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Original Research Article

EVALUATION OF DYNAMIC CHARACTERISTICS OF THE FOOTBRIDGE WITH INTEGRAL ABUTMENTS

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Abstract

The paper presents the results of dynamic field tests and numerical analysis of the footbridge designed as a three-span composite structure with integral abutments. The adopted design solution which has allowed to achieve a high resistance of the structure to dynamic loads and to meet the requirements of the criteria of comfort of use with a large reserve has been characterized. For comparative purposes, numerical analyzes of three construction variants of the footbridge were presented: *F-1* - construction with integral abutments (realized variant), *F-2* - construction with girders anchored in the abutments by means of tension rocker bearings, *F-3* - construction with concrete side spans.

Keywords: dynamics, vibration, footbridges, integral abutments bridges, comfort of use

1. STRUCTURAL CHARACTERISTIC OF THE FOOTBRIDGE

The footbridge is located over the E77 dual carriageway in Mogilany near Krakow (direction Kraków-Zakopane). It was designed as a composite steel-concrete, three span structure with spans of 7.0 + 30.0 + 7.0 = 44.0 m (Fig. 1) supported on intermediate pillars by means of an unidirectional sliding pot bearings. Steel girders and concrete deck are integrated with reinforced concrete abutments made in the form of reinforced concrete blocks C30/37 founded directly on the excavation slopes (without foundation piles) (Fig. 1 and 3).

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The cross-section of the footbridge (Fig. 2 and 3) consists of reinforced concrete slab and two 830 mm height steel plate girders (bottom flange 400x40 mm, top flange 400x20 mm, web 770x14 mm) placed in axial spacing 1400 mm. Main girders are transversely connected by means of steel beams HEB300 located above the intermediate supports and in the middle of the main span.

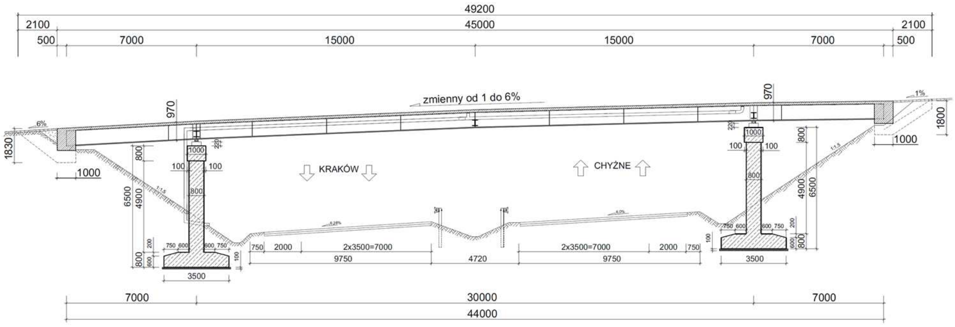


Fig. 1. Longitudinal section of the footbridge in Mogilany

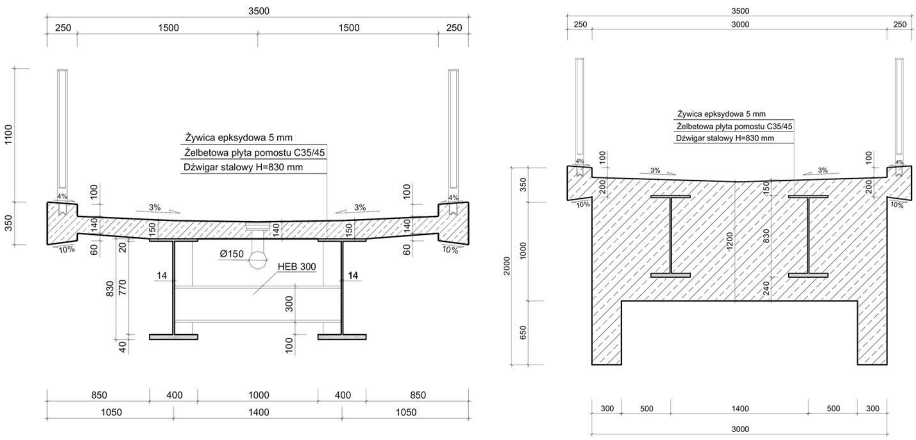


Fig. 2. Cross sections of the footbridge a) mid-span, b) near the abutments

The web plate of the plate girders were stiffened with transverse ribs a thickness of 14 mm (double-sided ribs placed over the supports and single-sided ribs placed along the main span). Steel structure was made of S355J2 steel.

The footbridge deck was designed as a reinforced concrete plate, 140 mm thick, made of C35/45 concrete and covered by pavement made of epoxy resin with mineral filler. The plate was connected with steel girders using stud shear connectors.

Fig. 3. General view of the footbridge and selected details

2. DYNAMIC FIELD TESTS AND NUMERICAL ANALYSES OF THE FOOTBRIDGE

2.1. Field tests

In order to identify the basic dynamic characteristics and assess the dynamic susceptibility of the footbridge to dynamic force generated by users during walking, running and jumping the field dynamic tests of the footbridges were carried out.

During the tests five mode shapes of the footbridge were identified: f_1 = 4.39 Hz - vertical vibration (one extreme), f_2 = 4.88 Hz - torsional vibration (one extremum), f_3 = 6.91 Hz - transversely-torsional vibration (one extremum), f_4 = 11.00 Hz - torsional vibration (two extrema), f_5 = 11.55 Hz - vertical vibration (two extrema). It should be noted that identified natural frequencies of the footbridge achieve values that extend beyond the range of frequencies of the dynamic loads generated by users during the various forms of their activity (walking, running, jumping) which are situated within the ranges:

1.40 - 3.40 Hz - vertical loads and 0.70 - 1.20 Hz - horizontal loads. This feature effectively reduces the risk of the resonance vibration of the structure. The adopted design solution has contributed to achieving the proper dynamic characteristics of the structures as well as a high resistance of the object to dynamic influences.

In order to check the vibration levels of the footbridge, characterized by favorable dynamic parameters, the forced vibrations tests of the footbridge were carried out including dynamic excitations in the form of: 1) free walking, 2) walking, running, jumping with frequency $0.5f_1$ = 2.19 Hz and 3) excitation of the resonance vibrations by running and jumping persons with frequency f_1 = 4.39 Hz.

The maximum values of the vertical vibration of the footbridge obtained during vibration excitation by one person (weight 86 kg) and two persons (weight 86 kg and 113 kg) are shown in Tab. 1.

Table 1. The maximum values of the vertical vibration of the footbridge and values of logarithmic decrement Δ for different cases of dynamic loads (results of the field tests)

A method of vibration excitation (A form of user activity)		a_{max} *	Δ **
		[m/s^2]	[%]
Free walking	1 - 3 persons	0.02 - 0.04	-
Walking with frequency 2.19 Hz (0.5 f_1)	1 person	0.17	2.4 - 2.9
	2 persons	0.25	
Slow running with frequency 2.19 Hz (0.5 f_1)	1 person	0.28	2.6 - 3.2
	2 persons	0.46	
Jumping with frequency 2.19 Hz (0.5 f_1)	1 person	1.12	4.3 - 4.7
	2 persons	1.28	4.4 - 4.9
Fast running with frequency f_1 = 4.39 Hz	1 person	0.95	3.2 - 3.6
	2 persons	1.56	3.4 - 3.7
Jumping with frequency f_1 = 4.39 Hz	1 person	1.83	4.3 - 4.8
	2 persons	2.83	4.7 - 5.4

* a_{max} - maximum value of vibration acceleration

** Δ - logarithmic decrement

Additionally, in Tab. 1 the values of the logarithmic decrement Δ, determined from the free vibration waveforms recorded during field tests are shown. It can be seen that the values of Δ depend on a method of vibration excitation (a form of user activity) and are within the range Δ = 2.4 - 5.4 %.

Analysis of the results of the field tests shows that the vibration acceleration induced during free walking achieves very small values (a_{max} = 0.04m/s^2), which can be considered as imperceptible for footbridge users. Value of permissible/accepted acceleration of vertical vibrations (a_{acc} = 0.7 - 1.0 m/s^2 [1, 2, 3]) were exceeded only in cases of intentional excitation of resonance vibration of the footbridge. However, it should be emphasized that due to the high vibration frequencies of the first form of vibration (f_1 = 4.39 Hz > 3.5 Hz) cases of intentional vibration excitation has a low probability of occurrence during the footbridge exploitation (vibration with a frequency f > 3.5 Hz exceed the frequency range of dynamic loads generated by people and are difficult to excite in the absence of pulses measuring the correct rhythm of steps, e.g. metronome beeps, etc.).

2.2. Numerical analyses

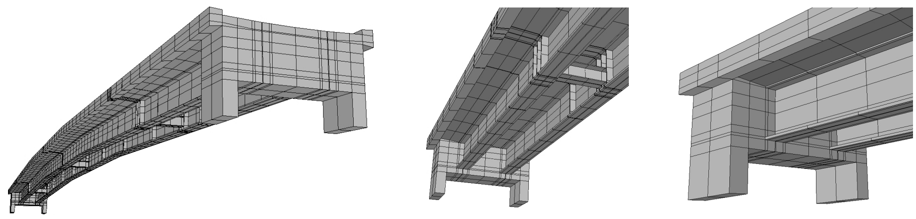
Numerical dynamic analyses of the footbridge were realized using a spatial FEM solid computational model constructed of three-dimensional elements (solid elements) in three-dimensional space (Fig. 4). Dimensions of elements in the computational model were taken according to the actual geometry of the components in compliance with the detailed design of the footbridge.
In order to take into account occurrence of two steel railings (2x40kg/m) and epoxy resin in the footbridge deck the increased value of the volumetric weight of the reinforced concrete plate γ_m = 27.0 kN/m^3 was assumed in analyses.
To examine the influence of the adopted structural solution (girders integrated with reinforced concrete abutments cooperating with the soil) on the natural vibration frequencies of the structure and to check the dynamic characteristics of the alternative design solutions of the footbridge, numerical analyzes of the three variants of the computational model were performed:

- *F-1* - computational model with integral abutments elastically connected with the surrounding soil by means of spring supports (realized variant),
- *F-2* - computational model with main girders fixed in the abutments by means of tension rocker bearings that provide freedom of the longitudinal movement of the girders and securing the girders against breaking away from the abutments,
- *F-3* - computational model with concrete side short spans made by filling the space between steel girders with a massive reinforced concrete slab with a height equal to the height of steel girders. Girders supported on the abutments by means of pot or elastomeric bearings.

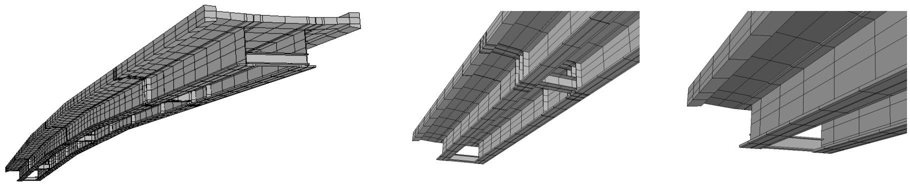
Collaboration of the abutments with the surrounding ground in the *F-1* model was modeled by means of spring supports with the following coefficients of elasticity $s_{xg} = s_{yg}$ = 450.00 MN/m, s_{zg} = 250.00 MN/m (*x, y* - longitudinal and transverse axes respectively, *z* - vertical axis). Within both abutments 195 elastic joints were modeled. Each of the springs were modeled by springs supports with the coefficient of elasticity equal respectively: $s_{xg1} = s_{yg1}$ = 450/195 = 2.308 MN/m (235.0 t/m) and s_{zg} = 1.282 MN/m (131.0 t/m).
At the intermediate supports the unidirectional sliding bearings (two pot bearings on each support) were modeled assuming full freedom of longitudinal displacement (in the direction parallel to the longitudinal axis of the

bridge – x axis) and full freedom of rotation in all directions. In transverse and vertical direction (y and z axes respectively) elastic joints with coefficient of elasticity equal s_y = 193.2 MN/m, s_z = 624.0 MN/m were introduced. Each of the bearings were modelled by 12 elastic elements with coefficient of elasticity respectively s_{y1} = 16.1 MN/m, s_{z1} = 62.0 MN/m.

a)



b)



c)

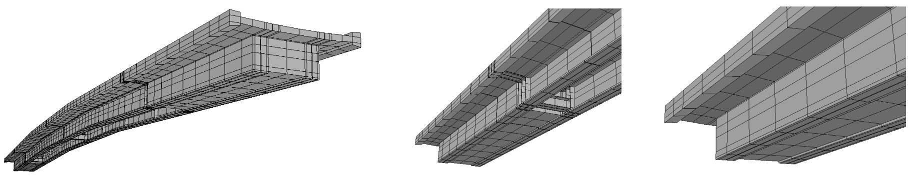


Fig. 4. Variants of computational models: a) *F-1* - model with integral abutments, b) *F-2* - model with tension rocker bearings, c) F-3 - model with concrete side spans

In computational models *F-1* and *F-2* parameters of the supports points over abutments and pillars were modified. Over the both abutments and one pillar, unidirectional roller support were modeled with full freedom of displacement in the direction parallel to the longitudinal footbridge axis, the elastic connections of the girders with the supports in the transverse direction were left the same as in the model *F-1* (coefficient of elasticity s_y = 193.2 MN/m) and the freedom of vertical movements of the girders (possibility of breaking away the girders from the abutment) was blocked. On the second pillar, one pinned support with blocked freedom of displacement in all directions and one roller support with freedom of displacement in the lateral direction y and blocked freedom of displacement in the x and z directions were modeled.

In Fig. 5 the mode shapes and natural vibration frequencies of the footbridge were presented. It should be noted that the modifications of the parameters of the computational models did not change the mode shapes of the analyzed construction variants of the footbridge. Only the vibration frequencies of the analyzed construction variants have changed. The values of the vibration frequencies of the construction variants are shown in Tab. 2.

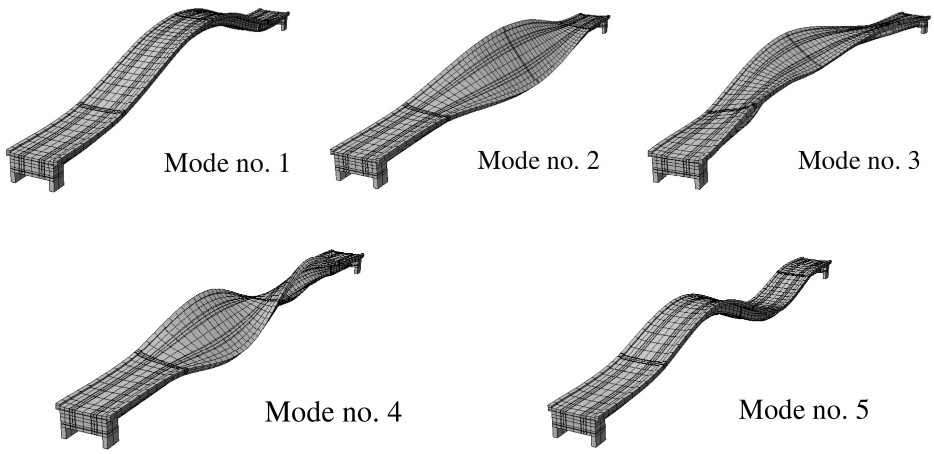


Fig. 5. The mode shapes of the footbridge

Table 2. The natural vibration frequencies of the various construction variants of the footbridge (result of the field tests and numerical analyses)

Mode shape	Vibration frequency [Hz]				Description
	Field tests	*F-1*	*F-2*	*F-3*	
1	4.39	4.39	4.41	4.75	Vertical vibration
2	4.88	4.89	5.36	5.65	Tortional vibration
3	6.99	6.93	7.51	8.55	Transverse vibration
4	11.00	11.37	11.90	12.52	Tortional vibration
5	11.55	11.90	11.97	12.56	Vertical vibration

Additionally, for illustrative purposes, the frequencies of the first mode shape for *F-1*, *F-2*, *F-3* models were calculated, assuming the total lack of connection/cooperation of the integral abutments with the surrounding ground in the *F-1* model, and allowing to break away the girders from the abutments in the *F-2* and *F-3* models. The natural vibration frequencies of the first mode shape of the modified models were respectively: $f_{1W1} = 2.14$ Hz, $f_{1W2} = 2.41$ Hz, $f_{1W3} = 2.13$ Hz. This illustrates the advantages resulting from the structural solutions adopted in the *F-1*, *F-2* and *F-3* variant structures leading to increasing their vibration frequencies ($f_1 > 4.0$ Hz) and thus reducing the risk of excitation of the resonance vibrations of the structures by users.

3. SUMMARY

The paper presents the results of the dynamic field tests and numerical analysis of the footbridge characterized by high resistance to vibration excitation. The basic dynamic parameters of the footbridge have been identified and the advantages resulting from adopted structural solutions have been presented. Due to high value of fundamental vibration frequency leading to reduction of the risk of excitation of the resonance vibration of the structure the maximum comfort of use of the structure was achieved.
For comparative purposes, analyses of the variant construction solutions of the footbridge were performed. It has been shown that the analyzed design variants have a high basic natural frequency what consequently favorably reduce the risk of excitation of the resonance vibration of the structure during its operation.

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OCENA PARAMETRÓW DYNAMICZNYCH ZESPOLONEJ KŁADKI DLA PIESZYCH Z PRZYCZÓŁKAMI ZINTEGROWANYMI

Streszczenie

W referacie przedstawiono wyniki dynamicznych badań terenowych i analiz numerycznych kładki dla pieszych zaprojektowanej jako trójprzęsłowa konstrukcja zespolona z przyczółkami zintegrowanymi. Scharakteryzowano przyjęte rozwiązanie konstrukcyjne oraz metodykę numerycznych analiz dynamicznych kładki. Zaprezentowano wyniki analiz numerycznych trzech wariantów konstrukcyjnych obiektu (*F-1* - konstrukcja z przyczółkami zintegrowanymi (wariant zrealizowany), *F-2* - konstrukcja z dźwigarami zamocowanymi w przyczółkach za pomocą łożysk wahaczowych, *F-3* - konstrukcja z betonowymi przęsłami bocznymi).

Słowa kluczowe: drgania, kładki dla pieszych, mosty zintegrowane, komfort użytkowania

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