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Section: Roads and Railways

Field load testing and structural evaluation of steel truss footbridge

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Abstract

The paper presents the main results obtained during a field load testing conducted on a recently built steel footbridge spanning the new 6 lanes of Western bypass highway in City Vilnius. The footbridge is a single span 48,8 m long and 4,0 m width structure composed of two identical steel trusses. The footbridge was subject to static and dynamic tests as well as theoretical calculations in order to perform an evaluation of the static behaviour of the new footbridge and to identify its dynamic characteristics. The results of the tests were used to validate the FE modelling. A comparison of the measured and analytical results for both static and dynamic tests is presented. Results of investigation are also compared to the provisions of LST EN standards.

Keywords: steel footbridge; field-load testing; modal characteristics; FE analysis; comfort criteria.

1. Introduction

In the last year's design of modern footbridges are focused towards greater and lighter spans having increased flexibility and sensitivity to ambient actions. Full-scale load tests along with numerical simulation allow determining the realistic bridge response to static and dynamic human induced loading and to verify the assumptions made in the design of pedestrian structures.

Footbridges are designed to ensure the safety and serviceability of structures and safety and comfort for pedestrians. During the last few decades numerous investigations have been performed [1–3] and field load testing and monitoring systems of footbridges are employed [4], [5] in order to validate design conceptions, to evaluate condition state and overall performance of structures. The problems related to serviceability failures and sometimes to ultimate limit states of pedestrian bridges are reported in the literature [5–8].

Lithuanian standards LST EN 1991-2 [9] and LST-EN 1990 [10] which are based on Eurocodes provisions present the recommendations in terms of resonant frequencies and acceptable accelerations based on the response for a single pedestrian only. Although, the models for human-induced dynamic loading for different traffic scenarios as well as limiting values of footbridge vibrations are still under development.

The aim of this investigation was to establish more realistic understanding of the behaviour of steel truss footbridge. Static and dynamic loading as well as FE modeling was performed. The main results of this investigation are presented in the paper.

2. Truss steel footbridge

2.1. Description of the structure

The bridge under consideration is a part of Vilnius Western bypass and was constructed in 2013. A superstructure shown in Fig. 1 is widely used in Lithuanian roads and railways. Two main steel trusses of a rectangular configuration is 48,8 m long and 4,0 m width. At the ends of the span the superstructure is supported by elastomeric bearings based on reinforced concrete abutments and corresponds to simply supported beam. The depth-to-span ratio of truss span is 1/7–1/8. The typical cross-sections of footbridge generally consist of tubular hollow section members. Orthotropic bridge deck comprises a

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structural steel plates stiffened in both directions and 8 mm thick polymer wearing surface. The bridge was designed according to LST EN specifications which are based on Eurocode standards.

2.2. Numerical model

Linear elastic finite element (FE) analysis was performed to assess vertical displacements of the bridge deck under static loading and modal characteristics under dynamic excitations. In the numerical analysis commercial finite element software Staad.Pro was used. FE model, shown in Fig 2, was considered in a plane stress state. This model simplifies the three-dimension action of real structure. The finite element model used frame elements for the trusses and four node quadrilateral elements for the orthotropic bridge deck.

Fig. 1. Side view of the steel truss footbridge

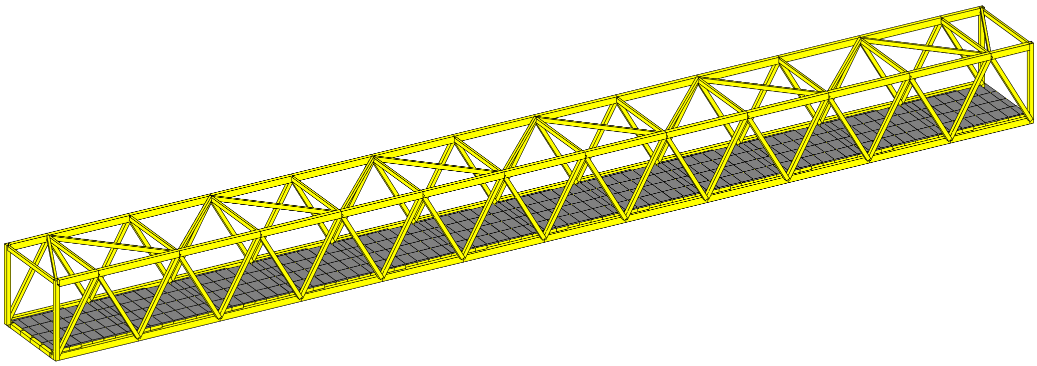

Fig. 2. General view of the 3D FE model

3. Tests and instrumentation

Before the opening of the footbridge, static or dynamic tests were performed in order to judge the functionality and safety of the structure. During static tests the bridge was loaded by precast concrete footway slabs (Fig. 3). During dynamic tests the span was excited by dropping the weight and by the synchronized running of a group of pedestrians.

Fig. 3. View of loaded footbridge by concrete slabs

For tests a total of 26 sensors were installed on the footbridge superstructure at locations where a maximum response was expected. These sensors included linear variable differential transducers (LVDT) at mid-span, quarter span and supports, vertical and horizontal accelerometers at mid and quarter span (Fig. 4). Dynamic measurements and analysis were conducted using Bruel&Kjar LAN-XI 16-channel data acquisition system and software program Pulse. The static tests consisted of measuring displacements and strains to assess the linearity of behaviour as well as load carrying capacity of the footbridge. Dynamic tests are executed to obtain the dynamic characteristics (natural frequencies, mode shapes, damping ratios) and to assess the serviceability of the bridge. All tests were conducted during the same day, when the temperature was around +5-7°C.

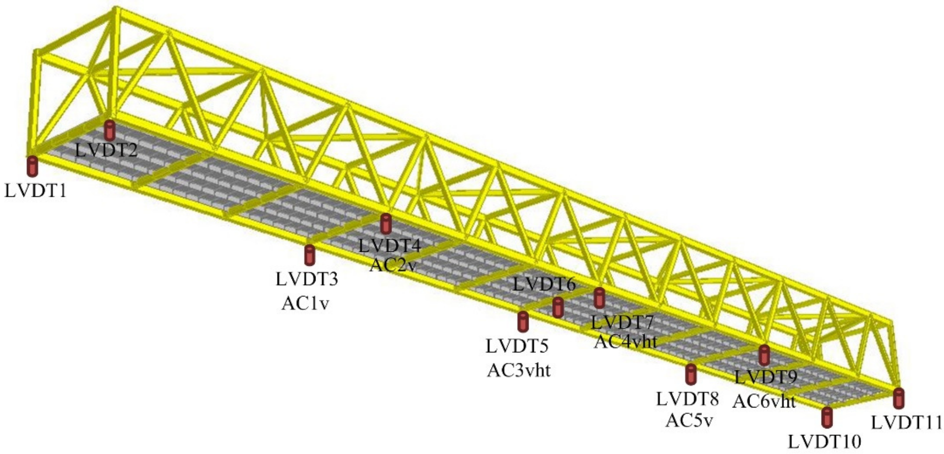

Fig. 4. Typical instrumentation of the footbridge deck: LVDT – vertical linear variable differential transducers; AC – accelerometers in vertical (v) and horizontal transverse (ht) directions (horizontal transducers and strain gauges are not shown)

4. Static test results

Static test of the footbridge was performed using 9 loading and unloading stages in order to determine the live load distribution in the longitudinal and transversal direction of the superstructure. The maximum test load on the bridge deck was ~0.8 of the characteristic design load of 5 kN/m^2. For the specified load position, deflection and strain readings were measured and recorded.

The maximum vertical displacements at mid span in longitudinal and transversal directions are presented in the Fig 5. The average maximum deflection recorded at mid-span (Fig. 5,a) at a total test load was 20.66 mm or only 1/2362 of the span well under allowable value of L/400. The maximum deflection in the transversal direction at the longitudinal axis of the deck was 22.39 mm. In both directions the response behaviour was symmetric. Tests showed the residual deflections at mid-span after removal of the test load up to 0.268 mm. The maximum residual deflection was only in the range of 1.27% of the maximum recorded. A linear relationship exists between the applied load and measured deflections and, also, between the applied load and the measured truss member's strains. Field test measurements indicate a good agreement between the measurements for different loading stages and the superposition of the measurements for both steel trusses.

FE analysis was performed to predict the vertical displacements and to check the load carrying capacity of the footbridge according to the current design standards. A comparison between predicted and measured maximum deflections at mid span gives the ratio of 1.019 and 1.084 for vertical displacements along the bridge and in the transversal direction, accordingly. The predicted and measured values are shown to be in good agreement.

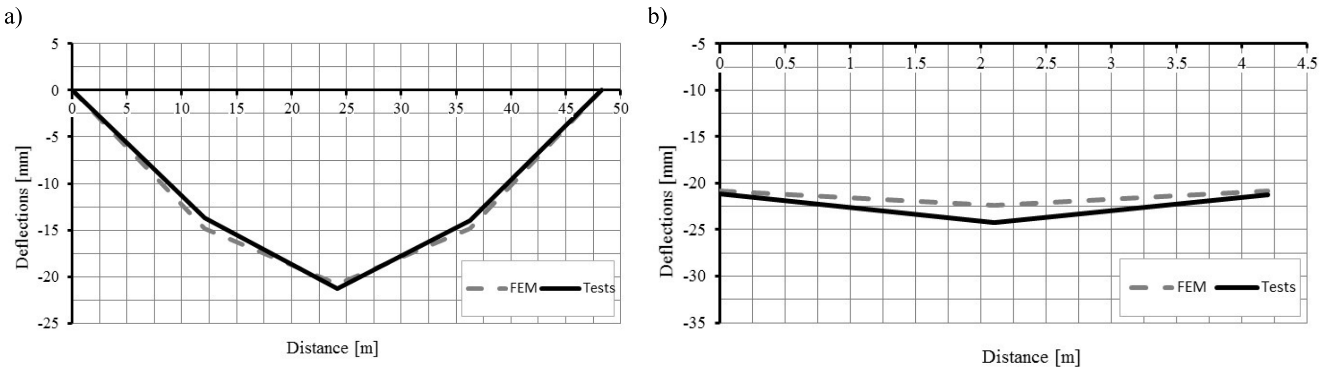

Fig. 5. Mid-span deflections at maximum test load in the longitudinal (a) and transversal (b) directions of the superstructure

5. Dynamic test results

Footbridges are usually slender then highway bridges, that may lead to greater vibration responses when they are subjected to dynamic loads. Footbridges may vibrate vertically, longitudinally or laterally. According to LST EN 1991-2 [9] the critical ranges for natural frequencies f_i of footbridges with pedestrian excitation are: 1.6 Hz $\leq f_i \leq$ 2.4 Hz for vertical and longitudinal vibrations and 0.5 Hz $\leq f_i \leq$ 1.5 Hz for lateral vibrations. Verification of the vibration comfort criteria for pedestrians should be performed when the fundamental frequency of the footbridge is less than 5,0 Hz for vertical vibrations and 2.5 Hz for horizontal and torsional vibrations.

The steel truss footbridge was excited by dropping the weight and by the small group of runners. In Fig. 6, the identified eigenfrequencies up to 10 Hz corresponding to the resonant frequencies of the superstructure are shown. The frequency spectrum showed five clear peaks at 2.31; 3.61; 5.15; 6.20 and 9.99 Hz. Observed modes can be classified as both bending and torsional modes of the deck. In the longitudinal direction one dominant mode with frequency of 6.12 Hz are identified.

It is recognized that the first fundamental vibration modes usually predominate the structures overall response. Two first symmetric bending resonant modes (f_{h1} =2.41 Hz lateral and f_{v1}=3.61 Hz vertical) over the range of interest 1 to 5 Hz to be important for pedestrian induced excitations. At the design of the footbridge the values of 3.02 Hz and 3.64 Hz were assumed for vertical and lateral modes, accordingly. At two lowest frequency peaks, the accelerations were bandpass filtered. The modal amplitudes are shown in Fig 7. The damping ratio of the 1st lateral mode ξ_h=1.316% and that of the 1st vertical mode ξ_v=0.5226%. The damping of the footbridge is low, but it is in the usual range for the steel footbridges (in average 0.4 %).

The footbridge was also modelled by FE software program Staad.Pro. The natural lateral frequency obtained for model was 2.32 Hz and the vertical frequency was 3.62 Hz. These frequencies are very close to the measured natural frequencies obtained by impulse testing. According to LST-EN 1990 [10] pedestrian comfort criteria should be defined in terms of maximum acceptable acceleration of any part of the deck: 0.7 m/s^2 for vertical vibrations and 0.2 m/s^2 for horizontal vibrations. The vertical acceleration due to a single walking person (LST EN 1991-2 [9]):

$$a_{v1} = 4\pi^2 f_{v1}^2 y\Psi \ \text{ m/s}^2, \tag{1}$$

where f_{v1} is the first fundamental frequency (Hz); y is maximum static deflection at-mid span due to a force of 700N; Ψ is dynamic response factor.

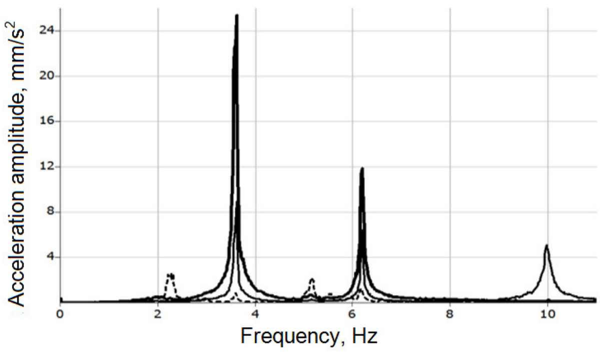

Fig. 6. Frequency (Furier) spectra of the footbridge deck from impact load testing (peaks at 2.31; 3.61; 5.515; 6.20 and 9.99 Hz)

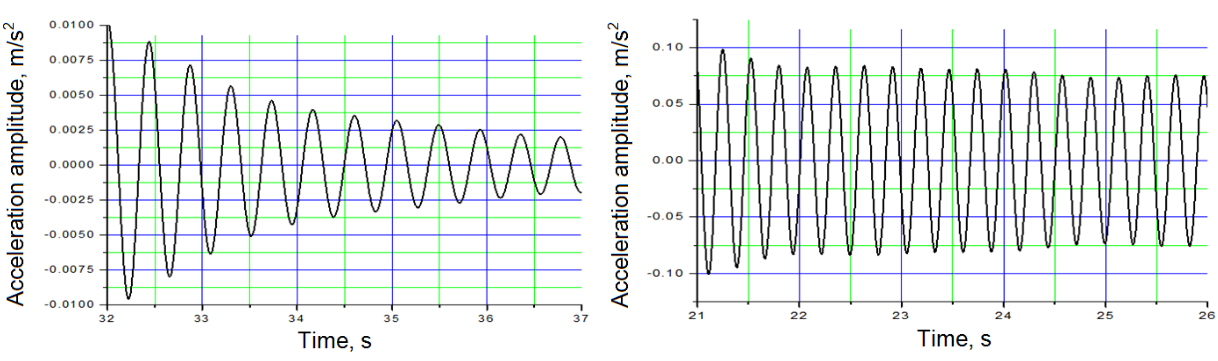

Fig. 7. First lateral (2.31 Hz) and second vertical (3.61 Hz) bending modes of vibration

In the case of several pedestrians walking at the pacing average frequency 2.0 Hz, the vertical acceleration can be determined as follows:

$$a_n = \lambda_n a_1 \tag{3}$$

In the case of small number ($n \leq 5$) of pedestrians synchronous walking and linearity between the number of pedestrians and bridge response can be accepted [5], e.g. $\lambda_n = n$. For the group of pedestrians (n= 6-20) walking at random pacing rates that is usual probable event $\lambda_n = \sqrt{n}$. In the case of lateral vibrations the acceleration according to (4) can be reduced by factor 0.2.

The FE footbridge model was also used to assess the vibration serviceability limit state using maximum bridge lateral and vertical accelerations due to harmonic moving pedestrian load G (700 N) specified in LST EN 1991-2 [9]:

$$F(x,t) = G \sin(2\pi f_o t) \text{ (Newtons)} \quad (4)$$

Numerical simulation was performed with one person walking across the bridge at normal vertical pace frequency 2.0 Hz and lateral frequency 1,0 Hz. One person fast running (sprint) at a pacing rate equal to the lateral and vertical fundamental frequencies of the bridge was also simulated. The maximum acceleration response for all pedestrian numerical simulations and computations according to Eq. (1) and (3) are shown in Table 1. As can be seen, increasing the number of pedestrians increases the acceleration response of the bridge. During the FE simulations maximum accelerations at mid-span in the case of fast running of 0.023 m/s^2 in the lateral and 0,61 m/s^2 in the vertical direction were recorded. The values of vertical and lateral accelerations did not exceeded serviceability criteria set forth in the standard indicating that the footbridge is not vulnerable to pedestrian induced vibrations.

In field experiments a group of 3 persons simulated running along the deck at a pace frequency of ~2,75 Hz. Time series of the accelerations were recorded during these tests (Fig. 8). The maximum accelerations from the actual tests can be seen in Table 1. In this test the maximum response don't exceeded the critical values of accelerations. It should be noted that the recommendations of the LST-EN 1990 [10] exclude the impact of this type of human activity on the permissible amplitude of the vibration accelerations.

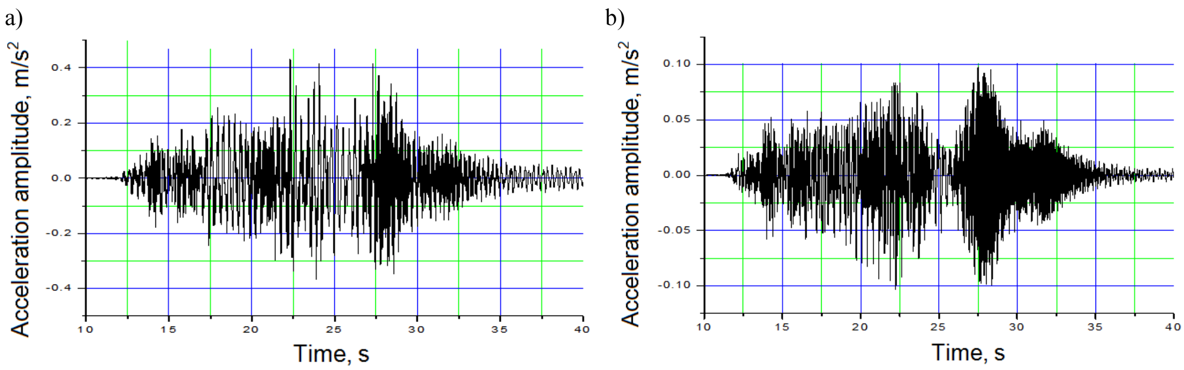

Fig. 8. Typical vertical (a) and lateral (b) acceleration time histories due to excitation by fast running of three persons

Table 1. Results from acceleration analysis

	Natural frequency, Hz	a_{max}, m/s^2		a_1, m/s^2			a_n, m/s^2		
		LST EN	Eq(2)	Eq(1)	FEM f_s at 1.0 and 2.0 Hz	FEM f_s at f_{h1} and f_{v1}	Eq(3) n = 5	Eq(3) n = 20	3 running at 2.75 Hz
Lateral	2.31	0.2	-	-	0.0087	0.0230	0.0435	0.0389	0.1095
Vertical	3.61	0.7	0.95	0.1020	0.0940	0.6100	0.4700	0.4204	0.4334

6. Conclusion remarks

In this paper full scale load testing and analytical modelling of new steel truss footbridge located in City Vilnius is presented. Results of the static test showed that the bridge superstructure remained essentially in elastic state in the service load test. Stresses in the steel members of the truss superstructure's due to dead and live loads are below allowable values. Field test measurements indicate a good agreement between the measurements for different loading stages and the superposition of the measurements for both steel trusses. Dynamic tests and numerical simulations indicated that the peak responses of the footbridge due to pedestrian walking predicted by initial study are lower than the recommended serviceability comfort criteria for vertical and lateral vibrations. Obtained information will be useful for future investigations subject to influence of various scenarios of human activities on the structural response. The experimental results obtained in the static and dynamic tests have a good correlation with the numerical values obtained by FE model. The results of investigation allow making the conclusion that the design of the new steel truss footbridge meets serviceability and strength requirements prescribed by Lithuanian standards LST EN.

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