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CRC for Rail Innovation

Track Stability Management – Part 2: Field Testing and Data Analysis
Document:

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Executive Summary

In this report (Part 2), a detailed experimental design of field testings using thermocouples, strain gages, rail stress module (RSM) and rail creep using total station survey equipment are used. Initially calibration of the transducers had been carried out in laboratory (Chapter 2) before putting those into the live track for data acquisition (Chapter 3). As the current Stress Free Temperature (SET) of the rail is very important for track stability problems, it is estimated using various methods and compared. SET was determined for left and right rails, straight track and curved track and its daily range.

Field test showed that Stress Free Temperature (SFT) can be $2-3^\circ$C at the maximum rail temperature on a day than the SFT at minimum temperature. Based on this observation and the theory developed in Chapter 2, an improvement in rail creep data by utilising internal stress resulted from rail temperature has been suggested. The new method suggests determining a range of expected SFT on a day rather than a single value of SFT that cover the variation of SFT over a day.

The quantified values of SFT with respect to rail creep and rail temperature may be used in the best practice. The use of adequate number of SFT sensors is dependent on the reliability of sensors, track resistance and locations to represent the representative SFT on any specific track section.

Determining rail temperature based on empirical relationship of air and rail temperature can be inappropriate if characteristics of local surroundings of track and weather parameters are not considered. Considering unavailability of any model to accurately predict rail temperature this study suggests increasing rail temperature for rails oriented in N-S directions by $2^\circ$C.

Part 2 of this report series presents on measurement of SET from creep, Rail Stress Module, strain gauges and thermocouples. Mode of differences of SFT in left rail and right rail, SFT in straight track and in curved track is discussed. The relationship of SFT to rail temperature is also presented. Daily variation rail temperature due environmental air temperature is illustrated.
Abbreviations and Acronyms

DSFT  Design Stress Free Temperature
FEA  Finite Element Analysis
RSM  Rail Stress Monitors
SFT  Stress Free Temperature
STPT  The Single Tie Push Test
Introduction

A worldwide search on different preventive and predictive maintenance strategies to reduce the risk of track buckling and to improve the speed restriction policy has been carried out in Part 1 of this report series. It has been clarified that proper management of rail stress and lateral resistance would help to manage the stability of track. In addition to periodic inspection, an assessment tool to determine stability of track in situ can help to identify priority based locations requiring rail adjustment. However, absence of deterministic parameters such as SFT and lateral resistance of track in situ can lead to uncertainty and inaccurate assessment.

Several empirical relationships have been developed in the last 30 to 40 years to determine the relationship of track lateral resistance with different ballast, sleeper and fastening combinations. Of these, the relationship used in the CWR-SAFE software is the most recent which was developed based on tests on North American tracks. Considering the weak track structures used to develop the criteria for assessment of track buckling potential in all other studies that are in use in Australia now, the relationship of CWR-SAFE has been suggested for use in Australian conditions until tests on modern Australian track structures are available.

A unified tool is necessary to better manage track stability. The tool should incorporate all information about maintenance operations, history of track buckling and rail adjustment, weather data and assessment of track condition. The parameters affecting rail stress and lateral resistance have been summarised in part 1 which may be used in the unified management tool.

The speed restriction policy implemented in Australia is conservative compared to that implemented in the UK. The consideration of air temperature to impose speed restrictions and other special hot weather precautions in Australia does not give enough confidence in acting according to rail stress state. In order to better manage track stability and improve hot weather speed restriction setting, the variation of SFT, variation in rail temperature due to rail orientation and issues of rail creep have been quantified in a field test in Chapter 3 of this report and Chapter 2 addresses the field test design and data acquisition strategies.

2. Methodological Approach and Experimental Design

2.1 Methodological approach

A brief methodology of the part 2 report is presented in Figure 2.1. It was stated in report 1 that the main objective of this research is to gather knowledge of the theory and actual field management practices around the world on the stability of continuously welded rail with a view to finding variabilities and gaps among different practices and develop a best practice tool. A literature review has been conducted to understand the theoretical basis of track buckling and to determine the critical parameters responsible for track buckling. Practices around the world are usually targeted to maintain the critical parameters to the allowable limits. However, the procedures to maintain those parameters are not the same in all railway companies around the world.
Figure 2.1: Methodological approach

Finally, theories of track buckling, requirements for safe operating conditions, effects of maintenance operations, climatic conditions and track structures on track stability along with required inspection procedures have been used to develop a best practice tool to manage the stability of track.

2.2 Experimental design

It was revealed that SFT, rail temperature and buckling temperature are the three most influential parameters based on the theory of track buckling. Maintenance and operational parameters influencing any of these three parameters can affect the potential of track buckling at a specific site. Though it is important to measure these parameters, the variation in measurement techniques has led the railway companies to depend on a range of limiting values that are mostly conservative in nature.

In this report, an experimental design has been developed to quantify the variation in SFT. Inability of installing SFT sensors has led the railway companies to depend on measuring rail creep in problematic areas to determine the expected change in SFT. However, the procedure and equipment used in conventional rail creep measurement can show a large deviation from the actual result. As a result, the measurement method of rail creep has been thoroughly investigated and a new methodology to determine the SFT based on rail creep has been suggested.

The variation in SFT leads to an uncertainty in determining appropriate speed restriction settings. SFT has been found to decrease over time due to longitudinal, lateral and vertical settlement of track. Even a highly variable air temperature cycle can also change the SFT. It is important to have the information/measurement of the SFT in order to manage the stability of track. However, the measurement techniques to determine SFT differ in principles, applicability and accuracy. Of the different techniques, the strain gauge based Rail Stress Module (RSM) was installed at several locations in a representative track section of the QR Blackwater heavy haul export coal system with 60kg/m rail section on both straight track and a 400m radius curve to observe the long term variation in SFT. A strain gauge and thermocouple technique was also used on the straight track. Railway
companies usually monitor rail creep on a routine basis over problematic areas to estimate the change in SFT. However, the process and equipment used in the current measuring method can give significantly erroneous results as consideration is not given to the non-uniformity of track resistance along the track length and the resulting variability of rail internal stress due to temperature rise. In the field test setup for this study, total station surveying equipment has been used to quantify the effect of rail creep on the SFT.

Secondly, the rail temperature is usually determined based on the empirical relationships between the maximum rail and air temperature established in different parts of the world. However, these empirical equations can be conservative on track with specific compass orientations because the amount of solar radiation striking the rail and the reflectivity of the rail surface affect the maximum rail temperature differently in different track orientations. Air temperature and rail temperature have been measured at the field test site by using a weather station and thermocouples on the rail.

The third critical parameter, buckling temperature, is a function of track lateral resistance, initial misalignments, maintenance operations and ballast stabilisation, and can be determined by using CWR-SAFE software. The Single Tie Push Test (STPT) device has been widely used on tracks in the USA to measure lateral resistance of the track and develop empirical relationships for the lateral resistance of different track structures; these are incorporated in the CWR-SAFE software (Samavedam et al., 1999). Table 2.1 summarises the measuring parameters and techniques used in this report.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measuring Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFT</td>
<td>RSM</td>
</tr>
<tr>
<td></td>
<td>Strain Gauge and Thermocouple</td>
</tr>
<tr>
<td>Rail Temperature</td>
<td>Thermocouple</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>Weather Station</td>
</tr>
<tr>
<td>Buckling Temperature</td>
<td>Stress Net web-based database (based on CWR-SAFE software)</td>
</tr>
<tr>
<td>Creep</td>
<td>Total Station Survey equipment</td>
</tr>
<tr>
<td>Misalignment</td>
<td>Tape measure</td>
</tr>
<tr>
<td></td>
<td>Total Station Survey equipment</td>
</tr>
</tbody>
</table>

2.3 Lab installation and test

Strain gauges and rail stress monitors (RSM) were installed on two 60kg/m rails of length 4m and 6m in the Heavy Testing Laboratory of the Centre for Railway Engineering at CQUniversity, and tested by applying a vertical load of 5 tons using a hydraulic actuator (Figure 2.2). Data were recorded at 100Hz during loading and unloading cycles of the actuator. The recorded data shows that all strain gauges were working (Figure 2.3). The data from the strain gauge rosettes were used to determine strains along the longitudinal direction using Mohr’s circle equations.
The observed strains were compared with the results from a three dimensional finite element model developed in the ABAQUS software package (Figure 2.4). The vertical load of 5tons was transferred to a surface area of 20X50 mm$^2$ over rail head that constituted a pressure load of 50 MPa in the finite element model. A 3 metre long three dimensional (3D) finite element rail model has been developed with 4 fixed supports corresponding to the concrete sleepered track design, and an applied pressure load of 50MPa at the middle of the rail section. The strains in longitudinal (E33), vertical (E22) and lateral (E11) directions can be obtained from the model. In this finite element analysis (FEA), strains at the neutral axis of the rail (at 79.3mm above the bottom of the 60kg/m rail) have been obtained to compare with the strains in longitudinal direction (E33) obtained from the laboratory tests.
The longitudinal strains obtained from the FEA analysis show a maximum variation of 2.5\% from the strains measured in the load tests in the laboratory, which has been considered adequate to confirm the validity of test data given the expected variation between real world results and theory (Table 2.2).

<table>
<thead>
<tr>
<th>Strain gauge</th>
<th>Strain (mm/mm)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lab test</td>
<td>FEA</td>
</tr>
<tr>
<td>4.2</td>
<td>0.0000373</td>
<td>0.0000383</td>
</tr>
<tr>
<td>3</td>
<td>0.0001039</td>
<td>0.0001042</td>
</tr>
<tr>
<td>6.2</td>
<td>0.0000411</td>
<td>0.0000416</td>
</tr>
<tr>
<td>8</td>
<td>0.0001061</td>
<td>0.0001042</td>
</tr>
</tbody>
</table>

### 2.4 Field instrumentation

The two instrumented rail pieces were installed on straight track at the 82.806km point on the QR Blackwater heavy haul export coal system (Figures 2.5 – 2.6). All sensors were zeroed when the rails were free before welding into the existing operational track. Additionally, an RSM was installed on each rail of the 400m radius curved track at 82.500km approximately (Figure 2.5). The weather station and wayside monitoring system (which wirelessly collects RSM data) were installed nearby on a pole outside the rail corridor (Figure 2.7). The detail drawing of field instrumentation has been presented in Appendix A.
Figure 2.1: Field test setup

Figure 2.2: Field instrumentation (82.806- 82.811km)
2.5 Measuring SFT

SFT has been measured by using both strain gauges (section 2.5.1) and RSM (section 2.5.2).

2.5.1 Strain gauges

Six strain gauge rosettes (each rosette has three strain gauges) and four linear strain gauges were installed on both the left and right rails (Figure 2.8). Of these, fifteen gauges were connected to a National Instruments CompactRIO data acquisition system, while others were kept disconnected with a provision to connect in case of failure of any of the connected gauges. The strain gauges at the web of the rail were utilised to determine the SFT of the rail.

The CEA series strain gauge with self temperature compensation (S-T-C) number 06 has been selected for the instrumentation considering the similar thermal coefficient range of the gauge materials and the rail steel (AS 1085.1, 2002). The rail composition as described in AS 1085.1 (2002) has been found to be similar to that of SAE
AISI-1566 (ASM, 1993). The similarity in thermal expansion coefficients of the rail steel \((11.5 \times 10^{-6} \text{ m/m.}^{0}\text{K})\) and that of the bonded strain gauges \((10.3-13.5 \times 10^{-6} \text{ m/m.}^{0}\text{K for S-T-C Number 06})\) helps to minimise the thermal output over a wide temperature range. The procedure of correcting the thermal output is described in (Vishay Micro-Measurements, 2009).

The strain gauges were connected with the CompactRIO data acquisition system by a three wire quarter bridge circuit that provides intrinsic bridge balance, automatic compensation for the effects of lead wire temperature changes on bridge balance, and increased measurement sensitivity compared to the two wire configuration (Figure 2.9).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{three-wire-quarter-bridge-circuit.png}
\caption{Three-wire quarter bridge circuit}
\end{figure}

2.5.1.1 Calculation of SFT by longitudinal strain
The stress free temperature can be calculated by using strain and rail temperature data using the following Equation 2.1 (Grabe et al., 2007; Harrison et al., 1999):

\begin{equation}
T_N = T_r + \frac{\varepsilon}{\alpha}
\end{equation}

where \(T_N\) = stress free temperature \(^0\text{C}\), \(T_r\) = rail temperature at the time of welding or design neutral temperature or rail laying temperature \(^0\text{C}\), \(\varepsilon\) = the measured longitudinal strain in the rail, \(\alpha\) = coefficient of thermal expansion \(^0\text{C}\).

2.5.1.2 Calculation of SFT by longitudinal stress
Since SFT can change due to both longitudinal and vertical movement of rail, it is important to measure both longitudinal and vertical strain while measuring the SFT. The longitudinal stress considers strains in both longitudinal and vertical directions. The longitudinal stress due to strains can be calculated by using Equation 2.2 (Gere and Goddno, 2009). The longitudinal stress can then be used to determine the SFT using Equation 2.3 which is nothing but a reorientation of the basic equation for thermal stress (Equation 2.1)

\begin{equation}
\sigma_3 = \frac{E}{1-\nu}(\varepsilon_3 + \nu \varepsilon_2)
\end{equation}

\begin{equation}
\sigma_3 = E\alpha(T_N - T_r)
\end{equation}
where $\sigma_3$ = normal stress component in longitudinal direction, $\varepsilon_3, \varepsilon_2$ = normal strain components in longitudinal and vertical directions respectively, $E$ = Modulus of elasticity (207 GPa for rail steel), $\nu$ = Poisson’s ratio (= 0.3 for rail steel), $\alpha$ = coefficient of thermal expansion (11.7E-6/°C), $T_N$ = SFT (°C), $T_r$ = rail temperature at the time of welding or design neutral temperature or rail laying temperature or initial SFT (°C).

The three element $45^0$ rosettes have been used with a view to obtain an accurate stress state at the point. In order to transform strain of the three elements to the required perpendicular direction, it is necessary to measure principal strains and angle of principal axis (Equations 2.4 and 2.5) (vishay Micro-Measurements, 2008). Mohr’s circle concept has been used in formulating these equations (Figure 2.11). Here, normal strains are calculated along longitudinal and vertical direction from the principal strains obtained by strain gauge rosettes by using Equation 2.6. The graphical representation of the installed gauges is shown in Figures 2.12 and 2.13.

\[
\varepsilon_{P,Q} = \frac{\varepsilon_1 + \varepsilon_3}{2} \pm \frac{1}{\sqrt{2}} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2}
\]

\[
\theta = \frac{1}{2} \tan^{-1} \left( \frac{\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3}{\varepsilon_1 - \varepsilon_3} \right)
\]

\[
\varepsilon_\theta = \frac{\varepsilon_P + \varepsilon_Q}{2} + \frac{\varepsilon_P - \varepsilon_Q}{2} \cos 2\theta
\]

where $\varepsilon_{P,Q}$ = algebraically maximum and minimum principal strains, $\varepsilon_1, \varepsilon_2, \varepsilon_3$ = measured strains by three elements of a rosette, $\theta$ = acute angle from the principal axis to the reference grid of the rosette (Figure 2.10).

Figure 2.3: Strains in $x_1$ and $y_1$ directions (Gere and Goddno, 2009)

Figure 2.11: Mohr’s circle representation of a $45^0$ rectangular rosette
2.5.1.3 Calculation of SFT by graphical method

SFT can be measured by plotting longitudinal stress with respect to rail temperature (Figure 2.14). The rail temperature at which stress becomes zero would be the SFT of the rail. This method requires sufficient data on longitudinal stress to plot the line intersecting rail temperature. This method is suitable to determine the average daily SFT by predicting the line of longitudinal stress to zero temperature line in the graph. The variation of SFT with rail temperature has been discussed in Chapter 3.
2.5.1.4 Rail Stress Monitor

In the RSM, a full bridge strain gauge circuit installed on a single side of the rail web is used to measure the longitudinal stress (Harrison et al., 1999). The RSM also uses an integrated circuit temperature sensor to measure rail temperature. Based on the longitudinal stress and rail temperature, the SFT is calculated by using Equations 2.7 and 2.8.

\[
\varepsilon_L = \frac{\sigma_L}{E} + \alpha(T_r - T_N)
\]  

\[
T_{N_0} + \varepsilon_L \frac{\alpha}{E} = T_N = \varepsilon_L \frac{\alpha}{E} + T_r
\]

where \(\varepsilon_L\) = longitudinal strain, \(\sigma_L\) = longitudinal stress (MPa), \(T_r\) = rail temperature (°C), \(T_N\) = SFT (°C), \(T_{N_0}\) = initial SFT (°C), \(E\) = Modulus of elasticity (207 GPa for rail steel), \(\alpha\) = coefficient of thermal expansion (11.7E-6 /°C).

2.6 Measuring rail creep

In the field test, Total Station Survey equipment has been used to monitor the changes in longitudinal and vertical displacements of the rail at points on a tangent track section in the heavy haul Blackwater system of the QR National network at Edungalba. The creep in this section has been quantified in terms of rail strain and rail stress with respect to the rail temperature. Here, a method is proposed considering the longitudinal creep data, vertical displacement of the rail and rail temperature to accurately predict the stress state of a tangent rail track.

2.6.1 Basic theory of rail creep

The rail is laid at the desired rail stress free temperature which is considered as the initial unstressed rail section. When rail temperature increases or decreases from this initial rail laying or stress free temperature, rail expansion or contraction occurs that can be calculated by using Equation 2.9, which is used in many railway companies to calculate the change in SFT due to rail creep (ARTC, 2009).

\[
\Delta L = L \alpha (T_{N_0} - T_N)
\]
where $\Delta L =$ expansion or contraction in rail (mm), $L =$ length of rail section (mm), $\alpha =$ thermal expansion coefficient ($^\circ$C), $T_{in} =$ initial rail laying or stress free temperature (SFT) ($^\circ$C), $T_{nf} =$ stress free temperature at the time of creep measurement ($^\circ$C). For a difference of 1$^\circ$C in the stress free temperature within a 100m section of rail, the net creep required is 1.15mm. In other words, 1mm of creep into or out of a 100m section of rail can change the SFT by 0.87$^\circ$C.

2.6.2 Measurement method of rail creep and instrumentation

The theoretical measurement SFT from creep does not consider the effect of residual longitudinal stress present in the rail. Longitudinal stress developed in the rail is a combination of both longitudinal and vertical strains in the rail, and it can be developed due to train load and track resistance. Considering longitudinal stress and thermal expansion, Equation 2.10 can be used to determine the net strain developed in the rail (Harrison et al., 1999).

\[
\varepsilon_3 = \frac{\sigma_3}{E} + \alpha \Delta T
\]  

where $\varepsilon_3 =$ longitudinal strain due to longitudinal force only, $\alpha =$ thermal expansion coefficient ($^\circ$C), $\sigma_3 =$ longitudinal stress (MPa), $E =$ Modulus of elasticity of rail (207GPa).

Here, an empirical relationship between rail temperature, stress free temperature and longitudinal stress has been developed from the field observation of a 60kg/m instrumented rail section installed on the QR Blackwater system to predict longitudinal stress in rail (Equation 2.11).

\[
\sigma_3 = 2.3805(\Delta T)
\]  

where $\Delta T = (T_{nf} - T_R)$, $T_{nf} =$ Stress Free Temperature ($^\circ$C), $T_R =$ Rail temperature ($^\circ$C).

In the absence of data on stress free temperature, $T_{nf}$ can be taken as the design stress free temperature for that region. The strain caused by longitudinal tension force can be obtained by using Equation 2.12 (Kerr and Babinski, 1997):

\[
\varepsilon_{3e} = \frac{\Delta L_3}{L} + \frac{1}{2} \left( \frac{\Delta L_2}{L} \right)^2
\]  

where $\varepsilon_{3e} =$ equivalent axial strain, $\Delta L_3 =$ longitudinal movement of rail over length L (mm), $\Delta L_2 =$ vertical movement of rail over length L (mm).

Putting equivalent strain into Equation 2.10 and considering the accuracy of instrument ($\delta$), the general expression for the change of SFT can be obtained by using Equation 2.13.

\[
\Delta T_{cf} = \frac{1}{\alpha} \left\{ \frac{\Delta L_3 \pm \delta}{L} + \frac{1}{2} \left( \frac{\Delta L_2 \pm \delta}{L} \right)^2 - \frac{\sigma_3}{E} \right\}
\]  

where $\delta =$ accuracy of instrument which needs to be adjusted based on the distance of the measuring unit from the target point, $\Delta T_{cf} =$ corrected change in SFT. It can be seen from Equation 2.13 that change of SFT is lower when a long track section is considered. To get the desired result applicable for the whole section of rail, the rail should move proportionately over the whole track section considered for measurement of creep. In reality, uniform displacement over the whole 500m section is unlikely due to non-uniform track resistance and temperature distribution.

RSMs measure the force in the rail by using a strain gauge bridge circuit. Based on the measurements, it has been observed that rail stress (in terms of $\Delta T$) and rail temperature can be related linearly (Figure 2.15). The stress developed in the rail depends on the resistance provided by the track structure. Hence, the relationship between rail stress and rail temperature can be taken as a measure of longitudinal resistance of track. In the field test, two
different correlations were observed for left and right rail (Equations 2.14 and 2.15) due to the difference in existing SFT. According to the graphical method, the intersecting point of rail temperature with zero longitudinal stress on a stress versus temperature plot should be the SFT of that rail.

\[
\Delta T_F = -0.98T_R + 40.84 \quad 2.14
\]
\[
\Delta T_I = -0.93T_R + 37.23 \quad 2.15
\]

where \(\Delta T_I, \Delta T_F\) = change in SFT in left and right rails respectively.

The average of the two SFTs and temperature produce a relationship between stress and rail temperature for the overall track (Equation 2.16). The average SFT crosses the rail temperature line at 39°C which is close to the Design Stress Free Temperature (DSFT) of the instrumented site (38°C). It is obvious that the availability of stress versus temperature relationships in the absence of adequate SFT sensors over the network is not possible. So, based on Equation 2.16, a general rule for applying the stress versus rail temperature relationship has been proposed in Equation 2.17 using the method developed here to correlate rail creep data with the SFT.

\[
\Delta T_{av} = -0.96T_{Rav} + 39.03 \quad 2.16
\]

\[
\Delta T = -T_R + T_{N0} \quad 2.17
\]

where \(\Delta T_{av}\) = Average stress on the instrumented rail (°C), \(T_{Rav}\) = Average rail temperature on the instrumented rail (°C), \(\Delta T\) = Stress in terms of temperature difference between rail temperature and SFT (°C), \(T_{N0}\) = DSFT (°C).

Here, a methodology has been developed to determine the expected range of stress free temperature corresponding to rail temperature and rail creep (Figure 2.16). Rail temperature has been used to determine \(\Delta T\) by using the empirical relationship developed for the test section (Equation 2.16, Figure 2.15). Longitudinal stress corresponding to the \(\Delta T\) can be determined by using Equation 2.11. Finally, Equation 2.13 has been used to determine the change in SFT due to creep and stress present in the rail. To take into account the variation in rail temperature over the day, the maximum and minimum temperature of the day has been used to determine a probable range of SFT. It must be mentioned here that, in order to make this approach widely applicable, it is...
necessary to establish representative relationships between rail temperature and rail stress in all track structures with different longitudinal resistances.

Develop ΔT vs rail temperature relationship

If relationship for the given track structure is not available: ΔT = T_N0 - T_R, where, T_N0 = design stress free temperature, T_R = rail temperature

Measure rail temperature, and/or get the information about daily temperature range

Measure rail stress corresponding to rail temperature and ΔT

σ_S = 2.3805 * ΔT

Measure rail creep, ΔL

Measure expected change in SFT, and/or expected range of SFT

ΔT_c = \frac{1}{a} \left( \frac{ΔL_2 + δ}{l} + \frac{1}{2} \left( \frac{ΔL_2 + δ}{l} \right)^2 - \frac{σ_S}{E} \right)

Figure 2.16: Methodology to determine change in SFT from the measurement of rail creep

In the field test, Total Station Surveying equipment (Figure 2.17d) has been used to measure longitudinal, vertical and lateral movement of rail at two different sites (Figures 2.17a and b). Figure 2.17c shows a mark glued onto the rail at the instrumented rail site at Edungalba. In this method, two or more fixed points have been used to determine the relative position of the instrument. This minimises the effect of any movement of the fixed measuring points. The Total Station gives linear and angular distances in three directions from a fixed point. The laser of the total station has been aimed at permanent marks glued on the rails to determine the distance from the total station and the angle between them (Figure 2.17).

2.6.3 The Total Station Survey Equipment

The Total Station surveying equipment is capable of measuring distance in longitudinal, lateral and vertical direction with an accuracy of +/- 0.5mm over 80m compared to +/- 10mm within 10m of a typical laser level used for creep monitoring. Though setup of a total station is more time consuming than the traditional method, it has been selected to measure the movement of track in all three direction that can affect the SFT.
2.7 Measuring rail temperature

Rail temperature has been measured by using both thermocouples and RSMs. The T type (copper constantan) thermocouple with accuracy of $\pm 0.5^\circ C$ over $-250$ to $+300^\circ C$ has been selected for the experiment. The manufacturer of the RSM claimed the accuracy of the integrated temperature sensor used in their RSMs is $\pm 1^\circ C$ from $-20$ to $+60^\circ C$. The temperature of the curved track was measured by using the RSMs only, while temperature on the straight track was measured by both thermocouples and RSMs.

2.8 Data acquisition

The National Instruments CompactRIO computing hardware and DAQ card have been used to collect the data from the strain gauges and thermocouples. Initially 60 samples were collected at the 60th minute of every hour and stored in memory disks which were collected periodically from the track site.

The wayside monitoring system collects data from the RSMs at every ten minutes by radio technology (IEEE802.15.4) and sends via the wayside network to the Stress-Net database (Harrison et al., 2007). The data from the RSMs have been collected remotely from the Stress-Net web based database.

2.9 Site selection

In the process of selecting a site for field testing, emphasis was given to track with an increased buckle risk. A list of criteria likely to define buckle prone locations was developed.

2.9.1 Condition criteria for selection of Site

These are the condition criteria of selection at the site

- Newly laid track (reduces calibration difficulties);
- Sites with recent ballast renewal (exhibit less resistance and hence are more susceptible to buckling);
- Recently maintained track (provides the opportunity to obtain characteristic data of building up track stability over a period of time and also reduces the chance of damage of instrumentation likely to occur during surfacing operations on the track);
- Prior to restressing a site (to observe the accuracy of the process to retain a desired SFT);
- Buckle prone sites with available data or identical in type and construction to other such sites with available data;
- Interface between old track and renewed track, as in practice problems occur at these locations.

2.9.2 Geographic Location Criteria

- Orientation of topographical features such as cuttings, tunnels etc. (produces different temperatures due to sun and shade, lack of cooling wind);
- Track within 100 metres of a turnout is more prone to buckling (Ryan and Hunt, 2005);
Track Stability Management Part 2 – Field Testing and Data Analysis

- Track within 100 metres of fixed track structures (e.g. tunnels, level crossings) and points of increased track strength is more prone to buckling (as shown in QR statistical data (Queensland Railways, 1988));

2.9.3 Dynamic Action
- SFT changes due to longitudinal movement of rail at sites subjected to train braking and acceleration which occur in downhill and uphill sections.

2.9.4 Different sleepers and fastening systems
- Effects of concrete/ timber/ steel sleepers or interspersed sleepers on track stability;
- Combination of different aged fastenings and type;
- Mixing of different type of sleepers and age;
- The effect of unsupported sleepers in reducing lateral resistance;
- Every second sleeper anchored/ every fourth sleeper anchored (for timber sleepered track).

2.9.5 Geometry
- Curve/ transition/ tangent portion of track has potential for misalignment which can reduce track stability;
- Curve movement (e.g., winter curve pull in) changes RNT
- Sites with tight radius are subjected to high lateral forces;
- Sites with high gradient are prone to rail creep.

2.9.6 Data collection requirements
Mobile telephone network coverage at the proposed site is necessary to implement remote data collection. However, it was obviously not feasible to get a site with all of these characteristics. Considering costs involved with the instrumentation, one site with a steep gradient and including a curve of relatively tight radius was selected for the implementation of the field tests for this project. The features of the selected site are as follow:

- Km markings (82.255- 82.755 km)
- Gradient: 1 in 92
- Radius: 400m
- Rail profile: 60 kg/m, Head Hardened
- Sleeper type: Concrete
- Sleeper spacing: 685 mm
- Fastening type: Fist clip
- Ballast type: Granite
2.10 Summary

A detail methodological approach and experimental design has been proposed in this Chapter. The calculation methods of SFT, rail creep related stress has been presented which are used in Chapter 3.

.
3. Data Analysis, Results and Discussions

3.1 Introduction
The empirical relationships between air and rail temperature were developed to provide maximum safety, which may prove to be conservative in determining the setting of speed restrictions. The maximum rail temperature corresponding to an air temperature does not take account of the orientation of the track and exposure of the rails to sunlight which may overestimate the rail temperature on track oriented in a specific direction. On the other hand, the well-known tendency of SFT to decrease over time increases the risk of track buckling unexpectedly at a low rail temperature. However, measurement of the rail temperature and SFT throughout the network is not cost-effective. In this Chapter, the effect of rail temperature and curvature on SFT, and the variation in rail temperature due to different compass orientations of track have been quantified using a field test.

The main objectives of the field test are:

- Improve creep measuring procedures and quantify the effect of rail creep on SFT
- Quantify the variation in SFT with rail temperature and curvature
- Quantify the variation in SFT within a diurnal cycle and over a long period of time

3.2 Data collection and analysis technique
The strain and rail temperature data were stored at 60 samples at the 60th minute of every hour from 25 May to 13 August, 2010. The collected data from the National instruments CompactRio were in .tdms format which were converted into .xls format by using a matlab program. The calculation of SFTs by using both longitudinal strain and stress techniques (discussed in Chapter 2) have been used in the same program by taking averages of 60 samples at each hour. A separate matlab code has been used to import the data of RSMs from stress-net web and compare the data of strain gauges, thermocouples and RSMs. The downloaded data from stress-net web was in .csv format which needed to be converted to .xls (excel) format in order to facilitate the xlsread function of matlab.

3.3 Quantification of rail creep
A creep measurement method has been described in Chapter 2 (Figure 2.16). Three surveys were carried out at Edungalba on the QR heavy haul Blackwater export coal system to identify rail creep at different points glued to the rail (Figure 2.17). It was evident that both rails moved in the down direction (+) at site 1 (82.804 - 82.820km) and moved in the up direction (-) at site 2 (82.890 - 82.900km) (Table 3.1) which indicates a rail movement into the track section between sites 1 and 2 (Figure 2.17). The large amount of movement in the rails between survey 1 and survey 2 might be due to the rail movement caused by the installation of two insulated rail joints close to the test site. Survey 3 shows little rail movement at all points except points 6 and 7. Points 6 and 7 were within 16m of points 1 and 2. This observation leads to an analysis into limits required on the distance between two creep measuring monuments to measure SFT reliably within a section. A theory has been developed in Section 3.3 to determine the maximum allowable length based on longitudinal resistance and load on track.

Table 3.1: Movement of rail with respect to datum line established by two fixed points as shown in Figure 2-17

| Point ID (Approximate kilometrage) | Left rail movement since previous survey (mm) | Point ID (Approximate kilometrage) | Right rail movement since previous survey (mm) |
A rail movement, for example 2.5mm over a length of 14.98m between points 1 and 6 should theoretically (Equation 2.9) change the SFT by 14.3°C (Table 3.3). However, the data from the RSM shows a change in SFT of 1.88°C within the time period between survey 2 and survey 3 (Table 3.2). This observation also leads to the determination of the required length used to reliably measure rail creep. The track resistance might be strong enough to stop the rail movement from point 1 to 6 within the 14.98m and the movement at point 6 might be related to the resistance provided by the section of track on the other side of point 6 opposite to point. The data of GHD (2005) on rail creep over 300m shows the following relationship to determine the change of SFT due to rail creep that result in slight variation from the theoretical value.

\[ \Delta T_{GHD} = \frac{\Delta L}{L} + \frac{0.742 \cdot \Delta L}{25} \]  

\[ 3.1 \]

Results show that the changes in SFT as determined by the rail stress monitors (RSMs) are 4°C and 1°C higher than those obtained by longitudinal creep measurement on left and right rail respectively between survey 2 and survey 3 (Table 3.2). Change of SFT by RSMs was taken as the difference between average SFTs of RSMs within 10am - 3pm on the dates of surveys 2 and 3. This difference reveals that the current method of using rail creep data based on the longitudinal movement only is not adequate to determine the true stress state of the rails. The difference in internal stress might be the cause of the variation in SFT between two rails. It was observed that small vertical movements of rail (1 - 2mm) do not change the SFT significantly (Table 3.3).

Two measurements over a 89.9m track section (points 1 to 9) correlate better with the data from the RSM than for those points a short distance apart (points 1 to 6, and points 1 to 3) (Table 3.2). However, while creep measurement between points 1 and 9 shows a decrease in SFT by 1.83°C, RSM data shows a decrease of 1.88°C. Data from the RSMs reveal that SFT is 2-3°C higher at maximum rail temperature than that at minimum rail temperature within a day, and SFT is changed by rail temperature. So the use of rail creep data without taking account of rail temperature will not give an accurate indication of stress state. Hence, a range of SFT based on maximum and minimum rail temperature on that day has been established by using the methodology developed in Chapter 2 (Figure 2.16). In Table 3.3, Equation 2.13 has been used to determine the corrected change in difference between rail temperature and SFT (\( \Delta T_T \)) from which maximum and minimum SFTs (\( T_{N_{\text{max}}} = T_{R_{\text{max}}} - \Delta T_{c_{\text{max}}} \) and \( T_{N_{\text{min}}} = T_{R_{\text{min}}} - \Delta T_{c_{\text{min}}} \)) have been determined on the track sections.
Track Stability Management Part 2 – Field Testing and Data Analysis

<table>
<thead>
<tr>
<th>Rail</th>
<th>Points From-to</th>
<th>Distance (mm)</th>
<th>Creep (mm)</th>
<th>Change in SFT (°C) due to Creep Theoretical</th>
<th>Change of SFT by GHD (2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Rail</td>
<td>4-10</td>
<td>83040</td>
<td>-1.31</td>
<td>-1.35</td>
<td>-1.39</td>
</tr>
<tr>
<td></td>
<td>4-11</td>
<td>83788</td>
<td>-0.79</td>
<td>-0.81</td>
<td>-0.83</td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>82368</td>
<td>-1.7</td>
<td>-1.76</td>
<td>-1.81</td>
</tr>
<tr>
<td></td>
<td>5-11</td>
<td>83116</td>
<td>-1.18</td>
<td>-1.21</td>
<td>-1.25</td>
</tr>
<tr>
<td>Right Rail</td>
<td>1-8</td>
<td>89100</td>
<td>-2.18</td>
<td>-2.09</td>
<td>-2.16</td>
</tr>
<tr>
<td></td>
<td>1-9</td>
<td>89907</td>
<td>-1.93</td>
<td>-1.83</td>
<td>-1.89</td>
</tr>
<tr>
<td></td>
<td>3-8</td>
<td>83020</td>
<td>-1.39</td>
<td>-1.43</td>
<td>-1.47</td>
</tr>
<tr>
<td></td>
<td>3-9</td>
<td>83813</td>
<td>-1.14</td>
<td>-1.16</td>
<td>-1.20</td>
</tr>
</tbody>
</table>

Note: creep into a rail section is considered as negative (-), creep out of a section is considered positive (+)

Table 3.3: Change of ΔT due to longitudinal and vertical track movement and rail temperature

<table>
<thead>
<tr>
<th>Track section</th>
<th>Longitudinal movement</th>
<th>Vertical movement</th>
<th>Length of track section (mm)</th>
<th>ΔT for L and V</th>
<th>∆T for L</th>
<th>TRmax</th>
<th>TRmin</th>
<th>ΔTcmax</th>
<th>ΔTcmin</th>
<th>TNmax</th>
<th>TNmin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>0.79</td>
<td>1</td>
<td>6080</td>
<td>14.26</td>
<td>11.11</td>
<td>11.11</td>
<td>42.8</td>
<td>21</td>
<td>11.6</td>
<td>31</td>
<td>30</td>
</tr>
<tr>
<td>1-6</td>
<td>-2.5</td>
<td>2</td>
<td>14986</td>
<td>-14.26</td>
<td>-14.26</td>
<td>42.8</td>
<td>21</td>
<td>-13.7</td>
<td>-33</td>
<td>56</td>
<td>55</td>
</tr>
<tr>
<td>1-8</td>
<td>-2.18</td>
<td>1</td>
<td>89100</td>
<td>-2.09</td>
<td>-2.09</td>
<td>42.8</td>
<td>21</td>
<td>-1.4</td>
<td>-20.7</td>
<td>44</td>
<td>43</td>
</tr>
</tbody>
</table>

Note: L = longitudinal movement (mm), V= vertical movement

Based on the method developed in this report, a graph has been plotted in Figure 3.1 to demonstrate the change of SFT with respect to rail creep and rail temperature within a 100m track section at a DSFT of 38°C that shows that SFT increases with the increase of rail temperature and decrease of rail creep. The developed general relationship (Equation 2-17) have been found to show low increasing trend than those trend for instrumented site (Equations 2.14 to 2.16) with known stress trends (Figure 3.2).
Equations 2.11, 2.13 and 2.17 have been used to determine SFT corresponding to different values of rail temperature and rail creep over a 100m length of track, which have been presented in Table 3.4. As an example, at a rail temperature of 45°C rail creep of 5mm into a 100m track section with DSFT of 38°C should give SFT of 33.8°C. The quantified information of Table 3.4 has then been used to reflect the change in SFT corresponding to rail creep and rail temperature.

Table 3.4: Quantified SFT with respect to rail creep and rail temperature at a DSFT of 38°C

<table>
<thead>
<tr>
<th>Rail temperature</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>to a 100m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>37.9</td>
<td>37.9</td>
<td>38.0</td>
<td>38.1</td>
<td>38.2</td>
<td>38.3</td>
<td>38.4</td>
</tr>
<tr>
<td>5</td>
<td>33.6</td>
<td>33.7</td>
<td>33.8</td>
<td>33.9</td>
<td>34.0</td>
<td>34.1</td>
<td></td>
</tr>
</tbody>
</table>
3.4 Maximum allowable distance between creep monuments

Current practice to determine the length over which to measure rail creep does not consider the resistance of the track. If the thermal and vehicle loading is fully restricted by the track resistance there would be no rail creep. At low resistance the longitudinal load would be distributed over a longer section of track. If two measurement points are not within a minimum length on any track structure over which the longitudinal load is distributed, the net change in SFT on that section cannot be reliably determined. The longitudinal resistance is determined as per unit length while thermal and vehicle load does not depend on length. In order to minimise the load developed on a track section, the total track resistance \( (F_R) \) over a length needs to be equal and in the opposite direction of the longitudinal force developed by heat and vehicle action. Based on the empirical fraction of 25% of the axle loadings acting along the longitudinal direction by braking, and using the conventional thermal load relationship, the following condition can be developed to determine the required length of any track structure based on track resistance.

\[
0.25F_V + F - F_R L = 0
\]  

3.2

where \( F_V \) = vertical axle load (N), \( F \) = thermal load (N), and as per Equation 2-1 = \( AE\alpha (T_R - T_N) \), \( F_R \) = longitudinal resistance per metre of track (N/m), \( L \) = length of track (m).

The above Equation 3.1 can be used to determine the minimum length of any track section required when measuring rail creep between two points on any given track structure.

\[
L = \frac{0.25F_V + F}{F_R}
\]  

3.3

Equation 3.3 can be used to determine the maximum length required for different track resistances, thermal and axle loads. For a track resistance of 3kN/m, axle load of 26 tonnes and expected temperature deviation from the SFT of 1°C, the following graph (Figure 3.3) has been generated which shows the longitudinal force becomes equal to the track longitudinal resistance over a length of 83m. This length can be considered as the maximum allowable distance \( (L_{max}) \) between two creep measuring monuments. The significance of this \( L_{max} \) is that beyond this length the there would be no longitudinal movement due to thermal and vehicle load because the resistance provided by the track is higher than the longitudinal loads. Table 3.5 shows typical allowable maximum distance...
between creep measuring monuments based on track resistance of a track subject to maximum rail stress corresponding to $10^6$C and axle load of 26 tonnes.

The difference between the longitudinal force and resistance is responsible to produce the longitudinal movement. The force, $F_C$ in Figure 3.3 is responsible to create any longitudinal movement of track at any length of track. It is obvious that after $L_{\text{max}}$ the $F_C$ becomes negative, i.e., no longitudinal movement is possible at any length beyond $L_{\text{max}}$.

\[
\text{Axle load} = 26 \text{ tonnes}
\]
\[
\text{TN} - TR = 20^6C
\]

**Figure 3.3: Longitudinal force and resistance along length of a track section**

**Table 3.5: Maximum allowable distance ($L_{\text{max}}$) between two creep monuments based on track resistance**

<table>
<thead>
<tr>
<th>Sleeper type</th>
<th>Track condition</th>
<th>Resistance (kN/m)</th>
<th>$L_{\text{max}}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber</td>
<td>Medium</td>
<td>3</td>
<td>83.60</td>
</tr>
<tr>
<td>Concrete</td>
<td>Weak</td>
<td>6</td>
<td>41.80</td>
</tr>
<tr>
<td>Concrete</td>
<td>Medium</td>
<td>8</td>
<td>31.35</td>
</tr>
<tr>
<td>Concrete</td>
<td>Strong</td>
<td>12</td>
<td>20.90</td>
</tr>
</tbody>
</table>

Note: Axle load = 26 tonnes, $T_R - T_N = 10^6$C

**3.5 Confidence in data from RSMs**

In search of a suitable option to measure the SFT of a track over a long period of time, the RSM has been selected based on its wide application all over the world. However, this instrument has never been used in the QR Network of Australia. So, a careful observation was carried out on the installation and nature of the data obtained from the RSMs.
Of the four RSMs installed at the test site, two modules show large irregular variations in SFT (Figure 3.4). It was suspected that a rail break might have happened around 22 July of 2010, within 500m of the track section when measured rail temperature increased after a cool night compared to the previous few days (Figure 3.5). The installation of a rail joint as an emergency repair might make the rail run forward and backward, and that can change the SFT of the rail. However, after a walking inspection it appeared that there were no rail breaks. But a careful observation revealed that about 10% of the First clip fastenings were inactive near the disturbed module. Inactive fastenings can reduce the longitudinal restraint of the rail. Hence the rail might move forward and backward more than the normal magnitude expected in that track structure.

In the current analysis, data obtained from the suspect modules are taken up to the date that they were in good agreement with the desired stable change in SFT (Figure 3.6). Two additional modules have recently been installed by the track owner near the suspect modules to observe the variation in SFT. However, the validation of the RSM product has been considered as outside the scope of this thesis. Analysis has been made restricted to data that showed regular trends only (Table 3.6). It has been observed that one RSM on each straight and tangent track showed a desired range of SFT. However, the other two RSMs did not match well with the theoretically acceptable range of SFT over a long period of time.
Figure 3.6: SFT and Temperature distribution on straight track (km 82.810)

Table 3.6: Period of regular data obtained by different RSMs

<table>
<thead>
<tr>
<th>RSM no. - Left/ Right rail</th>
<th>Track condition</th>
<th>Data Start</th>
<th>Data End</th>
</tr>
</thead>
<tbody>
<tr>
<td>794-L, 795-R</td>
<td>Straight</td>
<td>24 May, 2010</td>
<td>1 September, 2010</td>
</tr>
<tr>
<td>795-R</td>
<td>Straight</td>
<td>24 May, 2010</td>
<td>1 March, 2011</td>
</tr>
<tr>
<td>796-L</td>
<td>Curved</td>
<td>24 May, 2010</td>
<td>1 March, 2011</td>
</tr>
</tbody>
</table>

3.6 Comparison of data obtained by RSMs, Strain gauges and thermocouples

The longitudinal strain and longitudinal stress based relationship (Equations 2.1 to 2.6) have been utilised to determine SFTs using installed strain gauges and thermocouples with a view to compare with the SFTs obtained by RSMs. It was observed that RSMs showed higher SFTs (Figure 3.7) than those obtained by longitudinal strain method (Equation 2.1) but lower/similar SFTs than those obtained by longitudinal stress method (Equations 2.2 to 2.6). The comparison however was restricted to observation of left rail only because of the variability in the data of strain gauges installed on the right rail. The number of occurrence is higher in case of RSMs due to the higher sampling rate of RSMs (one in every 10 minutes) than the sampling rate of strain gauges and thermocouples (one in an hour).
3.7 Quantification of variations in SFT

SFT is measured and maintained to a desired level based on the climatic conditions of any region. Measurement of SFT can be long term or following an event. The long term observation of SFT over the entire network has not been implemented yet by Australian railway companies due to the high installation cost and uncertainty in data quality. Portable measurement systems are cost effective in terms of measurements per kilometre. However, scheduling of measurement on a regular basis may not be possible on a busy track. The accuracy of different systems varies by 2-3°C which may not always be appropriate to decide on whether or not emergency maintenance or speed restrictions are necessary. Some of the portable measurement systems require unclipping of rail during measurement so that the rail can be lifted to induce tension. Hence, it is necessary to determine the appropriate time needed to measure SFT and decide on maintenance requirements and speed restrictions based on the information on track strength and maintenance history.

An assessment of track stability can help to decide on any necessary maintenance. In a track stability management tool, all the information can be collated to determine the required action. In order to make the management tool suitable for use, it is necessary to quantify the expected change in SFT under different track and maintenance conditions. In this section, variation of SFT in the instrumented site over a day and in the long term has been presented and a relationship has been developed between rail temperature, rail creep and SFT.

3.7.1 Variation of SFT with rail temperature

It is known that temperature induces stress in rail whenever it varies from the actual SFT. In the RSM device, internal rail stress has been measured using strain gauges, and rail temperature is used as a measure of thermal stress in the rail (Equations 2.7 and 2.8). It has been observed that SFT tends to increase with rail temperature on a day with high rail temperature (Figure 3.8). This can be useful to determine an improved speed restriction policy when the apparently expected high stress at maximum rail temperature can actually be lowered by 2-3°C based on this observation.
SFT has been calculated based on rail stress and longitudinal strain (described in Chapter 2, Equations 2.1 to 2.6) by using strain gauges and thermocouples. Strain gauges and thermocouples based calculations (Figures 3.9a and 3.9b) showed a decreasing trend of SFT at the high rail temperature, but RSM showed an increasing trend of SFT at the high rail temperature (Figure 3.9c). The circuit design in RSM measures rail force and then convert it to stress and SFT by using Equations 2.7 and 2.8 that continually refer to the previous SFT and hence a cumulative reading is achieved. On the other hand strain gauges and thermocouples were zeroed to initial zero stress condition and do not consider the change in zero stress condition.

3.7.2 Variation in SFT with curvature
SFT on the curved track showed a decreasing trend over the period of the data acquisition, but SFT on the straight track did not show any change trend (Figure 3.10). SFT of the straight track was found to be 3-5°C higher than that of the curved track within the time interval observed (Figure 3.11). The inside rails on the curve experienced a higher rate of change of SFT than the outside rail (Figure 3.12). It is noted that the variation between inside and outside rails on the curve is significant only during the heat of the day, and can be due to the difference in rail temperature between left and right rails at the peak of the day (Figure 3.12).
Figure 3.10: Variation in SFTs on left rail between straight and curved track

Figure 3.11: Difference in SFTs (°C) between straight and curved track

Figure 3.12: Variation in SFT on inside (module 799-R) and outside (module 796-L) rail of curve
3.7.3 Variation in SFT between two rails

In stable conditions, RSMs showed a difference in SFTs between the two rails of about 5°C (Figures 3.13 – 3.14) on straight track and of about 12°C on curved track (Figure 3.15). During this observation, rail temperature between the two rails varied by about 2°C and 4°C on rare occasions (Figure 3.16) which does not justify the reason for the large variation in SFT on curved track. The right rail showed higher SFT than the left rail on both straight and curved portions of the track (Figures 3.14 and 3.15).

Figure 3.13: Variation in SFT between left and right rail on straight track (1 June- 1 September, 2010)

Figure 3.14: Frequency of difference in SFT between left and right rail on straight track (1 June-1 September, 2010)
3.7.4 Diurnal cycle of SFT
SFT has been found to change within an entire daily cycle (Figures 3.17 and 3.18). Considering the negligible rail movement in any direction within a day on a stable track, the reason behind the variation in SFT is the internal stress developed in the rail due to change in rail temperature related stress. Though SFT doesn’t really show any trend at low rail temperature, it was observed that, at high rail temperature, SFT can be increased by 2-3°C. The increase in SFT means reduced risk of track buckling. Based on this result speed restrictions due to hot weather can safely be set at a higher rail temperature threshold.
3.7.5 Long term observation of SFT
Whenever direct measurement of SFT is not possible, it is important to know the general SFT trend of a specific track structure. Based on the observation on the instrumented site (whose DSFT was 38°C) frequency charts of SFT have been plotted for the straight and curved sections of track (Figures 3.19 and 3.20). The SFT of the track is usually considered as the average of SFTs of the two rails. However, in this case the SFT sensors on both rails were found to be providing reasonable data only up to the date shown in Table 3.6. Average SFTs of both straight and curved track have been considered up to that period only. The most frequent average SFT for straight track was 40°C, while for curved track it was 37°C.

The observation of SFT over a long period has been considered for the sensors which showed reasonable data for the time period given in Table 3.6. Data show that the straight track right rail possessed a higher SFT of 41°C for
most of the case while the curved track left rail possessed a lower SFT of 33°C for most of the case. Based on this observation an overall range of SFT has been specified as 32-43°C for the instrumented track structure.

![Figure 3.19: Frequency distribution of SFT on Straight Track](image)

![Figure 3.20: Frequency distribution of SFT on Curved Track](image)

3.7.6 Change of misalignment

Lateral rail movement on the curved track has been measured by tape from the fixed overhead traction power supply poles. No significant lateral movement was observed on the curved and straight tracks. Hence the change in SFTs over all sites is presumably due to longitudinal stress variations only.

3.8 Variation in rail temperature

The relationship between air and rail temperature depends on a number of climatic variables which are site specific. The empirical relationships are site dependent and were developed to ensure maximum safety, which may prove to be conservative in certain geographical conditions. In this section, variation of rail temperature with air temperature in the entire diurnal cycle has been presented. Though orientation of rail on the instrumented
sites was not perpendicular to each other, a variation in rail temperature was observed in the instrumented site within the 300 metre length of track.

### 3.8.1 Hours of daylight

Hours of daylight at any particular date and location can be calculated (Iqbal, 1983) by using the track latitude in the following Equation 3.4:

\[
N_d = \frac{2}{15} \cos^{-1}(-\tan \phi \tan \delta)
\]  

(3.4)

where \(N_d\) = day length (hour), \(\phi\) = geographic latitude in degrees, North positive, \(\delta\) = declination, the angular position in degrees of the sun at solar noon with respect to the plane of the equator, North positive (can be measured for each day using values given in Iqbal (1983)).

Equation 3.4 has been applied for Rockhampton (latitude -23.378) and it shows an accuracy within 10-15 minutes when compared to observed data provided by the website timeanddat.com (2010) (Table 3.7). Thus using this equation can predict the day length hours across the whole network. A plot of maximum rail temperature versus length of day hour has been presented in Figure 3.21 that does not establish a direct relationship between these two parameters. However, consideration of latitude, orientation of rail, relative humidity, cloud cover and wind speed in a combined model can help better approximate the maximum rail temperature based on the length of day hour.

**Table 3.7: Verification of day hour calculation using the data of Rockhampton (latitude -23.378)**

<table>
<thead>
<tr>
<th>Date</th>
<th>Inclination</th>
<th>Calculated Day hour</th>
<th>Observed day hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Mar, 2010</td>
<td>1.63</td>
<td>11.91</td>
<td>12.02</td>
</tr>
<tr>
<td>2 June, 2010</td>
<td>22.15</td>
<td>10.65</td>
<td>10.77</td>
</tr>
<tr>
<td>1 Sept, 2010</td>
<td>8.51</td>
<td>11.51</td>
<td>11.63</td>
</tr>
<tr>
<td>20 Dec, 2010</td>
<td>-23.44</td>
<td>13.44</td>
<td>13.57</td>
</tr>
</tbody>
</table>

**Figure 3.21: Maximum rail temperature versus length of day hour (25 May-12 August, 2010)**

### 3.8.2 Maximum rail temperature

Results from the weather station and the thermocouples on the rails (Figure 3.22) showed that rail temperature increased by about 20°C over air temperature when air temperature started to increase over 20°C. At low air...
temperature, the rail temperature is nearly the same as that of air. A typical daily curve (Figure 3.23) shows rail temperature increased rapidly by about 17°C from 9am to 12pm when air temperature increased by 5°C. The peak rail temperature was observed between 12pm and 3pm. Rail temperatures tended to decrease after 3pm even though there was an increase in air temperatures (Figures 3.24 – 3.26). This observation reveals that rail temperature cannot be approximated based on air temperature only.

Figure 3.22: Rail temperature and air temperature variation with date

![Figure 3.22: Rail temperature and air temperature variation with date](image)

Figure 3.23: Typical daily variation in rail temperature with air temperature (1 June, 2010)

![Figure 3.23: Typical daily variation in rail temperature with air temperature (1 June, 2010)](image)
Figure 3.24: Typical daily variation in rail temperature with air temperature (8 June, 2010)

Figure 3.25: Typical daily variation in rail temperature with air temperature (5 July, 2010)

Figure 3.26: Typical daily variation in rail temperature with air temperature (5 August, 2010)
3.8.3 Orientation of rail
The rail oriented in E-W and N-W/S-E directions experience direct solar irradiation at the time of highest air temperature which increases the maximum rail temperature compared to that of other rail orientations (Chapman et al., 2005). A typical daily curve shows a variation in rail temperature of about 4-5°C at the peak rail temperature due to change in orientation of the rail (Figures 3.27 – 3.28). At the instrumented site, the curved track oriented in the N-S direction exhibited higher rail temperatures than that of the straight track oriented in an approximate E-W direction. The rail temperature reached its peak in the late afternoon for track in N-S direction, while this occurred in the late afternoon for track with the approximately E-W direction. This observation can be useful to justify the reduction of the duration of speed restriction on any particular geographic area where a significant portion of rail is oriented to a particular direction.

![Figure 3.27: Variation in rail temperature due to different orientation of rail on curved and straight sections](image)

![Figure 3.28: Variation in daily rail temperature due to change in orientation of rail](image)
3.9 Results and Discussions

Though rail creep is considered as a widely used tool to check the variation in SFT, the current string line and laser techniques have been identified as inaccurate and a crude estimate of variation in SFT only. The current practice of determining the distance between two creep measuring monuments does not consider the non-uniformity of track strength that can lead different SFTs within the track section considered. In this report a theoretical maximum allowable distance between two creep monitoring monuments has been established which shows that the allowable distance decreases with the increase in longitudinal resistance of track. However, the small length suggests that there is a need for a laser equipment to measure the longitudinal movement within a fraction of a millimetre which is not practical in field condition because the small movement of rail may not be permanent to set a SFT. Therefore, a minimum length of 100m track section has been considered in this analysis assuming uniform resistance within 100m.

Field instrumentation has been carried out at Edungalba on the QR Blackwater heavy haul export coal system to quantify the change of SFT due to rail temperature, rail creep and misalignment. It has been identified that rail temperature needs to be incorporated with rail creep data to provide a range of expected SFT on any given day. However, in case of inability to get the data on any specific track structure to develop Equations similar to 2.14 to 2.16, an approximate relationship has been used assuming SFT to be the DSFT of that track section (Equation 2.17). The general relationship based on theoretical DSFT showed a less response to rail temperature compared to those (Equations 2.14 to 2.16) obtained from field test when estimating the SFT. The relationship between rail temperature and stress can be changed with track resistance, which can affect the relationship between SFT and rail creep on different track conditions. The theoretical estimate does not account for track resistance that might have an influence on the change of internal stress due to rail temperature.

In search of a suitable measurement option for SFT, four RSMs have been installed to observe the long term variation in SFT. Considering the inconsistency of some of the data from two of the RSMs, the reliable data within a time period was considered for analysis. In that time period, SFT on curved track showed a decreasing trend, but SFT on straight track was reasonably stable. SFT was found to be 2-3°C higher at the maximum rail temperature than that at the minimum rail temperature over the course of a day. This information can be used to increase the temperature threshold for speed restrictions. The reason behind the high SFT has been identified as the change in internal stress due to change in rail temperature and included in the improved presentation of measuring SFT from rail creep data. The inclusion of rail temperature related internal stress component in the calculation of rail creep data to determine the SFT has led to determination of a range of the expected SFT rather than a single SFT value.

Comparison of SFTs obtained by RSMs and strain gauges showed that SFT obtained by longitudinal stress method better correlate with the SFT of RSMs. Considering the inclusion of vertical strain in the longitudinal stress method of determining SFT it can be concluded that the effect of vertical strain on the change of SFT is not insignificant. In order to get accurate reading it is necessary to install strain gauges at the neutral axis of the rail which is 79.23mm from the bottom of a 60kg/m rail. The manual installation of strain gauges on this fraction of a millimetre is not practically achievable. The comparison was restricted to left rail only because of the variability of strain data of right rail which might be due to the unexpected off centre of strain gauges from the neutral axis on the right rail.

The empirical relationships used to measure rail temperature from air temperature are site dependent and only maximum rail temperature has been used to develop the relationships. Latitude, compass orientation of rail, relative humidity, cloud cover, wind speed, precipitation and length of the day affect the complex relationship.
between air and rail temperature (Chapman et al., 2008). Of these parameters latitude, orientation of rail and length of day are site specific while weather parameters vary over the day and year.

Latitude is not a dominant parameter affecting maximum temperature on the longest day of the year; however, on the shortest day there is a decrease in predicted rail temperature towards higher latitudes (Chapman et al., 2008). A model has been developed by RSSB of UK to deal with all these parameters (Chapman et al., 2005). The availability of accurate information on rail temperature based on weather and site parameters can help to reduce the duration of blanket speed restrictions and to reduce the geographical extent of the imposition of hot weather speed restrictions. A similar model is going to be developed for Australian conditions in another part of this project; however, still being under development, it cannot be used in this thesis and is expected to be incorporated into the best practice tool when it becomes available.

An observation was carried out on the change of rail temperature due to rail orientation. Rail oriented in the N-S direction showed a higher maximum temperature during the late afternoon. Depending on the orientation of rail and exposure to sun the maximum temperature can be lower than the establish relationships which can reduce the need for speed restrictions considering low stress at a low rail temperature.

### 3.10 Summary

Field test showed that SFT can be 2-3°C at the maximum rail temperature on a day than the SFT at minimum temperature. Based on this observation and the theory developed in Chapter 2, an improvement in rail creep data by utilising internal stress resulted from rail temperature has been suggested. The new method suggests determining a range of expected SFT on a day rather than a single value of SFT that cover the variation of SFT over a day.

Determining rail temperature based on empirical relationship of air and rail temperature can be inappropriate if characteristics of local surroundings of track and weather parameters are not considered. Considering unavailability of any model to accurately predict rail temperature this study suggests increasing rail temperature for rails oriented in N-S directions by 2°C.
Conclusions and Future Research Options

4.1 Introduction
This study records the maintenance practices, inspection procedures and operating conditions from the standards of different railway companies and rail transport regulators of the world affecting the two most important parameters when considering the stability of continuous welded rail: rail stress and lateral resistance of track. The imposition of regional/blanket train speed restrictions during hot weather in Australia is currently based on air temperature only which is not an appropriate process given the other factors affecting rail stress resulting from changes in SFT and rail temperature. The localised nature of SFT variability and the current overestimation of high rail temperature effects on rail stress result in the current Australian buckle risk management process providing a conservative prediction of the likelihood of the occurrence of a track buckle across a large region. This study, and the quantified information on the SFT, rail temperature and track strength obtained from a field test, have been used in developing the best practice decision making tool to manage the stability of track proposed in this thesis.

4.2 Conclusions
The literature review and gap analysis (Part 1) performed here can be used as the basis to decide on the setting up of new rules and practices in the Australian railway companies. The segmented railway companies of Australia can implement unified track stability management practices based on this study. Recently, RISSB of Australia has developed a draft Australian Standard on track lateral stability. It was expected that the outcome of this literature review may be included in the draft standard. However, due to time constraints it was not included in that standard and is expected to be considered in the later version of the Australian Standard.

4.3 General conclusions
- In a gap analysis approach, the practices that can change the most important parameters of track stability, i.e., rail stress and resistance of track have been collated with a view to finding the gaps among different studies and practices.
- Quantified information on rail stress and lateral resistance can help better manage the stability of continuously welded rail.
- A theoretical maximum allowable distance between two creep monitoring monuments has been established which shows that the allowable distance decreases with the increase in longitudinal resistance of track. Considering the variability of measured rail creep data within the ideally short distance according to track resistance, a distance between two creep monitoring monuments of 100m has been selected which reflects better correlations with the SFT measured in the field test.
- Without knowing the quantified trend of SFT due to different maintenance operations on a specific track structure, it is not always appropriate to consider the imposition of speed restrictions based on air temperature only.
- Depending on the orientation of rail and exposure to sun, the maximum rail temperature can be lower than the established relationships indicate which can reduce the need for speed restrictions.
- There is a need for a model to determine rail temperature from weather parameters rather than depend on air temperature only.
- Considering the reliability of SFT sensors and the complexity in determining the required number of sensors within a kilometre, the statistical approach of determining the probability of buckling based on statistical
SFT data and rail temperature is not a practically feasible solution to decide on the need for hot weather speed restrictions.

- The combination of information on weather parameters, history of track maintenance and the statistical distribution of SFT in a single tool can help better manage the stability of track.

4.4 Specific conclusions

The most important observation of the field instrumentation carried out in this report was that SFT tends to become 2-3°C higher at the maximum rail temperature than the SFT at the minimum rail temperature of the day. The reason behind the higher SFT has been identified as the change in internal stress due to change in rail temperature and has been included in the improved methodology for measuring SFT from rail creep data. This observation can be used to increase the rail temperature threshold to apply hot weather train speed restrictions.

The inclusion of rail temperature related internal stress components in the calculation of rail creep data to determine the SFT has led to the determination of a range of the expected SFT rather than a single SFT value within a day.

An observation in to a track section of the QR Blackwater export coal system revealed that speed restriction is not necessary until air temperature reaches 42°C on that track section which is 4°C higher than the current QR standard.

Each parameter has been given three levels of value to determine the required preventive measures. The identification of any particular parameter responsible for a low margin of safety would help better manage the stability of track by managing that parameter specifically.

The inclusion of a priority rating for rail restressing has made the developed tool in this report suitable for making decisions on both maintenance requirements and the appropriate operation of trains when maintaining the stability of track.

4.5 Future research options

- It is necessary to carry out an investigation into available technology to measure track lateral resistance and, if required, develop a better method to measure track lateral resistance and carry out field experiments with any existing/developed tool. Field experiments need to be carried out over different track structure combinations with a view to develop empirical track lateral resistance relationships in Australian conditions. These can then be used in the track stability management tool instead of data of US track conditions.

- SFT needs to be quantified for a range of maintenance activities that affect SFT. Of them rail break and defect removal in winter can lead to the addition of steel in rail which can increase the risk to track buckling during summer. Hence, measurement of SFT during rail cut and after defect removal is recommended to restore the SFT to its desired condition and determine any requirement for future rail restressing.

- Train-track dynamic interaction has an effect on track stability at the points near braking zones, near fixed structures such as bridges, level crossings etc., and on track gradients. The dynamic effect has not been quantified in terms of increased buckling risk. A better understanding of the effect of dynamic action, in particular, braking and acceleration on track gradients can improve the track stability management tool to a great extent. Hence, a study into train dynamic effects on stability of track is also recommended.

- A better track management tool is necessary that can incorporate future rail temperature and rail stress to quantify the track conditions for proper speed restriction.
References


GHD (2005) Artc wolo speed restrictions raising of threshold temperature. Australian Rail Track Corporation Ltd.


Appendix A: Instrumentation drawings

Figure A-01: Instrumented track section

STRAIN GAUGE INSTRUMENTATION

LEFT RAIL STRAIN GAUGE SETUP

RIGHT RAIL STRAIN GAUGE SETUP
Figure A-02: Strain gauge

Figure A-03: Strain gauge wiring detail
Figure A-04: Thermocouples

Figure A-05: Wiring of thermocouples