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AN INFLUENCE OF A GENERATED TRACK INTENTIONAL IRREGULARITY ON A STATIC WORK OF A RAILWAY TRACK

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The purpose of the following paper is to present the experimental field investigations in jointless railway track subjected to the author's generated imperfections on its static work. The main concept for the executed investigations is to induce an intentional imperfection (both a concave and convex irregularity) in an actual railway track, propose a way of appropriate measurement (using the PONTOS system), and utilize author's field investigations results to calibrate necessary parameters for theoretical calculations. An experimental formula describing the value of the force transferred from the rail to the railway sleeper on the grounds of the survey site caused by a locomotive is provided. Furthermore, the deflection of the chosen railway rail and sleeper due to the generated imperfection is subjected to analysis. Finally the objective of the present consideration is to resolve the calculations into the beam element such that the results can be used in computational railway practice. The scheme of the so-called a "hanging sleeper" is particularly unfavourable, a gap arises between the sleeper and the foundation, for which the significant changes appear, especially in the rail deflections and stresses. A work scheme of the railway track elements is described on the generated short concave and convex irregularity.

Keywords: railway track's imperfection; simulation of irregularity; a concave and convex irregularity

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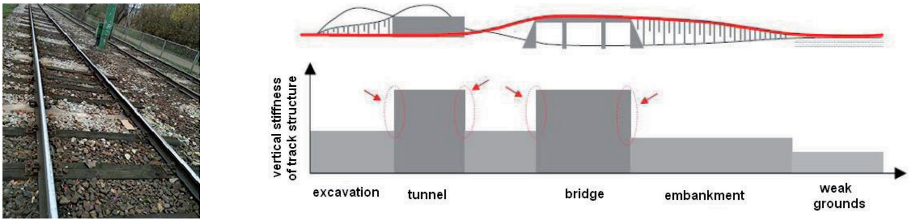
1. INTRODUCTION

The jointless railway track's operating leads to an arising a various form of wheel contact with rail, sleeper with ballasted roadbed or unfavourable, unintended imperfections of track contact with foundation [1,2,3,4,5.6,7,8,9]. In the paper an imperfection is interpreted as a defect, geometry deviation and state significantly different from idealized properties and features (in railroads usually it is mainly identified with track's irregularity or deformation of rail foundation) [3,4,8,10]. Under an influence of moving trains arise the imperfections both wheel and rail foundation, which reduce a track's structure durability (Fig. 1).



a) b)

Fig. 1. Examples of arising imperfections in railway track [4,11,12,13]

a) an irregularity (change of sleeper types); b) a variable support of the track structure along the railway track

The arising imperfections in railway track mainly lead to:

- a following degradation of track structure;
- an increasing its cost of maintenance and a decreasing a railroad safety and travellers' comfort.

Because of that, learning a meaning of an occurring imperfections is essential (e.g. in foundation or on vehicle's wheel) and first of all a learning significance its possible consequences. A typical distribution of arising imperfections in track can be given in following form (after the analyses of literature and author's personal experiences) [4,8,14]:

- imperfections resulting from railroad specificity (shown on Fig. 1*b*) [11,12,15],
- imperfections connecting with human mistakes: arising due to mistakes during designing; improper building technology; improper or insufficient diagnostic; improper a repair of track,
- geometrical imperfections in railway track [4,8]: vertical and horizontal irregularity; track's twist; track's width change; difference of rails height,
- imperfections appearing in the rails [16,17,18,19,20,21,22]: contact fatigue failure; hidden defects; wear of rail profile

- imperfections of railway sleepers [4]: the wooden sleepers (e.g. cracks, damages of sole-plates, dividers and screws); the concrete sleepers (e.g. scratches, cracks, breaks, dividers compressing),
- imperfections and changes in the ballast [23,24],
- imperfections of vehicle's wheel [1,19,25]: a wheel's tread; a wheel's flange surface; improper wheel's balance and ovalization,
- imperfections of railway track foundation [3,4,12,13]: sudden change of foundation elasticity; local irregularity of foundation; degradation of foundation,
- imperfections arising in railway subgrade [3,4],
- other imperfections (e.g. mining damages).

Therefore the necessity comes into being for the adaptations of the innovative solutions to increase the durability of the jointless track (e.g. USP, UBM [23,26,27,28]) and the analyses of the arising imperfections. In paper, the author's simulation method of intended imperfection in railway track with adequate field investigations using a PONTOS system is described [4,5]. The obtained results from research in real railway track are used in theoretical analysis. In the placed diagrams and tables are shown the obtained parameters for description of static work of jointless track resting on elastic foundation due to induced an intentional in its imperfection. Particular attention is paid to a proper presentation of obtained dependences for engineering interpretations and applications.

2. A DESCRIPTION OF AUTHOR'S SIMULATION METHOD OF INDUCED AN INTENTIONAL DEFORMATION IN TRACK

In order to complete the work analyses of loaded elements of railway track on local, short irregularity the field investigations are made at the Poznan-Franowo station. The goal of research is to carry out the intended deformation in railway track through the irregularity simulation in track support in two forms (a considered section – Fig. 2):

- decreasing of one cross-section in examined railway track (Fig. 2*a*),
- raising of one cross-section in examined railway track (Fig. 2*b*).

An imperfection is created by placing a hard metal plate between the railway sleepers and the rail except one railway sleeper, where contact loss between sleeper and subgrade arises on the length of $2a$ – c. see Fig. 2*a*). In the second case an imperfection is created by placing a hard metal plate between the railway sleepers and the rail only on one railway sleeper (see Fig. 2*b*). The following measuring schemes for analysis such imposed a problem are taken – Fig. 2:

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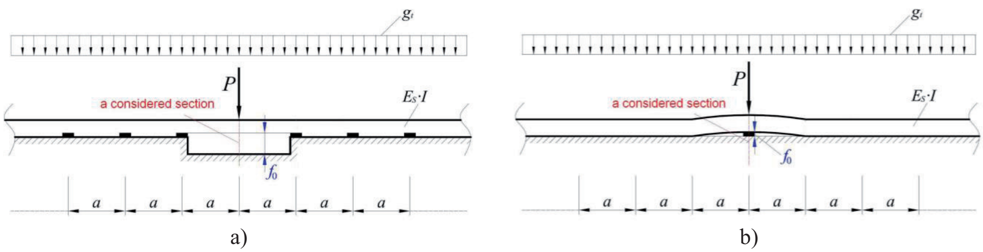


Fig. 2. The schemes of local imperfections generated in railway track

a) a decrease of a considered section in railway track; b) a raise of a considered section in railway track

where: f_0 – the imperfections created in the railway track [mm]; P – a force applied on wheel [MN]; EI – a railway track's stiffness in vertical plane [MNm^2]; g_t – a track's weight [MN/m]; a – a railway sleeper's spacing [m]

In the railway track, a local imperfection is generated through track hogging at a defined height (parameter f_0 on Fig. 2). This height irregularity is either caused by:

- loose fasteners or by the use of a railway jack (while considering the railway track stability in the horizontal plane according to mandatory regulations),
- then the metal plates are placed between the rail and the divider,
- next, the rail is lowered onto the divider and fastened to the railway sleeper.

This method includes an intentional imperfection in the track, which is described by its depth f_0 and e.g. its length 2 a. The value of f_0 is determined at the initial track state (0 mm) and the successive states (noted as 1, 2, 3 mm). A total of 24 railway crossings are made by the SM-42 locomotive on the track with the previously created imperfections (for 12 rides for each variant of imperfection; static load of locomotive SM42-448 amounts to 180 kN/axle). In the paper a static ride is analyzed (a speed below 20 [km/h]) of succeeding SM-42 locomotive axles). Considering a small speed of the moving locomotive, the problem is treated as a static one. An obtained load from locomotive allows for an analysis of track work (particularly for a rail and a sleeper) through measurement of force transferred from the rail to the railway sleeper and the both deflections of the railway rail and sleeper. Due to placing an indicator in sole-plate (Fig. 3*a*), investigations are made on concrete sleeper (in author's opinion this solution secured a proper support of indicator for measurements recording). In the place of generated track's imperfection in intended way it is measured among other things (Fig. 3): the rail's deflection under moving train and the rail's stress under moving train and the deflection of concrete sleeper's end and a force transferred from rail on railway track. To analyse deflections, an optical measurement system by GOM mbh (*Gesellschaft für Optische Messtechnik, Technischen Universität, Braunschweig*) is used (shown on Fig. 3). The main purpose of this system is to produce 3D digitisation (e.g., in coordinate measurements). The

PONTOS system is used for the static and dynamic analysis of deflections in 3D, making precise (at an accuracy of 0.001 mm), non-contact measurements of position, motion and deformations at short time intervals (on the order of 0.005 s) [4,5]. The PONTOS Viewer version v6.3.0-5 (by GOM mbH) and catmanEasy version 2.1 (by HBM GmbH) programs are used.

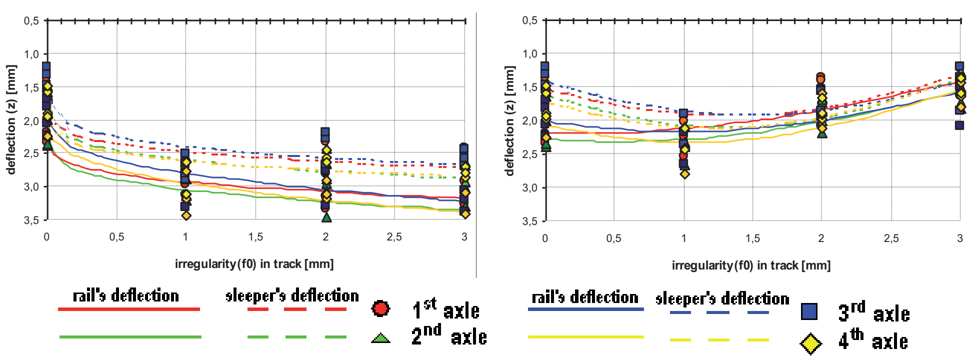
a) b) c) d)

Fig. 3. The site surveys at the Poznan-Franowo station [author's photos]

a) the KMR200 HBM indicator placed in the sole plate for the measurement a force transferred from the rail to the railway sleeper due to f_0 imperfection; b) a tensometer for a measurement of rail stress; c) the points on the rails for measurements (PONTOS system); d) a measuring position for precise measurements recording

3. THE OBTAINED RESULTS DURING THE FIELD INVESTIGATIONS FOR THE CONSIDERED CROSS-SECTION

During the following locomotive's rides on the deformed railway track, as shown in Fig. 2, measurements are made of: a rail and a sleeper's deflections, a stress changes in the rail and changes of force direct transferred from the rail to the sleeper, for axles of the SM-42 locomotive. As can be seen on the Fig. 4, the generated f_0 arrows of irregularities in a significant way cause the work change of the loaded railway track elements in the track.



a) b)

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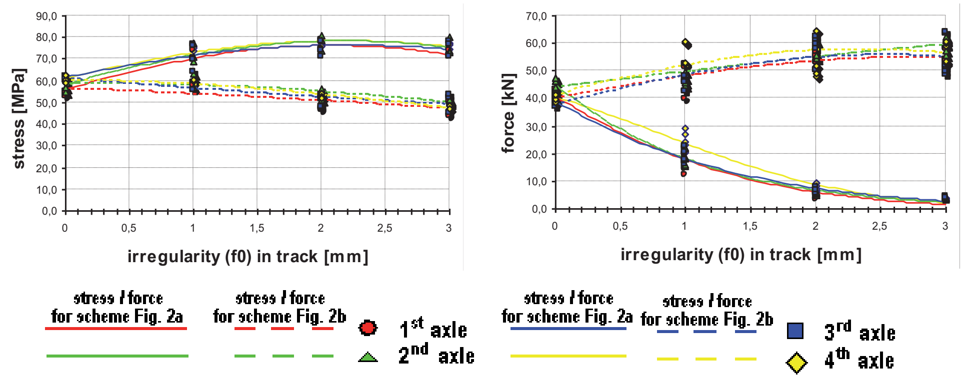

c) d)

Fig. 4. An obtained values due to induced an author's irregularity in the railway track (for successively locomotive's axles)
a) a rail's and sleeper's deflection (scheme - Fig. 2*a*); b) rail's and sleeper's deflection (scheme - Fig. 2*b*); c) a stress in rail's flange; d) a force change on the indicator placed in the sole plate

Particularly in the considered cross-section, a large influence of these irregularities on the work of the railway track can be observed:

- for the scheme in Fig. 2*a*, without irregularity in the track (f_0 = 0 [mm]), the deflection of the rail is about 2 [mm] (e.g. under the chosen 2nd axle of the locomotive, the value 1.996 [mm] is obtained); at f_0 = 3 [mm], the rail deflection increases to 3.537 [mm], i.e. about 77.2%, and the sleeper deflection increases from 1.437 [mm] to 2.873 [mm], i.e. up to 99.89%,
- for the scheme in Fig. 2*b*, it is observed a decreasing of the rail deflection under the chosen 2nd locomotive axle from 2,269 [mm] to 1,553 [mm] strongly depending from the quantity of induced irregularity f_0; the decreasing of rail deflection in this case amounts to 31.55% (in relation to the track without initial irregularities) and also, the sleeper deflection decreases from 1.864 [mm] to 1.481 [mm], i.e. by 20.56% (in relation to the track with f_0 = 0 [mm]),
- the formulas for rail's and sleeper's deflection: $\boxed{z_r(f_0) = 0{,}889\cdot(f_0)^{0{,}267} + 2{,}155}$, $\boxed{z_s(f_0) = 1{,}162\cdot(f_0)^{0{,}193} + 1{,}437}$ (Fig. 2*a*); $\boxed{z_r(f_0) = e^{0{,}819+0{,}0714\cdot f_0 - 0{,}066\cdot(f_0)^2}}$, $\boxed{z_s(f_0) = e^{0{,}6177+0{,}2103\cdot f_0 - 0{,}0942\cdot(f_0)^2}}$ (Fig. 2*b*).

As clearly shown in Fig. 4 the generated irregularities in the track according to the scheme from Fig. 2*a*, change the deflections, and in this way, they cause a change in stress values in the rail's foot (Fig. 3*b*) for the considered cross-section. The increasing rail deflection, depending on the generated f_0 irregularity, causes a change (increasing) in the rail stresses from 58,478 [MPa] up to 75,561 [MPa], i.e. an increase about 29.22%. The stress changes in the rail's foot for the scheme from Fig. 2*b* for a considered section are shown in Fig. 4*c*. Similarly to the scheme from Fig. 2*a*, the influence of irregularity on static rail work is estimated for the scheme in Fig. 2*b*. In this cross-section, as a result of the change of rail and sleeper support, decreasing rail deflection, depending on the simulated irregularities f_0 in the track, causes a change (decreasing) stresses in the rail from 58.668 [MPa] to 50.349 [MPa], i.e. a decrease of 14.18%. These significant stress changes can be described by the formulas and the corresponding graphs shown in Fig. 4*c*, on which the scale of changes can be evaluated in the section. A consequence of changes in the rail and the sleeper deflections and stresses in the rail's flange result in noticeable changes in the value of force transferred from the rail to the railway sleeper, as shown in Fig. 4*d*. The induced irregularities in the track at the f_0 value, according to the scheme in Fig. 2*a*, change the value of the force transferred from the rail to the ground for a considered section. In this section, the increasing deflection of the rail reduces the value of this force from 45,094 [kN] to 2,351 [kN], i.e. up to 94,79%. Such a significant decrease is due to the fact that:

- this force is of small value until the contact between the foundation and the ground is achieved,
- only the deflection of the rail together with the sleeper after contact with the foundation results in the force transferred from the rail to the sleeper.

Simulated irregularities f_0 in the railway track according to the scheme from Fig. 2*b*, change the values of the recording force transferred from the rail to the sleeper for a considered section. The changing deflection of the rail and sleeper in this section results in an increasing in the value of the force transferred from the rail to the sleeper from 44.284 [kN] to 59.763 [kN], i.e. by 34.95%. The significant increase in the value of this force is due to the fact that full contact of the track with the foundation occurs from the moment of the force transferring from the wheel to the rail.

The changes in the value of the force transferred from the rail to the railway sleeper as a function of the arrow value in irregularity for a considered section are described by formulas and the relevant graphs shown in Fig. 4 are made, on which the scale of changes in this section can be estimated [4]:

- for the stress in rail's flange and the force transferred from the rail to the sleeper:

$\boxed{\sigma_{meas}(f_0) = 58{,}259 \cdot e^{0{,}0037+0{,}268 \cdot f_0 - 0{,}061 \cdot f_0^2}}$ and $\boxed{Q_{meas}(f_0) = 45{,}026 \cdot e^{0{,}00151-0{,}866 \cdot f_0 - 0{,}0395 \cdot f_0^2}}$ (for irregularity - Fig. 2*a*);

$\boxed{\sigma_{meas}(f_0) = 58{,}259 \cdot e^{0{,}0071+0{,}014 \cdot f_0 - 0{,}0217 \cdot f_0^2}}$ and $\boxed{Q_{meas}(f_0) = 45{,}02547 \cdot e^{-0{,}01661+0{,}12854 \cdot f_0 - 0{,}00954 \cdot f_0^2}}$ (for irregularity - Fig. 2*b*).

The similar considerations for the others axles are widely presented in publication [4].

4. AN ANALYSIS OF THE OBTAINED MEASUREMENT RESULTS FOR AN ENGINEERING APPLICATION

In order to adapt the theoretical analysis of the obtained results from field investigations, the considered elements of the railway track are treated as elements of the beam resting on the elastic foundation. The problem of a beam resting on an elastic and a visco-elastic foundation is widely described in the literature [4,29,30,31,32,33]. The first soil model is proposed by Winkler, in which the foundation is described by a series of closely-spaced independent elastic springs. Furthermore, the reacting pressure at each point of the soil surface is directly proportional to the deflection of the beam through a material constant called the Winkler modulus. However, many alternative soil models are proposed to obtain more accurate descriptions of the soil-beam interaction and to avoid the limits of the Winkler's assumption [29,4,34,35,36,37,38], e.g.: a model in which the soil is modelled as a homogeneous isotropic elastic half space, the Wieghardt model, the Pasternak model, the Vlasov model and the analogue Vlasov model [32,39], the model with a modified Vlasov foundation, in which the additional parameter is treated as a function of the beam and the foundation soil (using an iterative procedure) [32,40,41]. The unilateral nature of the beam-soil contact results in a nonlinear feature. For a further analysis in this paper, the considered railway track is analyzed as an Euler-Bernoulli beam of infinite length resting on a one-parameter foundation (e.g. rail). Additionally, an analysis of static forces in a railway sleeper (a beam of finite length) as the Euler–Bernoulli (E-B) elastic beam resting on a two-parameter modified Vlasov foundation (defined by k_1 [MPa] and k_2 [MN] coefficients) is done. For comparison purposes a sleeper is also modelled as the Euler–Bernoulli beam resting on an elastic one-parameter foundation (defined only by k_1 [MPa] coefficient). Also, an attempt is made to calculate the considered railway element (sleeper) as a short-length Timoshenko beam on a two-parameter analogue Vlasov foundation (suitably with k_w [MPa] and k_u [MPa] coefficients) for further comparison [39]. Specifically, the concentrated static forces causing the deflection of the rail and sleeper are investigated. During the analysis the following simplified schemes for the theoretical and computational analyses of author's generated irregularities in track are assumed – Fig. 5. The other parameters of identification are widely described in [4,5].

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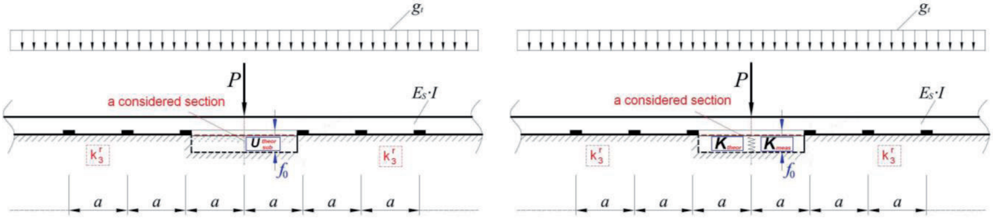
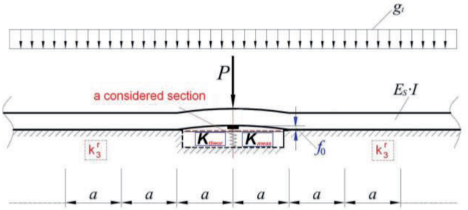
Scheme from Fig. 2*a*



Scheme from Fig. 2*b*



f_0, P, $E_S{\cdot}I$, g_t, a – the denotations (c. Fig. 2);
U_{sub}^{theor} – a substitute and a theoretical of rail's support for the case of „weak" its support;
K_{meas} – the empirical coefficients for calculation of rail's deflection for irregularity schemes from Fig. 2*a* and *b*;
K_{theor} – the theoretical coefficients for calculation of rail's deflection for irregularity schemes from Fig. 2*a* and *b*; k_3^r – rail's parameter of foundation.

Fig. 5 The exemplary assumed simplified schemes for a analysis of generated irregularities in the track
a) a decreasing of a considered section in track; b) a raising of a considered section in track

For a further analysis presented in this work, exact parameters of the rail and the sleeper foundation are determined using results of a test–driving the locomotive without irregularities (i.e. f_0 = 0 [mm]); the parameters are also determined by the methods described in publications [4,5,34]. The obtained values of the foundation parameters for the theoretical consideration are given in Table 1:

Table 1.The values of the foundation parameters for the theoretical calculations

Scheme from Fig. 2*a*			
for a rail	for a sleeper	for a sleeper	for a sleeper
a one-parameter foundation: $\boxed{k_3^r = 26{,}605\,[MPa]}$	a one-parameter foundation: $\boxed{k_3^s = 22{,}836\,[MPa]}$	a two-parameter foundation: $\boxed{k_3^1 = 22{,}8362\,[MPa]}$ $\boxed{k_3^2 = 2{,}7262\,[MN]}$	a two-parameter foundation Timoshenko beam (an analogue Vlasov foundation) $\boxed{k_w = 22{,}8362\,[MPa]}$ $\boxed{k_u = 1{,}1927\,[MPa]}$
Scheme from Fig. 2*b*			
for a rail		for a sleeper	
an one-parameter foundation: $\boxed{k_3^r = 26{,}357\,[MPa]}$		an one-parameter foundation: $\boxed{k_3^s = 22{,}536\,[MPa]}$	

The tables 2–5 present the theoretical calculations and the measured value of the rail and the sleeper deflection, the measured a stress in the rail and a force transferred from the rail to the railway sleeper for the section in which the intended deformation is generated in the railway track under the influence of force from the selected the 2nd locomotive axle. The calculations are made using the finite element method (FEM) [30,31,35,39,40,41]. The rail 49E1 of track is divided into elements:

- a contacting with the foundation at the length l=0,1625 [m] and without contact with the foundation at the length l = 0,05 [m]; E_S = 210 [GPa] and I_{49E1} = 1819 [cm^4].

However, the considered concrete sleeper is divided into 80 elements with a length of l = 0.03125 [m]. The following data is adopted for the railway sleeper treated as Timoshenko's beam:

- an element stiffness is calculated as the harmonic mean [42]: $EI_{(H)}^{sleeper} = \dfrac{2 \cdot E_1 I_1 \cdot E_2 I_2}{E_1 I_1 + E_2 I_2}$, where:

  E_1I_1 – the stiffness of the element at its beginning, E_2I_2 – the stiffness of the element at its end,
- $G = \dfrac{E_b}{2 \cdot (1+\nu)} = 0{,}43 \cdot E_b$, it is assumed: $\nu = \dfrac{1}{6}$ and E_b = 35 [GPa] [4,5], κ = 1,2, $\varsigma = \dfrac{\kappa \cdot E_S \cdot I}{G \cdot A_{el}}$,

where: G – Kirchhoff's module [GPa]; κ – a shape's coefficient of the cross-section; A_{el} – a cross-sectional area of the element; $G \cdot A_{el}$ – a shear beam's stiffness and a concrete sleeper prestressing force: S= 0,309 [MN]; during the behavior analysis of beam with varying cross-section (e.g. concrete sleeper), the change of stiffness along its length should be taken into account.

Table 2. The deflection of the rail and the stress in the rail due to the f_0 imperfection – 2nd axle load for Fig. 2*a*

a track's imperfection f_0 [mm]	z_{meas} [mm]	z_{theor} [mm] FEM	$z_{k\neq 0}$ $(z_{theor} - f_0)$ [mm]	U_{sub}^{theor} [MPa]	K_{meas} [kN/mm]	K_{theor} [kN/mm]	$P_{k=0}$ [kN]	$P_{k\neq 0}$ [kN]
1	2	3	4	5	6	7	8	9
0	1,996	2,031	-	26,605*	45,089	44,309	-	90
1	2,887	2,722	1,722	17,526	31,172	33,068	16,68	73,32
2	3,054	3,237	1,237	14,181	29,469	27,803	34,51	55,49
3	3,537	3,689	0,689	12,099	25,445	24,391	54,19	35,81

a track's imperfection f_0 [mm]	σ_{meas} [MPa]	$\sigma_{theor}^{U_{sub}}$ [MPa]	$\sigma_{theor}^{k=0}$ [MPa]	$\sigma_{theor}^{k\neq 0}$ [MPa]	σ_{theor} [MPa] FEM
10	11	12	13	14	15
0	58,474	63,392	-	55,187	55,187
1	71,949	69,016	18,793	44,311	63,104
2	78,367	71,881	42,367	32,685	75,053
3	75,561	74,064	64,778	18,615	83,394

*) the value obtained during the test–driving the locomotive for f_0=0 [mm] (without the irregularity)

Table 3. The force transferred from the rail on the sleeper and the railway sleeper's deflection due to the f_0 imperfection in the track – 2nd axle load for the diagram 2*a*

a measurement and an analysis for the rail					
an one-parameter foundation: $\boxed{k_3^r = 26{,}605\,[MPa]}$					
1	2	3	4	5	6
a track's imperfection f_0 [mm]	z_r [mm]	$z_{k\neq 0}$ [mm]	Q_{meas} [kN]	$Q_{meas}^{k_{spr}}$ [kN]	U_{sub}^{theor} [MPa]
0	1,996	-	45,094	45,094	26,605*
1	2,887	1,722	18,229	18,224	17,526
2	3,054	1,237	6,810	6,845	14,181
3	3,537	0,689	2,351	2,368	12,099

a measurement and an analysis for the sleeper						
a sleeper's deflection [mm]	an one-parameter foundation (*1-par*) $\boxed{k_3^s = 22{,}836\,[MPa]}$		a two-parameter foundation (*2-par*) $\boxed{k_3^1 = 22{,}8362\,[MPa]}$ $k_3^2 = 2{,}7262\,[MN]$		a two-parameter foundation Timoshenko beam (*TB 2-par*) $\boxed{k_w = 22{,}8362\,[MPa]}$ $k_u = 1{,}1927\,[MPa]$	
7	**8**	**9**	**10**	**11**	**12**	**13**
z_s [mm]	$z_s^{1-par}(f_0)$ [mm] FEM $k_2 = 0$ [MN]	$z_{k_1 \neq 0}^{1-par}$ $\left(z_s^{1-par} - f_0\right)$ [mm]	$z_s^{2-par}(f_0)$ [mm] FEM	$z_{k_1 \neq 0}^{2-par}$ $\left(z_s^{2-par} - f_0\right)$ [mm]	$z_s^{TB\ 2-par}(f_0)$ [mm] FEM	$z_{k_1 \neq 0}^{TB\ 2-par}$ $\left(z_s^{TB\ 2-par} - f_0\right)$ [mm]
1.4373	1.5283	-	1.5051	-	1.5162	-
2.5994	2.2109	1.2109	2.1914	1.1914	2.2978	1.2978
2.7653	2.6064	0.6064	2.5907	0.5907	2.6437	0.6437
2.8731	3.1898	0.1898	3.1857	0.1857	3.1522	0.1522

*) the value obtained during the test–driving the locomotive for f_0=0 [mm]] (without the irregularity)

The denotations for scheme from Fig. 2*a*: z_r and z_s – a rail's and a sleeper's deflection (p. 3); z_{meas} and z_{theor} – a measured and theoretical deflection (suitably for a rail and for a sleeper); $z_{k\neq 0} = z_{theor} - f_0$ – a deflection from the moment a contact of track with foundation; U_{sub}^{theor}, K_{meas} and K_{theor} – denotations (c. Fig. 5); $P_{k=0}$ and $P_{k\neq 0}$ – wheel's force transferred on track, suitably for a case without track contact with foundation (according to f_0) and after track contact with foundation; σ_{meas} (p. 3), σ_{theor} and $\sigma_{theor}^{U_{sub}}$ – a stress in the rail's flange, suitably: a measured, a theoretical and a theoretical with assumption U_{sub}^{theor}; $\sigma_{theor}^{k=0}$ and $\sigma_{theor}^{k\neq 0}$ – a theoretical stress in rail's foot, suitably for a case without track contact with foundation (according to f_0) and after track contact with foundation; Q_{meas} (p. 3) and $Q_{meas}^{k_{spr}}$ – a measured force transferred on the sleeper (with an assumption a theoretical "spring" in a considered section)

Table 4. The deflection of the rail and the stress in the rail due to the f_0 imperfection – 2nd axle load for Fig. 2*b*

an one-parameter foundation: $\boxed{k_3^r = 26{,}357\,[MPa]}$							
a track's imperfection f_0 [mm]	z_{meas} [mm]	$z_{theor}^{f_0=0}$ [mm]	$z_{theor}^{f_0\neq 0}$ [mm]	z_{theor} [mm]	$P_{theor}^{f_0\neq 0}$ [kN]	$P_{theor}^{f_0=0}$ [kN]	α [-] $P_{theor}^{f_0=0} = \alpha \cdot P_0$ $P_0 = 90\,[kN]$
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	2,269	2,124	0	2,1248	-	90	1,000
1	2,282	2,097	0,142	2,239	1,19	88,81	0,987
2	2,011	1,993	0,537	2,530	5,78	84,22	0,936
3	1,553	1,797	1,110	2,907	14,48	75,52	0,839

an one-parameter foundation: $\boxed{k_3^r = 26{,}357\,[MPa]}$						
a track's imperfection f_0 [mm]	K_{meas} [kN/mm]	K_{theor} [kN/mm]	$K_{theor}^{f_0\neq 0}$ [kN/mm]	$K_{theor}^{f_0=0}$ [kN/mm]	σ_{meas} [MPa]	σ_{theor} [MPa]
9	**10**	**11**	**12**	**13**	**14**	**15**
0	39,663	42,377	-	42,377	58,669	59,248
1	39,446	42,916	8,375	42,349	58,222	58,465
2	44,758	45,149	10,768	42,249	55,329	55,443
3	57,941	50,081	13,050	42,023	50,350	49,716

*) the value obtained during the test–driving the locomotive for f_0=0 [mm]] (without the irregularity)

Table 5. The force transferred from the rail on the sleeper and the railway sleeper's deflection in a considered section due to the f_0 imperfection in track – 2nd axle load for the diagram 2*b*

a measurement and an analysis for the rail									a measurement and an analysis for the sleeper		
an one-parameter foundation: $\boxed{k_3^r = 26{,}357\,[MPa]}$									an one-parameter foundation: $\boxed{k_3^s = 22{,}536\,[MPa]}$		
1	2	3	4	5	6	7	8	9	10	11	12
f_0 [mm]	z_{meas} [mm]	$z_{theor}^{f_0\neq0}$ [mm]	$z_{theor}^{f_0=0}$ [mm]	z_{theor} [mm]	Q_{meas} [kN]	Q_{theor} [kN]	$Q_{effect}^{f_0=0}$ [kN]	$Q_{f_0\neq0}$ [kN]	$Q_{effect}^{f_0=0}$ [kN]	z_{meas} [mm]	$z_{theor}^{f_0=0}$ FEM [mm]
0	2,269	0	2,124	2,124	44,284	44,283	44,283	-	44,283	1,864	1,864
1	2,282	0,1421	2,097	2,239	49,879	46,689	43,727	2,963	43,728	2,067	1,841
2	2,0108	0,537	1,993	2,531	55,121	52,757	41,564	11,193	41,564	1,966	1,752
3	1,553	1,1096	1,797	2,907	59,763	60,607	37,471	23,135	37,471	1,481	1,584

*) the value obtained during the test–driving the locomotive for f_0=0 [mm]] (without the irregularity)
while: $\boxed{P_{theor} = K^{f_0=0}\cdot\left(z_{theor}^{f_0\neq0} + z_{theor}^{f_0=0}\right) = 20{,}8513^{*}\cdot\left(z_{theor}^{f_0\neq0} + z_{theor}^{f_0=0}\right)}$ [kN] (the parameters widely described in p. 4),
The denotations for scheme from Fig. 2*b*: z_{meas} and z_{theor} – a measured (p. 3) and a theoretical deflection (suitably for a rail and for a sleeper); $z_{theor}^{f_0=0}$ and $z_{theor}^{f_0\neq0}$; $P_{theor}^{f_0=0}$ and $P_{theor}^{f_0\neq0}$ — a theoretical rail's deflection and force for a case, in which a track is treated as "straight" and for a case of further wheel's force action; $P_{theor}^{f_0=0} = \alpha\cdot P_0$ – a effective force causing a deflection $z_{theor}^{f_0\neq0}$, where $P_0 = 90\,[kN]$; K_{meas} and K_{theor} – denotations (c. Fig. 5); $K_{theor}^{f_0\neq0}$ and $K_{theor}^{f_0=0}$ – the theoretical coefficient for calculation of rail's deflection for a analyzed irregularity, suitably for a case, in which a track is treated as "straight" and for a case of further wheel's force action; σ_{meas} (p. 3) and σ_{theor} – a stress in the rail's flange, suitably: a measured and a theoretical; Q_{meas} (p. 3) and Q_{theor} – a measured and a theoretical force transferred on the sleeper; $Q_{effect}^{f_0=0}$ and $Q_{f_0\neq0}$ – an effective force transferred on the sleeper for a case, in which a track is treated as "straight" and for a case of further wheel's force action

The simulated short irregularity in the railway track (Fig. 2) causes the change of the work of its individual elements. On the basis of the carried out the investigations and analyses the dependences between the deformations arising in the track and changes in the values of deflections and stresses in the rail and the sleeper are obtained for the engineering interpretations and applications. The results of experimental investigations used for a determination the force transferred from the rail to the railway sleeper are used to analyse the changes of the track support with the following result:

- the changes in the rail support due to the generated a f_0 arrow of irregularity can be calculated from equations:
- $k_{spr}(f_0) = 22{,}591 + 9{,}185\cdot f_0 - 25{,}464\cdot f_0^{0{,}605}$ [kN/mm] (scheme from Fig. 2*a*),
- $k_{spr}(f_0) = 19{,}904 + 71{,}573\cdot f_0 - 69{,}657\cdot f_0^{0.951}$ [kN/mm] (scheme from Fig. 2*b*),

where: $k_{spr}(f_0)$ – a substitute parameter obtained during the field investigations (with an assumption a theoretical "spring" in a considered section),

- the experimental value of the force transferred from the rail to the railway sleeper is in the following form: $P_{meas}^{k_{spr}} = k_{spr}\left(f_0\right)\cdot z_{meas}$ [kN] (for the schemes from Fig. 2),
- the dependence of the force transferred from the rail to the sleeper (P_{meas}) on the value of the effective force that causes the track deflection after its contact with the ground ($P_{k\neq 0}$) for the case of "weak" track support (scheme from Fig. 2*a*): $P_{meas}\left(P_{k\neq 0}\right) = 3{,}233\cdot 10^{-7}\cdot P_{k\neq 0}{}^{4{,}166} + 0{,}044$,
- for the scheme from Fig. 2*b*, the experimental coefficient of force transfer from rail to sleeper is in the form: $K^{f_0=0} = 20{,}851\left[kN/mm\right]$ (a parameter obtained during the test–driving the locomotive for $f_0 = 0$ [mm]), where the force transferred to the sleeper is calculated from the following formula: $P_{theor} = K^{f_0=0}\cdot\left(z_{theor}^{f_0\neq 0} + z_{theor}^{f_0=0}\right) = 20{,}851\cdot\left(z_{theor}^{f_0\neq 0} + z_{theor}^{f_0=0}\right)$.

5. DISCUSSION AND CONCLUSIONS

The carried out site surveys allow for describing the problem of transferring the force from the wheel to the rail and from the rail to the railway sleeper for the assumed schemes (Fig. 2), in which the author's irregularity in the track are simulated (both a concave and convex irregularity). In the considered section (Fig. 2), a large influence is observed of the generated irregularity on the work of the railway track. The author's field investigations made in the real railway track enabled a direct determination of the rail and sleeper deflections and a determination of the actual value of the force transferred from the rail to the cooperating sleeper (Tables 3 and 5). According to the author's opinion, the placement of the indicator in the steel sole-plate (Fig. 3*a*) does not disturb the work conditions of the track and can be used to measure the actual force transferred from the rail to the sleeper during the simulated irregularities in the track. The noticeable changes in stress in the rail foot and force values (Fig. 4*c* and *d*) are observed for a considered section. On the basis of the investigations carried out, it can be stated that the described, significant changes in deflections and stresses in the elements of the railway track are visible only in the loaded railway track. Stiffness of the track makes that, it is impossible to adjust its shape to the arising, specially a short irregularity of the foundation. As a consequence, the areas of non-contact arise which generate changes in the work of individual track elements. Particularly an unfavourable is the scheme of the so-called a "hanging" sleeper (Fig. 2*a*), in which a gap arises between the sleeper and the foundation, for which there are significant changes, especially in the rail deflections and stresses (Fig. 4*a* and *c*). The executed theoretical-experimental analyses confirm therefore the usability of the proposed method of simulating and measuring the track deformation (using a non-destructive the PONTOS system).

The generated irregularity in the track with the known a initial values of length and arrow is subjected to theoretical analysis, in which it is possible to determine the character of transferring loads to successive elements of the railway track and to determine, among others, the actual characteristics of the force transferred from the rail to the railway sleeper.

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WPŁYW WYWOŁYWANYCH W TORZE ZAMIERZONYCH NIERÓWNOŚCI NA STATYCZNĄ PRACĘ TORU KOLEJOWEGO

Słowa kluczowe: imperfekcja toru kolejowego, generowanie nierówności, wklęsła i wypukła nierówność

STRESZCZENIE

Celem niniejszej pracy jest przedstawienie eksperymentalnych badań terenowych w bezstykowym torze kolejowym poddanym generowanym autorskim imperfekcjom na jego statyczną pracę. Główną koncepcją przeprowadzonych badań jest wywoływanie zamierzonej nierówności rzeczywistego toru kolejowego, zaproponowanie odpowiedniego sposobu pomiaru (z wykorzystaniem systemu PONTOS) oraz wykorzystanie wyników badań terenowych autora do skalibrowania niezbędnych parametrów do obliczeń teoretycznych. Wykonane badania terenowe pozwalają opisać problem przenoszenia siły z koła na szynę i z szyny na podkład kolejowy dla przyjętych schematów (rys. 2), w których symuluje się autorskie nierówności w torze (zarówno wklęsła jak i wypukła nierówność). Autorskie badania terenowe przeprowadzone na rzeczywistym torze kolejowym umożliwiły bezpośrednie określenie ugięć szyny i podkładu (rys. 4*a* i *b*) oraz określenie rzeczywistej wartości siły przenoszonej z szyny na współpracujący podkład (tabele 3 i 5). Według opinii autora umieszczenie czujnika w stalowej płycie podkładki szynowej (rys. 3*a*) nie zakłóca warunków pracy toru i może być wykorzystane do pomiaru rzeczywistej siły przenoszonej z szyny na podkład podczas symulacji nierówności na torze. Uzyskane zmiany naprężeń w stopce szyny i wartości siły przekazywanej z szyny na podkład kolejowy (rys. 4*c* i *d*) są zauważalne dla rozpatrywanego przekroju (rys. 2*a* i *b*). Na podstawie przeprowadzonych badań można stwierdzić, że opisane znaczące zmiany ugięć i naprężeń w elementach toru kolejowego widoczne są tylko w obciążonym torze kolejowym. Sztywność toru sprawia, że nie jest możliwe oddanie przez niego kształtu powstającej, zwłaszcza krótkiej nierówności w jego podparciu. W konsekwencji powstają obszary braku kontaktu, które generują znaczące zmiany w pracy poszczególnych elementów toru. Końcowym efektem rozważań jest wykorzystanie przeprowadzonych obliczeń i badań dla elementu belkowego, aby uzyskane rezultaty i parametry mogły być wykorzystane do obliczeń w praktyce inżynierskiej. Przyjęto dla pracy szyny model belki spoczywającej na jednoparametrowym podłożu gruntowym, a dla podkładu kolejowego model belki spoczywającej na jednoparametrowym i dwuparametrowym podłożu gruntowym. Schemat tak zwanego *wiszącego podkładu* (rys. 2*a*) jest szczególnie niekorzystny, powstaje bowiem luka między podkładem a podłożem oraz pojawiają się znaczące zmiany, zwłaszcza w ugięciach szyn i naprężeniach. Schemat pracy elementów toru kolejowego opisano na wygenerowanej krótkiej wklęsłej i wypukłej nierówności.

Przeprowadzone analizy teoretyczno-eksperymentalne potwierdzają zatem przydatność proponowanej metody symulowania i pomiaru deformacji toru (z wykorzystaniem nieniszczącego systemu PONTOS). Wytworzona nierówność w torze ze znanymi początkowymi wartościami długości i strzałki poddano analizie teoretycznej, w której możliwe jest określenie charakteru przenoszenia obciążeń na kolejne elementy toru kolejowego oraz określenie, między innymi, zmierzonej rzeczywistej charakterystyki siły przenoszonej z szyny na podkład kolejowy.

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