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EFFECT OF THE LOADING MODELLING, HUMAN HEEL IMPACT AND STRUCTURAL DAMPING ON THE DYNAMIC RESPONSE OF FOOTBRIGES

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Abstract. *The demands imposed by daring architectural projects led to design and construction of light pedestrian footbridges with large spans. This trend generated very slender structural footbridges and consequently changed the serviceability and ultimate limit states associated to their design. In the particular case of pedestrian footbridges this phenomenon occurs when the fundamental frequency is equal or near the existing loading frequencies or some of its multiples. The present investigation was carried out based on a more realistic loading model developed to incorporate the dynamical effects induced by people walking when the dynamical response of pedestrian footbridges is investigated. In this particular loading model the movement of legs that cause an ascent and descending of the effective mass of the human body, at each step, was considered while the position of the dynamical loading is changed according with the individual position. This fact implies that the generated time function has a space and time description. The investigated structural model was based on several footbridges, with main spans varying from 10m to 35m. The structural system was made of a composite (steel-concrete) solution built with an "I" steel beam section and a reinforced concrete deck. The proposed computational model, developed for the composite slab dynamic analysis, adopted the usual mesh refinement techniques present in finite element method simulations. The footbridges dynamic response was investigated and the peak accelerations were obtained and compared to results recommended by design standards to take into account human comfort evaluations.*

1 INTRODUCTION

In the last few years footbridges have been constructed with daring structures that consider the experience and knowledge of structural engineers by using newly developed materials and technologies boosted by the ever-growing investigations on this field. It widely known that the main objective of the structural engineer is related to the design of slight structures whose conception requires a substantial amount of theoretical knowledge associated to structural design and construction processes. This fact have generated very slender pedestrian footbridges and consequently changed the serviceability and ultimate limit states associated to their design [1] - [3].

In the particular case of footbridges this phenomenon precisely occurs when the structural fundamental frequency is equal or near of the existing loading frequencies, or is similar to some of its multiples. Another important aspect that still deserves further investigation is related to the modelling of the harmonic dynamical loads induced by pedestrians walking.

The present investigation was carried out based on a more realistic loading model developed to incorporate the dynamical effects induced by people walking in the footbridges dynamical response [1], [2]. In this particular loading model, the leg motion of that causes a human body effective mass ascent and descending movement at each step was considered. The position of the dynamical loading also changed according to the individual position and the generated time function, corresponding to the excitation induced by people walking, have a space and time description [1], [2].

The investigated structural model was based on several footbridges, with main spans varying from 10m to 35m. A composite (steel/concrete) solution made of an "I" steel profile and a reinforced concrete slab was the adopted structural system. The proposed computational model, developed for the composite slab dynamic analysis, adopted the usual mesh refinement techniques present in finite element method simulations [4].

In this paper, the developed analysis methodology is described and discussed. Based on an extensive parametric study, the footbridges dynamic response was obtained in terms of peak accelerations and compared to the limiting values proposed by several authors and design codes [3], [5] In specific design situations, the obtained results have shown that the code recommendations could lead to unsafe values based on the adoption of excessively simplified load models [3]. Hence, it was detected that this type of structure can reach high vibration levels, compromising the footbridge user's comfort and especially its safety.

2 MODELLING OF THE DYNAMIC ACTIONS INDUCED BY PEOPLE WALKNG

In this paper a loading model were developed in order to incorporate the dynamical effects induced by people walking in the dynamical response of pedestrian footbridges. The mathematical model behind this strategy was proposed by [1], [2], as well as a numerical approach to evaluate the floor structure reaction, as illustrated in Figure 1.

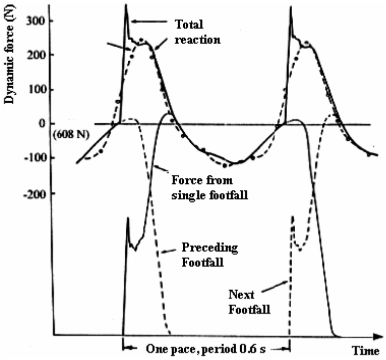

Figure 1: Footfall force and reaction on the floor structure [2].

It must be emphasized that the geometry of the human body walking is an organized motion of legs that cause an ascent and descending of the body effective mass at each step. The human body mass accelerations are associated to floor reactions, and it is approximately periodic to the step frequency. The two feet produce this type of loading, as function of the static parcel associated to the individual weight and three or four load harmonic components. These harmonic appear due to the interaction between the increasing load represented by one foot and the simultaneous unloading of the other foot.

In this particular model the position of the dynamical loading changes according to the individual position, while the generated time function has a space and time description. However, the study of several other parameters related to this type of modelling like the step distance and step frequency, as illustrated in Table 1 became necessary to fully represent the investigated problem.

Table 1: Human walking characteristics.

Activity	Velocity	Step Distance	Step Frequency
Slow Walking	1.1	0.6	1.7
Normal Walking	1.5	0.75	2.0
Fast Walking	2.2	1.0	2.3

The pedestrian motion on the footbridge was modelled based on the Equation (1) to (4) and four harmonics were used to generate the dynamical forces, Table 2. Like in the previous model, the third harmonic with a 1.79Hz step frequency, as shown in Table 2, was the walking load resonant harmonic (3 x 1.79Hz = 5.37Hz), Figure 2. In this situation, the finite element mesh has to be very refined and the contact time related to the dynamical load application on the structure depends on the step distance and frequency, Table 2.

$$F(t) = \begin{cases} \left(\dfrac{f_{mi}\, F_m - P}{0.04 T_p} \right) t + P & if \;\; 0 \leq t < 0.04 T_p \\ f_{mi}\, F_m \left[\dfrac{C_1 \left(t - 0.04 T_p \right)}{0.02 T_p} + 1 \right] & if \;\; 0.04 T_p \leq t < 0.06 T_p \\ F_m & if \;\; 0.06 T_p \leq t < 0.15 T_p \\ P + \displaystyle\sum_{i=1}^{nh} P \alpha\, sen\left[2 \pi i\, f_c \left(t + 0.1 T_p \right) + \varphi_i \right] & if \;\; 0.15 T_p \leq t < 0.90 T_p \\ 10 \left(P - C_2 \right) \left(\dfrac{t}{T_p} - 1 \right) + P & if \;\; 0.90 T_p \leq t < T_p \end{cases} \tag{1}$$

$$F_m = P \left(1 + \sum_{i=1}^{nh} \alpha_i \right) \tag{2}$$

$$C_1 = \left(\frac{1}{f_{mi}} - 1 \right) \tag{3}$$

$$C_2 = \begin{cases} P \left(1 - \alpha_2 \right) & if \;\; nh = 3 \\ P \left(1 - \alpha_2 + \alpha_4 \right) & if \;\; nh = 4 \end{cases} \tag{4}$$

Where:

F_m : maximum value of the Fourier series, given by Equation (4);
f_{mi} : heel-impact factor;
T_p : step period;
C_1 : Equation (5) coefficients;
C_2 : Equation (6) coefficients.

Table 2: Forcing frequencies (f_s), dynamic coefficients (α_i) and phase angles (Φ_i).

Harmonic	Human Walking		
	f_s (Hz)	α_i	Φ_i
1	1.6 - 2.2	0.5	0
2	3.2 - 4.4	0.2	$\pi/2$
3	4.8 - 6.6	0.1	π
4	6.4 - 8.8	0.05	$3\pi/2$

According to [2], the proposed mathematical function, Equations (1) to (4), used to represent the dynamical actions produced by people walking on floor slabs is not a Fourier series simply because the equation also incorporates in its formulation the heel impact effect.

This mathematical model was evaluated considering four harmonics, see Tables 1 and 2, and also incorporated the transient effect due to the human heel impact. The load model used a heel impact factor equal to 1.12 (f_{mi} = 1.12) [2]. However, it must be emphasized that this value can vary substantially from person-to-person. An increase of the dynamic load due to the human heel impact could be observed when a comparison to an analysis that did not consider this effect is made. Figure 2 illustrates the dynamical load function for an individual walking at 5.37Hz (3 x 1.79Hz = 5.37Hz), based on Equations (1) to (4).

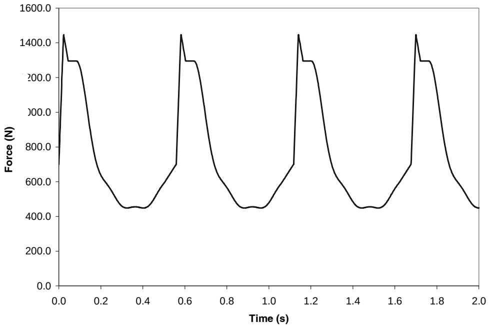

Figure 2: Dynamic loading function for a single human walking at 5.37Hz (3 x 1.79Hz = 5.37Hz) [1].

The following strategy was adopted: a 0.65m step distance corresponding to the third harmonic with a 1.79Hz step frequency, as shown in Table 2. The step period is equal to 1/f = 1/1.79Hz = 0.558s, corresponding to a distance of 0.65m. This way, the modelling considered six forces to model one human step where each of the loads P1, P2, P3, P4, P5 and P6 were applied to the structure during 0.558/5 = 0.1116s, corresponding the contact time of each dynamical load [1], see Figure 3.

However, the dynamical forces were not simultaneously applied. The first applied load would be P1, according with Equation (2), by 0.1116s, and at the end of this period of time, the load P1 becomes zero and the load P2 is then applied for 0.1116s. This process successively occurs until all dynamical loads are applied along the structure, as presented in Figure 3. It should be emphasised that all the dynamical actions associated to the time function will be correctly applied to the structural system [1].

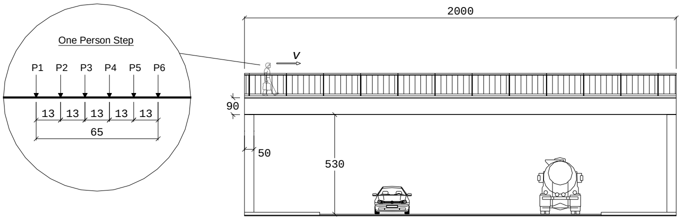

Figure 3: People walking on the footbridge (dimensions in cm).

3 STRUCTURAL SYSTEM AND COMPUTATIONAL MODELLING

The outdoor footbridge studied in this paper is simply supported by columns at its extremities, spanning from 10m to 35m by 2.5m, currently used for pedestrian crossing. The structural system was made of composite girders and a 100mm thick concrete slab, as presented in Figure 4.

The steel sections used were welded wide flanges (WWF) made with a 300MPa yield stress steel grade. A 2.05x105 MPa Young's modulus was adopted for the steel beams. The concrete slab has a 30MPa specified compression strength and a 3.84x104MPa Young's Modulus. Table 3 depicts the geometrical characteristics of all the steel sections used in the structural model. It is also assumed that an individual human weight was equal to 700N (0.7kN) [3]. In this investigation a damping ratio, ξ, equal to 0.005, 0.0075 and 0.01 ($\xi = 0.5\%$, 0.75% and 1%) was adopted in all the structural systems [3], based on the Rayleigh proportional damping formulation [1].

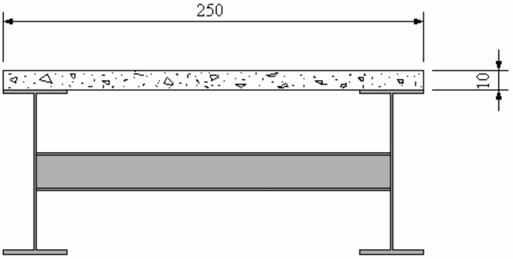

Figure 4: Footbridges cross section (dimensions in cm).

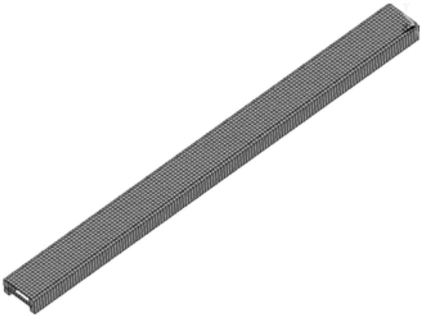

Figure 5: Footbridge finite element model.

Table 3: Geometrical characteristics of the beam steel sections.

Main Span (m)	Beams	Height (mm)	Flange Width (mm)	Top Flange Thickness (mm)	Bottom Flange Thickness (mm)	Web Thickness (mm)
10.0	400x58	400	200	12.5	12.5	6.3
12.5	500x73	500	250	12.5	12.5	6.3
15.0	550x100	550	250	19.0	19.0	6.3
17.5	600x140	600	300	22.4	22.4	8.0
20.0	700x154	700	320	22.4	22.4	8.0
22.5	800x173	800	320	25.0	25.0	8.0
25.0	900x191	900	350	25.0	25.0	8.0
27.5	1000x201	1000	400	22.4	22.4	8.0
30.0	1100x235	1100	400	25.0	25.0	9.5
32.5	1200x244	1200	450	22.4	22.4	9.5
35.0	1200x307	1200	450	31.5	31.5	9.5

The proposed computational model, developed for the composite slab dynamic analysis, adopted the usual mesh refinement techniques present in finite element method simulations implemented in the ANSYS program [4]. In this computational model, floor steel girders are represented by three-dimensional beam elements, where flexural and torsion effects are considered. The concrete slab is represented by shell finite elements, as presented in Figure 5. The computational model considered a full interaction between steel and concrete simulating a composite (steel-concrete) structural system.

4 DYNAMIC ANALYSIS

For practical purposes, a linear time-domain analysis was performed throughout this study. This section presents the evaluation of the structural systems vibrations levels when submitted to dynamic excitations coming from human walking. The outdoor footbridges dynamic responses were determined through an analysis of its natural frequencies, displacements and accelerations. The results of the dynamic analysis were obtained from an extensive numerical analysis, based on the finite element method using the ANSYS program [4]. These values were compared with the results supplied by current criteria for structural design [3], [5]. This comparison was performed to evaluate a possible occurrence of unwanted excessive vibration levels and human discomfort.

4.1 Natural Frequencies and Vibration Modes

The footbridges natural frequencies were determined with the aid of the finite element method simulations [4], as illustrated in Table 4. These results were compared to those obtained according to the design criteria [3] and were used to evaluate only the footbridges fundamental frequencies.

When the footbridges freely vibrate in a particular mode, it moves up and down with a certain configuration or mode shape. Each footbridge natural frequency has an associated mode shape. It was observed in all investigated structural models that flexural effects were predominant in the fundamental mode vibrations. However it is important to observe that torsional effects are present starting from the second vibration mode, see Figure 6. Figure 6 also illustrates the mode shapes corresponding to the first six natural frequencies of the pedestrian footbridge with the main span equal to 20m.

The numerical results for the footbridges fundamental frequency, with the main span varying from 10m to 35m, were in accordance to the literature values [3]. It could be clearly observed, as expected, that as the structural span is increased the footbridge fundamental frequency decreases, see Table 4. This fact also serves to demonstrate that the developed models are coherent to the theory.

Table 4: Footbridges natural frequencies.

Main Span	Natural Frequencies f_{0i} (Hz)						AISC*	Differences
	f_{01}	f_{02}	f_{03}	f_{04}	f_{05}	f_{06}	f_{01} (Hz)	(%)
10.0	9.04	19.52	30.58	53.31	53.76	62.87	8.58	5.14
12.5	7.72	17.83	26.66	46.31	46.88	50.53	7.23	6.26
15.0	6.63	16.19	22.85	36.76	39.87	45.98	6.03	9.03
17.5	5.91	15.07	20.07	29.98	35.32	42.12	5.23	11.55
20.0	5.37	14.60	18.23	24.87	32.95	39.16	4.74	11.87
22.5	4.99	14.11	16.83	21.28	30.87	36.73	4.35	12.66
25.0	4.65	13.51	15.63	18.79	28.96	34.50	4.04	13.13
27.5	4.31	12.61	14.45	17.11	27.04	32.17	3.74	13.17
30.0	4.11	11.47	13.59	16.19	24.86	30.52	3.52	14.48
32.5	3.84	10.36	12.67	15.51	22.99	28.58	3.28	14.55
35.0	3.55	9.45	11.53	14.68	21.07	26.21	2.96	15.41

*AISC: [3]

Table 4 indicated that the difference between the footbridge fundamental frequency evaluated by the developed model or by the AISC recommendations [3] is proportional to the footbridge span. Considering that the finite element model (FEM) was developed to determine accurate results and the AISC equations [3] are in fact based on simplified models, associated to a single degree of freedom system (SDOF), it is reasonable to accept that the numerical results determined in the present study are closer to the actual value.

(a) Mode shape associated to the 1st natural frequency: f_{01}=5.37Hz.

(b) Mode shape associated to the 2nd natural frequency: f_{02}=14.60Hz

(c) Mode shape associated to the 3rd natural frequency: f_{03}=18.23Hz.

(d) Mode shape associated to the 4th natural frequency: f_{04}=24.87Hz.

(e) Mode shape associated to the 5th natural frequency: f_{05}=32.95Hz.

(f) Mode shape associated to the 6th natural frequency: f_{06}=39.16Hz.

Figure 6. Footbridge vibration modes. Main span equal to 20m.

4.2 Peak Accelerations

The present analysis proceeded with the evaluation of the footbridges performance in terms of vibration serviceability due to dynamic forces induced by people walking. The first step of this investigation concerned in the determination of the footbridge peak accelerations. These peak accelerations were compared to the limits recommended by design criteria and codes [3], [5], see Table 5.

Table 5: Outdoor footbridges peak accelerations at resonance.

Main Span (m)	Heel Impact Coefficient (f_{mi})	Structural Damping (ξ)		
		0.50%	0.75%	1.00%
10.0	1.12	1.060	1.010	0.967
12.5		1.660	1.580	1.510
15.0		0.934	0.892	0.851
17.5		1.670	1.590	1.520
20.0		0.969	0.926	0.883
22.5		1.200	1.140	1.090
25.0		0.481	0.460	0.439
27.5		1.390	1.330	1.270
30.0		0.675	0.645	0.615
32.5		1.570	1.500	1.430
35.0		0.559	0.531	0.509

Limit acceleration: a_{lim} = 0.490 m/s^2 [3], [5] The peak accelerations values have shown that for all analyzed outdoor footbridges the peak accelerations were higher than those proposed by the design criteria and code recommendations [3], [5], violating human comfort criteria, see Table 5. This fact emphasizes that when the position of the dynamical loading corresponding to the excitation induced by people walking was changed and at the same time the human heel effect was incorporated in the analysis there is a substantial increase in the structure dynamical response and that the structural models indicated possible problems related to human comfort for the load model, see Table 5.

It must be emphasized that the footbridges structural damping and heel impact coefficients considered in this investigation are in accordance to current design recommendations [3], [5]. The obtained results have shown that when the structural damping, ξ, decrease the peak accelerations values increase and when the heel impact coefficient, f_{mi}, increase the peak accelerations values also increase. Such fact is relevant, because the limit states related to excessive vibrations were violated and the human comfort was compromised when the transient effect due to the human heel impact was considered in the analysis, Table 5.

5 FINAL REMARKS

This paper considered the investigation of the dynamic behaviour, in terms of vibration serviceability limit states, of several outdoor composite (steel-concrete) footbridges. The developed loading model incorporated a more realistic load where the dynamic action position changed according to the individual position on the structural model. Another important point is related to the fact that the generated time function has a space and time description and the load model also considered the human heel impact effect. On the other hand, the AISC recommendations only considered a single harmonic applied at the pedestrian footbridge midspan, without varying the load position.

The outdoor footbridges dynamic responses in terms of peak accelerations were obtained and compared to the limit values proposed by current design code recommendations. The obtained results in this investigation have shown that when the position of the dynamical loading was changed according to the individual position and, at the same time the human heel effect was incorporated in the analysis, the peak accelerations were higher than current design code recommendations limit values.

6 ACKNOWLEDGEMENTS

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