In situ monitoring of multi-stage rail surface defects in three dimensions using mobile ultrasonic technique

Sakdirat Kaewunruen
Makoto Ishida
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Sakdirat Kaewunruen and Makoto Ishida

1Birmingham Centre for Railway Research and Education, University of Birmingham, Birmingham, B15 2TT, UK
2Railway Engineering Department, Railway Division, Nippon Koei Co. Ltd., 5-4 Kojimachi, Chiyoda-ku, Tokyo 102-8539 Japan

Abstract

Rail surface defects (such as rail squats, corrugation, rolling contact fatigue damages, wear, etc.) are one of the top priorities in infrastructure maintenance management. Typically rail squats are classified as the growth of any cracks that have grown longitudinally through the subsurface. In addition, some of the cracks can branch off from initial longitudinal cracks with a depression of rail surface, and then transversely propagate to the bottom of rails. The rail surface defects are commonly referred to as ‘squats’ when they were initiated from damage layer caused by rolling contact fatigue, and as ‘studs’ when they were associated with white etching layer caused by the transform from pearlitic steel due to friction heat generated by wheel sliding or excessive traction. For over 60 years, these rail surface defects have been often observed in railway tracks operated for either light passenger or heavy freight traffics and with a variety of train speeds: low, medium or high speed trains all over the world. The exception exists at some locations such as sharp curves where large wear takes place under severe friction between wheel flange and rail gauge face. The rail surface defects become a much-more significant issue when the crack grows and sometimes flakes off the rail, resulting in severe rail surface irregularities. It is often noticed that the rail surface defects induce wheel/rail impacts and large amplitude vibrations of track structure, resulting in poor ride quality. The rail squats/studs have occasionally turned into broken rails in many countries such as Australia, Germany, France, Great Britain and Japan. Many research investigations from the fracture mechanical and material scientific points of view are being carried out in order to evaluate the root cause, early warning signs and preventive solutions. Some patterns of squat/stud development related to both of curve and tangent track geometries have been observed, and squat growth has also been monitored for individual squats using ultrasonic plotting techniques. This paper investigates squat/stud distribution and its growth in the fields. The squat/stud growth has been examined and monitored using the ultrasonic measurement device on a reference grid applied to the rail surface. Three dimensional contours of rail
squat cracks can then be formulated by the measurement records. It has been found that crack propagation is non-linear to repeated train loads when the crack is getting larger. In this study, the crack propagation of medium-scale squats/studs can be observed to be almost linear to repeated train loads called as accumulated passing tonnages up to a certain degree of propagated crack length.

**Keywords:** Rail surface defect; Squats and studs; Ultrasonic mapping; Field monitoring; Asset management; Field experimental technique; Multi-stage growth.

1 Introduction

Significant experiences of railway infrastructure owners and operators all over the world have underlined a critical safety concern and maintenance priority of rail surface defects. Such rail surface defects undermine safety and operational reliability of either moderate or high speed trains including passenger suburban, metro, urban, mixed-traffic and freight rail systems. The cost of rail replacements due to rail squats and studs has reportedly become a significant portion of the whole track maintenance costs, especially in European countries e.g. Austria, Germany and France\[1\]. Typically the rail squats and studs are classified as the growth of any cracks that has grown longitudinally through the subsurface due to repeated train loads, which means both of squats and studs are typical rolling contact fatigue (RCF) defects but the mechanism of initiating cracks of those two defects are different. Also, the subsurface horizontal crack later results in a depression of rail surface sometimes called ‘dark spot’\[2\]. ‘Squats’ are defined as the crack initiated from rolling contact fatigue damage layer, and as ‘studs’ are defined as the crack initiated from white etching layer (WEL) due to wheel slides or excessive tractive effort\[3\].

It has been found that the rail surface defect is one of widespread problems in both passenger and freight rail networks in many countries. The rail squat/stud defects could be observed in all arrays of track geometries and gradients, in all types of track structures, and in all possible operational rail traffics as shown in Fig. 1. One exception where almost no squat could be observed is inside the dry tunnels\[4-5\]. However, a recent collaborative research shows some rail studs appear in London Underground due to excessive wheel traction issues\[6\]. The cracks of studs initiate in the WEL and grow horizontally at the depth of 3-6mm below the rail surface. The rail surface becomes depressed, giving rise to vibration impact and transient noise. The cracks of squats propagate from surface cracks initiated by rolling contact fatigue (RCF) and similarly grow at the depth of 3-6mm below the rail surface. Squats are often found in tangent tracks and in high rails of moderate radius curves, in particular squats caused in high rails of moderate radius curves are called gauge corner cracks, and in turnouts with vertical, unground rails. Accordingly, a number of research and development projects have been initiated around the world in order to investigate the root causes and feasible economical solutions to rail squat problem, which will have a significant impact on rail asset management strategy. It
is noted that the significance of the rail squat/stud problems has led to the international collaboration on rail squats, which bring together the best and brightest minds from academia and industry to attend the ‘International Workshop on Rail Squats’ annually.

![Image of rail squat](image)

**Figure 1.** Rail squats in railway tracks based on their initiation types

a) WEL-related stud (multiple squats)

![Image of WEL-related stud](image)

b) RCF-related squat (single squat)

Often, the ride comfort of the passenger trains and freight body dynamics exceeds acceptable limits due to the rail squat/stud problem\(^7\). Excessive noise and vibration also result in more complaints against rail operators. Most importantly, the impact forces due to the wheel/rail interaction undermine the structural integrity and
stability of track components\textsuperscript{[8-12]}. In Japan and Europe, it is usually found that the rail squats can transversely grow and later turn into the broken rails, which could derail the trains and potentially result in a catastrophe\textsuperscript{[2]}. A similar infamous example of the tragedy was the Hatfield accident in the UK. Fig. 2 shows some examples original rail squats found over 60 years ago in Japanese ballasted tracks. The dark spots, so-called ‘rail surface shelling’ in Japanese practice, were observed in both gentle curves and tangent (straight) tracks.

Extensive laboratory tests using twin disks and rail ring rollers in Australia showed that, once initiation crack occurred, any third-body fluid between wheel and rail (i.e. lubrication greases, moisture, carbon and paint sprays) tends to promote the growth of squats and studs, which was coincide with the field observations\textsuperscript{[13-16]}. It is thus believed that the crack propagation in squats or studs could be promoted by a similar process of water entrapment and cyclic dynamic wheel loading regime.

![Figure 2. Classic rail squats in Japanese railway tracks](image)

a) dark spots in gentle curve

b) dark spots in tangent track
This paper highlights the root causes and features the field investigations of squat/stud distribution and its growth using a non-destructive testing technique by a handheld ultrasonic device. Several squat/stud defects have been chosen for field monitoring. The demonstration of measuring depth and dimension of cracks is presented using the hand-held ultrasonic device. The growth rate of squat/stud could then be examined on a reference grid applied to the rail surface. The crack depths at each grid node and the extension of crack dimension form a three dimensional contour of rail squat/stud defects. This 3D crack mapping technique was firstly developed for field experiments on a living rail network and has now been used to monitor rail squats and studs in operational railways around the world. This paper also provides technical background of ultrasonic testing method for a companion paper related to the potential development of automated rail squat detection using magnetization technology.

2 Ultrasonic Technique for Live Rail Networks

Currently, a special attention has been paid to develop an automated detection system for rail squats using on-board technologies. However, the handheld ultrasonic testing technique to complement such on-board technology is still required for verification and assurance. This paper will discuss such the mobile experimental technique intended for field testing in live rail networks. In order to develop the technique, three samples of squats were taken, following up from previous inspections at a rail track in NSW, Australia. The rail was manufactured in 2006 with the dimension for 60kg/m HH One-Steel rail. All three samples were used in this study and later sent to a university for laboratory tests in order to investigate the role of third-body fluids on the growth of rail squats and studs in details. In these specimens, the rail squat defects were mostly associated with gauge corner checking (hair cracks initiated due to rolling contact fatigue). It was observed that the squat cracks tend to grow longitudinally along the surface throughout the rail samples. In the case of multiple type of squats, mostly high rail gauge corner cracks, white etching layer (WEL) formed on the running band of rail crown must be checked to investigate the main cause of those squats such as the impact of WEL and/or hair crack of gauge corner checking propagation\cite{17}.

For practicality, mobility and suitability in the field measurement, the hand-held ultrasonic testing device (with the accuracy range of +/- 0.1 mm) is chosen for this test. The square grids of 10mm x 10mm size were developed over the cracks, in order to map the cracks with a benchmarking reference. At each grid point, the digital ultrasonic testing device with a 10mm-diameter probe was applied to detect the existence of crack. If the crack exists, the depth of crack will be recorded. In some cases, a smaller probe (e.g. 5mm diameter) will be used to accurately evaluate shallow cracks and the thickness of crack tip (<3 mm deep). It is important to note that the orientation of the probe should be set consistently as illustrated in Figure 3 to obtain consistent measurements. Using this technique, the squat defects can be examined and monitored in great details. A standard reference grid on transparent
plastic slides and the reference punch mark system has then been developed for field work.\textsuperscript{[18]}

\textbf{Figure 3.} Illustrative testing method for mobile handheld ultrasonic device\textsuperscript{[18]}

Using this reference technique, the crack depth data can be examined and used for developing a crack contour. As a case study, a data set of the 3D mapping of rail squats is demonstrated in this paper\textsuperscript{[17-20]}. Note that an attempt to change the probe orientation has been made. It was found that when the crack is about flat, the orientation has little effect on the crack depth reading. The subsurface crack depths can be measured at each grid point using the ultrasonic testing. In Figure 4, the

\textbf{Figure 4.} Ultrasonic testing (Top: crack depths at each grid; Bottom: top view rail surface)
testing grid is first marked at about 210 mm away from the left end of a rail sample. Squat depths at each grid intersection (10mm x 10mm) are shown in the top chart. It is found that crack does not exist in row three (about 30 mm from the gauge face). It is clear that the squat cracks were developed from the depression of rail surface around the V-shape. This phenomenon can be observed in the field visual inspections, whilst it has proven to be quite difficult to detect this trait by using on-board monitoring technology.

3 Field Monitoring

Field monitoring of rail squats is imperative in order to maintain the safety of rail network and to prioritise rail rehabilitation activities. In situ investigations of squat growth patterns were conducted on a selected site at Chatswood in a very busy Sydney network. The headway (the shortest time interval between trains) is about 5 mins at Chatswood. Appropriate actions proceeded as follows\(^5\):

- Squats in early stages of development were selected, marked and photographed. Comparisons with sequential digital image correlation from earlier observations were also made.
- A 10mm square grid marked on a transparent plastic sheet was fastened in position over the selected squats using magnets, with punch marks for repeat positioning.
- Each squat was photographed with the grid in position, to facilitate location of surface features.
- Crack depths were measured at grid points using Krautkramer DM4-DL ultrasonic thickness gauge.
- Positions of crack edges were established by noting positions where loss of ultrasonic reflection occurred.
- All ultrasonic depth measurements were conducted with consistent probe orientation.
- Positions of visible surface cracks (typically on the gauge side of each squat) were also plotted for each squat.
- Thickness adjustment for plastic sheet was determined from measurement of steel item with known thickness (calibration block).

Figure 5 shows the dimensional growth of a rail squat in NSW, Australia, between 2009 and 2012\(^{[5, 20-24]}\). The classic double ended kidney shape of a squat can be seen developing in the last 2 outlines (2010 and 2011). The increase in equivalent radius appears quite constant for small to medium sizes of squat. It was believed that such the nonlinear growth pattern corresponded to a period of low rainfall in Sydney, and it can be seen that the growth rate was lower here than for other periods. It is evident from the squat under monitoring that the very small squat (which is barely visible in 2007) could grow to a very much larger size of squat. It is important to note that the squat crack was too shallow to be detected by the ultrasonic equipment used in 2007. This issue has triggered the developments of on-board technologies to detect a very small crack or to identify white etching layers (WEL) formed on the rail running surface.
Rail surface defects especially rail squats and rail studs have been observed in railway tracks catered for either light passenger or heavy freight traffics and for low, medium or high-speed trains for several decades. For better clarification, ‘squats’ is referred to when they were initiated from rolling contact fatigue layer, and ‘studs’ when they were associated with white etching layer due to wheel slides or excessive tractive effort. These rail surface defects will continue to be a serious problem for railway organizations such as owners, operators and maintainers around the world even in the 21st century. The horizontal crack, which results in a depression of rail surface, induces increased maintenance level, more frequent monitoring, compromised rail testing (as the crack shields the signal echoes), and possible broken rails. Repair and maintenance associated with rail squats and studs have become a significant cost to rail infrastructure owners. This is because such the rail surface defects could be found almost everywhere, and every type of track structures, gradients and geometries. Their consequences become more pronouncing...
when the crack grows and finally fractures off the rail by itself or by insufficient rail grinding. Later, the rail surface irregularity aggravates wheel/rail impact and large amplitude vibrations of track structure and induces poor ride quality. In a worst case scenario, rail squats/studs could occasionally turn into broken rails of which such incidents have already been experienced in Australia, Europe and Japan. This study presents field monitoring of squats/studs and their growth using a mobile handheld ultrasonic technique. The case study based on the field monitoring of rail squats in operational railway tracks has been demonstrated. It is found that multi-stage of growth can be observed when the squat grows. However, the rate of crack propagation can be observed to be gentle and almost linear with slight increment over time.

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