Experimental Derivation of Dynamic Load Factor for Transparent Glass Pedestrian Systems

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Abstract. The vibration performance assessment of pedestrian structures attracts, since decades, the attention of several research studies. In this paper, the attention is focused on the experimental vibration analysis of in-service structural glass assemblies that are used to take part in in-service pedestrian systems. In most of cases, these systems are characterized by low mass, low frequency and high sensitivity to operational conditions (temperature, humidity, etc.). Non-destructive in-field experimental methods are specifically used to analyse and quantify the human-induced reaction forces and the corresponding dynamic load factor (DLF). To this aim, body centre of mass (CoM) experimental measurements are recorded for a single pedestrian during random normal walks. As shown, in case of structural glass pedestrian systems that are characterized by relatively small mass compared to pedestrian and (often) low vibration frequency, as well as intrinsic transparency, marked variations can be expected in typical dynamic behaviours and DLF trends, when compared to literature experimental derivations on opaque floors.

Keywords: Structural Glass · Transparency · Vibrations · Human-induced Reaction Forces · Dynamic Load Factor (DLF) · In-field Experiments

1 Introduction

Modern constructional systems are frequently designed in the form of slender and rather flexible systems, which are particularly demanding for more sophisticated calculations and attention against vibrations.

Major issues for slender footbridges or walkways are in fact commonly represented by uncomfortable vibrations induced by occupants [1, 2]. To this aim, a multitude of research investigations can be found in the literature, in the form of methods of analysis [3], numerical procedures [4, 5], simplified description of human-induced loads [6–8].

In this paper, a special attention is given to slender and transparent substructures, like structural glass pedestrian systems, in which specific dynamic mechanical features and behaviours should be properly taken into account. Also, glass pedestrian systems are fundamental components of the so-called "emotional architecture", in which design choices aim at evoking major nervous states in customers. For in-service glass walkways, it has for example shown in [9, 10], based on traditional monitoring strategies, that the motion of different numbers of pedestrians and walk features can strongly affect the expected

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dynamic parameters and performance of structures. In [11] with physical experiments and then [12, 13] based on remote testing, it was proved with different experimental approaches and protocols (including biometric analyses and micro-facial expression analyses based on Artificial Intelligence tools) that also emotional and nervous states can affect the human behaviours in the context of glazed constructed facilities.

Following previous research efforts [14–16], original experimental investigations are presented in this paper, by taking advantage of a single Wi-Fi body motion sensor which is used to track the acceleration components and motion feature for a single adult volunteer during normal walks on glass. Differing from previous literature contributions, the current investigations are characterized by the determination, based on a single body motion sensor, of the dynamic load factor (DLF) corresponding to human-induced reaction forces during normal walks on glass systems like in Fig. 1.

2 Experiments

2.1 Methods

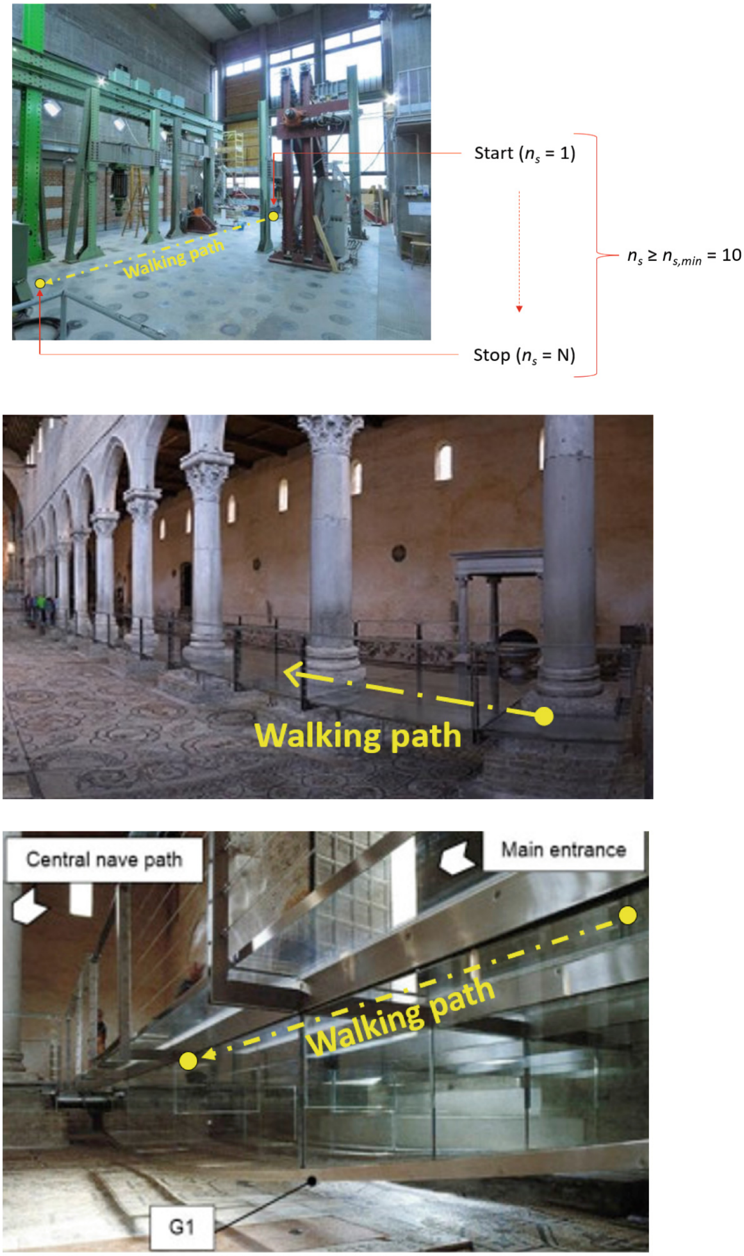
Two different structural glass solutions characterized by specific dynamic features were explored for this study (Table 1). In terms of experimental setup and methods, an acquisition system consisting of a Wi-Fi micro electromechanical system (MEMS) sensor was used during the in-field experimental investigations, as also in accordance with previous studies reported in [14–16]. Comparative results were thus compared and validated towards selected literature data as in [7, 17]. The extended discussion of tet methods and results is reported in [18].

More precisely, for the current experimental investigation, a single female adult volunteer ($p = 1$) was invited to walk with assigned frequency ($f_p \approx 1.5$ Hz) on different substrates. According with Fig. 1, the first configuration (SLAB#1) consisted in a rigid laboratory concrete floor (80 cm thick) with very high frequency ($f_{1,e} > 80$ Hz) and mass, and was taken into account for validation of experimental methods towards literature DLF estimates. Two flexible and transparent slab systems (SLAB#2 and SLAB#3) were detected as portions of the indoor suspension laminated glass walkway structurally investigated in past efforts [9, 10, 18].

The in-service system consists of a transparent slab in which the laminated glass section layout includes three 12 mm thick glass panels and interposed PVB® bonding foils (0.76 mm thickness for each). To note that an additional glass layer, 6 mm in thickness, is used to protect the laminated section on the top.

For SLAB#2, these glass panels are in beam-like configuration over a total span of 2.65 m. For SLAB#3, conversely, the glass panels are linearly supported along edges by a metal grid composed of C-shaped steel members. This steel-glass solution is used to cover a total surface of 14.5 m × 2.8 m. The overall slab system is sustained by four longitudinal steel-glass girders, spanning over the full bending length of 14.5 m.

Most importantly for structural dynamics considerations, the flexible SLAB#2 system is characterized by a total mass for modular unit in the order of $M_{stru} \approx 460$ kg and a vibration frequency $f_{1,e} = 15.1$ Hz (experimental measure for the empty structure [18]). In the case of SLAB#3, the reference parameters are $M_{stru} \approx 10{,}730$ kg for structural



(a) SLAB#1

(b) SLAB#2

(c) SLAB#3

Fig. 1. Experimental analysis on (a) rigid or (b)–(c) flexible substrates (figures (a) and (c) reproduced with permission from [18] under the terms and conditions of CC-BY license agreement).

mass (with 4020 kg for pedestrian glass panels) and $f_{1,e} = 7.28$ Hz for the fundamental frequency (experimental measure for the empty structure [18].

Table 1. Summary of present experimental configurations and literature selection for DLF estimation of human-induced reaction forces.

	Present study	Rainer & Pernica [7]	Kerr & Bishop [17]
Volunteer(s)	1	3	40
Pedestrian(s) p	1	1	1
Walking frequency f_p (in Hz)	1.5	$1 \div 3$	$1 \div 3$
Test setup	In-field	Laboratory	Laboratory
Substructure type	Two flexible glass systems (in-field)	Laboratory floor strip made of thick precast concrete panels sustained by steel trusses (17 m span)	Laboratory floor strip made of sandwich section (5 m span)
Reaction force	Vertical, longitudinal, lateral	Vertical	Vertical
Floor frequency (in Hz)	7.28 & 15.1	12	650
Floor view	Transparent	Opaque	Opaque
Instruments	Single CoM sensor (MEMS accelerometer + inclinometer)	Two force transducers at floor strip mid-span	Force plate with 4 Kistler piezo-electric transducers

2.2 Selected Results

For post-processing purposes, we chose to remove via signal windowing the initial and final gaits of this set of collected records, and thus to elaborate data on human-induced loads and DLFs by accounting for the 10 central gaits only.

In this way, the analysis of results was separately carried out on a number of 8 (for SLAB#1), 10 (#2) and 9 (#3) "reduced" walking records (i.e., representative of 10 central gaits only for each one of them), and then elaborated upon the "average ± standard deviation form". Major elaborations and signal processing analyses were carried out with the support of a Matlab® toolbox [19].

For design purposes, it is clear that a major attention should be given, at first, to the DLF of vertical force component and its 1st harmonic.

In this sense, it is worth to note that for the opaque rigid RC floor, SLAB#1, the presently derived DLF trend was found typically in line with several literature efforts.

Such a finding is also confirmed by quantitative comparisons proposed in Fig. 2, where the presently calculated average DLF of 1st harmonic is found equal to ≈0.1832. This value has a good match with previous data proposed in [7, 17], based on extended experimental analyses in laboratory conditions. Also, the present DLF result has minimum scatter with the analytical model proposed in [20], based on statistical analysis of a very extended database of experimental observations (with ≈0.2255 the expected DLF for the assigned walking frequency $f_p = 1.5$ Hz, with around a −18% scatter for present DLF outcomes on the opaque SLAB#1).

Most importantly, Fig. 2 also reports the present DLF results derived from SLAB#2 and #3 test setup configurations, characterized by intrinsic slab transparency and various dynamic parameters. In this case, it can be noted that present experimental derivations for SLAB#2 and #3 (with an average DLF approximately equal to ≈0.11–0.12 for both) are placed at the lower bound of selected literature data from [7, 17]. Compared to the opaque SLAB#1 configuration, the calculated DLF has down to ≈−37% scatter. Also, these DLF results are markedly lower compared to analytical estimates based on statistical analysis in [20], with a scatter down around to −49%. This kind of correlation suggests a major influence of selected transparent floors on human-structure interaction phenomena, and thus requires additional investigations.

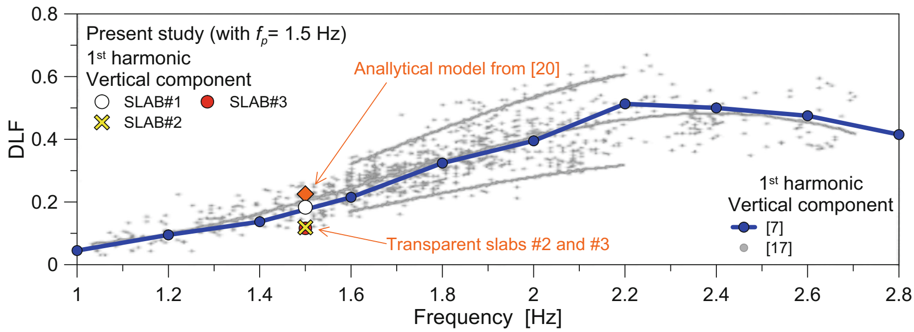


Fig. 2. Present experimental derivation of average DLF values (1st harmonic of vertical force component) for a single adult pedestrian volunteer under normal walks ($f_p = 1.5$ Hz), and comparison with selected literature outcomes [7, 17, 20]. Present average DLF values calculated for a single adult pedestrian, based on 8 walking records for SLAB#1, 10 for #2 and 9 for #3.

Another relevant outcome can be found from the analysis of experimental DLF estimates as a function of harmonic order. Figure 3 shows the five lower harmonics, experimentally calculated from the present investigations. The graphical results, more in detail, are grouped by force component, as well as by floor type, in terms of DLF. It is worth noting how the substructures can affect human-induced loading, and specifically the corresponding DLF for a given pedestrian.

For the rigid and opaque RC floor (SLAB#1), the presently derived DLF trends are characterized by a 1st harmonic which typically prevails on the higher harmonics, for both the vertical and longitudinal force components based on CoM motion. This is also in line with several literature contributions.

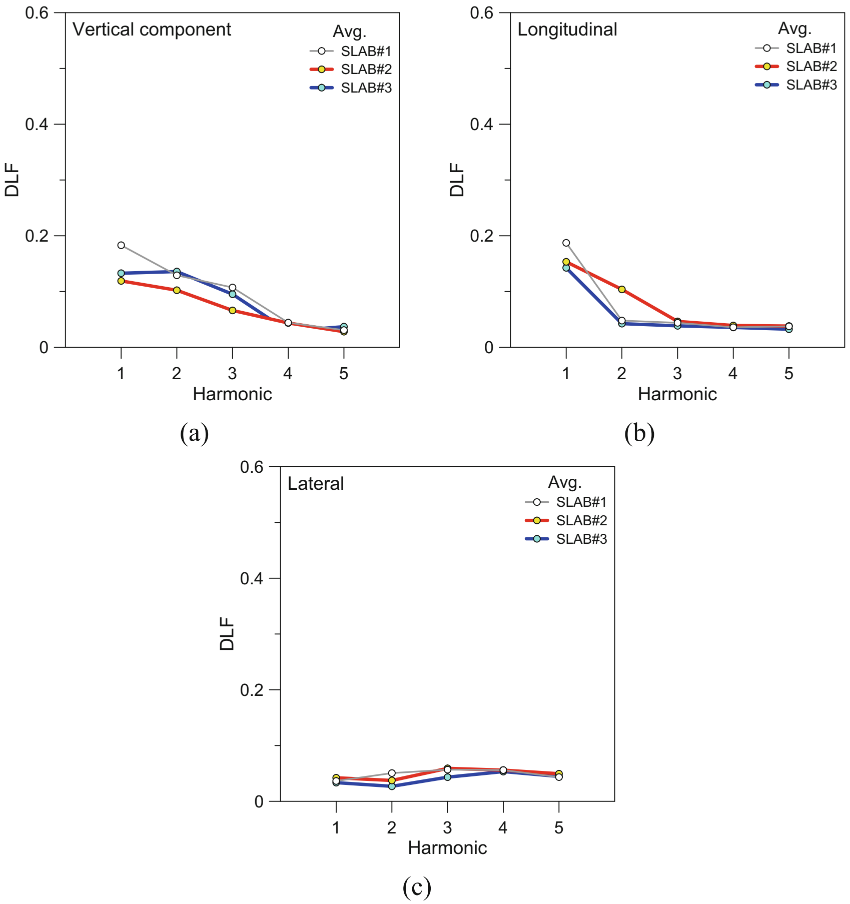


Fig. 3. Experimentally derived DLF trends (average), as a function of harmonic order, for a single adult volunteer under normal walks on rigid floor (SLAB#1) or flexible SLAB#2 and SLAB#3 transparent systems, with evidence of (a) vertical, (b) longitudinal, and (c) lateral force components based on body CoM measurements. Average DLF values calculated based on 8 walking records for SLAB#1, 10 for #2 and 9 for #3.

As shown, the average DLF amplitudes experimentally derived for both SLAB#2 and SLAB#3 are relatively smaller than SLAB#1. This can be noted both for the 1st harmonic but also for the higher harmonics of vertical force component. Most importantly, the 2nd harmonic of vertical force on SLAB#3, which is the most flexible among the examined floors, is characterized by higher DLF than the 1st harmonic. Such an additional finding is again rather in line with past discussion from various literature studies, where it has been emphasized that the 2nd harmonic of vertical forces induced by pedestrians is, in general terms, the most sensitive to floor flexibility.

Overall, similar qualitative average trends of DLF can be noted also for the longitudinal and lateral reaction force components presented in Figs. 3 (b)–(c) respectively, for all the examined configurations. The exception, in this latter case, is represented again by the DLF corresponding to the 2nd harmonic in Fig. 3(b), which is more sensitive in terms of lateral force component on SLAB#2, and is found to be significantly higher than SLAB#1 and SLAB#3.

3 Conclusions

In modern constructions, the presence of slender and aesthetically fascinating components and assemblies is rather frequent, for several reasons. From a practical design point of view, this requires dedicated calculation procedures and studies, especially against vibration serviceability issues.

The attention of this paper was given to slender and transparent floors like structural glass pedestrian systems. Major efforts were spent for the in-field experimental derivation of the dynamic load factor (DLF) due to a single adult pedestrian, asked to repeatedly walk at a fixed walking rate on different substructures. Discussion of experimental parametric results was thus proposed toward an opaque and rigid, reinforced concrete (RC), laboratory foundation system (SLAB#1), which was used as a reference against two flexible and transparent glass flooring systems belonging to an in-service indoor walkway (SLAB#2 and SLAB#3).

Overall, from the present experimental investigation, it was found that floor transparency – in addition to other influencing parameters – can be reasonably detected as a possible source of body motion modifications, and thus reaction force and DLF modifications under normal walks.

In this regard, further experimental studies will be developed to extend the currently explored walking frequency configuration, so as to further explore and possibly confirm the present evidence of floor interaction on human body motions and walking features, thus corresponding reaction forces and DLF amplitudes.

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