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The influence of unloaded rails on the distribution of switch tie deflection in connecting tracks

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ABSTRACT The paper presents the findings of a study exploring the influence of unloaded rails in connecting tracks on the distribution of deflection of reinforced concrete switch ties when a train moves along the direct track. The finite element method (FEM) was used to develop a spatial analytic model of connecting tracks at a turnover, including both loaded and unloaded rails and switch ties on a continuous elastic cushion. The model was verified by comparing the FEM calculations against the conventional solution for a beam on an elastic cushion using the initial parameter method (Krylov functions). The comparison of results has shown good convergence. The study has identified quantitative relationships between changes in system stiffness and distribution of deflections along the switch tie length based on its length and loading patterns. It has been shown that unloaded rails reduce the maximum deflection by 5–15%, displace the deflection point towards the centre of the switch tie, and contribute to more uniform distribution of deflection. When unloaded rails are excluded from the calculation, the load transfer efficiency factor for switch tie-to-ballast load transfer is overestimated. The “reverse” bending of the switch tie ends typical of the design model of a beam on a continuous elastic cushion remains virtually unchanged when unloaded rails are introduced. This value is mainly determined by the length of a switch tie and stiffness of the cushion, which supports and elaborates on the conventional approaches offered by V.F. Yakovlev and I.I. Semenov.

KEYWORDS: turnout; switch tie; track stiffness; unloaded rails; deflection; finite element method; initial parameter method; elastic cushion

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Research article

Влияние ненагруженных рельсов на распределение прогиба стрелочного бруса в соединительных путях

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АННОТАЦИЯ Представлены результаты исследования влияния ненагруженных рельсов в соединительных путях на распределение прогибов железобетонных стрелочных брусьев при движении по прямому направлению. На основе метода конечных элементов (МКЭ) построена расчетная пространственная модель соединительных путей стрелочного перевода, включающая нагруженные и ненагруженные рельсы и брусьями на сплошном упругом основании. Проведена верификация модели путем сопоставления расчетов МКЭ с классическим решением для балки на упругом основании методом начальных параметров (функции Крылова). Сравнение полученных результатов показало хорошую сходимость. Установлены количественные зависимости изменения жесткости системы и распределения прогибов по длине бруса в зависимости от его длины и схемы нагружения. Показано, что ненагруженные рельсы

снижают максимальный прогиб на 5–15%, смещают его точку к середине бруса и способствуют более равномерному распределению нагрузки. Исключение из расчетов ненагруженных рельсов дает завышение коэффициента эффективности распределения нагрузок стрелочным брусом на балласт. «Обратный» изгиб концов бруса, характерный для расчетной схемы балки на сплошном упругом основании, практически не изменяется от наличия ненагруженных рельсов. Данный параметр в основном определяется длиной бруса и жесткостью основания, что подтверждает и уточняет классические подходы В.Ф. Яковлева и И.И. Семенова.

КЛЮЧЕВЫЕ СЛОВА: стрелочный перевод; стрелочный брус; жесткость пути; ненагруженные рельсы; прогиб; метод конечных элементов; метод начальных параметров; упругое основание

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INTRODUCTION

The interaction between a turnout and rolling stock is one of the key topics in rail transport that determines the safety, efficiency, and durability of railway infrastructure. It involves a variety of aspects, from physical parameters of turnouts through the undercarriage of rolling stock to dynamic processes that occur during movement [1]. The rolling stock – turnout system is a dynamic system that changes over time during movement. Interactions between rolling stock and a turnout produce intense dynamic loads. These have a destructive effect both on parts of rolling stock and components of turnouts [2].

Scholars from the All-Russian Scientific Research Institute of Railway Transport, Moscow State University of Railway Engineering, Leningrad Institute of Railway Transport, Dnepropetrovsk Institute of Railway Engineering, and other railway universities have made major contributions to studying the dynamic rolling stock–turnout interaction. These include V.I. Abrosimov, V.G. Albrecht, S.V. Amelin, G.E. Andreyev, M.F. Verigo, B.E. Glyuzberg, E.I. Danilenko, N.N. Yelsakov, G.G. Zhelnin, G.V. Zotkin, G.I. Ivaschenko, L.G. Krysanov, N.N. Putrya, I.I. Semenov, M.P. Smirnov, A.M. Teitel, M.I. Titarenko, M.Yu. Khvostik, G.M. Shakhunyants, V.F. Yakovlev, and others.

The majority of studies on turnouts are devoted to methods for improving them, increasing the reliability of their individual components and assemblies, dynamic testing, technologies for routine maintenance and repairs, and increasing operational durability [3–8].

Despite all the experience gained to date, the influence of design features of turnout connecting tracks on the value and nature of distribution of the sub-rail base elasticity in the current operating conditions has not yet been sufficiently studied.

One of the recent works of interest is a study by M.A. Egorov [9], in which the author simulated the dynamic interaction between turnouts and rolling

stock. The paper studied the effects of rail joint welding, grinding of the tread surface of rail elements, and the elastic modulus of the turnout base in the vertical plane. However, it did not consider the influence of unloaded rails on stiffness.

Uneven wear of turnout components (track switches, connecting tracks, frogs) is due to the spatial heterogeneity in structural stiffness characteristics both along the length and in the cross-section of a turnout. The heterogeneity is caused by a set of factors, with the main being the variable nature of the force interaction in the rolling stock–turnout system [1]. Contemporary research [10–12] also supports the relevance of studying spatial heterogeneity of track stiffness in turnout areas.

The key components are:

- a variable mass ratio between rolling stock and tracks at different load points;
- complex, variable patterns of load application relative to the supporting elements (switch ties), especially in areas of track branching and rails crossings;
- structural features that create stress concentration zones due to fluctuations of rolling stock in vertical and horizontal planes.

Thus, the problem of identifying elastic irregularities of track rails within a turnout is a relevant issue for turnout facilities. One of the key aspects of the problem is a precise assessment of the influence of unloaded rails on switch tie deflections, as the conventional methods only produce estimated results.

CALCULATING DEFLECTIONS AND IDENTIFYING RELATIONSHIPS

Deflection of a switch tie in cross-section under a loaded rail is an integral indicator that depends on a complex interaction of several elements:

- the switch tie's stiffness (material, cross-section geometry, length);

- the bearing capacity of the ballast and subgrade formation (the modulus of subgrade reaction);
- load application coordinates relative to the support points and the centre of the switch tie; and
- the influence of unloaded rails attached to the same switch tie.

The deflection of unloaded rails together with the switch tie will cause reactive forces (moments) in the fastenings that are directed against the displacement vector. This produces the effect of additional elastic support, significantly reducing the overall deformability of the system.

To take this effect into account, V.F. Yakovlev [13] offered a reduction method, where the moment of inertia of a loaded rail I_1 is increased by a certain value $K_0 I_2$ equivalent to the resistive action of unloaded rails. In a simplified form, this can be represented as follows:

$$I_0 = I_1 + K_0 I_2, \tag{1}$$

where I_0 is the reduced moment of inertia of the track rail; I_1 is the moment of inertia of the loaded rail; I_2 is the moment of inertia of the unloaded rail which is structurally connected with the loaded rail; and K_0 is the coefficient that accounts for the fraction of combined action of the unloaded and loaded rails.

Numerically, K_0 is equal to the fraction of the moment of inertia of the unloaded rail. It was proposed to determine values of K_0 using a design model (Fig. 1) from the ratio of rail sagging under load:

$$\begin{aligned} K_{01} &= \frac{q_3}{q_1}, \\ K_{02} &= \frac{q_4}{q_2}. \end{aligned} \tag{2}$$

This formula is not exact, as it does not take into account changes in the form of deflection of the switch tie axis caused by changes in external and reactive forces.

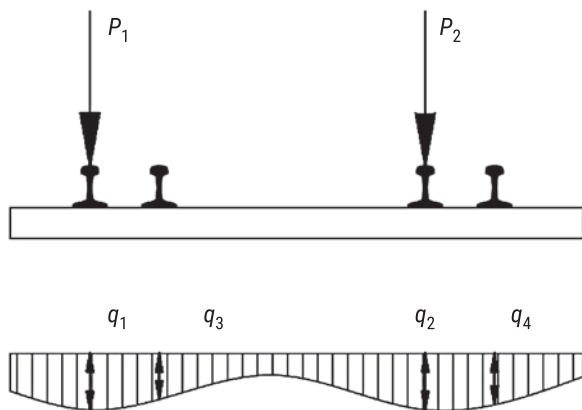


Fig. 1. V.F. Yakovlev's design model for determining K_0 [14]

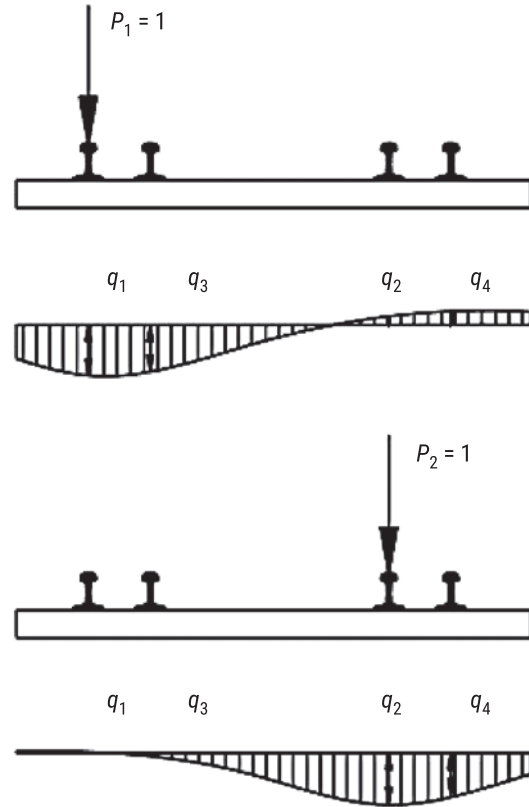


Fig. 2. V.F. Yakovlev's design model for determining K_0 [14]

Using formula (2) to determine K_0 will also produce approximate values that need to be refined.

In his paper [14], I.I. Semenov proposes to take into account that both unloaded rails, rather than just one, influence the deflection of a loaded rail. Based on the principle of superposition, the deflection under an unloaded rail is obtained by adding load actions of both loaded rails (Fig. 2).

Taking this into account, the value of K_0 is determined using the following formulas:

$$\text{from force } P_1 \quad K_{01} = \frac{q_3}{q_1} + \frac{q_4}{q_1}; \tag{3}$$

$$\text{from force } P_2 \quad K_{02} = \frac{q_3}{q_2} + \frac{q_4}{q_2}.$$

A well-known model for determining switch tie deflections disregarding unloaded rails is the analytic model in the form of a short beam on a continuous elastic Winkler foundation. Deflections are estimated, for example, by the initial parameter method using Krylov functions [15]. This approach is only applicable to static loading cases. However, this is reasonable, as at the realistic speeds of rolling stock, the inertial forces of track elements are small compared to the weight component and the inertial forces of the gyrating masses of the rolling stock. Therefore, they can be neglected without introducing a substantial error to re-

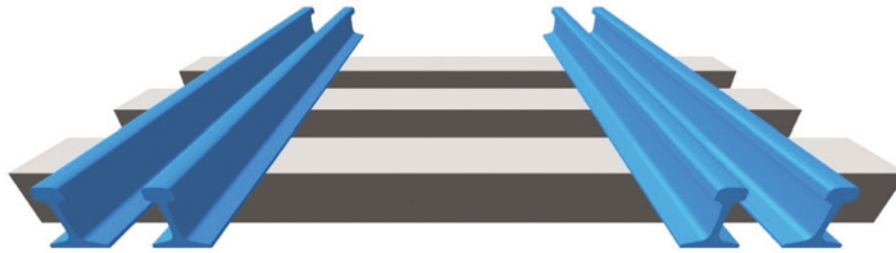


Fig. 3. 3D visualization of the design model with a 3.0 m long switch tie

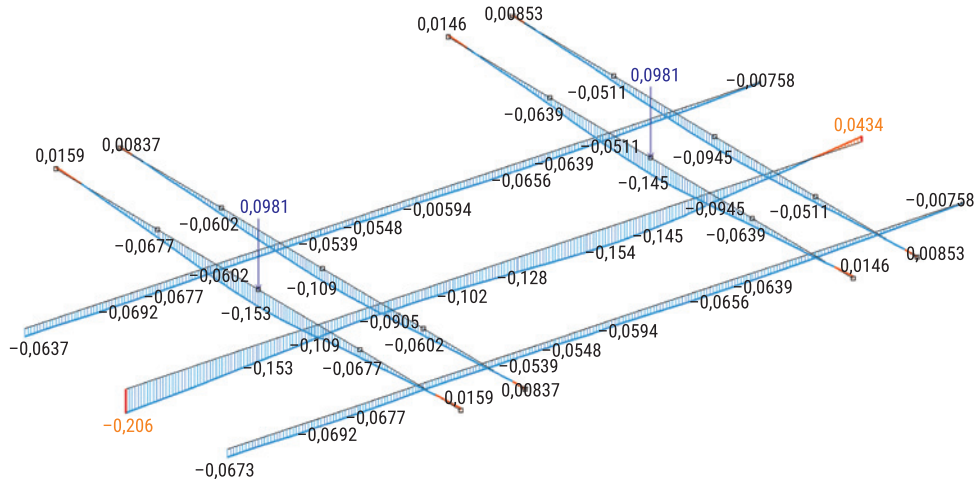


Fig. 4. Diagrams of deflections of both rails and 3.0 m switch ties taking into account unloaded rails

al-world design. In recent years, problems of dynamic interaction have been actively explored using numerical methods [9, 12].

The physical essence of the phenomenon is more accurately reflected when a switch tie is seen as a beam on an elastic isotropic half-space, in which the relationship between stress and deflection is non-linear. However, in this case, the calculations are more cumbersome, and the input conditions and parameters are not more accurate [16].

It is difficult to directly use this method for the “switch tie–multiple rails” system due to static indeterminacy (the reactive forces from unloaded rails are unknown).

To solve the problem, the authors used numerical modelling using the finite element method (FEM). We built a spatial model consisting of three adjacent switch ties, operating (rolling) and non-operating rails (Fig. 3), in which:

- the model switch ties and rails are designed as beam elements that carry bending stresses and have relevant stiffness ($E_{st} = 36,000 \text{ MN/m}^2$ and $E_r = 206,000 \text{ MN/m}^2$);
- the model elastic foundation is designed using discrete spring elements that are uniformly distributed over the lower plane of the switch tie with the modulus of subgrade reaction $C = 388 \text{ MN/m}^3$;

- the model connection between loaded and unloaded rails and switch ties at the locations of tie pads is designed as an elastic connection (FE 51) with a stiffness equal to that of the intermediate rail fastening ($R = 150 \text{ MN/m}$);
- the load from a single wheel set is applied in the form of concentrated forces to the nodes of the loaded rails, $P = 196.13 \text{ kN}$.

Similar approaches to modelling a track-foundation system are also used in contemporary research [10–12].

An example of a diagram of deflections of both rails and 3.0 m long switch ties taking into account unloaded rails is given in Fig. 4.

To assess a degree to which unloaded rails influence the switch tie deflection under a load of a single wheel set, we used the LIRA-SAPR software to complete a multivariate calculation for switch ties with a length of 3.0 m to 4.1 m, with an increment of 0.1 m both for switch ties without rails (Fig. 5) and for the “switch tie with unloaded rails” system (Fig. 6).

To verify the developed and used FEM model, the analytical initial parameter method was used to calculate switch tie deflections disregarding unloaded rails. The comparison of the results suggests that the adopted analytic model is appropriate (Fig. 7).

Let us assess the resulting transfer of load from the rail to the ballast by a switch tie using the coefficient

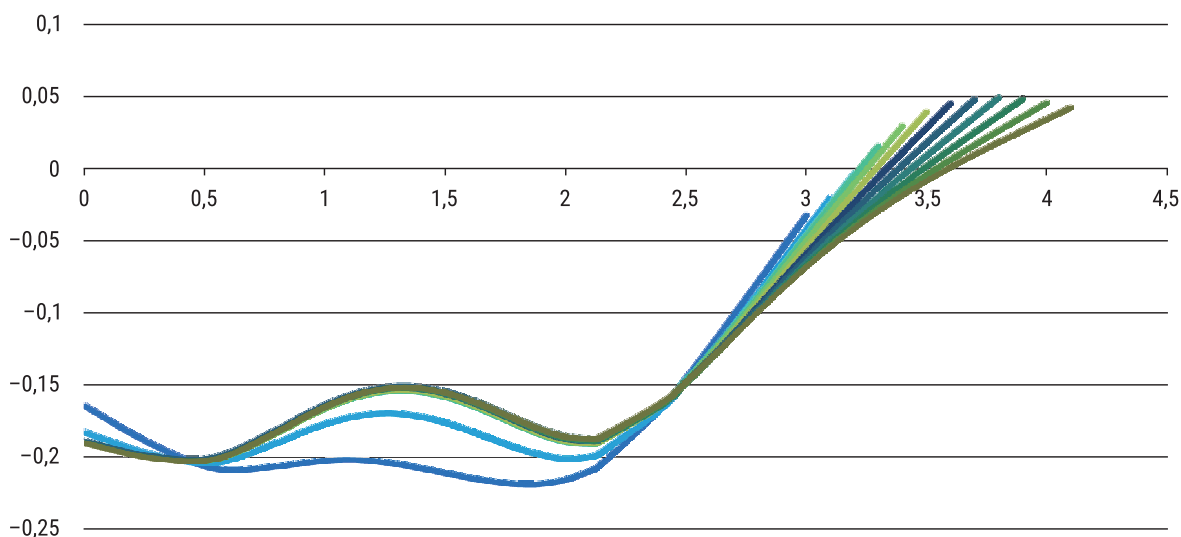


Fig. 5. Switch tie deflections under load $P = 98.1$ kN excluding unloaded rails (LIRA-SAPR software)

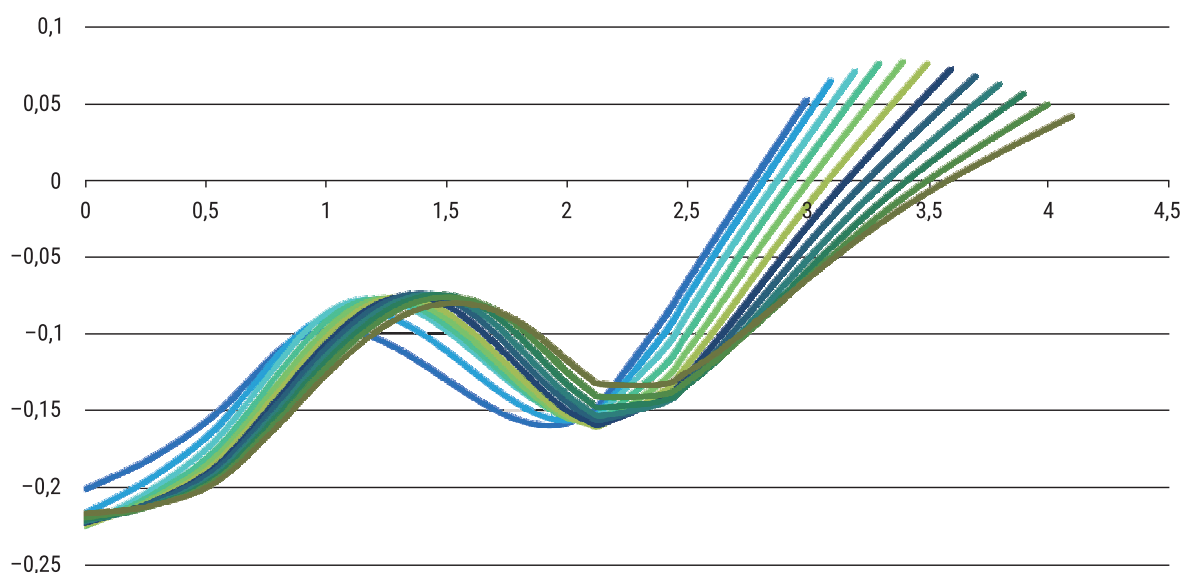


Fig. 6. Switch tie deflections under load $P = 98.1$ kN including unloaded rails (LIRA-SAPR software)

of variation in load transfer from the switch tie to the ballast along its length [16]:

$$k = \frac{y_{av}}{y_{max}}, \quad (4)$$

where y_{av} is the average deflection along the switch tie length, mm; and y_{max} is the maximum deflection of the switch tie, mm.

The k calculation results are given in Table 1.

Table 1

Coefficient of variation in load transfer from the switch tie to the ballast

Tie length, m	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1
Efficiency factor for unloaded rails excluded	0.8316	0.8402	0.8167	0.8171	0.8183	0.8196	0.8201	0.8194	0.8211	0.8207	0.8200	0.8191
Efficiency factor for unloaded rails included	0.5903	0.5441	0.5274	0.5427	0.5593	0.5751	0.5868	0.5939	0.5994	0.6016	0.6034	0.6077

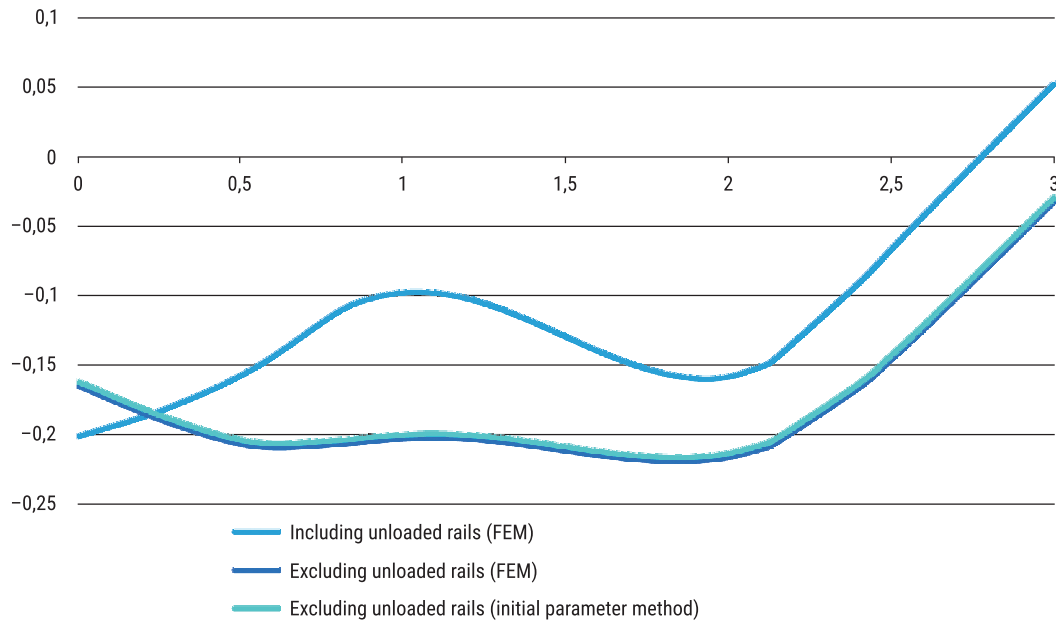


Fig. 7. Distribution of deflections along the length of a switch tie ($L = 3.0$ m) when loaded by a wheel set: 1 – calculation by the initial parameter method excluding unloaded rails; 2 – FEM calculation excluding unloaded rails; 3 – FEM calculation for the “switch tie with unloaded rails” system

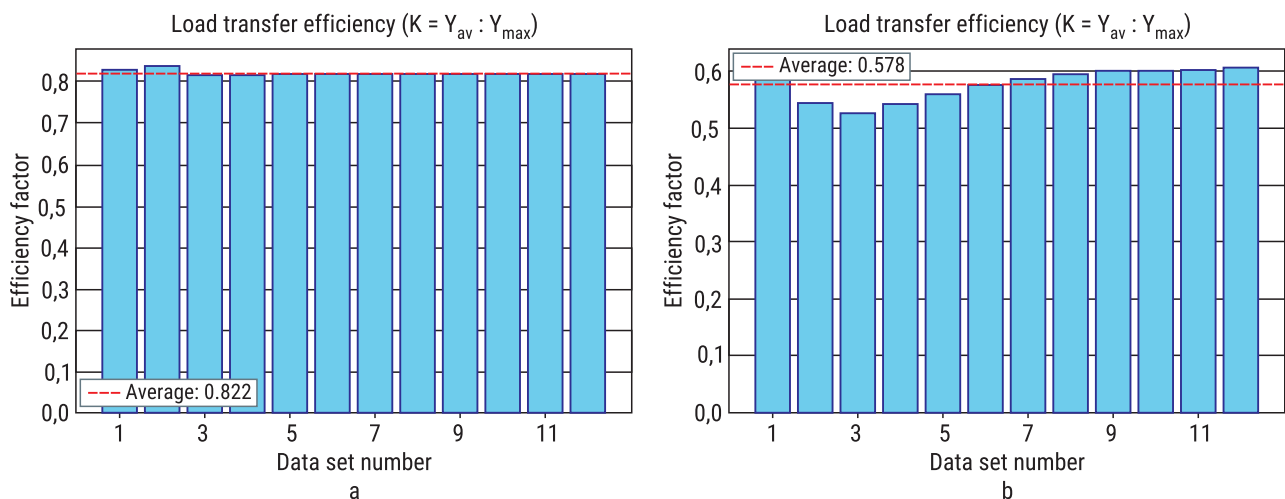


Fig. 8. Uneven load transfer from the switch tie to the ballast: a – unloaded rails excluded; b – unloaded rails included

Figure 8 shows the efficiency of train load transfer by switch ties depending on their length and whether or not non-operating rails are available.

ANALYSIS OF RESULTS

The calculations for various lengths of switch ties (from 2.5 to 4.1 m) revealed the following patterns in the influence of unloaded rails on the distribution of deflection of switch ties in connecting tracks:

1. The availability of unloaded rails adds an elastic support, reducing the absolute maximum deflection in the middle part of the switch tie and, hence, increasing

the stiffness of the system. The maximum deflection is reduced by 5–15% depending on the length of a switch tie and the load point;

2. Unloaded rails displace the maximum deflection point towards the geometric centre of the switch tie, making the distribution of elastic deformations more symmetrical, i.e. changing the shape of the elastic line.

3. When unloaded rails are excluded from the calculation, the efficiency factor for load transfer from the switch tie to the ballast is overestimated.

4. The “reverse” bending of the switch tie ends typical of the design model of a beam on a continuous elastic foundation remains virtually unchanged when unloaded rails are introduced. This value is mainly de-

terminated by the length of switch ties and stiffness of the foundation.

5. The resulting figures support, in a qualitative way, the physical principle underlying the approach to assessing the influence of unloaded rails on the deflection of switch ties offered by V. F. Yakovlev: when the calculation takes account of unloaded rails of connecting tracks the reduced stiffness increases.

CONCLUSION

1. The developed finite model properly describes the operation of switch ties in a system with unloaded rails on an elastic foundation, which is supported by the fact that it is well consistent with the conventional solution for switch ties without rails.

2. We have established that unloaded rails operate as additional elastic constrains that increase the integral stiffness of switch ties by 5–15% and contribute to more uniform longitudinal distribution of deflection.

3. The observed displacement of the maximum deflection point towards the centre of a switch tie suggests a better (more symmetrical) distribution of stress in the material of the switch tie, and this may prolong its fatigue life.

4. The findings of the study may be used to substantiate the need to take into account the combined action of all rails during the design stage to assess the stiffness characteristics of crossing tracks. This will allow for making more accurate predictions of their safe operating life and rates of wear, which should be taken as a basis for developing technical solutions to align vertical stiffness both along and across a turnout.

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