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Assessment of Image Processing Methods for the Determination of Propagation of Squat-Type Defects in Rails

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Abstract. We demonstrate the idea of squat-type defect measurement in the rail and the concept of tracking of the defect development using the techniques of image acquisition and image processing as well as the methods of metric spaces. We introduce the concepts of a set diameter $\delta(A)$ and the metric ρ_1, which come from the properties of plane figures, to compare and to observe the development of the defects.
We characterize the feasibility of the method to determine the dynamics of the defect development. The tests have shown that it is possible to apply the method with a camera during current diagnostic procedures provided that the distance to the rail is similar. Normalized metric enables easy comparison of the results and allows for the assessment of the reliability of the rails. The advantages of the method include simplicity and ability to observe the defects during the entire cycle of their development, which makes it possible to take the diagnostic decisions at the appropriate time.

Keywords: Squat-Type Defects, Image Processing Methods, Rolling Contact Fatigue (RCF) Defects, Measurement of Rail Defects.

1 Introduction

The defects in the rails can be classified as the defects at or outside the rail ends, and the defects caused by rail damaging, the defects developing during rail joining or rail repair. The rolling contact fatigue (RCF) defects are the most frequent defects located outside the rail ends. This group includes squat-type defects, which are indicated as 227-defects (Fig. 1).

Fig. 1. Squat-type rail defect.

Squat-type defect develop at the running surface of the rail in the region of the contact between the rail and the wheel. Squat-type defect has the form of a darker localized depression containing cracks with semi-circular arc or V-shape (Fig. 2). Squat can be located randomly as a single or multiple defects, and it is usually detected in the rail joints (in that case squat is classified as the defect due to the process of rail joining) [1].

Fig. 2. Typical forms of squat-type defects: V-shaped crack (left) and arc-shaped crack (right).

The number of squat-type defects reaches ca. 48% of all rail defects in some railway lines. The diagnostics of squat-type defects is challenging due to the physical effects and technical limitations such as the lack of devices enabling the measurement of the defects during rail exploitation.

The details of mechanisms of generation and development of squat-type defects are actually not known. In this project, we tried to analyze that challenges.

The investigations of defect development during the exploitation are difficult due to the limitations of observation automation of those processes and due to the inability to assess the early-stage defects. In fact, it was reported that high-speed photography cannot achieve sufficient level of accuracy. Therefore, the dynamics of the development of defects is not a criterion of their repair due to the problems with the measurements and the analysis [1,2,3].

2 Assessment of the Squat - Type Defects

We performed the measurements of the squat-type defects in rails of the running train line. We measured the parameters such as the length of depression, length of defect, the depth of depression and the depth of defect (Fig. 3).

Fig. 3. Measurement of defects.

The experimental section of the length of 31,5 km is located in the track #1 and #2 of the train line #131 Chorzów Batory – Tczew. The analysis was performed for the track #2. The rails were made of the R260 steel manufactured by the Katowice Steelworks (K). The rails were fastened to the sleepers using K-type rail clips. General repair of railroad surface in 2012 caused changes in the track #2 design at the analyzed section.

Table 1. Development of 227-squat defects

		initial measurement		measurement after 6 months		measurement after 15 months		
Defect number	Rail (R-right, L-left) (number of items)	Length of depression [mm]	Length of defect [mm]	Length of depression [mm]	Length of defect [mm]	Length of depression [mm]	Length of defect [mm]	Depth of degression/defect [mm]
1	R	45	20	50	20	65	25	1,0
2	R	135	65	140	65	140	65	3,0
3	R	50	0	50	0	50	0	< 1,0
4	L	50	0	65	10	65	45	6,0

5	R	120	0	120	0	130	10	1,0
6	L (2)	120	50	120	105	130	115	4,2
7	R	65	5	75	5	75	5	1,0
8	L	140	35	220	40	220	160	4,6
9	R	50	0	50	0	50	10	< 1,0
10	L (3)	140	15	150	40	150	40	4,2
11	L (2)	100	15	100	15	115	30	2,8
12	L	55	0	90	0	100	0	< 1,0
13	R	90	10	90	15	100	40	5,2
14	L (2)	115	30	130	60	145	85	3,2
15	R (4)	70	5	85	5	85	5	1,6
16	R	140	25	140	25	150	25	1,7

The studies showed that the rate of the defects' development is different at various locations in both rails [2,3]. It means that the rails are more vulnerable to defect development (Table 1). The technical and exploitation conditions impacting the rate of defect development include: the type of rail, rail steel grade, type of track, type of sleepers, condition of other elements of rail surface, the type of rail traffic, the load of the line, train line geometry, brake and start zones.

From practical point of view it is important to automatize the measurements and to assess the dynamics of defect development in rail (Fig. 4) and to use the results for forecasting the maintenance works. This is crucial since the vehicles use the tracks with defected rails, which impacts the safety of passengers and freight.

Fig. 4. Development of defect in the rail over a period of 15 months of rail exploitation.

3 Idea of the Measurement and Acquisition of Data on Squat - Type Defects

The cameras can be used to acquire the images of the squat-type defects. Formally, both the cameras and the photographs are non-metric [4].

We used KODAK camera to check the usefullness of those devices to measure plane linear deformations such as scratches, cracks, contours etc.

We used line segments of different lengths and circles of different radii as models. To perform the measurement, we took a photo of a model line segment of the length of 100 mm from the distance 1,3 m using the focal distance of the camera of 200 mm. the photographs were taken at different inclination angles of the camera axis with respect to the CCD array. The most precise results were obtained for photographs taken in the plane parallel to the model plane since the principles of perspective projection that decide about reliable mapping of the model on the photograph [5]. The obtained errors were of the order of 1%. The largest error (10%) was observed for the inclination angle of 20 degrees. The error of 4% was detected for inclination angle of 10 degrees.

From the geometrical point of view, the squat-type defects can be treated as the plane set (plane geometric shape) A if the depth (usually 3 mm) is not taken into account. This set can be easily identified (imaged) with the camera during the entire period of the experiment. How can the obtained images be used to assess the propagation of the defect? This can be achieved with the aid of the concept of metric spaces, the quantities and their properties. This allows to propose the following methodology.

In a metric space (X, ρ) [6] one define the diameter of the set A in X [7]. In the case of the set $A \neq$ its diameter is the finite or infinite number $\delta(A)$ given by:

$$\delta(A) = \sup_{x,y \in A} \rho(x, y) \tag{1}$$

(sup indicates supremum).
Additionally, we have $\delta(\ ) = 0$. As a consequence, $0 \leq \delta(A) \leq \infty$ and for a bounded set A we obtain $\delta(A) < \infty$.

One can directly conclude from the definitione of the diameter of the set that

$$if\ A \subset B\ , t\ \ en\ \ \delta(A) \leq \delta(B). \tag{2}$$

For two arbitrary non-empty sets A, B so that $A \cap B \neq$ the following relations holds

$$\delta(A \cup B) \leq \delta(A) + \delta(B). \tag{3}$$

In a metric space (X, ρ) one can introduce a metric ρ_1 given by

$$\rho_1(x, y) = \frac{\rho(x,y)}{1+\rho(x,y)} \quad for\ x, y \in X \tag{4}$$

with the following interesting property [8]

$$0 \leq \rho_1(x, y) < 1 \tag{5}$$

The property of the metric ρ_1 is important from practical point of view since $\rho_1 \epsilon < 0, 1)$ (Fig. 5).

The quantities changing in time for a given defect are the metric parameters of the defect (Table 1), as shown in the photograph (see Fig. 4).

We take the photo of the defect u in time t_0, so that $u(t_0)$ is imaged according to the rules, and the image (photograph) $z(t_0) \leftrightarrow A(t_0)$ is assigned to the defect u. The defect $u(t_0)$ corresponds now to the two-dimensional figure (plane set) $A(t_0) \subset R^2$. In this way, we introduces the correspondence between $u(t_0)$, $z(t_0), A(t_0)$, therefore $u(t_0) \leftrightarrow z(t_0) \leftrightarrow A(t_0)$. In this geometric shape $A(t_0)$ one can further assign the quantities: diameter $\delta(A(t_0))$ of the set $A(t_0)$, its area $\mu(A(t_0))$, center of gravity $S(t_0)$, and the distance between selected (characteristic) points $P(t_0), Q(t_0) \in A(t_0)$ in different metrics.

This procedure can be repeated in time instances $t_i = t_0 + \quad t_i$, $i = 1, 2, 3, \dots, n$ during defect analysis $u(t_i)$, $i = 1, 2, 3, \dots, n$. We will obtain finite sequences of the quantities $\delta\big(A(t_i)\big)$, $\mu\big(A(t_i)\big)$, $S(t_i)$, $\rho\big(P(t_i), Q(t_i)\big)$ dla $\mathrm{i} = 1, 2, 3, \dots, \mathrm{n}$, which enable acquisition of the analysis of the defect development in time.

One can introduce different metrics in a set $X = R^2$. In particular, rail metrics given by the equation

$$\rho(x,y) = \begin{cases} |x_1 \quad y_1| + |x_2| + |y_2| & for\ x_1 \neq y_1 \\ |x_2 \quad y_2| & for\ x_1 = y_1 \end{cases} \tag{6}$$

is an interesting metric to determine the development of the squat-type defect. The rail metric is especially useful to determine $\rho\big(P(t_i), Q(t_i)\big)$ for i=1,2,3,…,n or $\rho_1\big(P(t_i), Q(t_i)\big)$ for i=1,2,3,…,n.

Table 2 includes metric $\rho_1(x,y)$ calculated for the data from Table 1. This allows an easy comparison of the results. Additionally, selected results in the form of normalized trends of defect development are demonstrated in Fig. 5. Varying dynamics at different stages of defect development is shown here.

Table 2. Metric ρ_1 for the defects mentioned in Table 1

		initial measurement	measurement after 6 months	measurement after 15 months
Defect number	Rail (R-right, L-left) (number of items)	ρ_1	ρ_1	ρ_1
1	R	0,9524	0,9524	0,9615
2	R	0,9848	0,9848	0,9848

3	R	0,0000	0,0000	0,0000
4	L	0,0000	0,9091	0,9783
5	R	0,0000	0,0000	0,9091
6	L (2)	0,9804	0,9906	0,9914
7	R	0,8333	0,8333	0,8333
8	L	0,9722	0,9756	0,9938
9	R	0,0000	0,0000	0,9091
10	L (3)	0,9375	0,9756	0,9756
11	L (2)	0,0000	0,0000	0,9375
12	L	0,0000	0,0000	0,0000
13	R	0,9375	0,9375	0,9677
14	L (2)	0,0000	0,0000	0,0000
15	R (4)	0,9091	0,9375	0,9756
16	R	0,9677	0,9836	0,9884

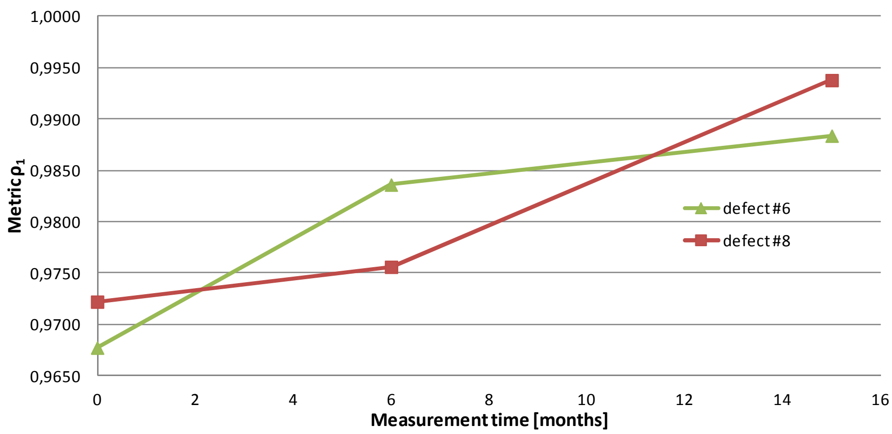

Fig. 5. Metric ρ_1 for two selected defects (# 6 and 8 in Table 2) measured three times.

The parameters defined earlier can characterize the development of the defect and reveal different forms of the defect allowing for a more comprehensive quantitative analysis of the data. The meaning of the parameters of $\delta(A)$, $\mu(A)$ is demonstrated in Figs. 6-8.

Fig. 6. Defect with a short length and a significant width (the difference between defect length and its diameter $\delta(A)$)

Fig. 7. Defect with a significant length and a significant width.

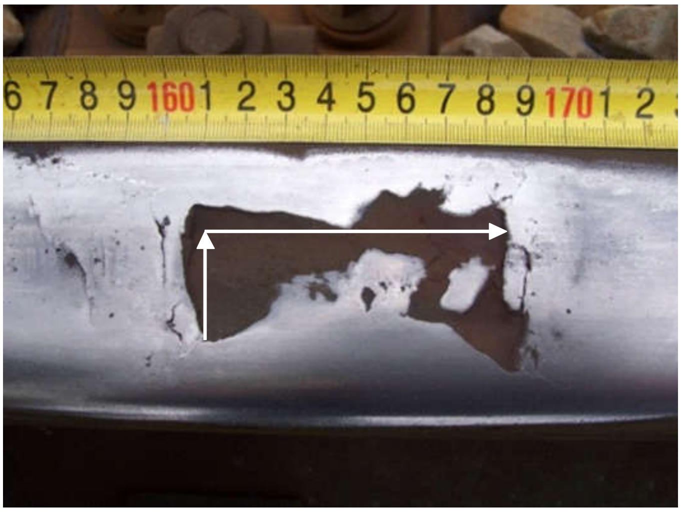

Fig. 8. Defect with a significant length, a very irregular shape and a small area.

Fig. 6 shows that in some situations the lengths and corresponding metric ρ_1 cannot be the objective parameters for shape assessment and defect development. In that case, $\delta(A)$ should be included in the measurement. The length of the defect is shorter than $\delta(A)$ in Fig. 6 and Fig. 8. The significance of that parameter is presented here. Since the defects are of different and very irregular character, a more precise quantity is the defect area $\mu(A)$**.** The significance of the area $\mu(A)$ is given in Figs. 6-8. On the other hand, the significance of the train metric in the measurement procedure of the squat-type defects in rails is revealed in Figs. 7-8.

4 Conclusions

The images of the defects $u(t_i)$, $i = 1, 2, 3, \ldots, n$ are the starting points of the proposed method.

The method enables registration, identification, characterization and archiving the defect during current maintenance and diagnostic works.

The method does not require any sophisticated equipment or highly experienced specialists.

The photograph of the defect should be taken in the plane parallel to the surface of the object. This provides homogenous scaling of the entire photo and minimizes the errors [9].

The studies showed that the photo can be taken in a standing position to improve the acquisition of the images.

The proposed methodology is not subjective and does not involve labor consumption of the applied technologies.

The analytical apparatus is relatively simple allowing for the assessment of the trends in dynamics of defect development.

The proposed method using metric spaces is effective in determination of dynamics of defect development.

The results can be compared using the metric ρ_1 with the property (5).

The analyses of the metric quantities for $A(t_i)$, $i = 1, 2, 3, \ldots, n$ offer opportunities to use the results for the determination of the reliability of rails.

The proposed methodology opens new gates towards development of the devices for quantitative analysis of the squat-type defects.

The analyses shown in this paper represent contribution for the explanation of the mechanism of generation and development of squat-type defects of rails.

The advantage of the method is the possibility to perform the measurements during regular exploitation of the rails in the track.

However, the method is not able to determine the depth of defect.

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