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Research paper

"Track-Bridge" Interaction Problems in High Speed Bridge Design

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Abstract

Track-bridge interaction problems have a main role in the design of bridges on high speed railways (HSR). In this paper, a technique is described for performing calculations of the interaction of the elements of the "bridge-jointless track" system. The complexity of these calculations lies in the nonlinear relationship between the bridge spans and the railway track. The characteristics of these relationships are largely determined by climatic factors (summer and winter conditions), as well as the presence of temporary loading on the bridge. The results of the interaction "bridge-jointless track" system are presented at temperature and train impacts for the characteristic types of bridge structures in the form of multi-span beams and continuous beams. The influence of the length, the construction scheme, the longitudinal stiffness of the intermediate supports on the magnitude of the forces arising in the rails of the continuous path is shown. Based on the performed calculations, conclusions were drawn about the characteristic modes of operation of the "bridge-jointless track" system and recommendations were made on constructive measures reducing efforts in rails.

Keywords: high speed railway, track-bridge interaction, jointless track, bridge

1. Introduction

Bridge construction merged with continuous welded rail function as the unique system "bridge - jointless track", and the system's elements interact actively. It achieves the reallocation of efforts inside the system, that depends on the elements' options and on type of its connection. A bridge as a foundation for jointless track is substantially different from a roadbed with construction high deformability under the influence of external factors (temperatures and forces), whereupon additional efforts, absent in rails on the roadbed, appear in rail on the bridge [[1]-[11]]. The aim of the study is analysis track-bridge interaction and development of recommendations for the design of bridges on HSR. Rails stress state outside the bridge is determined, as known, by wheels concentrated pressure and appearing temperature forces, determined by rail temperature changes according to the rail fastening to sleeper temperature to the actual temperature. Mentioned longitudinal efforts in rails of jointless track are basic.

Additional efforts in rails of jointless track are due to [[12]]:

• bridge constructions deformability because of change of the surrounding air temperature;

• bridge constructions deformability under the action of temporary vertical load [[13]-[17]];

• horizontal train load effort lengthwise path axis (acceleration or braking force).

The factor causing stress in rails while usage of jointless track on a bridge common to a track on roadbed and on bridge constructions is rail temperature change from the rail fastening temperature to sleeper t_f to the actual temperature t (in the interval ΔT_p).

In this case temperature axial stress σT_{Rn} can be determined by:

$$\sigma T_{Rn} = \alpha_p \times E \times \Delta T_p \quad (1)$$

where α_p and E - coefficient of thermal expansion and steel elastic modulus.

In construction design code for engineering structures and superstructures on HSR [[18]-[20]] there are rail temperature values, that are possible for different regions of the country (t_{max} and t_{min}), then:

$$\Delta T_R = t_{\max} - t_з ; \Delta T_R = t_з - t_{\min} \quad (2)$$

When designing continuous welded track on bridges special attention should be given to such a factor as temperature axial deformations of the span structure as a result of which longitudinal forces are transferred to the rails of jointless track through the superstructure. In this case the rate of interaction between rails and bridge is determined depending on the season (possibility of ballast freezing) and on existence on the bridge of the train load. In winter conditions the resistance value to rail displacement (when the ballast is frozen) significantly exceeds the relevant "summer" characteristic. Loading the bridge by train leads to an increase of values of the connections' characteristic between the rails and the span. While calculating for temperature effect it's necessary to consider two design cases:

• rails and spans heating in warm season with the minimum allowable rail fastening to sleeper temperature in cold season;

• rails and spans cooling in cold season with the maximum allowable rail fastening to sleeper temperature in warm season.

A characteristic feature of system "bridge - jointless track" work, that causes the appearing of additional efforts in rails, is span deformation at the level of passage under the action of temporary continuous vertical load. The span in this case rolls back to the movable supports and bends, whereupon in the rails in fixed supports zone tension occurs. Over the movable supports of the span, generally, compressive forces appear in the rails, but it can be tension if the beam has a large construction depth.

Additional efforts in rails also occur due to the effect of horizontal loads of the rolling stock during braking or starting from the place (acceleration force). Longitudinal braking or acceleration forces are taken in the form of a linear load equal to 10% for freight trains from the standard vertical load. With the longitudinal action of the load from high-speed trains, the determining factor is the tractive force (based on the limitation of acceleration force on the clutch) in the amount of 25% of the vertical mobile load [[18],[20]].

Due to the static indeterminateness of the jointless track on bridge system the rigidity of the abutments and piers exerts a great influence on the forces values in the rails arising under the action of the horizontal traction forces (braking) of the rolling stock and the temperature influences transmitted to the piers through the supports of the span structures. Insufficient stiffness of the piers in the direction along the axis of the track may require special actions to provide the facility of the jointless track organisation on the bridge. In addition, the longitudinal forces and bending moments in the rails depend significantly on the state and physical and mechanical characteristics of the track superstructure on the bridge.

Excessive mutual displacements of the track and the span structure can lead to the decompaction of the ballast and changes in the parameters of the interaction of the track and the structure. The maximum displacements also indirectly limit the additional longitudinal stresses in the rails. It is necessary to control the following mutual displacements from the braking or accelerating forces as shown in Fig. 1, 2 and Table 1.

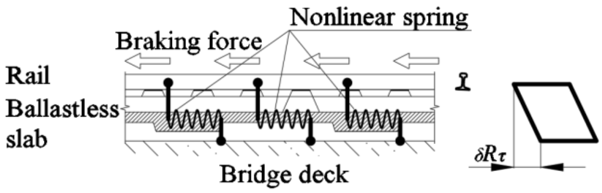

Fig. 1. Mutual displacements of rails and spans from the longitudinal forces

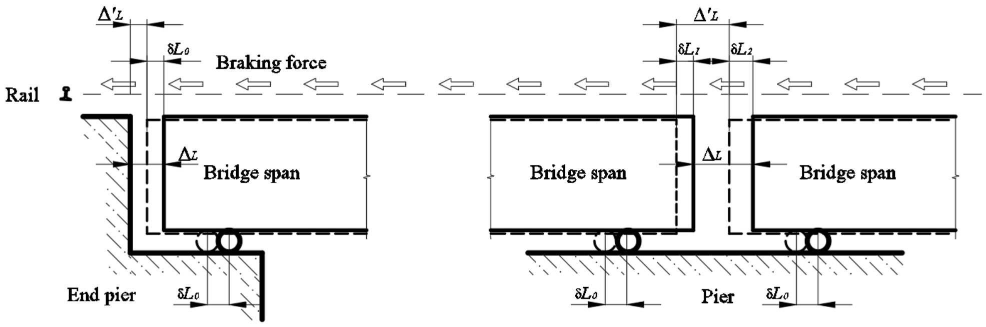

Fig. 2. Mutual displacements of spans from the longitudinal forces and temperature

Table 1. Maximum mutual linear displacements from braking and accelerating forces [[18]]

Type of railway track	**The presence of expansion device from both ends of the span**	
	without expansion device	**with expansion device**
Mutual displacements of rails and spans δRτ (Fig. 1)		
Any type of railway track	≤ 4,0 mm	no limit
Mutual displacements of spans δL = Δ'L- ΔL (Fig. 2)		
Ballast track	≤ 5,0mm	≤ 30,0 mm
Ballastless track	≤ 5,0 mm	no limit

2. General Regulations of the "Bridge-Jointless Track" System Design

According to the design documentation developed for the Moscow-Kazan HSR, a continuous track with rail strings of any length, laid within the bridge and approaches on reinforced concrete sleepers and crushed stone ballast or on reinforced concrete slabs (the ballastless superstructure) [[20]].

In calculating the longitudinal interaction of a continuous welded track and a bridge structure, the nonlinear nature of the connections between the rail and the slab track is assumed. According to the current normative documents [[18]-[20]], the connections are described by the Prandtl diagram, which takes into account that, at small mutual displacements of the rail and bridge, the elastic work of the bonds is realised, and at large - the plastic one. A similar nature of the connections is adopted for the calculation of the interaction of jointless tracks and bridge structures in European Codes for the design of high-speed railways objects.

For the numerical solution of the problem, the continuous connection between the rail and the span structure can be replaced by concentrated bonds (nonlinear springs) at a number of points along the length of each span structure of the bridge and approaches. The design scheme, therefore, will represent a rod system with a finite number of degrees of freedom, which includes a number of nonlinear elements.

2.1 Design Scheme

The design scheme of "bridge - jointless track" system is adopted as a rod model with 3 types elements:

• simple elastic rods that help to describe the work of rails, beams of spans and piers;

• nonlinear springs describing the work of bonds between rails and span structures;

• "rigid inserts", simulating mutual eccentricities and the height position of rails, span structures and supports.

In the elements of the system "bridge - jointless track" under the influence of train and temperature loads, internal forces (normal forces, transverse forces and bending moments) arise. Each node of the design scheme has three degrees of freedom (two components of the vector of the linear displacement of the system and the angle of rotation).

As part of the design scheme (Fig. 3) there are three characteristic areas: the left approach, the bridge, the right approach.

In the first and third sections of the diagram there are horizontal elastic rods (rails) and associated "springs", resisting horizontal (shift) and vertical (compression) displacements. The springs are rigidly fixed at the bottom of the superstructure of the track, which is considered to be undeformable in the sections of approaches.

The rigidity characteristics of springs can be along the length (the variability of the characteristics is determined by the existence of a temporary load). The second section of the design scheme includes:

• a group of rods modelling each span structure;

• springs modelling superstructure (connections between rails, sleepers and span);

• horizontal rods (rails);

• additional flexible springs, the rigidity characteristics of which take into account the elastic compliance of piers in the direction along the bridge.

The beam span structure is modelled by horizontal elastic rods with corresponding rigidity characteristics and with axial deformations. The rods are located at the level of the beam axis and have rigid vertical elements at their ends, which ensure the connection between the beam and the pier in the level of hinges of the supports.

When calculating multi-span structures the adopted scheme can consider any variants of connecting spans (a split system, a chain of split beams joined together, a continuous span structure, a frame).

Piers are modelled by elastic springs characterised by rigidity, which is defined as the magnitude reverse to the magnitude of the displacement of top of the pier in the hinge level from the unit force. When determining the rigidity characteristics of the spring simulating the pier, the compliance of the soil foundation and the deformation of the above-foundation part of the pier are taken into account.

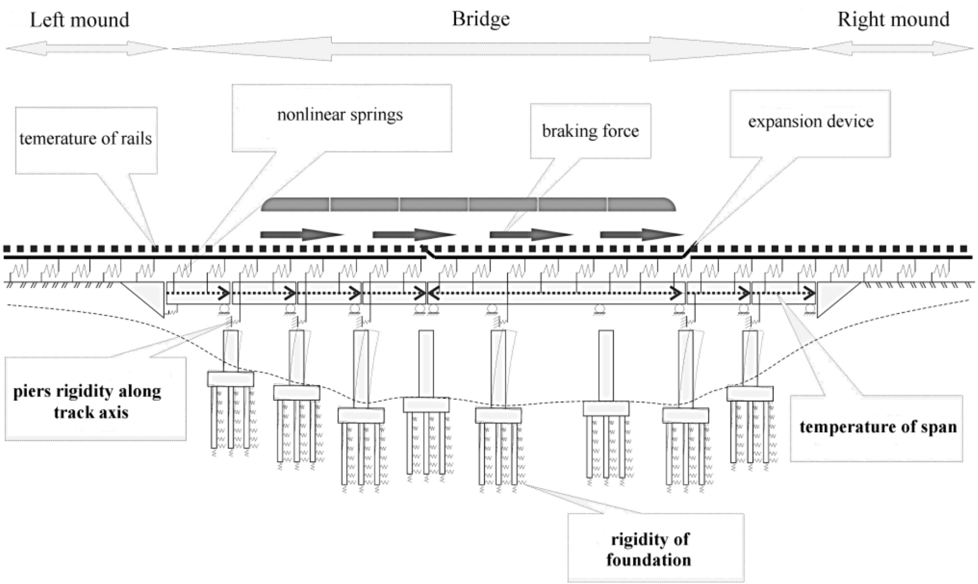

Fig. 3. The design scheme of the "bridge - jointless track" system

2.2 Rigidity characteristics determination of bonds between rails of the jointless track and bridge spans

To make calculations to determine the forces and displacements in the "bridge - jointless track" system, it's necessary to know the rigidity characteristics of the rods (finite elements) forming the system. For rods that simulate rails, beams of spans and piers rigidities are determined by known methods. In turn, the determination of the rigidity of nonlinear springs, imitating the connections between the rail and the beams of spans, is difficult. This is explained by the fact that the rigidity characteristics of the bonds depend significantly on the level of temporary loads, the degree of compaction and contamination of the ballast, on the season, climatic characteristics of the area, and so on. When the rail threads are tightly fastened to sleepers, for example, separate type of fasteners, and the ballast is not compacted sufficiently, the resistance of the rails to the longitudinal shift is determined by the resistance of the ballast (more exactly, the entire rail-sleeper grid in the ballast). This is a calculating case for the usage of a jointless track in summer season; in winter season, such a situation occurs only in case of clean ballast (such a ballast doesn't freeze) and with a good enough drainage from the span.

From the experience of usage the track superstructure it is known that over time, in connection with the compaction and contamination of the ballast, the freedom of movement of the sleepers along the track axis decreases and in winter it becomes close to zero. In this case, the resistance from friction between rail and tie plate will be defining.

For both of these calculating cases (summer and winter) the displacement and force relationship is nonlinear (Fig. 4).

The rigidity characteristics of bonds, as shown by experiments, depend substantially not only on time of year and the ballast state, but also on the magnitude of the temporary vertical load on the track. In this work the data determining horizontal bonds according to the recommendations of the norms [[18]] is accepted.

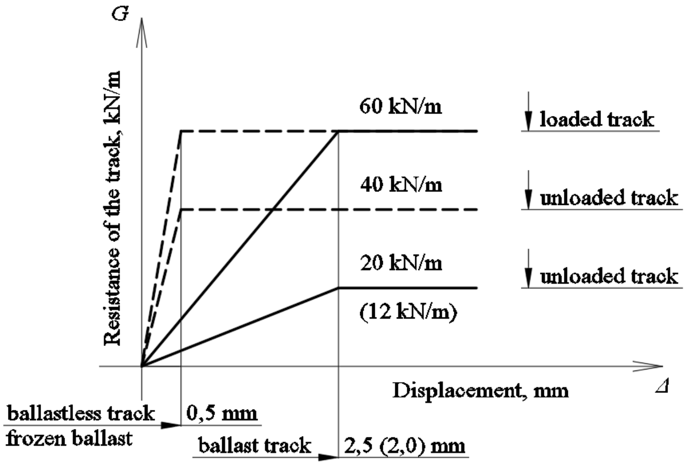

Fig. 4. Diagrams of the dependence of the displacement - the force (rigidity) of the track relative to the span structure from the value of the mutual displacement

Resistance to ballast shear in cold season (winter calculation case), the very high possibility of ballast freezing and compacting is taken into account. It can be assumed that the shift resistance is determined by the friction of the ballast prism over the concrete of the ballast tank. This resistance is sufficiently high, which is confirmed by the fact that in winter conditions, as a rule, it is not possible to obtain experimentally the displacements of sleepers in ballast. Assuming that the compacted ballast of the bridge floor has frozen and froze to the ballast tank, the interaction of the rail and the slab track will be determined only by the rigidity of the rail joint and fastenings. For the ballastless track, norms determine the character of the bonds close to the frozen ballast, characterised by higher rigidity.

3. Methodology for Beam Bridges Calculation with a Jointless Track for Temperature and Longitudinal Train Forces

The considered design model allows to determine the magnitude of longitudinal forces in the sections of rails on the bridge with temperature changes and the effects of the train load. When calculating the interaction of a jointless track and a bridge, the load SK (at K = 8.0) and the load from high-speed trains [[18]] are taken as a temporary movable load.

When calculating two situations should be considered: passage for the construction of a high-speed train (main load) and the passage of a train corresponding to the SK load (alternative load).

When calculating the forces it is necessary to consider the vertical and horizontal effects of the movable loads, taking into account the number of tracks, counting the decrease of load intensity while two track are loaded together and dynamic coefficients.

To search for extreme values of controlled factors the following situations should be considered:

- positive or negative temperatures;
- various positions of trains on the structure;
- different directions of horizontal load (braking or acceleration);
- arrangement of trains on one or two routes.

In some cases it is necessary to perform calculations using different models and with different details to find the most dangerous situations.

Additional stresses in the rails on the bridge (in relation to the stresses on the roadbed) caused by the effects in the calculated combinations should be calculated by the formula and should not exceed the values of Table 2:

$$\sum \sigma_R = \eta_T \cdot \sigma T_R + s_1 \cdot \eta_F \cdot \sigma F_R + s_1 \cdot \eta_\Theta \cdot (1+\mu) \cdot \sigma \Theta_R - \sigma T_{Rn} \leq \Delta\sigma_R \tag{3}$$

$\Delta\sigma_R$ – limiting additional stresses in rails according to the table [MPa];
$\Sigma\sigma_R$ – additional stresses in rails due temperature, longitudinal forces (braking and acceleration) and bending of the span [MPa];
σT_R – stresses in rails due temperature [MPa];
σF_R – stresses in rails due longitudinal forces (braking and acceleration) [MPa];
$\sigma\Theta_R$ – stresses in rails bending of the span [MPa];
σT_{Rn} – stresses in rails on the embankment [MPa];
η_T, η_F, η_Θ – coupling ratios;
s_1 – coefficient taking into account the appearance of trains on neighboring tracks;
$(1+\mu)$ – impact factor.

Table 2. Maximum additional tensions in rails

Additional stresses	Ballast track, MPa	Ballastless track, MPa
compression	72	92
tension	92	

4. Piers Rigidity along Track Axis

In studies about the interaction of jointless track and bridge structures it is emphasised that the values of the longitudinal forces in rails are largely determined by the rigidity of the bridge piers in the direction along the track axis: with increasing of rigidity of piers the force in rails from the longitudinal loads decreases [[20],[22]].

The rigidity of piers and foundations is considered in the calculating model by a horizontal elastic bond with equivalent rigidity.

When modelling the body of reinforced concrete piers it is assumed that the cross-sections work in an elastic stage and there is no disclosure of cracks.

When modelling pile foundations, their compliance was determined according to the instructions of the [[18]].

Investigation of the interaction of the jointless track and trestles of large length (more than 1 km) confirms the fact that a noticeable change in longitudinal forces in rails under the action of force and temperature factors occurs only at the end sections of the overpass. In the middle part the temperature forces in the bridge rails practically do not change from the span to the span. Much more important is the length of the train following in the braking mode by the overpass. In this case the increase of the force Np can be very significant, determined by the length of the brake load and the rigidity of the piers in the direction along the bridge.

The results of calculations of the longitudinal interaction of a continuous welded track and bridge structures HSR "Moscow - Kazan" on the example of a bridge across Kliazma river. Scheme of construction: 43×34,2+58+110+58+3×34,2m. Type of the track superstructure: slab track.

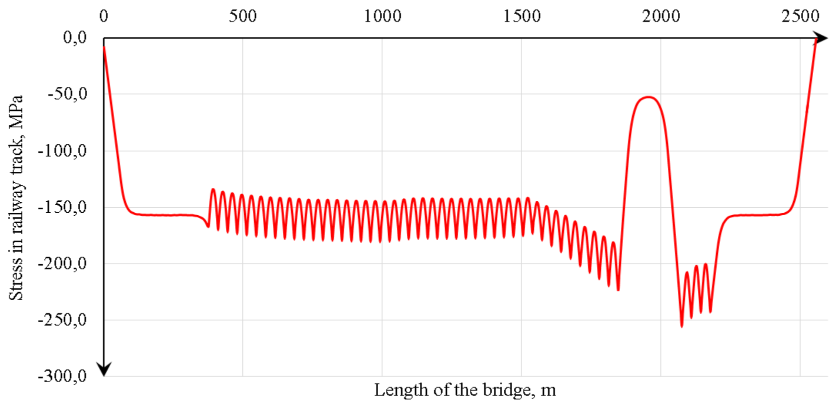

Fig. 5. Additional efforts in rails on the bridge across Kliazma river on HSR "Moscow - Kazan"

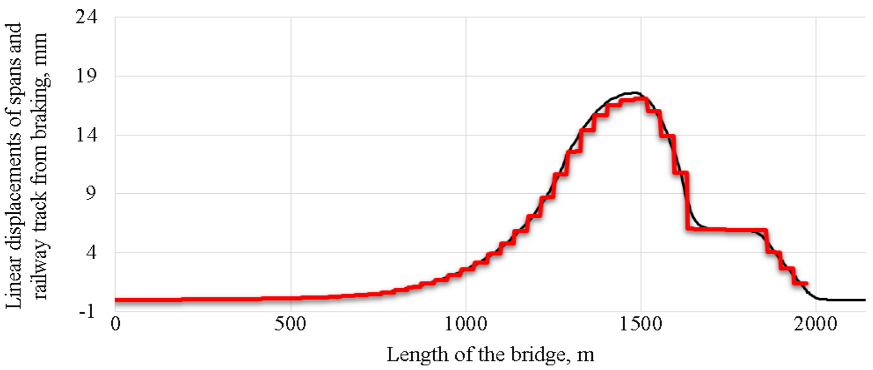

Fig. 6. Linear displacements of spans and track under the braking load on the bridge across Kliazma river on HSR "Moscow - Kazan"

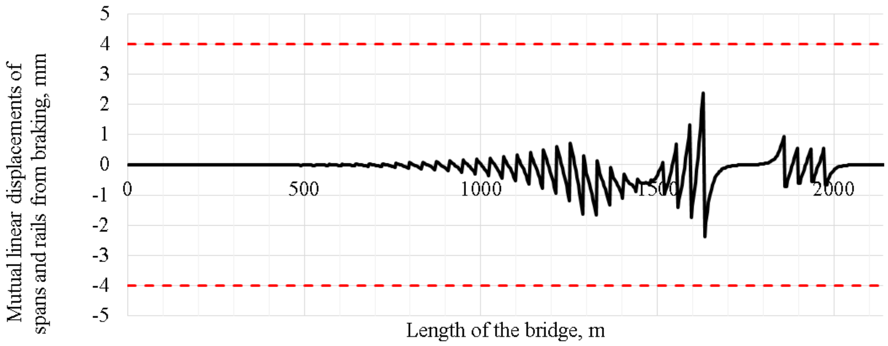

Fig. 7. Mutual linear displacements of spans and track under the braking load on the bridge across Kliazma river on HSR "Moscow - Kazan"

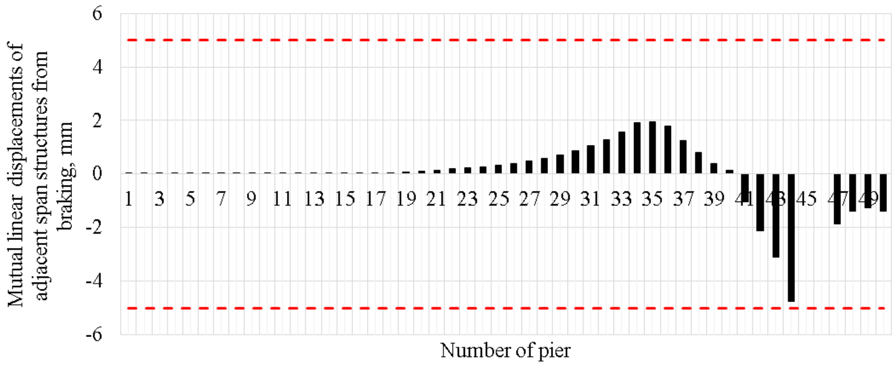

Fig. 8. Mutual linear displacements of adjoining spans under the braking load on the bridge across Kliazma river on HSR "Moscow - Kazan"

5. Conclusions

On the basis of the presented provisions of the methodology and carried out studies of the bridge structures and railway track interactions for HSR "Moscow-Kazan", the following conclusions can be drawn:

1. Analysis of the longitudinal interaction of the jointless track and trestles of a frame, beam, beam-continuous system and beam overpasses joined in chains showed that in the case of beam split systems the longitudinal forces in the bridge rails are the smallest.
2. In beam overpasses the longitudinal forces in rails of the jointless track of the bridge, span beams and horizontal piers reactions increase with the length of the temperature span, the temporary load class and the calculated temperature range (from the rails and structures at which rails are fixed to the extreme for this region), and also depend on the length of the structure.

The greatest efforts in the elements of the "bridge - jointless track" system arise under the temporary vertical load and the longitudinal train load with the conditions of the rail temperature change, taking into account the effect of deformation of the span beams caused by the temperature change of the elements of the bridge and the effect of temporary vertical load. In this case the maximum axial forces in the rails can occur not only within the trestle, but also on the approach - behind the backwall, where the movable span supports are located.

3. When loading a multi-span overpass of beam split system with a longitudinal train load, the horizontal reactions of the piers from the ends of the overpass to its middle part gradually increase to the maximum determined by the product of the linear load value on the span length l. At the end sections of the overpass with a length of 150-200 m, the piers are significantly unloaded by transferring part of the longitudinal train load through the rail track to the approaches. However, the horizontal support reactions caused by temperature changes to the ends of the overpass increase slightly, so that the effect of decreasing the horizontal loads on the piers of the end sections of the overpass, marked by the action of horizontal train forces, decreases somewhat.
4. The dependence of the longitudinal force magnitude in the rails of the bridge on the rigidity of the connections between the track rails and the span structure is nonlinear. The influence of the rigidity of the bonds on the forces in the rails increases with the increase of the span length.
5. The values of the longitudinal forces in rails of a continuous welded track on the overpass from the combined effect of temperature and force factors depend on the rigidities of the piers in the direction along the axis of the track: with decreasing of piers rigidity, the forces in the rails increase, with increasing of rigidity, forces decrease. However, the increase of piers rigidity is effective up to certain limits, the excess of which practically does not reduce the effort in the rails.
6. The placement on the trestle pier of the same supports slightly reduces the values of the longitudinal forces in the rails of the jointless track as compared with the case of different supports on each pier. But the decrease is insignificant, mean while the axial forces in the beams of the span structures and the load on the piers increase significantly.
7. The longitudinal forces in rails along the length of the structure, caused by temperature and longitudinal (for example, braking) loads, significantly change along the length of the trestle at the lengths of the structures only up to 300-350 m on the overpasses of the beam-split system with regular schemes (equal spans, equal rigidity of the piers). For large trestles lengths, the longitudinal forces in the rails change along the length of the structure only at its end sections. In the middle part of the overpass with the increase of its length, the efforts increase in rails is not observed if there is no longitudinal train load on the trestle section. In the presence of the train load longitudinal forces arise in the rails of the bridge, the larger the magnitude, the larger the length of the braking train and the less overpass piers rigidity in the direction along the axis of the track. This leads to the necessity to limit the minimum possible piers rigidity.

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