Characterizing and Inspecting for Progressive Epoxy Debonding in Bonded Insulated Rail Joints

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Progressive epoxy debonding is a common factor in many failures of bonded, insulated joints (IJs) in heavy axle load railroad service. This paper describes a study in which IJs with different amounts of debonding were visually inspected and measured and then disassembled. The shape and area of the debonded region for each IJ was quantified and variability between joints recorded. Because of some degree of ambiguity in the visual appearance of the interior surfaces, two different criteria for identifying the boundaries of the debonded region are described and applied. Debonding usually extends farther along the upper and lower portions of the rail–joint bar interface, resulting in a V- or U-shaped debonded region. Additionally, debonding tends to be more extensive on one end of the joint than the other, although it appears that debonding is generally about equal on the field and gage sides. The total debonded area was compared with several linear measurements of damage to the externally visible top edge of the epoxy–insulator layer—the part that is available for inspection in an in-service IJ. There is a strong correlation between the total debonded area in the joint and the total extent of damaged (missing or loose) top insulator edge. The debonded area can be estimated visually, with 80% confidence, to within 12,000 to 28,000 mm^2, depending on which criteria are used to define the debonded region.

Most North American mainline railroad tracks use conventional direct current (DC) or coded-DC track circuits for detecting train presence within a signal block. Such circuits require a pair of insulated rail joints (IJs) at every block boundary, typically about 5 km apart, with several pairs at each control point. Bonded IJs, which fasten the rail, insulator, and joint bar together with a strong epoxy, are the most common type of IJ used in continuously welded rail. The epoxy allows the joint to resist high longitudinal loads; Cox showed that the epoxy bond also increases vertical stiffness (*1*). But IJs still represent a local weak spot in the track structure. Bonded IJs have shorter service lives in heavy axle load service than any running surface component except high-angle crossing frogs (*2*). Because IJs are relatively numerous compared with other short-lived components, their replacement has a large impact on both direct maintenance costs and train operations. The impact is sometimes magnified by imperfect or poorly understood techniques for predicting and detecting IJ failures.

A common factor in many failures of bonded IJs is a tendency for the epoxy to come debonded from the rail or joint bar near the center of the joint (*2*). The debonded region starts small but grows with time and traffic, spreading outward toward the ends of the joint bars. As the debonded region grows, the joint becomes weaker and loses stiffness. Eventually, the remaining epoxy bond does not have sufficient strength to resist longitudinal loads and the bond ruptures, leaving a joint that is held together only by the mechanical action of the bolts. For clarity, the authors define two terms to refer to the two phases of epoxy degradation: progressive epoxy debonding (or debonding) is used to describe the gradual spread of a debonded region; the sudden failure of the remaining bond is referred to as complete epoxy failure.

This paper primarily covers progressive epoxy debonding in joints that have not yet experienced complete epoxy failure. Understanding this progressive deterioration is necessary both for designing improved joints and joint materials and for developing better maintenance practices to deal with deteriorating joints. The research focuses on understanding the effects of progressive debonding on IJ performance and on developing and evaluating techniques for assessing the extent of debonding in an in-track joint (*3*). In this paper, the authors develop a rigorous approach to characterizing and quantifying the extent of epoxy debonding in a degrading IJ. The ability to measure debonding does not itself affect the rate at which IJs deteriorate. However, condition assessment is a necessary (if not sufficient) component of any maintenance program. Furthermore, any empirical research program into the functional consequences of epoxy debonding requires that the input variable—debonding—be characterized in a consistent, complete manner.

SCOPE

This paper describes an analysis of a set of IJs with varying amounts of epoxy debonding. The purpose of this investigation is to answer questions that have not been adequately addressed in the published literature:

1. What is the typical shape of the debonded region? How does it vary within a given IJ and across a set of IJs?
2. Can visual inspection of the exterior of an intact IJ yield accurate information about the state of the epoxy bond on the hidden, interior surfaces? If so, what metrics should be used, and how should they be interpreted?

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The first question has been previously addressed in general terms. Davis et al. conducted an investigation of failure modes of IJs based on destructive disassembly of failed joints (*2*). This investigation reported that epoxy debonding typically begins near the endpost and over time spreads out toward the ends of the joint bars. However, Davis et al. did not report quantitative results about the size or shape of the debonded region.

The second question is one that also has been considered in practice, but not in published studies of which the authors are aware. Railroaders and suppliers have noticed certain visual cues that indicate when an IJ is deteriorating and have developed empirical rules that use these cues as the basis for maintenance procedures. Quantification of the relationship between visual cues and objective measures of debonding will contribute to the scientific and engineering understanding of IJs and development of improved designs and maintenance practices.

In this study, IJs with varying degrees of epoxy debonding were collected, measured, and analyzed, and then disassembled so that the condition of the epoxy bond could be viewed directly. The data were then analyzed to quantify the shape of a "typical" debonded region and the variability between different joints. Additionally, one commonly used method of estimating debonding through visual inspection was tested for accuracy.

METHODOLOGY

Test Specimens

A set of IJs, including a short section of the rail on either side of the joint, was obtained from several Class 1 North American railroads and suppliers. Two of these were new, unused, factory-manufactured IJ plugs, referred to here as the control specimens. The control specimens were assumed to have no epoxy debonding. A number of other IJs were obtained from four Class I railroads. These joints had been subject to unknown amounts of traffic before being removed from track for unknown reasons. Six of these were selected as test specimens on the basis of visual indications suggesting varying amounts of epoxy debonding. Of these six test specimens, four had been in service in the U.S. states of Illinois and Indiana and two came from a high-tonnage coal line in the western United States.

The control specimens came from two suppliers and consequently had different joint bar sections. The six test specimens each had a joint bar that matched one of the two control specimens. All samples used RE136 rail, except for one test specimen that had RE132 rail (*4*), and all had identical bar length and bolt spacing.

The specimens were labeled as follows:

- The first letter (C or T) indicates whether the specimen is a control (unused) or test (deteriorated) joint.
- The second letter (A or B) indicates the supplier, which controls both the shape of the joint bar and the epoxy–insulator materials used in its construction.
- A one-digit number differentiates between specimens that are otherwise identical. Thus, TA2 indicates the second test specimen from supplier A.
- The eight specimens included one control and three test specimens from each supplier. The two control specimens are referred to as CA1 and CB1, and the six test specimens were labeled TA1, TA2, TA3, TB1, TB2, and TB3.

Visual Inspection

The most widely used method for detecting epoxy debonding in a bonded IJ is visual inspection of the joint's exterior. FRA mandates two to four visual inspections of all rail joints in continuously welded track per year depending on traffic (*5*). These inspections must look for any of the following problems or symptoms of problems:

1. Visible cracks in the joint bar;
2. Loose, bent, or missing bolts;
3. Excessive rail end batter or rail end mismatch; and
4. Excessive longitudinal rail movement in or near the joint.

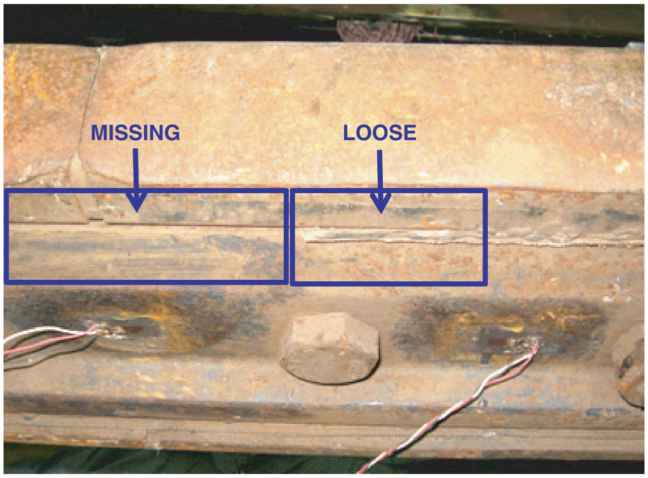
In a bonded IJ, excessive longitudinal rail movement is sometimes related to complete epoxy failure on at least two of the four rail–joint bar interfaces. When the bond fails, the rail can slip relative to the joint bars by an amount equal to the play in the bolt holes. This situation is undesirable, as the epoxy is an important part of the IJ's load-bearing mechanics. Repeated loadings under these conditions may cause insulation failures, broken bolts, and bolt-hole cracks. If the rail is in tension when the IJ is inspected, the clearest symptom of such a bond failure is a loose endpost and a wide gap between the rail ends. Another symptom is an obvious longitudinal shift in the position of the end of the joint bar relative to the rail. None of the six test specimens analyzed in this study showed any such symptoms, indicating that they had experienced progressive debonding but not complete epoxy failure.

Most railroads have inspection programs for mainline IJs that exceed FRA requirements. Signal maintainers generally conduct inspections every 30 to 90 days. The American Railway Engineering and Maintenance-of-Way Association (AREMA) publishes a recommended practice for visual inspection on bonded IJs that includes looking for, among other things, missing, cracked, worn, or broken insulation (*6*). Unfortunately, most of the insulation in a bonded IJ is hidden between the rails and the joint bars. Only the top and bottom edges of the epoxy–insulator layer are visible, at the top and bottom of the joint bars.

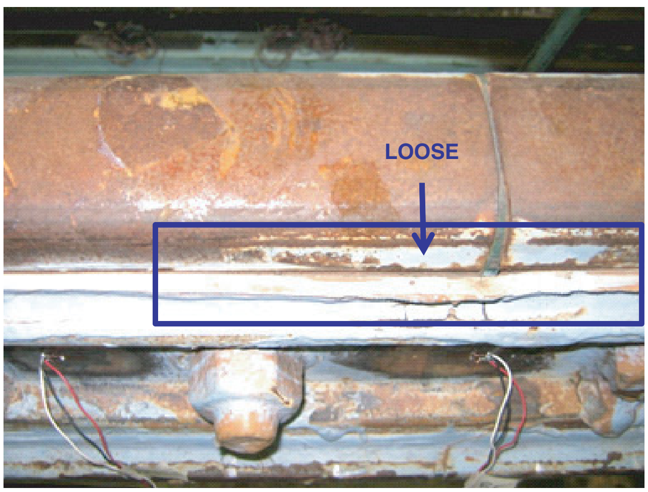
Despite this limitation, the bead of excess epoxy and the small section of the epoxy–insulator layer visible along the top of the joint bar provides useful information about progressive epoxy debonding on the interior surfaces. This outer edge of the bond layer near the center of the joint appears to pull away and break off from the joint as the interior surfaces debond. This exterior separation is probably a symptom rather than a direct cause of the deterioration on the interior surfaces, although it is possible that loose edges allow more water to penetrate into the joint. All six test specimens had at least some amount of damage to the upper edge of the insulator layer.

For this investigation, damage to the edge of the insulator and to the bead of excess epoxy was classified into two types: loose and missing (Figure 1).

1. Loose. Some or all of the insulator and excess epoxy was still present, but it was no longer sealed to the metal surfaces. In other words, this section of the edge of the insulator layer was pulling away from the joint.
2. Missing. No epoxy or insulator was visible at the top edge of the joint bar. This does not necessarily imply that the insulation between the rail and joint bar had worn away completely, only that the outside edge—the part that fills the space between the fillets on the top outer edge of the joint bar and the bottom outer edge of the rail head—had broken off.



(a)



(b)

FIGURE 1 Classifications of damage to top edge of insulator layer: (*a*) loose and missing and (*b*) loose only.

Generally damage of both types extended outward from the endpost, with the region of missing insulator (if any) occurring closest to the endpost and the region of loose insulator occurring adjacent to the missing section. This finding suggests that the outer edge of the insulator and excess epoxy tends to loosen before eventually cracking off. In view of this finding, two damage metrics were adopted:

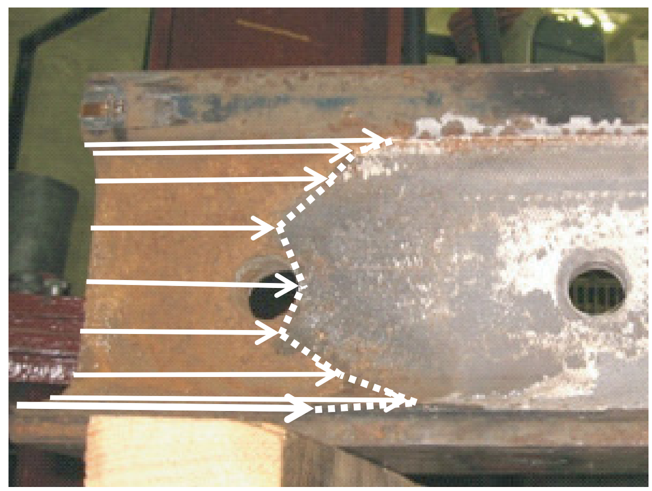
1. Distance from the endpost to the end of the missing epoxy, denoted V_m for missing, and
2. Distance from the endpost to the end of the missing or loose epoxy, denoted V_d for damaged. V_d is equal to V_m plus the length of loose epoxy.

Destructive Disassembly of Test Specimens

The six test specimens were disassembled by removing the bolts with a cutting torch and separating the joint bars. Removing the joint bars from a bonded IJ is difficult, even for joints with extensive debonding. For the two test specimens with the least debonding, only one joint bar was successfully removed.

The interior surfaces of the joint were then examined. The areas that had been affected by progressive epoxy debonding can be identified visually in a disassembled joint (*2*). Areas in which the epoxy debonded during the IJ's service life have a reddish or brown color caused by oxidation on the unsealed metal surfaces. Areas in which the metal is visible but shiny and unoxidized show where the epoxy pulled away from the metal only during disassembly. Such a surface appearing on the rail will usually be matched at a corresponding location on the joint bar by clean epoxy or a clean insulating fibers, and vice versa. Finally, areas with clean, exposed fibers on both sides indicate that the insulator fabric itself fractured, implying that it was still bonded to both the rail and joint bar. Thus, a dark or reddish color indicates an area that debonded before disassembly, whereas a light, epoxy-colored, or shiny surface indicates a part of the layer that stayed bonded until disassembly.

For each test specimen, the distance from the endpost to the first intact epoxy was measured along nine horizontal lines—three on the underside of the rail head, three on the web, and three on the top side of the base (Figure 2*a*). These measurements were repeated for each



(a)

(b)

FIGURE 2 Disassembled IJs: (*a*) measuring the debonded region and (*b*) inclusive versus strict debonding.

of the four rail–joint bar interfaces, on both the rail and the corresponding joint bar. (For two joints, TB1 and TB2, only one joint bar was successfully removed; therefore, only two rail–joint bar interfaces were available for measurement.) When the measured distance on the rail differed from the measured distance on the joint bar, the maximum value was used. These one-dimensional measurements were then used to estimate the shape and area of the debonded regions.

There is some subjectivity in measuring the debonded region. Two patterns in particular introduced some uncertainty:

1. Areas in which small dark red or brown patches were speckled with other light-colored patches.
2. Areas with dark brown or black, but not reddish, discoloration. All of the bonded metal surfaces should have remained clean and shiny while sealed beneath the epoxy. Given that such areas tend to occur in proximity to heavily rusted areas, they might show where the surface has debonded and been exposed to air and moisture, but not long enough for visible rust to form. Or a dark color could simply mean that some carbon or dirt was present when the joint was assembled. It could also indicate some chemical process in the curing epoxy, which might or might not affect bond strength.

It is difficult to say whether these phenomena indicate anything that would affect joint performance. Therefore, two sets of measurements were included in this study. One set, called the inclusive measurement of debonding, included all areas with dark discoloration or heavy speckling. The other set of measurements, referred to as strict debonding, included only those areas in which reddish brown rust or dirt covered all or most of the surface. An example of the difference between the two measurement sets is shown in Figure 2*b*. The area of the debonded region measured using the inclusive criteria is referred to as A_i, whereas the area measured using the strict criteria is A_s.

The appearance of the surfaces exposed by disassembly differs between IJ manufacturers. Debonding was easier to identify on test specimens from Supplier B, on which the areas of intact epoxy bond tended to be silver or white in color, than on those from Supplier A, on which the bonded areas often had a yellow or brown hue.

In most cases, some debonding also occurred near the outer edges of the joint bars, spreading toward the endpost. These areas were also measured, but turned out to be small in relation to the corresponding debonded region near the endpost. These areas were not included in the reported results or considered in the analysis.

SIZE AND SHAPE OF DEBONDING REGIONS

Total Area

The total area of the debonded region for each test specimen—A_i for area measured using the inclusive criteria, A_s for strict criteria—is given in Table 1. This is the simplest single statistic for representing the extent of epoxy debonding in a rail joint. Note that the total debonded area for a joint is the sum of the debonded areas on each of the four bonded rail–joint bar interfaces.

A_i Versus A_s

Because A_i is defined to include some areas not included in A_s, the ratio A_s:A_i will always be less than or equal to 1 for all rail–joint bar interfaces. For the test specimens studied, the average ratio A_s:A_i was 0.67. The maximum value of this ratio was 0.95, the minimum was 0.36, the median was 0.69, and the standard deviation was 0.17. The difference between these two measurements of debonding is large enough that they must be analyzed individually.

TABLE 1 Debonded Areas

Specimen	A_i (mm^2 × 1,000)	A_s (mm^2 × 1,000)
TA1	99	58
TA2	134	79
TA3	180	160
TB1[a]	34	21
TB2[a]	20	8
TB3	140	111

[a]Estimated from measurement of one side only.

Distribution of the Debonded Area Within a Joint

Four interfaces are formed between the two rails and the two joint bars, which may have different amounts of debonding. It is possible that IJ behavior might be sensitive not only to the total amount of debonding over all four interfaces, but also to the distribution of debonding over these interfaces. For instance, the longitudinal strength of the epoxy bond is likely to be determined by the two interfaces with the weakest remaining bond strengths, because slippage can occur when the bonds at only two interfaces fail.

Some nomenclature must be defined to formulate the questions of interest. The term "side" is used to denote the two interfaces associated with one joint bar—the field side versus the gage side. The term "end" is used to denote the interfaces associated with one particular piece of rail. To an observer standing to the side of the rail, one end will be to the left, and the other end will be to the right.

Practitioners have noted that one end often appears more deteriorated, especially on tracks with directional traffic or heavier tonnage in one direction than the other. It is also possible that more debonding might occur on one side than the other, given the presence of lateral loads in the track. However, even if there is no systematic difference in debonding between the two sides, some random variation will occur. Therefore, it is necessary to analyze the data carefully to determine whether debonding tends to be more extensive on one side or end than the other.

The average ratio of debonding on one end versus the other was 1.4 for inclusive debonding and 1.7 for strict. By contrast, the average ratio for one side versus the other was only 1.1 for inclusive and 1.0 for strict. An analysis by Peltier showed that the tendency for one end of the joint to have more debonding than the other is statistically significant (*3*). It is not known if the specimens had been exposed to directional traffic, but the results are consistent with practitioners' observations that one end tends to degrade faster than the other. The smaller differences in debonded area between the field and gage side were not statistically significant, however, and can likely be attributed to random variation.

Shape of the Debonded Region

In addition to the distribution of debonding over the different rail–joint bar interfaces, some consideration must be given to the shape of the debonded region. As noted above, debonding tends to begin near the endpost and grow outward toward the edges of the joint bar; however, the interface between bonded and debonded is usually not a straight vertical line. More common is a V or U shape (Figure 3*a*), where debonding extends farther along the top and bottom of the interface than along the bolt line.

The shape can be described using the following measurements:

- *H* is the average distance from the endpost to the first intact epoxy along the upper part of the interface, where the joint bar meets the underside of the rail head;
- *W* is the average distance from the endpost to the first intact epoxy along the part of the interface adjacent to the rail web; and
- *B* is the average distance from the endpost to the first intact epoxy along the bottom of the interface, where the joint bar meets the top of the rail base.

The characteristic shape in Figure 3*a* corresponds to values of *H* and *B* that are larger than *W*. It appears that debonding tends to begin along the upper and lower edges of the interface (Figure 3*b*); that is, *H* and *B* grow to a certain value while *W* remains small. It is assumed that after a certain amount of degradation all three measurements start to grow equally, so that *H*–*W* and *B*–*W* remain approximately constant.

Summary statistics of the relevant measurements of *H*–*W* and *B*–*W* for each rail–joint bar interface were calculated for all of the test specimens (Table 2). The average and median values were generally close to 30 mm and approximately one standard deviation above zero. (The sole exception was the *H*–*W* measurement for inclusive debonding, which had similar average and median values but larger variance.) It is difficult to draw strong statistical conclusions from these numbers, because the four interfaces of each joint may not be independent, but it does appear that debonding tends to be more extensive near the top and bottom of the insulator layer than at the center.

(a)

(b)

FIGURE 3 Shape of debonded region: (*a*) debonding (dark area) extends farther on head and base than on web and (*b*) onset of debonding at endpost.

TABLE 2 Difference Between Extent of Debonding on Different Parts of the Rail–Joint Bar Interface as Measured from the Endpost (mm)

	Inclusive		Strict	
	H–*W*	*B*–*W*	*H*–*W*	*B*–*W*
Average	35	27	24	35
Median	26	28	20	31
Maximum	179	78	75	85
Minimum	–89	–22	–3	–6
Std. Dev.	62	27	21	27

This conclusion is consistent with several known features of the debonding process. Finite element modeling has suggested that shear and peel stresses due to wheel loads, which are believed to promote debonding, are highest near the top and bottom edges of the layer in a fully bonded IJ (*7*). Due to both simple bending deformation and shear lag, the same tendency could be expected to continue as the epoxy bond recedes from the endpost. The top and bottom regions are also more exposed to moisture, which has been experimentally demonstrated to hasten the debonding process (*8*).

EFFECTIVENESS OF VISUAL INSPECTION

The visual inspection conducted in this study examined the top edge of the insulator layer where it is visible between the rail and joint bar. The debonding patterns observed in the disassembled IJs suggested that inspecting only this part of the bond might be somewhat misleading. In some cases, disassembling the joint revealed that the outer edge of the insulator layer had itself come debonded from the filleted edges on the rail or joint bar, but this debonding did not extend inward past the fillets (Figure 4). More generally, the tendency for debonding to extend farther along the top of the interface than along the center is a potential problem for a measurement based only on the very top edge. However, comparing the results of the predisassembly inspection with the postdisassembly debonding measurements showed that the visual metric V_d can be used to estimate the area of the debonded region with reasonable accuracy.

Estimating the Debonded Area of a Joint

The visual inspection metrics V_m and V_d were measured for each rail–joint bar interface of each joint. The results from each interface can be compared with the debonded area on that interface, but statistical analysis of the relationship is complicated by a possible lack of independence of multiple data points recorded for each joint (*3*). This problem is avoided by comparing the inspection results for the entire joint with the total debonded area of the joint.

FIGURE 4 Debonding behind visible edge of insulator without corresponding debonding on hidden surface.

V_m and V_d were computed for a whole joint by summing the length of missing, or missing and loose, top insulator edge on each of the four interfaces of that joint. Plotting these measurements versus the debonded area of each interface revealed a strong correlation (Figure 5). The relationship between V_d and debonding appears linear over the whole range of measurements; a straight line, constrained to pass through the origin, was fit to these data. V_m was complicated by several joints with measurable debonding having $V_m = 0$. It does appear that V_m has some relationship with debonding when it is nonzero, but the correlation is not as strong as for V_d. Therefore, it appears that V_d is a more useful indicator of debonded area than V_m.

The purpose of visual inspection is to estimate debonding from the visual metrics, and so a goal of this statistical analysis was to develop confidence intervals for that estimate. Because V_d appears to be the more useful metric, the error analysis included estimates of A_i and A_s that are based only on V_d, not V_m. The debonded area was estimated by multiplying V_d by the slope of the regression line in Figure 5. It is reasonable to assume that the residuals of the estimate are independent and normally distributed, so that a confidence interval can be estimated using the Student's t distribution with 7 degrees of freedom (see below). The results show that V_d allows for A_s to be estimated more accurately than A_i.

Debonding Criteria	*80% Confidence Interval*
Inclusive	$A_i = V_d \times 206\ \text{mm} \pm 27{,}000\ \text{mm}^2$
Strict	$A_s = V_d \times 161\ \text{mm} \pm 11{,}000\ \text{mm}^2$

Visual Damage Versus Average Extent of Debonding

V_d is a linear measurement taken from the endpost out along the top edge of the insulator to the point at which the edge is no longer missing or loose. A_i and A_s for each joint were also estimated using a

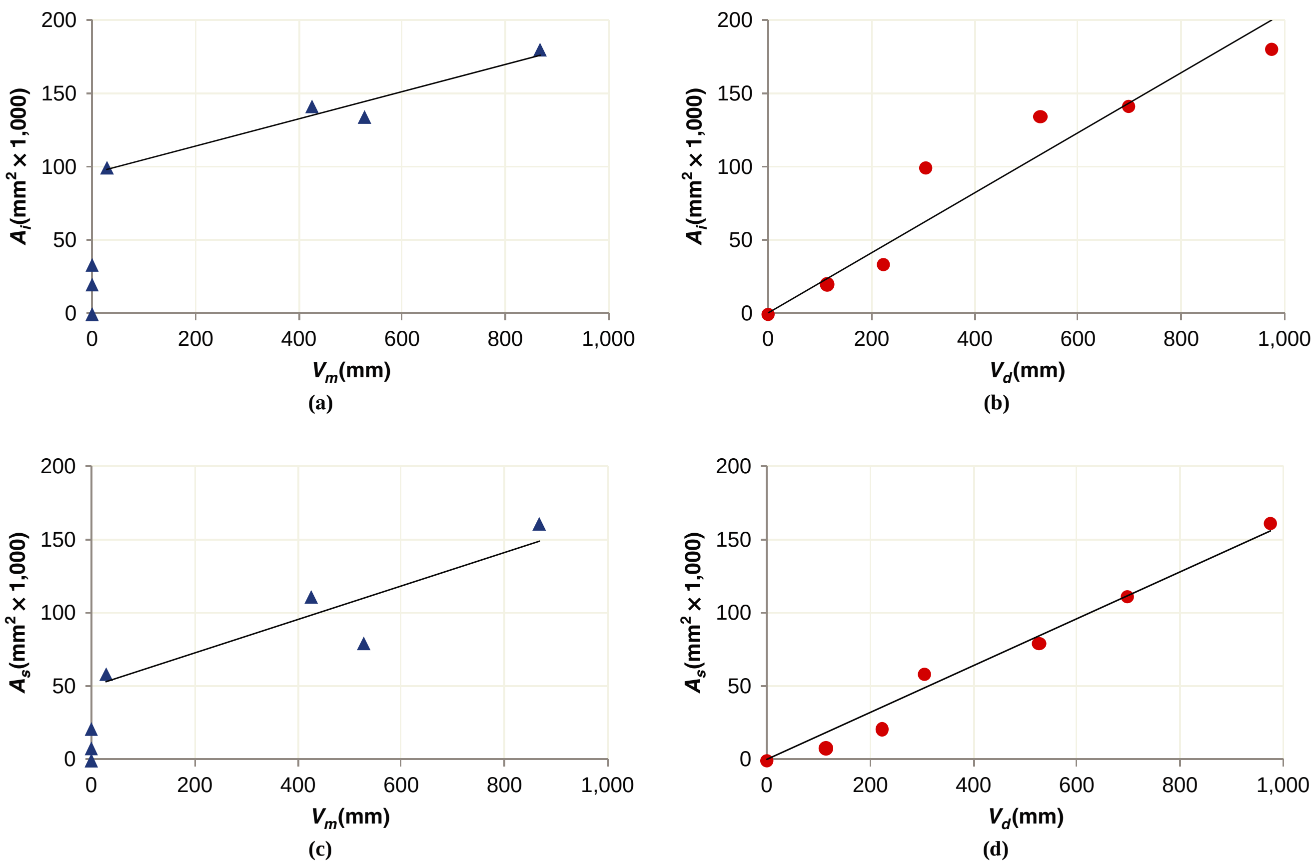


FIGURE 5 Actual debonding versus visual inspection metrics for control and test specimens: (*a*) A_i versus V_m, (*b*) A_i versus V_d, (*c*) A_s versus V_m, and (*d*) A_s versus V_d.

number of similar linear measurements from the endpost to the point of first intact epoxy. It is interesting to consider how these linear measurements compared in absolute terms. The previous section implies that the length V_d of the loose or missing insulator edge correlated with the extent of the debonding, but was it in fact equal to the average distance from the endpost to the intact epoxy over the whole interface?

The distance along the joint bar–epoxy interface from bottom edge to top edge is approximately 175 mm. Given a debonded area, the "average" distance from endpost to intact epoxy can be calculated by dividing the debonded area (either A_i or A_s) by 175 mm. If V_d were exactly equal to the average extent of debonding, debonding would equal $V_d \times 175$ mm. In fact, V_d must be multiplied by 201 mm to estimate A_i, or by 159 mm to estimate A_s (see above). Thus, the damage to the edge of the insulator layer extended, on average, about 15% less than the average extent of inclusive debonding and about 9% more than the average extent of strict debonding.

CONCLUSIONS

Subjectivity of Measurements of the Debonded Region

Although it is possible to learn a great deal about the state of progressive epoxy debonding in an IJ by disassembling it and visually examining the rail–joint bar interfaces, certain areas displayed some but not all of the expected visual signs of debonding. Therefore, some judgment and interpretation is needed to determine the exact shape of the debonded region. Two different criteria for determining the debonded region (inclusive and strict) were used to calculate the debonded area. Of the two, the strict criteria yielded more consistent statistical measurements of the shape of the debonded region and correlated better with visual inspection metrics, although this does not necessarily imply that the strict criteria are more important to the performance or likelihood of failure of a given joint.

Shape and Distribution of the Debonded Region

Epoxy debonding tends to begin at the endpost near the top edge, bottom edge, or both edges of the joint bar. At some point debonding also begins to affect the part of the insulator layer adjacent to the rail web, but it tends to remain more extensive on the upper and lower portions—the parts adjacent to the bottom of the rail head and top of the rail base. On average, debonding extends about 30 mm farther along these head and base portions than along the web portion of the layer, but there was considerable variation among specimens. The variability was greater when using the inclusive measurement of debonding than when using the strict measurement.

Debonding occurs on all four rail–joint bar interfaces within a joint. The size of the debonded region does not vary significantly between the field side and the gage side. However, there is a significant tendency for one end of the joint to have more debonding than the other end.

Visual Inspection

Two visual inspection metrics were defined for each rail–joint bar interface on the basis of the appearance of the upper edge of the insulator layer, where it is visible between the rail head and the top of the joint bar. V_m is the distance from the endpost to the first visible epoxy or insulator, even if it has pulled loose from the surface. V_d is the distance from the endpost to the first section of the insulator layer edge that is intact in its original position and not separated from either metal surface.

V_d turned out to be the more useful of the two. This result is largely because V_m tends to remain zero until the debonded area becomes sufficiently large, whereas V_d begins to increase with very little debonding.

V_d correlates well with the strict debonded area, A_s, and, to a lesser extent, the inclusive debonded area, A_i. One millimeter of missing or loose top edge corresponded to 201 mm^2 of A_i and 159 mm^2 of A_s. These relations allow the debonded areas A_i and A_s to be estimated to within ±28,000 mm^2 and ±12,000 mm^2 respectively.

Application and Future Studies

The results of these experiments have several applications to future studies of IJ deterioration and maintenance standards.

There is little published information on the quantitative relationship between the extent of debonding and the functional failure of IJs. Three research questions are worthy of study:

1. What is the relationship between the debonded region and the longitudinal strength of the epoxy bond?
2. How does debonding affect the response of the IJ to vertical loads, such as the track deflection or the development of fatigue cracks?
3. What influence does the amount of debonding have on the development of electrical faults?

In each case, the shape and extent of the debonded region must be characterized to see how the variation in debonding influences the results. The results of this study show that at least two parameters are required to describe the extent of debonding because there can be more debonding on one end than on the other. It may also be necessary to consider the extra debonding that occurs along the top and bottom of the rail–joint bar interface, which can vary from sample to sample.

It is also helpful to know that debonding on the field and gage sides is roughly equal. For instance, the longitudinal strength of the epoxy bond is theoretically equal to the sum of the strengths of the two weakest rail–joint bar interfaces. Results of this study suggest that the two weakest interfaces generally lie on the same rail end. Therefore, longitudinal strength of an IJ with debonding can be calculated by sawing through the joint bars at the endpost and testing the shear strength of the bond on each half individually, as described by AREMA for acceptance testing of new joints (*4*).

In practical terms, railroads wish to know whether a given IJ with a certain amount of deterioration should be left in service or replaced. Replacement costs money, but reduces the potential for disruptive electrical or physical failure. The above proposed research would help to clarify this question, but would be moot unless debonding can actually be quantified in the field. Results of this study show that the size of the debonded area can be determined quite accurately using careful visual inspection, and is therefore appropriate to use as a basis for IJ maintenance and replacement criteria.

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