REVENUE SERVICE EVALUATION OF ADVANCED DESIGN INSULATED JOINTS

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ABSTRACT
This paper discusses the performance of long-angle cut/lap joint insulated joints (IJ) in revenue tests on Union Pacific (UP) and BNSF coal routes. It also briefly describes current improvements to conventional joints and the motivation behind the development of the new design.

Advantages of the new design include a more mechanically efficient joint that lowers adhesive and joint bar stresses significantly. In addition, the overlapping rails of the joint provide for a smooth running surface transition across the joint, greatly reducing the dynamic loads that conventional butt joints generate.

A summary of proof testing done at Facility for Accelerated Service Testing (FAST) will be provided. Design considerations, such as running surface profile, corner radii and foundation designs were evaluated.

Initial revenue service testing since late 2006 will be reviewed. Tests on BNSF and UP have shown promising results to date.
INTRODUCTION

Background
Bonded insulated joints (IJJs) are the backbone of the present rail signal system. The IJJs divide the track into blocks of about 2-mile lengths. Each block has traffic control signals and IJJs on both ends. This signal system is used to detect train presence within the block and to control the traffic. Using the present IJ-based signal system, the presence of broken rails can be detected in many circumstances, and warning lights at railroad/highway crossings are also controlled.

On heavily used coal routes, the performance of IJJs has become a significant economic problem due to the relatively short service life of IJJs. Today, IJ service life can be as short as 200 million gross tons (MGT). This service life is lower than virtually all other running surface track components, including turnout frogs and switch points. IJJs may be replaced in as little as 12 to 18 months, with direct costs of $10,000 per mile per year. Indirect costs due to train delays can be higher. Besides economic implications, IJJs pose a significant threat to service reliability and efficiency.

To assist the U.S railroad industry in its efforts to improve service life and reliability of IJJs, Transportation Technology Center, Inc. (TTCI) conducted Association of American Railroads (AAR) sponsored research to investigate the causes of IJ degradation and failures, and to evaluate appropriate mitigation remedies.

TTCI has adopted a thorough and structured strategy to appropriately address and mitigate the IJ service life problems. The first step evaluated the load environment IJJs are subjected to during their service life. The second step determined the failure mechanisms. In particular, the different modes, causes, and factors responsible for IJ failure were understood. As a third step, TTCI is working to identify and evaluate potential designs
and remediation techniques that can improve the IJ service life. The final task will be to implement the appropriate techniques and monitor the effectiveness of the solution.

The early phase of this research included field inspections, destructive evaluations of failed components, field tests, stress-analysis, and interviews and surveys with track engineering staff at AAR member railroads. This document presents a review of the improvements made to conventional joints and their performance in heavy axle load (HAL) coal routes. This paper also describes the limitations of these improved IJs, and it discusses the design details and performance of an alternate design.

Load Environment
The real-time dynamic data collected from supported and suspended instrumented joints shows that impacts from wheels may be up to three times the static wheel loads. Figure 1 shows the wheel load histogram for a 286-kip unit coal train.

![Figure 1. Histogram of Dynamic Loads of a Typical Unit Coal Train](image)

The maximum measured bending stresses in joint bars for both supported and suspended IJs were less than 10 percent of the material yield stress. The IJs were
generally installed at high neutral temperatures, which resulted in high longitudinal
tensile loads during winter conditions. The longitudinal force and temperature
relationship of insulated joints are subjected to tensile forces of up to 300 kips during
winter conditions. The effect of bending and longitudinal stresses is accumulative.²

The IJs are designed as “slip-critical” joints; i.e., the load is transferred from one
rail to another through the joint bars only with adhesive shear strength and bolt preload,
and the bolts do not bear against the bolt holes. It is believed that during service life, and
with joint slippage, the joint changes to a “bearing-type” joint, which also transfers loads
due to bearing of bolts. This type of joint can short the rails and can induce fatigue-
related cracks in bolt holes.

Stress analysis of a 6-bolt (36-inch joint bar) conventional IJ predicted that under
normal service loads and fair foundation conditions, the joint components are subjected
to stresses that are well below the material yield limits.²

**Failure Analysis**
The most frequent cause of IJ insulation failure, as documented by the railroads, is
adhesive debonding.¹ The weakened adhesive bond allows moisture intrusion causing
metal corrosion and adhesive debonding. The higher stiffness of epoxy adhesives, as
compared to the rail steel, seems to be responsible for cracks at the end post.

The current design joints are expected to fail in this manner due to the butt joint
(i.e., rails placed end-to-end) design and tie configurations used. This arrangement
produces epoxy shear stresses above the long-term strength of the epoxy.
There is a strong correlation of foundation condition with IJ condition and service life. Figure 2 shows the distribution of foundation conditions for IJs in good and distressed conditions. A poor foundation was one that had mud present, rail fastener problems, and low ties.

![Figure 2. Effects of Foundations on IJ Service Life](image)

The IJs were also removed from service due to broken bars and bolts. Since the measured and predicted stress levels in IJ components supported on fair foundations are well below the material yield limits, these causes seem secondary in nature and may be the result of poor foundation conditions, or deterioration of the epoxy.

Some of the IJ failures are related to quality control issues in components and assembly. Problems with batches of joints from any given supplier, batches of adhesive and batches of IJ components, have been reported by the railroads. Steel surface preparation for epoxy is critical to long-term performance.
Impacts from wheels may be defined as the single most important cause of IJ failures. They are responsible for increased metal flow at rail ends, end post battering, and degradation of ballast. As a result of fouled ballast, IJ deflections increase, which induces distress into IJ components.

IMPROVEMENT TO CONVENTIONAL IJS
Railroad and supplier efforts have focused on increasing the service life of IJs by modifying the joint bar designs, by using better insulators, more durable adhesives, longer joint bars, and better foundation conditions. TTCI is tracking the performance of test IJs and the results are discussed in the following sections.

High Modulus Bars
High modulus joint bars are designed to match the vertical stiffness of IJs to the surrounding rail. This type of joint distributes the wheel loads to at least three ties, reducing ballast degradation. Due to higher section properties, the stresses in adhesive in these IJs are lower. Performance of this type of joint is satisfactory, with an average service life of 400 MGT. Wraparound joint bars and thick web rail are other variations of this design, as Figure 3 shows.

Figure 3. High Modulus 48-inch Joint Bars—(Left) Conventional (Right) Wraparound
Resilient Foundations
Dynamic loads on IJs are higher than dynamic loads on the surrounding track. This gives a reason to provide better foundations under IJs. Tests at FAST have shown that using wider ties, closely spaced ties, and frame ties improve the damping properties of IJ foundations, thus reducing ballast degradation (see Figure 4).

![Peak to Peak Values Acceleration Data](image)

**Figure 4. Acceleration Data for Different IJ Foundations**

Tie Plates
Directly supported joints with specially designed insulated tie plates provide benefits by reducing (or eliminating) bending stresses. Different configurations of plates are currently being tested, such as three-tie plates, two-tie plates, and single-tie plates. These plates are performing well, except those with weld details that failed due to fatigue at about 400 MGT.

Wider Ties, Three-Tie Plates and 48-Inch Joint Bars
BNSF uses wood tie panels (in concrete tie track) for track transitions and high dynamic load components like IJs. The panels have wider ties (typically 11-inch versus 9-inch standard ties) under the IJs and longer ties (9 1/2-foot versus 9-foot standard ties) on the whole panel. The panels provide additional track damping with a footprint similar to
concrete ties. The change in tie type does create two new transition zones 20 feet away from the IJs. While no comprehensive records exist (there are now many in service), the expert opinion is that these wood panel IJs are providing a longer service life, perhaps 300-400 MGT versus 200 MGT. The effects of new ties and ballast versus the material change cannot be separated in these tests (see Figure 5).

![Image of rail ties and ballast]

**Figure 5. IJ System: 48-inch-Long Bars, 11-inch-Wide Ties and Insulated Three-Tie Plate**

**Center Liner Insulators**
Special center liner insulators create a stiffer joint through a mechanical wedging action between the joint bars and the rail, which delay the unzipping that typically begins at the high stress end post area. This insulator is used in 48-inch-long joints and has 30 percent less deflection than a conventional joint. Various railroads have installed this type of IJ design. Maximum tonnage on this design has been recorded up to 850 MGT on UP’s track; however, the average service life is between 500 and 600 MGT (see Figure 6).
Reconfigured Insulation
The typical bonded IJ isolates the rails from each other, from the joint bars, and from each bolt. The joint bars and bolts are electrically connected. Under tensile stresses, the joint bars can move relative to the rails, causing failure of the bolt sleeve insulation at the rail/bar/bolt-hole interface. To address this problem, a reconfigured design that isolates the bolts from the joint bars is in test. As the joint deteriorates or slips, the resulting force exerted on each bolt’s insulation is reduced two-fold. The bolt is also replaceable. In the typical standard bolt insulation failure, bolt replacement is not possible without shunting the circuit. Several joints of this design are in test with average service of 170 MGT to date (see Figure 7).
Stronger/Tougher Insulators
Stronger and tougher insulators are providing benefits to IJ service life. Kevlar™ has been used to replace the fiberglass insulator cloth that is placed between rail and joint bars. Kevlar is embedded in the adhesive layer of bonded joints and serves the functions of a spacer, an insulator, and an adhesive reinforcement. Conventional laboratory testing of Kevlar joints shows them to be no stronger and marginally more durable than fiberglass cloth joints. However, revenue service testing shows them to provide a significantly longer service life. Combined with a direct support foundation and longer joint bars, many Kevlar joints have accumulated service life up to 600 MGT. It is speculated that Kevlar performs better in the more complex load environment of the field (where impacts and multi-planar stresses occur) than it does in the single direction lab tests. It may also be that the Kevlar joints are less subject to environmental degradation.
Limitations of Improvements to Existing IJ Designs

Service life up to 850 MGT has been reported for some conventional joints with improvements. This is still less than the railroads’ goal to reach the service life of rail (~2,000 MGT). There are two hurdles to achieve this goal: (1) impacts due to the inherent running surface discontinuity in IJs and (2) adhesive durability.

Impacts at IJs are generated due to the running surface discontinuity at a butt joint (i.e., the gap needed for electrical isolation of the rails). Under load, current joints dip more than open track, creating a “kink” in the vertical profile. Elimination of this discontinuity in the running surface will be very difficult with butt joint designs. Thus, TTCI evaluated other joint configurations, including successful frog heel designs.

Figure 8 shows the data collected from commercially available structural adhesives. Most of the adhesives lose strength rapidly at temperatures in excess of 100°F. The adhesive further reduces its strength due to rapid cooling and heating cycles. An ASTM standard weathering test shows the effects of cooling and heating cycles from -40°F to 150°F.
Recent work by Virginia Tech on steel surface preparation and alternative epoxies\textsuperscript{3,4} suggest that we can reduce the effects of environmental degradation on IJs. These improvements will be incorporated into the next generation of advanced design prototypes.

**Advanced Design**

Based on the failure modes of conventional joints and limitations of the improvements to conventional joints, TTCI pursued the development of a low impact angle cut IJ. As Figure 9 shows, the main feature of the design is the full section angle cut through the rail. This design allows smooth transition of wheels from one rail to another. It also provides higher resistance to longitudinal forces due to three layers of adhesive-impregnated fiberglass and triple shear bolts in the middle of the IJ. Commercially available adhesives and insulators can be used with this design with little or no
modifications. The center layer of adhesive, which is protected from the environment, and the triple shear bolts are the main strengths of this design.

Figure 9. Sketch of Lap Joint Design, Built and Tested by TTCI

Figure 10 shows that the maximum stresses in the adhesive were about 60 percent lower than those in the conventional joint. These stresses are within allowable limits, mainly due to the more efficient transmission of load across the two rails (absence of shear lag) in this design.
TEST RESULTS OF ADVANCED DESIGNS

Tests at FAST

Based on encouraging analytical results, TTCI built two long-angle cut/lap joints. Wheel transition length from one rail to another was 18 and 24 inches. Thick web rail was used to provide enough web support for the railhead ends. Vertical dynamic load data was measured, as Figure 11 shows. The goal of reduced impacts was achieved with this design. However, both of the joints lived less than 40 MGT.
Figure 11. Wheel Impact Comparison—99 Percentile

The High Tonnage Loop at FAST has many curves. Thus, the wheels wear more at the flange root than at the wheel tread. Excessive flange root wear generates a “hump” on the wheel tread, as Figure 12 shows. This hump is believed to ride over the longitudinal gap of the rail ends, causing very high contact stresses. This is evident from accelerated metal hardness on the running surface, which increased from 348 to 422 in just 40 MGTs. Both joints were removed due to excessive railhead chipping.
Allegany Rail Products built a lap joint in which the cuts at the ends were straight instead of angled. The joint had a 12-inch-long wheel transition zone. This joint was also removed after 30 MGT due to excessive chipping of railhead material on the running surface. The rails for all three joints were rolled by the same manufacturer. Results showed that a stronger, more deformation resistant rail was needed.

Portec Rail Products milled and assembled four long-angle cut/lap joints for TTCI with significant improvements to previous designs. Conventional RE section, high strength rail is used by bending the two rails so that their centerlines are parallel, but offset from the nominal rail centerline. This allows both railheads to be supported through the angle cut. In this design, staggered end post halves are connected with a long-angle cut. The two rail ends comprising the joint have opposing point slopes. This allows for a smooth transition from one rail to the other for most wheel profiles. This joint has the capability to resist 1.5-million pounds longitudinal loads.
The smaller rail running surfaces of the angle cut joint presents some running surface profile design issues. Obviously, metal flow across the long taper cut end post is a concern. Each of the four test joints had a different railhead corner radius at the taper cut. These ranged from 1/8- to 5/16-inch corner radius.

Two of these test lap joints were installed at FAST. Both were removed from FAST at about 200 MGT. The metal flow was ground twice on both joints. The failure mode was the same as those of the previous lap joints; i.e., chipping of the railhead. During the service life, hardness increased from 400 to 450.

Figure 13 compares the stiffness of this joint with other joints.
Revenue Service Tests
UP Gering, Nebraska Test
The third of the four test lap joints was installed in UP’s track in Gering, Nebraska. It was removed after 280 MGT due to a track wire weld defect near the joint. The metal flow at the gage side of the rail was ground once. In general, the joint condition was good and no chipping at the railhead surface was observed. The joint location was surfaced almost every month. This appears due to the general track condition. During tests at FAST, the lap joint did not need any surfacing. Figure 14 shows the lap joint in the revenue service test.

Figure 14. Lap Joint in Gering, Nebraska

BNSF Belen, New Mexico Test
The fourth test lap joint was installed in BNSF’s track in Belen, New Mexico. The joint has up to 100 MGT of intermodal traffic, and no maintenance has been performed to date. Overall condition of this joint is good.
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