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Federal Railroad
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Repair of Budd Pioneer Coach Car Crush Zones

Rail Passenger Equipment Impact Tests

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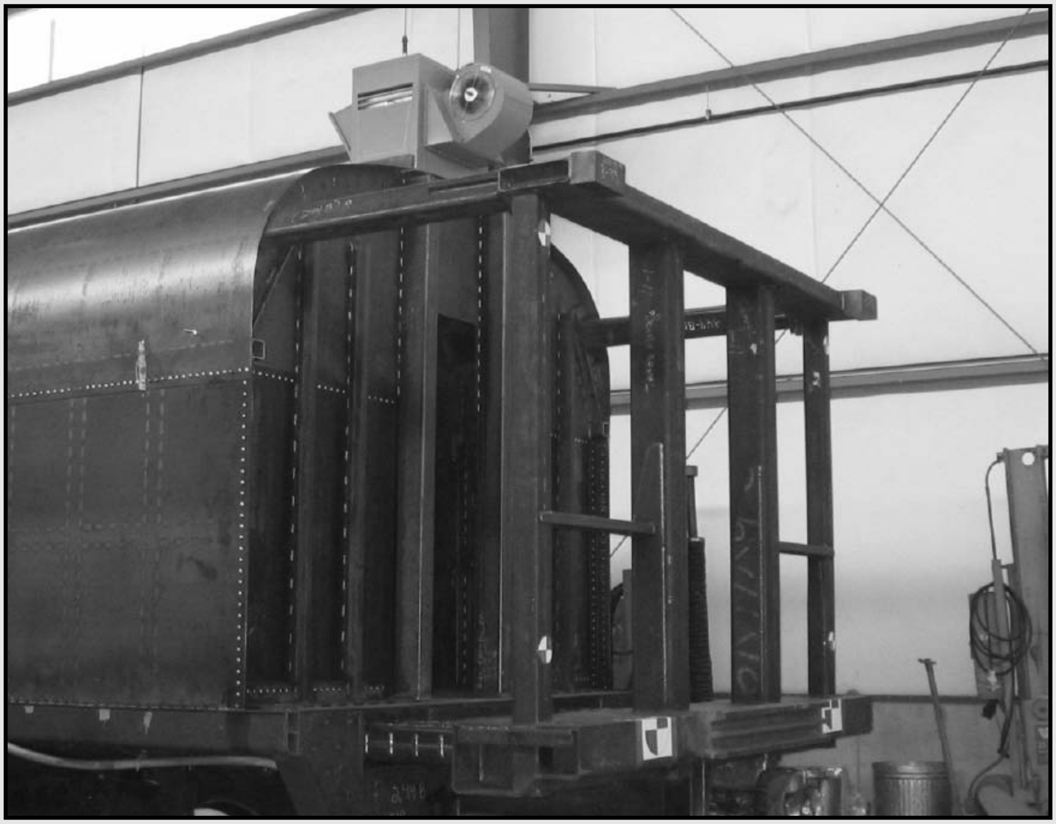

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13. ABSTRACT (MAXIMUM 200 WORDS) The research team conducted a project to repair cars for use in a full-scale train-to-train collision test with crash energy management systems. The two cars had been damaged in previous dynamic tests. Several components required replacement, and some required design modification. This report describes the damage to the cars from the tests, and the various actions needed to repair and modify the components. Some collision dynamics and finite element analyses were conducted in support of the modifications. The project included fabrication and assistance in implementing the repairs.			
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1 pint (pt)	= 0.47 liter (l)		
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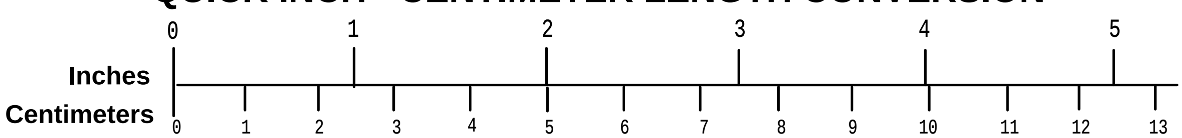

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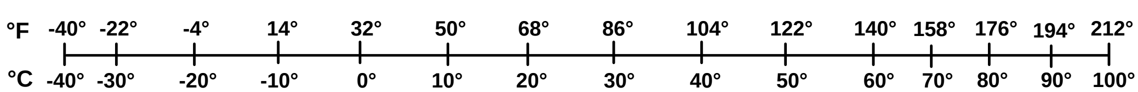

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Preface

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Executive Summary

The Volpe National Transportation Systems Center (Volpe Center) and the Federal Railroad Administration (FRA) conduct active research to improve rail vehicle crashworthiness. The Volpe Center and FRA conducted a baseline 30 mph (48 km/h) train-to-train crash test with conventional (strength-based) equipment in which the cab car was leading. The cab car experienced about 22 ft (6.7 m) of crush with substantial loss of occupied volume. Studies by the Volpe Center indicate that implementation of crash energy management (CEM) will greatly mitigate the amount of crush in such a collision, isolating deformation to unoccupied areas and preventing override and lateral buckling. The research team conducted one- and two-car tests on cars retrofitted with CEM crush zones on December 3, 2003, and February 26, 2004, respectively.

The next phase of the program was to conduct a full-scale train-to-train test similar to the baseline test but with equipment in the moving train retrofitted with crush zones at each vehicle end (except for the locomotive). This program required a total of 10 crush zone ends: two cab car ends–one at the lead end of the moving train and one coupled to the trailing locomotive–and eight coach car ends. A separate program designed and built the two crush zone ends for the cab cars. Of the eight coach car crush zones, four were attached to Budd M1 cars, and the other four were repaired and modified versions of the crush zones tested in the one- and two-car CEM tests. A separate program adapted the existing coach car crush zone to the Budd M1 cars. The program described in this report focuses on the repair and modification of the tested Budd Pioneer crush zones that were used in the full-scale train-to-train test. The program includes examination and assessment of the condition of the tested cars, development of repairs and modifications to address some of the lessons learned in the previous tests, fabrication of components needed to achieve the repairs and modifications, and support in the actual repairs at the Transportation Technology Center (TTC).

The crush zones performed as intended in the one- and two-car full-scale CEM crash tests. Damage was isolated to the components designed to be sacrificial and replaceable. The shear bolts of the push-back coupler fractured as intended, and the honeycomb absorber was crushed to the design value. (After the test, the buff lug had to be sacrificed in order to remove the honeycomb absorbers.) The bell-mouth plate and the coupler carrier were also damaged as the coupler pushed back, again as intended. An unexpected result was the deformation of the cover plate below the push-back coupler buff lug. The rear face of the end beam deformed in the area where the primary energy absorbers contacted it. In addition, the corner posts and the antitelescoping (AT) beam experienced a small amount of bowing due to impact between the top corner spacers and the impact wall. These modes of deformation required only minor repair. Both the sliding sill and the fixed sill shear bolt holes were slightly elongated; the hole elongation was more significant in the fixed sill. All sliding sill-to-fixed sill shear bolts fractured as intended during the trigger of the sliding sill. Each primary energy absorber was crushed to some extent so that none of them could be reused. The shear rivets of each roof absorber fractured, and some of the roof absorber cartridges crushed. Several uncrushed cartridges, however, could be reused. The two-car CEM test also revealed that the sliding components could be pulled out of the car as the cars rebounded from the impact.

Many of the components required replacement using the original design and materials. These included the buff lug, the push-back coupler honeycomb absorber, the coupler carrier, the shear bolts and shear rivets, and the roof absorber cartridges. Some components required modification. The bell-mouth plate was restored to original condition by welding together pieces rather than using a single piece. A new, larger cover plate installed below the buff lug in the sliding sill prevented buff lug rotation during push back. Adding a plate to the back of the end beam reinforced the rear of the buffer beam. The AT beam and the corner posts were not straightened, but adjusting the spacers on the outboard surface of the AT beam compensated for the displacement associated with the slight bowing. A spacer was also added at the center of the AT beam to better distribute the impact load. The slightly elongated holes in the sliding and fixed sills were reused for the shear bolts. The primary energy absorbers had essentially the same design as before, but they were shortened by 1.5 in (38 mm) to account for the reinforcing plate on the back of the end beam and a plate at the inboard end of the absorber that was used to facilitate installation in the repaired cars. Modifications were made to the sliding tube of the roof absorber to prevent cracking at the welded connection to the AT beam. The shear rivet pattern was changed to permit access for the riveting tool now that the roof absorber system was assembled in the cars. A retention device was designed to prevent the sliding components from being pulled away from the car on rebound. This device attaches the ends of the primary energy absorbers to the end beam but transfers load only in draft.

The program included the fabrication of the components needed for the repairs and assistance in carrying out the repairs at TTC. As part of the program, tests were conducted to determine the shear strength of the push-back coupler and sliding sill-to-fixed sill shear bolts. The research team conducted analysis on the design modifications made in the repair of the Budd Pioneer cars to verify that the crush zone would perform as intended.

1. Introduction

FRA and the Volpe Center are engaged in active research to improve rail vehicle crashworthiness. A key element of this program is the study of CEM, or crush zone, systems for passenger vehicles and the manner in which such technology provides practical benefit in American operations. The passenger rail equipment impact test program has completed full-scale tests on equipment designed to current, strength-based standards. These tests established a baseline against which improvements provided by CEM systems can be measured.

The baseline train-to-train test consisted of a train moving at about 30 mph (48 km/h), with the cab car leading, colliding with a standing train in which the locomotive was the lead (impacted) vehicle. The cab car leading train included the cab car, followed by the equivalent of four coach cars and, at its aft end, a passenger locomotive. The cab car experienced about 22 ft (6.7 m) of crush in the test. Figure 1 shows the visible damage to the cab car after the test. Implementation of CEM will greatly mitigate the amount of crush in such a collision, isolating deformation to unoccupied areas and preventing override and lateral buckling.

Figure 1. Cab Car Crush in the Train-to-Train Test

The first part of the crush zone test program included design, fabrication, and testing of coach car crush zones for one- and two-car full-scale tests. These crush zones were designed for integration onto existing Budd Pioneer cars. The crush zones functioned as intended and experienced only minor damage.

The next phase of the program, completed on March 23, 2006, was to conduct a full-scale train-to-train test essentially identical to the baseline test but with equipment in the moving train that has a crush zone at each vehicle end (except for the locomotive.). Thus, a total of 10 crush zone ends were needed: two cab car ends–one at the lead end of the moving train and one coupled to the trailing locomotive–and eight coach car ends. A subsequent program designed and built the two crush zone ends for the cab cars. Of the eight coach car crush zones, four were attached to Budd M1 cars, and the other four were repaired and modified versions of the crush zones tested in the one- and two-car CEM tests. A separate program adapted the existing coach car crush zone to the Budd M1 cars.

The program described in this report focuses on the repair and modification of the tested Budd Pioneer crush zones so that they can be used in the next full-scale test. The program included examination and assessment of the condition of the tested cars, development of repairs and modifications to address some of the lessons learned in the test, fabrication of components needed to achieve the repairs and modifications, and support in the actual repairs at TTC.

2. Budd Pioneer Coach Car Crush Zone End Design

Figure 2 shows a photograph of one of the crush zone ends before testing. Separate documents [1-3] describe the design and fabrication of these crush zones. Figure 3 shows a model of a coach end structure with callouts to key components. The crush zones include the following key components (see also Figure 3):

- *A push-back coupler with energy absorber.* The coupler is supported longitudinally by the yoke and draft gear elements, the latter of which are in turn supported by a buff lug. The buff lug is bolted to the sliding sill through eight shear bolts, four on each side. When the impact force on the coupler reaches a load of about 600,000 lbf (2,668 kN), the bolts shear and the buff lug moves back, crushing an aluminum honeycomb block. This block is in turn supported by a spacer bolted to the rear of the sliding sill. The push-back coupler absorbs approximately 330,000 ft-lb (0.45 MJ) of energy and has 0.67 ft (0.20 m) of stroke.
- *The sliding sill mechanism.* The sliding sill provides a guide for the end crush of the car and a vertical and lateral load path for offset loads. It consists of a box beam sliding within guide channels. It is attached to the fixed sill through 12 shear bolts, six on each side. After the push-back coupler and its absorber are activated, the ends of coupled cars come into contact through the end beams (with ribbed anticlimbers), as well as spacer blocks on the AT plate. The load at the end frame rises, and the sliding sill shear bolts fracture when the impact load reaches a value of about 1,200,000 lbf (5,338 kN).
- *Primary energy absorbers.* Two primary energy absorbers are on the car, one on each side of the centerline of the car. Each absorber consists of two crushable tubes that, at their inboard ends, are welded to and supported by car structure that is not intended to deform. The load on the outboard ends of the primary energy absorbers is applied by the back of the end beam. An initial gap exists between the outboard end of the absorber and the back of the end beam before activation of the crush zone (so that the absorbers do not carry operational loads). The energy absorbers absorb approximately 1,920,000 ft-lb (2.6 MJ) of energy and have 2 ft (0.6 m) of stroke.
- *Roof absorbers.* Two roof absorber assemblies are on the car, one on each side. They consist of a plunger element attached to the back surface of the AT beam. This plunger is riveted to a tube of larger size that contains aluminum honeycomb cartridges. When the load at the roof absorber reaches a value of about 90,000 lbf (400 kN), the rivets shear and the plunger pushes back against the honeycomb pieces. The roof absorbers absorb approximately 220,000 ft-lb (0.3 MJ) of energy and have 2 ft (6 m) of stroke.
- *Integrated end frame.* The integrated end frame is designed to remain sufficiently stiff in transmitting the impact load to the energy absorbers, ensuring the proper functioning of the crush zone elements. The integrated end frame can appropriately trigger and allow crushing of the energy absorbers when the couplers and the anticlimber share the impact load or when the lead path is only through the coupler or the anticlimber.

Figure 2. Crush Zone End 244B Before Testing

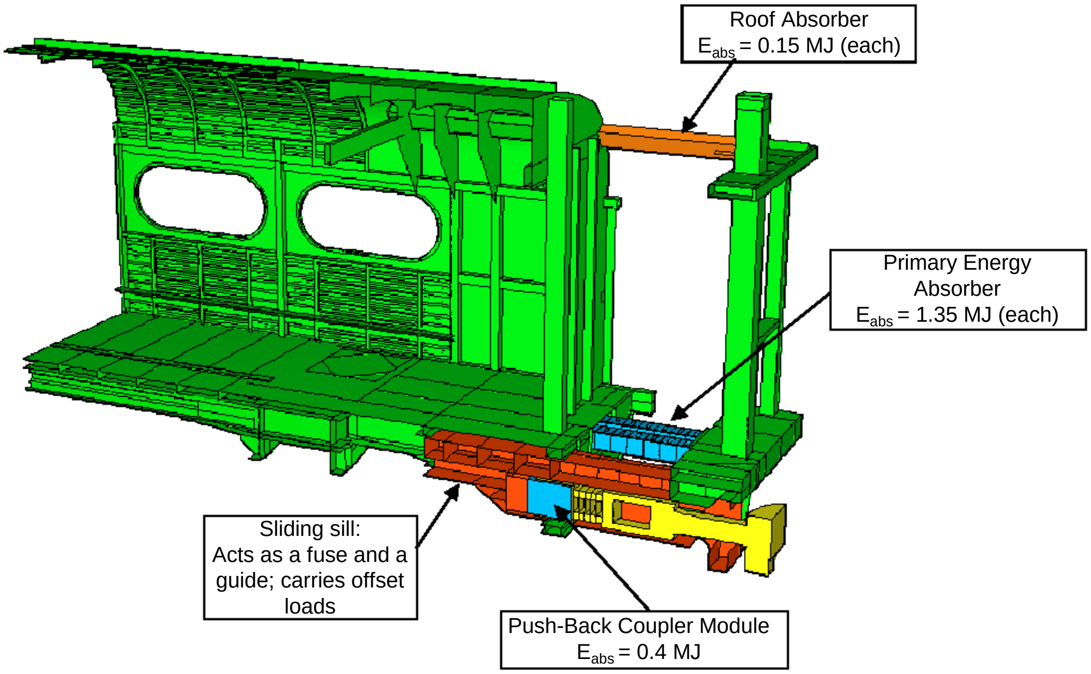

Figure 3. Schematic of the Budd Pioneer Coach Car Crush Zone

3. Condition of the Tested Crush Zones

Table 1 lists the four crush zones that the researchers tested in the one- and two-car full-scale CEM tests. (See references 4 and 5 for more information on these tests.) The table includes the positions of each crush zone for these two tests.

Table 1. Test Positions of the Budd Pioneer Coach Car Crush Zones

Crush Zone End	Test	Position
248A	One-car	Lead end
248B	Two-car	Car 2, lead end
244A	Two-car	Car 1, lead end
244B	Two-car	Car 1, trailing end

The research team used Car 248 for the one-car CEM test. The A-end impacted the rigid barrier at 34.1 mph (54.9 km/h). The crush zone was nearly exhausted with a total crush, not including coupler push back, of approximately 27 in (690 mm); the maximum possible crush of the crush zone is 30 in (760 mm).

The crush zone was also exhausted for end 244A, which was at the impact interface in the two-car test. The other two ends, 248B and 244B, which were at the coupled interface of the two-car test, experienced a relatively small amount of crush.

Table 2 lists the components that were damaged in the test and the required repair. The table discusses each component.

Table 2. Components Requiring Repair

Subsystem	Component	Key Observations
Push-back coupler	Couplers	• The two couplers used on ends 244B and 248B were in good shape and could be reused. • The other two couplers used on ends 244A and 248A had part of the head cut off for the wall tests and could not be used for the next tests.
	Yokes and pins	• The yokes used in the original crush zones were in good shape.
	Draft gear elements	• The elements used in the original crush zones were in poor condition; all needed to be replaced.
	Buff lug	• The buff lugs on all four crush zones could not be reused.
	Buff lug shear bolts	• All fractured.
	Push-back coupler, honeycomb absorber	• The absorbers were crushed to some extent in all cases. For the B-ends, the absorbers were nearly completely crushed; for the A-ends, the absorbers were crushed about 20 percent; all needed to be replaced.
	Cover plate for the push-back coupler	• The cover plates were deformed; design needed to be changed.
End beam	End beam rear surface	• The rear of the end beam on which the primary energy absorbers bear during crush was dished toward the car end by about 0.25 in (6.4 mm) at its center. • The frames (intended to contain the absorbers laterally and vertically) had to be removed. • The border around the dished area was relatively flat.
	Bell-mouth face plate	• The face plate was cut at the point at which it intersected with the angle side plates of the sliding sill to prepare for the repair. • The remnant was in good condition.
	Coupler carrier	• The coupler carrier components were damaged beyond repair.
	Anticlimber	• The two anticlimbers were in good condition. • The plates were welded onto the end beam on two crush zone ends that required new anticlimbers.
End frame	AT beam	• The corner posts and the AT beam were bent back about 0.25 in (6.4 mm) on the crush zones that impacted the crash barrier; spacer blocks had to be adjusted to account for the deformation.
Sliding sill/fixed sill	Holes in sliding sill for buff lug shear bolts	• The holes did not appear to be elongated in the longitudinal direction: the original (nominal) diameter was 0.813 in (20.7 mm); the measured dimension in the longitudinal direction did not exceed 0.815 in (20.7 mm).
	Sliding sill-to-fixed sill shear bolt holes	• The holes were elongated in the longitudinal direction: the original (nominal) diameter was 1.0625 in (27 mm); the measured dimension in the longitudinal direction was as much as 1.10 in (28 mm).
	Fixed sill shear bolt holes	• The sliding sill slid into the fixed sill with little resistance. • The holes were elongated in the longitudinal direction: the original (nominal) diameter was 1.0625 in (27 mm); the measured dimension in the longitudinal direction was as much as 1.09 in (27.7 mm). • It did not appear to be possible to drill new holes without also removing the front reaction group and all components welded to it; the drill was too large. • It was technically possible to enlarge the holes with a smaller tool, but it would have been very difficult; holes were left as is.

Table 2. Components Requiring Repair (cont.)

Subsystem	Component	Key Observations
Primary energy absorbers	Primary energy absorbers	• The absorbers were crushed to some extent in all cases; for the B-ends, the absorbers were nearly completely crushed; for the A-ends, the absorbers were crushed about 20 percent.
	Front reaction group	• The surface of the center plate was in good condition after removal of the damaged primary energy absorbers.
Roof absorbers	Roof absorber, sliding tube	• The sliding tubes were in very good condition. • The tubes slid easily into the fixed tubes. • The end that is against the AT beam needed modification because of cracks in the welded connection.
	Roof absorber, fixed tube	• The end plate was removed to the absorber elements. • The fixed tubes were in very good condition. • A slight bulge was in one tube between intermittent welds where honeycomb material bunched up. • The existing rivet holes were only slightly elongated. • The area of shear rivet holes could not all be reached with the rivet tool.
	Roof absorber, honeycomb elements	• Most of the honeycomb elements were crushed too much for reuse. • About 20 cartridges could be reused.
	Roof absorber, adjacent carline	• The carline immediately inboard of the inside end of the fixed tube required cutting to permit access to the honeycomb absorbers.

3.1 Coupler Hardware

The two couplers used on ends 244B and 248B experienced no damage and could be reused. The heads of the couplers on ends 244A and 248A had been cut off for the tests against the flat wall and therefore were not suitable for any of the ends in the CEM train-to-train test. The yokes, pins, and some of the draft gear pads also had no perceptible damage and could be reused.

During the one-car test, the cover plates for the draft gear and push-back coupler components deformed. To avoid this deformation for the two-car test, an additional welded tie plate joined the buff lug cover plate and the lengthened draft gear cover plate.

3.2 Buff Lug Hardware

The buff lug hardware includes the buff lug, the shear bolts, the honeycomb absorber, and the honeycomb absorber support. The buff lug is a box structure that supports the draft gear before and after the push-back coupler is activated. The bolts that connect it to the sliding sill fractured (by shear), as intended, in all four car ends. The push-back coupler aluminum honeycomb absorber, which fits within the buff lug, crushed for each car end and could not be reused. In each case, the honeycomb jammed within the buff lug so that the lug had to be cut to remove the absorber for inspection. Therefore, all of the buff lugs also required replacement. The honeycomb absorber support was not damaged for any car end during the tests and could be reused. Figure 4 shows a photograph of one of the supports with the push-back coupler honeycomb absorber.

Figure 4. Push-Back Coupler Honeycomb Absorber with Its Support Element After the Full-Scale Test

3.3 Sliding Sill and Related Components

Deformation of the sliding sill occurred only at the bolt holes that connect the sliding sill to the fixed sill; the holes for connecting the buff lug to the sliding sill were not perceptibly deformed. The holes that did deform were elongated in the longitudinal direction by less than 0.010 in (0.25 mm) in every case. (The holes in the fixed sill showed greater deformation; see below.) Figure 5 shows an example of the holes after the test. The sliding surface was generally in very good condition, but burrs were in proximity to the deformed holes, requiring limited grinding.

The bell mouth on each crush zone was severely deformed, as intended. Figure 6 shows an example. The damaged components included the face plate and the coupler carrier hardware (two channels and three springs). The sides of the bell mouth experienced no significant damage.

Figure 5. Bolt Hole in the Sliding Sill of One of the Crush Zones After the Test

Figure 6. Bell Mouth on End 248A After the One-Car CEM Test

The cover plate below the bottom buff lug and push-back coupler absorber deformed, as shown in Figure 7. A combination of load eccentricity on the buff lug from the draft gear and asymmetrical deformation of the honeycomb absorber led to large loads on this plate. To avoid this deformation, the cover plate required a modified design.

Figure 7. Cover Plate on the Bottom of the Sliding Sill Immediately Below the Buff Lug

3.4 End Frame

The end frame includes the collision and corner posts, the end beam, the AT beam, and the shelf. Three areas experienced some damage as a result of the tests.

The rear (inboard) face of the end beam deformed as a result of the high load from the primary energy absorbers. Figure 8 shows a photograph of this area for one of the cars. The deformation is not very clear from the photograph, but after the frame members were removed, use of a straight edge indicated that the face had deformed inward by approximately 0.125 in (3 mm) at its center. The inside of the end beam, which includes reinforcing gussets, was not opened for inspection.

Figure 8. Back Surface of the End Beam After the CEM Test in the Area at Which the Primary Energy Absorber Contacts

The AT beam of ends 244A and 248A, which collided with the wall, experienced a perceptible bowing such that the center of the beam protruded outward further than the ends. The reason for this deformation is the loading on the AT beam spacers, positioned on the outboard surface adjacent to the corner posts, as they struck the test wall. The research team also observed a corresponding slight bowing in the corner posts. The magnitude of the AT beam bowing, as measured by the difference in longitudinal position between the center and either end, was approximately 0.25 in (6.4 mm). The researchers had to remove the AT beam spacers on ends 244A and 248A because their dimensions are not appropriate for the case in which they are included at a coupled interface, as they will be in the CEM train-to-train test.

Figure 9 shows evidence of cracking between the sliding tube of the roof absorber and the back of the AT beam for car end 248A. A fillet weld connects the sliding tube to the AT beam.

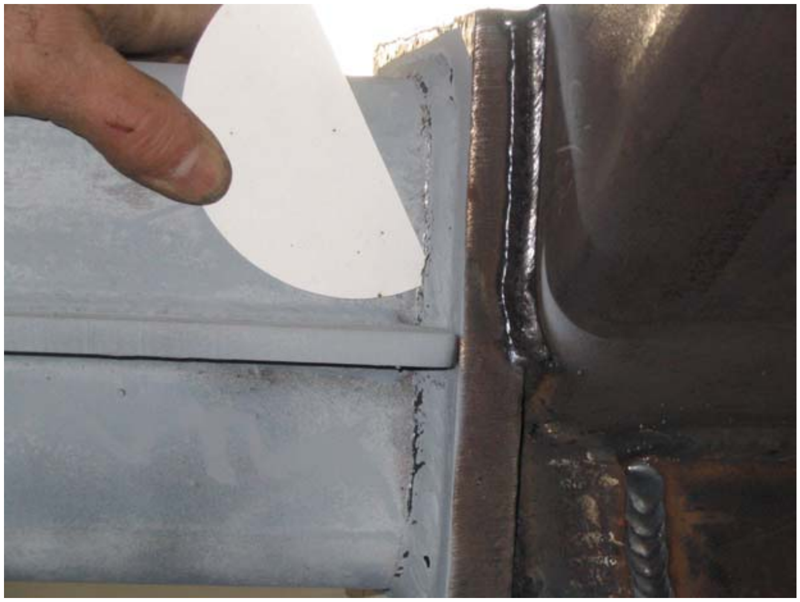

Figure 9. Crack at the Connection Between the Sliding Roof Absorber Tube and the Back of the AT Beam for End 248A After the One-Car CEM Test

The fixed tube of the roof absorber experienced no damage during the test with the exception of a slight bulge in a few locations. One or more of the honeycomb absorbers jammed within the tube, causing this bulge. The shear rivet holes were slightly elongated as a result of the shear load from the test. These holes, however, could not be reused because the riveting tool is too large to fit into the space adjacent to the holes. (The rivets were originally installed before the entire roof absorber was put into the car.) Finally, the end plate (on the inboard side of the fixed tube) was removed to permit extraction of the honeycomb elements.

3.5 Fixed Sill

As shown in Figure 10, the fixed sill was in good condition after the test. The points of largest deformation were the holes that contained the shear bolts for the connection to the sliding sill. These holes elongated in the longitudinal direction of the car by approximately 0.030 in (0.76 mm), although variability occurred from hole to hole. As with the sliding sill, areas at the edges of the holes with burrs also required some grinding. After grinding, the sliding sill slid easily into the fixed sill for all four ends.

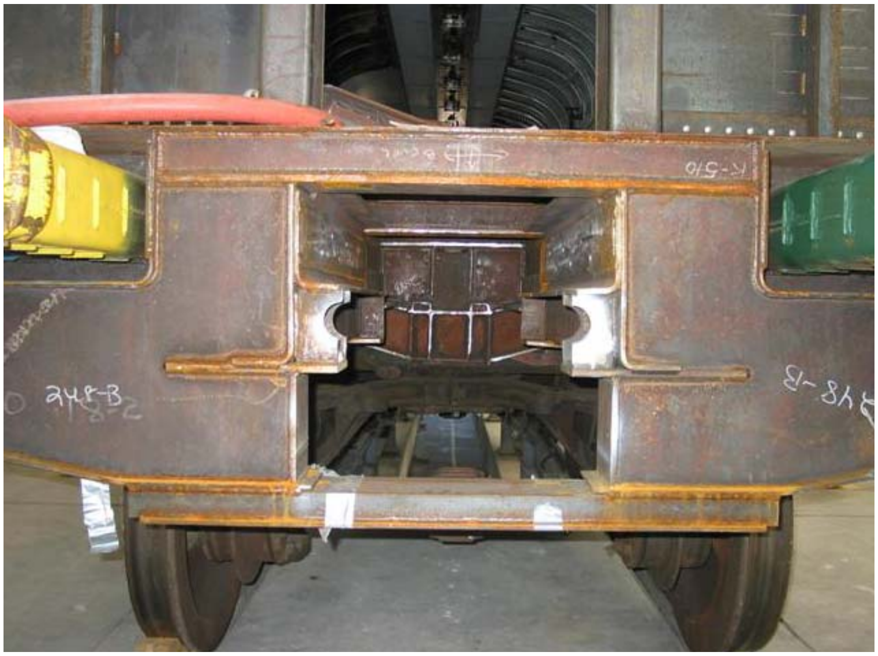

Figure 10. Fixed Sill for Car 248B Before Repair

3.6 Primary Energy Absorbers

Figure 11 shows that the primary energy absorbers at the impacted end crush zones were almost completely crushed. The primary energy absorbers at the coupled ends of the two-car test also experienced permanent crush but of much lesser magnitude. Figure 12 shows the smallest amount of crush, which occurred in the absorbers on the trailing car at the coupled interface. Thus, all eight of the primary energy absorbers required replacement. The front reaction group, to which the inboard end of the primary energy absorber is welded, experienced no obvious damage for any end.

Figure 11. Condition of the Primary Energy Absorbers After the One-Car CEM Test; End 248A

Figure 12. Primary Energy Absorber from Car End 248B After the Two-Car Test

3.7 Sliding Sill/Fixed Sill Connection

A required modification found after the CEM tests was the connection between the sliding sill and the fixed sill. The research team observed that the sliding structure, which includes the sliding sill, the end frame, and the sliding roof absorber tubes, began to pull out of the car end as the cars rebounded from the wall in the two-car CEM test. No explicit mechanism in the test car crush zone ends prevented this tension load from developing after the sliding sill-to-fixed sill shear bolts are broken. In a car for actual service, the side and roof structure at the end would play this role. Thus, it was necessary in the repair of the cars to include some type of retention device.

3.8 Roof Absorber Components

The shear rivets of all roof absorbers sheared as a result of the test; depending on the location of the end, the aluminum honeycomb absorber cartridges substantially crushed. In addition, researchers observed cracking at the connection between the sliding roof absorber tube and the back of the AT beam (see Figure 9).

Figures 13 and 14 show photographs of some honeycomb roof absorbers. The absorbers in Figure 13 are from end 248A. The absorbers in Figure 14 are from end 244B; a few of these experienced a minor amount of crush. The research team saved and reused approximately 20 crush elements in the repair process.

Figure 13. Roof Absorber Elements from End 248A That Experienced Substantial Crush

Figure 14. Aluminum Honeycomb Roof Absorber Elements from End 244B After the Two-Car CEM Test

4. Repair Descriptions

This section describes the repairs and modifications made to the Budd Pioneer crush zones. The process for making these repairs and modifications included the development of initial concept layouts followed by discussions with the team, particularly the Volpe Center. The research team generated detailed drawings. In some cases, supporting finite element analyses were conducted. Researchers then used the drawings to procure repair components, and the components were shipped to TTC for implementation.

4.1 Preparation and Repair Sequence

The repair included preparation of the cars for new components and modifications. The sliding components were first removed from the car as a single unit and placed in a special location for examination and repair; Figure 6 shows one such end. Several components were then cut from the car, including the primary energy absorbers, the bell-mouth face plate, and the coupler carrier. The surfaces to which these components had been welded were then ground flat. Floor plate sections were cut for access in the vicinity of the inboard ends of the primary energy absorbers and in the area in which the sliding sill connects to the fixed sill. Figure 15 shows the access hole.

Figure 15. Access Hole Cut in the Floor Plate in the Vicinity of the Sliding Sill/Fixed Sill Connection

The general sequence of preparation and repair follows:

1. Repair loose roof absorber sliding tube ends.
2. Repair AT beam components and insert roof absorber sliding tubes into fixed tubes.

3. Cut away floor and related components for primary energy absorber replacement.
4. Partially insert sliding end (end frame/sliding sill) into fixed sill, and insert sliding sill inner components (push-back coupler components).
5. Replace primary energy absorbers.
6. Connect roof absorber tubes to end frame.
7. Repair buffer beam back face.
8. Complete installation of underframe components.
9. Repair roof absorber fixed tube.
10. Install AT beam spacers.

4.2 Coupler Hardware

As stated earlier, the team ordered two new couplers, identical to those used on ends 248B and 244B, for installation on the A-ends. Some additional draft gear pads were also ordered. Some of these pads had a thickness that was too large and were consequently used inside the yoke (in draft). The pads that were formerly in the yoke were then used in buff (behind the yoke) after modification by adding welded steel bars to their bottom and sides for proper centering within the sliding sill pocket.

4.3 Buff Lug Hardware

Similarly, researchers ordered new aluminum honeycomb absorbers and new buff lugs, both with exactly the same design used for the original crush zones. The existing holes in the sliding sill served as the template for drilling the holes in the new buff lugs after they were positioned within the sliding sill.

The team also ordered and installed a new carrier plate, covering the area from the back of the sliding sill to the edge of the yoke pin support plate.

4.4 Sliding Sill and Related Components—Retention Mechanism

The bell mouth represents the most substantial repair for this set of components. The damaged coupler carrier components and the bottom portion of the face plate were cut away, leaving two straight, vertical edges of the face plate. The replacement components for the coupler carrier had the same design as before, and the face plate was restored by welding two pieces onto the remaining portion using a single bevel groove weld. Figure 16 shows the repair. This provided a bell mouth with the same strength as for the original crush zone.

The holes in the sliding sill did not need modification or repair except for some grinding and polishing to provide smooth sliding surfaces.

Figure 16. Bell-Mouth Face Plate Repair

4.5 Anticlimber

Two of the ends, 248A and 244A, had flat plates in the place at which the ribbed anticlimber is normally situated. These flat plates were removed, and the remaining weld material was ground off of the end beam face. A slight depression (corresponding to the size of the original flat plate) remained in the end beam, and the edges of the new ribbed anticlimbers, which had the same geometry and material as used in the original 248B and 244B crush zones, were chamfered to ensure that good contact would occur between the rear of the anticlimber and the slightly depressed face of the end beam. Figure 17 shows the anticlimber welded in place.

Figure 17. Anticlimber with Chamfered Edge Welded to the End Beam

4.6 End Frame

The primary repair on the end frame was the stiffening of the end beam's rear face at the locations at which the primary energy absorbers contact. The collar on the back of the end beam into which the primary energy absorbers protrude was first removed on each side. The end beam surface was then built up with weld metal and ground as flat as possible. A 0.75 in (19 mm), A572-50 plate (or A36 in some cases), whose area was larger than the area originally bounded by the collar, was then welded onto the rear of the end beam; the rear thickness of the A710 (minimum yield strength, 75 ksi [517 MPa]) end beam is 0.375 in (9.5 mm). The decreased length of the primary energy absorber accounted for this added plate (see below). Figure 18 shows a photograph of this region, together with the new retention device and the primary energy absorber.

Figure 18. Modified Inboard Surface of the End Beam in the Vicinity of the Primary Energy Absorbers and the New Retention Device

Researchers conducted a finite element analysis to demonstrate the ability of this repair to prevent distortion of the end beam. Figure 19 shows images of the calculated deformation (in section) of the end beams for the original and repaired configurations.

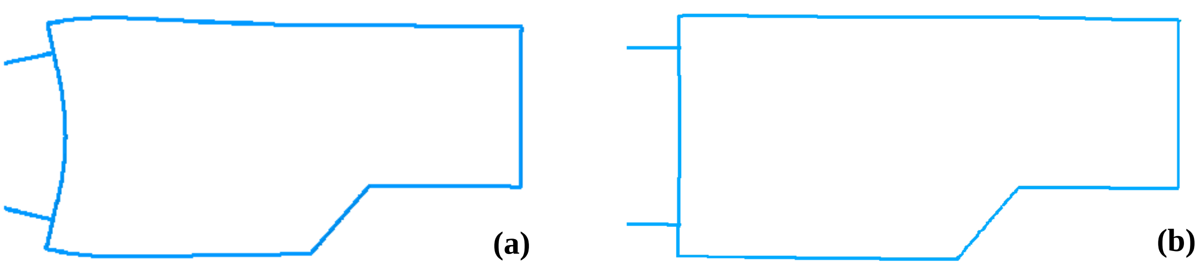

Figure 19. Finite Element Results Comparing the Calculated Deformation of the End Beam Due to the Loads from the Primary Energy Absorber During Crush (Cross Section Ahead of Primary Energy Absorbers): (a) Original Configuration and (b) Repaired Configuration

The spacers on the outboard face of the AT beam were removed, and the AT beam face was ground smooth. New spacers were provided with a (vertical) height about 1 in greater than that of the original spacers. Researchers believed that this larger dimension would increase the certainty of car-to-car contact at the roof for the less controlled train-to-train test. An additional center spacer was also added to ensure that, on coupler push back, contact at the roof would occur in three locations instead of two, thus reducing the chances of bowing the AT beam and the corner and collision posts. Figure 20 shows a spacer welded to the AT beam. The spacers had a greater (longitudinal) length than in the original car 244 crush zones so that they could be machined during installation to ensure that proper contact would occur when the couplers push back. The final dimensions of the spacers also helped to compensate for the slight bowing of the corner posts and AT beam described earlier.

Figure 20. Newly Added Center Spacer on the AT Beam to Reduce Its Bowing When Coupled Ends Collide

The corner posts were adequately straight and did not require modifications or repairs.

4.7 Fixed Sill

Possible approaches to restore the shear bolt holes in the fixed sills to their original size included drilling holes in new locations or filling the previous holes with weld metal.   None of these, however, could be carried out without substantial effort. In the end, the research team decided to leave the holes unmodified. The literature suggests that this will have little or no effect on the ultimate shear strength of the overall fixed sill-to-sliding sill joint (c.f. [6]). The sliding surfaces of the fixed sill were ground to provide a smooth surface.

4.8 Primary Energy Absorbers

The basic geometry–cross section, dividers, and trigger holes–and the type of material for the primary energy absorbers were the same as for the original crush zones. The decreased length of the absorbers accounted for the addition of the reinforcement on the end beam's inboard face and for the addition of a plate at the absorber's inboard end to facilitate reattachment to the absorber support structure. (Section 3.4 discusses the plate on the end beam.) A 0.75-in (19-mm) thick, A572-50 plate was also welded to the inboard end of the primary energy absorber (Figure 21). This plate was in turn welded to the face plate of the front reaction group. Researchers thought that this welding approach would provide a more feasible alternative than if the absorber tubes were welded directly to the front reaction group. In the original crush zones, that weld had been made in the shop before installation onto the car. Thus, the reduction in length of the crushable part of the primary energy absorber for the repaired cars was 1.5 in (38 mm). These repaired cars were near the end of the consist in the full-scale test, where the predicted crush was substantially less than 30 in (76 mm) of crush.

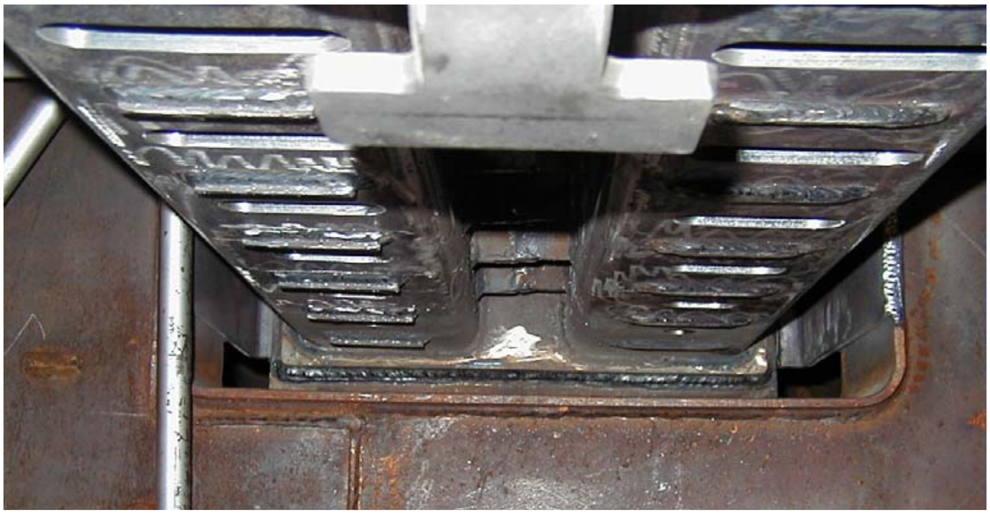

Figure 21. Plate Welded at the Inboard End of the Primary Energy Absorber to the Front Reaction Group

4.9 Sliding Sill/Fixed Sill Connection—Retention Mechanism

Researchers designed a retention mechanism to ensure that the sliding components of the crush zone do not pull out if any of the cars rebound during the full-scale test.

Figure 22 shows an image of the device's part attached to the primary energy absorber. The device consists of a hook and slot. The hook is a bent part that is welded to the inside surfaces of the primary energy absorber and to two straps that are in turn welded to the top and bottom of the absorber. The slots are part of the new frame on the end beam's rear surface that is used to restrict the primary energy absorber from lateral or vertical motion during crush. The top and bottom pieces of this frame each include a slot.

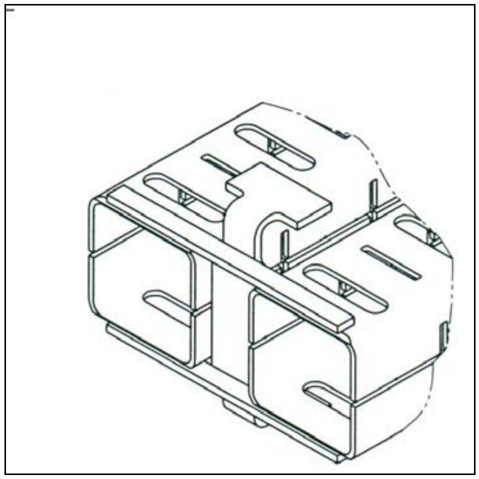

Figure 22. Image of Part of the Sliding Sill Retention Device

The dimensions of these new parts and their points of attachment were selected to ensure that no contact occurs between hook and slot during normal operation or during (inward) crush of the crush zone. The parts come into contact only if the end beam moves outward relative to the rest of the vehicle.

Researchers conducted both collision dynamics and finite element analyses to select and demonstrate that the strength of the retention device is adequate. The collision dynamics model simulates the upcoming train-to-train test with CEM equipment. The model of each vehicle end with a crush zone was modified to allow the end of the car to slide outward. A spring element represented the retention device. (The original model includes coupler elastic response.) Calculations for a 30 mph (48 km/h) collision included different values of the retention spring stiffness. Figure 23 shows the calculated maximum force on the retention device as a function of device stiffness for the various coupled interfaces in the train. The force, and therefore the required strength, decrease as the stiffness decreases. This occurs because, with a lower stiffness, the retention force is applied over a longer time. Lower stiffness requires a greater device displacement.

Figure 24 shows the calculated load-displacement response of the retention device that was installed on the cars, and Figure 25 shows the calculated deformation. These results are from a finite element analysis in which the back of the primary energy absorber was held and a rigid plate representing the end beam was displaced away from it at a speed of 30 mph (48 km/h).

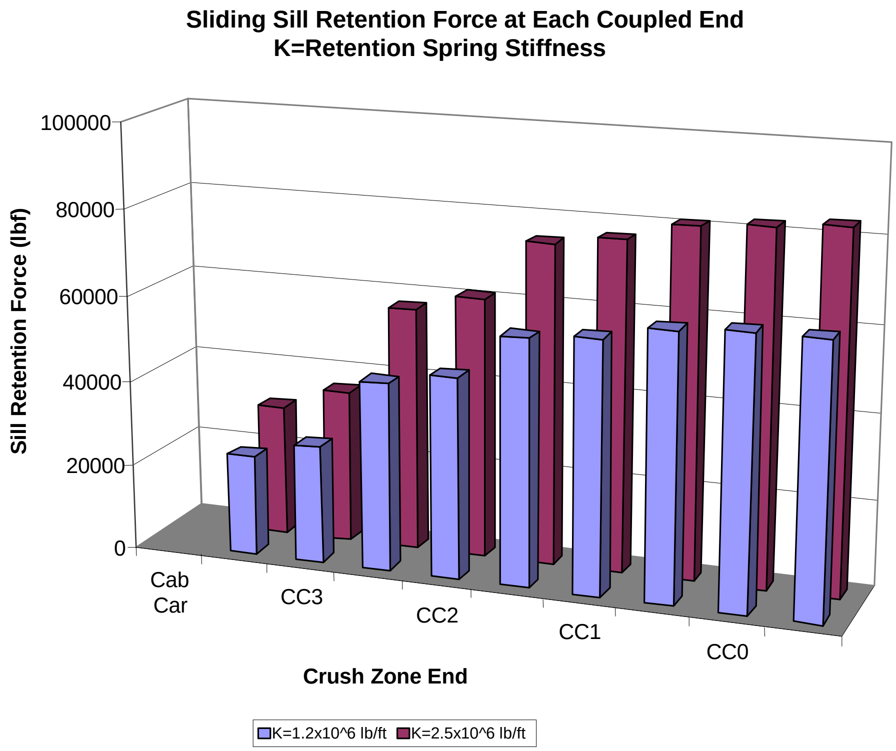

Figure 23. Results of Collision Dynamics Model for the Effect of Retention Device Stiffness on Calculated Maximum Load on the Device

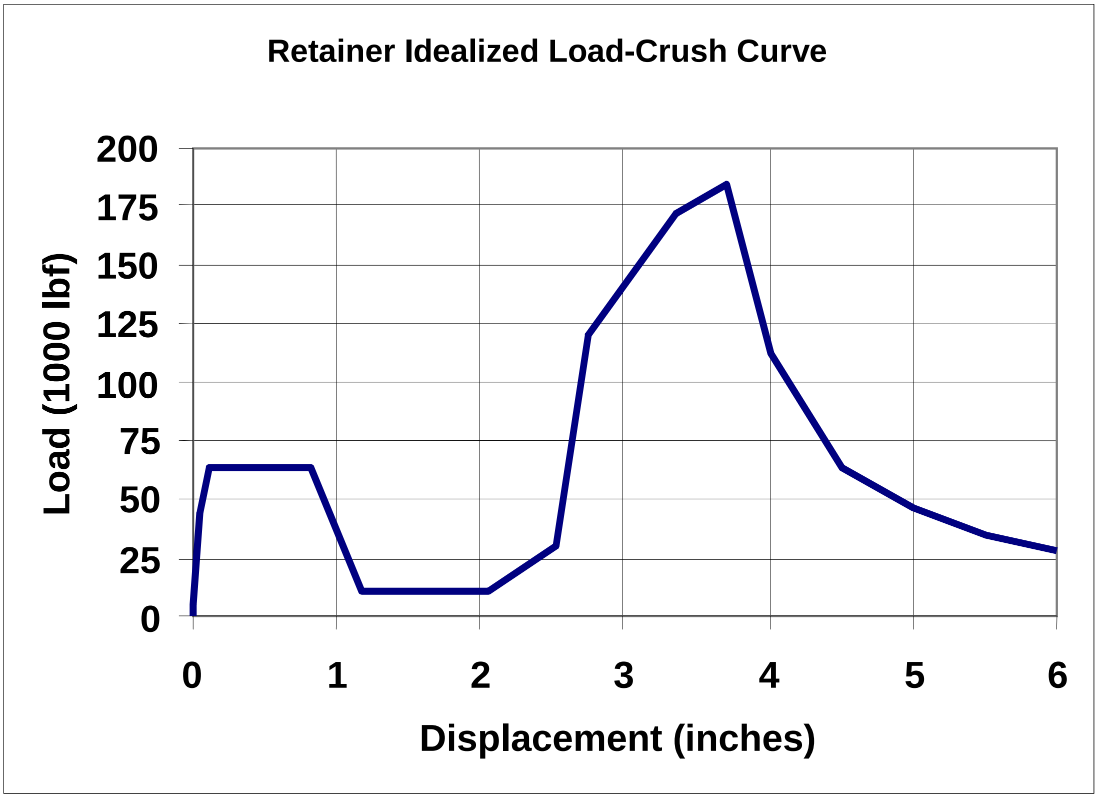

Figure 24. Calculated Load-Deformation Response for the Sliding Sill Retention Device

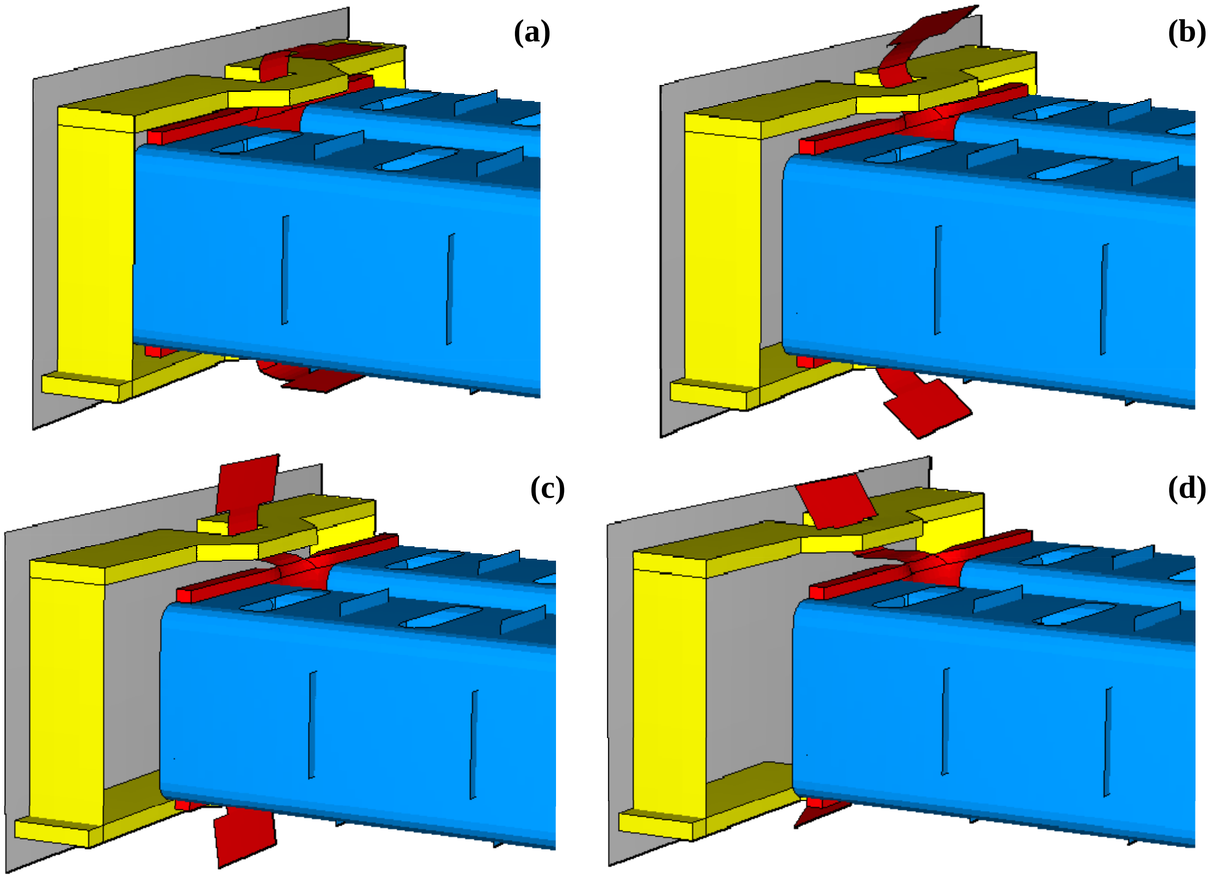

Figure 25. Calculated Deformation of the Retention Device: (a) Undeformed; (b) 0.6 in (15 mm); (c) 2.0 in (51 mm); (d) 3.3 in (84 mm)

4.10 Roof Absorber Components

Each sliding roof absorber tube was removed from the AT beam and chamfered to accommodate a full penetration weld (in contrast to the fillet weld used previously). Researchers recognized that in some cases the bowing of the AT beam would result in a gap at some locations around the periphery of the sliding roof absorber tube end, but the welder would account for this gap.

The rear plate of the roof absorber fixed tube required removal in order to extract the aluminum honeycomb cartridges. Figure 26 shows that the absorber tube deformed after the end plate was removed. In some instances, a section of the carline was also removed to allow extraction of the honeycomb cartridges. About one-half of the uncrushed honeycomb absorber cartridges were reused. The research team ordered the remaining required absorbers with the same specifications used for the original crush zone ends. Additional weld metal strengthened the regions at which a bulge had occurred in the fixed tube; the bulge remained untouched.

Figure 26. Inboard End of the Fixed Roof Absorber Tube After Removal of the End Plate to Extract Absorber Elements

Figures 27 and 28 show the locations of the new rivet holes for the connection between the fixed and sliding roof absorber tubes. The pattern is not as symmetrical as it is for the original configuration, but the rivet-to-rivet spacing is essentially unchanged, and the expectation is that the total shear strength of the joint will be close to that of the original. Researchers used the same type of rivets as for the original fabrication.

Figure 27. Rivet Pattern for the Repaired Roof Absorber Shear Joint (Top Surface)

Figure 28. Rivet Pattern for the Repaired Roof Absorber Shear Joint (Bottom Surface)

The inboard end plate on the fixed tube was cut and welded within the end of the tube, about 0.75 in (19 mm) from the end. This ensured that a good weld could be made around the entire perimeter of the end plate since part of the outside of the tube was not accessible in the installed position. (Recall that the absorber had originally been fabricated, with its end plate, before installation into the original crush zone.) Where removed, the carline section was Huck-bolted to the existing carline. Figure 29 shows the repaired roof absorber end and carline.

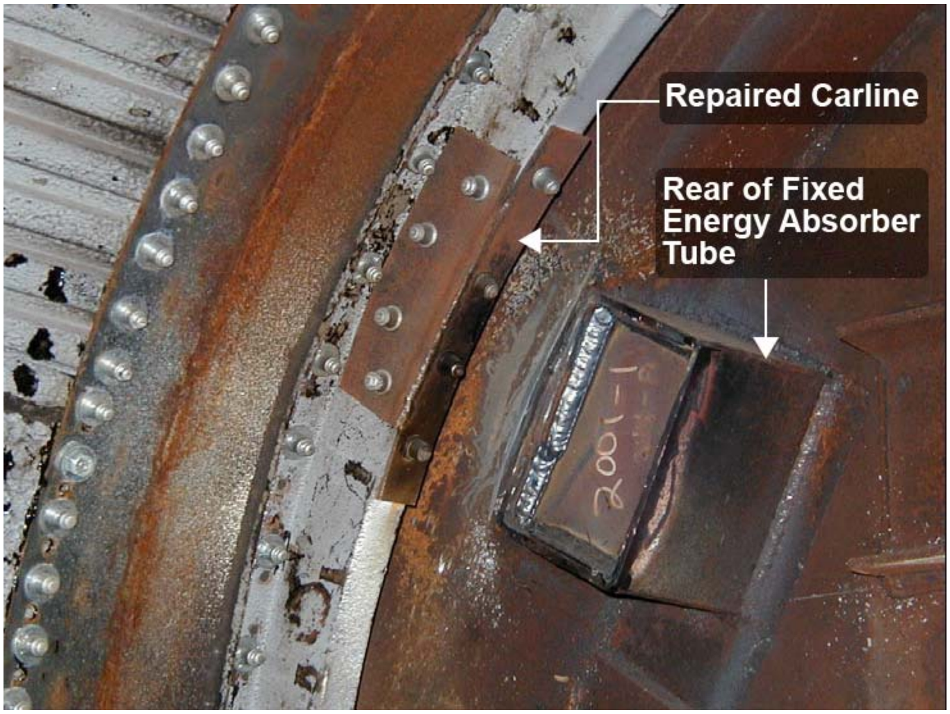

Figure 29. Repaired End of the Fixed Roof Absorber Tube and the Repaired Carline

5. Component Fabrication and Shipping

Ebenezer Railcar Service, West Seneca, NY, fabricated most of the components that were needed to conduct the Budd Pioneer crush zone repairs. Ebenezer fabricated the original crush zone components. Ebenezer used a quality control document specific to the components for these repairs and followed Association of American Railroads M-1003 [7] quality control requirements. All welding was conducted according to American Welding Society D15.1 criteria [8]. The quality control ream collected or checked the following information:

- Material certifications, particularly the shear bolts and the material for the primary energy absorbers as described below
- Dimensions of the incoming materials; most of the components were cut to shape before delivery to Ebenezer
- Dimensions of bent components
- Dimensions of finished assemblies
- Photographs of assemblies during and after fabrication

The certificates for the shear bolts ensured that they satisfied the requirements for A490 bolts and had measured properties similar to what had been used before. Some shear strength tests conducted on the bolts show their material properties. In particular, two tests, conducted according to American Society for Testing and Materials F606-D2 for the 0.75-in (19-mm) diameter (push-back coupler buff lug) bolts and the 1.0-in (25.4-mm) diameter (sliding sill-to-fixed sill) bolts, showed that the average shear strengths were 51,200 lbf (229 kN) and 78,300 lbf (350 kN), respectively. These values are within the range assumed in design. Table 3 gives the individual test results for these bolts, as well as the test results from the original crush zone program.

Table 3. Shear Bolt Test Results

Bolt Diameter (in)/(mm)	Bolt Grade	Shear Strength (lbf)/(kN)	Shear Strength (lbf/in^2)/(MPa)
From current program			
0.75 / 19	A490	44,200 / 197	100,000 / 690
0.75 / 19	A490	58,300 / 260	132,000 / 910
1.00 / 25.4	A490	79,100 / 353	101,000 / 696
1.00 / 25.4	A490	77,500 / 350	98,700 / 680
From previous program			
0.875 / 22	A490	62,400 / 279	104,000 / 717
0.875 / 22	A490	64,400 / 288	107,000 / 738
0.875 / 22	A490	64,700 / 289	108,000 / 745
1.00 / 25.4	Gr.8	87,200 / 389	111,000 / 765
1.00 / 25.4	Gr.8	89,200 / 398	114,000 / 786
1.00 / 25.4	Gr.8	89,100 / 398	113,000 / 779

Table 4 shows the comparison of the certified mechanical properties for the A572-50 steel used for the replacement primary energy absorbers with the certified properties of the original absorbers. The differences are less than 10 percent and acceptable.

Table 4. Comparison of the Certification Tensile Properties of the A572-50 Used for the Primary Energy Absorbers

Property	Original Material (1)	Repair Material (2)
Yield strength (ksi)/(MPa)	63 / 434	60 / 414
Tensile strength (ksi)/(MPa)	77 / 531	84 / 579
Elongation in 2 in (percent)	34	28

The fabricated components and piece parts needed for the repair arrived by flatbed truck to TTC, where the repairs were made.

6. Repair Examination

Participation in the repair procedure included discussions, primarily by telephone, to troubleshoot problem areas and visits to TTC to examine the cars during and after repair. This section provides some notes on areas that required modification or whose characterization it was thought could be useful in the eventual interpretation of the full-scale tests. In general, the repair procedure went smoothly, and few deviations from the original repair design were made.

Key items include:

1. Researchers put the honeycomb blocks for the push-back coupler together from leftover 6,500 psi (44.8 MPa) material from the previous crush zone project. This helped to overcome a delay caused by late delivery of new honeycomb blocks.
2. The new buff lugs did not fit into the sliding sill without interference, particularly with the cover plate, and needed to be ground to ensure that proper sliding would occur.
3. Distortion in the cars and slight imperfections in the fabrication of the primary energy absorbers sometimes caused the outboard (impacted) end of the absorber to be out of position. Various modifications were made depending on the car end and side. These included slight machining of the end of the absorber and machining of the plates of each end to which the absorber either attaches or impacts.

7. Summary and Conclusions

This report describes the process followed to repair four Budd Pioneer crush zones. These two cars had been used in previous crash tests, and a need existed to repair them for use in an upcoming CEM train-to-train test.

The crush zones performed as intended in the one- and two-car full-scale CEM crash tests. Damage was almost entirely isolated to the components designed to be sacrificial and replaceable. The shear bolts of the push-back coupler fractured as intended, and the honeycomb absorber crushed to the design value. The buff lug had to be sacrificed in order to remove the honeycomb absorbers. The bell-mouth plate and the coupler carrier were also damaged as the coupler pushed back, again as intended. An unexpected result was the deformation of the cover plate below the push-back coupler buff lug. The rear face of the end beam deformed in the area at which the primary energy absorbers contact. In addition, the corner posts and the AT beam experienced a small amount of bowing due to impact between the top corner spacers and the impact wall. These unanticipated modes of deformation required only minor repair. The only deformation to the sliding sill was at the shear bolt holes, which were slightly elongated; the hole elongation was more significant in the fixed sill. All sliding sill-to-fixed sill shear bolts fractured as intended. Each primary energy absorber crushed to some extent so that none of them could be reused. The shear rivets of each roof absorber fractured; depending on the location of the car end in the full-scale test, the roof absorber cartridges crushed. Several of the cartridges, however, could be reused. The two-car CEM test also revealed that the sliding components could be pulled out of the car as the cars rebound from the impact.

Many of the components required replacement using the original design and materials. These included the buff lug, the push-back coupler honeycomb absorber, the coupler carrier, the shear bolts and shear rivets, and the roof absorber cartridges. Some components required modification. The bell-mouth plate was restored to original condition by welding together pieces rather than from a single piece. A new, larger cover plate was installed below the buff lug in the sliding sill to prevent buff lug rotation during push back. The rear of the buffer beam was reinforced by adding a plate to the back of the end beam. The AT beam and the corner posts were not straightened, but the displacement associated with the slight bowing was compensated for by adjusting the spacers on the outboard surface of the AT beam. A spacer was also added at the center of the AT beam to better distribute the impact load. The slightly elongated holes in the sliding and fixed sills were reused for the shear bolts because evidence in the literature indicates that little change would occur in the overall joint strength. The primary energy absorbers had essentially the same design as before, but they were shortened by 1.5 in (38 mm) to account for the reinforcing plate on the back of the end beam and a plate at the absorber’s inboard end that was used to facilitate installation in the repaired cars. Modifications were made to the sliding tube of the roof absorber to prevent cracking at the welded connection to the AT beam. The shear rivet pattern was changed to permit access for the riveting tool now that the absorber assemblies are in the cars. A retention device was designed to prevent the sliding components from being pulled away from the car on rebound. This device attaches the ends of the primary energy absorbers to the end beam but transfers load only in draft.

The project included fabrication of the components needed for the repairs and assistance in carrying out the repairs at TTC. As part of the project, component tests helped determine the shear strength of the push-back coupler and the sliding sill/fixed sill shear bolts.

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Acronyms and Abbreviations

AT	antitelescoping
CEM	crash energy management
FRA	Federal Railroad Administration
ksi	kips per square inch
TTC	Transportation Technology Center
Volpe Center	Volpe National Transportation Systems Center