ABSTRACT

A key aspect of managing the stress state of the railroad involves controlling longitudinal rail stresses to safe levels. Rail networks are therefore focused on reducing the risk of both buckled track and broken rail for safety and security enhancement. The efficient management of longitudinal stress induced thermal forces in continuous welded rail (CWR) is an important aspect of railroad safety and maintenance. Balancing such forces is a complex issue which requires intimate knowledge of many parameters which include track strength as well as environmental operating conditions.

CWR track is prone to lateral buckling when the rails are under high compressive forces. Conversely, when high tensile forces dominate under cold temperature conditions, rail defect growth can cause rail fractures, weld failures and rail joints to pull apart. The magnitude of longitudinal thermal forces is governed by the rail neutral temperature (RNT) which is the rail temperature at which the net force is zero. It is well known that RNT is a highly variable parameter and that its measurement has proven to be both difficult and costly.

This paper presents evolving and proven measurement technologies as well as new safety tools for longitudinal force management. The safety aspects include track buckling prevention through hazard identification diagnostics in terms of a “yellow”, “orange” and “red” buckling margin of safety (BMS) warning, and rail break detection through sudden stress discontinuity (interruption) measurements. The maintenance aspects include providing and applying data for rail defect/break repairs when readjusting RNT to safe values in various operation conditions, and providing data for curve realignment and stability improvement through more efficient RNT management. The applications are illustrated through case study examples.

1.0 Introduction

Prevention of excessive longitudinal thermal forces in continuous welded rail (CWR) is an important track maintenance and safety issue. Thermal forces are generated when the rail temperature varies from the rail's neutral temperature (RNT) i.e. the rail temperature at which the longitudinal force is zero, which is typically the rail’s installation or fastening temperature. (Note: common terminology also uses SFT and T \text{N} to designate RNT). Compressive forces are produced when the rail temperature is higher than the RNT, and tensile forces are produced when the rail temperatures are below the RNT. High compressive forces can cause track buckling, while high tensile forces can accelerate rail defect growth and cause rail joints to fail or pull apart in cold weather, with both being potential derailment causes.

Longitudinal forces are controlled by installing and maintaining the rail at RNT levels within specified limits. However, it is a well known fact that the RNT will vary over time and that it typically shifts to a lower value that can increase the risk of track buckling. These lowered RNT values can result from rail repair or
other maintenance work undertaken during cold weather and from excessive rail movement. A key impediment to knowing these low and potentially dangerous RNTs is a lack of adequate measurement capability which has eluded researchers for the past three decades. There have been several measurement concepts/techniques proposed and evaluated over the years with mixed results. These included techniques based on various physics concepts as illustrated in Figure 1.

**Figure 1 – Summary of RNT Measurement Concepts**

The key compromising aspects being (1) measurement accuracy, (2) ease of deployment, (3) providing continuous data on a real time basis, and (4) having direct applicability to railroad maintenance and safety. Although several concepts partially fulfill these needs, the US Salient System’s Rail Stress Monitor (RSM) and its supportive StressNet™ data base system have evolved to be the most responsive to the above needs. The RSM and its StressNet™ technology have been developed and tested over twenty-five years of R&D, and have been recently expanded to support specific industry needs to not only measure RNT but interpret it for practical application to enhance overall CWR safety and performance. More specifically the RSM and StressNet™ technology:

- Measures longitudinal force and RNT
- Detects rail breaks and track buckles
- Alerts on potential buckling hazards
- Enables more effective rail break/defect repairs
- Monitors rail joint condition

In this paper several of these applications will be discussed with a particular emphasis on track buckling prevention through potential hazard identification diagnostics in terms of a “green”, “yellow”, “orange” or “red” buckling hazard warning.

**2.0 The RSM-StressNet™ System (The RSM Technology)**

The rail-mounted hardware represents continuing evolving technology developments starting with a stress measurement circuit first developed at Battelle Columbus Laboratories in the early eighties [1, 2,
3), and culminating in today's expedient and railroad friendly iPod/iPhone based data acquisition system. The system is based on current radio technology and novel antenna designs that allow for a seamless collection process in a hardened design capable of surviving normal freight railroad operations and maintenance with a power management system that allows 10+ year useful life, and the ability to collect the data with a variety of intermediate devices, including:

- Hand held iPod/iPhone reader carried by a track inspector
- End of Train (EOT) device
- High rail inspection vehicle
- Wayside reader

Figure 2 below shows the various uses and deployment options of the RSM-StressNet™ system.

### RSM Deployment Options: When and Where?

- When installing new rail
- When making rail break/defect repairs
- When destressing “hot” rail
- In curves to manage lateral stability
- At locations where fastener conditions are substandard
- At locations of high stress build-up (approaches to bridges, special track work, tunnels, etc.)
- In high tonnage lines to manage speed restrictions
- In high-speed passenger lines for RNT safety monitoring
- At joints for performance evaluation

### 3.0 RNT Monitoring and Rail Break Detection

Figure 3 is an example of a StressNet™ output of 5 years of RSM data at one location of Union Pacific test segment of newly laid CWR on a 2 degree (875 m radius) concrete tie track curve experiencing 230 MGTs of annual tonnage where both rails were instrumented with RSMs. The data show the RNT variation with time for the two rails (red for the low rail and green for the high rail) exhibiting the key features of: the overall RNT behavior trends, the daily variations (the shaded data and tooth-like spikes), the detection and influences of three rail breaks on the high rail (as shown by the sudden drop in RNT as denoted by RB1, RB2 and RB3), and the influence of track maintenance involving surfacing and lining. To get a more detailed look at a rail break scenario, Figure 4 shows an expanded view of RB1 and RB2 data taken by the RSM closest to the breaks. Further inspection of Figure 4 shows that the low rail (red data) is relatively stable in terms of RNT variation (ignoring the daily changes - tooth-like spikes). The high rail (green) data, however, show the dramatic influences of rail breaks as indicated by the sudden discontinuity in RNT. The influence of interim joint repairs is also evident in terms of large daily RNT shifts due to joint-gap movement with temperature as shown by A and B. Finally, the green dashed arrow shows the effects of joint welding and RNT restressing to the target RNT, and its effectiveness. Thus RNT knowledge and RNT monitoring during rail repair and readjustment is highly essential in CWR repair and maintenance, hence to more effectively managing the repair of broken and defective rail. Some inherent difficulties with these repair procedures are briefly outlined below in context of rail break mechanics.
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Figure 3 – Five Years of RSM Data on the Union Pacific

![Graph showing RSM data over five years on Union Pacific tracks.]

Figure 4 – RNT Behavior in Rail Breaks

4.0 Rail Break Mechanics, Repair and Restressing

A major reason for the reduced and possibly unsafe neutral temperatures is the difficulty in resetting the RNT to the desired target value after a rail break or after a rail defect removal. The fundamentals of rail break mechanics are discussed in [4, 5], while Figure 5 illustrates the basics. It is a well known that when the rail is broken or cut for defect removal the RNT drops to the temperature of the rail when the break/cut occurs. For example, in Figure 5 when the rail breaks at 40°F (4°C) its RNT is 40°F (4°C) at that location. Additionally in this case, the rail break/cut influence is experienced for a track length exceeding 635 ft (194m) on either side of the break/cut as indicated by L_d. As shown in [4, 5], these L_d’s can be on the
The basic difficulty with this procedure is that the “correct” amount of rail to cut out and unfasten would also be not known. The Salient RSM-StressNet™ System can be applied to provide this knowledge, thus promoting a more effective management of rail break/defect removal repairs in terms of RNT readjustment. Specifically, the RSM-StressNet™ System:

- Determines and monitors the RNT after plug/joint interim repair
- Alerts on when to return for the final repair/RNT readjustment to avoid a buckling prone condition (see Buckling Hazard description in next Section)
- Provides information on how to readjust to the desired RNT
- Provides information on effectiveness of the RNT readjustment

One such application is shown in Figure 6 where the RSM data shows the specifics of rail break (RB3 shown in Figure 3) repair on the Union Pacific test site. The RSM measured RNT data clearly shows the interim joint’s RNT of 60°F (16°C) to be readjusted. Without RSM/RNT measurement this would not be known, hence the amount of rail to cut out and unfasten would also be not known. RSM data also shows the effectiveness of the readjustment procedure and tracks the subsequent RNT condition.
5.0 Track Buckling Hazard Detection

With the annual buckle derailments in the US ranging from 20 - 40 at a cost of over $10M per year, the prevention of track buckle caused derailments remains a key industry goal. Railroad efforts are continuing to focus on improving buckling prevention practices and on to better identifying buckling prone conditions. To assist in these efforts Salient Systems has recently developed a “Buckling Hazard Index” which provides a warning on potential buckles in terms of a yellow, orange, or red alert. The yellow-orange-red alerts are based on the track having a prescribed buckling margin of safety (BMS). The BMS is determined by the StressNet™ system and is based on the RSM measured rail and neutral temperature data coupled with the track’s buckling strength evaluations. The latter is based on the Volpe/FRA “CWR-SAFE” model [6], a part of which has been incorporated into the StressNet™ system, referred to as BUCKLE. The BMS is a numerical temperature index on how close the track is to a “critical” condition in accordance with theoretical developments in [7, 8]. For completeness, a brief review of buckling safety concepts and BMS are provided below.

5.1 Buckling Safety Concepts for BMS Applications

Figure 7 shows the fundamental safety concept and criterion for buckling prevention as detailed in [9], as well as applied by the UIC in line with [10, 11].
Step 1 shows the track lateral deflection from an initial line defect with amplitude \( * \), with temperature increase. Step 2 exhibits the theoretically determined buckling equilibrium curve (shown in dashed) identifying the upper and lower critical temperatures \( \Delta T_{B_{\text{max}}} \) and \( \Delta T_{B_{\text{min}}} \). Step 3 shows that the actual buckling occurs at a temperature in a buckling regime bounded by the upper and lower critical temperatures, and Step 4 identifies the lowest point on the buckling response curve as the safe allowable temperature increase. According to theoretical concepts [5], at temperatures below this value buckling should not occur, and the track’s deflections are confined to the growth of the initial line defects with temperature. The safety criterion on track buckling prevention is based on this safe temperature value i.e. on the \( \Delta T_{B_{\text{min}}} \) on the buckling response curve.

Buckling prevention safety criterion then requires that rail temperature increase above neutral to be confined to values less than \( \Delta T_{B_{\text{min}}} \). Since \( \Delta T_{B_{\text{min}}} \) is an analytically determined quantity based on theory and on track condition/parameter inputs, for additional safety considerations it is customary to add a safety factor on \( \Delta T_{B_{\text{min}}} \). For most heavy-haul applications this safety factor is typically 10°F (6°C) less than \( \Delta T_{B_{\text{min}}} \) [9]. For the European rail network’s safety factors refer to [10, 11]. It is important to note that the safe temperature increase value, \( \Delta T_{B_{\text{min}}} \), and the buckling regime’s upper bound, \( \Delta T_{B_{\text{max}}} \), are highly track parameter/type/condition dependent, and are referenced to the track’s neutral temperature. Hence for buckling hazard detection both the safe allowable temperature (as modified by any additional safety factors) and the track’s RNT are required in accordance with the safety criterion that: thermal load < buckling strength, where the thermal load is based on the RNT, and the track strength is based on the safe allowable temperature.

In line with the above, the buckling margin of safety (BMS) is defined as the reserve “buckling strength” in terms of the additional temperature or thermal load required to produce a buckling prone condition i.e. reaching the track’s safety limit. This is graphically illustrated in Figure 8.
5.2 Buckling Hazard Index

Salient’s StressNet™ System has been recently upgraded to provide a buckling hazard warning based on the RSM’s RNT output. The warning is based on a "Buckling Hazard Index" which provides a color indexed alert in terms of a green, yellow, orange, or red conditions. The green-yellow-orange-red alerts are based on having a prescribed buckling margin of safety (BMS) where the BMS is determined by the StressNet™. This determination is based on the RSM provided rail and neutral temperature data, and on the track’s buckling strength as computed by BUCKLE. The BUCKLE algorithm based on the Volpe/FRA “CWR-SAFE” model (3), and it is customized for easy railroad use by requiring only simple input parameters readily available to the railroad engineer. The program determines the “allowable temperature increase”, and based on the RSM measured rail temperature and RNT it computes a buckling margin of safety (BSM). Based on the calculated BMSs falling into prescribed “safe”, marginally safe” or “unsafe” regimes in accordance with Table 1, alerts can be issued on a potential for an incipient buckle. Note that in Table 1 the green-yellow-orange-red BMS regimes are illustrative and provisional in line with current US practice, and are based on the RSM’s real time output and StressNet’s real time application for BMS determination. Automated “triggers” can be developed for specific railroad property or network needs.

<table>
<thead>
<tr>
<th>BMS</th>
<th>ACTION</th>
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<tbody>
<tr>
<td>Larger than 25°F (14°C)</td>
<td>OK; no action</td>
</tr>
<tr>
<td>Between 10 and 25°F (6 and 14°C)</td>
<td>Caution; advisory</td>
</tr>
<tr>
<td>Between 0 and 10°F (0 and 6°C)</td>
<td>Slow order; readjust RNT</td>
</tr>
<tr>
<td>Less than 0</td>
<td>Red flag; immediate attention</td>
</tr>
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5.3 Buckling Hazard Warning Example and Case Study

Based on RSM/StressNet™ data as outlined in Figures 2 and 3, buckling hazard evaluations were conducted for the Union Pacific at two RNT conditions for a maximum summer rail temperature of 140°F (60°C) application in line the green yellow-orange-red index definition. The results are shown in Figure 9 where the left-hand side shows the RNT profile, while the right-hand side the StressNet’s BUCKLE output providing the BMS and the hazard index. At RNT_{avg}=103°F(40°C) a high BMS=50°F (28°C) is calculated showing the “green” condition at a rail temperature of 140°F (60°C) i.e. that at the track is not buckling prone till 140 + 50 =190°F (88°C). At a lower RNT_{avg}= 75°F (24°C) BUCKLE output indicates a BMS=22°F (12°C) or a “yellow” alert i.e. that the track is not vulnerable to buckling till 140 + 22 =162°F (72°C). Based on such outputs the railroad can determine and apply remedial action as needed. For the Union Pacific, this test provided information on not needing summer slow orders. For additional hot-weather speed restriction concepts and applications refer to [12].
Figure 9 – Example of Buckling Hazard Warning

6.0 Conclusions

Track buckling hazard detection and rail stress management largely depend on the track’s RNT condition. Although techniques to measure and monitor RNT with sufficient accuracy have been lacking, a promising evolving technology based on continuous and real time RNT measurement system has been developed. The applications of this system’s measurements have been extended to cover several rail longitudinal stress management aspects, including rail break detection, improved rail break/defect removal repairs, and to a track buckling hazard detection and warning capability, all aimed at providing for more efficient CWR safety and maintenance strategies.

7.0 References


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