibrations induced by human activities. High levels of vibrations can result from a combination of several variables including low damping and/or a low natural frequency of the floor, which make the structural system prone to resonance under human excitations in the frequency range of 0 to 12 Hz (Racic, et al., 2009). The response of a dynamic system close to resonance strongly depends on the energy dissipation characteristic of the system itself (Chopra, 1995). Given the low amplitude of strain deformations induced by footfall vibrations, floor structures exhibit a low level of energy dissipation. For instance, the equivalent viscous damping in footbridges under footfall excitations ranges from 0.5% to 1.5%. In staircases, the equivalent viscous damping is approximately 0.5% and in composite floors, this ranges from 1% to 3% of critical, depending on the energy dissipation characteristics of the nonstructural components supported by the floor. The energy dissipation properties of a floor system can be enhanced by adding passive control devices, including viscous dampers, viscoelastic layers (Saidi, et al., 2009) or Tuned Mass Dampers (TMDs). Carmona et al. (2016) introduced a novel TMD using friction as energy dissipation mechanism. The energy dissipation characteristics of this device can be easily tuned by changing the contact force and sliding materials. Alternatively, to reduce excessive floor vibrations, active control strategies for floor structures can be employed as well (Hudson & Reynolds, 2012). It is clear that many devices can be adopted to control vibrations of both new and existing floor structures, but their implementation is costly and disruptive. This work aims to introduce simple to use design charts for the optimization of composite steel floors. When properly implemented, these charts allow minimizing the floor depth or the steel tonnage, while taking into consideration desired vibration criteria, location of loading and boundary conditions. It is worth noting that the proposed design tool is particularly handy for the preliminary design of the floor system, but a final iteration is needed to verify the vibration response of the chosen configuration. This task is responsibility of the designer. When used in the early stages of the

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design, the results of this work not only help designing a modern and optimized floor system, but they contribute towards the goals of (i) time-saving, (ii) material-saving with (iii) a positive impact on the on the environment.

Description of the parametric analysis

As mentioned, a large number of frequency-domain footfall vibration analyses have been performed on a typical composite floor system made of an IPE beam and a 130 mm thick concrete slab (E_c=43000 MPa). In particular, 21 different IPE beam sections (covering a range of depth from 80 mm to 750 mm) have been considered for the analyses. A beam spacing (S) in the range of 0.75 m to 2.5 m was considered, with floor spans from 4.5 m to 19 m. The analyses considered two levels of equivalent viscous damping, namely 1.5%, typical of bare floors, and 3%, usually assumed for fully furnished floors and other sources of energy dissipation. Boundary conditions and loading conditions covered 7 configurations: fixed or pinned supports were assumed for the analyses, while the excitation of one-person walking was considered at the centre of the beam or at a quarter of the span. A large set (70560) of floor systems has been analysed using frequency-domain analyses. To this aim, the walking functions suggested by (Willford & Young, 2006) have been adopted. In particular, a dynamic load as given in eq. (1) was considered, were G is the static weight of one person, f_p the frequency of loading, Φ_i the phase angle and α_i corresponds to the Dynamic Load Factor (DLF), shown in Figure 1 and defined in different frequency domains as follows (Young, 2001):

$$F_p(t)=G+\sum_{i=1}^{n} G\alpha_i \sin(2\pi i f_p t-\phi_i) \quad (1)$$

$$\alpha_1=0.41(f_p-0.95)\leq 0.56 \quad \text{for } f_p=1\text{-}2.8 \text{ Hz} \quad (2)$$

$$\alpha_2=0.069+0.0056f_p \quad \text{for } f_p=2\text{-}5.6 \text{ Hz} \quad (3)$$

$$\alpha_3=0.033+0.0064f_p \quad \text{for } f_p=3\text{-}8.4 \text{ Hz} \quad (4)$$

$$\alpha_4=0.013+0.0065f_p \quad \text{for } f_p=4\text{-}11.2 \text{ Hz} \quad (5)$$

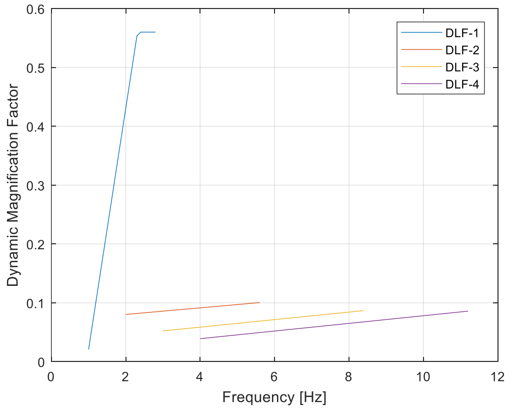

Figure 1 DLFs for walking excitation, from Willford and Young (2006)

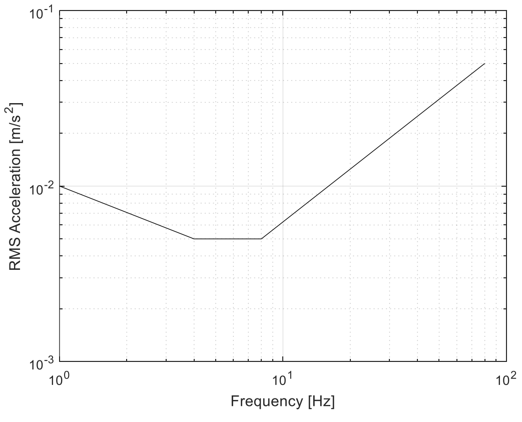

Figure 2 Baseline of the peak acceleration for human comfort for vibrations due to human activities (ISO 2631-2:2003)

Frequency domain analysis were performed considering frequency increments, i, of 0.01Hz. From these analyses, the peak floor acceleration (a_{SRSS}) and the corresponding frequency were determined following the procedures described in (Willford & Young, 2006). These data are required in order to determine the Response Factor (R), defined as follows:

$$R=\frac{a_{SRSS}}{a_{Baseline}}$$

where

$a_{SRSS}=\sqrt{a_{f1}^2+a_{f2}^2+a_{f3}^2+a_{f4}^2}$ is an estimate of the peak acceleration induced by the four harmonics of Equation (1), while $a_{Baseline}$ is the ISO baseline acceleration plotted in Figure 2.

According to the destination of use, acceptable response factors have been defined (e.g., Fahmy & Sidky 2012, Wyatt 1989). Table 2 reports the R factors consider for this study (Hicks et al. 2007).

Destination of use	Acceptable Response Factor (R)
Office 8	8.0
Shopping mall 4[35]	4.0
Dealing floor 4	4.0
Stairs – Light use (e.g. offices) 32	32.0
Stairs – Heavy use (e.g. public buildings, stadia)	24.0

Table 1 Acceptable response factor (R) based on the destination of use (from Hicks et al. 2007)

Numerical analyses

Numerical analyses were performed using SAP2000, a general-purpose finite element software, by CSI Berkeley. In particular, the software's OAPI tools have been employed in conjunction with a script written ad-hoc in-Python language. This script was capable of automatically updating any predefined structural model and analysis. Figure 3 shows a 3D view of one of the structural models: the concrete slab and the steel frame elements are divided in elements along the span, while a discretization in four elements is employed for the concrete slab in the transversal direction. Both the slab and the beams have been modelled using shell elements. At the slab edges, proper boundary conditions have been modelled to simulate the response of a large composite floor while modelling only one composite beam.

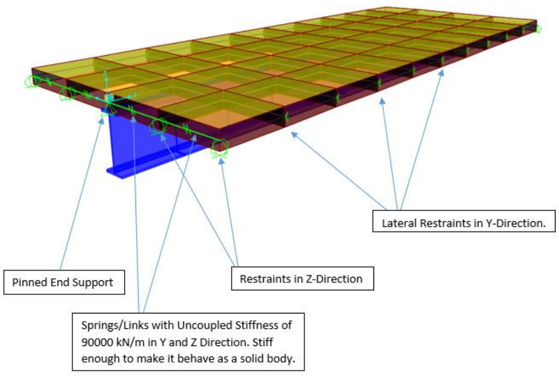

Figure 3 SAP2000 Model Preview

The model's mass includes the self-weight of the elements and Superimposed Dead Loads (SDL) of 2.0 kN/m^2. This is considered a typical value for office floors where floor finishes of 0.3 kN/m^2, partition-loads of 1.0 kN/m^2, service-loads of 0.3 kN/m^2 and ceiling-loads of 0.4 kN/m^2 contribute to the total design load (Fahmy & Sidky, 2012). Part of the live loads could be considered in the total mass of the system, but these are neglected in this study to reduce the number of variables and to err on the side of safety.

Numerical results and the design charts

For the 7 selected load and boundary conditions, frequency-domain analyses have been run. These considered the following variables: beam depth, beam span, spacing of the beams and two levels of damping. For each span, loading and boundary condition, the floors with the minimum steel weight and that with the minimum beam depth meeting a specified Response Factor were determined. The results of this study have produced a large variety of design charts; these will be published in a companion work. In this paper, for the sake of brevity, only the results corresponding to the simply supported beam with central load are reported, with reference to a beam spacing (S) of 1.0 and 2.0m. Figure 4 to 6 are a valid design tool to reduce the number of iterations required for the design of a composite steel floor meeting specified vibration requirements. For instance, knowing the floor span, and the desired response factor, Figure 4 allows the determination of the IPE section with the minim depth meeting the desire response. The adoption of Figure 5, instead will offer the beam with the minimum weight per unit length meeting the desired performance level. It is clear that, when the floor span increases, deeper beams are required to meet the same response, R. Moreover, as the spacing of the beams increases, the beam depth has to be increased to meet the same vibration response (this is due to a larger deformability of the system).

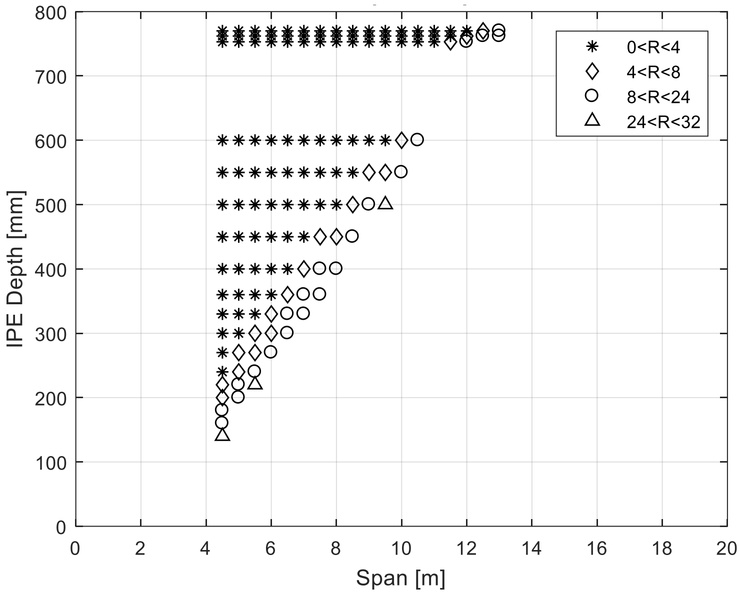

Figure 4 Floor span vs beam depth for a spacing of 1.0m and 1.5% damping

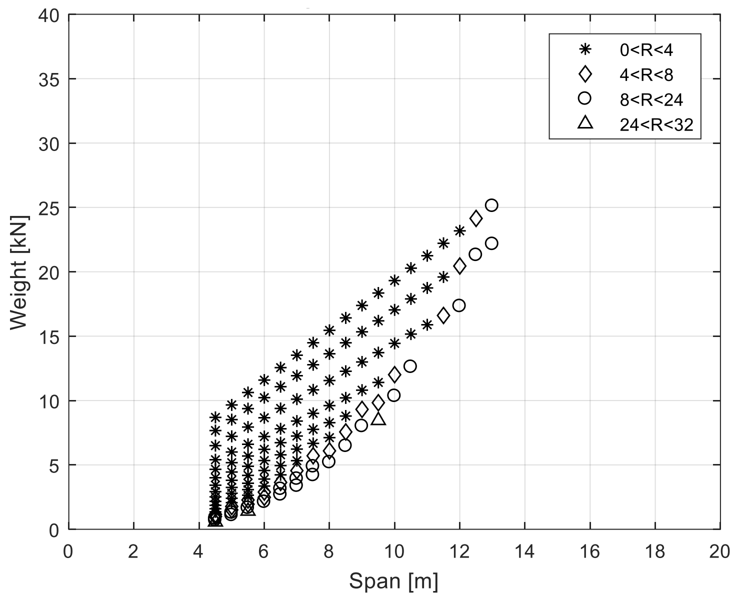

Figure 5 Floor span vs beam weight for a spacing of 1.0m and 1.5% damping

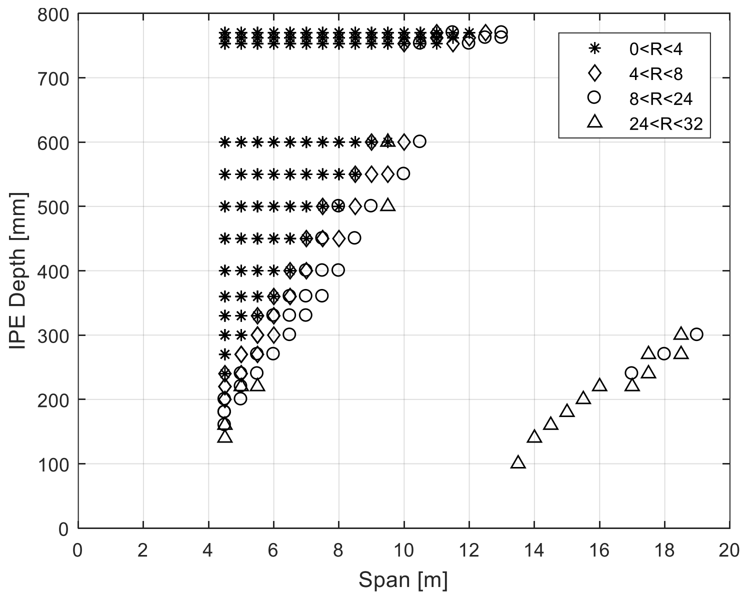

Figure 6 Floor span vs beam depth for a spacing of 2.0m and 1.5% damping

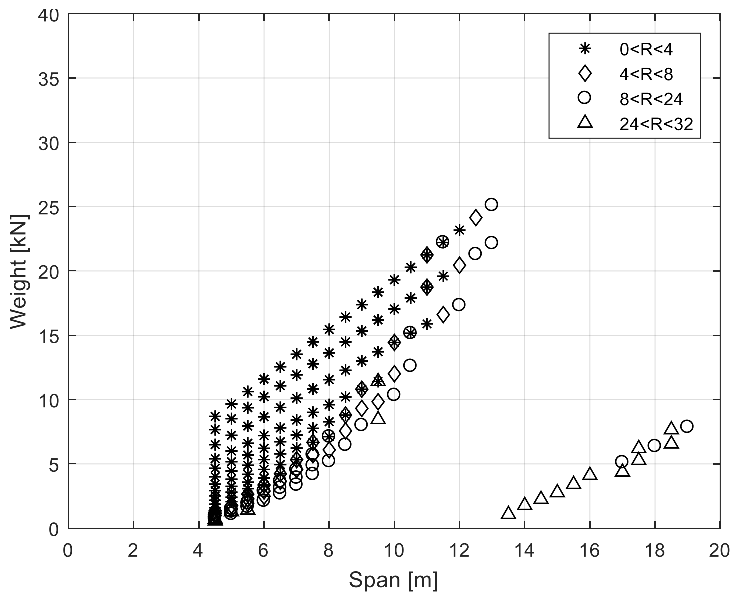

Figure 7 Floor span vs beam weight for a spacing of 2.0m and 1.5% damping

Conclusions

The aim of this work is to introduce some of the design charts obtained from a large series of analyses. These charts are deemed useful for the schematic design of composite steel floors, allowing for an easy determination of the IPE beam with the minimum depth or the minimum weight satisfying specified vibration response requirements. To this aim, a wide parametric analysis, investigating more than 70’000 composite floor systems, has been performed. The effects of beam depth, beam span, spacing of the beams, damping ratio, boundary and load configurations have been investigated by performing frequency-domain analysis as described in (Willford & Young, 2006). This paper gives only the results obtained for simply supported beams with central loading, the vast series on graphs obtained for this study will be published in a companion research report. Results of this work allow to immediately identify the optimal floor system meeting a desired vibration response. It is deemed that the graphs introduced in this work will not only simplify the design process of composite floors but will also lead to a rational use of materials.

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