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Problem of Damage to Curved Switch Rails in Ordinary Turnouts

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Summary
The article presents the problem of excessive wear of curved switch rails in ordinary railway turnouts, which is characterized by spallings and the decrement of material on a certain length of the switch rail near the tip. The problem is important, as such wear arises in turnouts on railway lines after several months of exploitation following modernization. The probable reasons behind the excessive wear of switch rails in railway turnouts are indicated on the basis of laboratory tests performed in accordance with PN-EN 13674-1:2011 and PN-EN 13674-2+A1:2010, as well as on the basis of simulations and analyses carried out by the finite element method (FEM).

Keywords: railway turnout, turnout switch rail, non-metallic inclusions, tension stresses, finite element method

1. Introduction

Rapid development of different types and constructions of railway turnouts has taken place over recent years. This was triggered by efforts to ensure high durability and high reliability for turnouts in view of the continuous increase in train speeds, axle loads on tracks and frequencies of train passages, both for passenger and freight trains. The development of turnout constructions is also a consequence of technological progress in the production of new grades of steel for railway turnouts, the development of methods for testing materials, as well as a better understanding of the wheel-rail interaction phenomenon [1. 2, 4].

A turnout is a special multi-track construction, built with rails and switch rail profiles (steel sections with a defined shape and grade of steel) and other elements, which enable railway vehicles to pass from one track to another keeping a defined speed [3]. One of the most widespread railway turnouts is an ordinary turnout [7], as shown in Figure 1. It is composed of three basic panels i.e. a switch panel, closure panel and crossing panel. The switch panel (see Figure 2) is a movable turnout panel, which moves switch rails thanks to a point machine, thereby enabling train movement from one track to another. Running stability and safe track change depend on the correct fabrication of the beginning of the switch rail, which is near the tip and has to have an appropriate shape ensuring correct intimate adhesion to the turnout outer rail (to the stock rail). Proper switch rail fitting to the stock rail influences safety and rolling stock running comfort and also ensures the correct exploitation of the switch panel within a turnout.

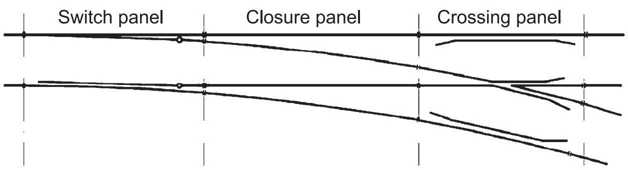

Fig. 1. Ordinary turnout block diagram [7]

Fig. 2. Ordinary turnout switch panel [photo. M. Czarnecki]

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2. Cases of excessive wear of switch rails

Cases of excessive wear of switch rails in turnouts on modernized railway lines were met within research works conducted by the Materials & Structure Laboratory. The cases have many common features i.e. similar wear near the tip of the switch rail, which has arisen within a short time following the installation of a new turnout in the track; damages pertain to ordinary turnouts with switch rails fabricated from the same material and the same switch rail profile shape. The characteristics of three turnouts with excessive wear of the curved switch rails are shown in Table 1.

The stock material in the form of switch rail profiles, used for the above-mentioned turnouts, comes from two different producers (the material for turnouts 2 and 3 come from the same ironworks). Additionally, fabrication of the turnout itself and its installation in the track was carried out by two different producers (turnouts 2 and 3 were produced by the same company). It can be assumed that producers of the switch rail profile material, as well as producers of the whole turnouts, ensure a similar quality of products as excessive wear was observed in each of the above cases, disregarding the radius of the curvature within the turnout (190 m, 300 m and 500 m), crossing angle (1:9, 1:12), construction of the switch rails (spring rail switches, flexible switches) and type of timbers (wooden, concrete).

As already mentioned above, similar switch rail damage is a common feature of the analysed turnouts. In each of the three cases, such damage was characterised by spallings of material near the tip of the switch rail, which has arisen in each case at the same height from the foot of the switch rail profile (see Figure 3). In a zone adjacent to the decrement of material, propagating and developing cracks were spotted (see Figure 4). These cracks, in the case of further exploitation, would probably lead to expansion of the spallings of material near the tip of the switch rail. As there is no data about the load transferred by turnouts, the respective factor influence on the switch rail degradation rate cannot be determined. The found spall material (see Figure 5) constituted part of a switch rail, which broke away from the switch rail profile. However, the preserved spall surfaces indicated normal wear peculiar to interaction with rolling stock wheels.

Table 1

Damaged turnouts

Parameters	Turnout 1	Turnout 2	Turnout 3
switch rail profile	60E1A6	60E1A6	60E1A6
steel grade	R260	R260	R260
exploitation time	~23 months	~9 months	~17 months
damage place	about 130mm from the switch rail tip	about 640mm from the switch rail tip	about 1105mm from the switch rail tip
damage length [mm]	approx. 260	approx. 280	approx. 470
highest vertical wear in the place of damage* [mm]	7.3	10.4	6.5
highest side wear [mm]	4.9	3.9	4.6

*value is an aggregate of the wear and spalling of material; [elaboration by author]

a) b)

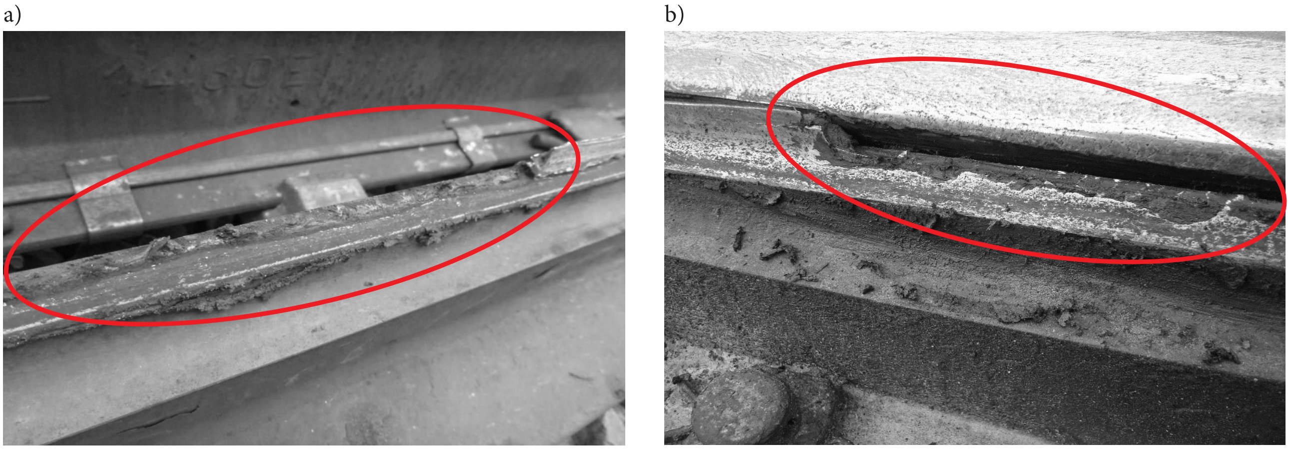

Fig. 3. Damage to switch rails in the form of spallings of material a) and b) [photo. M. Czarnecki]

Fig. 4. Crack propagating near spallings of material of the switch rail [photo. M. Czarnecki]

Fig. 5. Switch rail spall material [photo. M. Czarnecki]

Existing spalls created a real hazard that the wheel flange would climb over the switch rail onto the stock rail and that the switch rail would be broken, consequently possibly leading to rolling stock derailment.

3. Laboratory tests

It was decided to take samples from each damaged switch rail and perform laboratory tests according to the respective standards, i.e. PN-EN 13674-1:2011 [5] and PN-EN 13674-2+A1:2010 [6], in order to answer the question whether material used for production of the switch rail profiles fulfilled quality requirements. A range of tests foreseen by those standards for rail steel grades comprised, among others, tests of: chemical constitution, tensile strength, HBW hardness, micro and macro-structure as well as oxide purity. It was decided additionally to perform tests for determining residual (own) stresses, widening the test range by adding measurement of the stresses in a rail web and in a switch rail blade (usually according to PN-EN 13674-1:2011 [5] residual (own) stresses are measured only in the rail foot). Table 2 contains the chemical constitution of the switch rails from which samples were taken near blade damages. Mechanical properties are shown in Table 3, while the structure of materials features are shown in Table 4.

Table 2

Chemical composition of the switch rail material

Number of turnout	Mass fraction [%]								[ppm]	
	C	Si	Mn	P	S	Cr	Al	V	O	H
Turnout 1	0.74	0.32	1.11	0.019	0.019	0.045	<0.002	<0.003	11	<0.4
Turnout 2	0.79	0.32	1.15	0.010	0.011	0.034	<0.002	<0.003	12	0.5
Turnout 3	0.72	0.33	1.09	0.020	0.015	0.094	<0.005	<0.003	11	<0.5
Requirements for R260 steel according to PN-EN 13674-2	0.60÷0.82	0.13÷0.60	0.65÷1.25	0.030_{max}	0.030_{max}	0.15_{max}	0.004_{max}	0.030_{max}	20_{max}	2.5_{max}

[elaboration by author]

Table 3

Mechanical properties of the switch rail material

Parameters	Turnout 1	Turnout 2	Turnout 3	Requirements for R260 steel according to PN-EN 13674-2
Yield strenght $R_{0,2}$ [Mpa]	563	548	487	–
Tensile strength R_m [MPa]	979	994	935	min. 880
Elongation [%]	12	10	11	min. 10
Necking [%]	20	16	17	–
HBW hardness	271	279	281	260 ÷ 300
Residual stresses [MPa]	in rail foot: 26 in rail web: 62 in rail head: 100	in rail foot: 40 in rail web: 79 in rail head: 40	in rail foot: 47 in rail web: 18 in rail head: 100	max. 250 in rail foot

[elaboration by author]

Table 4

Features of the structure of switch rail materials

Parameters	Turnout 1	Turnout 2	Turnout 3	Requirements for R260 steel according to PN-EN 13674-2
Type of micro-structure	pearlite without the presence of other phases	pearlite without the presence of other phases	pearlite without the presence of other phases	pearlite without cementite at the grain boundaries, without martensite and without bainite
Oxide purity	K3 = 1.15	K3 = 1.56	K3 = 4.16	K3 < 10
Macrographic examination (Baumann method)	print consistent with D4 pattern	print consistent with D4 pattern	print consistent with D4 pattern	acceptable patterns from D1 to D7

[elaboration by author]

It was ascertained, on the basis of the performed laboratory tests, that the material used for production of the switch rail profiles, in each analysed case, fulfilled the material property requirements of the PN-EN ISO 13674-2:2010 standard [6]. Positive results were obtained as a result of tests for: chemical constitution, mechanical properties and structural tests. The performed measurements of residual stresses demonstrated that existing switch rail stresses are not large enough to cause cracks of the material. The highest registered stresses in the place of spallings of material (rail head), is 100 MPa (for turnout 1 and turnout 3).

During microscopic tests, on samples which were taken near the damage, it was seen that the main crack was initiated on the switch rail and stock rail contact surface, then propagated deeper into the material (see Figure 6a). Smaller cracks were spotted near the main crack. Smaller cracks, similarly to the main one, were initiated on the surface (see Figure 6b). This fact was also proven by magnetic particle inspection, which showed that discontinuities set themselves in a row located on one height (see Figure 7). Non-metallic inclusions located on the switch rail and stock rail contact surface could constitute places where cracks are initiated. They form potential structural indents where, in the point of contact between the inclusion and metallic body (rapid change in material properties), micro-cracks could arise, which as a result of further exploitation could merge together into one big crack. This can then lead to spallings of material and damage of the turnout switch rail. An example of the potential centre of material micro-cracks on non-metallic inclusions is shown in Figure 8.

a) b)

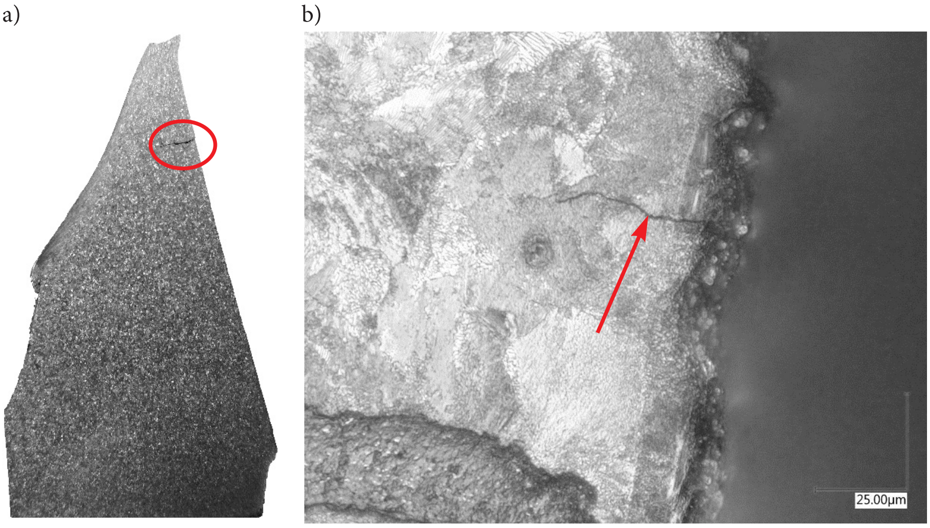

Fig. 6. Part of the switch rail with a propagating crack (a), a small crack near the main one (b) [photo. M. Czarnecki]

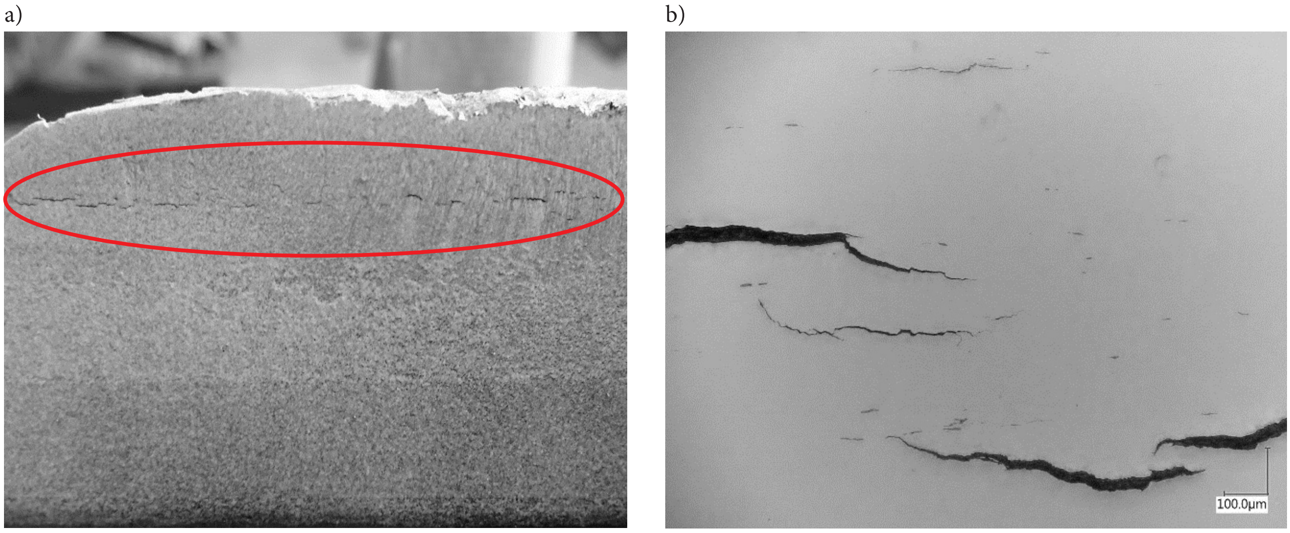

Fig. 7. Switch rail discontinuities in the place of contact with the stock rail detected during MT: tests (a) microscopic view of the marked area (b) [photo. M. Czarnecki]

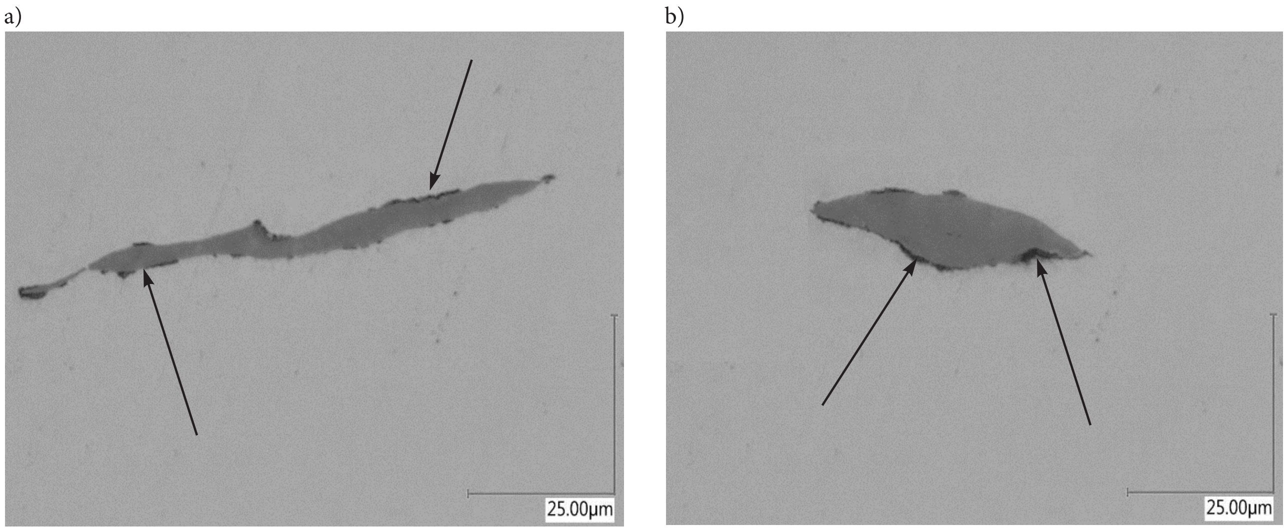

Fig. 8. Potential centre of material cracks on non-metallic inclusions (a) and (b) [photo. M. Czarnecki]

4. Analysis using the finite element method

It was decided to build a 3D model and simulate real turnout exploitation conditions in the course of rolling stock passage, for a better understanding of the phenomena taking place in the switch rail which leads to the cracking and spallings of material on a given height. HyperWorks software, enabling the creation of lump constructions and finite element method (FEM) analyses, was used for this purpose. The created model was composed of a switch rail sector with intimate adhesion to the stock rail, three systems fastening the stock rail to timber, and a passing rolling stock wheel acting on the above arrangement. An excerpt of the 3D model is shown in Figure 9. Calculation models used HEXA8N, SPRING2N, BEAM3N and RBE2 type elements, and an INTER/TYPE7 type contact. Grid size in the contact area was 2 mm. The assumed friction coefficient was $\mu = 0.1$. The parameters shown in Table 5 were used for FEM calculations. These parameters are specific for each element within the analysed arrangement. Lateral acceleration assumed for analysis was 2 m/s^2, which was the highest value registered by Railway Institute workers during real measurements on the track. Assuming such an acceleration value for analysis, an attempt was made to observe the behaviour of the analysed arrangements with possible extreme exploitation parameters.

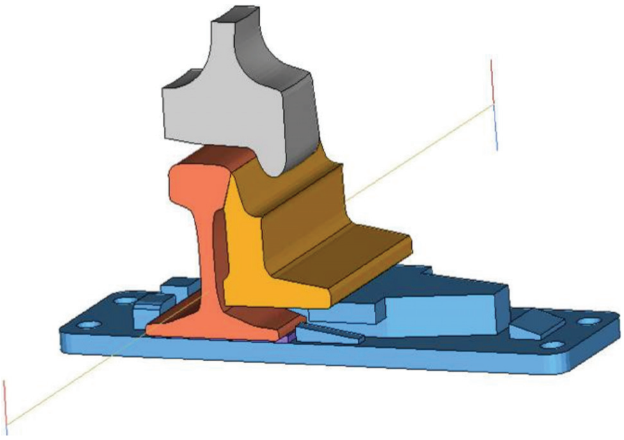

Fig. 9. Excerpt of the 3D model used for FEM analysis [own work]

Table 5

List of parameters and values used for FEM calculations

Parameter	Value
Static wheelset load on track [kN]	200
Wheel load on stock rail, considering lateral acceleration 2 m/s^2 [kN]	126.8
Side force acting on switch rail, considering lateral acceleration 2 m/s^2 [kN]	40
Timbers spacing [mm]	600
Stiffness of the rail pads [kN/mm]	1000
Stiffness of each spring of the fastening system [kN/mm]	1
Clamp force of a single spring of the fastening system [kN]	10
Switch rail and stock rail material	R260

[elaboration by author]

After creation of the 3D model and entering the appropriate material parameters, the stress field distribution (see Figure 10) was obtained for the wheel, stock rail and switch rail in the course of rolling stock passage through the turnout. It can be seen in Figure 10 that the highest stresses occur in the contact area between the wheel and stock rail (running surface) and in the contact area between the wheel flange and switch rail.

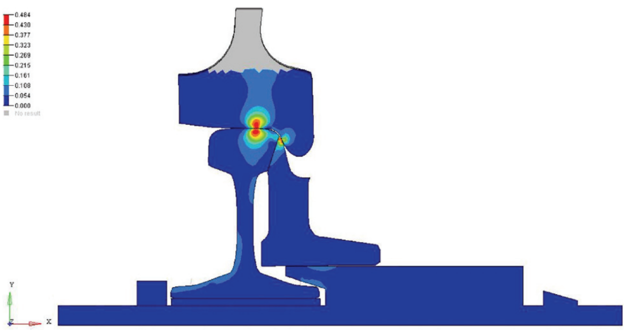

Fig. 10. Reduced von Mises stresses on a cross-section of the analysed arrangement in the course of rolling stock passage [own work]

In the case of the switch rail, the largest stresses occur in the contact area between the wheel flange and switch rail and in the contact area between the switch rail and stock rail (see Figure 11). Occurring stress can reach about 430 MPa, which is a value close to the yield point value for the R260 grade of steel. The largest plastic deformation areas also occur in those places (see Figure 12).

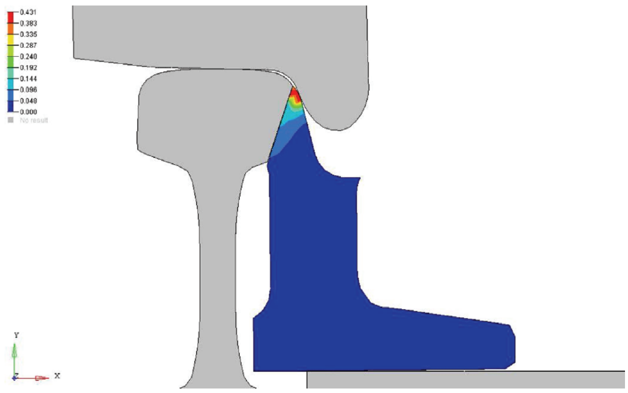

Fig. 11. Reduced stresses on the switch rail cross-section in the course of rolling stock passage [own work]

Reduced stress analyses show that, exclusively within the switch rail, the highest values occur slightly below the upper edge, both in places with the largest plastic deformations (contact with the wheel flange) as well as in the contact area between the switch rail surface and stock rail. In turn, the situation shown in Figure 13 is obtained when taking into account compressive and tensile types of stress. The areas being compressed are those of contact between the switch rail surface and the wheel flange (marked blue), whereas the areas which are tensioned are those of contact between the switch rail surface and stock rail (marked red). The highest compressive stresses obtained by simulation reached a value of about 420 MPa, whereas the highest tensile stress value was about 410 MPa.

Figure 14 shows the directions of tensile stresses occurring on the side of the switch rail contact with the stock rail, so in potential areas of switch rail damage centres (see Figures 6 and 7). The direction of tensile stresses is perpendicular to the longitudinal switch rail axis and the direction of arrangement of non-metallic inclusions in a switch rail, which is the most disadvantageous factor from the point of view of the appearance and propagation of cracks on non-metallic inclusions. This results in the occurrence of a row of cracks on a contact surface between the switch rail and stock rail, which was revealed during magnetic particle inspection (see Figure 7a).

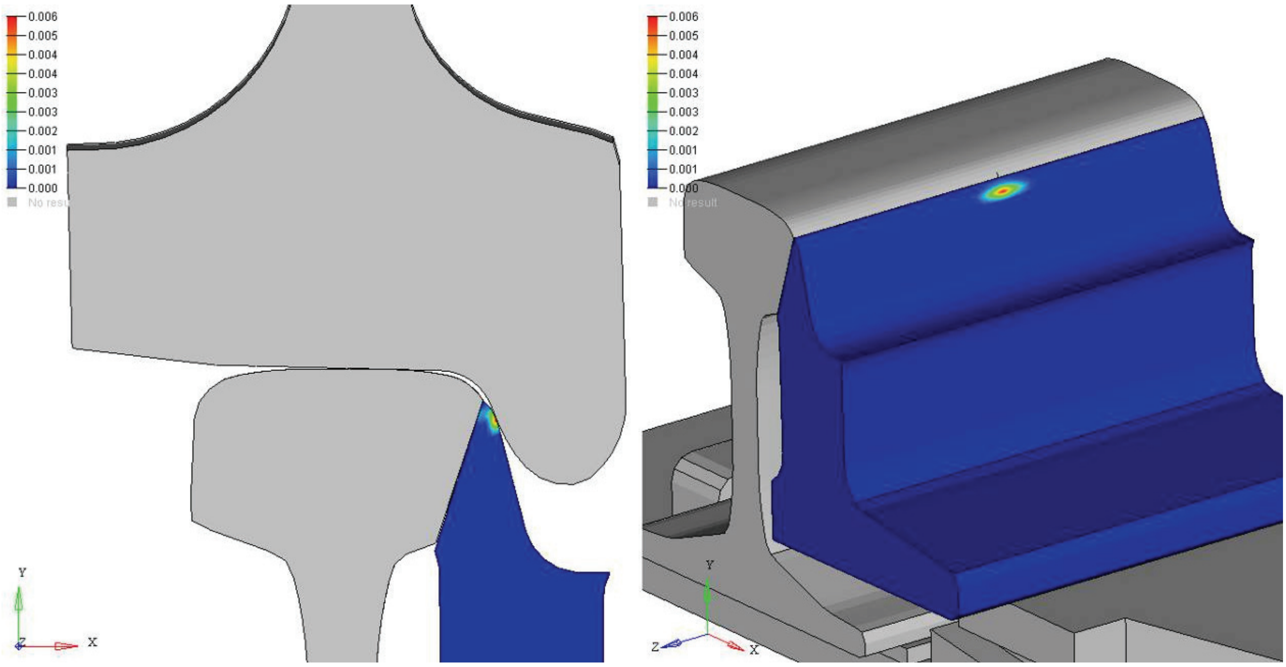

Fig. 12. Area of largest plastic deformations in the switch rail [own work]

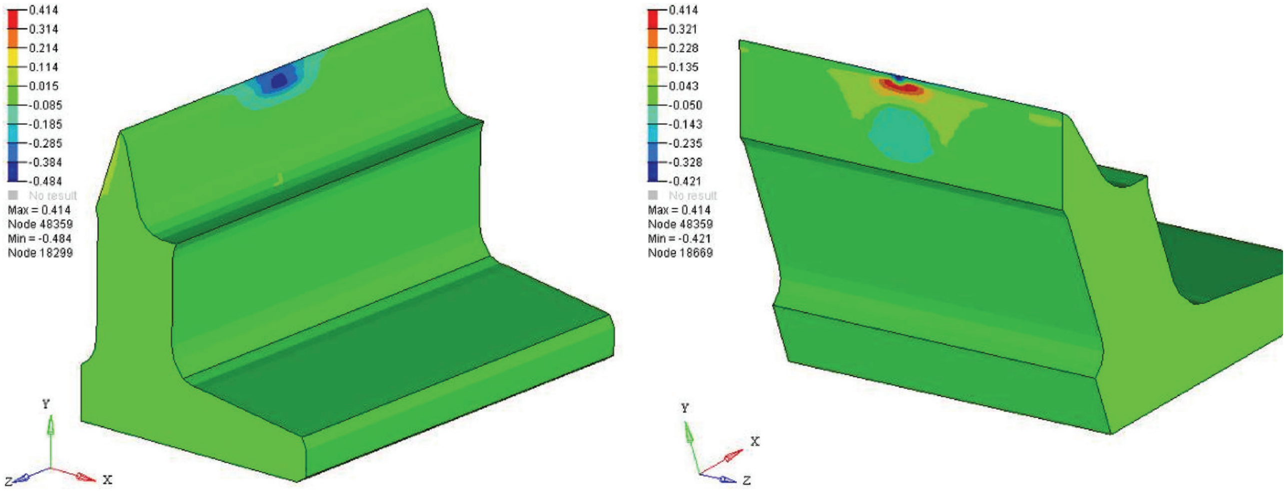

Fig. 13. Main stresses after considering compression – blue colour and after considering tension – red colour [own work]

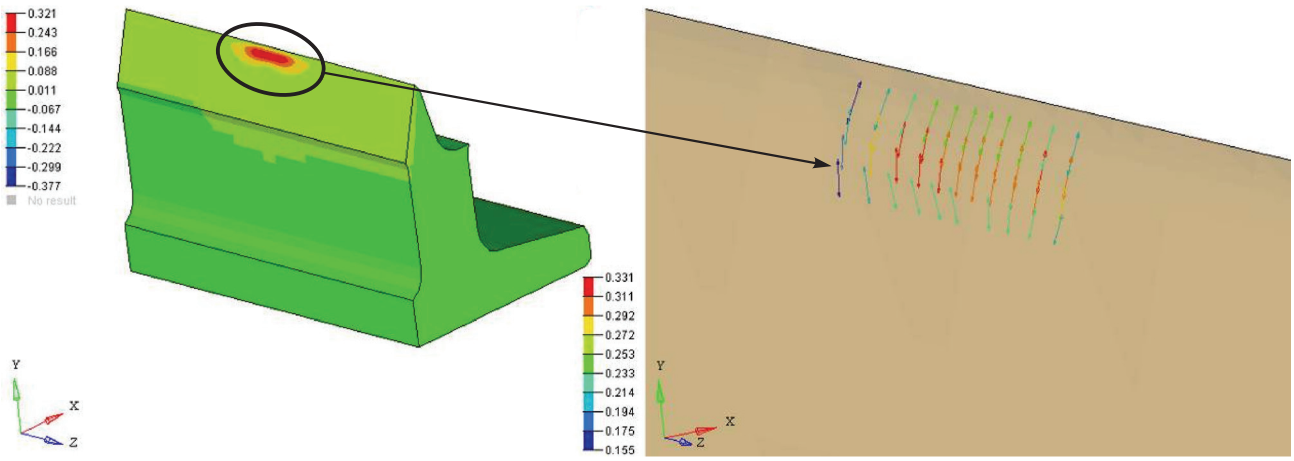

Fig. 14. Tension stress directions (first main stress σ1) occurring in a switch rail [own work]

5. Conclusions

It was alleged, on the basis of the conducted laboratory tests and performed FEM simulation, that one of the main reasons for damage of the curved switch rails in the analysed ordinary turnouts was uncompensated acceleration (horizontal force acting on the switch rail) caused by passing rolling stock. Uncompensated acceleration in switch rails resulted in the appearance of tension stresses on the side of contact between the curved switch rail and straight stock rail. Tension stresses as a result of uncompensated acceleration have led to the appearance of cracks on the boundaries between non-metallic inclusions and the metallic body, due to differences in the properties of those two materials. The state of tension stress has caused the detachment of the metallic body from inclusions. Conflation of such detachments around the inclusion has led to one bigger micro-crack, which was further propagated in the metallic body. A single bigger crack arose as a result of the propagation of individual micro-cracks and led to spallings of material and damage of the switch rail.

It should be mentioned that the fact that the switch rail material fulfilled the requirements regarding the presence of non-metallic inclusions (K3 index) did not mean that there were no inclusions at all in the material. Such inclusions are smaller and are not subject of analysis for establishing the value of the K3 material purity index.

Crack initiation places are determined by the character of the switch rail load caused by the wheel of passing rolling stock. Acting wheel flange in areas of the biggest switch rail plastic deformations (see Figure 12) has led to the grinding of material and material flow and, as a result, to wear of the switch rail (maximum measured side wear was 4.9 mm). The decrement of material and constant horizontal force acting on a switch rail could result in the appearance of stresses significantly higher than the ones obtained from FEM simulation. Those stresses could significantly exceed the yield point of the R260 steel material, thereby making it extremely dangerous in relation to turnout exploitation. It has to be underlined that, although values of compressive and tension stresses were obtained from FEM analysis concerning cases without any wear of the switch rail, stock rail and wheel and without any geometrical inaccuracies or errors in relative positioning (e.g. inappropriate intimate adhesion of the switch rail to stock rail), the assumed extreme side acceleration of 2 m/s^2 caused, in the switch rail, stresses which are close to the yield point of the material. Any geometrical inaccuracies in the relative positioning of individual elements within the turnout as well as their wear could increase the effect of fast degradation of the switch rails as a result of the fast growth of side accelerations in areas of their damage, which may even lead to bumping curved switch rails by the flanges of wheels of passing rolling stock.

To avoid similar cases in the future, it is reasonable to use material with better mechanical properties than R260 steel, e.g. R350HT grade of steel, for the turnout switch rails for diverging tracks carrying high loads with high speeds of rolling stock. R350HT has a yield strenght on the level of 700 MPa, which may cause a lowering of excessive wear and damages of the curved switch rails in ordinary turnouts. Moreover, precise fabrication and turnout assembling in the track, especially precise fabrication of the switch panel as well as continuous monitoring of the relative positioning of movable parts within turnouts, shall enable the switch rail damage hazard to be reduced.

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