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INFLUENCE OF VEHICLE VELOCITY AND ITS PARAMETERS ON THE BRIDGE STRUCTURE RESPONSE – CASE STUDY

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The dynamic analyses are of key importance in the cognitive process in terms of the correct operation of structures loaded with time alternating forces. The development of vehicle industry, which directly results in an increase in the speed of moving vehicles, forces the design of engineering structures that ensure their safe use. The authors of the paper verified the influence of speed and vehicle parameters such as mass, width of track of wheels and their number on the values of displacements and accelerations of selected bridge elements. The problem was treated as the case study, because the analyses were made for one bridge and the passage of three types of locomotives. The response of the structure depends on the technological solutions adopted in the bridge, its technical condition, as well as the quotient of the length of the object and vehicle. A new bridge structure was analyzed and dynamic tests were carried out for trainsets consisting of one and two locomotives. During the actual dynamic tests, the structure was loaded with a locomotive moving at a maximum speed of 160 km/h.

Keywords: dynamic analysis, static analysis, measurement in situ, high speed railways

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1. INTRODUCTION

Poland is one of many countries where great emphasis is placed on the development of railway infrastructure. This is directly related to the increase in the speed of moving trains. In Poland, at present, only about 80 km of railway roads are adopted to the speed of 200 km/h (a section of the Central Railway Main Line between Zawiercie and Olszamowice). According to the National Railway Programme (NRP), an additional 270 km of routes with a permissible speed of 200 km/h will be built by 2023. According to conceptual work from 2008, a high-speed railway line, the so-called Y-line, is to be built by 2030, which will connect Warsaw, Łódź, and after a separation in Nowe Skalmierzyce or near Zduńska Wola – Poznań and Wrocław. On this route, passenger trains are to travel at speeds up to 350 km/h. Currently, this concept was suspended and will be modified in 2022. At present, a large part of the existing railway infrastructure is being modernized and revitalized. The cruising speed of trains is being raised on them, which forces the identification and verification of limit states of bearing capacity and serviceability of existing engineering facilities located in the course of analyzed sections of rail roads. In Poland, the vast majority of railway bridges/viaducts are old objects, not adopted to dynamic loads of high intensity. Due to this fact, very often the dynamic expert opinions are carried out, the main purpose of which is to check whether a given object can carry the load of a train set, moving at a certain speed. There are many papers in the world literature on identifying the dynamic parameters of engineering objects subjected to the dynamic loads. The paper [1] reviews the literature on the field research on bridges. The essence of its implementation is described and it is explained why verification of dynamic features of the structure is so important. The authors [2] evaluated track horizontal parameters and ground damage for the possibility of safe track use by passing fast trains. The study carried out the analyzes necessary to determine the speed at which, in the event of track damage, railway traffic can be continued. The paper [3] describes how to determine dynamic features of structures, such as natural frequencies and forms (modes). It also presents the way of using the results obtained on the basis of the in situ tests, and an important aspect which is the monitoring of the structure was indicated. Currently, in addition to the field research, the theoretical analyzes are performed using the finite element method (FEM). They give the opportunity to verify the theoretical results in relation to the values obtained from direct measurements. One of many papers describing the method of conducting numerical tests and the methodology used to describe the issue of vehicle contact with a bridge object is described in the paper [4]. Analyses of this type give a wide spectrum of possibilities to analyze the work of the structure including the parameters that are impossible to verify at the stage of the field tests. The modelling method and numerical models used are an issue well described in the papers [5-12]. Also in Polish literature, works can be found related to the dynamic analysis of bridge structures. The papers [13] and [14] present selected aspects of the dynamic numerical simulations of a railway bridge with a steel orthotropic plate, loaded with high-speed trains. The papers describes the method of dynamic load modelling in accordance with the Polish regulations. Many books and monographs have been published, dealing with issues of construction dynamics, but one of the most important items should be [15 - 19], which describe the problems of a complex, mutually coupled dynamic system object - a vehicle that interacts together.

The above work may provide a starting material for a way of verifying existing engineering facilities in terms of the possibility of using them as objects on which vehicles can move at a higher speed than was foreseen at the design stage. Such verification may additionally be based on theoretical analyses, of which an integral part is the creation of numerical models of the objects together with the performance of complex dynamic analyses.

2. RESEARCH DESCRIPTION

2.1. DESCRIPTION OF THE BRIDGE

The structure for which the case study was carried out is located on the railway line No. E30 in Poland at 127.475 km, on the route Ropczyce - Sędziszów Małopolski, section Dębica - Sędziszów Małopolski. The superstructure is a truss with a bottom run. The bridge is a single-span structure with a theoretical span of 51.44 m and a theoretical width in cross-section equal to 5.00 m. Railroad tracks are based on concrete (prestressed concrete) railway sleepers, which are laid on gravel ballast with a thickness of over 60 cm. All structural elements are made of the S355J2-N steel. The bottom girders are steel beams with a height of 1500 mm and a web thickness of 16 mm, as well as bottom and top flanges with a width of 380 mm and a thickness of 30 mm. The crossbars have a variable height oscillating in the range from 640 mm to 710 mm and a thickness of 12 mm. The cross-braces are welded flat bars with a variable width from 240 mm to 460 mm, with a constant height of 420 mm. The structure has been transversely stiffened by the upper bracing consisted of 10x100x100 mm angles. The view of the structure analyzed is shown in Fig. 1.

a) 

b) 

Fig. 1. Railway bridge: a) side view of the bridge, b) cross-sectional view. Source: The authors.

2.2. TESTS IN A NATURAL SCALE

2.2.1. STATIC TESTS

Field tests consist of two parts: measurements of displacements from static loads and measurements of displacements and accelerations during the passage of the locomotive. Static tests were performed on 14/09/2016. During the static tests, the bridge was loaded with a load equal to the mass of two diesel locomotives type ST43 and ST45. The weight of both locomotives was 218 600 kg. The load of a single axle on the rail track was equal to 179 kN. The load train consisted of a total of 12 load axles, or 24 wheels. The total length of the two combined locomotives was 35.10 m, which is 68% of the theoretical length of the bridge. The diagram of the bridge and the position of the locomotives during the test is shown in Fig. 2.

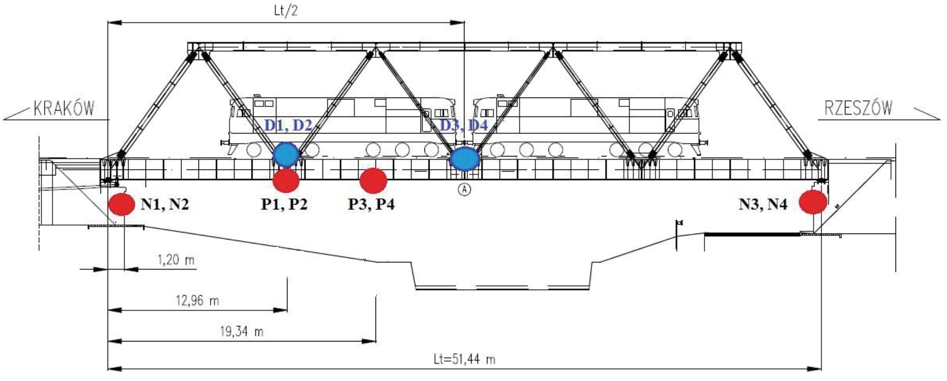


Fig. 2. The scheme of load distribution on the bridge in longitudinal section together with the distribution of measurement points. Source: The authors.

The measurements were carried out:

- displacements of the bridge supporting structure located on its both sides in 1/4 (points P1 and P2) and in 3/8 (points P3 and P4) of the Lt theoretical length of the span, as shown in Fig. 2,
- displacements of supports (abutment settlements) at points N1, N2, N3, and N4 as shown in Fig. 2,
- visual assessment of the bridge before, during and after loading.

Measurements of abutment settlements were carried out using levels with the use of precision leveling methods. The displacements measurements of the bridge supporting structure were made using linear displacement sensors located on the stands and connected to the bridge using invar wires (Fig. 3). The signal from the linear displacement sensors was processed using the Spider signal analyzer with an accuracy of 0.02 mm.

a)

b)


Fig. 3. Devices for the displacements measurements: a) stand to which a linear displacement sensor was attached, b) invar wire attached to the bottom of the truss girder. Source: The authors.

The tests started with the so-called zero readings on the measuring devices when there was no load on the bridge. After the locomotives were put on the object, deflections readings of the structure and supports were taken every 15 minutes for at least 45 minutes. If the difference after three readings (between the second and third one) was less than 2%, the load program for the structure was completed and the load was removed from the bridge. Then the displacement readings from unloading the structure were taken again. The execution of the unloading program was the same as for the loading one. On the basis of such readings, the permanent deflection of the structure was determined, calculated as the difference between the last readings after the structure was unloaded and during the loading. The elastic deflection was calculated as the difference between the total and permanent deflection. The results from the obtained tests are presented in section No. 3 of this paper.

2.2.2. DYNAMIC TEST

The main purpose of the dynamic tests performed was to measure changes in displacement values over time, identification of the frequencies of free vibrations, and identification of the dynamic superiority coefficients of the structure. The dynamic tests were carried out on two dates, because in September 2016 the condition of the track surface at the access to the bridge enabled testing to the maximum safe speed of 80 km/h. The first part of the tests was carried out on the same day that the static tests were performed, i.e., on 14/09/2016. The tests consisted of measuring displacements and accelerations during the passage of the two ST43 and ST45 locomotives, described in the previous section. Locomotives traveled at speeds of 10 km/h, 30 km/h, 50 km/h, and 80 km/h. The second part of the study was performed on the night of November 7, 2017, between 23:00 and 3:00. The dynamic load was one electric locomotive of the EP-09 series, which moved along the bridge at speeds of 10 km/h, 100 km/h, 120 km/h, 140 km/h, and 160 km/h. The weight of the EP-09 locomotive was 83 500 kg. The pressure of a single axle on the railroad track was 210 kN. The loading set consisted of a total of 4 load axles, i.e., 8 wheels. The total length of the locomotive was 16.74 m, which is 33% of the theoretical length of the bridge.

As part of the tests, measurements of displacements and accelerations were made at selected points of the structure (Fig. 2). Vertical displacements were measured at the P3 and P4 points using the linear displacement sensors described in the previous section. Accelerations were measured in ¼ of the theoretical length of the span at the D1 and D2 points, and in ½ Lt at D3 and D4 points (on both sides of the bridge). Two measurement sets were used to measure the vibration accelerations, which included the 6-channel SVAN SV106 signal analyzers and 4 three-axis piezoelectric sensors with 1000 mV/g sensitivity (Fig. 4). During the tests, the speed of the passing load was controlled using the Bushnell speed measuring apparatus with a measurement accuracy of 2 km/h. During passages there was no deviation from the average speed of the locomotive or locomotives greater than 5 km/h.

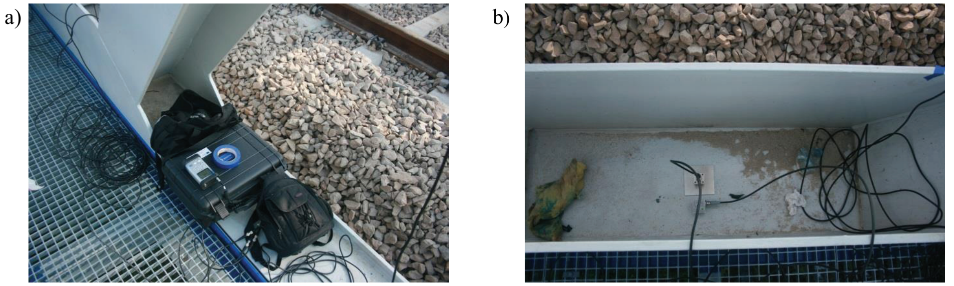


Fig. 4. Equipment for the accelerations measurements: a) the SVAN SV106 signal analyzer, b) piezoelectric sensors. Source: The authors.

Each run of the load set at a certain speed was performed twice in order to eliminate external factors that could adversely affect the results obtained. The test results are described in the next section.

3. IN SITU MEASUREMENTS

3.1. RESULTS OF STATIC ANALYSIS

The results of the u vertical displacements, caused by the static load during the loading and unloading process, are shown in Fig. 5. Based on these results, total displacements u_c, permanent u_t, and elastic u_s were calculated. These results are shown in Table 1. The permanent vertical displacements of the abutments were zero, which means that the values of the elastic displacements were the same as the total displacements. Maximum vertical displacements in 3/8 L_t did not exceed 12 mm.

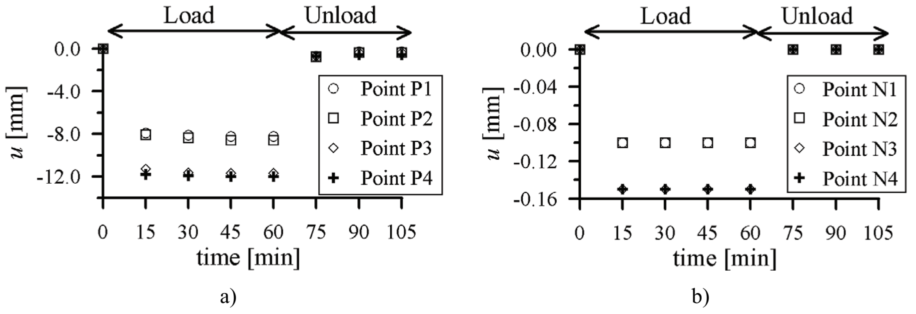


Fig. 5. The vertical displacements u due to the static load: a) on the span, b) on abutments.

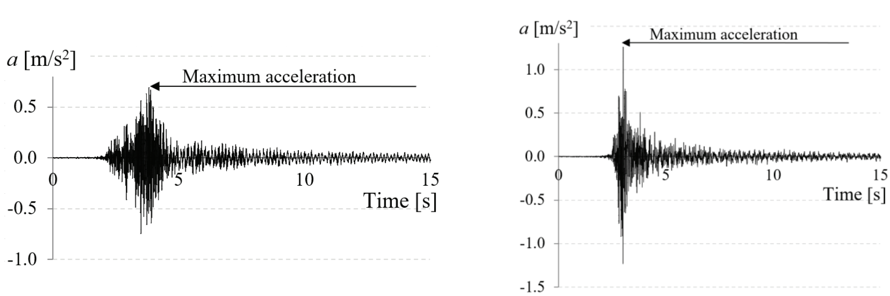
Table 1. Analysis of displacement results of the bridge span due to the static load.

	Measuring point			
	P1	P2	P3	P4
Total displacement u_c [mm]	-8.23	-8.58	-11.68	-11.99
Permanent displacement u_t [mm]	-0.27	-0.33	-0.35	-0.54
Elastic displacement u_s [mm]	-7.96	-8.25	-11.33	-11.45
u_t / u_c – the ratio of permanent to total displacement	3%	4%	3%	5%

3.2. RESULTS OF DYNAMIC ANALYSIS

During the dynamic tests changes in displacements at P3 and P4 (3/8 L_t) and accelerations at ¼ L_t and ½ L_t were measured (points D1-D4). An example of the measured values of the span acceleration since passage with the EP-09 locomotive at 10 km/h and 160 km/h is shown in Fig. 6. All time courses were filtered with a high-pass filter with a 30 Hz bandwidth. Extreme values were read from such modified waveforms from the places on the graphs that correspond to the location shown in Fig. 6. The extreme displacements of the span in points located in 3/8 L_t at different locomotive speeds are shown in Fig. 7, and the maximum accelerations a are shown in Fig. 8. Extreme vertical displacements for the set of ST43 and ST45 locomotives varied from 11.92 mm to 12.34 mm, and for the EP-09 locomotive ranged from 5.61 mm to 6.62 mm. The maximum accelerations values changed accordingly:

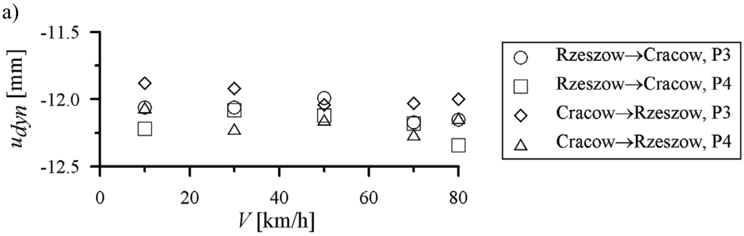
- at points D1 and D2 for the ST43 and ST45 locomotives, from 0.22 m/s^2 to 0.64 m/s^2, and for the EP-09 locomotive – from 0.11 m/s^2 to 0.38 m/s^2,
- at points D3 and D4 for the ST43 and ST45 locomotives, from 0.27 m/s^2 to 0.71 m/s^2, and for the EP-09 locomotive – from 0.12 m/s^2 to 0.47 m/s.



a) b)

Fig. 6. Examples of measurement results – the vertical component of the vertical accelerations in the mid-length of the span from traveling by the EP-09 locomotive at speed: a) V=10 km/h, b) V=160 km/h.

a)



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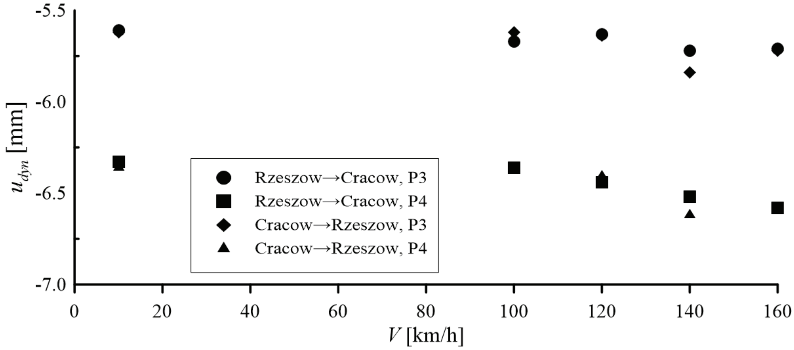
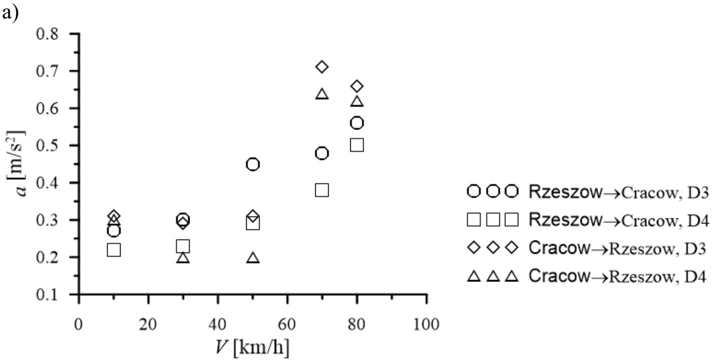


Fig. 7. Diagram of the extreme vertical displacements u_{dyn} of the span depending on the speed of the locomotives V: a) ST43 and ST45 during tests on the first date, b) EP-09 during the second period of testing.

a)



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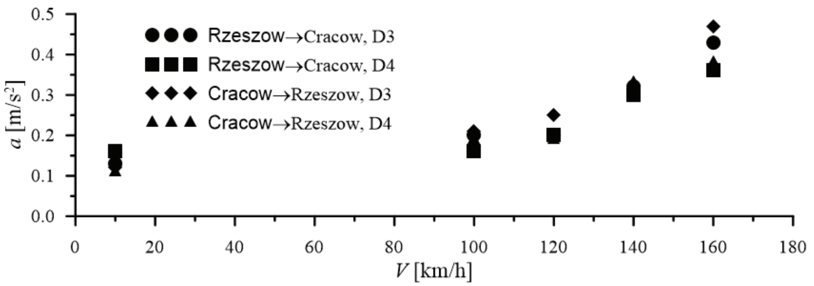

Fig. 8. Graph of the maximum value of the vertical component of the span accelerations *a* depending on the speed of locomotives *V*: a) ST43 and ST45 during tests on the first date, b) EP-09 during the second period of testing.

On the basis of direct analysis of the results, it was possible to determine the actual dynamic superiority coefficient, interpreted as the quotient of the maximum displacement at the analyzed measuring point when a locomotive passes through at different speeds, to the maximum displacement when passing through at a quasi-static speed, equal to 10 km/h. The maximum value of the dynamic coefficient reached the value equal to $\varphi_{rz} = 1.060$ as a result of passing at the speed of 140 km/h, and it is lower than the theoretical value of $\Phi_{teor} = 1.112$, determined according to the C annex of the PN-EN 1991-2 standard [20], [21].

In the next stage of analysis, the results of displacements were compared according to the weight of vehicles. For this purpose, the reduced values were calculated from the formulas:

- for displacements

$$u_{red} = \frac{\frac{1}{N}\sum_{i=1}^{N} u_i}{G}, \tag{1}$$

- for accelerations

$$a_{red} = \frac{\frac{1}{N}\sum_{i=1}^{N} a_i}{G}, \tag{2}$$

where: u_i and a_i – extreme values of displacements and accelerations, G – weight of locomotives.

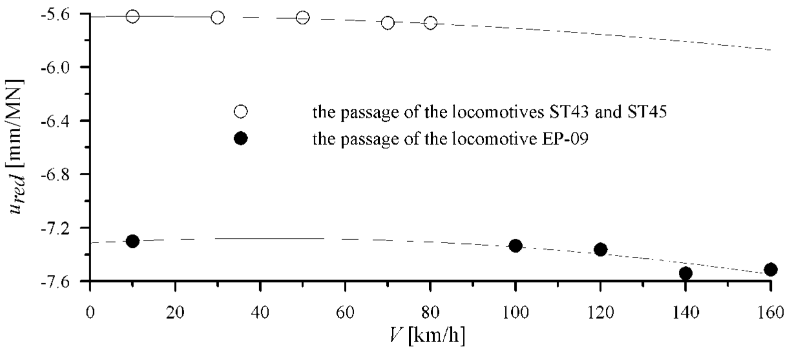

Fig. 9. Diagram of the reduced displacements u_{red} of the span depending on the speed of the locomotives V. Continuous line – the $u_{red}(V)$ dependency trend.

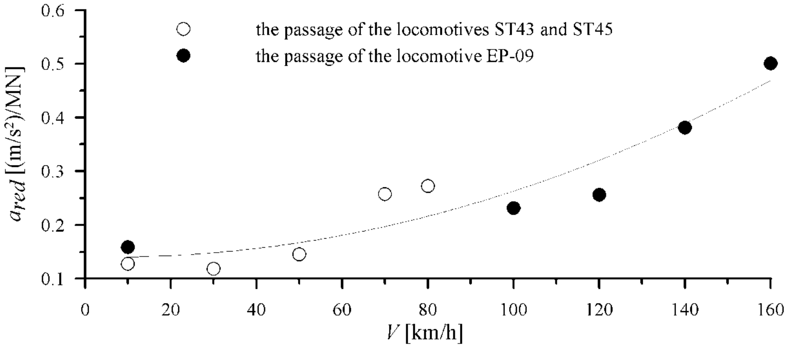

Fig.10. Diagram of the reduced accelerations a_{red} of the span depending on the speed of the locomotives V. Continuous line – the $a_{red}(V)$ dependency trend.

Fig. 9 and Fig. 10 show how the reduced values of displacements and accelerations change. On the basis of the analyses carried out, it can be concluded that regardless of the type of locomotive, a clear upward trend in the maximum values of both displacements and accelerations as the vehicle speed increases is visible. Moreover, the trend of reduced displacements changes indicates that reduced displacements during the passage of the EP-09 locomotive is greater than during the passage of the ST43 and ST45 locomotive set. This proves that the values of vertical displacements are influenced not only by the change in load values but also by parameters such as wheelbase, number of axles and vehicle length. In the case of the EP-09 locomotive, its weight is transferred to rail tracks via 8 wheels, in the set of ST43 and ST45 locomotives through 24 wheels. In addition, the inner wheels of the EP-09 locomotive are offset from each other by a distance of up to 8.0 m. The inner axles seem to be more loaded than the outer ones. The ST43 or ST45 locomotive has as many as 6 axles, of which the internal axles are offset by only 4.0 m, which significantly reduces the pressure of a single wheel on the railroad track. In the case of reduced accelerations, the monotonicity of the accelerations values changes along with the increase in speed is observed. The differences between the results forecasted for the passage of the ST43 and ST45 locomotives set and the EP-09 locomotive are insignificant. However, visible deviations may be the result of measurement errors.

Based on the measurements, the free vibration frequencies of the bridge were determined. For this purpose, the Fast Fourier Transform (FFT) algorithm was used, which is described in papers [22-26]. Fig. 11 shows the spectrum of the vertical component of the bridge girder vibration accelerations in ½ L_t, which were measured after the locomotive left the bridge.

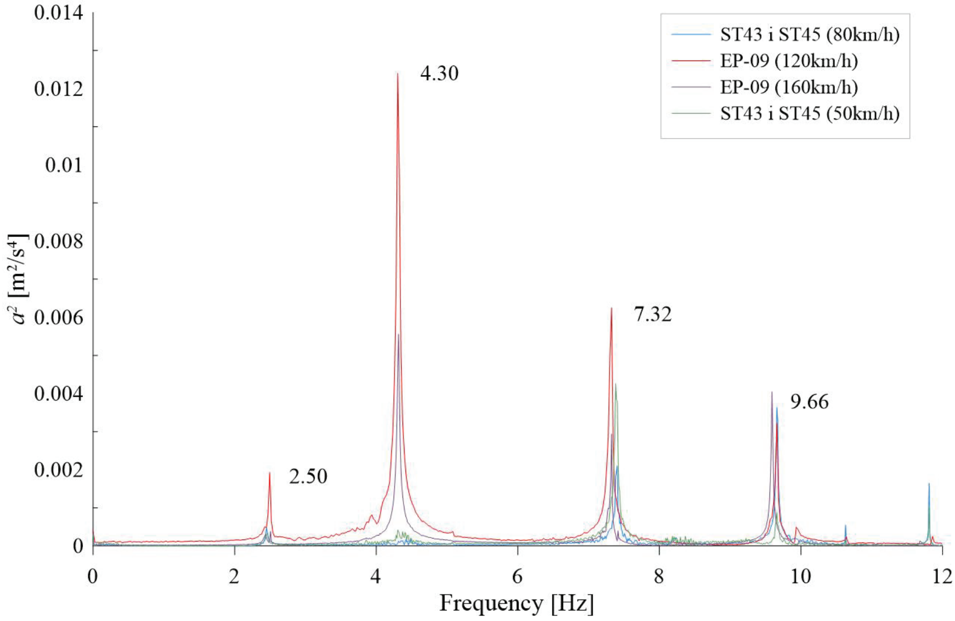

Fig. 11. FFT analysis of the signal after the exit of locomotives in the middle of the bridge span.

Based on the analysis carried out in this way, four free vibration frequencies of the bridge were found: the first – 2.50 Hz, the second – 4.30 Hz, the third – 7.32 Hz, and the fourth – 9.66 Hz. A small effect of the speed on the obtained values of free vibration frequencies of the bridge was noticed. The difference between their values depending on the speed did not exceed 0.75%. An important aspect that has been noticed is the fact that in the case of the ST43 and ST45 locomotives set, based on the dynamic in situ tests, no first vibration frequency of the bridge was found. Most likely this frequency was damped by the wheels of a set of locomotives (12 axles). Due to the close proximity of 6 axles (at the junction of the ST43 and ST45 locomotives) and the short distance between them, the frequency was suppressed. This proves that the wheelbase and their number, is of great importance for the work of the structure under the dynamic load.

4. CONCLUSIONS

Variable loads over time may increase or decrease the value of stresses or displacements in structural members caused by the static loads. In railway bridges, this is mainly due to the speed of a passing train, the effect of repeated loads (e.g., wheels of rolling stock spaced at the same distance), the weight and length of the bridge and train, or unevenness of the rails or the wheels themselves. On the basis of the field tests carried out, the effect of mass on the obtained values of displacements and accelerations of the bridge span was found. The analyses also proved a significant influence of the size of the wheelbase and number of wheels not only on the values of displacements but also on the frequencies of own vibrations of the bridge. A large number of axles placed next to each other may cause the effect of damping of a structure with a certain frequency, which was proved in the FFT analyses conducted.

In the opinion of the authors, the subject matter is of great cognitive and application importance, because it touches upon the issues of building mechanics, and gives an opportunity to assess the correct operation of the structure under variable load over time. Due to the development of materials technology and the use of lighter and lighter materials for the construction of engineering structures, the aspect of the influence of additional factors such as the quotient of vehicle mass to the mass of the structure, speed, length of the vehicle and the structure, should be taken into account at the stage of designing and performing complex analyses of bridge structures.

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Rys. 7. Wykres ekstremalnych przemieszczeń pionowych przęsła u_{dyn} w zależności od prędkości lokomotyw V: a) ST43 i ST45 podczas badań w pierwszym terminie, b) EP-09 podczas badań w drugim terminie.
Fig. 8. Graph of the maximum value of the vertical component of the span accelerations a depending on the speed of locomotives V: a) ST43 and ST45 during tests on the first date, b) EP-09 during the second period of testing.
Rys. 8. Wykres maksymalnej wartości składowej pionowej przyspieszeń przęsła a w zależności od prędkości lokomotyw V: a) ST43 i ST45 podczas badań w pierwszym terminie, b) EP-09 podczas badań w drugim terminie.
Fig. 9. Diagram of the reduced displacements u_{red} of the span depending on the speed of the locomotives V. Continuous line – the $u_{red}(V)$ dependency trend.
Rys. 9. Wykres przemieszczeń zredukowanych przęsła u_{red} w zależności od prędkości lokomotyw V. Linia ciągła – trend zależności $u_{red}(V)$.
Fig. 10. Diagram of the reduced accelerations a_{red} of the span depending on the speed of the locomotives V. Continuous line – the $a_{red}(V)$ dependency trend.
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Tab. 1. Analysis of displacement results of the bridge span due to the static load.
Tab. 1. Analiza wyników przemieszczeń przęsła mostu od obciążenia statycznego.

WPŁYW PRĘDKOŚCI POJAZDU I JEGO PARAMETRÓW NA ODPOWIEDŹ KONSTRUKCJI MOSTOWEJ – STUDIUM PRZYPADKU

Słowa kluczowe*: analiza dynamiczna, analiza statyczna, badania na miejscu, koleje wysokich prędkości*

STRESZCZENIE

Autorzy artykułu dokonali próby weryfikacji wpływu wartości prędkości z jaką porusza się pojazd szynowy oraz parametrów samego pojazdu na odpowiedź dynamiczną konstrukcji mostowej. Artykuł został podzielony na trzy części. Pierwsza z nich dotyczy studiów literatury, w której zawarto przykłady publikacji odnoszących się do zagadnień związanych z dynamicznymi badaniami in situ. Druga część przedstawia szczegółowy opis przeprowadzonych badań polowych w ramach których wykonano badania statyczne oraz dynamiczne analizowanej konstrukcji kratownicowej mostu kolejowego. Trzecia, ostatnia stanowi podsumowanie przeprowadzonych badań, w której zawarto najważniejsze wnioski. Badania przeprowadzono w ciągu linii kolejowej nr E30 w km 127.475 na szlaku Ropczyce – Sędziszów Małopolski odcinek Dębica – Sędziszów Małopolski w Polsce. Badania w terenie składały się z dwóch części: pomiarów przemieszczeń od obciążeń statycznych oraz pomiarów przemieszczeń i przyspieszeń podczas przejazdu zestawem lokomotyw. Badania statyczne zostały wykonane 14.09.2016 r. W trakcie badań statycznych most został obciążony obciążeniem równym masie dwóch lokomotyw spalinowych typu ST43 oraz ST45. Masa obu lokomotyw wynosiła 218 600 kg. Nacisk pojedynczej osi na tok szynowy był równy 179 kN. Skład obciążający składał się łącznie z 12 osi obciążeniowych, czyli 24 kół. Całkowita długość dwóch połączonych lokomotyw wynosiła 35.10 m, co stanowiło 68% długości teoretycznej mostu Badania w zakresie dynamicznym przeprowadzono w dwóch terminach, 14.09.2016r. i w nocy z 7 na 8.11.2017 r. w godzinach 23:00 – 3:00. Takie podejście było podyktowane stanem nawierzchni torowej na dojazdach do obiektu, który umożliwiał przeprowadzenie badań do maksymalnej, bezpiecznej prędkości równej 80 km/h. Głównym celem wykonanych badań dynamicznych był pomiar zmian wartości przemieszczeń w czasie, zidentyfikowanie częstotliwości drgań swobodnych oraz identyfikacja współczynników przewyższeń dynamicznych konstrukcji. W pierwszym terminie badania dynamiczne polegały na wykonaniu pomiarów przemieszczeń i przyspieszeń podczas przejazdu dwóch lokomotyw ST43 i ST45 z prędkościami 10 km/h, 30 km/h, 50 km/h i 80 km/h. W drugiej części obciążenie dynamiczne stanowiła jedna lokomotywa elektryczna serii EP-09, która poruszała się po moście z prędkościami 10 km/h, 100 km/h, 120 km/h, 140 km/h oraz 160 km/h. Masa lokomotywy EP-09 wynosiła 83 500 kg. Nacisk pojedynczej osi na tok szynowy był równy 210 kN. Skład obciążający składał się łącznie z 4 osi obciążeniowych, czyli 8 kół. Całkowita długość lokomotywy wynosiła 16.74 m, co stanowiło 33% długości teoretycznej mostu. Na podstawie bezpośredniej analizy wyników możliwe było wyznaczenie rzeczywistego współczynnika przewyższenia dynamicznego, zinterpretowanego jako iloraz maksymalnego przemieszczenia w analizowanym punkcie pomiarowym przy przejeździe lokomotywy z różnymi prędkościami do maksymalnego przemieszczenia przy przejeździe z prędkością quasi-statyczną, równą 10 km/h. W celu wyznaczenia częstotliwości drgań swobodnych mostu posłużono się algorytmem Szybkiej Transformaty Fouriera (FFT). Na podstawie tak przeprowadzonej analizy stwierdzono występowanie czterech częstotliwości drgań swobodnych mostu: pierwsza - 2.50Hz, druga - 4.30Hz, trzecia - 7.32Hz i czwarta - 9.66Hz. Zauważono mały wpływ prędkości na otrzymane wartości częstotliwości drgań swobodnych mostu. Różnica pomiędzy ich wartościami w zależności od prędkości nie przekraczała 0.75%. Przeprowadzone analizy dowiodły znaczący wpływ wielkości rozstawu osi i liczby kół nie tylko na wartości przemieszczeń, ale również na częstotliwości drgań swobodnych mostu. Duża liczba osi ustawionych obok siebie może powodować efekt tłumienia konstrukcji o określonej częstotliwości. *Received: 14.02.20 Revised: 03.06.20*