VERTICAL SPLIT HEAD RAIL DEFECTS – SOME INSIGHTS INTO THEIR DEVELOPMENT AND GROWTH

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SUMMARY:
A detailed study has been conducted at the Rail Infrastructure Corporation covering a wide range of aspects associated with vertical split head defects in rails, including:

- Why the defects occur in the older rail steels and what are the factors that cause the defects to initiate and grow.
- Assessment of the location of the defects within the rail head.
- The influence of various track parameters, such as sleeper type, rail type, track geometry and rail location).
- The analysis of the defect characteristics using finite element modelling.
- The wheel/rail profile relationships.
- The determination of the relative importance of the various influencing factors.
- The steps taken to minimise the occurrence and the risk level associated with the defects.

The work has led to major changes in the testing procedures and required responses associated with a potentially critical rail defect type.

1 INTRODUCTION

A Vertical Split Head (VSH) is a type of rail defect. It is described in the Federal Railroad Administration (FRA) Standards [1] as "a vertical split through or near the middle of the head, and extending into or through it. A crack or rust streak may show under the head close to the web or pieces may be split off the side of the head."

Figure 1 illustrates cross sections of the rail head containing a medium and a large VSH. It can be seen that in the former, the vertical crack is contained within the rail head, while in the latter the crack has almost joined the head/web transition region.

Such cracks may run along the rail for several metres in extreme cases. Large cracks approaching the top and/or bottom surfaces of the rail are accompanied by rail flow and a flattening of the rail head which may be observed by a widened contact band on the surface of the cracked rail (Figure 2 (a)), and a rust streak in the head/web fillet region, which occurs when the crack breaks out and joins the rail surface (Figure 2 (b)).
VSH defects are of special concern to railway engineers because: they are difficult to detect by normal ultrasonic testing; they can fail in a way which is particularly hazardous to trains when a section of the rail head may fall out; and because such rail breaks are not detected by the signalling system.

2 OVERVIEW OF EVENTS

2.1 A Problem Emerges

VSH defects had been found in the NSW rail network as far back as 1972 when records were available. The numbers varied from year to year but generally remained at a low level (see Figure 3). However, in 2001 there was an increase in the level of defects particularly in one or two areas.

The initial reaction was to implement improvements in ultrasonic testing and supplement this with additional visual inspection by track inspection staff.

As these improvements were rolled out, even more defects were found, triggering in turn greater concern and finding ever more defects. By the 2002 the numbers had skyrocketed.

2.2 Early Investigations

Initial investigations were directed primarily at the metallurgical causes of the problem firstly utilising in-house staff and then utilising the expertise of BHP Rail Research Unit of Monash University [2]. These investigations suggested that the problem arose from inclusions, which were endemic to rails produced prior to about 1980.

Field inspections were conducted to review the sites where defects were found and statistical data was reviewed for relevant factors.

A special committee was formed to address the problem and expertise sought from a variety of areas. A risk workshop was conducted so that key risks could be addressed and appropriate priorities allocated.

2.3 Ultrasonic Testing

Ultrasonic testing frequencies were increased in affected areas (from four months to six weeks), slower testing speeds were used and improved probe arrangements introduced. Additional testing cars were obtained and priority established for track access for ultrasonic testing in critical areas.

Side shooting 45 degree probes were commissioned to supplement the standard probes. Standard probes are oriented along the rail (3 x 70 degree forward and backward, 37 degree forward and backward and zero degree). The 45 degree probe was not fully effective and was later replaced by a 65 degree side shooting probe, (which is the current arrangement).

2.4 Defect Growth

It was not possible to determine defect growth rates just from on-rail ultrasonic testing. A testing program was introduced where small defects were left in track and their growth monitored by hand testing.

These testing programs shed additional light on the growth characteristics of the defects albeit with some limitations.
An additional classification was introduced to identify inclusions and very small cracking, termed “inclusion band” or IB. These defects were registered for future reference but not removed.

2.5 Statistical Review
Experts in statistical analysis from the CSIRO in Sydney were engaged to conduct an analysis of defect data to review possible factors that may be correlated with the occurrence of the VSH defects [3].

2.6 Finite Element Analysis
To better understand the internal rail stresses involved and identify the physical load features that were of most importance, a finite element analysis was conducted by Central Queensland University [4]. Fracture mechanics principles were then applied to examine the initiation and early growth characteristics of the defects.

2.7 Preliminary Cause Reviews
The state of understanding of the problem, its causes and remedies was updated as information became available. These prompted both corrective action strategies and further investigations.

2.8 Review of Wheel Condition and Wheel Rail Interaction
A review of wheel profiles and rail profiles was undertaken to establish the degree to which rails were subjected to eccentric loading. In addition a review of wheel impacts was conducted utilising an existing wheel impact system at Medford in the Hunter Valley and by installation of load cells at Warnervale on the main route north from Sydney.

2.9 Defect Classification and Assessment Review
Historically, VSH defects have been classified by their length. However a review of defects detected showed that many defects classified as large because of their length were in fact of negligible crack height in the rail.
A review was conducted of the ultrasonic techniques for the hand sizing of defects. A regime was developed to better classify defects considering both the height of the crack in the rail and its length. Other features also were considered including: the presence of physical dipping; evidence of under head stress commonly (but incorrectly) known as a “rust band”; and whether or not physical indeed cracks were present (giving rise to a genuine “rust band”). Other factors such as the presence of welds in the rail and multiple defects also were considered.
Defect classifications and defect response requirements (specifying removal times and speed restrictions) were also reviewed. The former “large” defect classification was subdivided into severity levels. The response requirements were moderated for the more common less severe category. Graded responses were implement as severity increased.

3 MAIN TECHNICAL FINDINGS
3.1 Why Defects Occur
There is very little in the recent international literature on the detailed causes of VSH defects. The main reason is that such defects occur predominantly in older rails, produced prior to the 1980’s by means of ingots, which generally exhibit much higher levels of impurities/irregularities, rather than the current continuous casting process. Furthermore, the inspection procedures implemented in the older rails were at best marginal, relative to those applied in more recent times.
Unfortunately, a considerable proportion of RIC (and other Australian) tracks still contain such older rails.
It is known that VSH defects initiate at very elongated clusters of inclusion or irregularities present within the rail head, at a considerable depth below the running surface, in a region approximately 17 to 27 mm from the original rail surface, and at about ± 10 mm from the vertical centre line of the rail (Figures 4, 5(a) and 5(b)).

![Figure 4 General Appearance of Large VSH Defects](image-url)
The inclusion band usually is evident visually on the fracture surface of the defect, and may be 1–2 mm in vertical height, and more than 400-500 mm in length. Also there may be several inclusion stringers in line with each other, each with the potential to initiate cracks, depending on their size and the applied stress level.

The initial crack growth occurs vertically from the elongated individual irregularity or group, both towards the running surface and the head/web transition region. Figure 6 (a) illustrates the potential crack growth from a single, relatively long irregularity. Growth from multiple irregularities that are in line is illustrated in Figure 6 (b). This shows that the initial crack growth (1 and 2) may occur from each of the irregularities, and the individual cracks then could join (3) and form a much longer crack (4).

The actual stress condition that produces such crack initiation and growth is not certain, but it is known that the crack opening does entail a tensile stress component across the rail. Such stress could be produced by a combination of the following:

- Rotation of the rail head due to off centre vertical loading, such as the field side loading that occurs with hollow wheels in combination with worn rails, as illustrated in Figure 7.
- Lateral displacement of the rail head due to the lateral creep forces that are produced as the wheelsets oscillate from one side of the track to the other, as also illustrated in Figure 7.

A more detailed discussion of rail stresses is presented in Section 3.3.

Some of the main factors that are thought to exacerbate the development of VSH defects include:

- Rotation of the rail head due to off centre vertical loading, such as the field side loading that occurs with hollow wheels in combination with worn rails, as illustrated in Figure 7.
- Lateral displacement of the rail head due to the lateral creep forces that are produced as the wheelsets oscillate from one side of the track to the other, as also illustrated in Figure 7.

A more detailed discussion of rail stresses is presented in Section 3.3.
• High incidence of large elongated inclusions or imperfections in the older rails.
• High dynamic and impact vertical wheel loadings. Impact loads are particularly harmful not only because they increase the level of applied load, and hence stress, but also because they reduce the threshold size of the irregularities required for VSH defect growth (refer to Section 3.3).
• Wheel contact towards the field or gauge sides of the rails, which may be obtained with rails that have not been maintained (ground) for an excessive time and/or hollow wheel profiles.
• High lateral dynamic characteristics of wheelseets and bogies (hunting), particularly in the shallow curves and tangent track.
• Increased rail head wear.

3.2 Assessment of VSH Defect Growth
It is not clear to what extent and by what mechanism the cracks actually extend along the rail. In particular, whether the cracks associated with the elongated irregularities actually grow longitudinally into the prime rail material, in which case the growth rate could be relatively low; or whether the longitudinal growth consists of the joining up of adjoining pre-existing cracks, in which case the growth rate could be relatively high. Fracture analysis work conducted to date (refer to Section 3.3) has suggested strongly the latter mechanism, which is illustrated in Figure 6.

Some limited field work has been conducted to quantify the longitudinal crack growth characteristics in smaller VSH defects under actual operating conditions. Control was attempted by trying to have the same Krautkrammer operator with the same equipment monitor the defects using the same procedure, but this was not always possible.

Growth was assessed only in terms of the longitudinal crack extension as detected ultrasonically so that the actual vertical size of the crack in the rail could be quite small. The growth as measured was found to be somewhat erratic.

Figure 8 shows the relationship between the growth in mm per week and the percentage of defects whose average growth was greater than this. For example about 25% of defects grew more than about 10mm per week. Only about 5% of defects grew more than 100 mm per week. The very fast growth may be indicative of the joining up of multiple pre-existing defects, as illustrated in Figure 6 (b), while the much lower growth rates may be indicative of growth from individual irregularities, as illustrated in Figure 6 (a).

Figure 8 Longitudinal Growth Characteristics of VSH Defects

3.3 Fracture Mechanics and Finite Element Analyses
In the known presence of small irregularities or inclusions, fracture mechanics principles may be applied to examine particularly the defect initiation characteristics.

Using previously published rail material fracture characteristics [5] and the fracture mechanics relationships applicable to a very elongated elliptical irregularity within the rail head [6], the relationships between the threshold crack size (above which growth will occur) and the applied stress level can be determined, as illustrated in Figure 9.
The following trends are of major interest:

- Dynamic, and in particular impact loading conditions (as defined in [5]) have a major adverse influence on the threshold irregularity size, i.e., at a particular stress level much smaller irregularities are capable of initiating crack growth. Assuming that the inclusion size distribution within the material is approximately exponential, a reduction in the threshold size would increase the population of potential defect initiation sites by a factor to the power of over 3.

- Dynamic and impact loadings have of course the additional affect of increasing the applied load levels.

- Much lower threshold defect values are obtained at point Y than at point X, even though it is known that the inclusion clusters can be very elongated. Consequently, the initial crack growth would occur from the top (and bottom) of the irregularity in the vertical plane, as actually observed. Indeed, very large defects would be required to grow in the longitudinal plane.

- Under impact loadings, the initiation of cracks from irregularities 1-2 mm in height, which are known to be present in the rail, would require tensile stress levels across the rail head above about 135 MPa. On the other hand, under normal loadings irregularities 1-2 mm in height would require stress levels above about 220 MPa, while under dynamic loadings the irregularities would require stress levels above about 175 MPa.

- Both the applied stress level and the fracture toughness of the material have a major adverse influence on the threshold irregularity size required to initiate cracks.

To establish how such stress levels could be obtained within the rail head, where VSH defects are known to initiate and grow, finite element modelling was conducted (FEM). The modelling examined a range of factors, including:

- Rail head wear.
- Rail support conditions.
- Location and magnitude of vertical load on the rail head.
- Location and magnitude of lateral load (as a proportion of the vertical load) applied on the running surface on the rail head, to simulate lateral creep and loads obtained with wheelset/bogie hunting.
- Various combinations of the above.
- Various wheel/rail contact conditions, ranging from point loading to broad contact.
- The presence of small irregularities.

Figure 10 illustrates one of the many bulk stress contours obtained from the analysis.
that satisfy only the impact loading regime. Furthermore the required stress levels are obtained only towards the top of the critical zone, which would not explain the initiation of defects towards the bottom of the rail head.

- The presence of even very small cracks, which have been observed in the vicinity of inclusions (refer to Figure 11), leads to stress concentrations near the crack tip, which increase the localised stresses by factors of 2-3 (refer to Figure 12). The resultant stress levels then become sufficiently high to cause further crack growth over an extended region within the critical zone, particularly under impact loading conditions, even for central loading with no lateral loads applied.

- Adjoining irregularities in the vertical plane act as one if they are separated by a distance less than about half their height. For example: two adjoining irregularities 1 mm in size, separated by 0.5 mm, would act as an irregularity 2.5 mm in size. In such cases, much lower stresses and adverse loading conditions of course would be required to generate further growth.

Once the crack initiation and initial growth occurs, further crack growth of course may be obtained under less extreme loading conditions. For example: once the crack reaches a height of 5 mm, further growth would require stress levels above about 140 MPa under normal loading conditions, 110 MPa under dynamic loading conditions and only about 80 MPa under impact loading conditions. In this case, such stresses could be produced readily by more centralised dynamic loadings even in the absence of lateral loads, particularly taking into account the stress amplifications that occur near the crack tip.

4 DEVELOPMENT OF STRATEGIES

From the various investigations described above, it was considered that a reduction in wheel impacts was a major priority. With the cooperation of operators, wheel condition has been improved and the number of wheel impacts reduced. For example, Figure 13 illustrates the impacts recorded at Medford (4 tracks) in the Hunter Valley. An additional four Wheel Impact monitoring sites have now been installed on the main routes into Sydney. These are in the process of being calibrated.

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5 CURRENT DEFECT TRENDS

Current defect trends are illustrated in Figure 14, for both large VHS defects and all VSH defects. Both categories show that following the significant increase in 2002 there has been a steady decline in levels.

![Figure 14 VSH Defect Trends](image)

6 CONCLUSIONS

For rail organisations with older rail developed in the days prior to fully killed or continuous casting procedures, there is a potential vulnerability and risk due to the development of vertical split head rail defects. This vulnerability can be hidden for many years and only emerge as damage accumulates from heavier and faster traffic, with potentially high wheel impacts and possibly poor wheel profiles. Traditional ultrasonic testing is not efficient at detecting these kinds of defects, particularly in their early growth stages. If no other steps are taken then the first indication of a problem may herald a large-scale increase in defect numbers.

The work described herein provides a good example of the considerable range of activities that were undertaken by RIC in a relatively short time to understand fully a critical problem and then to establish and apply the most effective solutions.

7 REFERENCES


4. M Dhanasekar, P Boyd and T McSweeney, “Finite Element Analysis of 53 kg/m Rail”, Centre for Railway Engineering, Central Queensland University, Reports 1 and 2, May-Aust 2002. *(Confidential to Rail Infrastructure Corporation and Central Queensland University - not published. Full report may only be obtained with permission from the Rail Infrastructure Corporation).


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