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Peculiarities of Ballastless Bridge Deck Slabs Interaction with the Main Girder of Metal Span Structures of Railway Bridges

The article deals with the peculiarities of the combined behavior of the ballastless bridge deck and the main girders of the metal span structures or the longitudinal girders of the carriageway of the span structures with through main trusses. Mathematical modeling of the combined behavior of plates and girders clarifies the idea of the actual nature of the operation of spans with a ballastless bridge deck and allows evaluating the efficiency of various areas for the structures improving. The effect of uneven inclusion of slabs in the girders behavior due to the deplanation of cross sections and the presence of transverse joints between the plates are taken into account in these studies. Estimates of the degree of inclusion of plates in the combined operation with girders and data on the redistribution of forces acting in the elements of the carriageway and main trusses are given. The main design schemes and analysis of the combined behavior calculations under the action of the rolling stock of the ballastless bridge deck plates and the main plate girders of the span structures are provided.

Key words: *design schemes, plates of a ballastless bridge deck, main girders, span structures, stiffness coefficients of elements.*

In the process of developing and improving the design of a ballastless bridge deck on RCC slabs, the main research efforts were focused on solving the problems of plate construction, deck laying technology and on field observations of the deck behavior under operating conditions. The problems of the theoretical study of the peculiarities of the combined behavior of a ballastless bridge deck and main girders of metal spans or longitudinal girders of the carriageway spans with through main trusses received much less attention.

The experience of operation without a ballastless bridge deck on the railways of Ukraine and the results of experimental studies show that the combined behavior of the ballastless deck plates with bending girders can cause various damages, which are mostly localized in the zone of attachment of plates to the top flange of the girders. Among these damages, there are the lining layer destruction, breaks in the studs attaching the plates to the girders. The cracks in RCC slabs are also observed.

When engaging in combined behavior with girders, plates of a ballastless deck significantly affect the stress-strain state of the girders. In particular, this should lead to a change in the stiffness of the span structure, as well as to a change in its dynamic properties. The significance of these changes highly depends on the degree of inclusion of plates in the combined behavior with girders. Along with experimental studies, mathematical modeling of the combined behavior of plates and girders is intended to clarify the ideas about the actual nature of the behavior of spans with a ballastless bridge deck and will allow us to evaluate the effectiveness of various directions of structures improving.

The effect of uneven inclusion of plates in the girders behavior due to the deplanation of cross sections and the presence of transverse joints between the plates was taken into account in these studies. Estimates of the degree of inclusion of plates in the combined behavior with girders and data on the redistribution of forces acting in the elements of the carriageway and main trusses were given.

The results were obtained using the averaged characteristics of the bracing compliance between the plates and the top flanges of the girders based on the calculation of linear-elastic models. At the same time, as it is shown in the observations and confirmed by the calculations, the plates can slip along the top flanges of the girders noticeably changing the whole nature of the combined behavior of the ballastless deck and the span structure. In this regard, it is necessary to develop a calculation method that allows taking into account the presence of nonlinear frictional bracings between the plates and the girders.

In addition, the stress-strain state of the gasket layer and the studs attaching the plates to the flanges was not investigated with sufficient completeness in the works mentioned above. Considering the often observed destruction of these structural elements, one should pay attention to the features of their behavior, which will allow drawing objective conclusions about the expediency of preserving this method of attaching plates to girders (maybe with some constructive improvement) or about the need to switch to fundamentally different methods of attachment.

To clarify the nature of the combined behavior of a ballastless bridge deck and main girders of metal span structures, the calculations should be performed for models that explicitly include design diagrams of all the main structural elements such as plates, girders, gasket layer and studs, as well as rails and angle protectors. A numerical study of such models will allow us to assess the mutual influence of various elements and the degree of their participation in the behavior of structures in general.

Due to the complexity of the design scheme describing the interaction of individual parts of the structure, when using the finite element method and modern computers, the final elements shall be enlarged, thus averaging the modeling properties of the parts of the structure. In this regard, a version of the calculation was carried out in this work where one structure fragment was considered in detail. First, this was done for more detailed assessment of the nature of the gasket layer and the studs behavior during operational impacts with considering such factors as the influence of the torsional rigidity of the top flange and the compression of its torsion at the locations of the vertical stiffeners. The results of this calculation are used together with the results of the calculation of the stress-strain state of the gasket layer performed during the previous tension of high-impact studs. The total stresses allow us to estimate the nature of the gasket layer behavior and, in particular, to reveal zones of local increase in the intensity of stress distribution. A mathematical model for calculating the interaction of the rail track, plates and girders of the span structure with a ballastless bridge deck, which takes into account the possibility of plates slipping along the flanges of girders and rails and angle protector along the plates is proposed in this work. Some of the simplifications used during building the model are not necessary, which allows its further improvement. In general, this model allowed a correct reflecting of the effect of the inclusion of a plate in the girders behavior when a span structure is bent in a vertical plane.

In the process of developing this mathematical model, an effective method for constructing the superelements for describing the plane stress state of thin plates and receiving a solution to a nonlinear system of special equations is proposed. Studies allow us to clarify the nature of the peculiarities of the ballastless bridge deck behavior together with the metal girders of railway bridges.

In the structures of the carriageway of the span with through main trusses and girder spans, the RCC slabs of the ballastless bridge deck are involved in the behavior of bending longitudinal (main) girders. In the contrary to the steel RCC span structures, the attachment of slabs to girders does not ensure their full inclusion in the behavior. The plates are associated with the girders by means of high-strength studs (see Fig. 1, a, b). The studs are pre-stretched, which should provide the desired value of the ultimate force, which acts between the slab and the top flange of the girder. The connection between the slab and the girder is elastic-friction.

It should be noted that the stresses from the pre-tension of the studs are distributed in the longitudinal direction extremely unevenly. Normal stresses at the contact of the plate and the gasket layer as well as at the gasket layer and the top flange are localized in the area of the stud and the connection between the plate and the girder is discrete.

The elastic component of the connection characteristics is negligible. Indeed, this component is determined by the flexibility of the stud, which is high compared to the flexibility of the plate and the girder flange. This consideration is confirmed by experiments on the plates displacement. On the "force-displacement" graphs, it is not possible to reliably identify the part that corresponds to a one-to-one (elastic) dependence of the shearing force and the plate displacement towards the top flange of the girder. Analysis of the experiment results allows us to consider that the connection characteristic between the plate and the girder is rigid-plastic (Fig. 1,d) until displacement force reaches its limit value T_n , the plate does not move the limit value along the girder (δ = 0). The maximum value of the displacement force does not depend on the value of the relative displacement δ.

The several types of slabs for the ballastless bridge deck are pbaruced; however, the ratio of the plates sizes in the plan can vary slightly. In general, the plates length l_n (Fig.1,c) changes between 1.5-2.0 m. The plates width $в_n$ is 3.2 m. In calculations of structures consisting of bending girders and wide plates associated with them, the deplanations of the plates cross sections during longitudinal deformations /6, 9/ shall be taken into account. Fig. 1d shows the character of distribution of the longitudinal displacements of the middle surface points of the plate with the symmetrical bending of the girders with respect to the axis of the span.

Technically, when bending the main girders and the longitudinal girders of the carriageway, the plates of ballastless bridge deck are not only deformed in their own plane, but also bend together with the girders. However, the effect of the bending stiffness of the plates on the bending stiffness of the composite structure can be neglected, since the intrinsic stiffness of the plates during bending is much less than the stiffness of both the girders and, especially, the stiffness of the built-up cross section (where the plate behavior in its plane is considered). This circumstance allows us to simplify the design scheme slightly when studying the interaction of plates and girders considering that the plate is in a flat stress state.

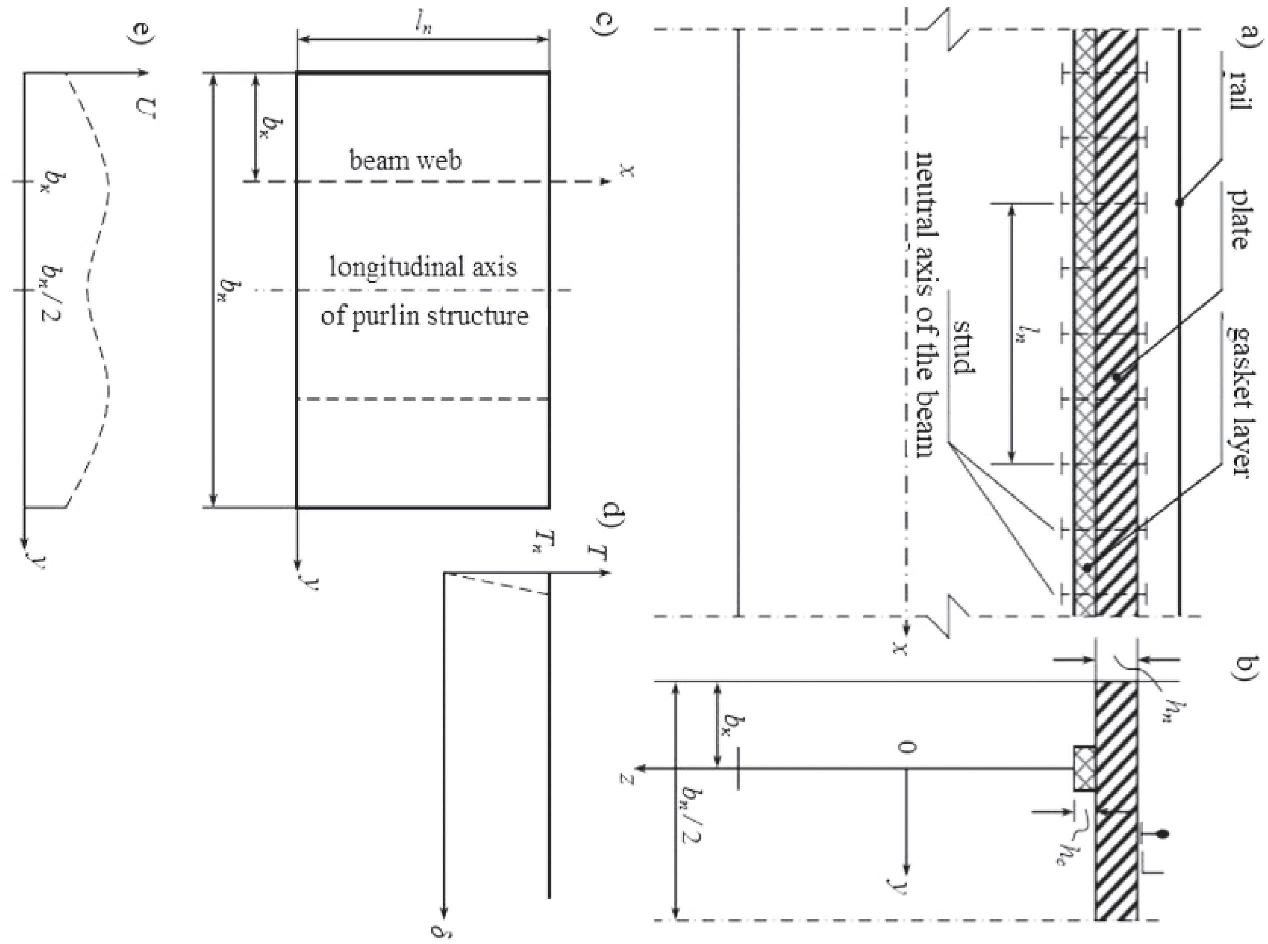

Figure 1. The design scheme of a ballastless bridge deck

The including of plates in the girders behavior can lead to a noticeable redistribution of forces and stresses in the elements of the span structure in general. For a fairly accurate assessment of the degree of plates including in the girders behavior and its consequences, it is necessary to calculate complex, multi-element objects formed by girders, tires, rails and angle protectors. The corresponding design schemes turn out to be quite complex and require the use of approximate methods for constructing resolving systems of equations. The theoretical analysis of the combined behavior of the balastless bridge deck at the RCC slabs with continuous main girders was carried out on the basis of the calculation of the girder span structure l_n = 23.6 m.

The continuous girder of the span structure was considered as a bar located along the neutral axis of the girder. Simulation of mutual deformations of the top and bottom flanges of the girder and the effect of girder deformations on the gasket layer, studs and plates was performed by scrubbing the horizontal bar, which replaces the girder, with supporting bars through fairly rigid vertical inserts. The load from the plates and the gasket layer were transferred to the bar, which replaces the girder through the vertical bars as well. Thus, in the design scheme, the span girder is presented as a frame with rigid units and a horizontal bar located at the level of the neutral axis of the girder and with vertical bars equal to half the height of the girder. In the supporting sections, the vertical bars are located both above and below the horizontal bar, and in the places of stud installations, they are located only above the horizontal bar.

Vertical bars simulate the retaining of flat sections when girder bending.

Vertical bars that simulate the gasket layer are attached to the vertical bars of the girder and are considered as a continuation of the latter.

The studs are also represented by vertical bars attached to the vertical bars of the girder, but in this case the attachment is carried out through the cantilever, the length of which allows keeping in the design diagram the relative position of all elements, namely, the girder, the plate and the gasket layer.

In the design scheme, the plates of the carriageway are located relative to the girder, rail and angle at the same distance as in the actual structure. The transverse division of the plates into individual elements coincides with the stud locations.

The longitudinal division of the plates coincides with the places of attachment of the angle, rail, studs and the gasket layer.

Four loading schemes with temporary load were considered, namely, two schemes of loading by concentrated forces from the wheels of the rolling stock and two other loading schemes corresponding to the load of the studied girder with load C14 for the maximum moment in the middle of the span and the maximum force acting on the support.

The displacements and stresses in the elements of the plate and the displacements and forces in the studs, in the gasket layer and in the bar replacing the girder were obtained as a result of the calculation.

The stiffness coefficients of the elements of the proposed design scheme were set in such a way as to maintain the ratio of the stiffnesses of the individual elements of the actual structure (Table 1).

Table 1. Stiffness factors of design scheme elements

Element description	EF t	EI_Y tm^2	EI_Z tm^2	$GI_{кр}$ tm^2
Horizontal elements of the girder	764400	474700	10000000	10000000
Rail	173460	745.08	119.49	2980.32
Angle	103110	246.75	246,75	987
Studs	2525 5050	0.121 0.242	0.121 0.242	0.483 0.966
Horizontal elements in studs fastening to vertical bars of the girder	840000 1680000	0,098 0,196	500000 1000000	500000 1000000
Gasket layer elements (without shear strain)	610500 1221000	0.1 0.1	1295.5 2581	0.1 0.1
Rail securing	10000	7.9	7.9	0.1
Angle holding	5000	3.95	3.95	0.05
Plates	3500000	0.15	0.16	–
Girder stiffeners. Vertical bearing bars of the girder	100000000 100000000	100000000 100000000	100000000 100000000	100000000 100000000
Vertical girder bars simulating flat sections	300000000 450000000	9000000000 450000000	900000000 450000000	9000000000 450000000
Gasket layer elements for shear strain	0 0	0.0005 0.001	1620 3240	0 0

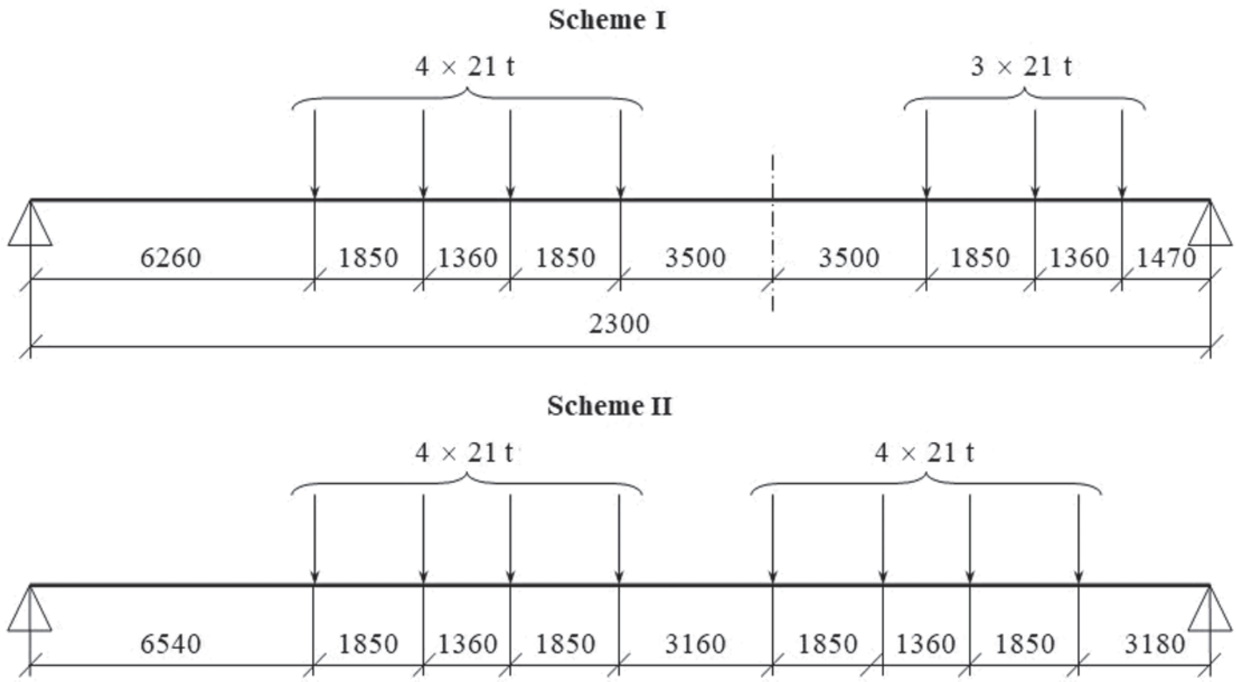

Figure 2. The real stiffness factors are set for the rail, the angle and the studs.

The stiffness of the bar that replaces the girder is equal to the stiffness of the girder. The stiffness of the vertical bars (Fig. 2, a) are given sufficiently large ($EF = 10^8$ t, $EI = 10^8$ tm^2) to keep flat vertical cross sections in the design scheme.

For the plates' elements, their actual thickness δ, the elasticity modulus of concrete E and Poisson's ratio ν are provided.

Figure 2. The real stiffness factors are set for the rail, the angle and the studs.

The gasket layer was simulated by two types of bars. Bars of the first type had actual EF, EI_Z, and $EI_y = 0.1$, when the second type bars had only actual stiffness EI_y.

Bars of the first type are rigidly attached to the vertical bars of the girder and to the slab. The bars of the second type are also rigidly attached to the vertical bars of the girder and have a hinge along the Y-axis at the point of attachment to the plate.

The stiffness coefficients of the bars simulating the attachment of the rail and the angle were set to transfer the vertical pressure and the longitudinal shearing force, T = 2 t/LM. Based on these requirements, the values of the geometric characteristics of the bars cross section were set (EF, EI_y, EI_Z, GI_{cr}).

Analysis of the calculation results is as follows:

– when C14 load is applied, the forces in the rail reach 32 tons.

– force N along the rail length is distributed unevenly. In the slots between the plates, the forces diagram has a boost of about 20%, for example, from 24 tons to 31 tons.

– the longitudinal force in the angle within the plates is 2-2.5 times less than the force of the rails. In the slots between the plates, the forces in the angle are approximately equal to the forces in the rail and reach 33.5 tons when C14 load is applied. Actually, the longitudinal force N in the rail and the angle are changed more smoothly. The boosts in the diagrams has occurred as a result of the specific peculiarities of the design scheme related to the attachment of the rail and the angle to the slab at the edges, whereas in fact this attachment is made at a distance of about 0.25 m from the edge. However, the assumption adopted in the design scheme does not affect the maximum values of the forces in the rail and the angle. When analyzing these efforts, their values shall be taken in sections located above the slabs.

– the shearing forces in rail fastening elements vary within the plate from 2.5 tons to -3.7 tons with a load according to schemes 1, 2, and from 5.8 tons to -5.9 tons when C14 load.

– the shearing forces in angle fastening elements are slightly higher than those in the fastening elements of the rails and vary from 8.8 tons to 9.4 tons when 1 and 2 loads and from + 16.9 tons to -17.5 tons when C14 load.

– N_{y1} force (along the centerline of the span structure) varies quite significantly along slab width and is maximal in the places of the plates bearing on the girder, i.e. in the places where the studs are installed.

– forces M_{x1} and M_{y1} reverse the sign in the places of plates attachment to the girders and in the places of rail and angle bearing.

– the longitudinal force N in the studs along the length of the girder varies slightly. In general, the studs are stretched, and due to load 1 and 2 additional axial forces are equal to 71.4 kg and 73.6 kg, respectively, and because of load 3 (load C14), additional force in the stud is 97.9 kg.

– elements of the gasket layer are mainly compressed, slight stretching is observed in some elements of the gasket layer when loaded by concentrated forces (load 1 and 2); the stresses in the concrete do not exceed 0.17 kg/cm^2. All elements of the gasket layer are compressed due to the application of evenly distributed load C14 (load 3).

– the occurrence of insignificant tensile stresses in the bars, which simulate the gasket layer, is explained by the fact that the calculated bar scheme of the model does not exactly correspond to the continuous layer.

– the shearing forces in gasket layer Qz varies along the plates significantly.

The maximum shearing force when load C14 is 29.14t. The shearing forces are increased by the middle of the span and to the edges of the plates.

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