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Analysis of cracking on running surface of rails

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Professional paper

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Analysis of cracking on running surface of rails

The problem of cracking at the rolling surface of rails is considered in the paper. This damage to the rolling surface of rails, known as "squat", may lead to disintegration of rail head in the length of 1 m or more. In the scope of this research, a detailed visual control of rail damage at the Vrbnica – Bar Section of the Montenegrin railway network was conducted in order to alleviate danger of rolling contact fatigue cracking in rails. Results obtained can be used as basis for preparation of technical regulations for railway track maintenance along the Montenegrin railway network.

Key words:
wheel and rail interaction, rail damage, fatigue of material, rail cracking

Stručni rad

Zdenka Popović, Vlatko Radović

Analiza napuknuća na voznoj površini tračnica

U radu se obrađuje problematika pojave napuklnuća na voznoj površini tračnice. Ovakva oštećenja vozne površine tračnica, poznata pod nazivom squat, mogu dovesti do raspadanja glave tračnice na duljini 1 m i više. U okviru istraživanja provedena je detaljna vizualna kontrola napuknuća tračnica na mreži crnogorskih željeznica, dionica Vrbnica – Bar, s ciljem smanjenja opasnosti od pojave napuknuća na voznoj površini tračnica uslijed umora materijala. Dobiveni rezultati mogu poslužiti kao podloga za izradu tehničkih propisa za održavanje željezničkog gornjeg ustroja na mreži crnogorskih željeznica.

Ključne riječi:
međudjelovanje kotača i tračnice, oštećenja tračnica, zamor materijala, napuknuća tračnica

Fachbericht

Zdenka Popović, Vlatko Radović

Analyse von Rissbildungen auf der Schienenfahrfläche

In dieser Arbeit wird das Problem von Rissbildungen auf der Schienenfahrfläche bearbeitet. Diese Art von Beschädigung, auch als Squat bekannt, kann zum Zerfall des Schienenkopfes auf einer Länge von über 1.0 m führen. Im Rahmen der gegebenen Studie ist eine detaillierte visuelle Kontrolle der Risse auf dem Gleisnetz der montenegrinischen Eisenbahn zwischen Vrbnica und Bar durchgeführt worden, um die Gefahr der durch Ermüdung des Materials bedingten Rissbildungen auf der Schienenfahrfläche zu vermindern. Die erlangten Ergebnisse können als Grundlage für den Entwurf technischer Vorschriften für die Wartung der Gleisanlagen des montenegrinischen Eisenbahnnetzes angewandt werden.

Schlüsselwörter:
Rad-Gleis Wechselwirkung, Gleisbeschädigungen, Materialermüdung, Schienenrissbildung

1. Introduction

Montenegrin railways are a part of the European railway network. In the scope of realization of interoperability of the European railway system, rail infrastructure managers are required to have infrastructure subsystem maintenance plans for each conventional railway line [1]. This plan should *inter alia* include inspection and an appropriate strategy against the rolling contact fatigue (RCF). The rail failure or damage generally results from fatigue cracks and reduces the rail service life, increases the cost of maintenance, and may cause train derailment [2]. An increased traffic density, higher axle load and speed, as well as lubrication of rails, these are all factors that contribute to RCF and are a serious hazard to rail traffic. On the other hand, problems due to RCF can be reduced by applying an appropriate track geometry, correct wheel/rail contact geometry, and better maintenance strategies. An adequate maintenance strategy should contribute to a longer rail service life, lower rail maintenance costs, and greater safety of railway traffic.

Around the globe, there are the two main rail RCF types: squats and head checkings. The study [3] proposes unique names for these defects in order to avoid current confusion in terminology. For this reason, the terms "head checking" and "squat" are officially used in all languages of the world in scientific and technical literature without translation. Also, essential differences exist between the initiation and growth mechanisms of these two rail RCF types. The research conducted in this paper focuses on squat rail defects on Montenegrin railways. The rail surface defects known as squats (cracks and local depressions on the running surface of rails – defect type 227 according to [4]), have in recent years become an important RCF problem for Montenegrin railway authorities. This paper presents Montenegrin experience and maintenance problems this country faces due to appearance of squat-type defects in rails. Unfortunately, the mentioned rail defect is not covered by the "Directive 339 on common criteria for controlling railway condition within the JŽ network", which is still in official use in Montenegro. The aim of this paper is to improve the rail maintenance strategy, and to implement state-of-the-art expertise and knowledge in new technical regulations for the railway infrastructure maintenance in Montenegro. Harmonisation of technical regulations with the UIC Codes [4, 5] would ensure creation of a uniform procedure for the determination, registration and classification of rail defects, and for creation of statistical parameters on rail defects within a single European database. The objective is to enable exchange of experience and development of common infrastructure maintenance management methodologies on the European level and beyond. This paper points to the necessity of early detection of rail squats using appropriate rail inspection methods, and preventive maintenance activities (rail curing), removal of smaller and severe defects (corrective activities), and cyclical (controlled) activities during the rail service life [4 - 7]. A successful rail defect management is a problem shared by all countries of the world. In this respect, infrastructure managers of Montenegro Railways need to adjust maintenance strategies to local conditions in order to achieve appropriate traffic safety improvements.

2. Squat-type defects in rails – Initiation, growth mechanism and locations

The objective of this research is to study the phenomenon, consequences, current experience and maintenance strategies of squat defects on Montenegrin railways. The research was conducted by visual inspection of squat defects at the Vrbnica – Bar railway section (Class C4 for mixed traffic according to UIC700, single track line, maximum speed 90km/h), in the course of May and June 2012 [8], following reports of severe RCF defects. It was established that squat and belgrospi defects are not restricted to high speed and heavy haul railways only. Unfortunately, due to the extremely high wear of outer rails in curves, and to use of lubricants, head checkings (HC) were not registered in this visual inspection. However, the existence of HC on this railway section can not be excluded.

However, the Montenegro Railways has still not devised a strategy that would enable it to deal with this highly dangerous phenomenon.

The term "rolling contact fatigue" is generic in nature and is used to describe a range of defects that are basically due to development of excessive shear stresses at the wheel/rail contact interface. The rolling contact fatigue is a gradual deterioration process that is initiated by creation and development of an initial crack, while finally it results in rail failure under the influence of variable traffic load, which is transferred to the rail via a small wheel/rail contact surface.

Squats were first observed in the 1950s in Japan and described as "black spots" [9, 10, 11]. In the 1970s, a RCF rail defect named "squat" was identified on the British railway network. In the majority of other European countries squats were registered and considered at a later date. The Montenegro Railways is making efforts to devise a strategy for successful management of this phenomenon.

In this research of squat defects on Montenegrin railways, the basic definition of squat (rail defect type 227), as given in [4], is used: squats are visible on the running surface of the rail head as a widening and a localised depression of the rail/wheel contact band, followed by a dark spot containing cracks with a circular V-shaped arc, but in any case the main characteristic is the shape in form of two "lungs" [9, 10]. (Figure 1). Over time, the cracks propagate inside the rail head. At first, they propagate inside the head at a shallow angle to the surface (max. 20 to 30 degrees from the horizontal). Then, when they reach 3 to 5 mm in depth, they propagate downward transversely and may cause rail failure. Generally, the shape of the fracture surface due to the rolling contact fatigue is quite characteristic. Two visually different surfaces can be distinguished: fatigue area and rail break area (Figure 2).

Figure 1. Typical defect in form of "lungs", Vrbnica – Bar Railway, Podgorica – Golubovci Section

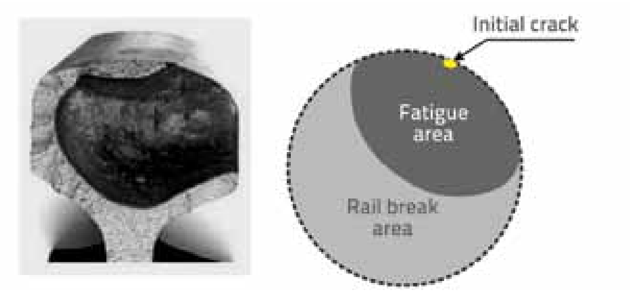


Figure 2. Typical shape of a steel surface after break caused by squat [6]

Squats on the running surface of the rail head are thought to be triggered by thermal traction effects associated with some form of wheel microslip/slip, and can occur anywhere (sporadically) in the rail contact band (Figure 3).

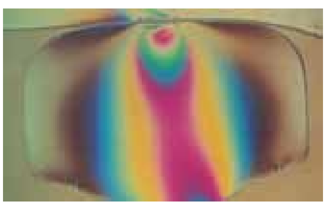


Figure 3. Squat emergence zone with high wheel/rail contact stress

The occurrence of squats is directly caused by excessive dynamic wheel/rail contact force due to vertical irregularities on the running surface of the rail. Squat zones are shown in Figure 4: running surface within the rail crown radius (R) and the gauge corner region.

According to experience of railway infrastructure managers, squats can occur at the straight track and in large curves (radius 800 – 1600 m, mostly on the high rail). They can also occur in small radius transition curves. In addition, they may appear on all track types (ballast or slab track, wooden or concrete sleepers, railway lines with freight, passenger or mixed traffic, metro lines, tramway lines, or conventional and high-speed lines), on lines that are electrified or non-electrified, and in Standard Carbon (SC) and Head Hardened (HH) rails.

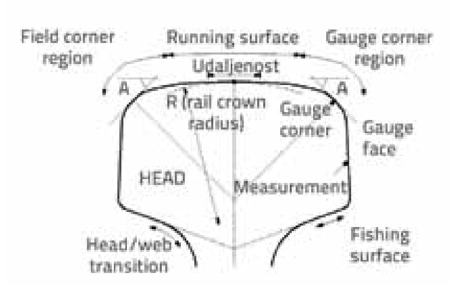


Figure 4. Squat zones in rail head: running surface

Visual inspection on the Vrbnica – Bar railway section [8] has confirmed the correlation between squat locations and the stiffness and damping characteristics of the track. Approximately 75 % of all squats were registered on the ½ of the rails centered on sleepers, and the remaining squats were note on the other ½ of the rails in the centre between two sleepers (Figure 5).

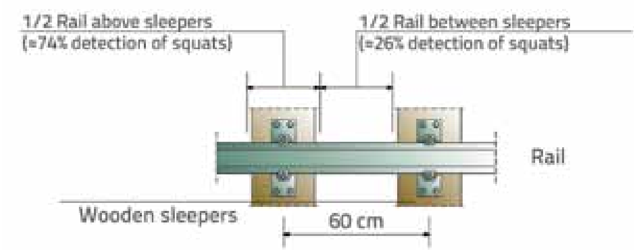


Figure 5. Squat locations on track

Unevenness of track stiffness along the track influences the dynamic load imposed by vehicles. French author Prud'Homme was the first to stress the importance of track stiffness, and its influence on dynamic loads [12, 13, 14]. Relevant technical literature points to the correlation between vertical track geometry deterioration and track stiffness, but fails to propose a more detailed quantification for practical applications. An optimum stiffness is dependent on individual stiffnesses of all superstructure and substructure elements, and also on their mutual compatibility [14]. Unfortunately, requirements for track stiffness still remain an open question [1].

Numerical analyses presented in [10] show that an increase in squat is accompanied and promoted by dynamic wheel-rail interaction force, which is affected by the squat itself, and whose wavelength corresponds to the short pitch corrugation (a wavelength ranging between 2 and 6 cm). As reported in literature [9], this suggests that the corrugation seen in the neighbourhood of the above mentioned 72 % of squats might not really be corrugation in the sense of track damages, but could be the wave pattern of uniform plastic deformation, or wear caused by the dynamic contact force.

To determine the force acting in the wheel/rail contact zone, the following range of geometrical parameters must be known: position of contact points on the left-side and right-side wheels, position of contact points on the left-side and right-side rails, current radius of circles at contact points (r_1, r_2) and their difference (Dr), equivalent conicity, profile angle at contact points (γ_1,γ_2), radius of wheel profile and rail curvature at contact point, coefficient of contact stress at contact point, angle of axle assembly toward the horizon (φ), and vertical displacement of its centre of gravity (ζ) (Figure 6).

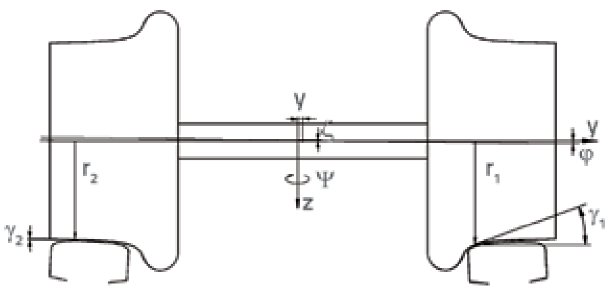


Figure 6. Geometrical parameters for determination of wheel/rail contact forces [15]

In addition, wheel/rail contact forces depend on: wheel profile and its current geometry, rail profile and its current geometry, rail inclination (1:20, 1:40, 1:∞), current track gauge, and current wheel flange gauge (Figure 7).

During visual inspection of the Vrbnica – Bar railway section [8], squats were often observed in corrugated zones of the rail head.

Railway research in the UK has confirmed that 75 % of squats are associated with corrugation, welds and periodic indentations in the rail running surface caused by hard objects brought forward by the wheels [18].

Appearance of squat defects in weld zones (about 10 – 15 % of the total) on the Vrbnica – Bar railway section [8] can be explained by inhomogeneity of material exposed to high temperatures during the welding process, and geometry imperfections at the cross section of the weld [9, 10].

Squats on rails have been located randomly, and they occur in great numbers (Figure 8), which is quite dangerous because of the risk of multiple fractures with significant gaps.

Figure 8. Multiple squat defect (typically shaped as "lungs")

The differential wear and deformation, as well as small local geometry deviations on rail surface, can bring about an increase in the dynamic force. These defects on rail running surface and gauge corner region, either due to differential wear and plastic deformation, or due to indentation etc., may develop into squats [11]. That hazard is more pronounced on railways without an adequate maintenance strategy.

3. Detection of squats

A crack has a certain detectable size (P - crack development potential prior to detection). The effectiveness of crack detection depends on the efficiency and accuracy of inspection equipment. It also depends on the skill and experience of inspectors. From this size the propagation of the crack can be monitored until it attains the critical size, when a rail break

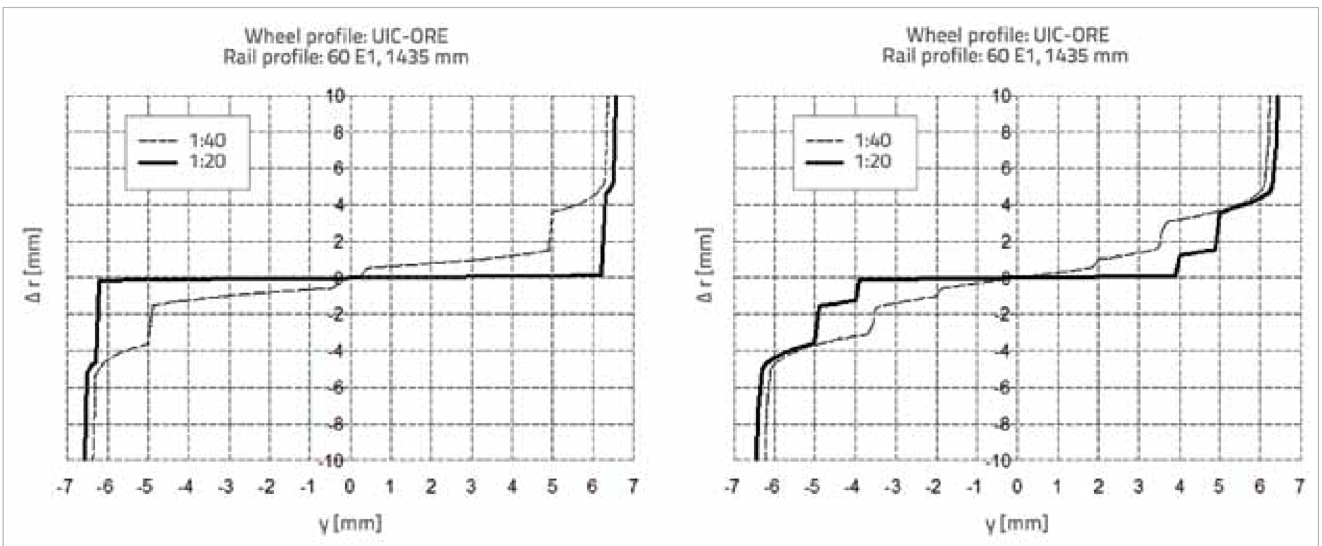


Figure 7. The Δr function (difference of current radii at the contact points) [15]

can be expected (F – failure due to breakage). The time or traffic load (expressed in millions of gross tons) between crack detection and rail break can be used to define the P-F interval (Figure 9).

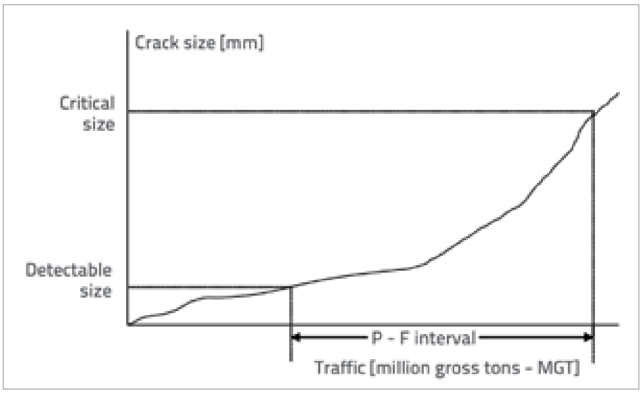


Figure 9. Definition of P-F interval [19]

An optimum squat detection method should enable early detection of rail damage and provide reliable data about measured length, depth and spatial position of fissure in the rail head. This kind of method for non-destructive testing of rails has not as yet been developed, although recent progress in this area has shown that the axle box acceleration is quite effective for early detection of squats, see [16, 17].

Unfortunately, a micrographic examination of rail is uncomfortable for use in track. In practice, several detection methods are usually combined in order to increase the possibility of early detection of the defect. Relevant literature [5] recommends visual inspection, optical system by camera, ultrasonic testing by vehicle, and manual check by ultrasonic testing.

Rail network should be subjected to visual inspection twice a year (every six months), with the help of photographs and video recordings. This method requires a large number of man-hours and implies subjectivity. However, visual inspection is still a highly important preliminary activity in rail testing. Although human eye has remarkable possibilities of detecting slight changes in material colour and texture over a large area, this method does not enable an early detection of rail damage. In addition, the method should be improved based on detection with fluorescent penetrants, especially under poor visibility conditions in tunnels, but only when the rail surface is clean.

Special attention should be paid to rails in main station tracks, at high upward grades (about 10 ‰ and more), at switches [23], crossings, expansion joints, and in weld zones. Sections with irregular track geometry should also be carefully investigated.

During visual inspection at the Vrbnica – Bar railway section, the fact that moderate to severe squats can often be mistaken for wheelburn defects was also taken into account. Wheel burns result from friction between wheel and rail due to braking and slip of the wheel relative to the rail. This leads to change in metallurgical structure of the rail surface. These metallurgical changes result in cracking. However, typical differences exist between squats and wheelburn defects. Squat defects develop gradually over several months or years, while wheel burn defects in rails occur instantly after a wheel slip incident. Wheel burn defects have a matching defect, while squats often do not have a matching defect on the opposite rail. Special care was taken to properly differentiate these two defects during visual inspection of the Vrbnica – Bar railway section.

All fields of rails between two consecutive sleepers were visually inspected. Information about defects was entered in the corresponding form according to [4], and was then saved into the data base.

The main form with information is shown in Table 1. Other necessary details and photos of defects are attached to the form. The attachment to the main form is shown in Table 2.

The ultrasonic inspection is not applicable for inspection of surface fissures situated close to one another, and at small angle towards the upper rail head surface. This method enables identification of cracks of more than seven millimetres in depth. Nevertheless, the method does not provide accurate results in the narrow rail gauge corner zone. By combining ultrasonic and eddy current inspection methods, the probability that squats and head checking defects will be found is improved [20]. The eddy current inspection of rail steel presents the following advantages: detection of the initial fissures (0.2 mm in depth), detection of fissures below the rail head surface, portability of testing device, possible integration of device into the recording cars, inspection cars and rail grinding trains, no use of consumable materials, and instant readout of measurement results [21].

4. Postupanje s napuknućima na voznoj površini tračnica

As a part of the project [19], a sensitivity analysis was performed to demonstrate how the crack growth rate is affected by different traffic and track conditions. Figure 3 shows the result of the analysis [19]. Various factors are ranked according to their impact on crack growth over the rail life span.

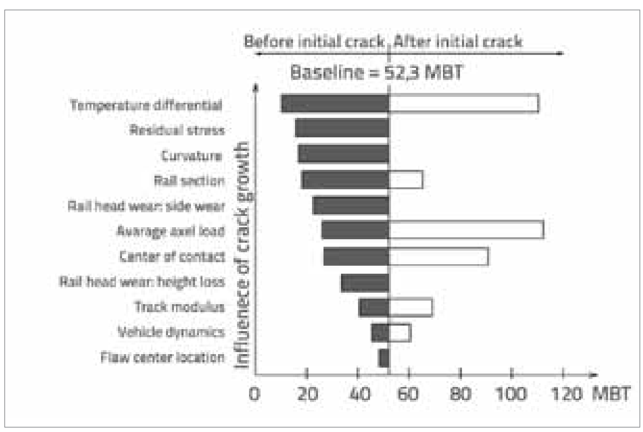
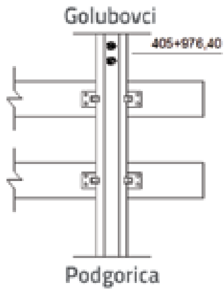


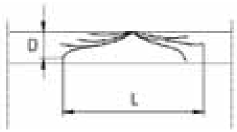
Figure 10. Influence of various factors on crack growth [19]

Table 1. Main form for squat defects

1. General information about squat rail defect (Code number: 227)				
Damaged rail ☐ (Any rail that is neither cracked nor broken, but has other defects, generally on the rail surface)	Cracked rail ☐ (Any rail that has, somewhere along its length and irrespective of the part of the profile, one or more gaps of no set pattern, apparent or not, the progression of which could not lead to rapid failure of the rail)	Broken rail ☐ (Any rail which has separated into two or more pieces, or a rail from which a piece of metal has detached, causing a gap of more than 50 mm in length and more than 10 mm in depth in the running surface)		
2. Precise location of the defect in the track and date				
Line:				
Section:	from km ....+ .... to km ....+			
Track:	Left track ☐	Right track ☐	One track ☐	
Rail:	Left rail ☐ On the ½ rails centered on sleepers ☐	Right rail ☐ On the ½ rails centered between two sleepers ☐		
Kilometer point	from km ....+ .... to km ....+			
Date the defect was dicaverd:	Date the defect was repaired:	Date the broken rail was removed:		
3. Detection method				
Visual inspection ☐	Ultrasonic testing ☐	Eddy current testing ☐	Other means of detection ☐	
4. Characteristics of the line				
Layout:	Straight line ☐	Curve ☐, Curve radius R = Switch ☐, Crossing ☐, Expansion joint ☐ Outer (high) rail in the curve ☐; Inner (low) rail in the curve ☐		
UIC group classification, (UIC CODE 700):	A' ☐, A" ☐, A ☐, B1☐, B2 ☐, C2 ☐, C3 ☐, C4 ☐, D2 ☐, D3 ☐, D4 ☐			
Max. speed: V= km/h	Temporarily reduced speed: V= km/h Date: from to			
5. Characteristics of the track				
Year laid:				
Method of laying:	Standard sections ☐	Continuously welded rail ☐		
Rail fastening:	Type:	With base plates ☐	Without base plates ☐	
Type of sleepers:	Wooden ☐	Concrete ☐	Steel ☐	Slab track ☐
Lokacion: from km ....+ .... to km ....+	Open line ☐	Station ☐ Name:	Tunnel ☐ Name:	Bridge ☐ Name:
Type of joint:	Ordinary ☐	Functioned ☐	Insulated ☐	Glued insulated ☐
6. Characteristics of the rail				
Rail condition:	New rail ☐	Reused rail ☐		
Rail profile:	49 E1 ☐	60 E1 ☐	Other:	
Length:	Length of new rail: .....m	Length of reused rail: .....m	Length of replaced rail: .....m	
Steel grade:	(700) R 200 ☐	(900) R 220 ☐	(900 A) R 260 ☐	
	(900 B) R 260 Mn ☐	(1100) R 320 Cr ☐	(900 A (HH)) R 350 HT ☐	R350 LHT ☐
Marks:	Rolling marks (in relief) ☐	Stamped marks (embossed) ☐		
Manufacturing process :	Total gross tonnage borne:			
7. Characteristics of welds or resurfacing				
Weld removed ☐	Weld repaired ☐			
Length of replacement rail:				
Profiles of the rails on either side of the weld:				
Steel grade of the rails on either side of the weld:				
Resurfacing:	at rail end ☐	away from rail end ☐		
8. Action taken				
Keep rail under inspection ☐	Reinforcing the rail with fishplates, or clamps ☐	Repair weld ☐		
Rail removed on	Rail dispatched to			

Table 2. Attachment on main form: km 405+804.00





L = 18 mm D = 2 mm

Notes:
Speed: 90 km/h; Axle load: 22,5 t; Rail profile: S49 (49E1); Quality of steel: R 260; Year of manufacture: 1980; Track: main; Rail: left; Straight line

Infrastructure managers can influence the occurrence and development of cracks by proper track maintenance. Early detection of defects is extremely important, as they can be removed by rail grinding. How to detect squats at an early stage by measurement of an appropriate dynamic response during passage of wheel over the damaged zone, is still an open question (recent progress has been shown in [16,17]. The authors recommend combination of methods for squat detection: visual inspection, optical system by camera, ultrasonic testing from vehicle, manual check by ultrasonic testing, as well as eddy current testing every 6 months. In addition, inspections are carried out as needed (see Table 3).

If conducted on time, grinding of surface fissures will prevent their further development. This effect is however not permanent. After a certain period, squats occur again and a new cycle of rail grinding becomes necessary. The modern strategy of rail grinding includes preventive, corrective and cyclical activities. The aim of preventive grinding (rail "care" once new rails have been laid in track, and before work acceptance) is to provide optimum conditions at the wheel-rail contact in the beginning of exploitation, and also to remove usual irregularities that appear during track laying (e.g. slight unevenness at rail welds). Cyclic (controlled) activities are conducted to remove a thin layer (from 0.1 to 0.2 mm) from the entire rail head surface, and up to 0.6 mm in the zones with defects. Corrective activities are characterized by small but intense interventions and long intervals between their implementation. The consequences are long periods characterized by relatively poor conditions at the rail head surface.

An optimum superstructure maintenance management must include control and analysis of the track geometry and railway substructure.

5. Conclusions

It is believed that the worsening of situation with regard to squat damage is due to: higher axle loads and greater traffic density, poor maintenance policies (deterioration of track geometry), new rolling stock with ABS and anti-spin devices, and new wheel and rail materials. Unfortunately, the superstructure maintenance activities currently applied

Table 3. Recommended actions against squat damage [22]

Recommendations	Length	Depth	Emergency action	Timescale
UIC	L > 200 mm	or > 25 mm		2 weeks
			Fit clamps	6 weeks
	50 < L < 200 mm	or 10 < D < 25 mm		12 months
	≤ 50 mm	or < 10 mm	Re-inspect	Normal Inspection interval
ProRail		> 50 % (>25 mm) head height	40 km/h	As soon as possible
			or fit clamps	3 months
		20% (10 mm) < D < 50 % (25 mm) head height		4 weeks
		<20 % (10 mm) head height		3 months
		No ultrasonic response	Re-inspect visually	6 months

in Montengero are rather sporadic, and are often undertaken without regard to actual condition at the level of rail substructure. The deterioration of vertical track geometry is corrected by tamping and ballast adding, without analyzing the causes and actual effectiveness of these measures. Such maintenance strategy is a short-term solution that eventually leads to high maintenance costs. The condition of the substructure is generally quite poor. Therefore, the superstructure maintenance management must include the analysis of both the substructure and superstructure, and the study of the rolling stock. The infrastructure manager has to define an appropriate maintenance plan for the infrastructure of each conventional rail line in Montenegro. This plan must *inter alia* include inspection and maintenance strategy against RCF defects. The maintenance strategy should ensure a longer rail service life, and reduce overall rail maintenance costs.

Synchronisation of the Montenegro Railways maintenance strategy with EU technical regulations would ensure uniformity of procedures that are used for identifying, reporting and classification of rail defects, and preparation of statistical indicators of rail defects within a single European database, which is all aimed at sharing experiences and developing a uniform management methodology for maintenance of rail infrastructure at the European level and beyond.

Finally, it should be emphasized that there is an urgent need for harmonization of railway maintenance regulations based on European legislation, while also respecting local distinctiveness and limitations.

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