DYNAMIC CHARACTERISTICS AND BEHAVIOUR OF THE ARCH FOOTBRIDGES DURING HUMAN-INDUCED VIBRATIONS

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SUMMARY

In the paper the dynamic characteristic of the arch footbridges with different structural systems have been presented. On the basis of the in-situ dynamic tests of the footbridges the basic dynamic parameters of the structures with spans of 24-63 m have been characterised. Presented results provide a database of the basic dynamic parameters and the levels of vibration acceleration of the medium span arch footbridges.

Keywords: *Footbridges, vibrations, comfort of use.*

1. INTRODUCTION

Footbridges are a type of the bridge structures which designing require performing the dynamic analyses in order to determine the level of vibrations induced by the users and the evaluation of comfort of use of the structure. In these analyses, it is necessary to determine the risk of exciting the resonant vibrations and to determine the values of the maximal vibration acceleration of the footbridge deck and its reference to the value of limit acceleration. Knowledge of the basic dynamic parameters of the designed structure is vitally important at the stage of evaluation of the adopted design solutions. In order to assess the risk of inducing of the resonant vibration it is necessary to know the natural frequency of the designed structure and comparison of them with the frequencies of the dynamic impact of the footbridge users. Determination of the value of the maximal vibration acceleration of the footbridge deck require analysis of the footbridge forced vibrations. In these analyses, an important parameter is the value of the damping coefficient, which may be defined as a logarithmic decrement, a fraction of critical damping or Rayleigh damping (mass and stiffness proportional damping).

Where there is any risk of occurrence of the resonant vibrations and large vibrations of the structure it is necessary to take corrective measures related to the change of the dynamic parameters of the designed structure. The changes can be achieved by structural changes related to changes in flexural rigidity of the structure (changing of the spans length, changing cross sections of the structural elements), changes in weight (mass) of the spans and/or changing of the structural damping (installation of the vibration dampers). In case of the resonant vibrations the most effective way to reduce the amplitudes of vibrations is to increase the level of structural damping. The vibration amplitudes at resonance are inversely proportional to the damping factor [1]. This relationship is the best justification of the recommendation presented in standard [2] concerning the need of prediction of the possibility of installation of the vibration dampers in footbridges already at the stage of its designing [3, 4, 5]. This becomes particularly important in the case of designing of the lightweight and slender footbridges made of steel characterised by low damping coefficient [6].

In the paper the detailed characteristics of structural solutions of the selected medium span arch footbridges and the basic dynamic parameters of the structures, determined on the base of the in-situ dynamic tests, have been presented.

2. SELECTED EXAMPLES OF THE ARCH FOOTBRIDGES

2.1. Footbridge in Wola Wieruszycka, Poland [7]

The footbridge superstructure consists of two steel arches with a tie rod and concrete deck made of precast concrete plates. The footbridge span is 63.0 m. The structure is located in the rural area exploited mainly for agricultural purposes.

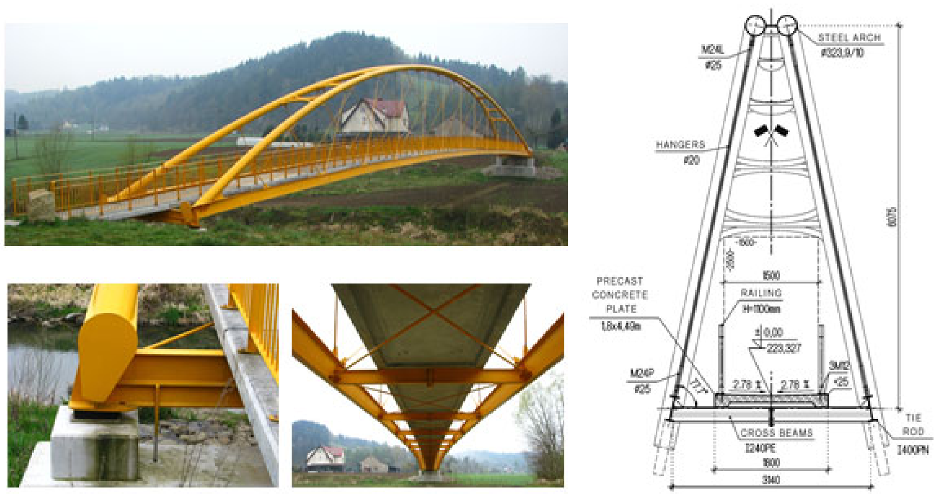

Fig. 1. *Arch footbridge in Wola Wieruszycka, Poland (Engineering Studio Project s.c.).*

Arches are designed with bent tubes Ø323.9x10 mm of steel S355J2 and are inclined inwardly toward the longitudinal axis of the bridge at an angle of 77.7°. The arches are transversally connected by set of steel bracings. The radius of the arches is 73.76 m. The tie rods of the arches are designed with hot-rolled beams IPN 400 and connected with transverse beams IPE240 spaced every 4.5 m.

The footbridge deck, designed in a vertical arch of radius 800.0 m, is created by precast concrete slabs with dimensions of 1.8 x 4.5 m and thickness 12 - 20 cm made of concrete C35/45. The precast concrete slabs are connected with steel transverse beams by means of metric screws M12 placed in plates corners. The deck is suspended to steel arches by means of steel bars made of steel S355J2H forming a network suspension system. Designed suspension system as well as the inclination and transverse connection of main steel arches has a positive effect on the distribution of internal forces, spatial rigidity and the aesthetics of the footbridge.

The footbridge is supported on the both ends of the span by means of elastomeric bearings and additionally anchored in abutments, also on the both ends of the span, with the aid of slender steel rods welded to the transverse beam placed on the end of the span (Fig. 1).

2.2. Footbridge in Węgierska Górka, Poland [8]

The footbridge superstructure is formed by two steel circular arches made of bent tubes Ø406.4/10 mm and filled with concrete C40/50 and steel and wooden deck suspended to the arches by means of ribbed steel bars Ø32 made of steel BSt500 *EPSTAL*. The span of the arches is 46.5 m, the rise of the arches is 10.6 m, the arches radius is 31.2 m and the span of the footbridge deck is 51.3 m. The footbridge was built in 2010.

Fig. 2. *Arch footbridge in Węgierska Górka, Poland (Wiewióra & Golczyk Architects s.c.).*

The arches are inclined inwardly toward the longitudinal axis of the bridge at an angle of 74.5º and transversally connected by means of bracings made of steel tubes Ø406.4/10 mm spaced every 5.5 m and by means of steel plate 10 mm thick placed at the key of the arches.

The footbridge deck is designed in a vertical arch with a radius of 451.0 m and is made in the form of a steel grillage with hot-rolled sections. The steel grillage consist of: two edge beams IPE 300, two stringers IPE 240, central stringer with box-section 2xC240 and cross beams C200 spaced every 2.75 m. On the steel grillage the wooden deck made of exotic wood Bongossi is placed. Usable width of the footbridge deck is 3.00 m. The steel grillage is placed on the transverse beams made of two channel sections C300, spaced at 5.50 m, connected to them and suspended to the arches.

2.3. Footbridge in Bieruń Stary, Poland [9]

The footbridge was built in 2006. Its appearance is unique and aesthetic. Because of location of the structure in the region of mining excavations the footbridge superstructure consist of two partially independent parts connected by means of hinges. The hinges are located over the intermediate support. One part of footbridge superstructure is designed as a spatial truss. Second part of superstructure, over a local road is formed as an arch with suspended deck. The footbridge spans lengths are 26.0 + 24.0 m.

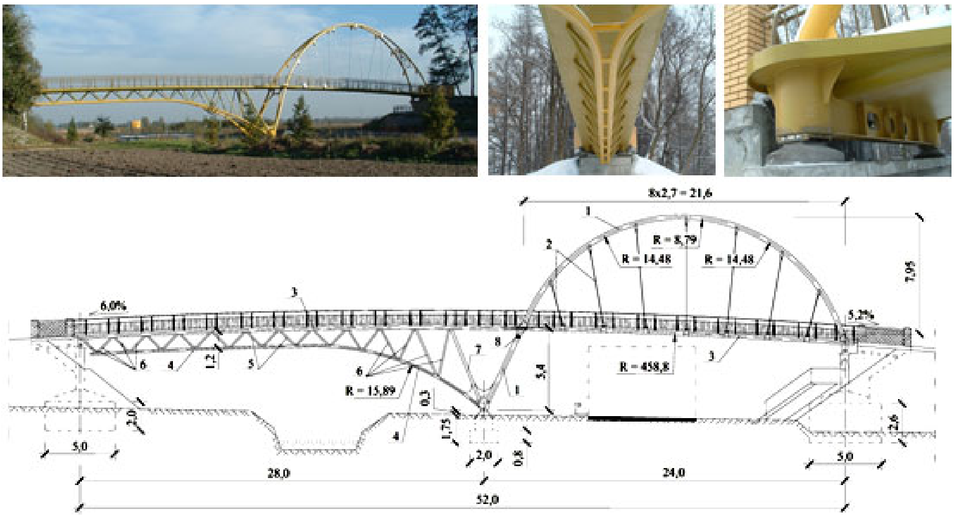

Fig. 3. Arch footbridge in Bieruń Stary, Poland (Engineering Studio Project s.c.): 1 – steel tube Ø244.5/8 mm; 2 – steel bar Ø30 mm; 3 – steel box-girder filled with concrete (steel plate 6 mm thick); 4 – steel tube Ø193.7/14.2 mm; 5 – steel tube Ø101.6/7.1 mm; 6 – steel tube Ø108.0/8.0 mm; 7 – steel tube Ø168.3/12.5 mm; 8 – hinged connection constructed using elastomeric bearing placed in steel tubes.

The footbridge superstructure is designed with the use of steel tubes as shown in Fig. 3. The footbridge deck is designed in form of a steel box-girder filled with concrete. The height of the box-girder vary from 160 mm in the middle of the deck to 245 mm at the outer edge. In the deck a transverse slope 2% toward the middle of the deck is designed. In the arched part of the footbridge the footbridge deck is suspended to the arch by means of steel bars Ø30 mm.

2.4. Footbridge in Łapanów, Poland [10]

The footbridge was built in 2010. It is a multi span structure with spans lengths 7.5 + 45.0 + 7.2 + 2 x 10.0 + 3.0 m. Total length of the footbridge is 82.7 m. The footbridge is designed as a steel structure with wooden deck.

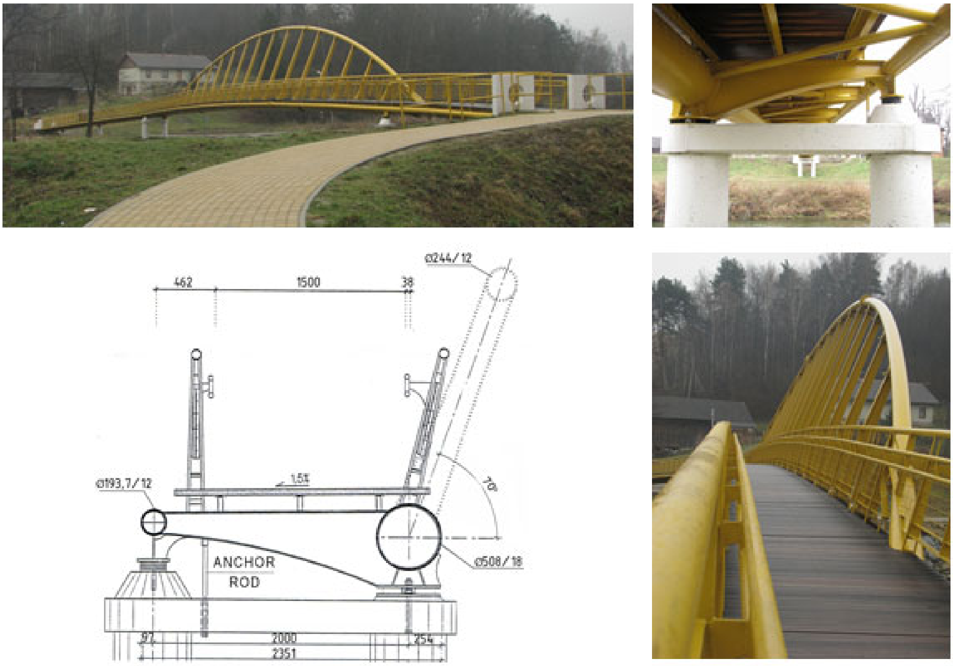

Fig. 4. *Arch footbridge in Łapanów, Poland (Engineering Studio Project s.c.).*

The footbridge deck, designed in the region of main span in a vertical arch of radius 455.0 m, is constructed with: steel tube Ø508/20 mm (forming the tie-rod of the arch), steel tube Ø193.7/16 mm placed on the second edge of the deck, transverse beams with variable height 100 – 200 mm designed as a T-section and with additional angle section 75x75x7 mm welded on to bottom chord of T-section, stringers made of Z-bars 120x60x4 mm, and horizontal bracings with steel tubes Ø76.1/6.3 mm constructed in a form of Warren-type truss.

Within the main span steel grillage of the deck is strengthened by the arch made of steel tube Ø244.5/12.5 mm inclined at an angle of 30º from vertical. The radius and the rise of the arch are respectively 45.0 m and 6.0 m.

The main span of the footbridge is supported on the intermediate pillars by means of elastomeric bearing and anchored in the pillars on the both end of the span by means of steel anchor rods (Fig. 4).

2.5. Footbridge in Cieszyn, Poland-Czech Republic border crossing [11]

The footbridge crossing the border river Olza in Cieszyn. It was built in 2012 during the modernization of recreation area Adam Sikora SportPark in Cieszyn founded by A. Sikora in 1909. The footbridge called “SportMost” is a four span structure with spans lengths 17.0 + 45.0 + 18.0 + 13.0 m. Total length of the footbridge is 93.0 m.

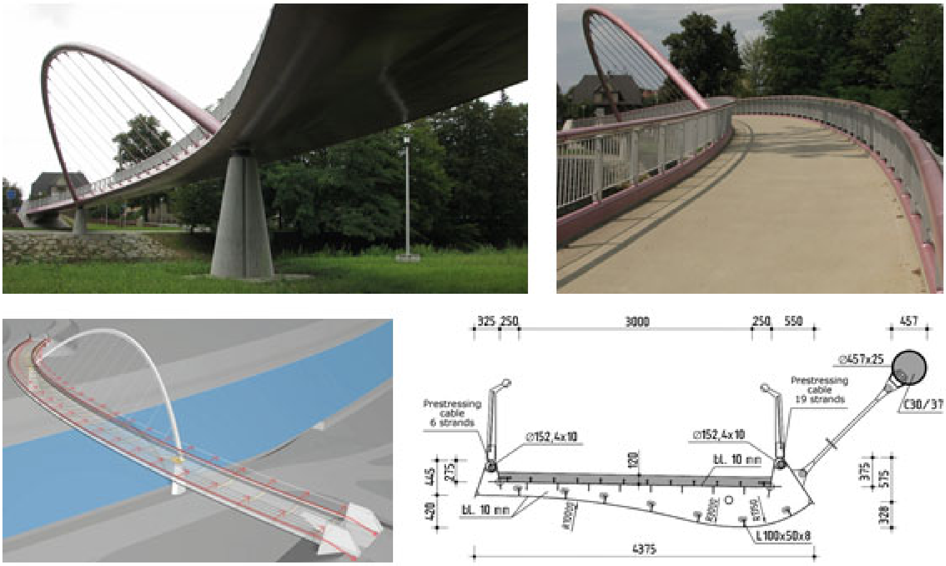

Fig. 5. *Arch footbridge in Cieszyn, Poland-Czech Republic border crossing (SHP s r.o.).*

Within the main span the footbridge deck is suspended to parabolic arch made of steel tube Ø457x25 mm filled with concrete C30/37. The arch is inclined at an angle of 30º from vertical. The hangers made of steel bars Ø40 mm are inclined at an angle 45º and spaced every 3.0 m.

The footbridge deck is designed as a steel box-girder made of orthotropic steel plates of 10 mm thick. The curved bottom plate of the box-girder is strengthened (stiffened) by longitudinal stiffening ribs with angle section L10x50x8 mm. The thickness of the bottom plate of the box-girder near the support is increased to 16 mm and 35 mm directly above the supporting points. The arch is connected with the box-girder and supported on the pillars by means of the conical steel blocks welded to the arch at both ends. The upper plate of the box-girder is stiffened by stiffening ribs made of flat steel bars 90x6 mm and connected with reinforced concrete plate 120 mm thick (Fig. 5). Within the steel box-girder the steel diaphragms with steel plate 10 mm thick, spaced every 3.0 m are designed.

The footbridge deck is curvet vertically and horizontally. At both ends the box-girder is fixed in concrete abutments. On the intermediate pillars is supported by means of elastomeric bearings. The footbridge deck is post-tensioned by prestressing cables placed at the side edges of the box-girder in guideways made of steel tubes Ø152.4x10 mm (Fig. 5). The prestressing cables are anchored in the footbridge abutments. Curved prestressing cables together with inclined hangers generate a set of forces balancing a torsion of the footbridge deck caused by the deadweight.

2.6. Footbridge E. Pittera in Ceske Budejovice, Czech Republic [12]

The footbridge was build in 2006. It is designed as a one-side inclined arch footbridge with composite deck and span length 53.2 m.

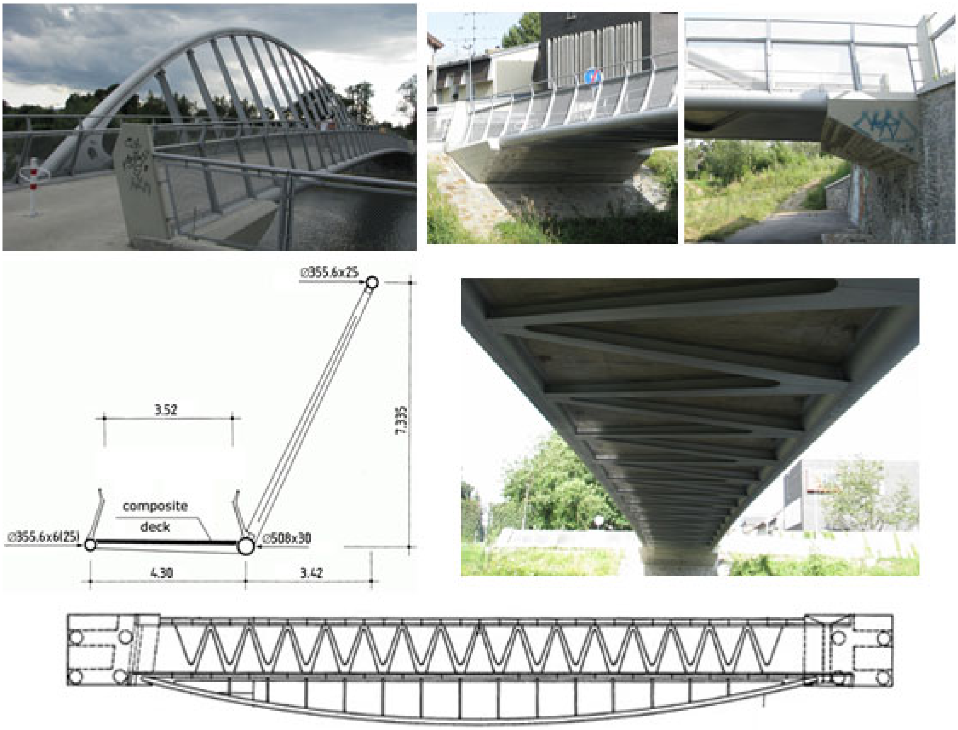

Fig. 6. *Arch footbridge in Ceske Budejovice, Czech Republic (SHP s r.o.).*

The footbridge deck consists of the reinforced concrete plate and steel grillage constructed with: steel tube Ø508x30 mm (forming the tie-rod of the arch), steel tube Ø355.6x6 (25) mm (placed on the second edge of the deck) and transverse beams in a form of Warren-type truss. At both ends of the span, in the region of abutments, the transverse beams are replaced by steel orthotropic plates connected with concrete plate by Nelson headed shear connectors. The footbridge deck is fixed at both ends in concrete abutments.

The side arch of the footbridge is designed with steel tube Ø355.6x25 mm and connected with the tie-rod made of steel tube Ø508x30 mm. The arch is inclined at an angle of 25° from vertical. The inclination of the arch and the weight of the deck is designed so as to avoid torsioning of the deck under the action of the deadweight.

3. DYNAMIC CHARACTERISTICS OF THE FOOTBRIDGES

Dynamic characteristics of the above footbridges were determined during is-situ tests of the structures. Parameters most important from the point of view of dynamic analysis of forced vibrations of the footbridges and evaluation of the dynamic susceptibility and comfort of use of the footbridges during vibration induced by the users are given in Tab. 1. The vibration accelerations of the footbridges decks were obtained during the footbridge dynamic resonant excitations by one person (the weight of 800 N) in the form of walking, running and jumping.

Table 1. *The basic dynamic characteristics of investigated footbridges.*

Footbridge	Main span length [m]	Frequency [Hz]	Type of vibration	Damping *Δ* [%]*	Vibration accelerations [m/s²] (excited by one person 800N)		
					Walking	Running	Jumping
Wola Wieruszycka	63.0	2.68	vertical	3.6-4.8	-	0.52	0.90
Węgierska Górka	46.5	2.62	vertical	2.6-3.7	-	1.50	2.51
Bieruń Stary	28.0+24.0	3.10	vertical	6.6-7.5	-	0.43	0.96
Łapanów	45.0	2.14	vertical	4.4-5.8	1.05	1.20	1.38
		2.64	torsional	4.9-5.9	-	1.11	1.35
Cieszyn	45,0	2.85	vertical	2.4-3.5	-	0.78	0.92
Ceske Budejovice	53.2	1.88	vertical	1.6-2.0	0.097	0.16	0.21
		2.44	torsional	4.3-5.2	-	0.37	0.41

* *Δ* – logarithmic decrement

Natural frequencies of the footbridges are in the range of 1.80 - 3.10 Hz. The mode shapes of the footbridge deck are mostly vertical and torsional. During the tests there were no horizontal mode shapes of the footbridge deck (transverse to the axis of the footbridge). In most cases, the natural frequency of the footbridges were beyond the range of the frequency of dynamic impacts of the users in the form of walking at a normal pace (1.7-2.2 Hz). The frequencies are situated in range of the frequency of dynamic impacts during running in a slow and normal pace (1.9 - 2.7 Hz). The dynamic impact in the form of walking can cause the resonant vibration only in two cases of footbridge in Łapanów and footbridge in Ceske Budejovice. The resonant vertical vibrations for the footbridge in Ceske Budejovice are ten times smaller than for the footbridge in Łapanów. It is most probably caused by higher speed of walking (higher vibration frequency of the footbridge) in case of the footbridge in Łapanów lying in the range of frequency of slow running and by the smaller mass of the deck of the footbridge in Łapanów. The occurrence of natural frequencies of the footbridges within the range of frequencies of running can disturb of the comfort of use of the structures especially in the case of the footbridges located in the recreation and leisure areas. In these cases the vibrations of the footbridge deck exciding the value of 0.25 m/s^2 will be clearly felt by people standing still (stopped and resting) on the deck.

In cases in which the levels of vibration acceleration of the footbridge deck, caused by running user, did not exceed the limit of acceptable acceleration a_{acc} = 0.5 m/s^2 the maximum comfort of use of the footbridge in everyday conditions of use is ensured. In cases in which the levels of vibration acceleration of the footbridge deck exceed the value of $a_{acc,r}$ = 1,0 m/s^2 the vibration disturb the comfort of use of the footbridge but they are allowed provided their rare occurrence (minimum comfort of use of the footbridge).

In the case of increasing of the number of pedestrians exciting the footbridge vibrations (2-3 pedestrians synchronized with the frequency of vibrations of a footbridge or a crowd of pedestrians partially synchronized with the frequency of vibrations of the footbridge) the level of acceptable acceleration a_{acc} will be exceeded in all analysed cases.

4. CONCLUSION

The results of the research presented in the paper create the database about the basic dynamic parameters of the arch footbridges useful to perform a preliminary assessment of the dynamic parameters of a newly designed footbridges of similar structural systems.

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