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Squat Monitoring Campaign: Set-Up and Results

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Abstract

Squats are rolling contact fatigue defects that may lead to rail fracture and hence increase of maintenance costs. This paper presents the results of a squat monitoring programme designed to measure fatigue crack growth under operational conditions. Four squats were monitored over a period of eight months using ultrasonic measurements, visual inspection, and magnetic particle testing. The observed crack growth is between $0\,\mathrm{mm}$ and $6\,\mathrm{mm}$ during the monitoring period, depending on the squat. The estimation of this growth depends on the used ultrasonic probe angle. In addition to these periodic inspections, a continuous monitoring system was installed, measuring the vertical acceleration of the track in the vicinity of the defect.

Keywords: squats, track monitoring, fatigue crack growth rate, ultrasonic inspection, rolling contact fatigue, R260mn.

1 Introduction

Rails are subjected to non-proportional multi-axial cyclic loading, that may lead to rolling contact fatigue (RCF). RCF can lead to defects in rails such as squats [1]. Squats are often decisive for rail maintenance [2, 3]. A squat is a crack network originating from the head of the rail and propagating into the head of the rail [4]. Fig. 1 shows a simplified schematization of a squat [5]. The squat consists of three parts: (a) A V-shaped crack mouth; (b) a subsurface leading crack that grows from the V-shaped crack mouth along the rolling direction; and (c) another subsurface trailing crack propagating from the V-shaped crack mouth in the opposite direction. After initiation, three crack growth phases can be identified. The first is the Stage-1 fatigue crack growth phase, which initiates under a relatively shallow angle beneath the surface. The second is the Stage-2 crack growth phase, during which the crack starts to deviate toward a more vertical direction. Finally, in Stage-3, unstable crack growth can result in failure of the complete cross-section. In the vicinity of the squat, a depressed zone is visible in the rail head, and the running band becomes wider. The blue region indicates the ultrasonic probes, which will be elaborated on later.

Predicting the residual life of a squat requires an accurate estimation of the dynamic interaction between load and defective rail, the fatigue crack growth propagation and the failure condition. The rail is subjected to several loads that depend on, amongst others, the static axle load, the track stiffness, and the local rail geometry. Next to these quasi-static components, there are also significant dynamic loadings [6], leading to large uncertainties in the prediction models. For the fatigue crack propagation, only a limited number of studies are available measuring crack growth in squats under realistic loading conditions [7, 8].

Therefore, the goal of this study is to measure squat fatigue crack growth under operational conditions. Four squats on a Dutch railway track were monitored over eight months through periodic visual and ultrasonic inspections performed approximately every two months. In addition to these periodic inspections, a continuous monitoring

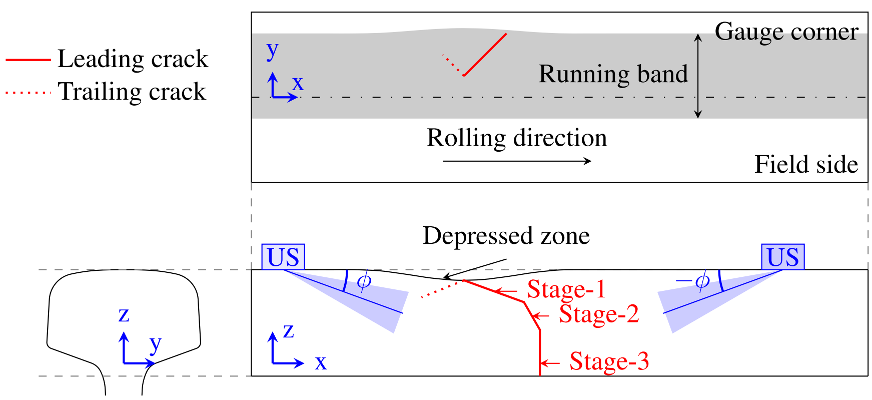


Figure 1: Schematization of squat defect and positioning of ultrasonic probes.

system was installed to study the correlation between vertical acceleration and squat dimensions. This paper presents the measurement set-up, inspection results for one squat, the main conclusions and further steps.

2 Test setup

The test location is a unidirectional mixed-traffic track (freight and passenger trains) in the Netherlands. The squats are located in a straight (non-curved) section of the track. The rail steel grade is R260Mn and the rail profile is E54E1. Axle load measurements are performed throughout the network, and the annual transported mass at the test location is approximately $22 \times 10^9\,\mathrm{kg}$. During the periodic inspections, the squats are inspected visually, using ultrasonic techniques and using a 3D scanner for a limited number of inspections.

In the visual inspections, in addition to regular photographs, the V-shaped surface-breaking crack mouth is visualised using magnetic particle testing.

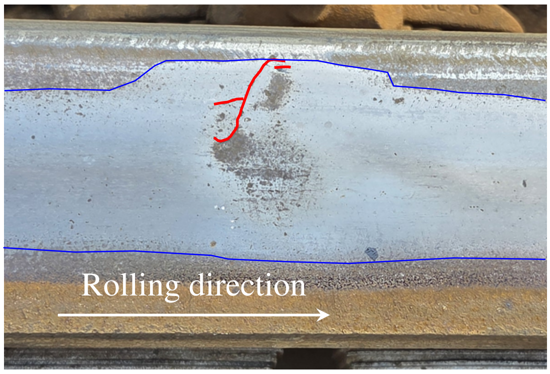
Manual ultrasonic pulse-echo measurements allow the subsurface defect to be measured. Three different probe angles ϕ (see Fig. 1) are used: $0°$, $45°$, and $70°$ to capture the different stages of crack growth. All probes measure at $4\,\mathrm{MHz}$. To measure both the trailing and leading cracks, measurements with the non-zero-angle probes are performed in the dominant rolling direction (denoted with $\phi > 0$) and against the dominant rolling direction (denoted with $\phi < 0$), see Fig. 1.

The applied monitoring system consists of 23 acceleration sensors mounted to the sleepers, both in the vicinity of the squats and outside the region of the registered squats, see Fig. 3a. Each measurement unit consists of two acceleration sensors that automatically record data for $6\,\mathrm{s}$ at $250\,\mathrm{Hz}$ when a train passage is detected.

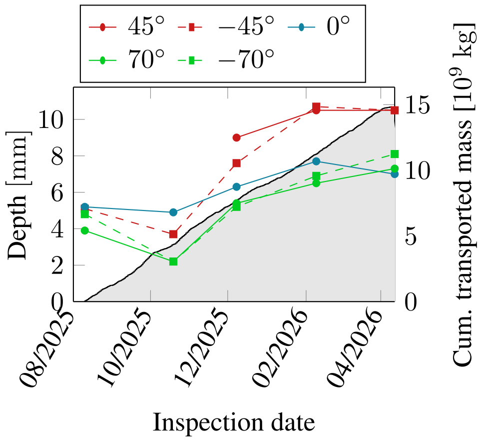
3 Results

Fig. 2a shows one of the squat defects examined in January 2026. The blue curves show the widening of the running band, and the red line indicates the approximate surface breaking crack-mouth, based on the magnetic particle inspection. Contrary to a typical V-shaped crack mouth, this squat shows a crack network at the surface, where several parts of the squat are surface breaking. In the vicinity of the squat, the dark region in the running band indicates that, at that location, there is no contact between the wheel and the rail, and the load is transferred either around the squat over the widened running band, or the load jumps over this region due to the increased dynamic effect [4] and the resulting depressed zone in the vicinity of the defect.

Fig. 2b shows the ultrasonic inspection results for this squat. The different colours represent the different probe angles, in which a distinction is made in the two scanning directions. The dashed region shows the cumulative transported mass, corresponding with the right vertical axis. Five inspections have been carried out. The $0°$ probe



(a)



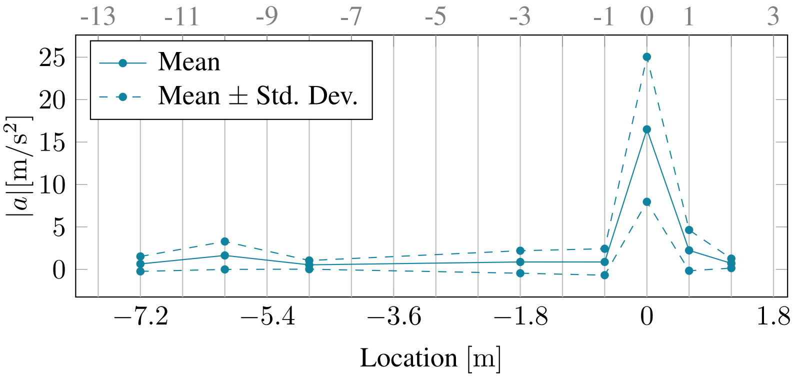
(b)

Figure 2: Squat 1: (a) Top view of rail, red line indicates surface breaking crack mouth, blue lines indicate running band; (b) Ultrasonic inspection results and cumulative transported mass.

measuring the depth of mainly the Stage-1 region shows an increase of approximately $3\,\mathrm{mm}$ throughout the monitoring period. The maximum measured Stage-1 depth is $7.7\,\mathrm{mm}$. Between August and November 2025, all probes indicate a slight decrease in crack length. A similar decrease is observed with the $0°$ probe between February and April 2026. These decreases are attributed to the measurement uncertainty. From the December measurement, significant crack growth is observed with the non-zero degree probes. Depending on the probe angle between $5\,\mathrm{mm}$ and $7\,\mathrm{mm}$ fatigue crack growth is measured between October 2025 and April 2026. The $45°$ probes indicate a larger crack depth than the $70°$ probes. A possible explanation could be that the squat is in the transition phase from from Stage-1 to Stage-2. One of the other monitored squats shows a similar amount of crack growth, while the other two squats show smaller crack growth between $0\,\mathrm{mm}$ and $3\,\mathrm{mm}$ for the same period. To further investigate these differences, the rails will be extracted from the track and examined using both non-destructive and destructive techniques to visualise the crack networks in detail and compare them with the last ultrasonic measurements.

From the continuously recorded data of the accelerometers, the maximum and minimum acceleration are calculated for every sensor and train passage. Fig. 3b shows the absolute maximum acceleration as a function of the distance to the squat ($x = 0\,\mathrm{m}$). The vertical grey lines indicate the sleeper positions. The squat is located approximately above a sleeper. A significant increase in acceleration is observed in the vicinity of the defect. However, the effect of the squat on the measured accelerations on the surrounding sleepers is limited.

(a)



(b)

Figure 3: Acceleration sensors: (a) Acceleration sensor mounted on sleeper; (b) Mean and standard deviation of maximum acceleration, grey vertical lines indicates sleepers, Squat is located at $x = 0$.

4 Conclusions and outlook

This study presents the monitoring programme developed to measure squat fatigue crack growth under operational conditions. Four squats were being monitored over a period of eight months. Vertical accelerations at the sleepers were continuously measured throughout the monitoring period. The results presented in this paper indicate that, depending on the angle of the ultrasonic probe, the crack growth during this period is between $3\,\mathrm{mm}$ and $7\,\mathrm{mm}$. Future research will include extracting the rail from the track and evaluating the acceleration data.

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