On-Track Testing of Insulated Rail Joints
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Synopsis:
This report presents a state-of-the-art field test set-up to measure the response of insulated rail joints (IRJs) under heavy axle loads due to coal train traffic. Four IRJs were carefully instrumented and installed with a view to understanding the effect of different design parameters and support conditions to their behaviour under heavy axle loading. The IRJs were instrumented with strain gauges, accelerometers and pressure cells, and installed in a coal line at Hunter Valley, Newcastle, NSW. A rail closure was also instrumented with the same sensors as the IRJs and installed in the test site to benchmark the data from the IRJs. This test set-up is innovative and has not been previously conducted to this scale in Australia, and the results obtained from these tests provide valuable information unavailable in the literature. This research report presents the process of instrumentations, track installations and data recording set-up. The analysis of the recorded data is presented in a separate report.

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Executive Summary

Insulated rail joints (IRJs) are sections of track critical to controlling the signalling system safely and, in some instances, help identify broken rails. IRJs are subjected to a wide range of cumulative axle loads: from 50-400 MGT for example, and the IRJs frequently fail under these stresses. Consequently, this uncertainty demands regular, close examination of the condition of the IRJs, usually by track maintenance and signalling crews, who have conflicting interests. While the track maintenance crew keenly strengthens a degrading IRJ, the signalling crew focuses on avoiding gap closure due to metal flow.

A state-of-the-art field trial of selected IRJ designs was recently commissioned for the Australian Rail Track Corporation Ltd (ARTC) Hunter Valley coal corridor with a view to collecting valuable data for calibrating some IRJ models being developed at the Queensland University of Technology (QUT) and Central Queensland University as part of CRC for Rail Innovation project R3.100: *Longer Life Insulated Rail Joint*. This report details the procedure of instrumentation, installation and commissioning of four IRJs and a rail closure.
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Abbreviations and Acronyms

ADC  analogue-to-digital
ARTC  Australian Rail Track Corporation Ltd
ch  channel
DAQ  data acquisition
Inc.  Incorporated
IRJ  insulated rail joint
LabVIEW  laboratory virtual instrumentation engineering workbench
MGT  million gross ton
NI  National Instruments
Introduction

Insulated rail joints (IRJs) are vulnerable to heavy axle load traffic. They exhibit highly variable, characteristically short service-life spans and suffer various modes of failure. The greatest number of IRJ failures occur on lines carrying heavy coal traffic. These IRJs fail either due to severe rail head defects or joint-bar fractures. Unfortunately, it is difficult to detect joint-bar fractures as they do not affect the signalling system. Consequently, it is necessary to find joint-bar fractures during visual inspections or by track patrols to avoid dangerous and costly train derailments.

Many theoretical studies have investigated the behaviour of rail joints for dynamic wheel–rail force values, vertical deflection, or the stress scenario at the joint gap. Little work has been published that measures actual values of stresses and loads in the field. To improve our knowledge of rail joint behaviour we placed four IRJs and a rail closure, each instrumented with a significant number of sensors, into the field to monitor their behaviour under coal trains.
1. Test Set-up

1.1. Test site

The test site was in the Hexham area, on the coal line between Newcastle and Maitland, NSW. Four instrumented insulated rail joints (IRJs) and a rail closure were installed in a test section 40 meters long (Figure 1). This site was recommended by Australian Rail Track Corporation Ltd (ARTC) engineers as a suitable test location based on the following factors:

- it is located on tangent ballasted track (not in curved track)
- it is located on heavy haul track
- frequent failure of IRJs is observed here
- it is easily accessed with minimum transportation cost

The track design properties in the test site are presented in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track gauge</td>
<td>1435 mm</td>
</tr>
<tr>
<td>Rail type</td>
<td>AS 60</td>
</tr>
<tr>
<td>Sleeper type</td>
<td>Prestressed concrete</td>
</tr>
<tr>
<td>Sleeper spacing</td>
<td>600 mm</td>
</tr>
<tr>
<td>Sleeper length</td>
<td>2500 mm</td>
</tr>
<tr>
<td>Sleeper width</td>
<td>200 mm</td>
</tr>
<tr>
<td>Fastener type</td>
<td>Pandrol</td>
</tr>
</tbody>
</table>

Figure 1. Test site

1.2. Test objectives

Objectives of the field tests included:
• monitoring the progressive degradation of the IRJs, as well as the support beneath each IRJ, due to accumulated traffic
• studying the effect of an improved support system on the performance of the IRJs
• comparing the performance of IRJs with different gap size and shape
• comparing the stresses and structural response of the track at IRJs sections with those of a regular track section (continuous welded rail)
• obtaining the required data for validating theoretical and computer models

1.3. Instrumentation

The test site was instrumented with strain gauges, accelerometers and pressure cells. The IRJs and rail closure were instrumented with strain gauges at the Thermit® Australia Pty Ltd factory and in the Centre Railway Engineering (CRE), Rockhampton laboratory and then transferred to the site to install into the track. Linear strain gauges were mounted on the rail closure and on IRJ components including the rail web, rail foot and joint-bars.

1.3.1. Selection of strain gauges

Bonded metallic strain gauges were used in this test. These strain gauges use a fine wire or metallic foil arranged in a grid, which maximises the amount of metallic wire or foil subject to strain in the plane parallel to the direction of travel. [Strain gauges are mounted to the test specimen/track/IRJ/rail closure using an adhesive/twist tie/weld/chewing gum.] It is very important that the strain gauge is properly mounted on the test specimen to ensure that the strain force is accurately transferred from the test specimen through the adhesive and strain gauge backing to the foil.

The choice of strain gauge for this experiment was influenced by the sensitivity, size, measurement range, fatigue life, and temperature range of the gauge. Gauge sensitivity, expressed as the gauge factor (GF), is defined as the ratio of fractional change in electrical resistance (R) to the fractional change in length (strain ε). We used single element gauges and multiple element gauges manufactured by Vishay Precision Group Micro-Measurements. The single-element strain gauges were wired into a Quarter-Bridge type circuit and the multiple-element gauges were wired into a full wheatstone bridge circuit (see next section for more detail).

1.3.2. Positioning of the strain gauges
Strain gauge position is critical to test success. The strain gauge needs to be located at a point fairly sensitive to the high magnitude strains created under static and dynamic loads whilst being technically feasible. Strain gauges can only be placed on the surfaces of IRJ components; the rail head surface and rail ends cannot be used because of wheel passage and space limitations, respectively. This leaves the rail web, rail bottom and the joint-bars as the best possible locations. Numerical results from the dynamic finite element model [1, 2] were employed to identify the most sensitive positions for locating the strain gauges. As lateral normal strain is of less significance in tangent track, the vertical normal strain and longitudinal normal strain are measured in this test. The rail web is sensitive to vertical strain, while the rail bottom and joint-bars are more sensitive to longitudinal strain. The location of strain gauges on the IRJs and rail closure are presented in Figures 2 to 5.

Figure 2. Strain gauge locations on IRJ 1 and IRJ 3
Figure 3. Strain gauge locations on IRJ 2 (placed on closely spaced sleepers)

Figure 4. Strain gauge locations on IRJ 4
Horizontal strain gauges

Horizontal strain gauges, mounted on the rail foot and joint-bar, were used to measure the bending strains generated under the wheel load. In the rail closure, the horizontal strain gauge was installed at the bottom of the rail. In the IRJs, the horizontal strain gauges were installed on the top and bottom of the joint-bars and also at the bottom of the rail. To capture the maximum bending strains on the joint-bars, the strain gauges are mounted on the highest practical distance to the neutral axis on both sides.

Vertical strain gauges

Vertical stain gauges were installed close to the rail head (100 mm from the rail foot) and were used to measure dynamic impact as well as the stress scenario near the rail end. In addition, some vertical strain gauges are installed on the rail neutral axis (80 mm from the rail foot).

Shear strain gauge bridge

Multiple-element shear strain gauges were mounted on the neutral axis of the rail web. These strain gauges were wired into a full-bridge circuit and calibrated in the field to determine the vertical wheel–rail contact force over the joint. Shear bridge output is a function of the difference between the two shear forces induced in the rail cross sections. The eight gauges were attached to the rail web at the level of the neutral
axis, rail web keeping the strain gauge gridlines at 45 degrees to the rail axis, then wired into a full-bridge circuit (Figure 6). Considering that the only vertical load applied to the rail between the two instrumented sections is the moving wheel, the shear bridge output voltage will be constant during wheel passage producing a trapezoidal-shaped signal. Therefore, as the wheel passes over the instrumented zone any load variation introduced by the wheel or rail irregularities and vehicle dynamics will influence the output signal shape showing the value and location of the dynamic impact within the instrumented section. The strain gauge-based wheel load detector has been reported in the literature as an effective method for measuring vertical wheel loads and wheel–rail dynamic impacts, in particular due to wheel flats[3, 4]. We have used this method to detect the values of vertical wheel–rail forces at rail joints for the first time.

The shear bridge was calibrated in the field by reconciling a number of known individual wheel loads with the raw voltage output from the strain gauge bridges. The theoretical background and the procedure for developing, testing and calibrating the shear bridge wheel load detector is the content of a separate CRC for Rail Innovation report [5]. Figure 6 illustrates the 3-element 45degree Rosette 6.35 x 3.05mm used to measure shear strain. The 90 degree elements (A and C) are wired in the bridge; the middle, horizontal gauge (B) is not used.

IRJs are produced in the Thermit® factory based on Australia Standard AS1085.12, Railway Track Material Part 12: Insulated Joint Assemblies [6]. IRJs comprise an insulation material (end post) fixed between the ends of two adjacent lengths of rail, and secured by bolted
joint-bars that connect the two rails. There is also an insulation layer between the rail and joint-bar. Strain gauges were mounted on the rail web at IRJs in the factory during manufacture. At gauge locations the insulation material was cut out to provide enough space to accommodate the strain gauge and associated wiring.

1.3.3. Accelerometer

An accelerometer senses the motion of the surface to which it is attached, producing an electrical output signal precisely analogous to that motion. The force caused by vibration or a change in motion (acceleration) causes the mass to ‘squeeze’ the piezoelectric material which produces an electrical charge that is proportional to the force exerted upon it. Since the charge is proportional to the force, and the mass is a constant, then the charge is also proportional to the acceleration. Our choice of a suitable accelerometer for this test was influenced by the frequency range, the temperature range, the environment, and the shape and size of the sample to be monitored.

It is important that the mounting surface of the accelerometer is tightly coupled to the test surface to ensure accurate duplication of motion, especially at higher frequencies. Some mounting methods may adversely affect accuracy, so for best results it is important to understand the mechanics of mounting the accelerometer. We could not use the stud mount method because drilling a mounting hole on the rail and sleeper was not allowed. Consequently, the only practical way to install the accelerometer was to mount with an adhesive. This required us to design some mounting bases to glue to the rail and sleeper surface for attaching the accelerometer. Before installing the mounting bases the area was cleaned with a solvent to remove all traces of metal chips, cutting oil, and any other surface contaminants. We connected the accelerometers to these mounting bases at the time of data recording. An accelerometer mounting base installed on a sleeper is shown in Figure 7.
Figure 7. An accelerometer mounting base installed on a sleeper

**Accelerometer on the rail bottom**

Acceleration measures are a good indication of the dynamic impact generated under a moving wheel, and can also be used to deduce the value of vertical displacement. To measure the vertical acceleration of the rail under a passing train we installed an accelerometer under the IRJ and rail closure. Any accelerometer installed on the IRJ/rail bottom must be capable of measuring high rail acceleration values within high frequency range, because current studies show that vertical rail acceleration due to wheel–rail dynamic impacts can exceed 2000 m/s² [7, 8]. Specifications for the accelerometer model used in this research are in Table 2. More details about the IRJ/rail accelerometer specifications can be found in the PCB Piezotronics Inc. manual [9].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>PCB 353B11</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.51 mV/(m/s²)</td>
</tr>
<tr>
<td>Measurement range</td>
<td>9810 m/s² pk</td>
</tr>
<tr>
<td>Frequency range</td>
<td>1 to 10,000 Hz</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-54 to +121 °C</td>
</tr>
</tbody>
</table>
Size (Hex*Height) | 7.9 mm * 10.9 mm  
Weight | 2.0 gm

**Accelerometer on the sleeper**

Accelerometers were also mounted on top of the sleepers adjacent to the instrumented IRJs and rail closure. Any change in magnitude of sleeper vertical acceleration over time indicates that support beneath the sleeper has deteriorated. We used a different type of accelerometer here because the expected values of sleeper acceleration and the frequency range are less than those of the rail. Sleeper accelerometer specifications are in Table 3. More details about the sleeper accelerometer specifications can be found in the PCB Piezotronics Inc. manual [10].

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<td>PCB 333B30</td>
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<tr>
<td>Sensitivity</td>
<td>10.2 mV/(m/s^2)</td>
</tr>
<tr>
<td>Measurement range</td>
<td>490 m/s^2 pk</td>
</tr>
<tr>
<td>Frequency range</td>
<td>0.5 to 3,000 Hz</td>
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<tr>
<td>Temperature range</td>
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</tr>
<tr>
<td>Size (Height<em>Length</em>Width)</td>
<td>10.2 mm * 16 mm * 10.2mm</td>
</tr>
<tr>
<td>Weight</td>
<td>4.0 gm</td>
</tr>
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**1.3.4. Pressure cell**

To measure the sleeper-ballast contact pressure adjacent to the IRJ and rail closure we placed earth pressure cells in the ballast directly below the sleeper. These pressure cells are designed to measure stresses in soil or the pressure of soil on structures. We used hydraulic-type pressure cells, where two flat plates are welded together at their periphery and are separated by a small gap filled with a hydraulic fluid. An applied load squeezes the two plates together increasing pressure inside the fluid. If the plates are flexible enough, i.e. if they are thin enough relative to their lateral extent, then the supporting effect of the welded periphery is negligible, and at the centre of the plate the external pressure is exactly balanced by the internal fluid pressure. We selected this model for this experiment as it is capable of measuring dynamic pressure, and the plates are thick enough to resist the high point loads applied from ballast material. In addition, the
accuracy and measurement range of this pressure cell model is suitable for capturing the maximum sleeper-ballast contact pressure generated under a coal train. More details about the pressure cell used in this test can be found in the Geokon Inc. manual [11]. Pressure cell model specifications are in Table 4. A view of the pressure cell and its location beneath the sleeper is in Figure 8.

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<td>Geokon 3515</td>
</tr>
<tr>
<td>Measurement range</td>
<td>600 kPa</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.5%</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-20 to +80 °C</td>
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</table>

**Figure 8.** Pressure cell location beneath the sleeper

### 1.3.5. Settlement pegs

Settlement pegs were used to monitor track settlement due to accumulated traffic. The pegs consisted of a 350mm long, Ø10mm rod attached to a square galvanised plate 100mm x 100mm x 6mm. They were installed in the ballast layer next to the sleepers (Figure 9). Any change in vertical position of the pegs over time was monitored using surveying equipment.
Table 5 gives the location, number of sensors and number of output channels for IRJs and reference rails. Note that only two accelerometers were used in these tests (i.e. one rail accelerometer and one sleeper accelerometer), but mounting bases were installed on all IRJs and on the rail closure. The accelerometers were reused for the IRJs and rail closure for different tests.
### Table 5. Location and number of sensors installed on IRJs and rail closure

<table>
<thead>
<tr>
<th>Location</th>
<th>Instrument</th>
<th>Direction</th>
<th>Number of sensors</th>
<th>Number of channels</th>
<th>Fixed at</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>IRJ 1</td>
<td>IRJ 2</td>
<td>IRJ 3</td>
</tr>
<tr>
<td>Rail web (under rail head)</td>
<td>Strain gauge (Linear)</td>
<td>Vertical</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Strain gauge (Linear)</td>
<td>Vertical</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Strain gauge (Linear)</td>
<td>Vertical</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<tr>
<td></td>
<td>Strain gauge (Linear)</td>
<td>Shear (45 degree)</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Rail foot</td>
<td>Strain gauge (Linear)</td>
<td>Horizontal</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Joint-bar</td>
<td>Strain gauge (Linear)</td>
<td>Horizontal</td>
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<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Joint-bar</td>
<td>Strain gauge (Linear)</td>
<td>Vertical</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rail foot</td>
<td>Accelerometer</td>
<td>Vertical</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sleeper</td>
<td>Accelerometer</td>
<td>Vertical</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ballast</td>
<td>Pressure cell</td>
<td>Vertical</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Single element strain gauges</td>
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<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of Sensors / channels</td>
<td></td>
<td></td>
<td>16</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>
2. Track Installation

Instrumented IRJs, rail closure and in-ballast sensors were installed in three sessions. In the first session, IRJ 1, IRJ 3 and adjacent sensors were installed into the track. In the second session, IRJ 2 and IRJ 4 were installed, and in the final session the rail closure was welded into the track. The general procedure used for track installation was:

1. The 4.57 m length of rail to be removed was marked on the existing rail.
2. Rail fastening/anchors were removed from the rail section.
3. The rail was cut and removed.
4. The sleeper spacing around the IRJ gap and the centre of the rail closure was adjusted to achieve the required sleeper spacing as shown in Figure 10. For IRJ 1, IRJ 3 and rail closure, the sleeper spacing was adjusted to be exactly 600 mm (centre to centre). For IRJ 2 and IRJ 4, two new sleepers were inserted into the track to achieve the closely spaced sleeper support as shown in Figure 10. A view of inserting the sleepers in test site is shown in Figure 11.
5. The instrumented IRJ or rail closure was inserted and welded into the track (Figures 12 and 13).
6. Fastenings/anchors were reinstalled in the rail.
7. Ballast around the adjacent sleepers (indicated in red in Figure 10) was removed to 100 mm below the sleeper bottom (330 mm below the sleeper top surface). Figure 14 shows a view of removing ballast around sleepers in the test site.
8. Pressure cells and settlement pegs were installed in the ballast (Figure 15). Pressure cells were placed beneath the sleeper below the rail seat where the maximum sleeper-ballast contact pressure was expected to occur.
9. Pressure cell cables were passed through conduits along the ballast shoulder and under the track.
10. Ballast was backfilled and compacted with a manual tamper (Figure 16).
11. Rail ends were ground to match the profile of the existing rail.
**Figure 10.** Sleeper spacing around IRJs and rail closure. Top: IRJ 1, IRJ 3 and rail closure. Bottom: IRJ 2 and IRJ 4.

**Figure 11.** Inserting the sleepers into the track and adjusting the required sleeper spacing
Figure 12. Inserting the instrumented rail into the track

Figure 13. Welding and grinding the rail ends

Figure 14. Removing the ballast around sleepers
Figure 15. Installing a pressure cell beneath a sleeper

Figure 16. Backfilling and compacting the ballast with a manual tamper

Figure 17. General view of Instrumented IRJs installed in-track
3. Data Recording

3.1. Trackside set-up and data acquisition system

After installing the IRJs and in-ballast sensors, sensor cables were run through conduits to the access road and terminated with plugs in a trackside terminal box. In total, three terminal boxes were installed on the access road (Figure 18). The first box contained the wiring and plugs connected to IRJ 1 and IRJ 3, the second box the wiring connected to the rail closure sensors, and the third box was connected to IRJ 2 and IRJ 4. Data recording used a laptop and a portable data acquisition system (DAQ) that was connected to the plugs in the trackside terminal box at the time of data logging.

The data acquisition plan was programmed in LabVIEW system design software (National Instruments) with a sampling frequency of 10,000 Hz (10,000 readings per second). This sampling frequency ensured that all high frequency dynamic impacts and their corresponding structural response were recorded. DAQ Cards used were:

- Single Element Strain ADC 8ch, DAQ side electronics (NI 9236)
- Multiple Element Strain ADC 4ch, DAQ side electronics (NI 9237)
- Acceleration ADC 4ch, DAQ side electronics (NI 9234)
- Pressure Cells, Generic ADC (NI 9201)

Figure 18. Location of trackside terminal boxes
In contrast to strain gauges and pressure cells, which are permanently installed in-track with their wiring terminated in a trackside terminal box, accelerometers were only connected to rails and sleepers on the day that data was recorded and were removed again when finished. Accelerometer wiring was not permanently connected to rails but placed in an enclosure attached to a sleeper when not being used. Figures 21 and 22 show an accelerometer being connected to a sleeper and beneath a rail.
3.2. Surveying the test site

Any change in track vertical profile (track vertical settlement) around the IRJs and the rail closure due to accumulated traffic was monitored by surveying the vertical surface of the rail, sleepers and in-ballast pegs. Using a digital level, a surveyor surveyed the site at weekly intervals for one month, then monthly intervals for 3 months, 3 month intervals for 9 months, and a final survey was made at 16 months after installation.
To monitor any progressive deterioration of the IRJs and/or the ballast beneath the IRJ, and to prevent damaging the ballast sensors, we tried not to disturb the test site by tamping or other maintenance activities during the test period (12–18 months). However, should any excessive track settlement, ballast pumping or foundation failure occur during the test, then tamping may be unavoidable.
References

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