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Evaluation of Adjustable Continuity Joint Variations for Use in the Restore Barrier

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EVALUATION OF ADJUSTABLE CONTINUITY JOINT VARIATIONS FOR USE IN THE RESTORE BARRIER

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### Evaluation of Adjustable Continuity Joint Variations for Use in the RESTORE Barrier

During MASH TL-4 full-scale crash testing of the RESTORE barrier, concrete cracking and spalling was observed on the barrier beams that would likely require repairs or replacement. This study sought to evaluate joint design alternatives for use in the RESTORE barrier in order to limit the amount of system damage. Three variations of the Adjustable Continuity Joint (ACJ) were identified as potential modifications: 1) incorporating rubber bearing pads within the ACJ, 2) utilizing normal weight concrete instead of lightweight concrete, and 3) incorporating a steel end cap into the ends of the beam segments.

Four dynamic component tests were conducted to evaluate the performance of these three joint variations against the performance of the original, as-tested, RESTORE ACJ. All three modified designs showed improved durability over the original ACJ. The normal weight concrete beams delayed the onset of cracking and fracture, but ultimately had similar damage to that of the baseline test. The rubber pad reduced cracking and prevented fractures, but it increased the flexibility of the joint. Finally, the steel end caps allowed only small hairline cracks to form while also stiffening the joint.

Although these component tests showed promise for the ACJ design variations, further evaluation and analysis is recommended prior to utilizing any of these joints in real-world barrier installations.

### Abstract

Prepared in cooperation with U.S. Department of Transportation, Federal Highway Administration.
DISCLAIMER STATEMENT

This report was completed with funding from the Federal Highway Administration, U.S. Department of Transportation and the Nebraska Department of Roads. The contents of this report reflect the views and opinions of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Nebraska Department of Roads nor the Federal Highway Administration, U.S. Department of Transportation. This report does not constitute a standard, specification, regulation, product endorsement, or an endorsement of manufacturers.

UNCERTAINTY OF MEASUREMENT STATEMENT

The Midwest Roadside Safety Facility (MwRSF) has determined the uncertainty of measurements for several parameters involved in standard full-scale crash testing and non-standard testing of roadside safety features. Information regarding the uncertainty of measurements for critical parameters is available upon request by the sponsor and the Federal Highway Administration. Test nos. ACJB-1 – ACJB-4 were non-certified component tests conducted for research and development purposes only and are outside the scope of the MwRSF’s A2LA Accreditation.
ACKNOWLEDGEMENTS

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1 INTRODUCTION

1.1 Background

In the early 2010s, the Midwest Roadside Safety Facility (MwRSF) developed the RESTORE barrier, a new energy-absorbing median barrier [1-4]. The RESTORE barrier consisted of 20-ft (6.1-m) long precast concrete beams supported by a combination of rubber posts and steel skids, as shown in Figure 1. A steel tube rail was mounted to the top of the concrete beams to contain heavy trucks. The height to the top of the concrete beams and steel rail were 30⅛ in. and 38⅝ in., respectively. Adjacent concrete beams were connected end-to-end utilizing an Adjustable Continuity Joint (ACJ). The ends of the concrete beams were chamfered at a 45 degree angle, and a pentagon-shaped vertical hole was cast into the beam near each end. This geometry allowed for 17-in. (432-mm) long L6 x 6 x ½ (L152 x 152 x 13) steel angles to be bolted to the front and back faces of the barrier. The angled, or wedge shaped, steel components were reinforced with ⅜-in. (10-mm) thick gusset plates and allowed the ACJ to transfer both shear and bending moment across the joint while also allowing for construction and installation tolerances.

The RESTORE barrier was successfully crash tested to the Manual for Assessing Safety Hardware (MASH) Test Level 4 (TL-4) safety criteria [5]. However, during full-scale testing, the test installation suffered more concrete damage than desired. Significant concrete cracking and spalling were observed around the ACJs in the impact regions during the 2270P pickup truck and 10000S single-unit truck crashes, MASH test nos. 4-11 and 4-12, respectively. Photographs of the damage sustained around the system joints during the full-scale tests are shown in Figures 2 and 3. To limit barrier maintenance after an impact event, it was recommended that the barrier be modified to reduce concrete cracking and spalling around the ACJs.
Figure 1. The RESTORE Barrier [4]
Figure 2. Joint Damage Resulting from Test No. SFH-1 with a 2270P Pickup [4]
Figure 3. Joint Damage Resulting from Test No. SFH-1 with a 2270P Pickup [4]
1.2 Objective

The objective of this research project was to evaluate three modified versions of the ACJ for use in the RESTORE barrier, which included: 1) incorporating rubber bearing pads within the ACJ, 2) utilizing normal weight concrete in the beams in lieu of the lightweight concrete currently specified for use in the RESTORE barrier, and 3) casting steel end caps into the ends of the concrete beams. These modifications were intended to increase strength while reducing the risk of concrete cracking and spalling around the joints.

1.3 Research Approach

The evaluation of the modified joint designs consisted of four dynamic component tests, one test for each of the three modified designs and one test of the original RESTORE ACJ for use as a baseline. The various joints were installed between two full-scale, 20-ft (6.1-m) long RESTORE concrete beams and impacted with a bogie vehicle to create 3-point bending in each test article. The performances of the ACJ modifications were then compared to one another in terms of strength, deflection, and durability (resistance to concrete cracking and fracture). Finally, conclusions and recommendations were formulated concerning the ACJ variations.
2 DESIGN DETAILS

Three variations of the ACJ were identified as possible modifications that could result in reduced concrete damage. The first variation incorporated rubber bearing pads between the steel angles and the concrete beams. The rubber pads were intended to better distribute the impact loads between the steel angle and the concrete beam ends, thereby reducing the propensity of concrete cracking. Additionally, the rubber pads had the potential to absorb some of the impact energy as they were compressed, which would also reduce stresses and cracking in the beams. Thus, \( \frac{1}{4}\)-in. (6-mm) thick neoprene pad was placed on both sides of each steel angle (front and back) of the ACJ.

The second joint variation utilized normal weight concrete instead of lightweight concrete. The beams were originally designed with lightweight concrete to limit the weight of the barrier, which reduced the barrier inertia and aided in the stability of the beam on the rubber posts. However, with the addition of the steel skids, the barrier weight was no longer critical to the stability of the system. Lightweight concrete typically has a lower shear strength than normal weight concrete. Thus, beams fabricated with normal weight concrete were expected to reduce the propensity of concrete cracking and spalling during loading. The lightweight concrete had an average density of 110 lb/ft\(^3\) (1,762 kg/m\(^3\)) and an average compressive strength of 6,652 psi (45.9 MPa), while the normal weight concrete had an approximate density of 140 lb/ft\(^3\) (2,243 kg/m\(^3\)) and a compressive strength of 7,022 psi (48.4 MPa).

The final ACJ joint variation incorporated normal weight concrete beams and a steel cap embedded into the ends of the concrete beam. In addition to the expected benefits of the normal weight concrete, the steel end cap confined the concrete in the ends of the beam, thereby increasing the concrete strength and resistance to cracking. The cap was designed as a \( \frac{3}{16}\)-in. (5-mm) thick
steel plate bent to match the shape of the end of the concrete beams. The cap was anchored to the beams with six steel shear studs and embedded into the beam at the time of casting.

Test installation details for all four joints, the original ACJ and the three design modifications discussed herein, are shown in Figures 4 through 21. System photographs are shown in Figures 22 and 23. Material specifications, mill certifications, and certificates of conformity for test nos. ACJB-1 through ACJB-4 are shown in Appendix A.
Figure 4. Test Layout, Test Nos. ACJB-1 through ACJB-4
Figure 5. Test Layout, Test Nos. ACJB-1 through ACJB-4
Figure 6. Barrier Cross-Section Details, Test Nos. ACJB-1 through ACJB-4

Notes: (1) Anchor Part b2 into tarmac with PowersFast 100+ Gold epoxy.
(2) Part e5 can compress as needed due to weight of rail.
Figure 7. Joint Variation Details, Test Nos. ACJB-1 through ACJB-4

Notes: (1) ACJ and attachment bolts remain the same for all tests.
(2) Beams removed from Plan View.
(3) ACJB-1 and ACJB-2 to use Part a1 concrete beam sections. ACJB-3 and ACJB-4 to use Part a2 concrete beam sections.
Notes: (1) The φ6.5/8" [168] through hole can be cast around a Φ8" [152] PVC pipe and then the pipe can later be removed.
(2) The three surfaces at each end of the barrier must be vertical – front and back of rail drafted for casting purposes.
(3) Internal reinforcement not shown.

Figure 8. Concrete Beam Details, Test Nos. ACJB-1 through ACJB-4
Figure 9. Concrete Beam End Details, Test Nos. ACJB-1 through ACJB-4

Notes:
1. φ1" [25] and φ1 1/8" [29] through holes can be cast with or without an insert left in the beam.
2. The 'house-shaped' through hole can be cast around an insert and then the insert can be removed; the radii can be varied if needed.
3. The 3 surfaces at each end of the barrier must be vertical – front and back of rail drafted for casting purposes.
4. φ1 1/8" [29] holes to be centered on 4 1/2" x 4 1/2" [114mm x 114mm] chamfer.
5. Internal reinforcement not shown.
Figure 10. Concrete Beam Reinforcement Details, Test Nos. ACJB-1 through ACJB-4
Figure 11. Concrete Beam Reinforcement Details, Test Nos. ACJB-1 through ACJB-4
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<table>
<thead>
<tr>
<th>Item No.</th>
<th>QTY.</th>
<th>Description</th>
<th>Material Spec</th>
<th>Hardware Guide</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>2</td>
<td>Lightweight Concrete Rail</td>
<td>Min. $f'c=5$ ksi [34.5 MPa], density=110 pcf</td>
<td>--</td>
</tr>
<tr>
<td>a2</td>
<td>2</td>
<td>Concrete Rail</td>
<td>Min. $f'c=5$ ksi [34.5 MPa]</td>
<td>--</td>
</tr>
<tr>
<td>a3</td>
<td>16</td>
<td>Morse E46496 Shear Fender</td>
<td>ASTM D2000</td>
<td>--</td>
</tr>
<tr>
<td>a4</td>
<td>4</td>
<td>6&quot;x6&quot;x1/2&quot; [152x152x13], 17&quot; [432] Long L-Bracket</td>
<td>ASTM A992 Galvanized</td>
<td>--</td>
</tr>
<tr>
<td>a5</td>
<td>16</td>
<td>5&quot;x5&quot;x3/8&quot; [127x127x10] Gusset Plate</td>
<td>ASTM A572 Grade 50 Galvanized</td>
<td>--</td>
</tr>
<tr>
<td>a6</td>
<td>4</td>
<td>17&quot;x5 11/16&quot;x1/4&quot; [432x144x8] ACJ Neoprene Pad</td>
<td>Neoprene</td>
<td>--</td>
</tr>
<tr>
<td>b1</td>
<td>64</td>
<td>3/4&quot; [19] Dia. UNC, 21&quot; [533] Long Hex Bolt</td>
<td>Grade 5 Galvanized</td>
<td>FBX20a</td>
</tr>
<tr>
<td>b2</td>
<td>64</td>
<td>3/4&quot; [19] Dia. UNC, 10&quot; [254] Long Threaded Rod</td>
<td>ASTM A193 Grade 37 Galvanized</td>
<td>FRR20a</td>
</tr>
<tr>
<td>b3</td>
<td>128</td>
<td>3/4&quot; [19] Dia. UNC Heavy Hex Nut</td>
<td>ASTM A194 Grade 2H Galv.</td>
<td>FNX20a</td>
</tr>
<tr>
<td>b5</td>
<td>16</td>
<td>1&quot; [25] Dia. UNC x 11 1/2&quot; [292] Long Hex Head Bolt</td>
<td>ASTM A325 Galv.</td>
<td>FBX24b</td>
</tr>
<tr>
<td>b6</td>
<td>32</td>
<td>3&quot;x3&quot;x1/4&quot; [76x76x8] Square Washer</td>
<td>ASTM A572 Grade 50 Galvanized</td>
<td>--</td>
</tr>
<tr>
<td>b7</td>
<td>16</td>
<td>1&quot; [25] Dia. UNC Heavy Hex Nut</td>
<td>ASTM A563 DH Galv.</td>
<td>FNX24b</td>
</tr>
<tr>
<td>b8</td>
<td>--</td>
<td>Epoxy</td>
<td>PowersFast 100+ Gold</td>
<td>--</td>
</tr>
<tr>
<td>d1</td>
<td>2</td>
<td>1 1/8&quot;x1 7/8&quot;x18&quot; [66x4.32x5] Bent Sheet</td>
<td>A36 or stronger</td>
<td>--</td>
</tr>
<tr>
<td>d2</td>
<td>16</td>
<td>1 1/2&quot; [13] Dia. x 4&quot; [102] Long Stud</td>
<td>A36 or stronger</td>
<td>--</td>
</tr>
<tr>
<td>e1</td>
<td>8</td>
<td>6 1/2&quot; [165] Dia. x 3 8/10&quot; [10] Thick x 19&quot; [483] Long Steel Pipe</td>
<td>AISI 1026</td>
<td>--</td>
</tr>
<tr>
<td>e2</td>
<td>8</td>
<td>16 9/16&quot;x10&quot;x1/4&quot; [421x254x6] Base Plate</td>
<td>ASTM A572 Grade 50 Steel</td>
<td>--</td>
</tr>
<tr>
<td>e3</td>
<td>16</td>
<td>3 1/2&quot;x10 3 8/1&quot;x2&quot; [89x264x13] Plate Gusset</td>
<td>ASTM A572 Grade 50 Steel</td>
<td>--</td>
</tr>
<tr>
<td>e4</td>
<td>8</td>
<td>12&quot;x12&quot;x3/8&quot; [305x305x10] Top Plate</td>
<td>ASTM A572 Grade 50 Steel</td>
<td>--</td>
</tr>
<tr>
<td>e5</td>
<td>8</td>
<td>12&quot;x12&quot;x1/2&quot; [305x305x13] EPDM Rubber Sheet</td>
<td>Minimum 50 durometer</td>
<td>--</td>
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</table>

Figure 20. Bill of Materials, Test Nos. ACJB-1 through ACJB-4
<table>
<thead>
<tr>
<th>Item No.</th>
<th>QTY.</th>
<th>Description</th>
<th>Material Specification</th>
<th>Hardware Guide</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1</td>
<td>2</td>
<td>Load Frame Assembly — From NDOR Precast Rail Joint Testing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f2</td>
<td>16</td>
<td>1 1/4&quot; [32] Dia. UNC, 12&quot; [305] Long Threaded Rod</td>
<td>ASTM A193 Grade B7</td>
<td></td>
</tr>
<tr>
<td>f3</td>
<td>16</td>
<td>1 1/4&quot; [32] Dia. UNC Heavy Hex Nut</td>
<td>ASTM 194 Grade 2H</td>
<td></td>
</tr>
<tr>
<td>f4</td>
<td>16</td>
<td>1 1/4&quot; [32] Dia. Hardened Washer</td>
<td>ASTM F436</td>
<td></td>
</tr>
<tr>
<td>f5</td>
<td>2</td>
<td>Load Frame Cylinder Assembly — From NDOR Precast Rail Joint Testing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f6</td>
<td></td>
<td>Epoxy</td>
<td>Min. 1,300 psi (9.0 MPa) Bond Strength</td>
<td></td>
</tr>
<tr>
<td>g1</td>
<td>8</td>
<td>1/2&quot; [13] Dia. UNC, 3&quot; [76] Long Hex Bolt</td>
<td>ASTM A307 Gr. A</td>
<td></td>
</tr>
<tr>
<td>g2</td>
<td>8</td>
<td>1/2&quot; [13] Dia. UNC Heavy Hex Nut</td>
<td>ASTM A563A</td>
<td></td>
</tr>
<tr>
<td>g3</td>
<td>8</td>
<td>1/2&quot; [13] Dia. Hardened Washer</td>
<td>ASTM F436</td>
<td></td>
</tr>
<tr>
<td>g4</td>
<td>2</td>
<td>1/2&quot; [13] Thick Neoprene or Rubber Pad</td>
<td>Neoprene/Rubber</td>
<td></td>
</tr>
</tbody>
</table>

Figure 21. Bill of Materials, Test Nos. ACJB-1 through ACJB-4
Figure 22. Test Installation Photographs, Test Nos. ACJB-1 through ACJB-4
Figure 23. Test Installation Photographs, Test Nos. ACJB-1 through ACJB-4
3 COMPONENT TESTING CONDITIONS

3.1 Purpose

During the MASH TL-4 crash testing of the RESTORE barrier, significant concrete cracking and spalling was observed surrounding the joint locations [4]. Subsequently, a system redesign was desired to minimize the amount of concrete damage resulting from vehicle impacts. Three different variations of the ACJ were identified as possible modifications that could result in reduced concrete damage.

Dynamic component testing was utilized to evaluate the effectiveness of these joint variations. A full-scale system joint was constructed for each modified joint design, including a baseline joint which incorporated the ACJ utilized in the crash testing of the RESTORE barrier. All four joints were then subjected to a dynamic impact that caused the joint to bend and the system to deflect laterally. Comparisons were then made between each joint regarding their respective deflections, strengths, and resistance to concrete cracking and fracture.

3.2 Scope

Four dynamic component tests were conducted to evaluate the performance of four variations of the joint design on the RESTORE barrier system. Each test incorporated two 20-ft (6.1-m) long RESTORE barrier concrete beam segments that were connected utilizing either the original ACJ or one of the three ACJ modifications discussed in Chapter 2. Each beam was supported by four rubber posts and two steel skids, in accordance with RESTORE barrier details. Two steel load frames located adjacent to the outermost rubber posts were utilized to laterally brace the test installations. The RESTORE barrier would typically incorporate a continuous steel tube rail mounted to the top of the concrete beams. However, since the objective of these tests was to evaluate the performance of the concrete beams and ACJ variations, the steel rail was omitted.
Test nos. ACJB-1 and ACJB-2 utilized barrier segments made from lightweight concrete with a density of 110 lb/ft$^3$ (1,762 kg/m$^3$) and a compressive strength of 6,652 psi (45.9 MPa). The lightweight concrete beams were undamaged segments from the full-scale RESTORE barrier test installations. Test nos. ACJB-3 and ACJB-4 utilized normal weight concrete beams fabricated specifically for these component tests. The normal weight concrete had a density of 140 lb/ft$^3$ (2,243 kg/m$^3$) and a compressive strength of 7,022 psi (48.4 MPa). Between test nos. ACJB-1 and ACJB-2, the segments were rotated 180 degrees such that the outer ends of the segments were now at the joint location. The same beam rotation was conducted between test nos. ACJB-3 and ACJB-4. Thus, each concrete segment was utilized during two tests with each end being adjacent to the joint only once.

A 5,000-lb (2,268-kg) bogie vehicle impacted the test installations 18 in. (457 mm) from the center of the joint between the two beam segments, creating a three-point bending test. The target impact conditions for all tests were a speed of 8 mph (13 km/h) and an angle of 90 degrees, or normal to the face of the longitudinal barrier. The test matrix is shown in Table 1.

Table 1. Test Nos. ACJB-1 through ACJB-4 Testing Matrix

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Target Bogie Weight lb (kg)</th>
<th>Target Impact Speed mph (km/h)</th>
<th>Impact Angle (deg)</th>
<th>Concrete Segments</th>
<th>Joint Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACJB-1</td>
<td>5,000 (2,268)</td>
<td>8 (13)</td>
<td>90°</td>
<td>Lightweight Concrete</td>
<td>Standard ACJ</td>
</tr>
<tr>
<td>ACJB-2</td>
<td>5,000 (2,268)</td>
<td>8 (13)</td>
<td>90°</td>
<td>Lightweight Concrete</td>
<td>ACJ with Neoprene Pads</td>
</tr>
<tr>
<td>ACJB-3</td>
<td>5,000 (2,268)</td>
<td>8 (13)</td>
<td>90°</td>
<td>Normal Weight Concrete</td>
<td>Standard ACJ</td>
</tr>
<tr>
<td>ACJB-4</td>
<td>5,000 (2,268)</td>
<td>8 (13)</td>
<td>90°</td>
<td>Normal Weight Concrete</td>
<td>ACJ with Steel End Caps</td>
</tr>
</tbody>
</table>
3.3 Equipment and Instrumentation

Equipment and instrumentation utilized to collect and record data during the dynamic bogie tests included a bogie vehicle, accelerometers, a retroreflective speed trap, high-speed and standard-speed digital video, and still cameras.

3.3.1 Bogie Vehicle

A rigid-frame bogie was used to impact the barrier system. The bogie head was constructed of a 6-in. thick x 8-in. wide x 24-in. tall (152-mm x 203-mm x 610-mm) timber post mounted to the front of the bogie. The timber impact head was bolted vertically to the front of the bogie frame so that contact would be made across the entire height of the concrete beam, as shown in Figure 24. The weight of the bogie with the addition of the impact head and accelerometers was 5,032 lb (2,282 kg).

Figure 24. Rigid-Frame Bogie
A pickup truck with a reverse-cable tow system was used to propel the bogie to a target impact speed of 8 mph (13 km/h). When the bogie approached the end of the guidance system, it was released from the tow cable, allowing it to be free rolling when it impacted the barrier system. A remote-control braking system was installed on the bogie, allowing it to be brought safely to rest after the test.

3.3.2 Accelerometers

A combination of two accelerometer systems were mounted on the bogie vehicle near its center of gravity to measure the acceleration in the longitudinal, lateral, and vertical directions. However, only the longitudinal acceleration was processed and reported. Table 2 denotes which accelerometers were utilized for each test.

The two systems, the SLICE-1 and SLICE-2 units, were modular data acquisition systems manufactured by Diversified Technical Systems (DTS) of Seal Beach, California. The acceleration sensors were mounted inside the bodies of custom-built SLICE 6DX event data recorders, which acquired data at 10,000 Hz to the onboard microprocessor. Each SLICE 6DX was configured with 7 GB of non-volatile flash memory, a range of ±500 g’s, a sample rate of 10,000 Hz, and a 1,650 Hz (CFC 1000) anti-aliasing filter. The “SLICEWare” computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

Table 2. Accelerometers Used for Each Test

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Accelerometers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLICE-1</td>
</tr>
<tr>
<td>ACJB-1</td>
<td></td>
</tr>
<tr>
<td>ACJB-2</td>
<td>X</td>
</tr>
<tr>
<td>ACJB-3</td>
<td>X</td>
</tr>
<tr>
<td>ACJB-4</td>
<td>X</td>
</tr>
</tbody>
</table>
3.3.3 Retroreflective Optic Speed Trap

The retroreflective optic speed trap was used to determine the speed of the bogie vehicle before impact. Five retroreflective targets, spaced at approximately 18-in. (457-mm) intervals, were applied to the side of the vehicle. When the emitted beam of light was reflected by the targets and returned to the Emitter/Receiver, a signal was sent to the data acquisition computer, recording at 10,000 Hz, as well as the external LED box activating the LED flashes. The speed was then calculated using the spacing between the retroreflective targets and the time between the signals. LED lights and high-speed digital video analysis are only used as a backup in the event that vehicle speeds cannot be determined from the electronic data.

3.3.4 Digital Photography

Three AOS high-speed digital video cameras and four GoPro digital video cameras were used to document each test, with the addition of a fifth GoPro camera for test nos. ACJB-3 and ACJB-4. The high-speed cameras were placed above, downstream, and laterally from the test article. The GoPro video cameras were placed in the same locations as the high-speed cameras with the addition of one located below the barrier joint. The fifth GoPro video camera used in test nos. ACJB-3 and ACJB-4 was added behind the barrier system. The AOS high-speed camera positioned above the system had a frame rate of 1000 frames per second and the remaining two cameras utilized a frame rate of 500 frames per second. The GoPro digital video cameras had frame rates of 120 and 240 frames per second. A Nikon D3200 digital still camera was also used to document pre- and post-test conditions for all tests.

3.4 Data Processing

The electronic accelerometer data obtained in dynamic testing was filtered using the SAE Class 60 Butterworth filter conforming to the SAE J211/1 specifications [6]. The pertinent acceleration signal was extracted from the bulk of the data signals. The processed acceleration data
was then multiplied by the mass of the bogie to get the impact force using Newton’s Second Law. Next, the acceleration trace was integrated to find the change in velocity versus time. Initial velocity of the bogie, calculated from the pressure tape switch data, was then used to determine the bogie velocity, and the calculated velocity trace was integrated to find the bogie’s displacement. This displacement is also the displacement of the barrier. Combining the previous results, a force vs. deflection curve was plotted for each test.
4 COMPONENT TESTING RESULTS AND DISCUSSION

4.1 Results

In all four dynamic tests, test nos. ACJB-1 through ACJB-4, the bogie vehicle and test installation interacted similarly. The majority of the impact force occurred early in the events as the momentum from the bogie vehicle was transferred into the system. Upon impact, the beams began to displace and the joints flexed. After a few inches of displacement, the bogie lost contact with the systems, but re-contacted the beams near the time of maximum deflection. Eventually, the system pushed the bogie vehicle backward as the rubber posts restored the beams to their original position. Although this general behavior was observed in all four tests, the magnitude of the deflections, forces, and damage to the test articles varied between tests, as described in the following sections.

The accelerometer data for each test was processed in order to obtain acceleration, velocity, and deflection curves, as well as force vs. deflection curves. Although the individual transducers produced similar results, the values described herein were calculated from the SLICE-1 data curves when available in order to provide common basis for comparing results from multiple tests. Test results for all transducers are provided in Appendix B.

Additionally, the high-speed video of each test was analyzed to measure the displacements of three separate targets on the test installations: 1) at the impact point, 2) adjacent to the joint on the impacted barrier, and 3) adjacent to the joint on the non-impact barrier. The x- and y-coordinates of the targets were tracked in order to measure the lateral displacements of the beams as well as the longitudinal displacements of the joints (joint opening) as they flexed. The maximum lateral and permanent set displacements provided in the following sections were determined by the lateral movement of the targets adjacent to the joint.
### 4.1.1 Test No. ACJB-1

Test no. ACJB-1 was a baseline test to evaluate the current ACJ utilized in the RESTORE barrier with lightweight concrete beams. During test no. ACJB-1, the bogie impacted the test article 18 in. (46 cm) from the centerline of the joint at a speed of 8.4 mph (13.5 km/h). Upon impact, the concrete beams began to displace laterally, and the joint began to flex. A peak resistance force of 107.6 kips (479 kN) was recorded at 0.0072 s after impact. At 0.010 s and a lateral displacement of 0.23 in. (6 mm), a crack formed on the top surface of the impacted concrete beam near the back of the joint. At 0.028 s, the bogie lost contact with the rail as it continued to displace laterally. At 0.045 s and a displacement of 3.68 in. (93 mm), concrete cracking began on the opposite side beam near the back-side joint bolts. The bogie impacted the rail a second time at 0.077 s and again lost contact with it at 0.110 s. A maximum joint opening displacement of 0.30 in. (8 mm) occurred at 0.120 s, and the concrete beams reached a maximum lateral displacement of 6.52 in. (166 mm) at 0.122 s. As the test article began to restore to its initial position, the beam re-contacted the bogie at 0.140 s and began to push the bogie backward. The bogie lost contact with the system for a final time at 0.300 s with a velocity of -2.0 mph (-3.2 km/h) (away from the system). The rail rebounded to a permanent set displacement of 0.19 in. (5 mm). Displacement vs. time curves for the bogie and the system targets are shown in Figure 25, while plots showing the joint opening as a function of time and displacement are shown in Figure 26. Force vs. time and force vs. displacement curves calculated from the accelerometer data are shown in Figure 27. Sequential photographs of the test are shown in Figure 28.

Damage to the test article consisted of concrete cracking and fracture, as shown in Figures 29 and 30. The impacted beam had a $\frac{1}{32}$-in. (1-mm) wide crack on the top surface extending from the rear ACJ bolt to the pentagon-shaped void in the beam, and a $\frac{1}{8}$-in. (3-mm) wide crack on the bottom surface that extended laterally between the ACJ bolts. The non-impact beam had a $\frac{1}{8}$-in.
(3-mm) wide crack on its top surface that extended between the ACJ bolts. Also, an 11-in. x 8-in. x 2¾-in. deep (279-mm x 203-mm x 70-mm deep) concrete piece fractured off from the bottom of the beam adjacent to the joint. When the joint was disassembled, additional concrete pieces that fractured from the ends of the two beams fell to the ground. The majority of the concrete between the ACJ bolt holes on the ends of both beams had disengaged, as shown in Figure 30. The fracture surfaces extended about 3 in. (76 mm) into the ends of the beams and exposed rebar in both beams.

The concrete damage sustained by the beams during test no. ACJB-1 was similar to the damage observed during full-scale testing of the RESTORE barrier, shown previously in Figures 2 and 3. Thus, it was determined that the 3-point bending test setup was loading the barrier joint in a similar manner to an impact on an actual system installation. Further, these results gave the researchers confidence that the remaining component tests on the modified ACJs would provide a reasonable estimation of system damage to the RESTORE barrier during actual vehicle impacts.

Figure 25. Displacement vs. Time Curves, Test No. ACJB-1
Figure 26. (a) Joint Opening vs. Time and (b) Joint Opening vs. Displacement, Test No. ACJB-1
Figure 27. (a) Force vs. Time and (b) Force vs. Deflection, Test No. ACJB-1
Figure 28. Time-Sequential Photographs, Test No. ACJB-1
Figure 29. System Damage, Test No. ACJB-1
Figure 30. System Damage with Joint Disassembled, Test No. ACJB-1
4.1.2 Test No. ACJB-2

Test no. ACJB-2 evaluated the ACJ with neoprene bearing pads between the steel angles and the lightweight concrete beams. During test no. ACJB-2, the bogie impacted the test article 18 in. (46 cm) from the centerline of the joint at a speed of 10.2 mph (16.4 km/h). Upon impact, the concrete beams displaced laterally and the joint flexed. A peak resistance force of 115.3 kips (513 kN) was recorded at 0.0056 s after impact. At 0.024 s, the bogie lost contact with the rail as it continued to displace laterally. At 0.042 s and a lateral displacement of 3.81 in. (97 mm), a crack formed on the bottom surface of the impacted concrete beam between the front and back joint bolts. At 0.067 s and a displacement of 6.10 in. (155 mm), concrete cracking began on the bottom surface of the opposite side beam adjacent to the rear joint bolt. The bogie impacted the rail a second time at 0.084 s and lost contact with it a second time at 0.108 s. The maximum joint opening displacement of 0.66 in. (17 mm) occurred at 0.143 s, and the concrete beams reached a maximum lateral displacement of 10.74 in. (273 mm) at 0.162 s. As the test article began to restore to its initial position, the beam re-contacted the bogie at 0.252 s and pushed the bogie backward. The bogie lost contact with the system for a final time at 0.370 s with a velocity of -2.6 mph (-4.2 km/h) (away from the system). The rail rebounded to a permanent set displacement of 0.20 in. (5 mm).

Displacement vs. time curves for the bogie and the system targets are shown in Figure 31, while plots showing the joint opening as a function of time and displacement are shown in Figure 32. Force vs. time and force vs. displacement curves calculated from the accelerometer data are shown in Figure 33. Sequential photographs of the test are shown in Figure 34.

Damage to the test article consisted of concrete cracking and spalling, as shown in Figures 35 and 36. A 7-in. (178-mm) hairline crack on the top surface of the impacted barrier started adjacent to the back bolt location and extended forward into the beam. A 1/8-in. (3-mm) wide crack on the bottom surface of the impacted beam extended laterally between the ACJ bolt locations. A
1/16-in. (2-mm) wide crack extended between the bolts on the bottom of the non-impact beam. After the joint was disassembled, additional hairline cracks were found extending vertically between the bolt holes on the backside of both beams. Minor spalling was also present around nearly all of the bolt holes. The worst spalling occurred adjacent to the backside bolt holes on the opposite side beam, where it extended from the holes to the edge of the beam chamfer with a maximum depth of 1/2 in. (13 mm).

Figure 31. Displacement vs. Time Curves, Test No. ACJB-2
Figure 32. (a) Joint Opening vs. Time and (b) Joint Opening vs. Displacement, Test No. ACJB-2
Figure 33. (a) Force vs. Time and (b) Force vs. Deflection, Test No. ACJB-2
Figure 34. Time-Sequential Photographs, Test No. ACJB-2
Figure 35. System Damage, Test No. ACJB-2
Figure 36. System Damage with Joint Disassembled, Test No. ACJB-2
4.1.3 Test No. ACJB-3

Test no. ACJB-3 evaluated the performance of the ACJ with normal weight concrete beams in lieu of the lightweight concrete beams of the as-tested version of the RESTORE barrier. During test no. ACJB-3, the bogie impacted the test article 18 in. (46 cm) from the centerline of the joint at a speed of 10.2 mph (16.4 km/h). Upon impact, the concrete beams displaced laterally and the joint flexed. A peak resistance force of 133.3 kips (593 kN) was recorded at 0.0073 s after impact. At 0.018 s and a lateral displacement of 1.26 in. (32 mm), a crack formed in the impacted concrete beam between the front and back joint bolts. At 0.032 s, the bogie lost contact with the rail as it continued to displace laterally. The bogie impacted the rail a second time at 0.090 s, and concrete cracking began on the top surface of the opposite side beam adjacent to the rear joint bolt at 0.093 s and a displacement of 7.31 in. (186 mm). The bogie lost contact with the beam for a second time at 0.110 s. The maximum joint opening displacement of 0.71 in. (18 mm) occurred at 0.152 s, and the concrete beams reached a maximum lateral displacement of 9.32 in. (237 mm) at 0.153 s. As the test article began to restore to its initial position, the beam re-contacted the bogie at 0.170 s and pushed the bogie backward. The bogie lost contact with the system for a final time at 0.330 s with a velocity of -2.6 mph (-4.2 km/h) (away from the system). The rail rebounded to a permanent set displacement of 0.46 in. (12 mm). Displacement vs. time curves for the bogie and the system targets are shown in Figure 37, while plots showing the joint opening as a function of time and displacement are shown in Figure 38. Force vs. time and force vs. displacement curves calculated from the accelerometer data are shown in Figure 39. Sequential photographs of the test are shown in Figure 40.

Damage to the test article consisted of concrete cracking and fracture, as shown in Figures 41 and 42. Concrete spalling occurred on the front of the impacted beam adjacent to the chamfered end. A concrete piece measuring about 7 in. (178 mm) wide and 2½ in. (64 mm) deep was observed.
on the top surface of the impacted barrier adjacent to the back joint bolt. A larger concrete piece measuring 12 in. x 13 in. x 3 in. deep (305 mm x 330 mm x 76 mm deep) disengaged from the impacted barrier and exposed the internal rebar on the bottom half of the beam end. Minor spalling and hairline cracks were observed on the top of the non-impact beam adjacent to the back joint bolt. After the joint was disassembled, further spalling and concrete disengagement around the bolt holes on the end surfaces of the beams were observed. Two $\frac{1}{16}$-in. (2-mm) wide cracks extended from the top to the bottom of the opposite side beam through the back bolt holes. A $\frac{1}{32}$-in. (1-mm) wide crack originated from the top-back bolt hole and extended across the end surface of the opposite side beam.

Figure 37. Displacement vs. Time Curves, Test No. ACJB-3
Figure 38. (a) Joint Opening vs. Time and (b) Joint Opening vs. Displacement, Test No. ACJB-3
Figure 39. (a) Force vs. Time and (b) Force vs. Deflection, Test No. ACJB-3
Figure 40. Time-Sequential Photographs, Test No. ACJB-3
Figure 41. System Damage, Test No. ACJB-3
Figure 42. System Damage with Joint Disassembled, Test No. ACJB-3
4.1.4 Test No. ACJB-4

Test no. ACJB-4 evaluated normal weight concrete beams with steel end caps. During test no. ACJB-4, the bogie impacted the test article 18 in. (46 cm) from the centerline of the joint at a speed of 9.9 mph (15.9 km/h). Upon impact, the concrete beams displaced laterally and the joint flexed. A peak resistance force of 96.9 kips (431 kN) was recorded at 0.0076 s after impact. At 0.028 s, the bogie lost contact with the rail as it continued to displace laterally. At 0.061 s and a lateral displacement of 5.15 in. (131 mm), a crack formed on the top surface of the impacted concrete beam near the rear joint bolt. The bogie impacted the rail a second time at 0.095 s, and concrete beams reached a maximum lateral displacement of 7.66 in. (195 mm) at 0.136 s. The bogie lost contact with the beam a second time at 0.145 s. As the test article began to restore to its initial position, the beam re-contacted the bogie at 0.180 s and pushed the bogie backward. The bogie lost contact with the system for a final time at 0.330 s with a velocity of -2.0 mph (-3.2 km/h) (away from the system). The maximum joint opening displacement of 0.12 in. (3 mm) occurred at 0.463 s when the test article reached its maximum forward displacement and began to return to its initial position. The rail rebounded to a permanent set displacement of 0.70 in. (18 mm). Displacement vs. time curves for the bogie and the system targets are shown in Figure 43, while plots showing the joint opening as a function of time and displacement are shown in Figure 44. Force vs. time and force vs. displacement curves calculated from the accelerometer data are shown in Figure 45. Sequential photographs of the test are shown in Figure 46.

Damage to the test article consisted of minor concrete cracking, as shown in Figure 47. A $\frac{1}{32}$-in. (1-mm) wide crack on the top surface of the impacted barrier began near the back joint bolts and extended toward the front of the beam. The non-impact barrier had a hairline crack at the same location that extended 2 in. (51 mm) toward the pentagon-shaped void in the beam. No
further damage was observed after the joint was disassembled as the steel end cap remained undamaged.

Figure 43. Displacement vs. Time Curves, Test No. ACJB-4
Figure 44. (a) Joint Opening vs. Time and (b) Joint Opening vs. Displacement, Test No. ACJB-4
Figure 45. (a) Force vs. Time and (b) Force vs. Deflection, Test No. ACJB-4
Figure 46. Time-Sequential Photographs, Test No. ACJB-4
Figure 47. System Damage, Test No. ACJB-4
4.2 Discussion

The general behavior of each test installation was similar among test nos. ACJB-1 through ACJB-4. Upon impact from the bogie vehicle, the joints flexed and allowed the concrete beams to displacement laterally. After absorbing the impact energy from the bogie vehicle, the elastic strain energy in the joints and rubber posts caused the beams to restore to nearly their initial positions. However, the ACJ design variations created differences in beam displacement, event duration, and sustained damage. A summary of the component testing results is shown in Table 3. Note that peak forces and system displacements were dependent upon the impact speed, or impact energy, of the bogie vehicle. To provide a better comparison of the strength and stiffness of each ACJ variation, the maximum displacement of the target adjacent to the joint was normalized by dividing by the impact energy.

While reviewing high-speed data, it was observed that all of the concrete cracking appeared to initiate at the backside of the joints adjacent to the bolts. As the beams displaced, the tension bolts (back side) were loaded and may have shifted and pressed against the sides of the bolt hole. The buildup of large shear forces against the side of holes likely led to stress concentrations and eventual cracking. The internal steel reinforcement limited cracks from propagating toward the middle of the beams, but the outer 3 in. (76 mm) of concrete at the end of the beam was susceptible to crack propagation and eventual fracture. Thus, the cracks tended to propagate adjacent to the rebar cage near the end of the beam and eventually reached the bolt holes in the front of the beams.

Although cracking was initiated in the same manner among all of the test articles, the amount of concrete damage sustained at the ends of the beams differed. Test nos. ACJB-1 and ACJB-3 displayed the worst damage as concrete pieces fractured off of the ends of the beams and exposed the internal steel reinforcement. This type of concrete damage was observed in the full-scale testing of the RESTORE barrier, and preventing such damage was the purpose of this study.
The use of normal weight concrete in test no. ACJB-3 reduced the amount of concrete cracking, spalling, and fracture in the beams as compared to the baseline test with lightweight concrete in test no. ACJB-1. Additionally, the onset of cracking in the normal weight concrete beams was delayed about twice as long as in the lightweight concrete beams. Thus, the normal weight concrete barriers would be less likely to sustain damage during low severity impacts. However, the cracking and fracture sustained during test no. ACJB-3 suggests that maintenance would likely still be required after moderate to severe impacts.

Table 3. Component Testing Summary

<table>
<thead>
<tr>
<th>Test No.</th>
<th>ACJB-1</th>
<th>ACJB-2</th>
<th>ACJB-3</th>
<th>ACJB-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact Velocity (mph)</td>
<td>8.4</td>
<td>10.2</td>
<td>10.2</td>
<td>9.9</td>
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<tr>
<td>Bogie Weight (lb)</td>
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<td>5,032</td>
<td>5,032</td>
<td>5,032</td>
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<tr>
<td>Maximum Displacement (in.)</td>
<td></td>
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<td>- Bogie</td>
<td>5.74</td>
<td>9.42</td>
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<td>6.94</td>
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<tr>
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<td>6.09</td>
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<td>8.48</td>
<td>7.10</td>
</tr>
<tr>
<td>- Rail @ Joint</td>
<td>6.52</td>
<td>10.74</td>
<td>9.32</td>
<td>7.66</td>
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<tr>
<td>- Rail Disp./Impact Energy (in./kip-ft)</td>
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<td>0.618</td>
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<td>0.46</td>
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<td>-2.60</td>
<td>-2.57</td>
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</tr>
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<td>115.3</td>
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<td>- Time (s)</td>
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<td>0.042</td>
<td>0.018</td>
<td>0.061</td>
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<tr>
<td>- Lateral Joint Displacement (in.)</td>
<td>0.23</td>
<td>3.81</td>
<td>1.26</td>
<td>5.15</td>
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<tr>
<td>First Cracking – Non-Impact Barrier</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>- Time (s)</td>
<td>0.045</td>
<td>0.067</td>
<td>0.093</td>
<td>NA</td>
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<tr>
<td>- Lateral Joint Displacement (in.)</td>
<td>3.68</td>
<td>6.10</td>
<td>7.31</td>
<td>NA</td>
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<tr>
<td>Joint Opening Width</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Initial Gap Width (in.)</td>
<td>¾</td>
<td>½</td>
<td>½</td>
<td>½</td>
</tr>
<tr>
<td>- Maximum Displacement (in.)</td>
<td>0.30</td>
<td>0.66</td>
<td>0.71</td>
<td>0.12</td>
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<tr>
<td>- Permanent Displacement (in.)</td>
<td>0.03</td>
<td>0.14</td>
<td>0.56</td>
<td>0.08</td>
</tr>
<tr>
<td>Damage Scale</td>
<td>Severe</td>
<td>Minor</td>
<td>Heavy</td>
<td>Minimal</td>
</tr>
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</table>
The rubber bearing pads utilized in test no. ACJB-2 resulted in a more flexible joint and allowed increased system displacements, illustrated by test no. ACJB-2 having the highest displacement per impact energy value. The increased flexibility allowed for a longer impact event and delayed the onset of concrete cracking compared to the baseline test. Additionally, the bearing pad may have distributed the impact loads more evenly across the joint and prevented stress concentrations and localized cracking. The combination of these factors caused by the introduction of rubber bearing pads within the ACJ resulted in greatly reduced concrete damage to the system beams.

The steel end cap utilized in test no. ACJB-4 provided the best durability and resistance to damage among the joint variations evaluated herein. The steel end cap provided a smooth bearing surface for the angled joint pieces and confinement strength to the concrete in the ends of the beams. Thus, only minor hairline cracks were observed during test no. ACJB-4. The increased strength of the system also increased the stiffness of the joint. Test no. ACJB-4 had the lowest displacement per impact energy and the lowest joint opening displacement among all four tests. Test no. ACJB-4 had the largest permanent set value, but the final displacement was still less than ¾ in. (19 mm) from its original position and was not a concern.
5 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The objective of this study was to evaluate three design variations of the ACJ for use in the RESTORE barrier. These new variations included: 1) incorporating rubber bearing pads between the steel angle and the chamfered corners of the concrete beams, 2) utilizing normal weight concrete instead of lightweight concrete in the beams, and 3) casting a steel end cap on the beam segments. The ACJ modifications were intended to limit the amount of concrete cracking and fracture that was observed on the ends of the beam segments during the full-scale crash testing of the RESTORE barrier.

Dynamic bogie testing was conducted to evaluate the performance of these ACJ variations. Two full-scale RESTORE barrier beams connected by one of the ACJ variations were subjected to a bogie vehicle impact causing 3-point bending in the test article. Four component tests were conducted: one baseline test on the original RESTORE ACJ and one test on each of the three ACJ variations. The baseline test resulted in cracking and fracture similar to the damage observed during full-scale testing. Thus, the 3-point bending test setup created joint displacements, loads, and failure mechanisms representative of a vehicular impact into a complete system.

All three of the new ACJ variations provided improvements to the original joint in terms of increasing durability and minimizing system damage. The normal weight concrete beams provided minimal benefits as they were still subject to similar cracking and fracture as the lightweight beam, just to a lesser degree. The rubber bearing pads resulted in increased flexibility in the joint, allowed for larger deflections, and reduced the concrete damage to only small cracks and minor spalling. The steel end cap provided the greatest resistance to damage as only a few hairline cracks were observed on the beam. The steel end caps also resulted in an increased stiffness in the joint. The steel end caps were incorporated into the normal weight concrete beams,
but similar results would be expected if the caps were used in combination with lightweight concrete beams.

Although all three ACJ variations showed improvements over the original, as-tested, RESTORE joints, further evaluation and analysis is recommended prior to utilizing these joints in real-world installations. While the dynamic component tests conducted herein may provide grounds for comparing the relative system damage between joint designs, the actual system damage sustained during a vehicle impact is unknown. Further, the changes in the stiffness and/or flexibility of these joint variations may affect the performance of the RESTORE barrier in terms of system deflections, resistance forces, and vehicle accelerations. Finally, the 50 percent increase in weight associated with normal-weight concrete as compared to lightweight concrete would likely affect the inertia and impact performance of the barrier.

The cost to incorporate these joint variations into the RESTORE barrier may also be considered prior to selecting the optimized joint design. At the time of testing, the cost for a lightweight concrete beam was approximately $50 more than a normal weight concrete beam. The cost to implement the steel end caps within the concrete beams was approximately $100 per beam. Finally, the cost to install four bearing pads in the ACJs adjacent to each beam was approximately $30. Note, all of the additional costs associated with these ACJ variations would account for less than 3 percent of the cost of the RESTORE barrier.
6 REFERENCES


7 APPENDICES
Appendix A. Material Specifications
<table>
<thead>
<tr>
<th>Item No.</th>
<th>QTY</th>
<th>Description</th>
<th>Material Spec</th>
<th>Hardware Spec</th>
<th>Reference</th>
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<tr>
<td>a1</td>
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<td>Lightweight Concrete Beam</td>
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<td>-</td>
<td>Mix#92443003</td>
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<td>a2</td>
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<td>Normal Weight Concrete Beam</td>
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<td>-</td>
<td>Job #3267 Mix#9382</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>f'c tests dated 3/9/2016</td>
<td></td>
<td>Part#EF6496, Order#54803</td>
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<tr>
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<td>16</td>
<td>Morse E46496 Shear Fender</td>
<td>ASTM D2000</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>a4</td>
<td>4</td>
<td>6&quot;x6&quot;x1/2&quot;, 17&quot; Long Steel Angle</td>
<td>ASTM A992 Galvanized</td>
<td>-</td>
<td>H#L92705</td>
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<tr>
<td>a5</td>
<td>64</td>
<td>5&quot;x5&quot;x3/8&quot; Gusset Plate</td>
<td>ASTM A572 Grade 50 Galvanized</td>
<td>-</td>
<td>H#A3V3389</td>
</tr>
<tr>
<td>a6</td>
<td>64</td>
<td>17&quot;x5 11/16&quot;x1/4&quot; ACJ Neoprene Pad</td>
<td>Neoprene</td>
<td>-</td>
<td>Motion Industries Invoice</td>
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<tr>
<td>b1</td>
<td>128</td>
<td>3/4&quot; Dia. UNC, 21&quot; Long Hex Bolt</td>
<td>Grade 5 Galvanized</td>
<td>FBX20a</td>
<td>KD Fastener's COC</td>
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<td>FRR20a</td>
<td>H#E11400347 L#213B249-13</td>
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<td>-</td>
<td>Tech Data available online</td>
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<td>48</td>
<td>1/2&quot; Dia., Bent Rebar, unbent 77&quot; Long</td>
<td>ASTM A615 Grade 60</td>
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<td>H#566673 and H#582530</td>
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<td>-</td>
<td>H#62133268/02 and H#58023680</td>
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<tr>
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<td>ASTM A615 Grade 60</td>
<td>-</td>
<td>H#62133268/02 and H#58023680</td>
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<td>2</td>
<td>26 1/8&quot;x17&quot;x3/16&quot; Bent Sheet</td>
<td>A36 or stronger</td>
<td>-</td>
<td>H#B314750</td>
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<td>d2</td>
<td>16</td>
<td>1/2&quot; Dia. x 4&quot; Long Stud</td>
<td>A36 or stronger</td>
<td>-</td>
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<td>e1</td>
<td>8</td>
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<td>AISI 1026</td>
<td>-</td>
<td>H#NLK1474573</td>
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Table A-1. Bill of Materials (Continued)
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<td>g4</td>
<td>2</td>
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<td>Neoprene/Rubber</td>
<td>Motion Industries Invoice</td>
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</table>
Figure A-1. Lightweight Concrete, Test Nos. ACJB-1 and ACJB-2
Dear Jim,

Below are the strength values to date for the UNL Barrier Curbs produced at Concrete Industries.

<table>
<thead>
<tr>
<th>Cast Date</th>
<th>Release</th>
<th>7 Day</th>
<th>28 Day</th>
</tr>
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<tr>
<td>2/25/2016</td>
<td>4728</td>
<td>6930</td>
<td>3/24/2016</td>
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General Testing Lab,  

Rod Leber, Manager

Figure A-2. Normal Weight Concrete, Test Nos. ACJB-3 and ACJB-4
Figure A-3. Rubber Posts
Figure A-4. Steel Angle for ACJ
**Figure A-5. Steel Angle Gusset Plates and Upper Skid Plate**
Figure A-6. Neoprene/Rubber Pads
Figure A-7. ¾-in. (19-mm) Dia. UNC 21-in. (533-mm) Long Hex Bolts
Figure A-8. ¾-in. (19-mm) Dia. UNC 10-in. (254-mm) Long Threaded Rod
Figure A-9. ¾-in. (19-mm) Dia. Hex Head Nuts
Figure A-10. ¾-in. (19-mm) Dia. Flat Washers
GAFFNEY BOLT COMPANY
6100 MATERIAL AVENUE
ROCKFORD, IL 61111

DATE SHIPPED: FEB. 24, 2014

LOT NO: 36546

CUSTOMER: THE STRUCTURAL BOLT COMPANY

P.O. NO: 15243

QUANTITY: 88

DESCRIPTION: 1-8 X 11 1/2 A325 HV HEX HDG

HEAT NO: 133762

HEAT CHEMICAL ANALYSIS ATTACHED

MATERIAL: 1045

ROCKWELL: 31-32 30.7

TENSILE: 96,940 LBS

PROOFLOAD: 51,500 LBS

PASSED VISUAL INSPECTION

ALL TEST ARE IN ACCORDANCE WITH THE METHODS PRESCRIBED IN THE APPLICABLE SAE
AND ASTM SPECIFICATIONS. PRODUCT MEETS ASME B18.2.6 DIMENSIONAL SPECIFICATION
AND THREADS MEET ANSI B1.1 CLASS 2A. WE CERTIFY THAT THIS DATA IS TRUE
REPRESENTATION OF INFORMATION PROVIDED BY THE MATERIAL SUPPLIER AND OUR
TESTING LABORATORY.

THESE PARTS WERE MANUFACTURED BY GAFFNEY BOLT COMPANY FROM STEEL MELTED AND
MANUFACTURED IN THE USA.

GAFFNEY BOLT COMPANY
MARY P. GAFFNEY
SECRETARY

Figure A-11. 1-in (25-mm) Dia. Hex Head Bolts
Figure A-12. No. 4 Rebar, Test Nos. ACJB-1 through ACJB-2
Figure A-13. No. 6 Rebar, Test Nos. ACJB-1 through ACJB-2
### Figure A-14. No. 4 Rebar, Test Nos. ACJB-3 through ACJB-4

**Heat Number**

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<tr>
<th>Heat Number</th>
<th>Sample No.</th>
<th>Yield (MPa)</th>
<th>Ultimate (MPa)</th>
<th>Elongation (%)</th>
<th>Reduction (%)</th>
<th>Bend</th>
<th>Wt./ft</th>
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<tbody>
<tr>
<td>582530</td>
<td>01</td>
<td>66133</td>
<td>95660</td>
<td>16.0</td>
<td>OK</td>
<td>0.671</td>
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<tr>
<td></td>
<td>02</td>
<td>456.0</td>
<td>665.8</td>
<td></td>
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<td>68123</td>
<td>96820</td>
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<td></td>
<td></td>
<td>469.7</td>
<td>667.6</td>
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</tr>
</tbody>
</table>

All melting and manufacturing processes of the material subject to this test certificate occurred in the United States of America. ERMS also certifies this material to be free from Mercury contamination.

This material has been produced, tested and conforms to the requirements of the applicable specifications. We hereby certify that the above test results represent those contained in the records of the Company.

Methods used: ASTM A370, A516, A615, A706.

Material test report shall not be reproduced except in full, without approval of the company.
**Figure A-15. No. 6 Rebar, Test Nos. ACJB-3 through ACJB-4**

<table>
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<tr>
<th>Chemical Composition</th>
<th>0.44</th>
<th>0.90</th>
<th>0.011</th>
<th>0.017</th>
<th>0.25</th>
<th>0.28</th>
<th>0.08</th>
<th>0.14</th>
<th>0.020</th>
<th>0.020</th>
<th>0.023</th>
<th>0.000</th>
<th>0.003</th>
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<td>MECHANICAL PROPERTIES</td>
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<td>Comments / Notes</td>
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<td>OK</td>
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</table>

The above figures are certified chemical and physical test records as contained in the permanent records of company. We certify that these data are correct and in compliance with specified requirements. This material, including the billets, was melted and manufactured in the USA. CMTR complies with EN 10204 3.1.

*Signature*

**Quality Director**

**Quality Assurance MGR.**
Figure A-16. Steel End Caps, Test No. ACJB-3 and ACJB-4
Weld Stud Certification

[Image]

Customer: APOLLO STE
Customer Purchase Order #: 9098
Work Order #: 138215
Invoice #: 144322
Part #: 6HCA050412
Heat #: NE15202872
Weld Stud Size: 1/2 X 4 1/8 HCA
QUANTITY:

Certified Chemical Test Report & Chemical Analysis Information

Product meets Standard A108 requirements for all Cold Finished Carbon & Alloy Steel Bars.

<table>
<thead>
<tr>
<th>AISI Grade</th>
<th>C1018AK</th>
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<tr>
<td>Carbon (C)</td>
<td>.17 %</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>.68 %</td>
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<tr>
<td>Sulfur (S)</td>
<td>.004 %</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>.07 %</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>.007 %</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>%</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>%</td>
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<tr>
<td>Nickel (Ni)</td>
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<tr>
<td>Molybdenum (Mo)</td>
<td>%</td>
</tr>
<tr>
<td>Others</td>
<td>%</td>
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Certified Mechanical Property Analysis Information

- Tensile Strength = 76,000 PSI
- Yield Strength (.2% Offset) = 66,500 PSI
- Reduction of Area = 69 Minimum %
- Elongation (2 inches) = 26 %

TSA Manufacturing certifies this product was manufactured from a single Heat Code of material. All Chemical and Mechanical Analysis properties reported above are true and in accordance with ASTM 29, ASTM A108, ASTM E8/E8M, ATM A370-97, AASHTO/AWSD1.5M /D15:2008ANNEX E.

This product is free from Mercury contamination. Melted and manufactured in the U.S.A.

Signed: [Signature]  Dated: 11-6-15
Don Condon, Quality Assurance Manager

TSA Weld Studs are certified to AASHTO/AWS D1.5M/D1.5.1.5ANNEX E Standards.

Figure A-17. Shear Studs for Steel End Caps, Test No. ACJB-4

88
Figure A-18. Steel Pipe for Barrier Skids

**SFH SKID SUPPORT TUBING R#14-0519**

- **HEAT NUMBER**: NLK1474573
- **PCS**: 40
- **TOTAL LENGTH SHIPPED**: 920'
- **Ys (ksi)**: 88.2 (608)
- **Ts (ksi)**: 97.6 (673)
- **% elongation**: 15%
- **HARDNESS**: 93 RB

**SPECIFICATIONS**
- **ERW STEEL MECHANICAL TUBES - CD SIZE**: 6.500 (165.10) OD x 5.750 (146.05) ID
- **SPEC**: ASTM A513-12 1026, ERW, TYPE 5, SRA, AW, MECHANICAL TUBING
- **CERTIFICATION**: Certification done in compliance with EN 10204:2004 Type 3.1

**HEAT NO.**
- **C**: 0.21
- **Mn**: 0.66
- **P**: 0.008
- **S**: 0.04
- **Si**: 0.21
- **Cr**: 0.08
- **Ni**: <0.1
- **Mo**: 0.00
- **Cu**: 0.00
- **Al**: 0.002
- **V**: 0.001
- **N**: <0.01

**CERTIFICATION**
- **CERTIFIED BY**: GADSL V1.0 2005-01-25, AND ROHS DIRECTIVE (2002/95/EC)
- **MATERIALS MANUFACTURED BY PTC ALLIANCE**
- **MELTED IN RUSSIA**
- **ALL MATERIALS ARE FREE OF MERCURY CONTAMINATION AND/OR MERCURY COMPOUNDS**
- **AS DEFINED BY**: GADSL V1.0 2005-01-25, AND ROHS DIRECTIVE (2002/95/EC)
### Chemical Analysis

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.0600</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.1500</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.0040</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.0030</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.1300</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.9600</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.0000</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.0000</td>
</tr>
<tr>
<td>Boron</td>
<td>0.3000</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0300</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.0000</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.0000</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.0000</td>
</tr>
<tr>
<td>Columbium</td>
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</tr>
<tr>
<td>Nitrogen</td>
<td>0.0000</td>
</tr>
<tr>
<td>Tin</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

### Mechanical/Physical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>6640.000</td>
</tr>
<tr>
<td>Yield</td>
<td>59949.000</td>
</tr>
<tr>
<td>Elong</td>
<td>30.10</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.0000</td>
</tr>
<tr>
<td>Grain</td>
<td>0.0000</td>
</tr>
<tr>
<td>Charpy</td>
<td>0.0000</td>
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<tr>
<td>Charpy Dr</td>
<td>NA</td>
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<td>Charpy Sq</td>
<td>NA</td>
</tr>
<tr>
<td>Temperature</td>
<td>NA</td>
</tr>
<tr>
<td>Olsen</td>
<td>NA</td>
</tr>
</tbody>
</table>

---

**Figure A-19. Base Plate for Steel Skids**
## SSAB Test Certificate

**Customer:** STEEL & PIPE SUPPLY  
P.O. BOX No. 1688  
MANHATTAN, NY 66592  

**Product Description:** ASTM A572 -50/M345(27)/A709-50/M345(11)  

### Tested Pieces

<table>
<thead>
<tr>
<th>Heat Id</th>
<th>Piece Id</th>
<th>Tested Thickness</th>
<th>YS (KSI)</th>
<th>TS (KSI)</th>
<th>%RA</th>
<th>Elong %</th>
<th>Tensile Test</th>
<th>Average Hardness</th>
<th>Abs. Energy (Ft-Lb)</th>
<th>% Shear</th>
<th>Tensile Test</th>
<th>Total Ft-Lbs</th>
<th>Total %Str</th>
<th>B Diss</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3D089</td>
<td>A27</td>
<td>0.495 (DISCRT)</td>
<td>11.66</td>
<td>86</td>
<td>30</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

### Chemical Analysis

<table>
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<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Ti</th>
<th>ORGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3D089</td>
<td>.18</td>
<td>1.24</td>
<td>.011</td>
<td>.021</td>
<td>.19</td>
<td>.028</td>
<td>.32</td>
<td>.18</td>
<td>.08</td>
<td>.04</td>
<td>.001</td>
<td>.049</td>
</tr>
</tbody>
</table>

**MERCURY IS NOT A METALLURGICAL COMPONENT OF THE STEEL AND NO MERCURY WAS INTENTIONALLY ADDED DURING THE MANUFACTURE OF THIS PRODUCT.**

**NMT EN 10204:2004 INSPECTION CERTIFICATE 3.1 COMPLIANT**

**PRODUCTS SHIPPED:**

<table>
<thead>
<tr>
<th>Heat Id</th>
<th>Piece Id</th>
<th>Pcs/lot</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3D089</td>
<td>A27</td>
<td>6, 1964</td>
</tr>
</tbody>
</table>

---

Figure A-20. Gusset Plates for Steel Skids
Appendix B. Bogie Test Results

The results of the recorded data from each accelerometer for every dynamic bogie test are provided in the summary sheets found in this appendix. Summary sheets include acceleration, velocity, and deflection vs. time plots as well as force vs. deflection and energy vs. deflection plots.
Figure B-1. Test No. ACJB-1 Results (SLICE-2)
**Test Information**

<table>
<thead>
<tr>
<th>Test Description:</th>
<th>Restore Barrier Joint Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Number:</td>
<td>ACJB-2</td>
</tr>
<tr>
<td>Test Date:</td>
<td>3/30/2016</td>
</tr>
<tr>
<td>Failure Type:</td>
<td>Joint Flexure</td>
</tr>
</tbody>
</table>

**Rail Properties**

- **Dimensions:** 20.5" x 18.5" x 239.5"
- **Concrete:** Lightweight Concrete
- **End Plate:** None

**Joint Hardware**

- **Bolts:** 1” Dia. ASTM A325
- **ACJ:** 6” x 6” x 0.5”
- **Rubber Pad:** 1/4” thick pad on both ACJ faces

**Bogie Properties**

- **Impact Velocity:** 10.17 mph (14.91 ft/s)
- **Impact Height:** 21
- **Bogie Mass:** 5032 lb

**Data Acquired**

- **Accelerometer:** SLICE-1
- **Camera Data:** GoPros, AOS

**Test Results Summary**

- **Event Duration:** 0.3699 sec
- **Max. Deflection:** 9.4 in.
- **Peak Force:** 115.3 k
- **Initial Linear Stiffness:** 122.7 k/in.
- **Peak Energy:** 208.5 k-in.
- **Absorbed Energy:** 194.9 k-in.
- **Exit Velocity:** -3.81 ft/sec

---

**Figure B-2. Test No. ACJB-2 Results (SLICE-1)**
MIDWEST ROADSIDE SAFETY FACILITY

Bogie Test Summary

Test Information

- Test Description: RESTORE Barrier Joint Testing
- Test Number: ACJB-2
- Test Date: 3/30/2016
- Failure Type: Jointed Flexure

Test Results Summary

- Event Duration: 0.3700 s
- Max. Deflection: 8.5 in.
- Peak Force: 161.2 k
- Initial Linear Stiffness: 148.6 k/in.
- Peak Energy: 208.5 k-in.
- Absorbed Energy: 188.3 k-in.
- Exit Velocity: -4.64 ft/s

Rail Properties

- Dimensions: 20.5” x 18.5” x 39.5”
- Concrete: Lightweight Concrete
- End Plate: None

Joint Hardware

- Bolts: 1” Dia. ASTM A325
- ACJ: 6” x 6” x 0.5”
- Rubber Pad: 1/4” thick pad on both ACJ faces

Bogie Properties

- Impact Velocity: 10.17 mph (14.91 ft/s)
- Impact Height: 21
- Bogie Mass: 5032 lb

Data Acquired

- Accelerometer: SLICE-2
- Camera Data: GoPro, AOS

Figure B-3. Test No. ACJB-2 Results (SLICE-2)
### Test Results Summary

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event Duration</td>
<td>0.3300 s</td>
</tr>
<tr>
<td>Max. Deflection</td>
<td>7.5 in.</td>
</tr>
<tr>
<td>Peak Force</td>
<td>133.3 k</td>
</tr>
<tr>
<td>Initial Linear Stiffness</td>
<td>109.8 k/in.</td>
</tr>
<tr>
<td>Peak Energy</td>
<td>209.1 k-in.</td>
</tr>
<tr>
<td>Absorbed Energy</td>
<td>195.8 k-in.</td>
</tr>
<tr>
<td>Exit Velocity</td>
<td>-3.77 ft/s</td>
</tr>
</tbody>
</table>

### Rail Properties

- **Dimensions:** 20.5” x 18.5” x 239.5”
- **Concrete:** Standard Weight Concrete
- **End Plate:** None

### Joint Hardware

- **Bolts:** 1” Dia. ASTM A325
- **ACJ:** 6” x 6” x 0.5”
- **Rubber Pad:** NA

### Bogie Properties

- **Impact Velocity:** 10.18 mph (14.93 ft/s)
- **Impact Height:** 21
- **Bogie Mass:** 5032 lb

### Data Acquired

- **Accelerometer:** SLICE-1
- **Camera Data:** GoPro, AOS

---

Figure B-4. Test No. ACJB-3 Results (SLICE-1)
Figure B-5. Test No. ACJB-3 Results (SLICE-2)
**Bogie Test Summary**

<table>
<thead>
<tr>
<th>Test Information</th>
<th>Test Results Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Description:</strong></td>
<td>- Event Duration: 0.3300 s</td>
</tr>
<tr>
<td><strong>Test Number:</strong></td>
<td>- Max. Deflection: 6.9 in.</td>
</tr>
<tr>
<td><strong>Test Date:</strong></td>
<td>- Peak Force: 96.9 k.</td>
</tr>
<tr>
<td><strong>Failure Type:</strong></td>
<td>- Initial Linear Stiffness: 77.9 k/in.</td>
</tr>
</tbody>
</table>

**RAIL PROPERTIES**

- **Dimensions:** 20.5" x 18.5" x 239.5"
- **Concrete:** Standard Weight Concrete
- **End Plate:** 1/8"-Thick Steel

**J o i n t H a r d w a r e**

- **Bolts:** 1" Dia. ASTM A325
- **ACJ:** 6" x 6" x 0.5"
- **Rubber Pad:** NA

**Bogie Properties**

- **Impact Velocity:** 9.88 mph (14.49 ft/s)
- **Impact Height:** 21
- **Bogie Mass:** 5032 lb

**Data Acquired**

- **Accelerometer:** SLICE-1
- **Camera Data:** GoPro, AOS

**Test Results Summary**

| **Event Duration:** | 0.3300 s |
| **Max. Deflection:** | 6.9 in. |
| **Peak Force:** | 96.9 k. |
| **Initial Linear Stiffness:** | 77.9 k/in. |
| **Peak Energy:** | 197.0 k-in. |
| **Absorbed Energy:** | 188.4 k-in. |
| **Exit Velocity:** | -3.02 ft/s |

**Force vs. Deflection At Impact Location**

**Bogie Acceleration vs. Time**

**Bogie Velocity vs. Time**

**Energy vs. Deflection At Impact Location**

**Bogie Deflection vs. Time**

---

Figure B-6. Test No. ACJB-4 Results (SLICE-1)
Figure B-7. Test No. ACJB-4 Results (SLICE-2)
END OF DOCUMENT