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CONSTRUCTIVE SOLUTION AND COMMENTS REGARDING STEEL GIRDER FOOTBRIDGES

BY

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Abstract. In this paper some aspects concerning the design and the constructive solution for the steel and steel-concrete composite footbridge structures are presented. In the design of the footbridge structure besides the ULS and the SLS verifications, also the comfort criterion has to be verified which is in direct correlation with the structure frequency and acceleration. If the frequencies and accelerations of the structure are situated in the critical domains some measures to modify them have to be taken.

Key words: steel footbridge structures; actions; traffic comfort; design.

1. Introduction

Footbridges are part of the bridges category and their main purpose is to provide for the access of the pedestrians in crossing natural or another kind of obstacles. In the range of small and average spans, the most used constructive solutions in the superstructure of footbridges are the rolled metal girders, plate web girders with welded sections, hollow girders and truss girders.

Besides the ultimate limit states (ULS) and serviceability limit states SLS verifications, in the design of the footbridge, the pedestrians traffic comfort

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criterion needs to be checked, in conjunction with the structure frequency (the risk of resonance) and acceleration. When the frequencies and accelerations of the structure are situated in the critical domain, measures should be taken to modify their magnitude so as they comply with the limits recommended in norms or other recognized technical documents.

Considering the nature of the deformations produced in the structure components, vibrations can be

a) transverse, when the deformations regard bending and shearing;
b) longitudinal, when compression and tensile axial deformations occur;
c) torsional, when the alternating deformations belong to torsion.

The maximum comfort criterion applied to crossing a footbridge requires a total lack of vibrations, but the structure erected would be less slender, or slender but provided with vibration dampening systems. The latter implies a higher construction cost and complex maintenance requirements.

A moderate comfort allows for limited structure vibration and this can be found with supple and good looking structures also provided with vibration dampers.

2. Calculation-Related Issues

2.1. Actions

The imposed footbridge loadings, defined in EC 1, result from the pedestrian bicycle riders traffic, loadings originating in minor constructions, structure maintenance and accidental situations.

2.2. Static Calculus Convoys for Vertical Loadings

Let us take three calculus convoys that mutually exclude one another:

a) a uniformly distributed force, q_{fk};
b) a concentrated force, Q_{fwk};
c) a loading, Q_{serv}, representing service vehicles.

The characteristic values of these loadings are used both for permanent design and transient design cases.

The recommended uniformly distributed force magnitude is

$$q_{fk} = 5 \text{ kN/m}^2. \tag{1}$$

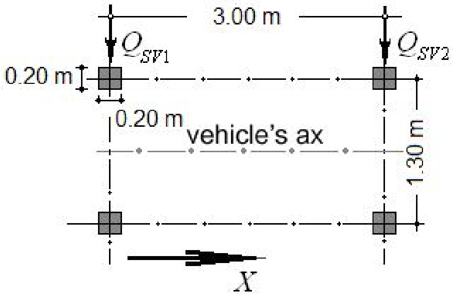
The characteristic value of the concentrated force, Q_{fwk}, is taken as

$$Q_{fwk} = 10 \text{ kN}. \tag{2}$$

The concentrated force acting on a square surface of side 0.10 m is recommended for the determination of local effects.

2.3. The Service Vehicle

This vehicle can perform maintenance, emergency (such as ambulances or fire patrols) actions or other services. It is advisable to use a service vehicle as defined in Fig. 1; in this case, it is not necessary to apply the vehicle loading as an accidental loading.



$$Q_{SV1} = 80\,\text{kN}$$
$$Q_{SV2} = 40\,\text{kN}$$

Fig. 1 – Service vehicle.

2.4. Static Calculus Convoys for Horizontal Forces

In the case of footbridges, a horizontal longitudinal force, Q_{flk} , is considered as acting along the axis on the carriageway.

The characteristic value of the horizontal force is taken as equal to the largest value of the following two magnitudes:

a) 10% of the total loading found from the uniformly distributed load;

b) 60% of the total load of the service vehicle, where appropriate.

2.5. Groups of Loadings in Footbridges

Where appropriate, the vertical loads and the horizontal forces due to traffic are taken into consideration with the help of some load groups, as defined in Table 1. The load groups mutually exclude one another and define actions typical of loading combinations not originating in traffic.

Table 1

Load Groups

Loading type		Vertical forces		Horizontal forces
Load systems		Uniformly distributed force	Service vehicle	
Load groups	gr.1	q_{flk}	0	Q_{flk}
	gr.2	0	Q_{serv}	Q_{flk}

2.6. Actions Related to Accidental Design Cases

Such actions could be:

a) forces coming from the hitting/impact of vehicles in traffic under the bridge;

b) forces coming from hitting/impact on to the pylons; according to SR EN 1991-2:2005, in stiff piles, the magnitudes recommended for impact forces are:

b$_1$) F = 1,000 kN – along the vehicle displacement direction or

b$_2$) F = 500 kN – along the perpendicular direction;

c) forces originating in the impact to the bridge floors.

2.7. Verification of Dynamic Parameters

In the case of footbridges, besides the USL and SLS related checks, it is necessary to verify the traffic comfort that is in direct correlation with the vibration frequency and acceleration. With the simply-supported beam of constant properties, the analytical calculus of the natural vibration modes is made with the relationships from Table 2.

Table 2

Relationships for the Analytical Calculus of the Natural Vibration Modes

Mode	Natural pulsation	Natural frequency	Vibration mode shape
Simple bending with n half-waves	$\omega_n = \frac{n^2\pi^2}{L^2}\sqrt{\frac{EI}{\rho S}}$	$f_n = \frac{n^2\pi}{2L^2}\sqrt{\frac{EI}{\rho S}}$	$v_n(x) = \sin\left(\frac{n\pi x}{L}\right)$
Tensile – compression with n half-waves	$\omega_n = \frac{n\pi}{L}\sqrt{\frac{ES_N}{\rho S}}$	$f_n = \frac{n}{2L}\sqrt{\frac{ES_N}{\rho S}}$	$u_n(x) = \sin\left(\frac{n\pi x}{L}\right)$
Torsion with n half-waves	$\omega_n = \frac{n\pi}{L}\sqrt{\frac{GI_\omega}{\rho I_r}}$	$f_n = \frac{n}{2L}\sqrt{\frac{GI_\omega}{\rho I_r}}$	$\theta_n(x) = \sin\left(\frac{n\pi x}{L}\right)$

In Table 2, the units of measurements are: L, [m]; $E = 210 \times 10^9$ N/mm^2; I, [m^4]; ρS, [kg/m]; m, [kg/m], while the parameters in the dynamic calculus represent: ρS – the construction linear density (from the permanent and variable loading); ρl_r – torsion inertia moment; ES_N – axial stress stiffness; EI – bending stiffness; GI_ω – restraint torsion stiffness.

Four conventional domains for the vertical and horizontal accelerations are defined (Fig. 2), in decreasing order relative to the maximum, medium and minimum comfort, while range 4 corresponds to admissible acceleration values.

The horizontal plane acceleration is constrained to magnitude 0.10 m/s^2 to avoid *”lock-in”*.

For the footbridges of I, II and III traffic grades (Moga, 2014; Sétra, 2006), it is necessary to calculate the structure own vibration frequency. This is appreciated along the three directions: vertical, horizontal transverse and horizontal longitudinal.

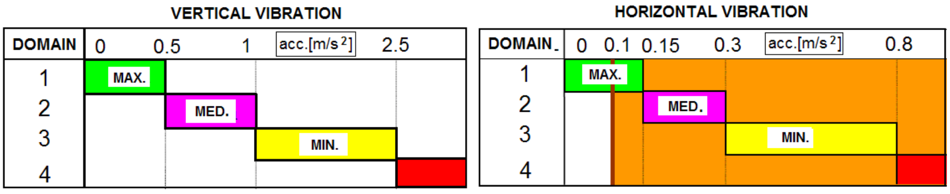


Fig. 2 – Acceleration range.

Frequencies are determined for two system mass hypotheses: unloaded footbridge; 700 N/m^2 loaded footbridge per traffic surface.

Depending on the range of the above frequencies, the risk of resonance due to pedestrian traffic can be appreciated and then the loading cases for the dynamic calculus can be established and the comfort criterion can be checked.

The vertical and horizontal frequencies can be ranged within four domains of risk resonance occurrence (Fig. 3), where: domain 1 – maximum resonance risk; domain 2 – average resonance risk; domain 3 – low resonance risk; domain 4 – negligible resonance risk.

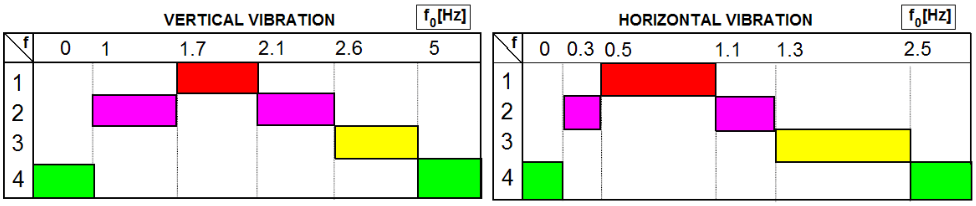


Fig. 3 – Frequency range.

According to EN 1990-EC0–Annex A2, the maximum recommended accelerations are: 0.7 m/s^2 – for vertical accelerations; 0.2 m/s^2 – for horizontal accelerations; 0.4 m/s^2 – for exceptional accelerations (crowd).

The comfort criterion verification must be performed if the fundamental frequency of the footbridge floor is smaller than: 5 Hz – for vertical vibrations; 2.5 Hz – for horizontal (lateral) vibrations and torsional vibrations.

When the criterion for limit accelerations is not satisfied, improvement measures for the dynamic behaviour should be considered.

3. Steel Girder Footbridges

The paper will go on by presenting some footbridge constructive solutions made with two simply-supported metal beams for a 24 m wide span.

In all the solutions, steel S355 J2 was chosen.

The strength calculus and dynamic parameter evaluation calculus were performed (MOGA *et al*., 2014) in all solutions in question. Where appropriate, issues requiring special attention are highlighted.

3.1. Rolled Steel Girder Footbridges (Fig. 4)

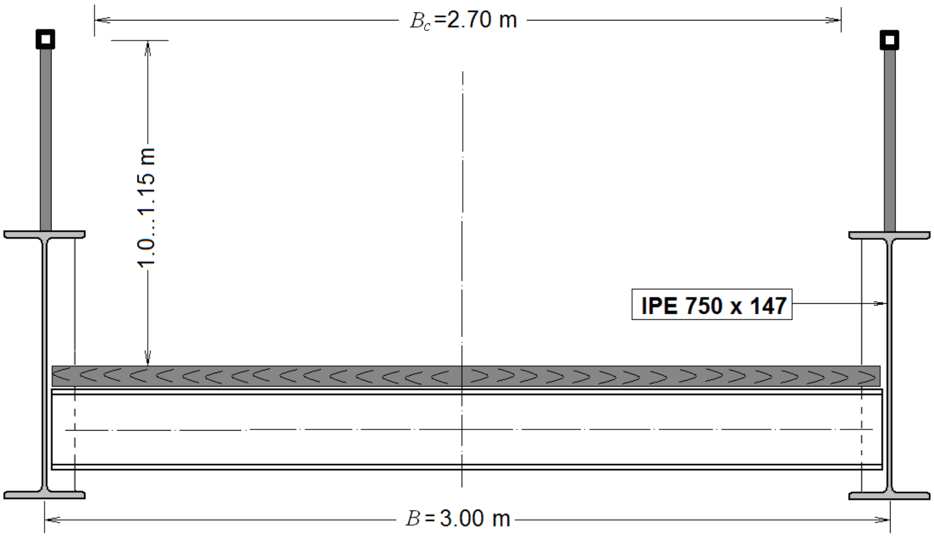


Fig. 4 – Rolled steel footbridge.

Following the evaluation of the actions, a total permanent loading (own load) of about 450 kg/m was found.

Frequencies for Vibration Mode 1:

a) upper frequency: f_1 = 3.39 Hz;

b) lower frequency: f_1 = 3.08 Hz.

Frequencies for Vibration Mode 2:

a) upper frequency: f_2 = 13.56 Hz;

b) lower frequency: f_2 = 12.32 Hz.

Frequencies for Vibration Mode 1 range in Domain 3: low risk of resonance, while frequencies for Vibration Mode 2 range in domain 4: negligible risk of frequency.

When the main beams are made with rolled steel of much more reduced stiffness (IPE 500), the dynamic parameter conditions are not met, respectively the *frequencies for Vibration Mode 1* are included in Domain1: maximum risk of resonance.

3.2. Main Beams with Hexagonal Hollows

In the case of main beams with hexagonal voids (hollows) the solution up way was chosen, cross bars being placed in the full section of the beam (Fig. 5).

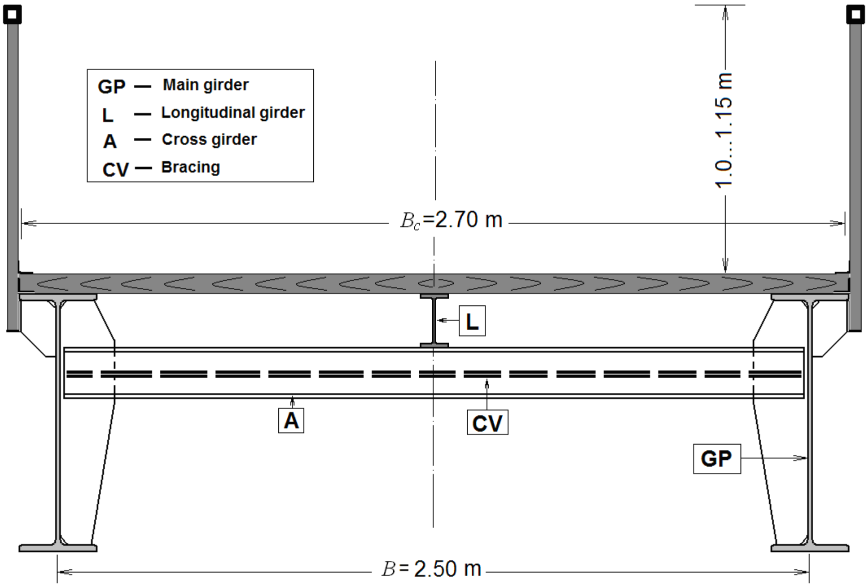


Fig. 5 – Hollow girder footbridge.

The main beams are built with variable section and the areas near the bearings are made with plate girders (Fig. 6).

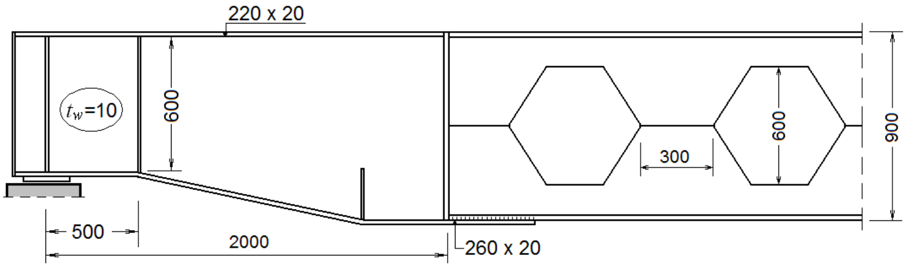


Fig. 6 – Variable cross section girders.

Moga, (2013), should be read for more details on the calculus of these beams.

3.3. Main Beams with Corrugated and Trapezoidal Webs

In the case of main beams with trapezoidal web, the solution of up-way is chosen; cross bars and cross ties provide for the stability of the structure in vertical transverse plane (Fig. 7).

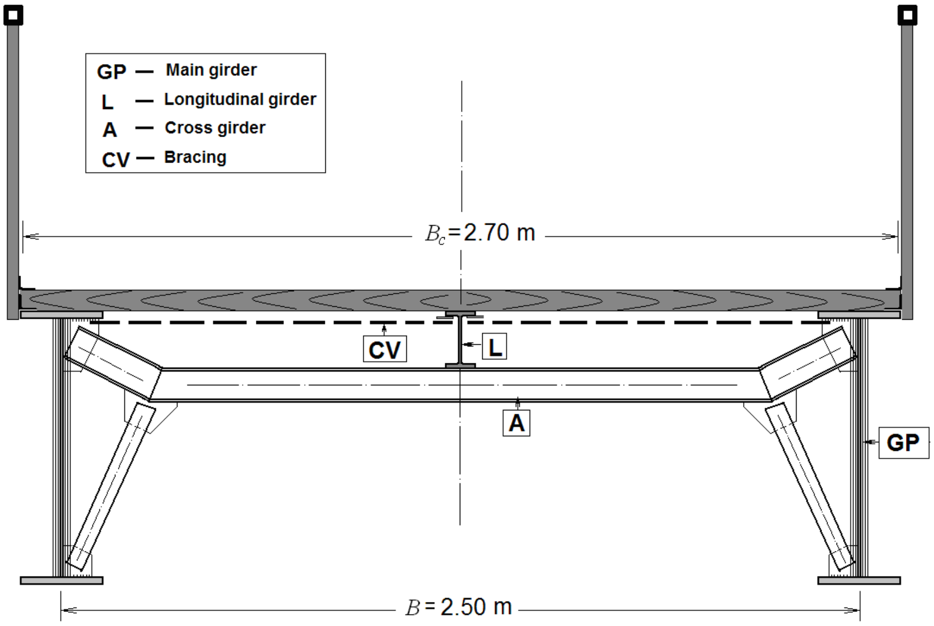


Fig. 7 – Trapezoidal webs girder footbridge.

The main beams are made in variable section and the areas near the bearings are made with plate girders (Fig. 8).

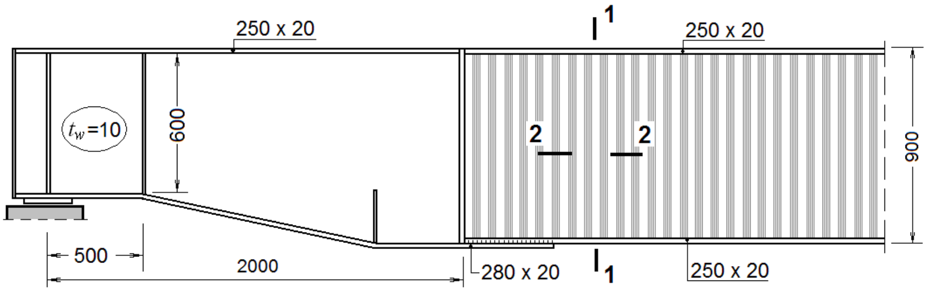


Fig. 8 *a* – Trapezoidal web girder; elevation.

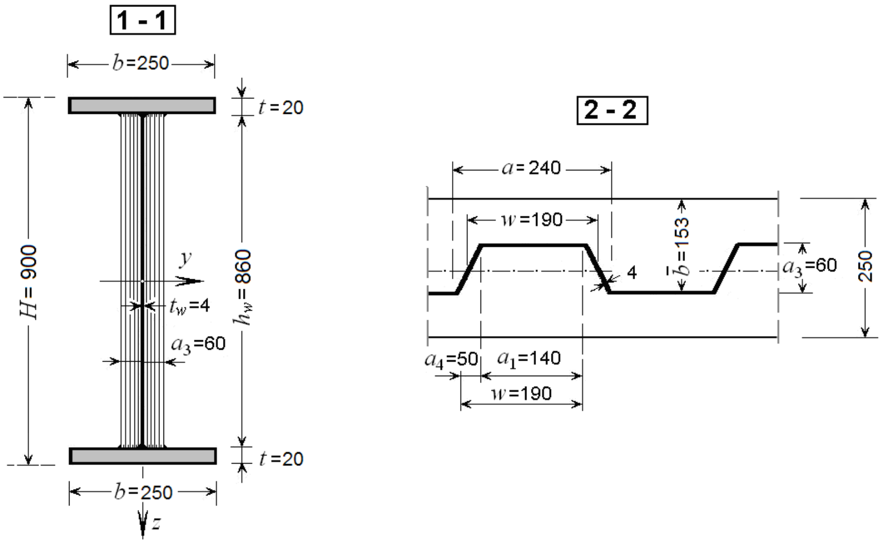


Fig. 8 *b* – Trapezoidal web girder.

For the calculus of the main beams with corrugated and trapezoidal webs it is advized to read paper (Moga, 2013).

3.4. Truss Girder Footbridge

The geometric scheme of the main trusses and the cross section chosen for this case are shown in Fig. 9.

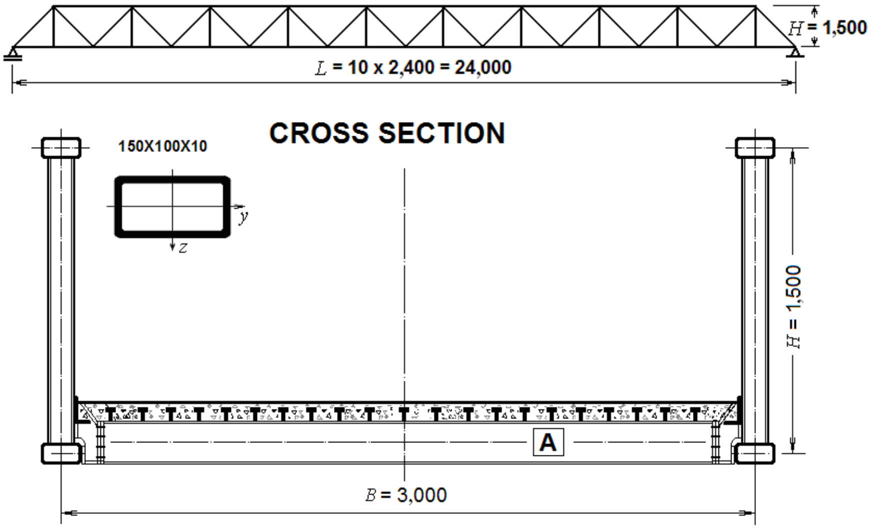


Fig. 9 – Truss girder footbridge.

The crosses bars are made of IPE rolled sections and are placed *versus* the struts at a distance of 2.40 m.

Cross bars are provided with bolt connectors working structurally with the concrete slab (as composite steel-concrete members).

Special care should be given to checking the general stability of the main girders, and the lateral buckling of the compressed flange, respectively.

3.5. Steel-Concrete Girder Footbridge

The footbridge floor strength structure is made up of two main girders or concrete and steel, cross bars joined to the concrete slab and the cast-*in-situ* reinforced concrete slab, Fig. 10.

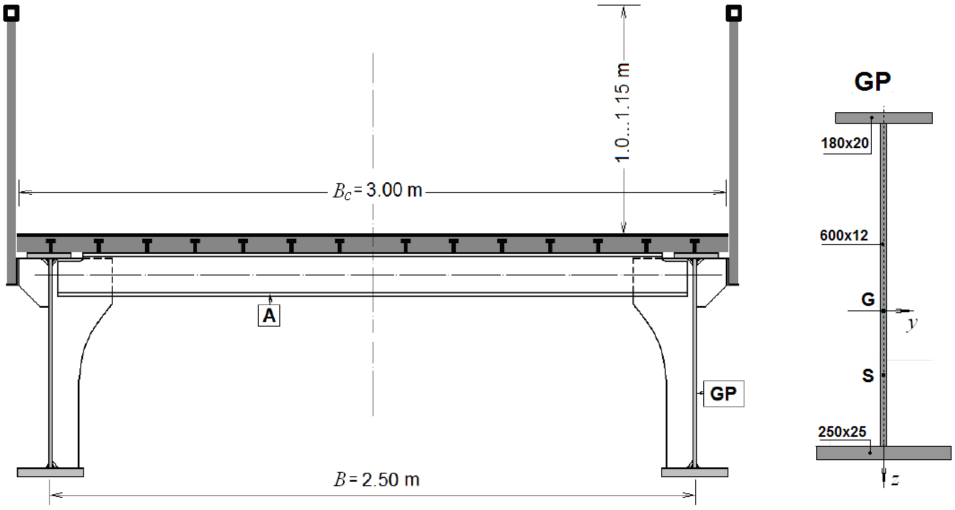


Fig. 10 – Composite steel–concrete girder footbridge.

The steel–concrete composite footbridge floor is verified in accordance with the European norms on the evaluation and grouping of actions, respectively on the calculus of steel members and composite steel–concrete members.

For a better understanding of composite steel–concrete structure calculus it is advisable to read papers concerning this case (Guțiu, 2012; Moga *et al.*, 2012).

Special attention shall be paid to verify the general stability of the main beams, and the lateral buckling of the compressed flange, respectively.

The higher natural frequency of the structure in mode 1 of vibration was verified. The magnitude found was: f_1 = 2.3 Hz – *average risk of resonance.*

4. Conclusions

In the domain of small and average spans, the most often used footbridge constructive solutions regard metal girders, made with rolled structures, plain web girders with welded sections, hollow girders and frame girders.

For pedestrian footbridges, besides the USL and SLS verifications, the pedestrian comfort in traffic needs to be checked, in correlation with the structure vibration frequency (risk of resonance) and its acceleration.

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PASARELE PE GRINZI METALICE

Soluţii şi comentarii

(Rezumat)

Sunt prezentate câteva aspecte privind calculul şi alcătuirea pasarelelor pietonale realizate pe grinzi metalice.

În cazul pasarelelor pietonale, pe lângă verificările corespunzătoare stărilor limită ultime şi ale stărilor limită de serviciu, este necesar să fie verificat confortul de circulaţie al pietonilor, aflat în corelare directă cu frecvenţa de vibraţie a structurii (riscul de rezonanţă) şi cu acceleraţia acesteia.

Dacă aceste caracteristici (frecvenţă şi acceleraţie) se găsesc în domeniul critic, trebuie luate măsuri de modificare a valorii acestora, astfel încât să se încadreze în limitele recomandate de norme sau de alte materiale tehnice recunoscute.