ТРАНСПОРТНЕ БУДІВНИЦТВО

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DYNAMIC BEHAVIOR OF TWO-SPAN CONTINUOUS CONCRETE BRIDGES UNDER MOVING OF HIGH-SPEED TRAINS

Purpose. The scientific work provides a comparison of the results of the movement of a high-speed passenger train across the bridge, obtained as a result of finite element modeling in the SAP2000 software package, and real tests of a double-span concrete railway bridge. Analysis of the rigid characteristics of flying structures. **Methodology.** The numerical method presented in this study shows valid results concerning the dynamic analysis of the behavior of bridges in conditions of high-speed train traffic. The factors influencing the dynamic behavior of bridges under moving loads, the influence of design parameters and rolling stock, as well as the interaction of the train and spans are determined. The system was used in the form of moving concentrated forces simulating the axes of the train. **Findings**. Maximum movements and accelerations were obtained as a result of the dynamic calculation for different speeds of the train and compared with practical tests. The correctness of the model of a span structure with regard to continuous ferroconcrete spans was verified. **Originality**. Within the framework of the work, the latest test results were used, including those with speeds calculated on the prospect of rail passenger traffic. For these tests, a model of a span structure was developed. **Practical value**. The results of the research can be used to plan the introduction of high-speed train traffic on existing and planned flying structures of reinforced concrete bridges. An approach to the design of span structures that will be effective when passing high-speed passenger trains is implemented.

Keywords: dynamic interaction; concrete bridges; continuous bridge; high-speed train; SAP2000

Introduction

Grain is one of the main export goods of Ukraine. Over the period from 2006 to 2016, the share of its value in the total value of goods exported from Ukraine increased from 3.5 to 16.5%. In 2015/2016 marketing year among grain exporters, Ukraine, with an indicator of 38.7 million tons, took the third place, behind the United States (78.5 million tons) and the European Union (52.2 million tons). Argentina (36.2 million tons), the Russian Federation (34.6 million tons), Canada (27.7 million tons) and other countries [1, 3] exported significant volumes of grain. One of the ways to increase the competitiveness of domestic grain in the world market is to build an effective logistics system. For Ukraine, this task is especially important, as the share of logistics costs in the cost of domestic grain is about 35%; for comparison, the share of logistics costs in the grain cost in the European Union is 12–16%, the United States – 9% [2]. In 2016 in Ukraine, about 97% of grain exports were made through seaports, while 63% of grain cargo was delivered to sea ports by

rail. Therefore, increasing the efficiency of grain cargo transporting by rail and water transportation is one of the key tasks that must be addressed to reduce logistics costs. The need to develop logistic schemes for the grain delivery to ports with the participation of rail transport is also conditioned by the need to increase Ukraine's energy independence. The railway transport of Ukraine performs about 90% of the turnover of electric power with the use of domestic energy carriers. On the contrary, 72% of oil products consumed in Ukraine are used for the needs of motor transport; while 80% of oil products are imported by Ukraine [5]. Following the increase of train weight and speed and, the lightening of bridge weight, the load induced by the moving train gained importance among the various external loads applied to bridge. Therefore, taking into account the bridges of the Korean high-speed train (KHST), as trains will run at speed of 350 km/h (in the future, this speed is planned to be increased up to 400 km/h), vibration analysis of bridges shall acquire more and more importance. In addition, when axle loads are repetitively applied at regular interval, as it is the

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case for trains, frequencies of the applied wheel load and of the bridge may coincide, favoring occurrence of resonance vibration in the bridge.

Purpose of the study

Significant progress in reducing costs of the transportation of grain was achieved in the USA and Canada in the late 20th, early XXI century. Changes in grain logistics in the US began in 1972-1973 in response to a sharp increased demand for grain in the world market [7]. These changes led to a change in the quantity, capacity and the location of elevators throughout the countries, improving the technology of grain transportation by rail and their tariff systems. Similar changes have occurred since the 1980s in Canada. Before the reform process, the logistics system for the delivery of grain by the North American Railways was working similar to Ukrainian railways. Empty wagons for transportation of grain were sent to technical stations, where were making groups from 1 to 25 cars loading stations. After loading the cars were sent to technical stations for compiling trains in accordance with the layout plan. In 1965, US began to use the technology of grain transportation for export to seaports by route transport [7]. Efficiency of grain transportation along the routes: with a decrease in the cost of the station, the more rational use of the capacity of wagons and throughput of the railways. At the same time, this technology requires the development of access roads and carrying capacity of elevators [10, 11, 12].

Methodology

Loads spaced at regular interval and bridge crossing at a given speed act as a repeated load, called beating, appears on the bridge. When the frequency of this repeated load approaches the natural frequency of the bridge, resonance of the bridge occurs. The axle loads of the considered 2P (18 ton) HSLM – (High Speed Load Model) coaches hit the bridge repeatedly and may induce resonance. In the case of the KHST running at high-speed, risk of resonance occurrence is larger than classical trains, and verification of vibration problems in the high-speed railway bridge is required during its design to guarantee the safety of the crossing train, which one is subordinated to strict crossing conditions. There-

fore, performing dynamic analysis that investigates resonance of the bridge induced by the bridge–train interaction constitutes an essential element of the design [7, 8, 9]. It is necessary to define the critical speed as the train speed for which resonance of the bridge occurs. Such critical speed is defined and based on the notion of resonance phenomenon due to regularly spaced loads moving at a constant speed and can be expressed as follows. The critical speeds corresponding to the dynamic characteristics of the bridge and the effective beating interval are summarized in Fig. 3. Structures operating at resonance show extremely sensitive dynamic responses according to their damping level. Following, the selection of damping becomes essential when dealing with resonance problems. In this study, the damping ratio of the actual bridge has been determined by means of field test using a rotary exciter. For details about the damping ratio used in this study refer to the Ministry of Construction & Transportation, the Ministry of Commerce, Industry and Energy, and the Ministry of Science and Technology [11]. The damping assumed for the dynamic analysis considered the Rayleigh damping using the measured actual damping. Field tests have been performed from August to September of 2001 in the experimental section of the KHST located in the construction area 5-2 of the Kyeong-bu high-speed railway line. The tested bridge is a PSCbox bridge. It is the Yeon-Jae Bridge, which characteristics make it representative of the bridges adopted for the KHST. The KHST has been designed for a maximum design speed of 350 km/h and is, actually, running at a maximum speed of 300 km/h in the experimental section situated at a distance of about 117 km far away to the South from Seoul. Field tests have been performed twice in two years under identical conditions, except the passengers' loading of the passenger coaches.

Findings

The obtained results indicate that the vertical interval shifts u_z (deflections) with simultaneous load taking into account spatial dynamic behavior structure and speed of cargo movement is nonlinear dependence on the magnitude of the track eccentricity. In all calculations relatively high shifts were obtained at loading speed of 200 km/h. The greatest range of extrema of vertical shifts is observed at eccentricity $e_y = 50$ mm; in other cases

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u_z amplitude variations are relatively low amplitude. The lateral displacement equations u_y have maximum if the amount of shift of the track $E_y = 10$ mm. The range of maximum displacements in longitudinal direction at loading speed of 100 km/h can be considered as motionless. Further increase in speed (up to 260-270 km/h) is accompanied by significant increase of u_x displacements and maximum amplitude of the longitudinal structure.
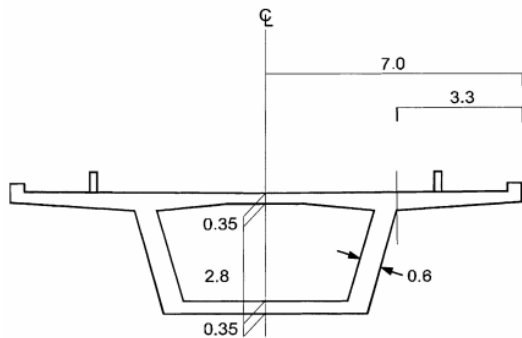

Fig. 1. Concrete span construction

Offset Value reduces and returns to the initial values in speed is 400 km/h. As a rule, the track magnitude of the eccentricity practically does not affect the longitudinal and torsional oscillations span of the bridge.
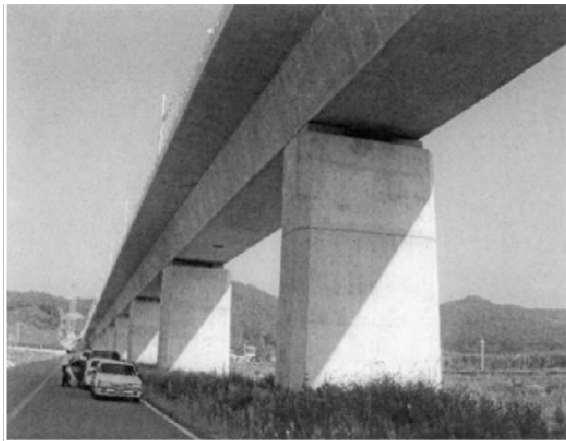

Fig. 2. View on Yeon-Jae Bridge for KHST

As the lifetime of railway bridges should be greater than 100 years for economic reasons, it is necessary to take into account long term considerations for choosing the traffic loads. Once having made a decision about future loads to be taken into account, there is no real problem in designing completely new bridges and for these bridges it is important to understand that heavier loads do not

significantly influence the costs of bridges. Greater problems arise however when it is necessary to upgrade existing lines and existing bridges need to be modified. In 1991, the ERRI (European Rail Research Institute) expert group D192 started research work into long term considerations on bridge loading and carried out a profitability study with a view to determine the effect of higher axle loads on the overall costs of bridges. They found that additional investment costs of only 3% where occurred when taking a 40% higher design load. Therefore, $\alpha = 1.33$ should be adopted for new bridges. This result is confirmed by a study within this EU-project «DETAILS»: Even if taking a factor $\alpha = 2,00$, that means 100% higher d sign load, the additional investment costs incurred reach only 10 %.
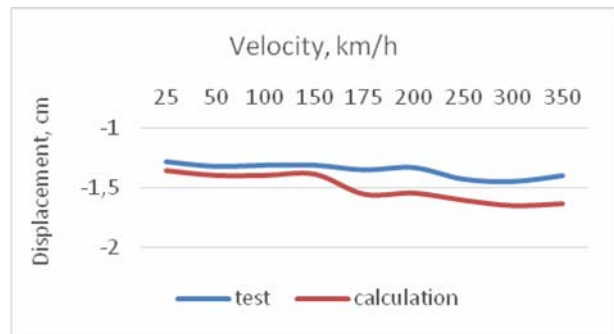

Fig. 3. Comparison of the calculations at SAP2000 and real test of the train movement under the bridge (2x40 m)
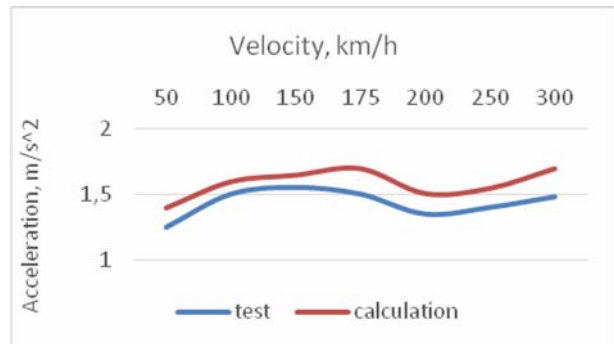

Fig. 4. Comparison of the calculations at SAP2000 and real test of the train movement under the bridge (2x40 m)

The Details project aimed at investigating the uncertainties concerning the real structural behavior of composite HSR bridges (i.e. resonance phenomena, train-bridge interaction effects, global and local dynamic loads, fatigue behavior, model-

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ing techniques, traffic spectra and exercise conditions) in order to improve the technical knowledge on the actual structural performance of such composite solutions. To this aim, an innovative global approach for the structural assessment was developed and calibrated on suitable case studies, representative of steel-concrete composite solutions currently adopted in European high-speed railway lines. Results permitted to elaborate final guidelines, were reported in chapter 15, for a reliable assessment of existing brides and the design of new ones. In particular, developed guidelines cover the following aspects of bridge engineering:

1. Experimental dynamic testing of composite bridges, i.e. indications for a correct identification of natural vibration modes and resonance phenomena considering the quality of experimental input data, the typology of excitation sources and the numerical procedures adopted for structural identification.

2. Evaluation of train-bridge interaction effects, i.e. general observations on train bridge dynamic interaction phenomena, descriptions of modeling techniques currently adopted to represent vehicle and structure dynamic properties, specific recommendations for a correct assessment of composite bridges under high speed-train passages.

3. Finite element (FE) modeling of composite bridges, i.e. integrated approaches, consisting of developing and updating numerical FE bridge models on the basis of experimental structural identifications, for a correct representation of the real dynamic behavior of composite bridges considering also the influence of secondary components and boundary conditions.

4. Recommendations for the design of railway bridges in accordance with the rules of the Eurocode, Specific instructions related to the Eurocode standards for the optimal design of the railway Bridges relative to the class of fatigue of bridge components, gain factors of vertical loads in accordance with effective rail traffic, permissible bridge deformations and vertical displacements.

In modeling the dynamic behavior of spatial rod system, some nonlinear components of motion nodes can be lost without taking into account moments of inertia of the nodes. In Euler-Lagrange differential equations of the relationship between angular velocity and angular acceleration, the node in the components is relative to the main axes of inertia, characterizing the connection between vertical, horizontal and torsional vibrations of the structure, as well as energy distribution in the system.

When resonance phenomena may influence significantly the dynamic performance of the bridge, suitable procedures for the correct evaluation of dynamic response and structural load distribution are needed. The moving load approach and the train-bridge dynamic interaction approach are two of the most adopted techniques for this purpose [1.4].

Originality and practical value

In this work, I performed dynamic measurements on the part of the Evon bridge, and also with the reactionary values from the Yonjaye bridge, the pre-stressed beam bridge. This bridge is along the Gyeong-bu high-speed rail. Then I compared results with standard dynamic performance values specified by the Eurocode and Korean high-speed rail. To determine dynamic performance of the bridges, I measured and analyzed the following elements: maximum vertical acceleration and maximum vertical displacement. Most measurements were within the control values. However, on the Yonjai Bridge some acceleration response is greater than the regulation value.

Conclusions

The steel composite bridge showed higher values of displacement and angles of rotation in comparison with the bridge of the pre-stressed beams. However, the acceleration response showed lower values. This result was not the effect of resonance, which occurs when a train passes through a steel composite bridge. Therefore, the component that monitors dynamic performance of the bridge is not included to calculation. Differences in the material of the bridge did not lead to differences in the dynamic characteristics of the bridges. Since the dynamic responses experimentally obtained in this study were the data obtained when the train moves at a working speed, complementing numerical analyzes I carry out with different train speeds and damping factors. As expected, the dynamic deviation can be amplified more than twofold when the speed of the train reaches a critical speed. In addition, the dynamic gain varies with the damping coefficient. The measured damping

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ratio has a certain amount of dispersion and calculated maximum dynamic response varies considerably due to the input damping coefficient. Future studies will be directed to determine the coefficient of input damping taking into account the distribution of the measured damping coefficient.

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ДИНАМІЧНА ПОВЕДІНКА ДВОПРОГІННИХ НЕРОЗРІЗНИХ ЗАЛІЗОБЕТОНИХ МОСТІВ ПІД ВПЛИВОМ РУХУ ШВИДКІСНИХ ПОЇЗДІВ

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Мета. Наукова робота передбачає порівняння результатів руху високошвидкісного пасажирського поїзда по мосту, отриманих внаслідок моделювання методом кінцевих елементів у програмному комплексі SAP2000, та реальних випробувань двопрогінного залізобетонного залізничного моста. А також аналіз жорсткісних характеристик прогонових будов. **Методика**. Система чисельного методу, представлена в цьому дослідженні, показує обґрунтовані результати, що стосуються динамічного аналізу поведінки мостів в умовах швидкісного руху поїздів. Визначено фактори, що впливають на динамічну поведінку мостів при рухомих навантаженнях, вплив проектних параметрів та рухомого складу, а також взаємодія поїзда й прольотів. Система використана у вигляді рухомих зосереджених сил, що моделюють осі поїзда. **Результати**. Були отримані максимальні переміщення й прискорення в результаті динамічного розрахунку для різних швидкостей руху поїзда та порівняні з практичними випробуваннями. Перевірена коректність моделі прогонової будови щодо нерозрізних залізобетонних прогонових будов. **Наукова новизна**. В рамках роботи використані новітні результати випробувань, в тому числі зі швидкостями, розрахованими на перспективу залізничних пасажирських перевезень. За даними випробування була розроблена і модель прогонової будови. **Практична значимість**. Результати досліджень можуть використовуватися для планування впровадження високошвидкісного руху поїздів за існуючими та проектованими пролітними будовами залізобетонних мостів. Виконано підхід до розробки конструкцій прогонових будов, які будуть ефективні при пропуску високошвидкісних пасажирських поїздів.

Ключові слова: динамічна взаємодія; бетонні мости; нерозрізний міст; швидкісний поїзд; SAP2000

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ДИНАМИЧЕСКОЕ ПОВЕДЕНИЕ ДВУХПРОЛЁТНЫХ НЕРАЗРЕЗНЫХ ЖЕЛЕЗОБЕТОННЫХ МОСТОВ ПОД ВОЗДЕЙСТВИЕМ СКОРОСТНЫХ ПОЕЗДОВ

Цель. Научная работа предусматривает сравнение результатов движения высокоскоростного пассажирского поезда по мосту, полученных вследствие моделирования методом конечных элементов в программном комплексе SAP2000, и реальных испытаний двухпролётного железобетонного железнодорожного моста. А также анализ жесткостных характеристик пролётных строений. **Методика.** Система численного метода, представленная в этом исследовании, показывает обоснованные результаты, касающиеся динамического анализа поведения мостов в условиях скоростного движения поездов. Определены факторы, влияющие на динамическое поведение мостов при движущихся нагрузках, влияние проектных параметров и подвижного состава, а также взаимодействие поезда и пролетов. Система использована в виде движущихся сосредоточенных сил, моделирующих оси поезда. **Результаты.** Были получены максимальные перемещения и ускорения в результате динамического расчёта для разных скоростей движения поезда и сравнены с практическими испытаниями. Проверена корректность модели пролётного строения касательно неразрезных железобетонных пролётных строений. **Научная новизна.** В рамках работы использованы новейшие результаты испытаний, в том числе со скоростями, рассчитанными на перспективу железнодорожных пассажирских перевозок. По данным испытания была разработана и модель пролётного строения. **Практическая значимость.** Результаты исследований могут использоваться для планирования внедрения высокоскоростного движения поездов по существующим и проектируемым пролётным строениям железобетонных мостов. Выполнен подход к разработке конструкций пролётных строений, которые будут эффективны при пропуске высокоскоростных пассажирских поездов.

Ключевые слова: динамическое взаимодействие; железобетонные мосты; неразрезной мост; высокоскоростной поезд; SAP2000

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