Resistance to rail creep – what do rail fastenings really have to do?

David Rhodes (Technical Director, Pandrol Ltd., UK)

and

Bob Coats (Vice President – Engineering, Pandrol USA LLP)

Introduction

Rail fastenings are just one part of the track structure, but they perform a number of critical functions. It is widely understood, of course, that one of their principle functions is to restrain the rail, longitudinally i.e. to control rail creep. What is less well understood is that the amount of restraint that is required varies from one application to another, and depends on many factors some of which depend on the detail design of the rail fastening, and some of which do not.

There are four main reasons to control rail creep:

- To constrain continuous welded rail when it is subjected to temperature variations.
- To prevent movement of the rail when it is loaded longitudinally by traction and braking forces.
- To protect switches and crossings, and insulated joints, from excessive longitudinal forces
- To limit longitudinal forces transferred between the track and other structures such as bridge decks.

In general, the first three of these involve restricting rail creep, but the last may involve allowing the rail to slip.

When continuous welded rail (CWR) was first introduced, it was generally assumed that the ideal rail fastening system would fix the rail to the tie as rigidly as possible, and withstand the highest possible force without permitting any movement of the rail, relative to the tie. This approach led to target values being set for longitudinal restraint tests on rail anchors and on elastic rail fasteners. In reality, it has always been necessary to make some compromises to allow for the requirement for other track parameters, such as the requirement for elasticity in tie pads, and the fact that the resistance of the tie in the ballast is also finite. Today, we know that there are many thousands of miles of track in North America, with CWR, functioning very well even though the creep resistance is less than that prescribed for new fastenings, but we also know that real problems can occur when the rail slips in an uncontrolled way. The time is right for a fundamental review of rail longitudinal
restraint issues, so that appropriate limits can be set for type approval of new fastening systems and for maintenance of existing track.

1. Force distribution - theory.

As a basis for more detailed discussion, it is important to understand the way in which longitudinal forces are distributed along a length of track.

The principle of distribution of vertical forces is very familiar. Fig. 1 shows a typical curve showing how the support of a vertical point load on the rail head is shared between a number of ties – the precise magnitude depends on rail size, tie spacing and ballast / formation modulus, but we can apply suitable factors to this curve for all standard track configurations. With 136 lb rail on concrete ties at 24 inch spacing, the tie directly under the loading point carries a little less than 30% of the applied load – move four or five ties to either side, and the vertical load is close to zero.

![Figure 1: Force distribution for a vertical point load on the rail.](image)

Figure 2 may be less familiar, but this is the corresponding diagram for a longitudinal point load. The most important thing to notice is that the load is spread over many more ties than the vertical load (because the rail is much stiffer longitudinally than vertically). Superimposing the curve from fig. 1 onto the curve from fig 2, as shown in fig.3, it becomes clear that close to the point of load application the track is subjected to high vertical and longitudinal forces, but a few ties away the longitudinal force remains significant, but there
is no vertical force. It is important to keep this picture in mind as we move from a theoretical point load on an elastically supported beam to the loaded wheels of a train on a railroad track!

Figure 2: Force distribution for a longitudinal point load on the rail.

Figure 3: Combined force distribution for vertical and longitudinal forces.
As a final point in the theoretical applied mechanics, before going on to look at some real engineering, it is important to note that there are always (at least) two interfaces where deformation and, ultimately, slip may occur as a result of longitudinal track forces – the interface at the tie pad, between the rail and the tie, and the interface at the soffit, between the tie and the ballast.

2. Longitudinal forces in track

2.1 Temperature changes, and CWR.

As CWR is constrained to have a constant length over a range of temperatures, we face different potential failure modes at the two extremes of temperature – track buckling (“sun kinks”) when it is hot and rail breaks when it is cold. Theoretical predictions of these failure conditions can be misleading, especially if it is assumed that the restraint is the same at every tie and the rail has uniform properties along its entire length.

In principle, temperature changes result in uniform longitudinal loading, and the weight of the track and the clip toe loads apply uniform longitudinal forces. In practice, track temperatures may vary as the route passes through shaded areas (e.g. cuttings) and then areas exposed to direct sunlight, and track bed properties are never as uniform as we would like them to be.

Sun kinks and rail breaks usually occur where the theoretical assumptions break down. Where the track buckles, there are usually local variations in restraint or in temperature (or both). If rails break in cold weather they usually break at welds or other defects. Uniformly high clip toe loads may help, provided that the constraint of the tie in the ballast is also uniformly high. Good control of rail neutral temperature also helps the situation.

2.2 Traction and braking forces.

With high traction forces, each powered wheel exerts both a vertical and a longitudinal point force on the rail, generating a force distribution similar to the curve in figure 3. The individual wheels of the locomotives are all close enough for each to have an influence on the next wheel, and so a real trace of rail stress against time, as a train passes a measuring point, looks like the one in figure 4. A few ties ahead of the train, there is a very large longitudinal force in the rail, but no vertical bending. There is, of course, a high clamping force between the rail and the tie, provided by the rail clips, and so the limiting factor for track strength is the constraint of the tie in the ballast. If anything slips, it is the whole tie. However, directly under the wheel, the weight of the locomotive pushes the tie down into the ballast where it is “locked” in place. Of course the longitudinal forces are even higher as well, but here if anything does slip it is the rail, through the fastening system. It is this combination of slip at two different interfaces (tie-ballast and rail-tie) which causes ties to skew at locations where loaded trains are hauled up steep grades. [1,2] As a general rule, problems of this kind begin to occur when the gross train weight,
multiplied by the gradient, is more than about 100 tons e.g. if a train weighing 10,000 tons is hauled up a grade of more than 1%, or a train weighing 4,000 tons is hauled up a grade of more than 2.5%. Where this problem occurs, it should be addressed by ensuring that the ballast is well compacted and that fastenings are in good condition.

**Figure 4 : Rail stresses under a loaded train.**

2.3 Protection of S&C.

Where CWR meets S&C, steps must be taken to prevent longitudinal track forces from acting on the moveable parts where they could cause seizure or damage to the mechanisms. This may be achieved by placing rail expansion joints at the ends of the CWR, or by providing strengthening by the use of extended wing rails, for example, through the S&C itself. In either case, the rail fastenings will be expected to provide high levels of constraint of the stressed rails.

2.4 Bridge ends and transitions.

Conversely, at the ends of bridges and in transitions from one track form to another (e.g. ballasted to non-ballasted track) it may be necessary to allow
the rail to slip through the fastening in a controlled way. The local use of fastenings which provide zero longitudinal restraint (ZLR) or reduced restraint can be a key part of the design of structures, especially on the non-ballasted viaducts required by modern mass transit systems. Of course, where such techniques are used care must also be taken to take into account the possible consequences of a rail break. Typically if ZLR fastenings are used directly over the structural movement joints at the end of bridge deck sections and full toe load fastenings are used at mid-span the maximum rail break gap can be limited, but local concentrated stresses in the rail and structure can be reduced significantly \[^3\].

3. Performance requirements.

3.1 Limiting conditions

It is a simple question to ask how much creep resistance is provided by a particular fastening. Unfortunately the answer is not so simple! Are we interested in the amount of longitudinal force which is needed to start the rail moving, or the amount which causes gross slip? Are we most interested in loaded or unloaded track? Looking at the track structure as a whole, if slip does occur does it matter whether it happens between the rail and the tie, or between the tie and the ground? Which is the “safer” potential failure mode? Which is the easier failure mode to fix?

In resisting forces due to temperature variations in CWR, it is the creep resistance of unloaded track which is of most interest, even though it is sometimes the disturbance caused by an approaching train which triggers the failure process. At high temperatures, “sun kinks” will occur where the ties can move in the ballast, laterally and the rail does not necessarily move in the rail seat. However, “sun kinks” often occur where the longitudinal restraint of the rail is not uniform and the stress is able to build up in a short length within the CWR. The performance of the rail fastenings is relevant in this case. In the case of low temperatures, rail fastenings play an important part in maintaining safety in the event of a rail break. In most cases, the rail ends should be held within 3 inches (75mm) of each other when CWR is fractured. The figure that is achieved depends on the creep resistance and the shear elasticity of the fastening system.

3.2. Current standards.

In the standard test prescribed in AREMA Chapter 30\[^4\] a longitudinal force is applied to the foot of a short section of rail and a force of 2.4 kips (10.7 kN) is applied and held for a period of 15 minutes. The rail should not move more than 0.2 inches (5mm) in the first 3 minutes, and then should not move more than 0.01 inches in the next 12 minutes.

A similar test is described in the European standard EN13481-8\[^5,6\], but in this case the longitudinal force is increased until gross slip occurs, and then the load is removed. The amount of non-elastic which has occurred is subtracted
from the total longitudinal movement to determine the point on the force-displacement curve at which slip began. The test is carried out four times – the first result is discarded and the longitudinal restraint calculated as the average value of the force needed to initiate slip in the second, third and fourth tests. For heavy axle load applications this value must be at least 9 kN (2 kips).

In both cases, the test must be carried out before and after a 3 million cycle durability test on the entire fastening. For AREMA, the fastening must meet the same pass criteria before and after the durability test; for the EN the results may not differ by more than 20% (even if the final result still exceeds the 9 kN requirement).

AREMA Chapter 30 (section 1.5.2) states that 2.4 kips per tie is “sufficient for general service” but points out that “there are specific locations of excessive longitudinal force where this value understates actual field conditions”.

4. Detail design influences.

The creep resistance measured in the laboratory depends on a number of factors within the detail design of a concrete tie fastening assembly:

1. Toe load / clamping force.

   High toe load fastenings result in high longitudinal restraint.

2. Coefficient of friction between rail and tie pad.

   The lowest friction coefficients are usually associated with metal-to-metal contact, and so occur with rails in metal tie plates without pads. This factor is also critically dependent on the condition of the rail surface. Writers of standards have tried (generally unsuccessfully!) to define the rail condition for laboratory tests in order to make results consistent, at least. In most cases loose flakes of corrosion and scale must be removed, but the rail surface left in an “as rolled” condition.

3. Coefficient of friction between tie pad and tie.

   This has become a significant issue, with the introduction of various systems to prevent or retard rail seat abrasion on concrete ties. All of the benefits of high clamping force may be lost if this figure is compromised.

4. Shear deformation of tie pad / anti-abrasion devices.

   In the EN test this factor does not contribute, because non-elastic deformation is taken out of the equation. In the AREMA Chapter 30 test, the requirement to sustain a high load for 15 minutes with “zero” deformation after the first 3 minutes may be compromised when elastic
tie pads are used. In practice, the very tight limits set on the rate at which elastic pads recover may limit the use of materials which do give benefits in terms of impact attenuation.

5. Mechanical interaction between tie pad / anti-abrasion devices and fastening or shoulders.

Rail creep resistance measured in the laboratory may also be influenced by the way in which anti-abrasion devices move during the laboratory test. In many designs there is a rigid plate which fits around the shoulder of the fastening system, and which may move as the test load is applied until it reaches a mechanical limit. If it stops at that point, the movement is probably irrelevant but it may affect the test result.

5. The answer?

Finally we should try to answer the question posed in the title of the paper. What do rail fastenings really have to do? The answer for Class 1 railroads in the US is that in most of the track with CWR they have to provide at least 1 kip (4.5 kN) of creep resistance throughout the life of the track, which means that when new track components are tested we should be looking for twice that figure – around 2 kips (9 kN) per tie end – to allow for manufacturing variations and subsequent loss of performance in service. On that basis, the requirement for 2.4 kips (10.7 kN) for a new fastening in laboratory conditions is not unreasonable, but it should not be seen as the minimum universal requirement.

At the other extreme there are clearly a few locations where fastenings designed to meet the 2.4 kips requirement are inadequate. It is not always clear whether this is because the fastening in service fails to resist forces less than 2.4 kips, or the force applied in service is actually more than 2.4 kips, but it is clear that there are places where, for example, rail anchors are installed as well as elastic fastenings as a pragmatic way of preventing rail creep. Work may be required to reach a better understanding of these local problems which may require a different mode of testing, rather than just higher numbers. Even if higher numbers are the answer, simply upgrading the performance requirements of millions of fastenings, in order to fix localised problems, is unlikely to be the most economical solution! We may need to develop ways of identifying the areas which require extra longitudinal restraint in the same way that we identify those which need zero longitudinal restraint.

Discussion may also be needed about the compromise between selection of elastic tie pads for vibration attenuation, and rigid tie pads to increase longitudinal restraint, or special systems to mitigate rail seat abrasion. If such designs prolong the life of the fastening and tie, they may ensure that the longitudinal restraint required in service is maintained even if the restraint measured on the new fastening is reduced.
6. References


