RAIL SQUAT DEFECTS

Malcolm Kerr – Chief Engineer Track, Engineering and Projects Group, RailCorp
Andrew Wilson – Wheel Rail Engineer, Engineering and Projects Group, RailCorp

Introduction

The development of squat defects has become a major concern in numerous railway systems throughout the world. In NSW they first came under notice in the Hunter Valley in the mid 1990’s and on the Sydney passenger network around 2000. They are now a serious problem affecting the network.

This paper details the findings of field investigations into squat and related rail defects within the RailCorp infrastructure network covering the Sydney metropolitan and interurban areas. It describes the investigations carried out to date and canvasses the various hypotheses regarding the principal causes of squat defects. It reviews the role of various potential rail surface initiators including slippage defects, rolling contact fatigue cracks and wheel burns. It then considers growth mechanisms and the role of the rolling stock interface.

The paper also outlines the research being carried out and current strategies for management of the squat problem.

What is a Squat?

Squats occur in several different forms and their precise definition is still the subject of some debate. All varieties however share some common features. They are characterised by cracking which initiates on the rail surface and grows down to a point about 3-6mm below the surface. The cracking then spreads along and across the rail, without growing substantially deeper. The rail surface becomes depressed and a dark patch appears due to reduced contact from train wheels. Eventually the rail surface may spall out. Figure 1 illustrates some areas of multiple squats commonly termed “squatty” rail.

Figure 1, squatty rail where multiple squat defects have formed on the running surface of a rail.

The characteristics of squats are described in more detail below:

Visual Characteristics of Squat Defects

As illustrated in Figure 1, in their mature stages of development, most squat defects are readily identifiable visually, consisting of a widening of the wheel/rail contact band with a darkened area caused by depression of the rail surface, often in the shape of a kidney or a bruise.

The defects found in RailCorp are of two main types:

Running surface squats – which develop on the running surface region or crown of the rails, located primarily in the low leg of curves, the high leg of shallower curves (with radii greater than about 1200m), and in tangent track. Figure 1 and Figure 2 show examples of these defects in their various stages of development.

From Figure 2, it is of interest to note that in their very early stages of development most defects exhibit only one circular region, rather than the two exhibited by the more advanced squats.

Moderate to severe squats are also often mistaken for wheelburn defects. The characterising differences are:

• Squats develop gradually over a period of months or years, whereas wheel burns occur instantly after a wheel slip incident.
• Squats often do not have a matching defect on the opposite rail.
At some locations, these squats appear to develop from wheel burn and wheel slip type defects, as illustrated in Figure 3.

**Gauge corner squats** – which develop on the gauge corner region of the high rails located in moderate curves (with radii up to about 1800m), and in uncanted rails in turnouts. Figure 4 and Figure 5 show examples of these defects in their various stages of development. Commonly, squatty rail with multiple squats is associated with gauge corner checking cracks. At other locations isolated squat defects have been found.
Surface / Subsurface Characteristics of Squat Defects

The sectioning and microscopic examination of the rails containing squat defects reveals the following main aspects:

- Generally, a ‘white etching’ surface layer (WEL) is present in most mild and moderate running surface squats, which can be up to 0.15-0.20mm deep (refer to Figure 6). This layer is very brittle and exhibits hardnesses generally up to 700-750 HB, which is considerably higher than the surface hardness of work hardened material near and across the squatty regions (about 300-330 HB for Standard Carbon rails and 380-420 HB for Head Hardened rails, depending on the traffic type).

- From Figure 6 it is also evident that the ‘white etching’ layer is brittle and develops small vertical cracks. Some of these cracks continue to grow into the parent material, both longitudinally and laterally.
at an angle of about 20°-30° to the running surface (refer to Figure 7), whilst others return to the surface and form a spall.

At a certain depth below the rail surface the cracks begin to branch and grow on multiple planes. The subsurface cracks grow noticeably longer in the direction of traffic.

**Figure 6:** Rail cross section showing ‘White Etching’ surface layer (arrowed) at Squat Defects and fine cracking into rail material

The development of the white etching layer is most likely associated with an adiabatic shear mechanism, which would be indicative of very high shear stresses produced by micro wheel slip, rather than the macro wheel slip that occurs with wheel burns.

- The high surface hardness ‘white etching’ layer has also been observed in some gauge corner region squats, with very similar early crack growth characteristics as running surface squats.

However other gauge corner squats have no white etching layer and exhibit surface hardness levels that are equivalent to the work hardened material. These squats appear to initiate from pre-existing gauge corner rolling contact fatigue or checking cracks, as illustrated in Figure 8. Noting that in the gauge corner area any ‘white etching’ is quite likely to be worn off.

**Figure 8:** Cross section of rail showing extension of Gauge Corner CheckingCracks into a Squat Defect

**Why are Squat Defects of Concern?**

Squat defects are of concern for the following main reasons:

- There has been a considerable increase in their numbers over the past 4-6 years.
- There is a danger that the secondary or minor sub-surface cracks (illustrated in Figure 7) may turn down and grow on a transverse plane similarly to transverse defects, with the possibility of resulting in a broken rail if not detected in time. To date there are no confirmed reports of this happening within RailCorp.
• The depression and spalling on the running surface associated particularly with large squats (refer to Figure 2) increases the vertical impact wheel loadings and vibrations applied to the rails, and consequently exacerbates the deterioration of both track and some vehicle components, in a similar way as dipped welds, rail corrugations and rail joints.
• Repair options are limited and expensive.
• There is a risk that the horizontal subsurface primary cracks will cause shielding of the ultrasonic signals from deeper defects during normal ultrasonic inspections.
• There can be an influence on environmental noise.

**Distribution Patterns**

Initially several particularly squatty locations came to notice but then as attention was drawn to this defect type, squats began to be found in a number of locations throughout the network. In an attempt to quantify the scale and distribution of squats and any patterns of occurrence a squat counting exercise was undertaken in 2007. Almost all the squats were counted by a single individual utilising existing track foot patrol inspections on an opportunistic basis. By the end of 2007 some 262 track kilometres had been examined. There have been no global reviews since the initial counting but detailed inspections have been carried out of various squat locations around the network which have cast some additional light on the problem. Also many of the initial squat locations identified have now been repaired.

The original findings may be summarised as follows:

**Squat densities:** These were determined by summing the lengths of track with different squat densities (Figure 9).

**Curvature:** Squats occur in both straight and curved track. There are two notable features in the data shown in Error! Reference source not found.). The higher values for the radius bands of 350m to 425m and for 800m to 1075m. These higher levels are not reflected in the adjacent curvature bands. Interestingly the numbers in each of the curve bands is driven primarily by a few high density squat locations.

**Defect Size:** A review of defect size (as per Table 1) shows that overall 73% of squats can be classed as small (mild), 22% medium (moderate) and 5% large (severe). For 53kg/m rail (which is older) there is a slightly greater proportion of large defects 6% compared to 4% for 60kg/m rail.

<table>
<thead>
<tr>
<th>Rail</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>53</td>
<td>954</td>
<td>322</td>
<td>84</td>
</tr>
<tr>
<td>60</td>
<td>1124</td>
<td>313</td>
<td>65</td>
</tr>
<tr>
<td>Total</td>
<td>2078</td>
<td>635</td>
<td>149</td>
</tr>
<tr>
<td>53</td>
<td>70%</td>
<td>24%</td>
<td>6%</td>
</tr>
<tr>
<td>60</td>
<td>75%</td>
<td>21%</td>
<td>4%</td>
</tr>
<tr>
<td>Overall</td>
<td>73%</td>
<td>22%</td>
<td>5%</td>
</tr>
</tbody>
</table>

**Table 1: Squats by Size**

**Track Configuration:** The occurrence of squats has also been assessed in terms of the track configuration (sleeper and rail type). The results in Table 2 show that squats occur in significant levels on all configurations of rail and sleeper type.
Table 2: Summary by Infrastructure Type

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Squats/100m</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete 53kg/m</td>
<td>0.9</td>
<td>29.4</td>
</tr>
<tr>
<td>Concrete 60kg/m</td>
<td>0.8</td>
<td>145.3</td>
</tr>
<tr>
<td>Timber 53kg/m</td>
<td>1.5</td>
<td>70.3</td>
</tr>
<tr>
<td>Timber 60kg/m</td>
<td>2.8</td>
<td>9.2</td>
</tr>
<tr>
<td>All Concrete</td>
<td>0.9</td>
<td>174.7</td>
</tr>
<tr>
<td>All Timber</td>
<td>1.6</td>
<td>83.0</td>
</tr>
<tr>
<td>All 53kg/m</td>
<td>1.8</td>
<td>102.5</td>
</tr>
<tr>
<td>All 60kg/m</td>
<td>1.2</td>
<td>158.1</td>
</tr>
</tbody>
</table>

High/ Low/ Rail: A review has been conducted of the presence of squats on high or low rails verses tangent track and separately whether at turnouts. High rails are nearly twice as likely to have squats as low rails, though overall curved track has similar rates to tangent track. Turnouts have about double the rates than for plain track.

Traffic: In looking broadly across the RailCorp System and the distribution of squats it is also evident that squats occur on:
- Lines with passenger only traffic.
- Lines with passenger and freight traffic.
- Lines with freight only traffic.
- Lines that are electrified and lines that are non-electrified.

Rail Type & Grinding: Squats also occur in:
- Both Standard Carbon (SC) and Head Hardened (HH) rails.
- Rails that have and have not been ground.

General: Squats have been found on all kinds of locations and situations. The only confirmed situation where squats do not occur is in tunnels (the exception being where there is water dripping onto the rails).

Update: Since the original review there has been additional evidence that suggests:
- Squats are rare in sharp curves themselves but squats are typically found in the transition areas where curvatures are moderate (see Figure 11). Squats are found in both the transitions at the beginning and end of curves.
- Several of the worst squatty locations are believed to be associated with previous wheelslip incidents.
- Squats are a growing problem in turnouts arising mainly from gauge corner checking cracks.

Figure 11: the location of squats within transition areas (3.5 degrees is about 500m radius and 1 degree is about 1700m radius)
The Cause of Squats

It appears that squats can be initiated by any number of different crack types. In running surface squats, the initiating cracks occur in brittle material associated with thermal traction effects (the white etching layer shown in Figure 6 and Figure 7). Gauge corner squats are initiated by existing RCF cracks.

Evidence has emerged connecting wheel slip damage with squat initiation. Squats have been found at various locations where there has been a known wheel slip incident in the past, usually 4 or more years ago. Curiously, squats do not appear to be prevalent at locations where wheel slip is a constant problem, such as Zig Zag or Cowan bank. This may be due to high levels of rail wear at these locations.

A number of locations have been observed where squats can be seen growing directly from wheel slip marks (Figure 3). Examinations of sections of squatty track have found some instances where the pattern of squats is repeated on the opposite rail, indicating involvement of a particular wheelset.

Wheel slip damage remains a problem on the RailCorp network including from normal freight and passenger trains as well as work trains and track machines.

Examination of wheel slip damage has found that elevated surface hardness is frequently found. Hardness levels up to 750HB have been measured, even in relatively innocuous looking scuff marks and discolouration. This level is comparable with hardness levels found in the white etching layers implicated with squat initiation. Monitoring of rails with wheel slip damage has shown development of fine cracks in the affected area.

Figure 12 shows a small wheel burn with a dark discoloured strip behind, which gave hardness values of 700HB, up to 900mm from the wheel burn. Fine cracks can be seen in this strip 11 months later. The rail had been ground 5 months after the slip event, removing hard material from the strip.

Wheelslip damage is often masked by subsequent grinding. The surface discolouration may be removed but the metallurgical damage may still be present. In Figure 13 the original wheelslip damage is still visible in a section of track where grinding was not able to be carried out due to a level crossing.

Squats growing from rolling contact fatigue (RCF) checking cracks have become increasingly evident. These are seen largely in the high rail of curves of medium radius (800m – 1600m), transitions of sharper curves and the gauge corner of uncanted rails in turnouts.
Metallurgical examination of gauge corner squats has shown that they tend to grow in a transverse direction from the ends of checking cracks, towards the centre of the rail. This is often associated with a change of direction in the checking crack, to create a wedge shaped feature as shown in Figure 4. Visual examination of squats in situ supports this finding.

To gain a better understanding of the mechanisms of squat growth, it is necessary to look in some detail at the rollingstock interface:

**Figure 13: Squats at a level crossing where grinding has not been carried out.**

**The Rollingstock Interface**

**The Contact Patch**

The interaction of rollingstock and track occurs at the contact patch. For tangent track the contact patch is somewhere near the centre of the rail and is roughly elliptical in shape. The progression of the contact patch along the rail forms a contact band. On the high rail of sharp curves the contact is typically on the gauge corner and the shape is more complex.

All the forces are translated via the contact patch. Basically as shown in Figure 14 this comprises a normal force (from the static axle load plus any dynamic impact), a longitudinal force such as from traction and braking) and a lateral force (mainly from curving). There are also forces arising from the rotation of the contact patch due to "spin creep" which mainly affects the gauge corner.

**Figure 14: Forces at the Contact Patch**

For a simple normal load the maximum stress arises below the rail surface of the rail as shown in Figure 15. This is where T/N (i.e. transverse / normal) = zero. However with increasing transverse loading the stress at the rail surface increases. Once T/N reaches 0.3 i.e. the transverse loading is 30% of the normal load the maximum stress is at the rail surface.
The forces arising from the rollingstock interaction at the contact patch are involved in the three phases of squat development:

- Squat initiation from surface cracking
- Squat initial growth down into the rail material
- Squat development across the rail head.

The maximum transverse forces are limited by the friction characteristics of the rail. The static coefficient of friction can be above 0.6 on the rail surface and less than 0.2 on a lubricated gauge face of the rail. Under traction axles higher levels of adhesion can be achieved by allowing creepage (where the wheel rotates with some controlled slippage). Creepage of up to 10% is utilised in some cases.

### Surface Cracking

Both the normal loading and in particular the transverse component are important factors in the generation of high contact stresses at the rail surface and in the initiation of surface cracking. Typically this arises from the accumulation of increments (ratchetting). Note that when the coefficient of friction/ traction increases this diminishes the allowable stress as shown in Figure 16.

On very sharp curves lateral creepage generates high levels of contact stress. However such lateral creepage also results in high levels of wear. If the wear keeps pace with the crack growth (the magic wear rate) then rail squats tend not to occur. It is notable for example that squats occur more commonly in the transitions of sharp curves and in the body of moderate radius curves.

Longitudinal forces arise in all track curvatures particularly from traction and to a lesser extent from braking. The impact may be enhanced by creepage which generates additional longitudinal force.

The so-called White Etching Layer (WEL) has been identified in centre of head squats from tangent track. This ultra-brittle very thin layer is believed to have formed from such a process of heat and pressure. The exact cause of this is not clear. Separate investigations have found rail surface damage from wheel slip though to a greater depth than the WEL above.

### Wheel Slip

Traditionally when wheels of traction axles slip they create “wheelburns.” Wheelburns are where a substantial wheel-shaped hole is worn into the rail. A related phenomenon is where the wheel slips but continues to move forward. Such wheelslip events have been noted over substantial distances (tens and possibly hundreds of metres). In such cases elevated hardness measurements are typically found. A significant depth of the rail surface may be affected.
As indicated previously, wheelslip has been found to initiate cracking on the rail surface and to be directly responsible for later squat growth. The role of lesser levels of slip as utilised in controlled creepage in traction axles is not clear at this stage.

Crack Growth
The crack growth behaviour is still somewhat of a mystery. It would appear today that all surface cracks have the capability of turning into rail squats. What causes the cracks to drive downwards at an angle of about 30% to the horizontal to depths of 3 to 5mm is not clear. Similarly the mechanism by which squat cracks laminate and grow across the rail head and along the rail head is also unclear.

Research within Australia and throughout the world is looking at this very question.

What's Changed?
One of the mysteries of rail squats is why they have started to occur. The fact that they occur on all manner of rails, sleepers and traffic types is puzzling. It is also a factor that squats have been found widely in Australia and throughout the world.

Changes that are potentially involved could include:
- Increasing levels of wheel slip from locomotives including from work trains (though this would not necessarily affect other rail systems which also have squat problems). Wheelburns are also an issue.
- The increasing consistency in wheels, rails and in the control of the wheel rail contact. RailCorp wheel profiles are similar and fairly consistent throughout their lives and so are rail profiles.
- Lower wheel and rail wear arising from better wheel tracking, better lubrication and harder steels used in wheels and rails. Contrary to popular belief harder wheels result in lower levels of rail wear and vice versa.
- Narrower contact bands on rails.
- Higher levels of adhesion utilised by traction axles of passenger vehicles and freight locomotives.
- Higher levels of creepage utilised by traction axles of passenger vehicles and freight locomotives.
- Higher steering wheel profiles.

Management of Rail Squats
RailCorp has developed strategies for the management of squat defects and revised these each year since 2007 based on the current state of knowledge. The current strategy was issued in July 2009.

The key issue with rail squats is prevention. Once they have developed there are very difficult to treat.

There are 3 methods of squat repair practised in RailCorp:
- Head repair welding using the wire feed process.
- Rerailing.
- Rail grinding.

Wire feed welding is an effective means of repairing isolated squats. It quickly becomes uneconomical, however, when multiple squats are encountered.

Care needs to be exercised when wire feed welding squatty rail. Squat laminations have been known to turn down and cause transverse defects and broken rails, when the heat affected zone of a wire feed weld is intersected.

Rail replacement is obviously an effective but relatively expensive means of repairing squats.

Rail grinding (corrective) - Complete repair requires a very large amount of metal removal typically until all signs of squats have vanished (and then a little more). This involves grinding off something like 6mm of metal. If this is not done then any residual squats will continue to grow. Removing a few millimetres of metal is just as likely to make things worse.

Simply carrying out a normal grind (0.2mm minimum metal removal) does assist in reducing the impact from vertical irregularity and broadening the contact area. This appears to slow the growth of squats and the rail deterioration. Light surface grinding of squatty rail can provide temporary relief to noise and vibration issues. More frequent grinding is also desirable at such locations.
Turnouts with mild/moderate gauge corner squats on uncanted rails can sometimes be successfully treated by grinding a canted profile on to the rails. This has the effect of moving the contact band away from the juvenile squats.

The most desirable strategy is one that ensures rail squat initiating conditions do not arise in the first instance. The next best is to treat precipitating conditions before squats get a chance to develop. Some strategies may act to slow growth and development and operate over different phases of the squat lifecycle.

Some of the current strategies being utilised or proposed that are preventive in nature include:

- Liaising with operators and project staff to reduce the incidence of wheelslip.
- Regular cyclic rail grinding.
- Adjustments to the rail profiles to broaden the contact band and reduce rail stress.
- Pre-profiling of turnouts to achieve targeted rail profiles before installation.
- Increasing the grinding frequencies for moderate curves.
- Revising the grinding profiles used in the transitions of sharp curves.
- Early intervention and increased depth of grinding when wheelslip is identified.
- Increasing the depth of grind at locations when squats are first identified. This is to ensure that any surface damaged material from wheelslip/ wheel creep in the surrounding area is removed before new cracks have a chance to develop further and grow into squats.

Better detection and monitoring of squats is also an issue. Squats are currently reported by maintenance staff and by the rail testing contractor (Speno) who also have a “Hocking system” for detecting surface cracks to supplement ultrasonic information. Generally these systems have limitations in the ability to detect potential squats when the cracks are very small and also in terms of their ability to quantify squat size and distribution.

RailCorp is also experimenting with different types of rail.

What is clear at the moment is that the life cycle of rail squats is not fully understood and that there is scope for further research. For this reason a national research project has been initiated as part of the CRC for Rail Innovation.

### Research & the CRC

The CRC for Rail Innovation was established under the Australian Government’s Cooperative Research Centres Programme formed to sponsor rail research in Australasia. It includes a number of rail organisations and several universities. There is a matching funding arrangement with the Federal Government. Various research projects are underway including project R3-105 on Rail Squats.

The aims of the Rail Squats Project are to deliver:

- Knowledge base: relative importance of key factors in squat initiation and growth.
  - Rules for avoiding conditions of squat formation.
  - Models for predicting initiation and growth.
- Manuals, practices for classification, direction, measurement and minimization of squat initiation and growth.
- Tools for early detection: non-destructive methods and instruments.
- Pro-active strategies for network management of squats.

The project is only really just getting underway with the recruitment of various full time researchers and research students. Already there has been extensive collaboration between the rail organisations including RailCorp, Queensland Rail and ARTC and the various university research organisations including: University of Queensland, Central Queensland University, Monash University, and the Institute of Railway Technology (also within Monash University). Professor Ajay Kapoor from Swinburne and Dr Stephen Marich from Marich Consulting are also involved in the project.

Research carried out to date includes:

- Collation of data on squats from the various rail entities.
- A literature survey.
- Measurement of squat growth from field measurement (see Figure 17).
- Metallurgical review of samples of squats (See sample microscopy in Figure 18 overleaf).
• Simulation of vehicle track interaction to determine wear and fatigue characteristics in various geometries especially transitions. The work has flagged how the balance of wear and fatigue controls squats in the sharp curves.
• Thermography as a means of identifying and sizing squats (see Figure 20).
• Modelling of rail stress condition looking at crack initiation and growth.
• Testing of rail steels to refine understanding of crack growth characteristics.

Further research work is to include:
• Detailed metallurgical review.
• Investigation of strategies for early detection of squat cracks.
• Further Modelling and testing of crack growth.
• Twin disc testing of the wheel rail interaction (looking at the role of friction, traction and creepage) as well as the role of contaminants and water.
• Investigating the role of water in squat growth. One interesting investigation is the use of a water displacing material to reduce the growth of existing cracks.

Some examples of the research work to date are given below:

![Figure 17: Growth rate of rail squat defects.](image1)

![Figure 19: Thermal image of squat which can see below the surface](image2)

![Figure 20: Microscopic examination showing large crack and smaller branching cracks](image3)
References


Acknowledgements

The authors are grateful to the CRC for Rail Innovation (established and supported under the Australian Government's Cooperative Research Centres program) for the funding of research Project No. R3-105 Rail Squat Strategies.