DYNAMIC BEHAVIOUR OF THE ARCH FOOTBRIDGE IN WLOCLAWEK DURING HUMAN-INDUCED VIBRATIONS

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SUMMARY

In the paper the dynamic behaviour and dynamic characteristic of the steel arch footbridge over Zgłowiączka river in Włocławek have been presented. The results were obtained during dynamic in-situ tests of the footbridge. The vibrations during the tests were induced by users in different form of activity. On the basis of the tests the evaluation of the comfort of use of the footbridge were carried out and presented.

Keywords: *Footbridge, vibration, dynamic, comfort of use.*

1. STRUCTURAL CHARACTERISTIC OF THE FOOTBRIDGE [1]

The footbridge is a single span steel arch footbridge with span of 40.0 m and two inclined steel arches (Fig. 1, 2). The main circular arches are inclined outwardly at an angle of 30.5º from vertical and made of a cold-formed steel tubes Ø406.4x30 mm – parts of arches over the footbridge deck and steel tubes Ø457.4x30 mm parts of arches under the footbridge deck. The arches are transversally connected at the top by means of steel rods Ø20 mm with turnbuckles enabling to stretch the transverse rods.

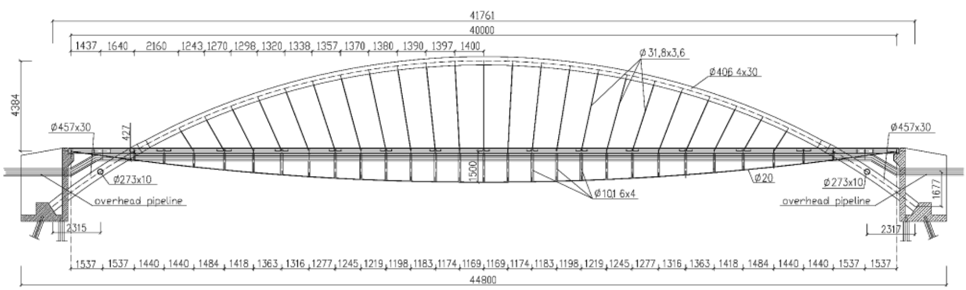


***Fig. 1.** Longitudinal section of the arch footbridge over Zgłowiączka river in Włocławek, Poland (MCS Modern Construction Systems Ltd.) [1].*

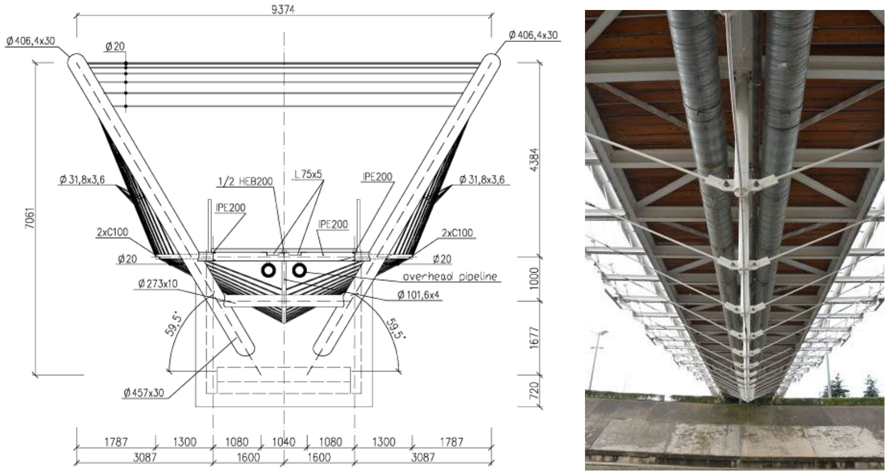


Fig. 2. *Cross section and the steel grillage of the deck of the arch footbridge over Zgłowiączka river in Włocławek, Poland (MCS Modern Construction Systems Ltd.) [1].*

Fig. 3. *General view of the arch footbridge over Zgłowiączka river in Włocławek, Poland.*

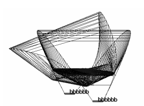
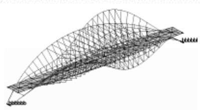
The rise of the arches is 8.25 m, the arches radius is 30.0 m, the span of the arches is 41.76 m. The arches are rigidly connected with stringers IPE 200 placed on both edges of the deck forming the tie-rod of the arches.

The footbridge deck is designed as a steel grillage formed with hot-rolled sections and stiffened by means of spatial web of steel rods. The spatial form of the footbridge deck is very complex (Fig 1, 2, 3). Steel grillage is formed with two stringers IPE 200 placed on both edges of the deck, central stringer 1/2 HEB 200, cross beams IPE 200 spaced irregularly (Fig. 1) and supported in the middle of the span by means of steel tube Ø101.6x4 mm with variable height. The bottom end of the supporting tube Ø101.6x4 mm is connected by means of steel rods Ø20 mm with steel cantilevers variable length of 406 – 1300 mm made of 2xC100 sections. The steel rods can be tensioned by means of turnbuckles placed along its axis. The steel cantilevers are placed in the upper part of the deck on the both sides of the cross beams and form the extensions of the cross beams (Fig. 2). The cross beams are also connected by mean of horizontal braces made of IPE 200 mm in the first two fields on both ends of the deck and angle section L 75x75x5 mm used in the remaining fields on the span length (in central part of the span). The deck is suspended to the main arches by means of steel tubes Ø31.8x3.6 mm with turnbuckles at the lower end of the hangers enabling to stretch the hangers.

2. DYNAMIC CHARACTERISTICS OF THE FOOTBRIDGE [1, 2]

Fundamental dynamic characteristic of the footbridge (mode shapes and natural frequencies) were established by designer using numerical 3D model of the footbridge and verified during the in-situ dynamic tests of the structure [1, 2]. Obtained results are presented in Tab. 1.

Table 1. *Results of dynamic analysis and in-situ dynamic tests of the footbridge [1, 2].*

Mode shape	**Frequency [Hz]** (3D model)	**Frequency [Hz]** (in-situ tests)	**Remarks**
	1.55	–	Transverse vibrations of the arches. Slight torsional vibration of the deck
	2.64	2.44	Asymmetric vertical vibration of the deck
	3.77	3.66	Asymmetric torsional vibration of the deck
	5.79	5.00	Symmetric vertical vibration of the deck

During the in-situ tests, particular attention was paid to identification of the mode shapes and natural frequencies of the footbridge in frequency range corresponding to frequencies of dynamic action of the footbridge users during walking, running and jumping (1.40 – 3.40 Hz).

From the perspective of evaluation of the comfort of use of the footbridge the most important is the mode shape with natural frequency identified as 2.44 Hz (asymmetric vertical vibration of the footbridge deck). This frequency is in the frequencies range corresponding to the frequency of running with normal speed 2.2 – 2.7 Hz (jogging).

3. DYNAMIC IN-SITU TESTS OF THE FOOTBRIDGE [2]

The program of the footbridge in-situ dynamic tests was developed taking into account the dynamic loads of daily nature (walking - for three moving speed: slow, normal, fast and free running), marching and running of a group of people synchronized with the natural frequency of the footbridge, and the dynamic loads in the form of synchronous jumping and squats in the largest amplitudes of the mode shape.

The research program included: identification of the natural frequency and mode shapes of the footbridge (Stage I), assessment of the identified mode shapes in terms of the probability of excitation of resonant vibrations by users (Stage II), recording of the forced vibration of the footbridge deck induced during various form of users activity (Stage III).

In the Stage III the excitation of the footbridge vibrations were realized in the form of:

- free walking of 1, 2 and 5 users for three moving speed: slow, normal, fast,
- free walking of 10 users,
- walking of 1, 3 and 5 users synchronized with the natural frequency of the footbridge,
- free running of 1, 2, 3 and 5 users,
- running of 1, 2 and 3 users synchronized with the natural frequency of the footbridge,
- jumping and squats of 1, 2 and 3 users synchronized with the natural frequency of the footbridge.

Additional information about the procedures of dynamic testing of the footbridges can be found in [3].

During the in-situ tests the two data acquisition systems were used: PULSE Brüel&Kjær with single-axis accelerometers DeltaTron 4507 B (±7g, 0.4 Hz – 6 kHz) and APEK AV32AKP with two-axis accelerometers MA24 (±2g, 0.4 Hz – 6 kHz). The locations of the measurement points are shown in Fig. 4.

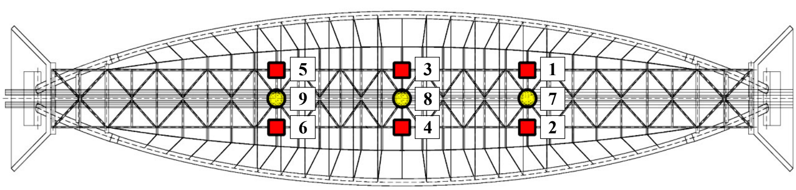


Fig. 4. *Locations of the measurement points.*

Values of the maximum vertical vibration acceleration for different types of footbridge users activity recorded in measurement points 1, 2, 7 and 5, 6, 9 are presented in Tab. 2 and Fig. 5.

Table 2. Values of the maximum acceleration of vertical vibration for different types of excitations.

Case No.	Users activity		Vibration acceleration [m/s²] Number of persons inducing vibrations 1	2	3	5	10
1	Free walking	slow	0.08	0.07	-	0.16	-
		normal	0.06	0.04	-	0.10	0.12
		fast	0.10	0.10	-	0.12	-
2	Walking synchronized with natural frequency of the footbridge 2.44 Hz		0.18	-	0.83	1.18	0.97
3	Free running		0.69	0.98	1.02	1.15	-
4	Running synchronized with natural frequency of the footbridge 2.44 Hz		0.42	0.79	1.34	-	-
5	Jumping synchronized with natural frequency of the footbridge 2.44 Hz		0.83	1.76	1.71	-	-
6	Squats synchronized with natural frequency of the footbridge 2.44 Hz		0.51	-	-	-	-

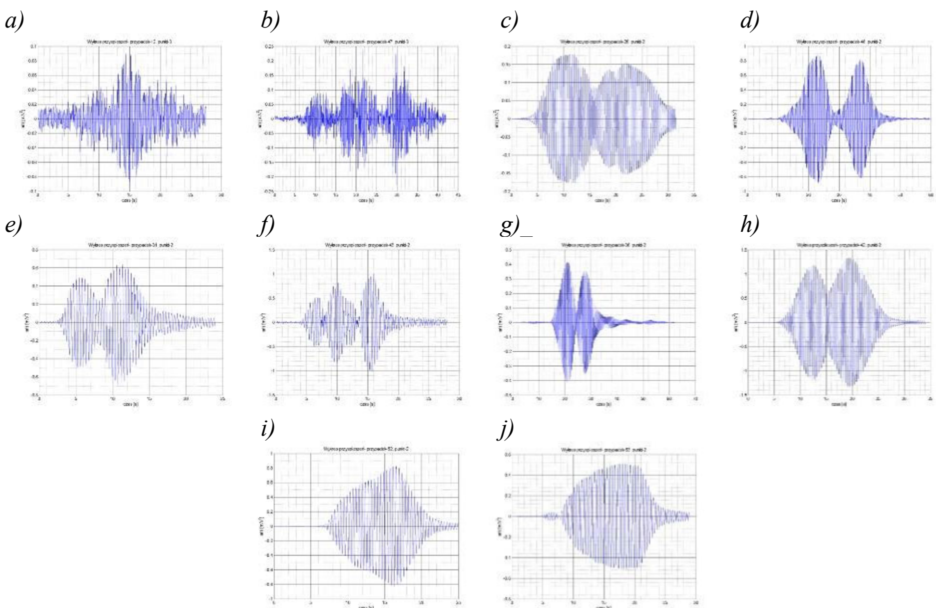


Fig. 5. *Exemplary records of the vibrations during: a) walking with normal speed - 1 user, b) walking with normal speed - 10 users, c) walking synchronized with natural frequency of the footbridge - 1 user, d) walking synchronized with natural frequency of the footbridge - 10 users, e) free running - 1 user, f) free running - 3 users, g) running synchronized with natural frequency of the footbridge - 1 user, h) running synchronized with natural frequency of the footbridge – 3 users, i) jumping synchronized with natural frequency of the footbridge - 1 user, j) squats synchronized with natural frequency of the footbridge - 1 user.*

It can be seen that vibration acceleration corresponding to slow, normal and fast walking is in the range of 0.04-0.16 m/s^2 (averaged value is about 0.10 m/s^2). These small amplitudes of vibration accelerations will not be felt by footbridge users. Comparison of vibration acceleration in cases no. 3 and 4 (free running and running synchronized with natural frequency of the footbridge) leads to the interesting conclusion. Vibration acceleration during free running (case no. 3) is greater than during running synchronized with the natural frequency of the footbridge (case no. 4). It means that probability of excitation of resonant vibration during free running is very high. In other words synchronization of running users with footbridge natural frequency 2.44 Hz is highly probable. It should also be noted that the differences between results for cases no. 3 and 4 can also be caused by lack of synchronization of the runners with natural frequency of the footbridge in case no. 4 and by lack of synchronization between runners (synchronization of the runners with footbridge natural frequency was forced by electronic metronome). In spite of this the above conclusion of high probability of synchronization of running users freely moving along the footbridge deck with natural frequency of the footbridge of 2.44 Hz is still correct. Because of the location of the footbridge in a recreation area, near the boulevards along the bank of the Vistula River, this type of dynamic load is very important for evaluation of comfort of use of the footbridge. The vibration acceleration during running is in the range of 0.4-1.34 m/s^2.

The vibration acceleration obtained in cases no. 5 and 6 during jumping and squats synchronized with natural frequency of the footbridge also reach the high values but these types of dynamic loads should be considered as a very rare vandal loads. The values of vibration acceleration reached during this type of dynamic loads should be compared with acceptable values of vibration acceleration appropriate for vandal dynamic loads that are higher than for everyday or rare events.

4. EVALUATION OF COMFORT OF USE OF THE FOOTBRIDGE

Acceptable amplitudes of vibration acceleration of any part of the footbridge deck defined in [4] (point A2.4.3.2) is 0.7 m/s^2 for vertical vibration and 0.2 m/s^2 for horizontal vibration. In additional annotation it is suggested that comfort criteria should be met with an adequate safety margin in order to avoid the need of mounting the vibration dampers on a footbridge deck.

In case of vertical vibration of the deck of the footbridge over Zgłowiączka river in Włocławek the acceptable value of acceleration is exceeded in all cases of users activity synchronized with natural frequency of the footbridge when the number of users is greater than or equal to 2. In case of activity of one person synchronized with natural frequency of the footbridge the safety margin required in order to ensure the suitable comfort of use of the footbridge is very small.

The requirement of the comfort criteria are fulfilled only in case of free walking both one person and larger group of users. In everyday conditions of use of the footbridge the comfort of use is ensured. However during walking of a group of users synchronized with natural frequency of the footbridge the vibration acceleration exceed the acceptable value. According to the comfort criteria presented in [5] in the case of vibration acceleration in the range of 0.5-1.0 m/s^2 merely a mean comfort of use of the footbridge is ensured (the vibrations will be slightly felt by footbridge users in motion and clearly felt by people standing on the footbridge deck).

In Fig. 6 the comparisons of the results of the footbridge dynamic tests with the proposals of comfort criteria characterized in [6, 7] have been presented.

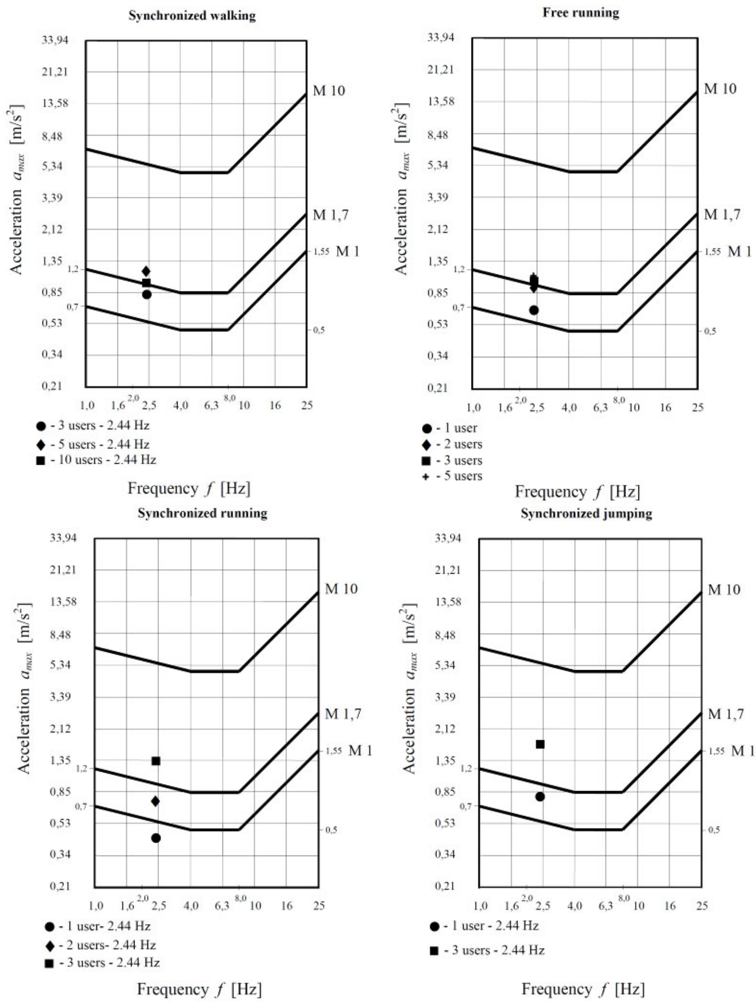


Fig. 6. *The results of the footbridge dynamic tests in relation to the comfort criteria by [6, 7]: M1 - comfort curve for everyday events i.e. vibrations occurring once a day or more frequently and not more rarely than once a week; M1.7 - comfort curve for rare events i.e. vibrations occurring more rarely than once a week; M10 – comfort curve for vandal loads i.e. vibrations caused by vandal intentional actions in a form of e.g. rhythmical jumping or squats of a single person or a group of persons etc.*

The above comparisons also indicate a disturbance of the comfort of use of the footbridge in the case of dynamic impacts in the form of users activity synchronized with natural frequency of the footbridge (especially in the form of running).

Given the above results the footbridge over the Zgłowiączka river in Włocławek must be classified as a structure with increased dynamic susceptibility.

5. CONCLUSIONS

Based upon the obtained results, following general conclusions can be formulated:

- The footbridge over Zgłowiączka river in Włocławek in situation of dynamic excitations in the form of free walking meets the requirements of maximal comfort of use with large margin of safety. Maximal levels of acceleration of vertical vibrations of the footbridge deck are much smaller than 0.5 m/s^2.
- The footbridge is characterized by increased level of dynamic susceptibility both in situations of free running, walking and running synchronized with the natural frequency of the footbridge as well as during the vandal dynamic actions. Dynamic actions of the users in the form of running can strongly impair the comfort of use of the footbridge. Due to the location of the footbridge in a recreation area a dynamic actions in the form of running can occur frequently, i.e. it can be an everyday events. It is recommended to limit the level of acceleration of vertical vibration of the footbridge deck to the value of 0.5 m/s^2, which will ensure the maximal comfort of use of the footbridge.
- In order to provide the appropriate comfort of use of the footbridge it is recommended to install the tuned mass dampers (TMD) with optimal parameters designed for asymmetrical mode shape with frequency 2.44 Hz.

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