Experimental Vibration Analysis of Composite Bridge Superstructure with Excessive Deformations

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Abstract. The paper presents results of experimental vibration tests of dynamic susceptible composite, steel-concrete, multi-girder superstructure of highway bridge with excessive deformations. The whole structural system exhibit disproportionate, low-damped vibrations induced by normal traffic crossing the bridge. The presented series of dynamic tests under real traffic were performed for identification of the bridge dynamic characteristics important for future safety and fatigue analyses.

In the paper the tested bridge structure as well as procedure of the performed dynamic tests and applied measuring systems are described together with the numerical model developed during design of the experiment and analysis of the tests results. Measured strains, displacements and accelerations as well as calculated Dynamic Amplification Factors (DAF) are presented for various load scenarios caused by vehicles crossing the bridge. Conclusions regarding effectiveness of applied testing method in identification of the bridge dynamic condition are formulated.

Keywords: Composite bridge · Excessive deformations · Experimental vibration test · Dynamic characteristics

1 Bridge Structure and Objectives of Study

The investigated bridge structure over the Warta River (built in 1989) is a part of the highway A2, one of the main highways in Poland, going from Warsaw to Berlin, Germany. The bridge consists of two separated superstructures, each built of seven semi-continuous beam type spans. Every span is constructed of four steel plate girders, 2.5 m high, composed with typical RC slab of variable thickness. Theoretical length of each span is 41.0 m. The composite superstructure has in each span an excessive, permanent deflections, up to 10 cm, possibly resulting from creep and shrinkage of RC slab as well as design and construction faults. The structural form of the investigated bridge is presented in Figs. 1 and 2, as well as in Fig. 4.

The whole structural system exhibit excessive, low-damped vibrations induced by normal traffic crossing the bridge. The aim of the presented study was to evaluate the bridge dynamic behaviour in terms of its current serviceability and for future safety and

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Fig. 1. Side view of investigated bridge – visible excessive permanent deflection of superstructure

Fig. 2. Investigated bridge: (a) bottom view of superstructure, (b) view of intermediate support area

fatigue analyses. Dynamic tests of the structure were executed according to recommendations specified in [1–5] and experience from previous similar tests, e.g. [6–12].

2 Testing Procedure

Evaluation of structural performance of the analyzed bridge was carried out in real traffic conditions during four whole-day experimental vibration tests carried out every month during the period of three months (June–September 2016). The detailed design of a measurement system were preceded by numerical analysis which enabled the most effective location of gauges during tests under regular traffic. Superstructure was modeled by means of one- and two-dimensional finite elements. One-dimensional, beam type elements, were utilized for representation of all steel components of superstructure, including stiffeners. Two-dimensional, shell type elements, were used for modelling of RC deck slab. Also non-structural joints were applied for connection of beams and shells together. For simplicity only two spans of one carriageway were considered in theoretical analysis. Applied finite element model of the structure (Fig. 3) was analyzed using ROBOT Structural Analysis system.

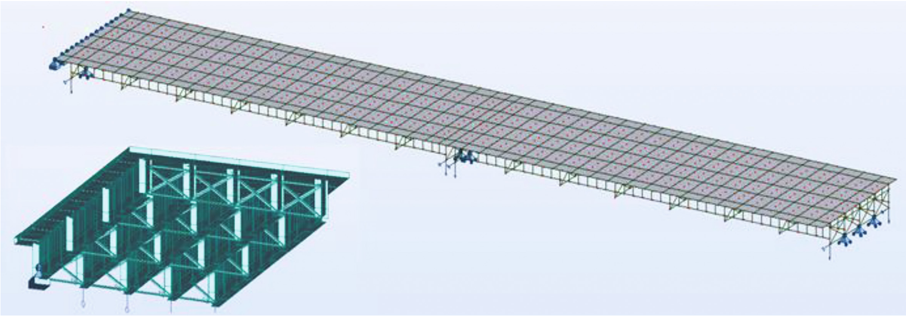

Fig. 3. Investigated bridge: (a) bottom view of superstructure, b) view of intermediate support area

The FEM analysis was carried out to discover how the superstructure behaves under theoretical loads representing heavy vehicles as well as for identification of its basic dynamic properties. In course of a preliminary linear-static analysis relatively low stiffness of multi-girder composite system was revealed - the maximum calculated deflection of span resulted from single 40-tonne vehicle crossing the bridge amounted for 7 mm. Theoretically obtained modal parameters revealed closely spaced bending and torsional vibration modes with associated relatively low frequencies (in a range of 2.0–2.5 Hz) indicating possible dynamic susceptibility. In addition, evaluation of stress ranges induced by the theoretical live load model FLM4 defined in Eurocode [13, 14] and recommended for fatigue analysis of existing road bridges in Europe [15], pointed out some critical spots of the steel superstructure with limited fatigue resistance and thus indicated the need of experimental verification.

On the basis of results of the preliminary structural analysis it was decided that precise assessment of bridge condition and its performance requires strain, displacement and acceleration measurements under real traffic loads. Selection of the bridge spans to examine were supported by detailed inspection of the bridge structure as well as by analysis of spans permanent deflections, which were measured by means of precise geodetic method every four years in previous 15 years of bridge operation. As a result of briefly described above preliminary evaluation two utmost adjacent spans (6–7 and 7–8) having the greatest permanent deflections were taken into consideration for experimental vibration analysis.

During consecutive four measuring sessions gauges arrangement scheme has been slightly modified according to current needs of the bridge evaluation. Exemplary gauges arrangement scheme applied during 4th session is presented in Fig. 4. According to presented sensors layout during the last testing session the following physical quantities were measured:

- strains induced in lower flanges of steel girders in span 7–8 at the measuring points numbered from 00 to 06 shown in Fig. 4; measurement was conducted using a strain gauges – see Fig. 5a,

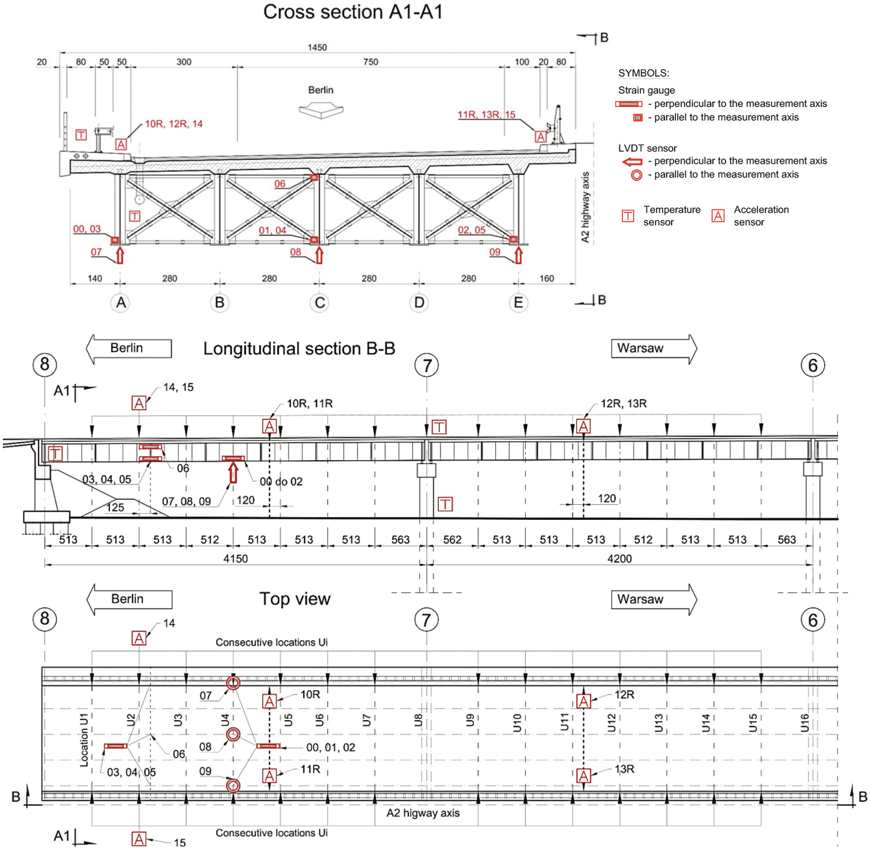

Fig. 4. Gauges arrangement scheme: (a) cross section, (b) longitudinal section, (c) top view

- vertical displacements in the middle section of span 7–8 at the measuring points numbered from 07 to 09; measurement was conducted using a LVDT sensors – see Fig. 5b,
- vertical accelerations at selected points of bridge deck numbered from 10R to 13R and 14 to 15 (shown in Fig. 4) located along both edges of single carriageway in spans 6–7, 7–8; measurement was conducted using a accelerometers – see Fig. 5c.

During whole-day measurements all vehicles crossing the bridge were registered using a camera and digital video recorder (DVR), for matching type of vehicles with the corresponding measured physical values. The temperature was controlled continuously in four specific areas of structure.

Fig. 5. Exemplary location of different types of measuring sensors in span 7–8: (a) strain gauge at point 00, (b) LVDT sensors at points 07–09, (c) accelerometer at point 10R

3 Results of the Vibration Tests

Measurements under service loads were made to get real-time information of the superstructure performance under normal traffic loads. During each measuring session between 20 and 25 measurements (10 min each) were carried out with the sampling frequency of 300 Hz. Selected results of the 4th testing session (September 14th, 2016) between 8.30 am and 18.00 pm are presented in Figs. 6, 7 and 8.

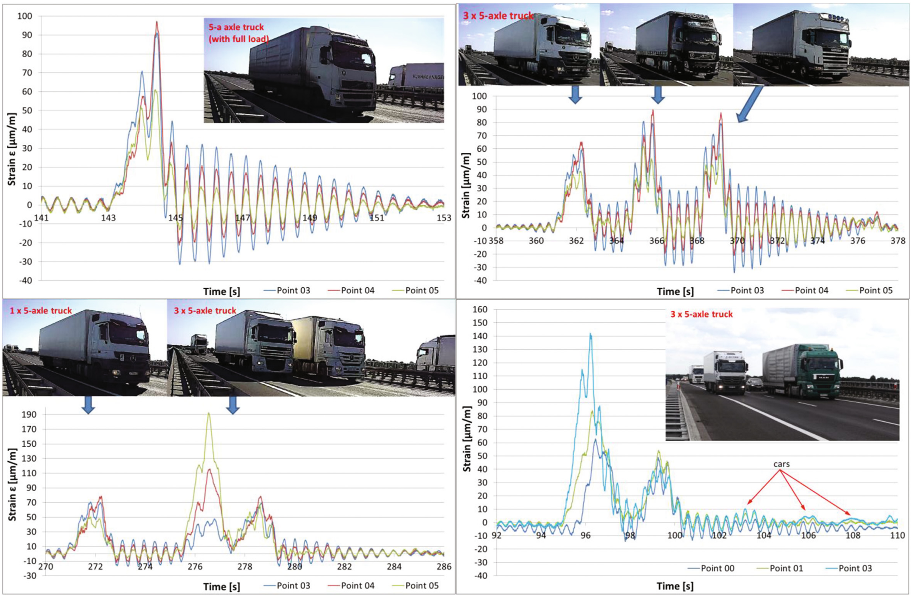

Fig. 6. History of strains induced in main girders by various schemes of 5-axle vehicles

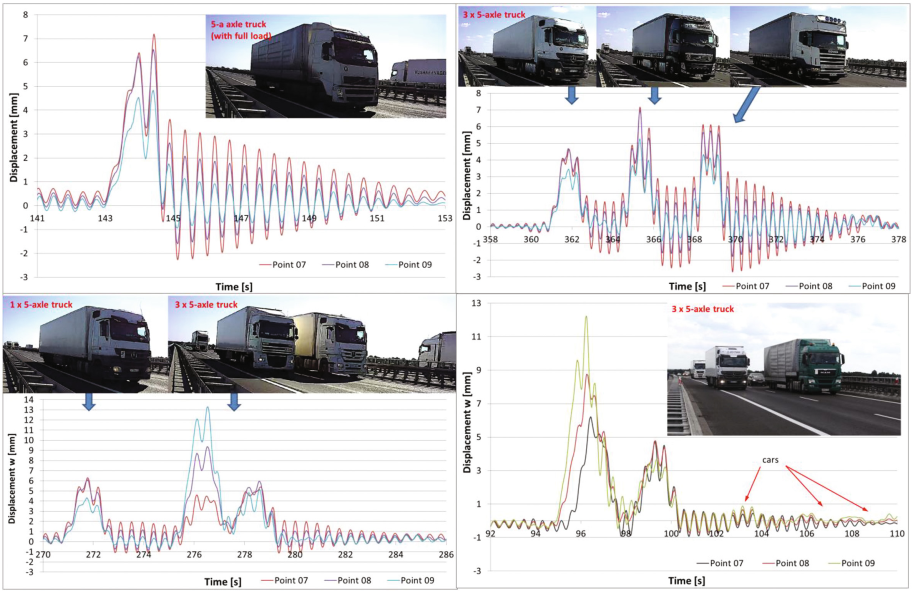

Fig. 7. History of main girders displacements induced by various schemes of 5-axle vehicles

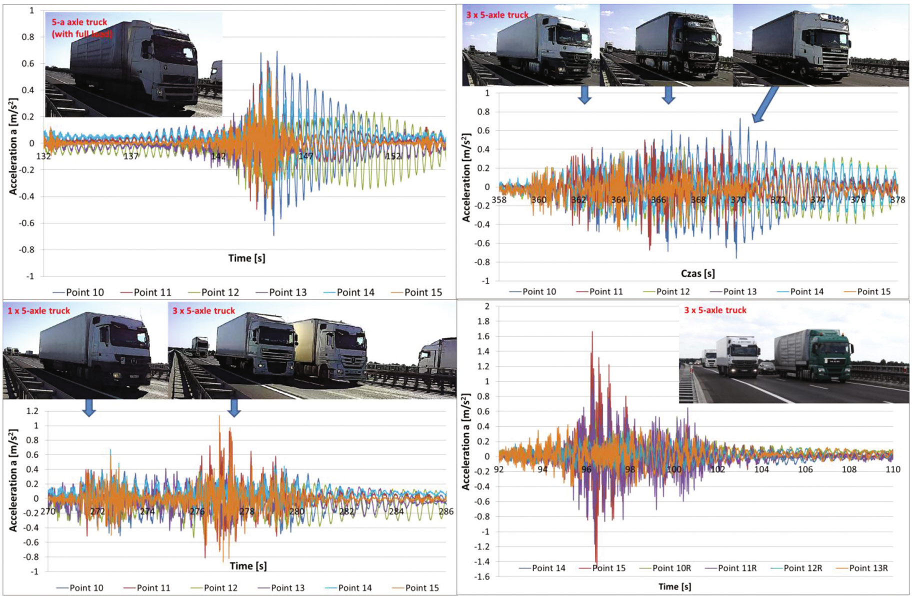

Fig. 8. History of main girders accelerations induced by various schemes of 5-axle vehicles

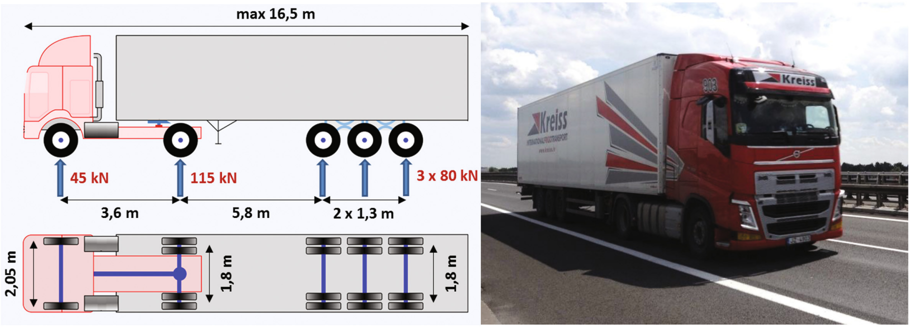

Fig. 9. Typical 5-axle trucks with a total maximum weight of 40 tones: (a) basic parameters – i.e. dimensions and axle loads, (b) general view of exemplary vehicle crossing analyzed bridge

Throughout the tests the traffic density was diversified, therefore it was possible to isolate structure response caused by various types of heavy single vehicles crossing the bridge. Measured values for heavy vehicles traveling in groups were also identified and registered – e.g. moving one by one along lane of slow traffic or moving simultaneously on both traffic lanes of highway. Recorded maximum strains, displacements and accelerations induced by various loading schemes during the last measuring session are presented in Figs. 6, 7 and 8. The analysis of the acquired results indicated that the highest values of measured physical quantities were caused by 5-axle lorries with total maximum weight of 40 tones, whose basic parameters (i.e. axle loads, dimensions) are shown in Fig. 9.

On the basis of analyzes of presented results it can be concluded that the whole structural system exhibit excessive, low-damped vibrations induced by typical cargo traffic crossing the bridge. Physical quantities caused by trucks are quite significant, clearly perceptible and visible to the naked eye. Even a single heavy vehicle generates considerable vibrations of bridge superstructure and the dynamic effects induced by those kind of trucks travelling in groups, especially moving simultaneously on both traffic lanes, are almost twice as large as caused by a single vehicle. The peak values of registered quantities shown in Figs. 6, 7 and 8 were as follows:

- for single 5-axle vehicle with total maximum weight of 40 tones crossing the bridge:
  - maximum strains (tension) of steel girder – ε_{max} = 98.16 μm/m (20.12 MPa),
  - maximum deflection of span – w_{max} = 7.16 mm,
  - maximum vertical acceleration of deck – a_{max} = 0.68 m/s^2,
- for pair of 5-axle vehicle with total maximum weight of 40 tones each, crossing the bridge simultaneously on both traffic lanes:
  - maximum strains (tension) of steel girder – ε_{max} = 190.82 μm/m (39.12 MPa),
  - maximum deflection of span – w_{max} = 13.20 mm,
  - maximum vertical acceleration of deck – a_{max} = 1.66 m/s^2.

The time required for total damping of vibrations is relatively long – about 10 s for span 7–8 and approximately 15 s for span 6–7. Calculated values of logarithmic decrement of damping δ [−] are in the range 0,08–0,15. ratio ξ [%], defined as a percentage of critical damping, determined on the basis of δ [−] is between 1.3% and 2.1%.

In general, the vibrations magnitude, in terms of amplitudes of displacements, strains and accelerations, is greater for the external spans than for intermediate ones but the outmost spans cease to vibrate faster than the others. This is due to the beat phenomenon (e.g. see point 12R in Fig. 8a) observed which is caused by mutual amplification of vibrations caused by similar vibration frequencies of adjacent spans.

It was found that measured values of strain ranges caused by heavy vehicles, especially traveling in groups, in the light of current knowledge (e.g. according to [2, 3]) can affect fatigue life of steel main girders. Assuming for bridge plate girders with transverse stiffeners welded to lower flanges fatigue category 71 MPa according to [14], the corresponding fatigue cut-off limit below which micro-damages do not accumulate in material is 103 μm/m considering safety factor γ_M = 1.35 and 118 μm/m for safety factor γ_M = 1.15. While calculated maximum strain ranges from strain history depicted in Fig. 6 are the following:

- $D\varepsilon_{max}$ = 120.61 μm/m (24.72 MPa) resulted from a single 5-axle truck travelling along slow lane of traffic,
- $D\varepsilon_{max}$ = 196.34 μm/m (40.24 MPa) resulted from pair of heavy vehicles moving simultaneously on both traffic lanes.

Dynamic Amplification Factor (*DAF*) was calculated using the following formula, examined among other in [6, 7]:

$$DAF = \frac{R_{dyn}}{R_{dyn}^{fil}} \tag{1}$$

where R_{dyn} is a maximum dynamic response and R_{dyn}^{fil} is quasi-static response obtained by filtering the dynamic response, taken at the time when the maximum dynamic response occurs. Obtained values of DAF for selected measuring points are presented in Fig. 10. In the diagram the dynamic factor ϕ = 1.14 calculated according to the Polish Design Code [16] is also included. Polish Standard for bridge design [16] defines the dynamic factor ϕ as a partial safety factor calculated individually for every single component of superstructure using the formula:

$$\phi = 1.35 - 0.005 \cdot L_t = 1.35 - 0.005 \cdot 41.0\, m = 1.14, \tag{2}$$

where L_t is the average theoretical span length of the semi-continuous superstructure.

It can be clearly seen that maximum values of DAF obtained for all performed measurements in many cases exceed the code's assumed value of ϕ. The maximum calculated DAF amounted for 1.27. It has been found that for a single vehicles passing the bridge the value of DAF is close to 1.14, which is suggested by code's [16] formula. In the vast majority of cases greater values of DAF than 1.14 were obtained during passing through the bridge a group of vehicles, e.g. moving one by one in close proximity to each other.

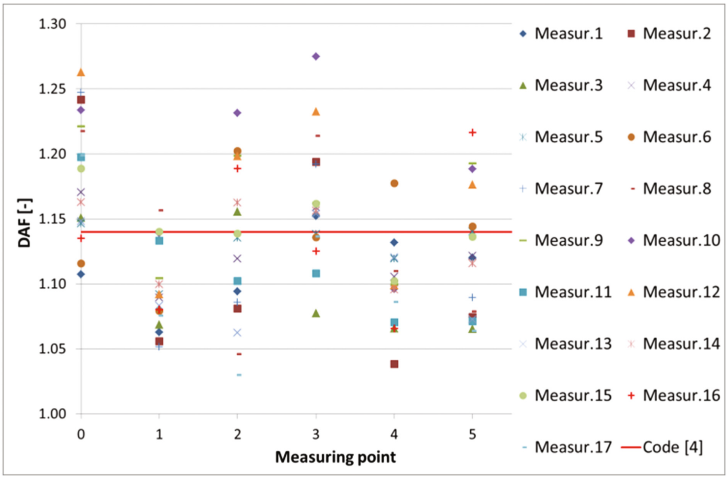

Fig. 10. Maximum values of Dynamic Amplification Factor (DAF) for consecutive measurements determined on the basis of experimental data

4 Conclusions

Evaluation of structural behavior of analyzed bridge was based on measured physical quantities (strains, displacements, accelerations) at various points of superstructure during four series of the whole-day dynamic tests carried out in real operational conditions. Presented results of the experimental vibration analysis of composite, steel-concrete, multi-girder superstructure of highway bridge with excessive deformations confirm relatively high dynamic sensitivity of the bridge. The main reasons of the situation can be listed as follows:

- the static system of superstructure which is in the form of semi-continuous beam – the adjacent spans are connected by the deck slab only (see Fig. 2),
- an excessive, up to 10 cm, permanent deflections of all spans and consequently – unevenness of the highway pavement,
- relatively low stiffens and mass of spans.

The applied method of testing planning and execution as well as measuring system confirmed practicability of the solutions in identification of dynamic characteristics of the structure. Video camera and recorder were very useful in documentation of the loads passing the structure during measurements.

The following general conclusions can be formulated on the basis of the collected and analysed experimental data:

- maximum vertical accelerations of the deck, in some cases, are over 1.6 m/s^2 and are negatively sensed by drivers and passengers of the vehicles passing the bridge,
- value of the Dynamic Amplification Factor in all measuring points is higher than the value accepted in the design code [16],

- time of vibration damping is relatively long and together with comparatively high level of normal stresses in the main girders increases hazard of fatigue cracks,
- the range of the collected experimental data is sufficient for assessment of the current serviceability of the bridge as well as for detailed analysis of potential fatigue hazard,
- dynamic characteristics of the considered bridge, obtained on the basis of live-load tests results, should be used in effective management of bridge operation and maintenance, including design of the structure rehabilitation.

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