Field monitoring of rail squats using 3D ultrasonic mapping technique

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Abstract. Rail squats and studs are typically classified as the propagation of any cracks that have grown longitudinally through the subsurface. Some of the cracks could propagate to the bottom of rails transversely, which have branched from the initial longitudinal cracks with a depression of rail surface. The rail 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. Such above-mentioned rail defects have been often observed in railway tracks catered for either light passenger or heavy freight traffics and for low, medium or high speed trains all over the world for over 60 years except some places such as sharp curves where large wear takes place under severe friction between wheel flange and rail gauge face. It becomes a much-more significant issue when the crack grows and sometimes flakes off the rail (by itself or by insufficient rail grinding), resulting in a rail surface irregularity. Such rail surface defect induces wheel/rail impact and large amplitude vibration of track structure and poor ride quality. In Australia, Europe and Japan, rail squats/studs have occasionally turned into broken rails. The root cause and preventive solution to this defect are still under investigation from the fracture mechanics and material sciences point of view. Some patterns of squat/stud development related to both of curve and tangent track

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geometries have been observed, and squat growth has also been monitored for individual squats using ultrasonic mapping techniques. This paper highlights the field monitoring of squat/stud distribution and its growth. Squat/stud growth has been detected and scanned using the ultrasonic measurement device on a grid applied to the rail surface. The depths of crack paths at each grid node form a three dimensional contour of rail squat crack. Fundamentally, crack propagation is a complicated topic and its non-linear relationship with repeated train loads is often found especially when the crack becomes larger. But in this study the crack propagation of squats/studs is roughly estimated 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; Studs; Ultrasonic; Crack mapping; Three dimensional; Field monitoring; Infrastructure condition; Asset management

1. **INTRODUCTION**

Railway infrastructure owners all over the world are suffering from many of rail surface damages, resulting in increased maintenance, more frequent monitoring and track patrol, and the rare but possible broken rail. It has been estimated that the cost of rail renewal program (rail replacement) due to rail squats and studs has become a significant portion of the whole track maintenance cost, reportedly in European countries e.g. Austria, Germany and France (Grassie, 2012). The rail squats and studs are typically classified as the growth of any cracks that has propagated 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’ (Ishida, 2013). ‘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 (Grassie et al., 2012).

Increasingly the rail defect has become a widespread problem in both passenger and freight rail networks in Australia. The rail squat/stud defects could be observed in all types of track structures, in all arrays of track geometries and gradients, and in all possible operational traffics as shown in Figure 1. Figure 1 shows typical photos of studs or multiple squats associated with running surface of WEL or a single squat caused by rolling contact fatigue (RCF). One exception where almost no squat could be observed is inside the dry tunnels (Ishida, 1989 and Wilson et al., 2012). However, recent collaborative research shows some rail studs appear in London Underground due to wheel traction issues (Grassie et al, 2012). The 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 noise. The 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. Consequently, 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 become a strong momentum to rail asset management strategy. It is important to acknowledge that the significance of the rail squat/stud problems has led to the international collaboration on rail squats, through the annual ‘International Workshop on Rail Squats’.
The rail squat/stud problem has largely been recognised when the ride quality of the passenger trains is below the acceptable limits (Remennikov and Kaewunruen, 2008). Excessive noise and vibration have later increased complaints against rail operators. Most importantly, the impact forces due to the wheel/rail interaction have undermined the structural integrity and stability of track components (Kaewunruen and Remennikov, 2009, 2010, 2013; Kaewunruen, 2014a, 2014b). In Japan and Europe, frequently the rail squats change from a longitudinal lamination to have transversely grown and turned into the broken rails, which could derail the trains and...
potentially result in a catastrophe (Ishida, 2013). An infamous example of the tragedy was the Hatfield accident in the UK. Figure 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.

![Image of rail squats](image.png)

**Figure 2** Classic rail squats in Japanese railway tracks

It is believed that the crack propagation in squats or studs is promoted by a similar process of water entrapment and cyclic dynamic wheel loading regime. Extensive laboratory tests using twin disks and rail ring rollers at Monash University in Australia showed that, once initiation crack occurred, any third-party 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 confirmed by a number of the field observations (Kerr et al., 2008; Kaewunruen, 2009a, 2009b; Peng and Jones, 2013).
This paper highlights the field monitoring of squat/stud distribution and its growth using a non-destructive testing technique. Several squat/stud defects have been chosen for field monitoring at various locations. The depth and dimension of cracks were evaluated using an hand-held ultrasonic device. The growth rate of squat/stud could then be determined and plotted on a 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 and has now been used to monitor rail squats and studs in operational railways around the world.

2. DEVELOPMENT OF ULTRASONIC TESTING TECHNIQUE

Three samples of squats were taken, following up from previous inspections at Illawarra Junction in NWS Australia. The rail was manufactured in 2006 with the dimension for 60kg/m head-hardened rail (Kaewunruen, 2014c). All three samples were used in this study and later sent to Monash University for laboratory tests in order to investigate the role of third-party fluids on the growth of rail squats and studs. 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.

For practicality 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. The following procedure was adopted:

- Each specimen was photographed with the grid reference.

- Crack depths were measured at every grid point using Krautkramer DM4-DL ultrasonic thickness gauge.
• Krautkramer ultrasonic gel (K-Y®) was used as a coupling for ultrasonic testing.

• Positions of crack edges were established by noting positions where loss of ultrasonic reflection occurred.

• Position and depth of crack edges were recorded at each intersection with grid lines.

• Trial of parameters was conducted to determine the variation and tolerance of the measurement method.

The parametric tests included the variation of probe size, orientation, type of rail damage or cracks, type of coupling gel, and the ability to detect a crack tip. 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 monitored and evaluated along the gauge corner surface in three dimensions. Data comparison with metallurgical analyses showed a very good agreement (Peng and Jones, 2013). The lesson learnt during the development of this technique was the inability for adjustment of the reference grid frame over the rail defect. It was also found that water could be an effective coupling material when the K-Y gel is running out. Accordingly, the standard reference grid on transparent plastic slides and the reference punch mark system was developed for field work.
a) Initial development of reference grids on the rails

**Figure 3** Schematic development of ultrasonic testing method

b) Illustrative testing method

**Figure 3** Schematic development of ultrasonic testing method
3. 3D MAPPING OF RAIL SQUATS

The crack depth data has been recorded accordingly in order to develop a crack contour. As a case study, two data sets of the 3D mapping of rail squats are demonstrated in this paper (Samples No. 1 and 2). Note that an attempt to change and alternate the probe orientation has been made by 90 degrees. It was found that when the crack is about flat, the orientation has little effect on the crack depth dimension reading (hereafter called ‘crack depth’). Using the ultrasonic testing, subsurface crack depths have been measured at each grid point, as shown in Figure 4 (Sample #1). Squat depths at each grid intersection are shown in the top chart. The results showed that there was no squat crack in row three (or about 30 mm from the gauge face).

In Figure 5, the testing grid is first marked at about 210 mm away from the left end of Sample No. 2. 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, which can be regularly observed in the field visual inspections. In this study, the crack depth is relatively thinner than the rail section, as a result, the effect of ultrasonic wave velocity due to rail residual stresses could not be observed.
Figure 4 Sample 1 for ultrasonic testing (Top: crack depths at each grid; Bottom: top view rail surface).
Figure 5 Sample 2 for ultrasonic testing (Top: crack depths at each grid; Bottom: top view rail surface)
4. FIELD MONITORING OF RAIL SQUATS

Mapping of squat growth patterns in three dimensions was conducted in situ on selected squats at Erskineville and Chatswood in the Sydney network. The following method was adopted:

- Squats in early stages of development were selected, marked and photographed. Comparisons with sequential photographs from earlier observations were also made.
- A 10mm square grid marked on a transparent plastic sheet was temporarily fastened in position over the selected squats using magnets, with punch marks for repeat positioning.
- The magnets enable the flexibility of quick installation and removal of the plastic sheet when the train is passing by.
- 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 over the calibrated reference plastic sheet.
- Krautkramer ultrasonic gel (K-Y®) was used as a coupling for ultrasonic testing.
- Positions of crack edges were established by noting positions where loss of ultrasonic reflection occurred. Position and depth of crack edges were recorded at each intersection with grid lines.
- 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 6 shows typical outlines of a squat dimension plotted using the 3D ultrasonic mapping technique. The squat was monitored at 11.196km on the down North Shore line, between 10/9/2009
and 20/3/2011 (Wilson et al., 2012). The classic double-ended kidney shape of a squat (around v-shape crack) can be seen developing in the last 2 outlines. Growth rates were plotted for all the selected squats, in terms of both area and equivalent radius (proportional to square root of area). The results for the dimensional growth rate of squats are shown in Figure 7. A regression analysis has been conducted using the least-square method. It can be seen from the equivalent radius growth that the crack propagation or growth of squats is almost linear to the tonnage haulage.

**Figure 6** Dimensional growth of a squat over time
Figure 7 Rate of growth of equivalent radius for squat defects

5. CONCLUDING REMARK

Rail squats and studs are continuing to be a serious problem for railway organisations around the world 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. At present, understanding common terminology of the rail defects are crucial to identify the root causes of ‘squats’, which is referred to when they were initiated from rolling contact fatigue layer, and of ‘studs’ when they were associated with white etching layer due to wheel slides or excessive tractive effort.

The rail defects 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. Managing rail squats and studs has become a significant cost to rail infrastructure owners. They 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 frakes 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 paper highlights the field monitoring of squats/studs and their growth. Some patterns of squat/stud development have been observed, and squat growth rate can also be monitored for each individual squat using 3D ultrasonic mapping/plotting technique. The non-destructive testing technique has been firstly developed for uses in the field and in situ under dynamic rail operations. Using the technique on a reference grid applied to the rail surface, the existence of squat/stud and its dimensional growth can be determined. The crack depths at each grid node form a three dimensional contour of rail squat crack. The case studies based on the in situ testing of rail defect samples in the yards and rail squats in operational railway tracks have been demonstrated. A linear relationship between squat growth and time/tonnage was established from the obtained data, for each individual squat/stud. From the field trials, there was some evidence to suggest that the otherwise constant rate of squat growth could be accelerated by the presence of water and other third-party fluids.

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