Relation of Natural Frequencies to Traffic Pedestrians' Comfort of Some Steel Footbridges

Moga Cătălin, Drăgan Delia and Nerişanu Raluca

Abstract – In this paper several aspects regarding the dynamic behaviour of the steel footbridge structures under the action of the loads generated by the pedestrians' displacement, correlated with the traffic comfort of the pedestrians crossing the structure are presented. The crossing pedestrians' comfort criterion requires the values of vibration frequencies and accelerations of the structures in certain limits so that the vibration amplification or resonance is avoided. The paper takes under investigation eight footbridges on steel, composite steel-concrete girders and a cable stayed structure from the viewpoint of frequencies in vibration Mode 1 in a vertical plane, generated by their own weight - natural frequency, or from a partial pedestrian loading, as well as the resulting resonance risk and the traffic comfort.

Keywords – *analysis of footbridges comfort, critical frequency and acceleration, dynamic response, steel and composite steel-concrete footbridges, traffic comfort.*

1. INTRODUCTION

This paper presents several aspects related to the dynamic behaviour of the footbridge structure under the loads generated by the displacement of the pedestrians along the footbridge. The maximum comfort criterion applied to footbridge crossing requires a total absence of vibrations which could lead to less slender structures or slender structures provided with vibration damping systems, which increase the construction costs.

The paper investigates the case of eight footbridges: rolled steel girder footbridges, composite steel-concrete girders, steel-concrete composite structure with circular web hollows, girders with corrugated webs, truss girders footbridge, trapezoidal steel box girder footbridge and footbridge on cable stayed structure. The analyses are made for the frequency in the 1st Mode of vibration in vertical plane, the vibrations being the result of own weight (natural frequency) or partial footbridge loaded and consequent resulting resonance risk, respectively the traffic comfort.

The load given by the pedestrian walking or running is equivalent to a time-concentrated force.

Conventionally, for walking, the frequency can be described by a Gaussian curve with an average value of 2 Hz and a standard deviation of 0.20 Hz.

In case of transverse vibrations, the lock-in phenomenon may occur, which refers to the fact that a crowd composed of units with different frequencies tend to gradually receive a common frequency, that of the structure, and enter in phase with the movement of the bridge.

2. DYNAMIC ANALYSIS AND TRAFFIC COMFORT

According to EN 1990-EC 0 – Annex A2, [1], the maximum recommended accelerations are as follows: 0.7 m/s^2 – vertical vibrations; 0.2 m/s^2 – horizontal vibrations; 0.4 m/s^2 – exceptional situations (agglomerations). Verification of the comfort criterion should be performed if the fundamental frequency of the structure is less than the value of 5 Hz for vertical vibrations and 2,5 Hz for horizontal (lateral) vibrations and torsional vibrations.

There are four Traffic Classes for walkways, depending on the size of the estimated traffic, Table 1, [1], [10].

Table. 1. Traffic classes

Class	Traffic characteristics
I	urban footbridges with high pedestrian density
II	urban footbridges, occasionally loaded on the entire surface
III	footbridges for normal use; occasionally crossed by large groups of pedestrians
IV	footbridges occasionally crossed

Four conventional areas for vertical and horizontal accelerations are defined (Figure 1) in ascending order, corresponding to maximum, mean and minimum comfort levels, where field 4 corresponds to inadmissible acceleration values, [10].

Horizontal acceleration is limited to 0.10 m/s^2 to avoid the "lock-in" phenomenon.

Fig. 1. Acceleration ranges for vibrations

For footbridges that fall into classes I, II and III, it is necessary to calculate the natural vibration frequency of the structure. Frequencies are determined for two mass assumptions of the system: unloaded footbridge; the bridge loaded on the walkway with 700 N/m^2 .

Vertical and horizontal frequencies may fall into four areas of the resonance risk, Figure 2, [10], where: Domain 1: maximum resonance risk; Domain 2: average (mean) resonance risk; Domain 3: low resonance risk; Domain 4: negligible resonance risk.

Fig. 2. Frequency ranges for vibrations

For the simply supported beam with constant characteristics, the analytical calculation for the natural vibration modes is performed using the relationships given in Table 2, [1...10].

Table. 2. Analytical relations for the natural vibration modes.

Mode	Natural pulse	Natural frequency	Vibration mode
Simple bending with n half-wave	$\omega_n = \frac{n^2 \pi^2}{L^2} \sqrt{\frac{EI}{\rho S}}$	$f_n = \frac{n^2 \pi}{2L^2} \sqrt{\frac{EI}{\rho S}}$	$v_n(x) = \sin\left(\frac{n\pi x}{L}\right)$
Tension compression with n half-wave	$\omega_n = \frac{n\pi}{L} \sqrt{\frac{ES_N}{\rho S}}$	$f_n = \frac{n}{2L} \sqrt{\frac{ES_N}{\rho S}}$	$u_n(x) = \sin\left(\frac{n\pi x}{L}\right)$
Measurement units: L [m]; $E = 210 \times 10^9$ N/mm ² ; I [m ⁴]; ρS [kg/m]; m [kg/m]. Parameters: ρS – the linear density of the construction (includes permanent and variable loading); ES_N – stiffness at axial stresses; EI – flexural stiffness.			

3. ANALYSIS OF DYNAMIC PARAMETERS

The following structures of pedestrian walkways shall be analyzed synthetically from the point of view of frequencies in Module 1 of vibration in the vertical plan, resulted from its own weight or partially loaded, considering a classification in Class III of traffic:

- six pedestrian bridges on metal beams, composite steel-concrete beams, composite beams with holes in the steel webs, beams with corrugated webs and truss footbridge, all of these having the span of 24.00 m and the width between parapets of approximately 3.00 m. The structures listed above are presented detailed from the point of view of the dynamic behaviour in the papers [3], [5], [6], [7] and in the handbook [1];
- a composite steel-concrete box section girder, with a span of 58,0 m, for crossing the Someş River in the municipality of Cluj-Napoca, for which the project documentation has been elaborated [4]; [12];
- a footbridge on metal arches with cable hangers with a span of 130,0 m, over the Someş River in the municipality of Satu Mare, [2], for which a feasibility study of the construction was developed [12].

P1: Footbridge on two rolled I-beams

The dynamic parameters for a footbridge with a 24.00 m span on two rolled IPE 750x147 beams were evaluated. The distance between the main beams is 3.00 m and the bridge cross-section is shown in Figure 3 [12].

P2: Footbridge on two flexible rolled I-beams

The footbridge is similar to P1 but in this case for the main beams, the rolled IPE500, instead of IPE750 are used.

Fig. 3. Footbridge structure on rolled beams

P3: Footbridge with composite steel-concrete structure

The composite steel-concrete deck of the footbridge has the following design data: span: $L = 24.0$ m; effective width of 3.00 m. The deck is made of two main beams with a steel-concrete composite section and the composite transverse beams with a monolithic reinforced concrete slab of 12 cm thick, Figure 4.

Fig. 4. Superstructure of a composite footbridge

a) Deck cross-section; b) Steel-beam cross-section; c) Composite design cross-section

P4: Footbridge with a composite steel-concrete structure using unsymmetrical steel beams with circular holes

The analysis of a composite steel-concrete structure is performed for a footbridge, knowing the design data: the span: $L = 24.0$ m; effective width $B_c = 3.00$ m, thickness of the concrete slab is of 12 cm. The deck is made of two main beams with steel-concrete composite section, made from rolled profiles with circular holes in the webs, welding different rolled elements for the two parts, Figure 5.

Fig. 5. Main beams with web holes: a) steel component; b) composite design cross-section

P5: Footbridge with steel beams with trapezoidal webs

In the case of the main beams with the web made of trapezoidal plate the solution presented in Figure 6 is chosen as a cross-section and the main beams are presented in Figure 7.

Fig. 6. Superstructure on beams with trapezoidal webs

Fig. 7. Main beams of the footbridge with trapezoidal webs

P6: Truss girder footbridge

The geometric scheme of the main trusses and the cross section chosen for this case are shown in Figure 8.

Fig. 8. Truss girder footbridge

P7: Footbridge across the Someș River in Cluj-Napoca

The solution adopted is that of a composite steel-concrete superstructure where the steel part is a box beam and the flooring is a monolithic reinforced concrete slab. The footbridge has a span of 58.0 m and a width of 6.0 m, that ensures two pedestrian sidewalks and a cycle track located in the central area, Figure 9, [2], [12].

Table 3 centralizes the natural frequencies obtained for the vertical vibrations Mode 1 for the analyzed structures, the resonance risk range in which they can fall.

Fig. 9. Footbridge cross-section and 3D rendering

Table. 3. Synthesis of analysis

Analyzed footbridges	Main beams	Natural frequencies (sup./inf.) f_1 [Hz]	Resonance domain risk
P1	Rolled IPE 750. L=24 m	3.39/3.08	Low resonance risk
P2	Rolled IPE 500. L=24 m	2.24/1.95	Mean/maximum resonance risk
P3	Welded steel beams. Composite steel-concrete structure. L=24 m	2.30/2.29	Mean resonance risk
P4	Steel beams with circular holes. Composite structure. L=24 m	3.98/3.97	Low resonance risk
P5	Steel girder with corrugated webs. L=24 m	3.80/3.40	Low resonance risk
P6	Steel truss girders. L=24 m	3.13/3.02	Low resonance risk
P7	Trapezoidal steel box beam. Composite steel-concrete structure. L=58m	1.38/1.24	Mean resonance risk

P8: Dynamic analysis of a footbridge structure over the Someș River

The dynamic response of a footbridge over the Someș River in Satu Mare Municipality, on a central arch have been analyzed in a Feasibility Study [12]. The footbridge superstructure, [2], [12] has 3 spans, Figure 10, with a central span of 130.0 m.

Fig. 10. Footbridge longitudinal view (elevation)

Vibration mode 1, in the vertical plane

The footbridge falls within Class II: urban footbridges, occasionally loaded on the entire surface. The deck cross-section analyzed in the first step is presented in Figure 11.

Fig. 11. Deck cross-section

The frequencies for Vibration Mode 1: superior frequency - $f_1 = 38$ Hz; inferior frequency - $f_1 = 37$ Hz. The frequencies for Vibration Mode 1 fall within Domain 4.

Vibration Mode 1, in the horizontal plane

The frequencies for Vibration Mode 1: superior frequency - $f_1 = 0.52$ Hz; inferior frequency - $f_1 = 0.51$ Hz. The frequencies corresponding to Vibration Mode 1 fall within Domain 1: maximum resonance risk. Considering that the footbridge deck has lateral cantilevers we verified if the dynamic parameters corresponding to the horizontal vibrations can be modified using longitudinal ties with a tubular cross-section.

Vibration mode 1 in the horizontal plane – horizontally stiffened deck

The deck cross-section, with the new cantilever system is presented in Figure 12.

Fig. 12. Deck cross-section reinforced with longitudinal ties

Table 4 centralizes the superior frequencies and the resonance risk for the two analyzed decks, for the case of unloaded structure and the case of partially loaded structure [2].

Table 4. Mode 1- Frequencies and the resonance risk.

The deck	Vibration mode	Frequency	Freq [Hz]	Resonance risk. Observations
Original unstiffened solution	Vibration mode 1 in the vertical plane	Superior frequency. Unloaded footbridge	38	Domain 4: Negligible resonance risk
		Superior frequency. Partially loaded footbridge	37	
	Vibration mode 1 in the horizontal plane	Superior frequency. Unloaded footbridge	0.52	Domain 1: Maximum resonance risk
		Superior frequency. Partially loaded footbridge	0.51	
Stiffened deck	Vibration mode 1 in the horizontal plane	Superior frequency. Unloaded footbridge	1.18	Domain 2: Mean resonance risk.
	Interrupted deck at the intermediate supports	Superior frequency. Partially loaded footbridge	1.15	
	Vibration mode 1 in the horizontal plane.	Superior frequency. Unloaded footbridge	1.50	Domain 3: Low resonance risk

4. CONCLUSIONS

In the case of footbridges, in addition to checks for the ultimate limit state and service limit states, it is necessary to check pedestrian traffic comfort in direct correlation with the vibration frequency of the structure (resonance risk) and its acceleration. If these characteristics (frequency and acceleration) are in the critical area, measures must be taken to alter their value so that they fall within the limits of the recommended norms or other recognized technical materials.

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Note:

Nerişanu Raluca – Technical University of Cluj-Napoca, 28 Memorandumului Street, 400114-Cluj-Napoca, Romania (corresponding author to provide phone: +40-728-671024; e-mail: Raluca.Nerisanu@cfdp.utcluj.ro).

Moga Cătălin – Technical University of Cluj-Napoca, 28 Memorandumului Street, 400114-Cluj-Napoca, Romania (e-mail: Catalin.Moga@dst.utcluj.ro).

Drăgan Delia – Technical University of Cluj-Napoca, 28 Memorandumului Street, 400114-Cluj-Napoca, Romania (e-mail: Delia.Dragan@cfdp.utcluj.ro).