MODELLING AND NUMERICAL SIMULATION OF SYMMETRIC VIBRATIONS OF THE KNI 140070 VIADUCT – – BALLASTED TRACK – KTX TRAIN SYSTEM

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Abstract

The paper develops a new methodology of FE modelling and simulation of the bridge – track – moving train system with the use of CAE systems. The KNI 140070 viaduct of span length 14.40 m, located on the Polish Central Main Line, has been selected. The modernized track contains: 60E1 main rails equipped with Vossloh 300-1 fasteners, 60E1 side rails with SB3 fasteners, B 320 U60 sleepers, crushed stone ballast, approach RC slabs. A KTX (Korea Train eXpress) high-speed train, being a modification of a TGV train, is taken into consideration. A methodology of physical and numerical modelling of the viaduct, the track and the train was developed using Altair HyperMesh and LS-PrePost software. The FE model of a bridge superstructure consists of 4-node shell elements (main beams) and 8-node 48 DOF solid elements (reinforced concrete platform). RAIL_TRACK and RAIL_TRAIN modules available in LS-Dyna system were applied for simulating the train – track interaction. Hughes-Liu beam elements were used for the rail modelling. Rail fastenings were simulated using one-dimensional discrete spring and damper elements. Carbodies, bogie frames and wheelsets were considered as rigid bodies and they were modelled using shell and beam elements. Cylindrical and revolute constrained joints and discrete springs and dampers were applied to connect all components of the FE model of rail-vehicles. The exemplary simulation of transient vibrations of the bridge – track – train system has been made for service velocity 300 km/h. Contours of displacement and stress and selected time histories for displacements, accelerations and stresses, created in LS-PrePost and HyperView software, have been analysed.

Keywords: *railway bridge, composite bridge, ballasted track, KTX train, modelling and simulation*

1. Introduction

In spite of a large number of references in design, dynamics, service and maintenance of railway bridges, there still occur serious problems with durability protection of bridge superstructures, tracks and approach zones. First of all, it results from complexity of bridge – track – moving train systems which nonlinear models are described by a huge number of parameters. Many of these parameters, describing fasteners, ballast, subsoil layers, rail-vehicles' suspensions, track irregularities, settlements etc., are still unknown as they are difficult for identification. Producers and research institutions involved in modern high-speed trains do not bring to light structural details, values of parameters or their research results. These circumstances make prediction of dynamic response of bridges to moving trains very difficult.

In the 2nd half of the 20th century scientists mostly developed analytic – numerical methods in dynamics of railway bridges, summarized in monographs [2, 5, 9, 10]. They modelled transient and quasi steady-state vibrations of the bridge – train or bridge – track – train systems, without or with snaking of wheel sets taken into account. Problem-oriented computer tools were created by writers and used for simulations. At present, one may observe various numerical approaches to dynamics of railway bridges but commercial CAE systems based on FEM are still not used in this field, e.g. [3, 14, 17]. Summing up, vibrations of the bridge – track – moving train are transient, spatial and nonlinear. Modern bridge spans are designed separately for each track and have quasi-symmetrical cross-sections. Structural solutions in reference to ballasted rectilinear tracks and high-speed trains lead to negligible lateral vibrations of rail-vehicles. In those circumstances, assuming vibrations of the bridge – track – train system to be 3D but symmetric in respect to the vertical longitudinal plane of symmetry are reasonable.

The study develops a new methodology of FE modelling and simulation of transient vibrations of the composite bridge – ballasted track – KTX train system, making the use of advanced CAE systems. The KNI 140070 viaduct of span length 14.40 m, located on the Polish Central Main Line, was selected. The ballasted track serviced on PCML has been modernized by Authors in order to accommodate it to high service speeds of trains. The KTX (Korea Train eXpress) high-speed train is a modification of the TGV train.

The composite (steel – concrete) viaduct No. KNI 140070, located at 200.794 km on the Polish Central Main Line No. 4 –E 65, was selected for numerical modelling and simulation [12]. The platform is made of C35 concrete reinforced with AII/18G2-b steel re-bars. The side wall is made of C30 concrete and has vertical dilatations at 1/4, 1/2, and 3/4 of the span length. The track structure before modernization consists of UIC 60 rails, sleepers with SB3 fasteners, and ballast of the first class.

In order to conform the track to high service velocities up to 300 km/h, theoretical modernization of the track has been designed. The 60E1 main rails are fixed to B 320 U60 and B 320 U60–U sleepers with Vossloh 300-1 fasteners. The 60E1 side rails, coinciding the length of the approach slabs, are fixed with SB3 fasteners. The RC (C30 concrete, 18G2 re-bars) approach slabs have dimensions $l \times b \times h = 1020 \times 480 \times 20$ cm. The embankment in the approach zones contains cement-stabilized subsoil, while outside the approach zones a 20 cm thick sand-gravel mix layer has been applied.

A KTX (Korea Train eXpress) high-speed train, operated by Korean Railways, is a modification of the TGV Réseau train [16], but it is longer than its French archetype. The trainset consists of 20 cars, in which the first and the last one are the power cars and an additional motorized bogie is located in each intermediate car close to the power unit. A schematic diagram of the KTX trainset is depicted in Fig. 1. The carriages are equipped with the Jacob’s bogies which are common for two adjacent cars. The top speed in service equals 300 km/h.

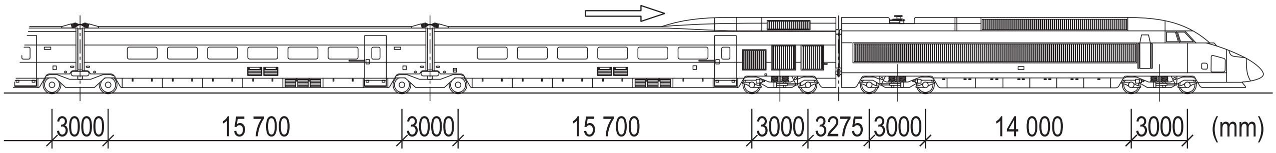

Fig. 1. A schematic diagram of the KTX train [16]

2. Physical and FE modelling of the BTT system

The following concept has been developed in physic modelling of the viaduct. The reinforcement of the RC platform and the platform side wall is distributed quasi-uniformly in specified platform sectors. The slab and the wall of the bridge platform are homogenized according to the mixtures rule [7]. The platform is symmetrised via replacing a single dilated wall with two smaller dilated walls on both sides of the platform slab. The vertical and horizontal bracing in the main beams set are neglected.

Schemes of the KNI 140070 viaduct are depicted in Fig. 2-4 where all elements taken in the FE modelling are marked, i.e. the homogenized platform (the slab and the walls), the main beams set, the vertical ribs welded to webs of the main beams, the horizontal bearing plates welded to the bottom flanges of the main beams over the bearings. Fig. 4 shows the original (grey lines) and symmetrised (black lines) cross-sections, whereas Fig. 5 – the longitudinal section of the viaduct and the symmetrised reinforcement close to the original one.

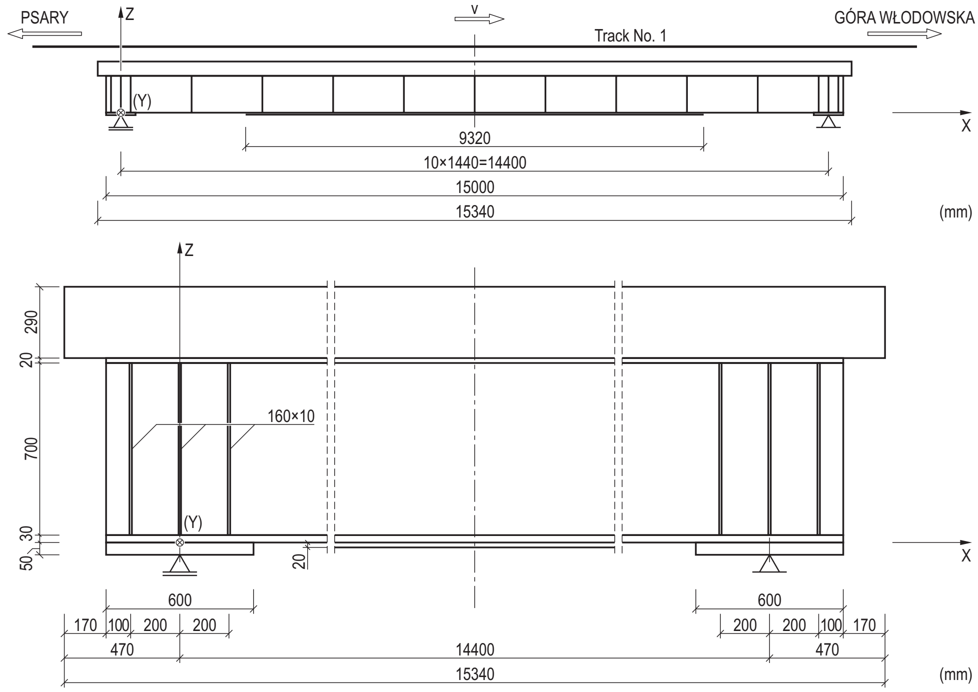

Fig. 2. The longitudinal sections of the KNI 140070 viaduct in the XZ plane

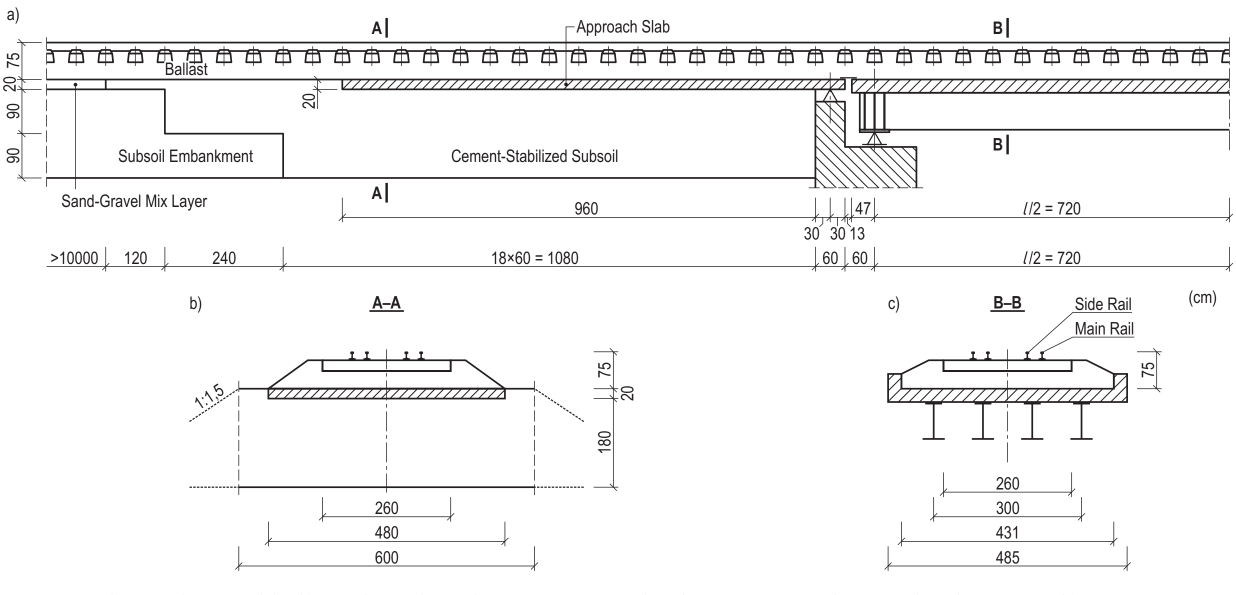

Fig. 3. The modernized ballasted track in the KNI 140070 bridge area: a) a longitudinal section; b) a cross-section in the approach zone; c) a cross-section over the bridge span

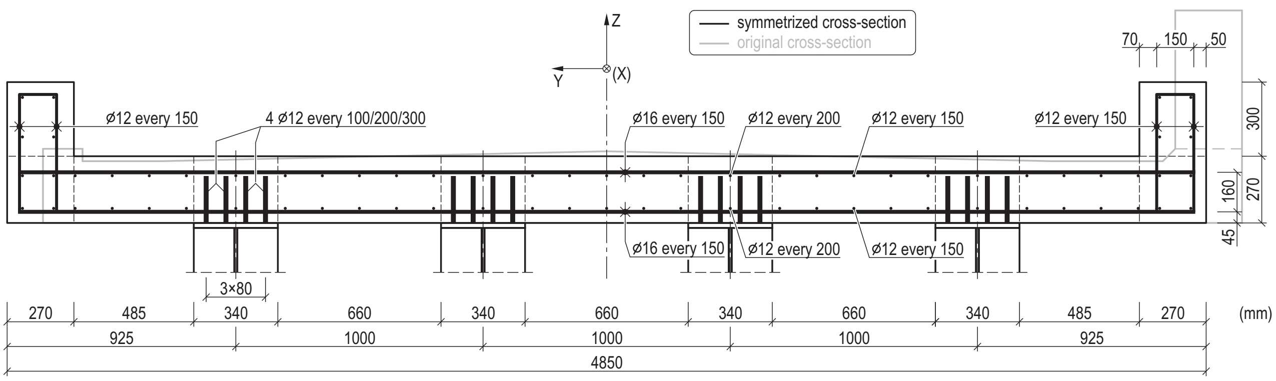

Fig. 4. The original and symmetrised cross-sections of the KNI 140070 viaduct and the symmetrised reinforcement

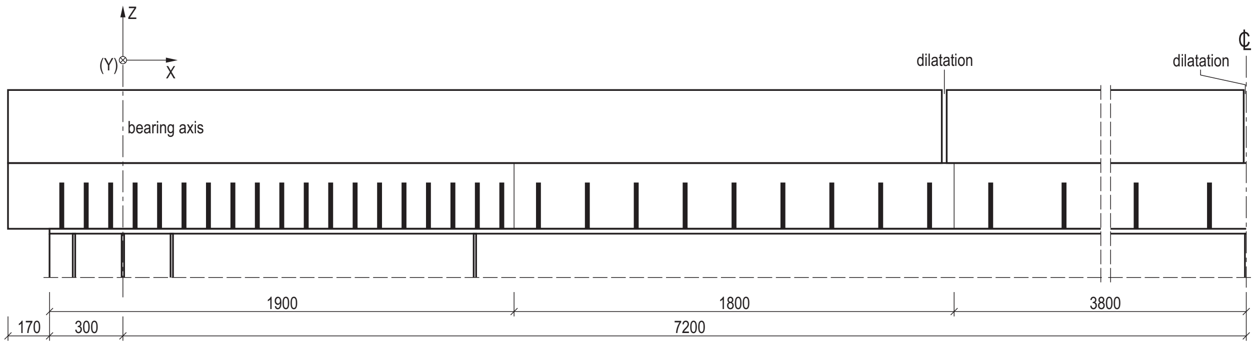

Fig. 5. The longitudinal cross-section of the KNI 140070 viaduct

The FE model of the bridge superstructure has been created in Altair HyperMesh software (Fig. 6). The numerical model of the bridge superstructure consists of 3896 4-node shell elements (steel main beams) and 5568 8-node 48 DOF solid elements (homogenized RC platform).

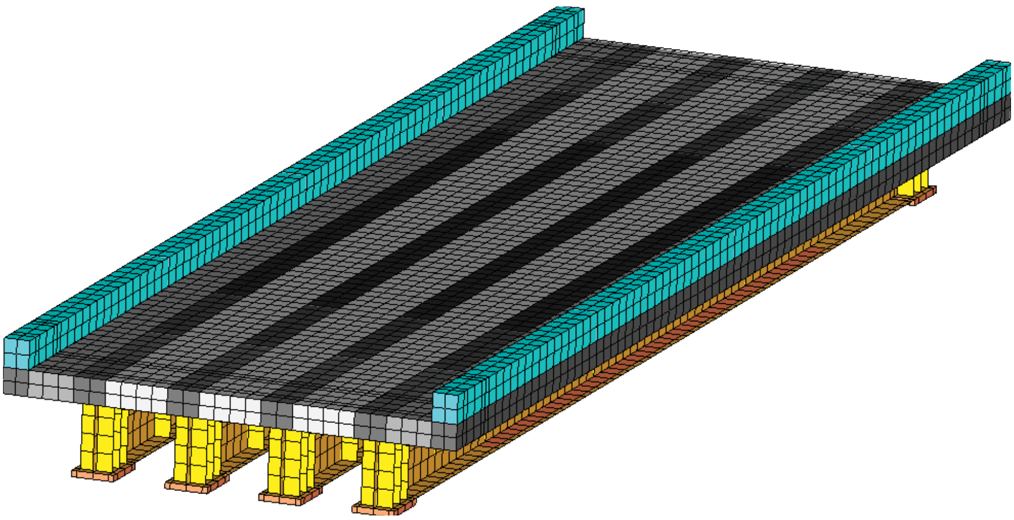

Fig. 6. The FE model of the KNI 140070 viaduct superstructure

The following assumptions have been made in physic modelling of the track. The rail-line axis is rectilinear, and in the unloading state the service rails are rectilinear. No rail surface irregularities appear. Vibrations of the track are small, symmetric with respect to the vertical *XZ* plane. The main and side rails are prismatic beams deformable in flexure and shear, made of linear viscoelastic material. Rail fastenings were simulated using massless one-dimensional nonlinear discrete spring and damper elements oriented vertically. Sleepers are modelled as rigid beams. Approach slabs are prismatic, modelled as linear viscoelastic isotropic continuum, and supported with non-deformable bearings. Layers of the embankment are considered as a linear viscoelastic material continuum. Values of the mechanical parameters of the modernized track parts have been determined mainly from Refs. [3, 4].

RAIL_TRACK and RAIL_TRAIN modules available in LS-DYNA [6] were applied for approximate modelling the train – track interaction (without simulation of wheels' rotation). Hughes-Liu beam elements (2-node elements with 12 DOFs [6]) were used for FE modelling of rails bent in the vertical planes. For main and side rails a substitute double-tee asymmetric cross-section was assumed, denoted in Ref. [20] as Type 10: I-Shape 1.

A concept of the FE mesh of the rail-track is partly reflected in Fig. 7 where the FE model of the track over the bridge platform is presented. Rail fasteners were simulated using massless one-dimensional discrete spring and damper elements oriented vertically [6]. The embankment has been reflected approximately by a rectangular prism with unmovable side and bottom boundary surfaces

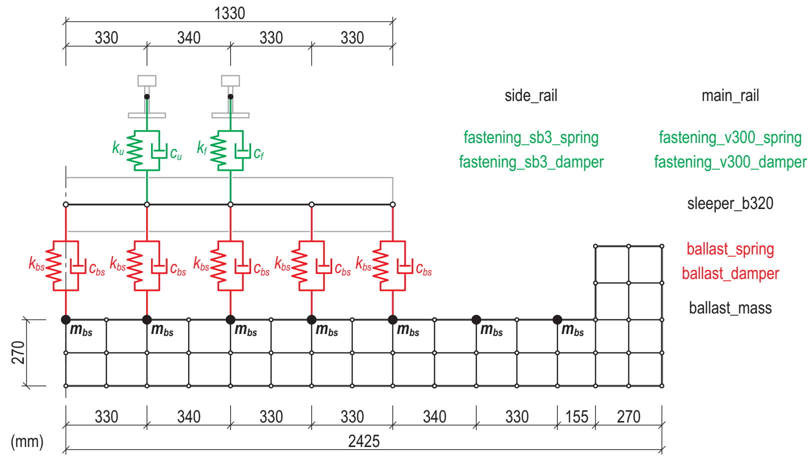

Fig. 7. The KNI 140070 viaduct's platform cross-section. The FE model of the track over the bridge platform (the components marked with different colours)

and meshed using 8-node 24 DOF solid elements. Sleepers are modelled as rigid beams vibrating only vertically, using finite beam elements and respective constraints. The ballast layer has been divided into cubicoid columns in coincidence with FE mesh of the parts under the ballast. Each ballast column was reflected by a vertical set of nonlinear spring and damper elements. The lumped mass distribution for the ballast has been applied in the bottom set of the nodal points contacting the platform slab, the approach slabs and the top subsoil layers.

The track section modelled numerically in the bridge – track – moving train system is of 810 m length. In total, the FE track model contains 141,770 beam, shell, brick and discrete elements and 21,658 point mass elements.

A numerical model of the KTX train consists of the following components: carbodies, bogie frames, wheel sets, vertical massless discrete linear viscoelastic elements reflecting the primary and secondary suspension systems. A numerical model of the KTX units with classic and Jacob's bogies is presented in Fig. 8. Vibrations of the train units are symmetric with respect to the main longitudinal vertical plane of symmetry of the bridge – track – train system. Respective constraints have been put into the system via incorporating translational CONSTRAINED_JOINT_CYLINDRICAL and rotational CONSTRAINED_JOINT_REVOLUTE elements [20]. A constant service velocity of the vehicle FE model was declared using INITIAL_VELOCITY and PRESCRIBED_MOTION_RIGID options for carbodies and bogies FE models [6]. The values of mechanical parameters of the vehicles have been taken from Refs. [4, 11].

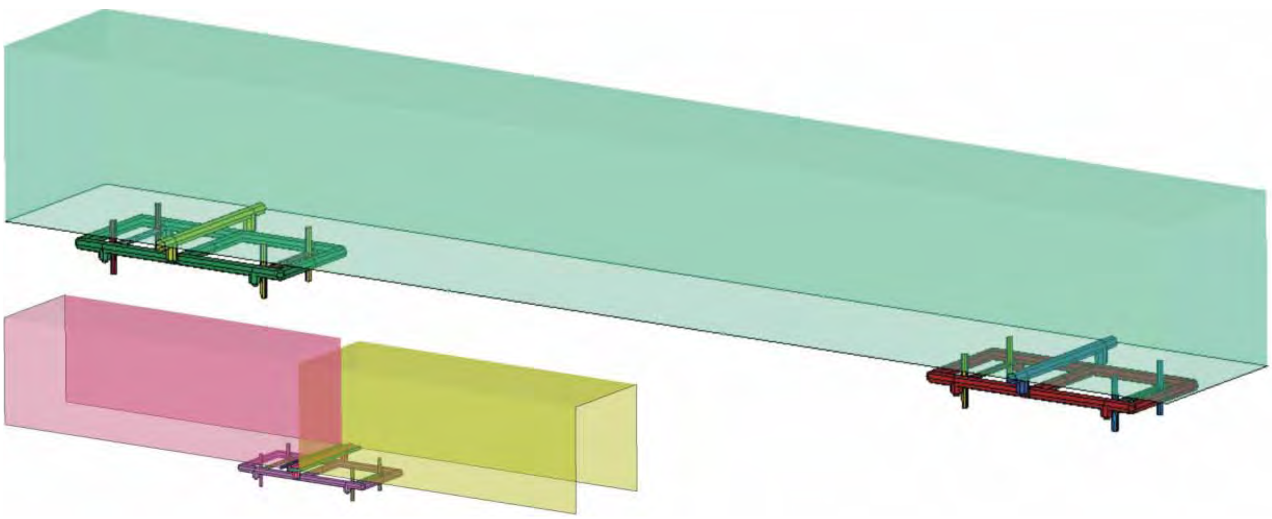

Fig. 8. A numerical model of the KTX units with classic and Jacob's bogies

In total, the FE model of the 8-unit KTX train contains 1,248 beam, shell and discrete finite elements and 66 point masses.

In simulations the DYNAMIC_RELAXATION option [6] has been replaced with loading the system by a set of vertical forces put in the moving vehicle – rail contact points according to the formula

$$P(t) = \frac{P_0}{2}\left(1 - \cos\frac{\pi t}{t_0}\right), \tag{1}$$

where P_0 is the static pressure of a single wheel on the rail head, t_0 = 2 sec is a time of the static loads increasing.

4. An example of simulation of transient vibrations of the BTT system

Selected output quantities were registered using following options: HISTORY_NODE_SET and HISTORY_NODE_SHELL. The computations have been made using the 120-P supercomputer. At the service velocity 300 km/h the real time equals 6.70 sec, while the CPU time amounts to 46 hours. Contours of displacement and stress and selected time-histories for displacement, acceleration and stress were created in LS-PrePost and HyperView software. Exemplary results are presented in Fig. 9 and 10.

Based on the numerical results the following detailed conclusions have been formulated. The dynamic response of the viaduct has the beam character with dominant influence of the first modal system of the viaduct. Vibrations of the internal main beams are slightly greater compared to the external main beams. The maximum deflection of the main beams amounts to 2.5 mm, whereas the maximum deflection of the main rails equals 3.8 mm. The approach zones designed in the study are very stable. The threshold effect is minimized. The vertical accelerations of the bridge superstructure reach 9 m/s^2 at the midspan and 130 m/s^2 in the main rails. The longitudinal normal stresses resulting from the dead load amount to 30 MPa, while the dynamic stress resulting from the train loading equals 15 MPa. The shear stress induced by the train are very small and <4 MPa. It testifies to high overdesign of the viaduct. Local concentrations of the effective stresses in the bottom flanges of the main beams over the bearings are visible. The dynamic response of the bridge superstructure to moving train is of quasi-static character, but stresses are fast-varying in time in a relatively wide interval. Thus, in the design calculations high-cycle fatigue should be taken into consideration.

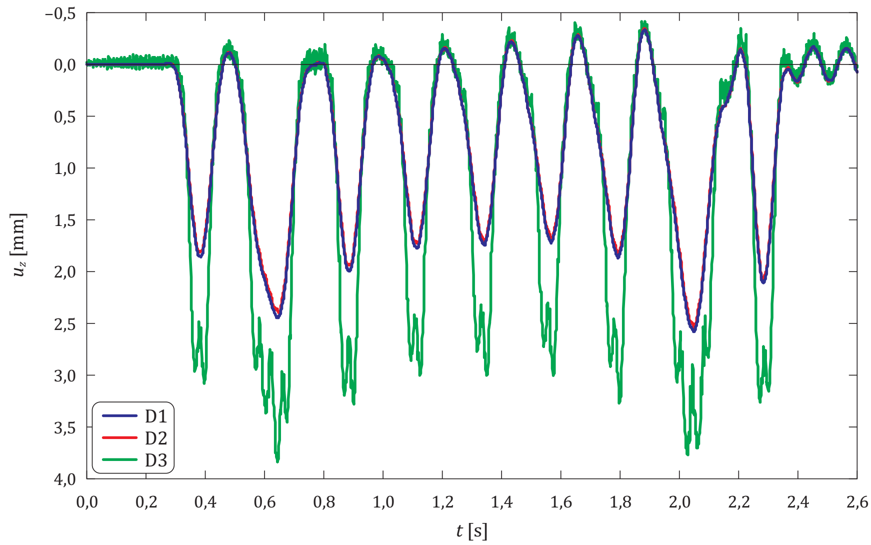

Fig. 9. Time-histories of selected vertical displacements at the midspan: D1 – the central point of the bottom flange of the internal main beam; D2 – the central point of the bottom flange of the external main beam; D3 – the main rail

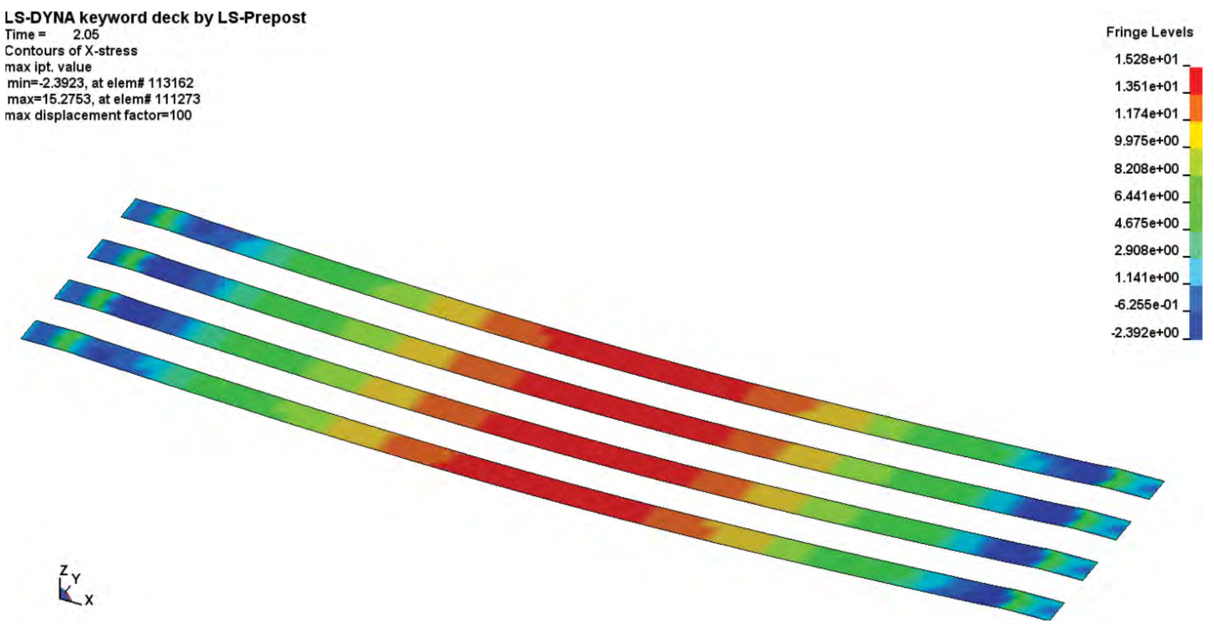

Fig. 10. Contours of the longitudinal normal stresses σ_x [MPa] in the bottom flanges of the main beams at t = 2.05 sec (the scale coefficient 100x for displacements)

5. Conclusions

The study develops FE modelling and simulation of the composite (steel – concrete) bridge – ballasted track – KTX train system. In the physical and numerical modelling of the system the following main limitations have been introduced: rectilinearity of the rail-line, no track irregularities, symmetrisation of the bridge superstructure, homogenization of the bridge RC platform, forced vibrations symmetric to the main longitudinal vertical plane of symmetry of the system.

The exemplary numerical analysis presented in the study is related to the KNI 140070 railway viaduct on the Polish Central Main Line hence the conclusions cannot be generalized. The analysed viaduct has appeared to be overdesigned what results in small dynamic effects at 300 km/h service velocity of the KTX train. Nevertheless, the results seem to be very credible and useful in engineering practice. Practical usability of advanced CAE systems, i.e. Altair HyperMesh, LS-PrePost, and LS-Dyna, in FE modelling and simulation of bridge – track – moving train systems has been proved. Other bridges or trains may be modelled and simulated via modification of the FE models created for the system undertaken in this study.

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