TECHNOLOGY DIGEST

TD-07-035

©October 2007

TIMELY TECHNOLOGY TRANSFER

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Development of Improved Materials and Surface Preparation for Insulated Joints in Heavy Axle Load Service

TTCI and Virginia Polytechnic Institute and State University*

Summary

Under sponsorship of the Association of American Railroads, Transportation Technology Center, Inc. (TTCI) is leading an industry-wide effort to improve the performance of bonded insulated joints (IJ's) in heavy axle load (HAL) freight service. This *Technology Digest* describes the results thus far in developing a stronger and more durable epoxy-insulator-steel bond. Focus has been on the following major areas:

- Stronger and more durable epoxies
- Steel surface preparation for the epoxy bond
- Improved performance insulators

TTCI and Virginia Polytechnic Institute and State University (VA Tech) have selected and evaluated candidate materials and processes for the improvement of the epoxy bond. Previous work has shown that epoxy bond failure is the primary mode for HAL IJs.[1] This is due to the high sheer stresses in the epoxy caused by the HAL loading and the configuration of the IJ design. Additionally, the epoxy-insulator-steel bond is subject to environmental degradation in the railroad environment.

Initial findings from this work include:

- Candidate epoxies were evaluated for railroad use. Some candidates were determined to be of higher initial strength, higher toughness, and higher laboratory "weathered" strength than those currently used. The most promising will be tested in the field under HAL traffic.
- Steel surface preparation processes, such as an amino-propyl silane treatment, were effective at reducing the effects of weathering on the epoxy bond. The initial strength of the bond was also improved by 10-20 percent. Environmental exposure significantly degrades the rail steel-epoxy bond. Oxidation of the surface is seen in laboratory weathered and failed in-field specimens. Additional work is under way to optimize the surface treatment; i.e., epoxy combination which provides the best performance.
- The insulator cloth used between rail and joint bars lowered the strength of the IJ compared to one built without the insulator. Thus, further R&D should be devoted to improving the method(s) to provide insulation.
- Kevlar cloth has the potential to provide benefits over fiberglass as the rail-to-bar insulator in IJs. In laboratory tests, there is little difference in IJ shear strength between insulator materials. This is because most weathered specimens fail at the rail-epoxy interface. However, Kevlar IJs withstand environmental effects better than the ones made with fiberglass.

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BACKGROUND AND INTRODUCTION

Bonded IJs have been used almost exclusively in railroads to provide track circuits that detect rail breaks and control signal traffic blocks. The joint design has remained virtually unchanged for over 100 years. However, recent advances in high-strength rails allow for the use of higher tonnage cars. With the increased loading of the freight lines, bonded rail joints are encountering early breakdown through either electrical or mechanical failure. These freight lines show significant reduction in the lifetime of insulated joints to about 200 million gross tons (MGT) or 12 to 18 months, significantly lower than other railway components.[1] In addition to the direct costs of repairing the joint, train delay/ capacity costs can be significantly higher. These operations costs have increased the desire for an improved joint.

Previous digests have described the typical bonded IJ failure modes under HAL traffic.[1,2] The most prominent failure mode is a shear failure of the epoxy, beginning near the center of the joint. Factors contributing to this failure mode are:

1. The configuration of the joint (structurally weak butt joint) produces very high epoxy stresses.
2. Environmental degradation of the epoxy. Weathering (e.g., water ingress) causes degradation of the steel-epoxy interface.
3. High dynamic load environment. Current epoxies are unable to resist the impacts and relative movement of rail and joint bar under HAL service.

This digest addresses factors 2 and 3 above. TD-06-014 describes a tapered joint design intended to lower epoxy shear stresses.[3]

THE ROLE OF ENVIRONMENTAL DEGRADATION

Examination of IJs removed from service show they have significant epoxy bond failures and steel surface degradation in the epoxied areas. This is shown in Figure 1 as a rusted surface near the center of the joint, extending back as far as the first bolt hole on each side of the endpost.

Figure 1. Failed IJ Removed from Service showing Degraded Surfaces

This failure condition is in sharp contrast to the typical laboratory shear test result. In laboratory tests, the joint usually fails in the epoxy layer, as intended. Most of the failures happen at the adhesive/fabric interface, but some occur within the adhesive itself. This change in failure location, from adhesive/ insulator interface in the lab to adhesive metal interface in the field, is indicative of the effects of environmental factors. The development of improved steel surface preparation methods for epoxied surfaces is needed.

Candidate Epoxies

Using initial strength and environmental degradation testing, several candidate epoxies were evaluated. These epoxies are commercially available and are used in similar applications.

A good candidate epoxy for IJ applications must have high initial strength, resistance to environmental degradation, and the ability to withstand high dynamic loads. Eight epoxies, including those used by IJ suppliers, were evaluated for initial strength and environmental degradation. As an initial screening, single lap shear tests were conducted for candidate epoxies. Figure 2 represents a comparison between different adhesives and different insulator materials. The eight adhesives considered are denoted with the capital letters A through H; the left column referring to each adhesive regards the system with fiberglass insulator and the right column the system with Kevlar® insulator. The shading of the column is an indication of the macroscopic failure mode, as stated in the legend. The data scatter bar refers to plus/minus one standard deviation.

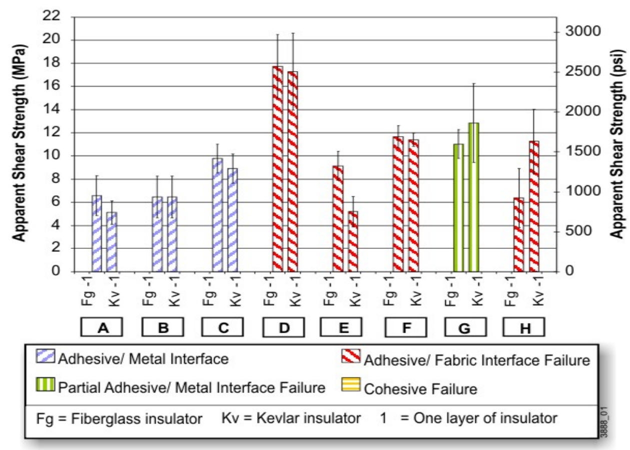

Figure 2. Apparent Shear Strength of As-Produced 1-Fabric-Layer SLJ (ASTM D1002), Quantitative and Qualitative Description

The specimens prepared with Adhesive D have apparent shear strength considerably higher than the others. This adhesive is not currently used by the IJ vendors. Most of the epoxies evaluated had higher laboratory shear strengths than currently used epoxies.

In addition to lap shear tests, double cantilever beam (DCB) tests were used to assess the fracture toughness of the epoxies to a tensile mode crack. This test provides an indication of the ability of the epoxied IJ to withstand dynamic loading in the field. Three candidate epoxies were evaluated with this test.

Results show that Adhesive D has a higher critical strain energy release rate than the other candidates. This means it is more difficult to propagate a crack or "unzip" a bond made with Adhesive D.

Additional findings from the DCB tests include:

- Under these constant displacement tests, some adhesives showed stop-start crack growth behavior. Others had a more uniform crack growth.
- Environmental exposure in the laboratory increased the toughness of the epoxies as compared to as-made samples. The exposure was not sufficient to weather the steel surfaces to any extent, but did toughen the epoxies. This suggests the as-produced epoxied joints are too brittle.

Laboratory Weathering Tests

Based on the observation that the steel surface of the epoxy bond degrades in railroad service applications, controlled experiments of the effects of environmental exposure were conducted at the laboratories of Virginia Tech. These tests helped identify the failure mechanisms and quantify their effects (Figure 3).

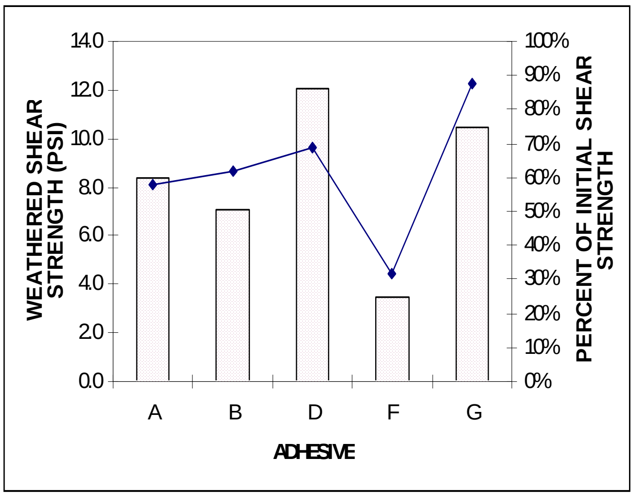

Figure 3. Apparent Shear Strength of As-Produced 1-Fabric-Layer SLJs (ASTM D1002), Quantitative and Qualitative Description

For the environmentally exposed single lap joint (SLJ), the main idea has been to measure the apparent shear strength at the different steps of exposure in order to understand how different systems were degraded by the environment.

The environmentally exposed SLJ have also shown some interesting aspects. The first is the role of the oxidation of the metal surface. Adherents prepared with some adhesive systems exhibited extensive oxidation upon failure and corresponded with significantly lower strengths. Some others were more resistant to the degradation of the surface and retained large fraction of as-produced strength. Adhesive D, the one with the best results in the as-produced SLJ tests, shows a reduction of the apparent shear strength. Nevertheless, its performance after 6 weeks of exposure is still the highest. On the other hand, Adhesive B does not seem to be particularly influenced by the exposure. The metal surface of specimens prepared with adhesives B and D were relatively free from oxidations after the exposure. The systems which underwent a drop in their strength have a metal surface with prominent oxidation. In general, a trend of the failure mode toward the metal/adhesive interface was exhibited. As-produced specimens that were failing at the interface between insulator fabric and adhesive, after the exposure, were likely to fail at the metal/adhesive interface. As-produced specimens failing at the metal/adhesive interface continued to fail at the same position.

At this point, the environmentally exposed SLJ specimens constructed with Kevlar® fabric seem to be less influenced by the exposure when compared to the specimens with fiberglass fabric. These tests are still underway since the results of the 3-month and some of the 1-month exposures are not presently available.

Improved Surface Preparations

Additional experiments were conducted with steel surface treatments to develop a more durable epoxy bond. Based on laboratory and field observations, prevention of steel surface oxidation is essential to having a more durable IJ.

A series of tests was conducted using precracked epoxy specimens and laboratory weathering to assess the effects of steel surface treatments on epoxy bond durability. Two surface treatments were applied to candidate epoxies to determine their durability under simulated field environment conditions. The current grit blast and solvent wipe surface treatment was used as the base case for comparison.

The test ensures that water has access to the epoxy and that environmental degradation is the source of any crack growth noted.

In this phase of the research, steel samples were surface treated, bonded with selected adhesives, and tested for performance and durability upon exposure of wedge-type bonded samples to severe environmental conditions. The specific accomplishments are summarized as:

- Grit blasted railroad steel samples were surface treated with one of two silane coupling agents (the silane functional groups included a primary amine (APS*), and a secondary amine (TMS**), and bonded with one of three epoxy adhesives from selected adhesive manufacturers. The adhesives are designated as A, B and D.
- Wedge-type specimens were stressed by inserting a wedge in the bonded sample and crack growth was measured as a function of time for specimens maintained at 80°C dry and at 80°C at 100-percent relative humidity.
- Samples were forcefully debonded (failed) after crack growth had arrested, and the failure surfaces were examined visually to determine the failure mode (cohesive or adhesive failure). The characteristics of the failure/debonding processes were related to or correlated with the environmental exposure conditions.

* 3-aminopropyltriethoxysilane; (C2H50) 3-Si-CH2CH2CH2NH2; Gelest product No. SIA0610.0

** Bis(trimethoxysilylpropyl)-amine [(CH3O)3-Si-CH2CH2CH2-]2NH ; Gelest product No. SIB1833.0

In all cases, treatment of the steel surfaces enhances bond durability. Figure 4 shows the time for crack growth to specimen failure in accelerated weathering tests.

Note that difficulty was encountered in preparing specimens with Adhesive B. The standard methodology of using a 2-millimeter (0.079 in.) wedge to initiate a crack caused the specimens to fail prior to the weathering cycles. Thus, a 1-millimeter (0.039 in.) wedge was used to initiate cracking, so that a relative comparison of surface treatments could be made. Direct comparison of the durability of joints made with Adhesive B and adhesives A and D in this test cannot be made.

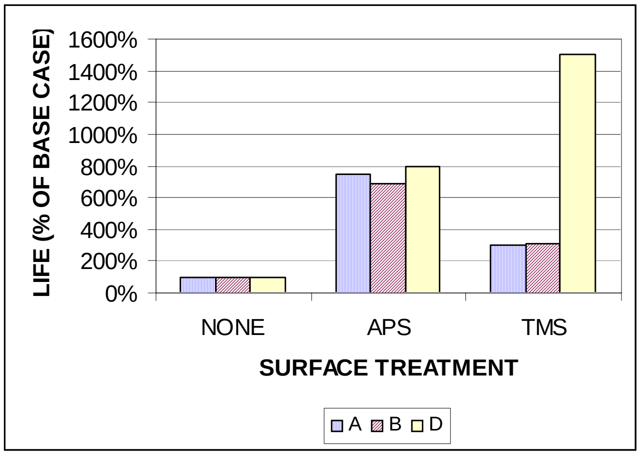

Figure 4. Effect of Surface Treatment on Epoxy-Steel Bonds

Two different surface treatment materials were used in the tests. These materials are both silanes used in other industries for epoxy bond preparations. Figure 4 shows the performance of each silane and epoxy combination. There is no clear trend, as APS appears to work better with adhesions A and B. TMS appears to work better with Adhesion D. While it can be stated with a high degree of certainty that an improved steel surface preparation with a silane material will improve the durability of the steel/ epoxy bond, additional work should be undertaken to optimize the surface preparation/epoxy combination used.

Insulators

Some other aspects have been observed by the as-produced SLJ tested. It has been found that the presence of the insulator layer reduces the strength of the joint compared to systems in which just a neat adhesive (not insulator) was present. Figure 5 shows the effect of insulator configuration and material on IJ bond shear strength. The presence of a double layer of insulator fabric reduces the strength even more. This may be due to the configuration of the test, with a thicker adhesive/ insulator resulting in higher bending stresses. On the other hand, the presence of dispersed fibers generally increases the strength of the joint, but the solution is not practical for the IJ. It has been noted that failures occurring at the fabric/adhesive interface are generally obtained at a higher apparent shear strength compared to the failures obtained at the metal/adhesive interface. The nature of the material of the fabric, fiberglass or Kevlar® has no great influence in the final strength, while the nature of the adhesive does.

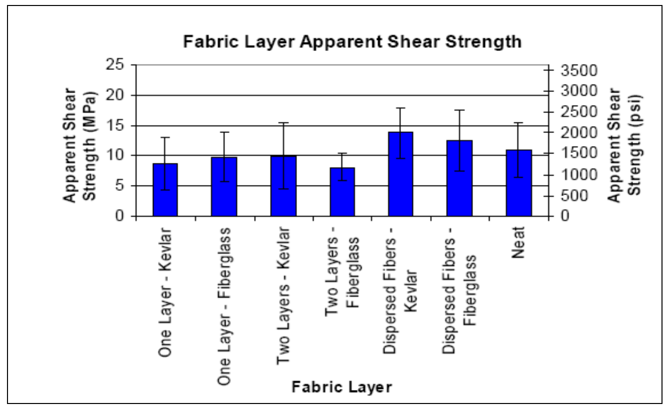

Figure 5. Effect of Insulator Configuration on IJ Bond Shear Strength

CONCLUSIONS

The as-produced SLJ tests have been helpful in identifying some commercial adhesives that perform better than the currently used adhesives. After environmental exposure, the differences are less obvious, although some systems lose a large amount of the as-produced strength quickly during the first two weeks while others show little effect. This behavior is directly linked to the level of oxidation of the metal surface under the bond line, which suggests that the surface preparation can be critical issue.

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