

Rail squats

Kaewunruen, Sakdirat; Ishida, Makoto

Document Version
Peer reviewed version

Citation for published version (Harvard):
Kaewunruen, S & Ishida, M 2015, 'Rail squats: understand its causes, severity, and non-destructive evaluation techniques', Paper presented at 2015 National Convention in Civil Engineering, Pattaya, Thailand, 8/07/15 - 10/07/15.

[Link to publication on Research at Birmingham portal](#)

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.



Rail squats: understand its causes, severity, and non-destructive evaluation techniques

Dr Sakdirat Kaewunruen^{1,*} Dr Makoto Ishida²

¹ School of Civil Engineering, College of Engineering and Physical Sciences, The University of Birmingham, Birmingham, UK

² Railway Engineering Department, Railway Division, Nippon Koei Co. Ltd, Tokyo, Japan

Abstract

Generally, rail squats are defined by the growth of any cracks that have grown longitudinally through the rail subsurface and some of the cracks propagating to the bottom of rails transversely have branched from initial longitudinal cracks with a depression of rail surface. The rail defects are commonly referred to as ‘squats’ when they were initiated from damage 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 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 mechanical and material scientific point of view. This paper highlights the root causes, dynamic wheel/rail interaction and its application, severity and consequences, and field monitoring of squat/stud distribution and its growth. A non-destructive testing technique to detect and evaluate crack forms in a three dimensional contour is also demonstrated using ultrasonic measurement method.

Keywords: rail surface defect, rail squats/studs, wheel/rail interaction, non-destructive testing, high-speed rail track

1. Introduction

Rail surface damages have been a critical safety concern and maintenance priority of railway infrastructure owners all

over the world who operate either moderate or high speed trains including passenger suburban, metro, urban, mixed-traffic and freight rail systems. 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 [1]. The rail squats and studs are typically 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].

In many countries, the rail defect has become a widespread problem in both passenger and freight rail networks. 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 Fig. 1. One exception where almost no squat could be observed is inside the dry tunnels [4-5]. However, recent collaborative research shows some rail studs appear in London Underground due to 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 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

* Corresponding author

E-mail addresses: s.kaewunruen@bham.ac.uk (S. Kaewunruen);

ishida-mk@n-koei.jp (M. Ishida)

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.



a) WEL-related stud (multiple squats)



b) RCF-related squat (single squat)

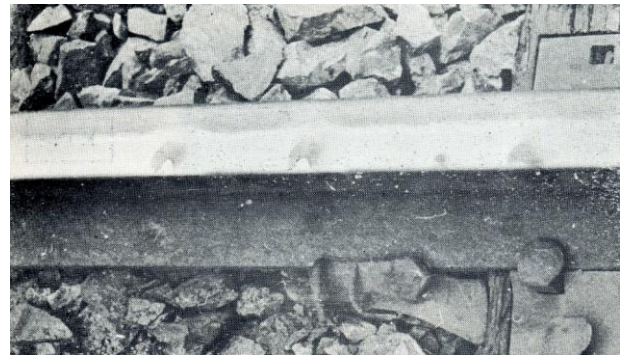
Fig. 1 Rail squats in railway tracks based on their initiation types

The rail squat/stud problem has largely been noticed when the ride quality of the passenger trains exceeds acceptable limits [7]. 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 [8-12]. In Japan and Europe, frequently the rail squats have transversely grown and turned into the broken rails, which could derail the trains and potentially result in a catastrophe [2]. An 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.



a) dark spots in gentle curve



b) dark spots in tangent track

Fig. 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-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 [13-16].

This paper highlights the root causes, wheel/rail interaction, and features the field monitoring of squat/stud distribution and its growth using non-destructive testing techniques including handheld and on-board ultrasonic testing methods. Several squat/stud defects have been chosen for field monitoring. The demonstration of measuring depth and dimension of cracks is presented using a 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. The wheel/rail interaction has been shown to unleash the potential development of on-board monitoring system for automated rail squat detection.

2. Severity of Rail Squats

2.1 Field Observations

In New South Wales Australia, an increasing tendency of rail surface defects has been observed, especially for RCF initiated squats to develop on the high rails of moderate radius (500m – 1500m) curves. In sharper curves, these squats can occur in transitions, where the instantaneous radius is in the moderate radius range. As a result, there has been a large campaign to investigate rail squat defects in the field and to evaluate the distribution of the defects.

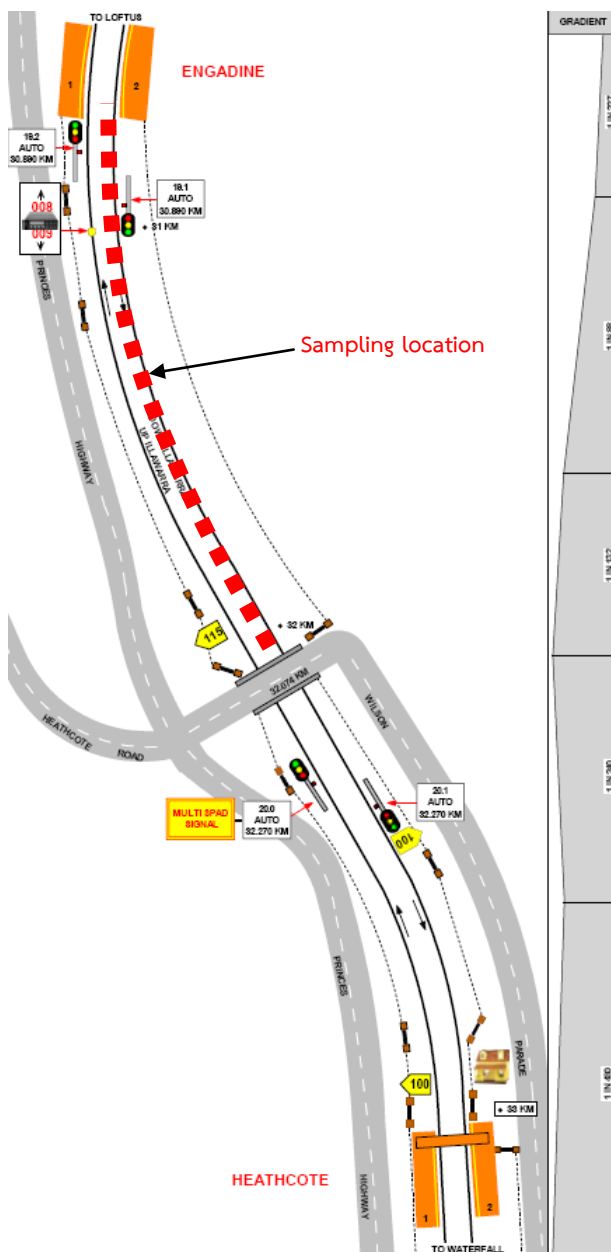


Fig. 3 Track diagram at Engadine [17]

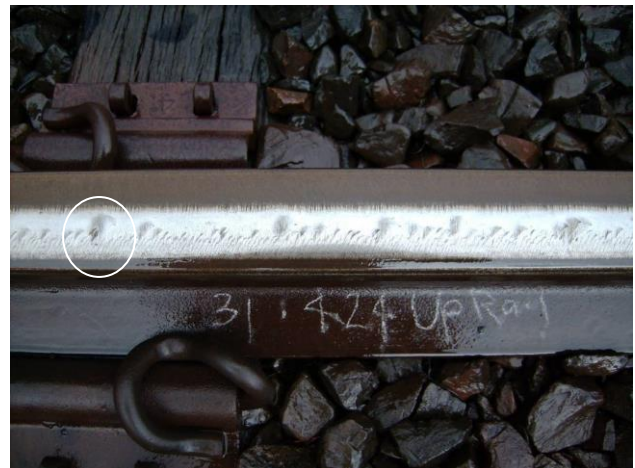
As a case study, Fig. 3 shows the location for a detailed investigation of squat on open plain tracks. The track speed is 115 km/h. A general view is shown in Fig. 4. An inspection was

carried out followed from previous inspections and maintenance reports in this area. All the squats are on the high rail of a moderate curve. The rail is 1996/ 97 60kg/m HH One-Steel rail. The squats are mostly associated with gauge corner checking. There is a cyclic component to this. There are also other odd squats and squat-like features.



Fig. 4 General view at Engadine

The rails at various locations have been assessed visually and recorded. Fig. 5 shows examples of rail squat found in the area.



a) High rail typical of squat features in a squat zone



b) Close up for visible Cracks

Fig. 5 Rail squats in the field

2.2 Distribution Analysis

The field investigation has resulted in significant amount of data of squat distribution. Expert interviews, maintenance records, and inspection reports are the main sources of data [17]. An important source of information is ultrasonic rail testing reports. These include rail surface reports on locations where rail testing is affected by surface defects and the like. The reports include an approximate kilometrage and cause. Since squats have a characteristic ultrasonic indication, the reports together with identifications by field experts are reasonably reliable. Only well-developed squats are reported, however, and minor inaccuracies of location can be observed at times.

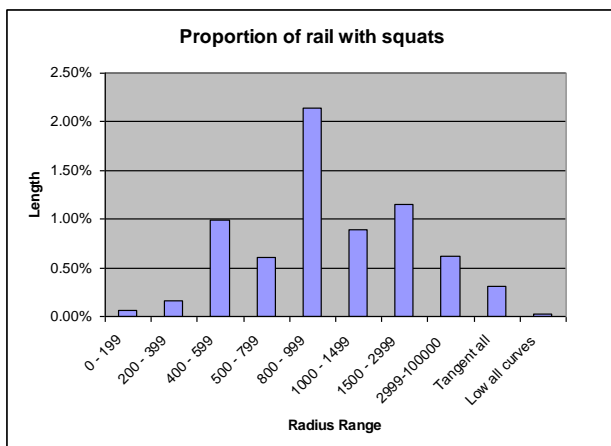


Fig. 6 Distribution of ultrasonically reported squats by curve radius.

Based on the data, Fig. 6 shows lengths of squat affected rail as a proportion of total length of rail in each curvature band of railway track geometry [5, 14-15]. Critical features are:

- Most squats recorded in separate curvature bands are high rail only.
- A peak of squat frequency in the track curvature band from 800m to 1000m radius.
- A secondary peak in the curvature band 400m-600m, possibly associated with squats in the transitions of sharper curves.
- A secondary peak of squat frequency for the curvature band 1500m-3000m.
- A relatively small proportion of squats in tangent track.
- A very small proportion of squats in curves <200m.
- Almost all the squats in curves are in the high rail. Only an extremely small proportion of squats are in the low rail of any curves.
- A lesser incidence of squats can be observed in curves sharper than about 900m radius in standard carbon (SC) rail compared to head hardened (HH) rail.

A study of squats on the down Illawarra line (NSW, Australia) showed significant squat development in the transitions of sharp radius (200m-400m) curves, while the arcs of the same curves have no squat. Squats were also found in

the arcs of longer radius curves. This pattern has also been noted on other lines. Analysis of the Illawarra line squats [5] revealed that:

- The instantaneous curve radius where squats occurred was predominantly in the range 400m – 1100m
- Squat affected locations had a lower curve wear rate than at squat free locations.

A more detailed analysis of ultrasonic rail testing data is proposed, using rail testing replays and GPS positioning facilities to obtain a more complete and accurate picture of squat distribution. Further comparisons will then be possible against parameters such as curvature, rail type, grinding history, rail profile, traffic type and track grade in the future.

2.3 Type of Rail Material

Some evidence has begun to illustrate that softer standard carbon (SC) rails, which are normally called 'hot rolled' or 'as rolled' rails, may be more squat resistant than head hardened (HH) rails in certain circumstances. This pattern has also been noted in France, where trialing of R200 grade rails in squat prone areas has commenced. An inspection of rails on the Sydney suburban lines between Redfern and MacDonalddtown was conducted [5, 14-15]. This site was chosen because it was rebuilt in different stages and it contains both HH and SC rails, moderate radius curves and large numbers of reported squats. Some findings from the inspection included:

- Squats occurred in both types of rail, but were significantly more extensive and severe in the HH rails.
- Several cases occurred where there was a significant contrast at the interface between the 2 rail types, with much more severe squat damage in the HH rail. These were in curves with radii in the range 800m–1,000m. The SC rail was generally older (around 1995) than the HH rail (around 2002), as shown in Fig. 7.
- Squats were prevalent at both aluminothermic and flashbutt welds, in both types of rail. They appeared to develop preferentially in the zones going from softer rail to harder rail and in the areas of harder rail.
- Squats occurred at flashbutt welds in otherwise squat free SC rail. The weld material was found to be harder than the parent metal, as illustrated in Fig. 8.
- Squat cracking occurred at insulated joints. These are normally made from a short length of HH rail and welded into the track. The worst squat growth occurred on the facing side of the joint which is subject to impact.
- Relationship between squat development and wheelslip in high traction areas was noted. There exist a high correlation between high traction and high rate of squats.



Fig. 7. Interface between SC rail and HH rail. The SC rail is squat free. Squats are visible at the weld and in the HH rail. High rail in transition to 932m radius curve [5].



Fig. 8 Squat at flashbutt weld in SC rail which is otherwise squat free. Measured hardness 305-312HB in parent rail and 372HB in weld. High rail in arc of 872m radius curve [5].

3. Non-destructive Testing Techniques

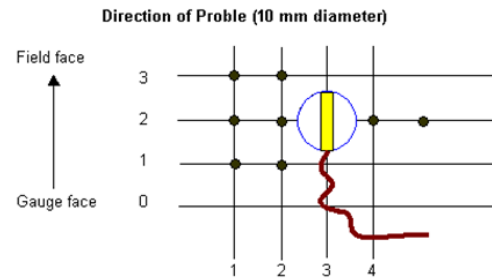
At present, there have been considerable attempt to develop an automated system for rail squat detection. In this paper, the handheld ultrasonic testing and the application of wheel/rail interaction will be discussed.

3.1 Development of 3D Ultrasonic Mapping

Three samples of squats were taken, following up from previous inspections at Illawarra Junction 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 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. 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 [18].

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. 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 Fig. 9 to obtain consistent measurements. Using this technique, the squat defects can be monitored. A standard reference grid on transparent plastic slides and the reference punch mark system was developed for field work.



This example reads the data of Point 2-3

Fig. 9 Illustrative testing method

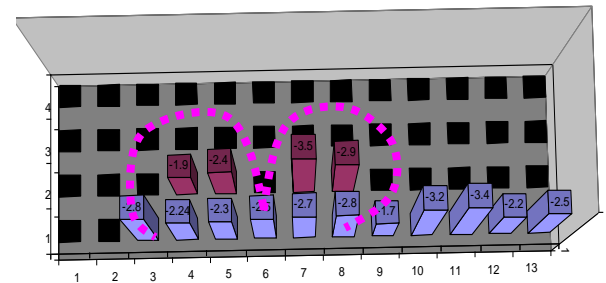
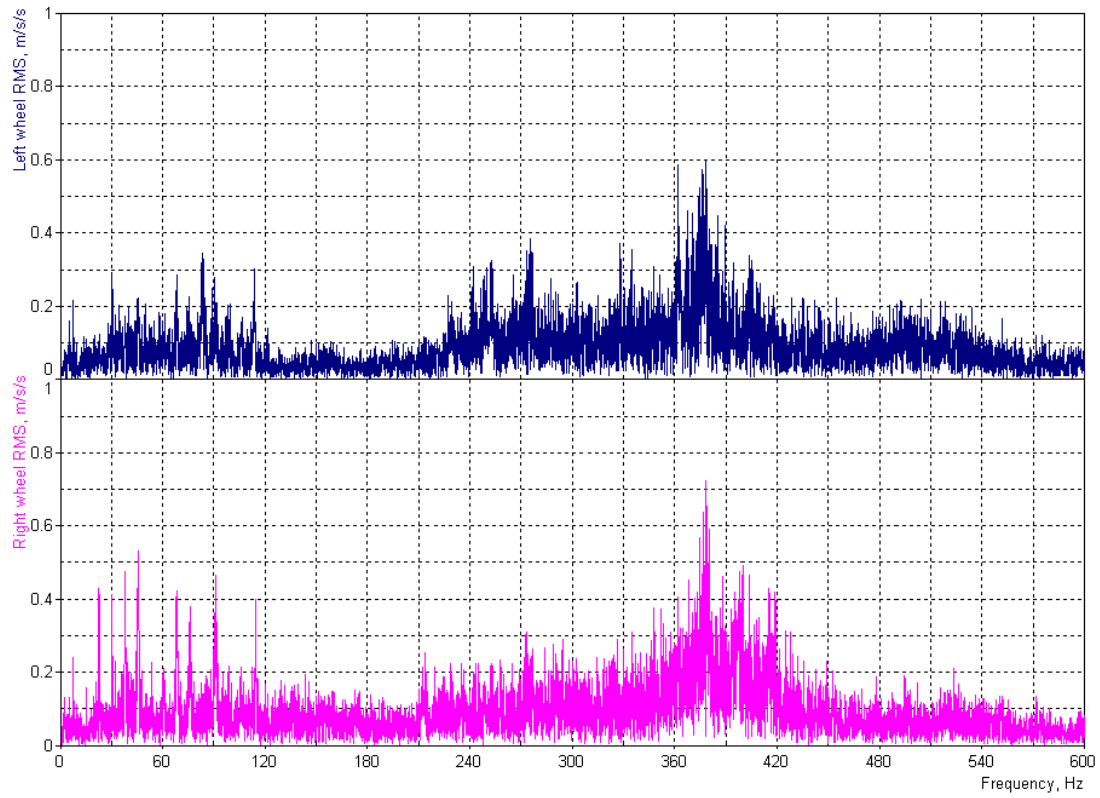
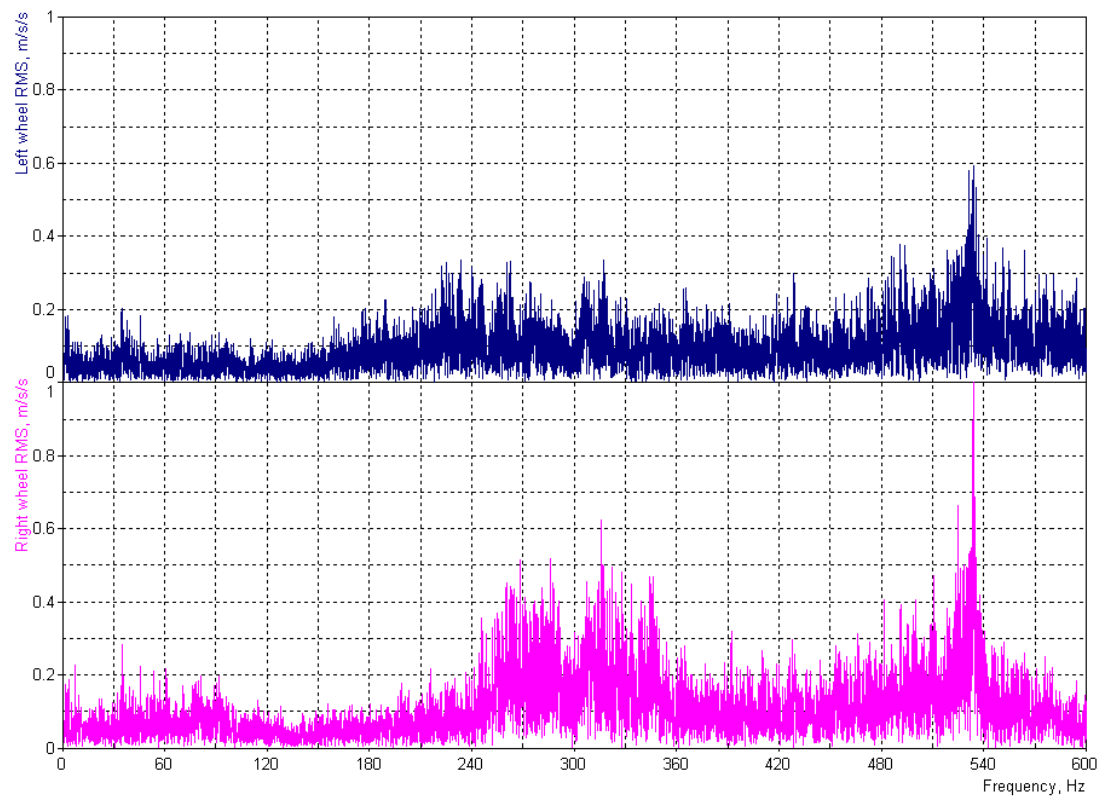


Fig. 10 Ultrasonic testing (Top: crack depths at each grid; Bottom: top view rail surface)

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 [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. Using the ultrasonic testing, subsurface crack depths have been measured at each grid point.



a) Axle box accelerations prior to grinding



b) Axle box accelerations after grinding

Fig. 11 Frequency spectra of axle box accelerations

In Fig. 10, 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.

3.2 On-board monitoring of rail squats using wheel-rail interaction

The rail profile at a particular location can be scanned by the laser profile detection devices installed on a track inspection car or “AK car”. The rail profile is captured by the AK Rail Geometry system. Depending on the AK car speed, the rail profile data is taken at about every 5m to 10m. It should be noted that the recorded wear data is not absolute. Some results can be spurious, especially at turnouts. It should also be noted that the km record might be slightly different from the real track route (± 2 -5m). However, the comparison of rail profiles obtained from AK Car and by using RailMate instrument was carried out [21-23], and the results were found in good agreement [23-26]. The wheel and rail interaction depends on the track structure and alignment curvature. The frequency spectra of the vibration levels measured on the wheel boxes on both rails on the track section of interest (in NSW, Australia) are presented in Fig. 11. The vibration amplitudes represent the ride quality of trains and are also associated with the operational loading condition applying between the wheel and the rail. It should be noted that the train/track analysis model has been developed and validated in another national RailCRC project (short-pitch irregularity). Either raw or filtered vibration levels can be used for back calculation of dynamic vertical P1 and P2 forces [24, 26-28].

Fig. 11 (a) shows the wheel/rail interaction based on axle box accelerations over the track section of interest prior to corrective rail grinding work. It is found that the location of poor top surface (vertical geometric alignment) has little influence on the axle box accelerations. It should be noted that the down rail or the left rail in the figures represents the low rail in curved track (or the inner rail). This coincides with the periodic nature of the squats as found in previous studies [23, 25].

On the other hand, it is noticeable in Fig. 11 (b) that there are continuing bands of transient vibration spikes representing the locations of continuous rail surface defects (or continuous squats), particularly on the high rail (right wheel). It should be noted that the grinding history report at the time identified the problem of severe gauge corner squats in this track section. This was because the rail grinding was effectively carried out and then the rail roughness (surface irregularity) was improved. However, it is very clear that the grinding can often leave the squat defects worse off. Detailed reports based on roughness

and vertical alignment measurements in the field [23, 25] showed that that some severe squats could not be removed totally because of the limited timeframe for grinding activities on the track. It demonstrates the presence of worse-off squat defects by the larger magnitude of vibration and the frequency shift on the high rail. These changes in frequency spectra demonstrate the potential capability of wheel-rail interaction for automated defect detection.

4. Growth and Severity of Rail Squats

Mapping of squat growth patterns was conducted in situ on selected squats at Erskineville and Chatswood in the Sydney network [5]. The following method was adopted:

- 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).

Fig. 12 demonstrates the dimensional growth using a typical plotted outlines of a squat in NSW, Australia, between 2009 and 2012 [5]. The classic double ended kidney shape of a squat can be seen developing in the last 2 outlines (2010 and 2011).

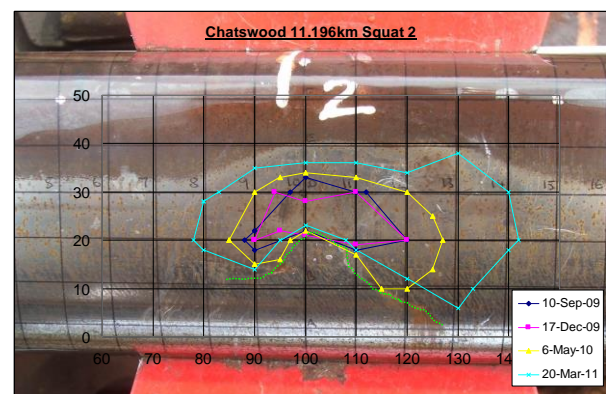


Fig. 12 Plot of squat outlines.



a) late 2007



b) early 2008



c) late 2008



d) early 2009

Fig. 13 Progressive squat development.

Fig. 13 shows evolution of a rail squat defect every half a year, dating from late 2007 through to early 2011. It can be seen that the area growth is higher for the larger squats, as would be expected. The increase in equivalent radius appears quite constant for all sizes of squat. The exception to this is the period in 2009. 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.



e) late 2009



f) early 2010



g) late 2010

Fig. 13 Progressive squat development.

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. The squat was firstly quantified in 2008 and it had a measurable depth of 3.5mm, and by 2011 maximum measured depth was 4.1mm. It had been reported that there was an intervention grinding during the period. The grinding removed approximately 1mm of rail metal and the rail squat could not be removed and eventually returned as shown in Fig. 13(g). In 2013, the rail section was replaced due to the severity of squat defects and excessive maintenance in the area [29].

5. Conclusions

Rail squat 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. They will continue to be a serious problem for railway organisations 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. 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.

Repair and maintenance associated with rail squats and studs have 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 flakes 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 turned into broken rails of which such incidents have already been experienced in Australia, Europe and Japan.

This paper highlights the root causes, severity, and field monitoring of squats/studs and their growth using a variety of non-destructive evaluation techniques. The case studies based on the field monitoring of rail squats in operational railway tracks have been demonstrated. The variability and capability of wheel/rail interaction as automated damage detection method are discussed. The lessons learnt around the globe on rail squats have been discussed in order to help railway authorities in Thailand develop strategic action and maintenance planning for rail and rolling stock interface issues. The dual-track corridor project recently planned to cater passengers and freights in Thailand will be benefited from these fundamental research outcomes.

Acknowledgement

This research project was part of a rail research project (‘Rail Squat Strategies’ chaired by RailCorp) supported by the Australian Cooperative Research Centre for Rail Innovation (RailCRC). Valuable field data, technical advice and comments by RailCorp experts (Malcolm Kerr, Andrew Wilson, Phouc Nguyen, Bob Forgarty and Allan Churchill) are gratefully acknowledged. The first author also wishes to thank Australian Government’ Department of Innovation, Education, and Research for Endeavour Executive Award, which financially supported his fellowships at Massachusetts Institute of Technology’s Department of Civil and Environmental Engineering; Harvard University’s John F. Kennedy School of Government; Chalmers University of Technology’s Centre for

Railway Mechanics; and Railway Technical Research Institute’s Division of Track Technology.

References

- [1] S. Grassie. “Studs: a squat-type defect in rails”. *Proceedings of the Institution of Mechanical Engineers Part F Journal of Rail and Rapid Transit*, 226(3), 243-256, 2012.
- [2] M. Ishida. "Rolling contact fatigue (RCF) defect of rails in Japanese railways and its mitigation strategies," *Electronic Journal of Structural Engineering*, 13(1), 67-74, 2013.
- [3] S. Grassie, D.I. Fletcher, E.A.G. Hernandez and P. Summers. “Squats and squat-type defects in rails: the understanding to date”. *Proceedings of the Institution of Mechanical Engineers Part F Journal of Rail and Rapid Transit*, 226(3): 235-242, 2012.
- [4] M. Ishida. “Statistical Analysis of Rail Shelling on Shinkansen”, *Proc. of 4th International Heavy Haul Conference*, Institution of Engineers, pp.205-209, Brisbane, Sep. 1989.
- [5] A. Wilson, M.B. Kerr, S. Marich, and S. Kaewunruen. “Wheel/rail conditions and squat development on moderately curved tracks”, *Conference of Railway Engineering*, Nov 17-19, Brisbane, Australia, 2012.
- [6] M. Molodova, Z. Li, A. Nunez, R. Dollevoet. “Automatic Detection of Squats in Railway Infrastructure”, *IEEE Intelligent Transportation Systems, Transactions*, 15(5), 1980-1990, 2014.
- [7] A.M. Remennikov and S. Kaewunruen. “A review on loading conditions for railway track structures due to train and track vertical interaction”. *Structural Control and Health Monitoring*, 15(2), 207-234, 2008.
- [8] S. Kaewunruen and A.M. Remennikov. "Progressive failure of prestressed concrete sleepers under multiple high-intensity impact loads." *Engineering Structures*, 31(10): 2460-2473, 2009.
- [9] S. Kaewunruen and A.M. Remennikov. "Dynamic properties of railway track and its components: Recent finding and future research directions." *Insight - Non-Destructive Testing and Condition Monitoring*, 52(1), 20-22, 2010.
- [10] S. Kaewunruen and A.M. Remennikov. "On the residual energy toughness of prestressed concrete sleepers in railway track structures subjected to repeated impact loads." *Electronic Journal of Structural Engineering*, 13(1), 41-61, 2013.
- [11] S. Kaewunruen. "Monitoring structural deterioration of railway turnout systems via dynamic wheel/rail interaction." *Case Studies in Non-destructive Testing and Evaluation*, 1(1), 19-24, 2014.
- [12] S. Kaewunruen. "Monitoring in-service performance of fibre-reinforced foamed urethane material as timber-replacement sleepers/bearers in railway urban turnout

- systems." *Structural Monitoring & Maintenance*, 1(1), 131-157, 2014.
- [13] M.B. Kerr, A. Wilson and S. Marich. "The epidemiology of squats and related defects", Proceedings of Conference on Railway Engineering, Perth Australia, 2008.
- [14] S. Kaewunruen. "Use of ultrasonic testing for mapping rail squat cracks" Technical Report No. TR147, Track Services RailCorp, Australia, March, 8p, 2009.
- [15] S. Kaewunruen. "Wheel and rail interaction with rail squats at Engadine, Sydney" Technical Report No. TR156, Track Services RailCorp, Australia, April, 30p, 2009.
- [16] D. Peng, R. Jones. "Modelling of the lock-in thermography process through finite element method for estimating the rail squat defects", *Engineering Failure Analysis*, 28, 275-288, 2013.
- [17] Rolling Stock Access Integrity Standards, "RSU 120 Track interface, Minimum Operating Standards for Rolling Stocks", RailCorp, May 2008.
- [18] M. Ishida, Y. Maruyama and T. Sasaki, White Etching Layer Formed on Rail Surface and its Detection Method, Proc. of 2nd International Conference on Railway Technology: Research, Development and Maintenance, Paper No.186, Ajaccio, April 2014.
- [19] S. Kaewunruen, A.M. Remennikov, A. Aikawa, H. Sato. "Free vibrations of interspersed railway track systems in three-dimensional space," *Acoustics Australia*, 14(1), 20-26, 2014.
- [20] D. Peng, R. Jones. "Modelling of the lock-in thermography process through finite element method for estimating the rail squat defects", *Engineering Failure Analysis*, 28, 275-288, 2013.
- [21] Pacific Real Time, *ROAMES Operator Training Manuals*, Sydney, Australia. 2009.
- [22] S. Kaewunruen, M. Ishida. "Field monitoring of rail squats using 3D ultrasonic mapping technique," *Journal of the Canadian Institute for Non-Destructive Evaluation*, (invited), 35(6), 5-11, 2014.
- [23] S. Kaewunruen. "Wheel/rail interaction at Engadine", Technical Report TR.156, RailCorp Track Services, Sydney, Australia, 2009.
- [24] Y.Q. Sun, C. Cole, M. McClanachan, A. Wilson, S. Kaewunruen and M.B. Kerr. "Rail short-wavelength irregularity identification based on wheel-rail impact response measurements and simulations", Proceedings of the 9th International Heavy Haul Conference, June 21-23, Shanghai, China, 2009.
- [25] A.M. Remennikov and S. Kaewunruen. "Determination of dynamic properties of rail pads using instrumented hammer impact technique," *Acoustics Australia*, 33(2), 63-67, 2005.
- [26] S. Kaewunruen, M. Ishida, S. Marich. "Dynamic wheel-rail interaction over rail squat defects," *Acoustics Australia*, (accepted), 2014.
- [27] M. Molodova, Z. Li, A. Nunez, R. Dollevoet. Parameter Study of the Axle Box Acceleration at Squats, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, in press, 2014.
- [28] M. Farjoo, S. Pal, W.J.T. Daniel and P.A. Meehan. "Stress intensity factors around a 3D squat form crack and prediction of crack growth direction considering water entrapment and elastic foundation". *Engineering Fracture Mechanics*, 94 37-55, 2012.
- [29] W.J.T. Daniel, S. Pal and M. Farjoo, "Rail squats: progress in understanding the Australian experience". *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 227 5: 481-492, 2013.