DRAFT REPORT

DEVELOPMENT OF THE TBC-8000 BRIDGE RAILING

Submitted by

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16. Abstract (Limit: 200 words)

A steel **T**hrie **B**eam and **C**hannel bridge railing system, "**TBC**-8000", was developed for use with longitudinal timber bridge decks located along high volume or high speed roadways. The TBC-8000 was subjected to one full-scale crash test in accordance with performance level 2 (PL-2) specifications in the American Association of State Highway and Transportation Officials' *Guide Specifications for Bridge Railings* (1989). The test involved a 1986 GMC 7000 Series truck, weighing 8,165 kg, striking the rail at 76.3 km/hr and 16.1 degrees. The safety performance of the bridge railing was acceptable according to PL-2 evaluation criteria. This steel system provides an economical bridge rail for timber decks.

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1 INTRODUCTION

1.1 Problem Statement

Historically, the majority of crashworthy bridge railing systems located along our highways have been developed using materials such as concrete, steel, and aluminum. Most of these railing systems have been constructed on reinforced concrete bridge decks. However, many of the existing bridge railings have not been adapted for use on timber deck bridges. Consequently, very few of these bridge railings have been tested for use on timber deck bridges. The demand for crashworthy railing systems on timber decks has become increasingly important with the increased use of timber bridge decks on secondary highways, county roads, local roads, national park and forest roads, and low-volume roads.

Only recently have researchers begun to develop crashworthy railing systems for timber bridge decks. Further, all of these railing systems were designed for low-to-medium service level bridges. In order for timber to be a viable material in the new construction of higher service level bridges, additional bridge railing systems must be developed and crash tested for timber bridge decks.

1.2 Objective

The objective of this research project was to develop an economical bridge railing system for longitudinal timber decks located on high service level roadways. Consequently, the railing system would need to satisfy the American Association of State Highway and Transportation Officials (AASHTO) performance level 2 (PL-2) criteria (1).

1.3 Scope

The research objective was achieved by performing several tasks. First, a literature search was performed to review the bridge railing systems for longitudinal timber decks located on high service level roadways previously evaluated according to the safety standards of the National Cooperative Highway Research Program (NCHRP) Report No. 230, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances* (2). Second, a concept development phase was performed to identify several prototype configurations to be further analyzed and evaluated. Third, computer simulation modeling was conducted to aid in the analysis, design, and evaluation of the bridge railing system configuration. Fourth, a full-scale vehicle crash test was performed using a single-unit truck, weighing approximately 8,165 kg, with a target impact speed and angle of 80.5 km/hr and 15 degrees, respectively. Finally, the test results were analyzed, evaluated, and documented. Conclusions and recommendations were then made that pertain to the safety performance of the bridge railing system.

2 LITERATURE REVIEW

In 1988, the Texas Transportation Institute (TTI) conducted a safety performance evaluation on the Missouri thrie beam bridge rail system and transition for the Missouri Highway and Transportation Department (3). The bridge rail consisted of W152x29.4 steel posts spaced on 1,905-mm centers and mounted to the surface of a reinforced concrete bridge deck. A 3.42-mm thick thrie beam rail was mounted to the traffic-side face of the posts without the use of spacer blocks. To further strengthen the rail, a C200x17 structural steel channel was mounted to the top of the steel posts at a height of 778 mm. The heights from the bridge deck to the bottom and top of the thrie beam rail were 279 mm and 787 mm, respectively.

Two full-scale crash tests were conducted on the bridge rail according to the NCHRP Report No. 230, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances* (2). The first test was performed with an 823-kg minicompact sedan at the impact conditions of 95.9 km/hr and 15.0 degrees. The second test was performed with a 2,039-kg sedan at the impact conditions of 98.0 km/hr and 24.0 degrees. According to TTI researchers, the Missouri thrie beam bridge rail was acceptable according to the NCHRP Report No. 230 criteria.

In 1988, Southwest Research Institute (SwRI) performed an evaluation of a longitudinal glulam timber and sawed lumber curb railing system attached to a longitudinal spike-laminated timber deck (4). The system evaluated at SwRI was constructed and tested with sawed lumber posts 203-mm wide x 305-mm deep. The system also had been constructed with a nonstandard size glulam rail measuring 152-mm wide x 273-mm deep. The curb rail measured 152-mm deep x 305-mm wide and was attached to the deck with four 190-mm diameter ASTM A325 bolts. Two crash tests were conducted according to the AASHTO *Guide Specifications for Bridge Railings* (1). The first test was a PL-1 test using a 2,383-kg pickup traveling at a speed of 76.4 km/hr and at an angle of 20 degrees. The second test was a PL-2 test using an 825-kg minicompact sedan traveling at a speed of 95.3 km/hr and at an angle of 20 degrees. Although the system met AASHTO PL-1 requirements, several of the deck timbers were delaminated and several spikes were pulled out slightly. Since this system was not widely used and was the only available crash tested railing for timber bridges, the demand continued for crashworthy bridge railings that would not damage the timber decks and that would be adaptable for use on other timber decks.

In the early 1990's, researchers at the Midwest Roadside Safety Facility (MwRSF), in conjunction with the United States Department of Agriculture (USDA) Forest Service, Forest Products Laboratory (FPL), developed and tested three PL-1 bridge railings for use on longitudinal timber bridge decks - two glulam timber railings systems and one steel railing system (5,6). This research effort provided several aesthetically pleasing and economical bridge railing systems for timber bridge decks on low-to-medium service level highways.

3 TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1 Test Requirements

Bridge railings must satisfy the requirements provided in AASHTO's *Guide Specifications for Bridge Railings* (1) in order to be accepted for use on new construction projects. For an AASHTO PL-2 bridge railing, the bridge railing must satisfy the requirements from three full-scale crash tests. The three required PL-2 tests are: (1) a 816-kg minicompact at 96.6 km/hr and 20 degrees; (2) a 2,449-kg pickup at 96.6 km/hr and 20 degrees; and (3) an 8,165-kg straight truck at 80.5 km/hr and 15 degrees. The AASHTO guide specifications require that the full-scale crash tests be conducted and reported in accordance with NCHRP Report No. 230 (2).

The Missouri railing system was successfully evaluated according to NCHRP Report No. 230 using two full-scale crash tests - a minicompact sedan and a large sedan. Since the Missouri railing system consisted of the same structural members as the AASHTO PL-2 bridge railing, it was deemed prudent to evaluate the AASHTO PL-2 bridge railing using only the 8,165-kg single unit truck. Thus, a case was made to eliminate the 816-kg and 2,449-kg full-scale crash tests.

The 823-kg minicompact vehicle test conducted on the Missouri railing system was performed at 15 degrees as required by the NCHRP Report No. 230 evaluation criteria (2). The test results indicated that the only evaluation criteria that was marginally met was the lateral occupant impact velocity of 6.58 m/sec, which is slightly higher than the NCHRP Report No. 230 recommended limit of 6.10 m/sec. The AASHTO PL-2 criteria requires the 816-kg minicompact vehicle test to be conducted at 20 degrees and with a recommended limit for lateral occupant impact velocity of 7.62 m/sec. MwRSF researchers determined that the results would have been acceptable if the test on the Missouri railing system had been conducted at 20 degrees. This determination was also made since there was no observable tendency for the vehicle to snag or underride the bridge railing. Therefore, the AASHTO PL-2 railing system would behave in a manner similar to the Missouri railing system. Thus, a minicompact vehicle test on the AASHTO PL-2 steel railing system would not be necessary.

The Missouri railing system successfully met the NCHRP Report No. 230 strength test using a 2,084-kg sedan at 98.0 km/hr and 24.0 degrees. MwRSF researchers determined that the AASHTO PL-2 strength test with a 2,450-kg pickup at 100 km/hr and 20 degrees would yield similar results to the sedan strength test on the Missouri railing system and not be necessary. With the elimination of the minicompact vehicle and pickup truck tests, the only remaining requirement for meeting PL-2 criteria is an evaluation of bridge rail performance using an 8,165-kg, single unit truck impacting at 80.5 km/hr and 15 degrees. The test conditions for the required test matrix are shown in Table 1.

3.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the bridge railing to contain, redirect, or allow controlled vehicle penetration in a predictable manner. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Vehicle trajectory after collision is a measure of the potential for the post-impact trajectory of the vehicle to cause subsequent multi-vehicle accidents, thereby subjecting occupants of other vehicles to undue hazards or to subject the occupants of the impacting vehicle to secondary collisions with other fixed objects. The evaluation criteria for AASHTO specifications are defined in Table 2. The full-scale vehicle crash test was conducted and reported in accordance with the procedures provided in NCHRP Report No. 230.

Table 1. Crash Test Conditions and Evaluation Criteria

Guidelines	Test Designation	Test Vehicle	Impact Conditions		Evaluation Criteria [1]
			Speed (km/hr)	Angle (degrees)	
AASHTO	PL-2	Minicompact Sedan	96.6	20	3. a,b,c,d,(e),(f),(g),(h)
	PL-2	Pickup Truck	96.6	20	3. a,b,c,d,(e),(f),(g),(h)
	PL-2	Single-Unit Truck	80.5	15	3. a,b,c,(d),(e),(f),(h)

[1] Evaluation criteria is explained in Table 2. Evaluation criteria in parenthesis is desired but not required.

Table 2. Relevant AASHTO Evaluation Criteria (1)

3.a.	The test article shall contain the vehicle; neither the vehicle nor its cargo shall penetrate or go over the installation. Controlled lateral deflection of the test article is acceptable.
3.b.	Detached elements, fragments, or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.
3.c.	Integrity of the passenger compartment must be maintained with no intrusion and essentially no deformation.
3.d.	The vehicle shall remain upright during and after collision.
3.e.	The test article shall smoothly redirect the vehicle. A redirection is deemed smooth if the rear of the vehicle does not yaw more than 5 degrees away from the railing from time of impact until the vehicle separates from the railing.
3.f.	The smoothness of the vehicle-railing interaction is further assessed by the effective coefficient of friction μ, where $\mu = (\cos\theta - V_p/V)/\sin\theta$. Assessment is described as either good (0.0 - 0.25), fair (0.26 - 0.35), or marginal (> 0.35).
3.g.	The impact velocity of a hypothetical front-seat passenger against the vehicle interior, calculated from vehicle accelerations and 0.6-m longitudinal and 0.3-m lateral displacements shall be less than 9.1 m/s longitudinally and 7.6 m/s laterally and for the vehicle highest 10-ms average longitudinal and lateral occupant ridedown accelerations subsequent to the instant of hypothetical passenger impact should be less than 15 g's.
3.h.	Vehicle exit angle from the barrier shall not be more than 12 degrees. Within 30.5-m plus the length of the test vehicle from the point of initial impact with the railing, the railing side of the vehicle shall move no more than 6.1-m from the line of the traffic face of the railing

4 THRIE BEAM AND CHANNEL BRIDGE RAILING DESIGN DETAILS

4.1 Design Considerations

Since the Missouri combination steel railing system had successfully met the NCHRP Report No. 230 safety performance evaluation, it was determined that concepts from the Missouri railing system could be successfully implemented into the design of the AASHTO PL-2 railing for timber bridge decks.

The previously accepted AASHTO PL-1 "Steel System" for timber decks (5,6) was selected as the basis for the design of the AASHTO PL-2 steel bridge railing. This bridge railing consisted of a thrie beam railing attached to the timber deck with steel wide-flange posts. When this design was tested, using a 2,540-kg vehicle traveling at 71.1 km/hr and an impact angle of 19.1 degrees, the dynamic and permanent set rail deflections were 351 mm and 206 mm, respectively. It was concluded that the original design should be stiffened to meet AASHTO PL-2 standards since three of the posts had significant deformation during the PL-1 pickup test (5,6). Further adding to the need to stiffen the rail, the Missouri rail had 159 mm of permanent set deflection when impacted by a 2,039-kg vehicle traveling at 98.0 km/hr and an impact angle of 24.0 degrees. The primary difference between the lateral strength of these two railing systems is the C200x17 steel channel section placed on the top of the thrie beam. Thus, the channel rail was added to the PL-1 "Steel System" for timber decks in an effort to strengthen the bridge rail to meet PL-2 strength standards.

The channel section was attached to the spacer blocks and mounted above the top of the thrie beam rail. The top mounting height of the thrie beam in the PL-1 "Steel System" is 784 mm and is the same for the PL-2 bridge railing. Although, the recommended minimum top mounting height for an AASHTO PL-2 bridge railing is 813 mm (1), the top of the steel channel section has a mounting height of 845 mm in order to provide clearance above the thrie beam. In addition, the 845-mm mounting height of the channel section provides vertical support for the bottom side of the truck box during impact. This increase in height can reduce the amount of roll motion of the truck box.

4.2 Thrie Beam and Channel Bridge Railing Design Details

The Thrie Beam and Channel bridge railing, or "**TBC**-8000", was attached to a longitudinal glulam timber deck supported by concrete abutments. The concrete abutments and the longitudinal glulam timber deck were the same as that used in the development of the "Curb System," "Shoe Box System," and "Steel System" (5,6). This test, however, used a 51-mm asphalt surface on the top of the timber deck in order to represent actual field conditions.

Design details of the TBC-8000 bridge railing and approach guardrail transition systems are provide in Figures 1 through 15. Photographs of the bridge rail and approach guardrail transition are shown in Figures 16 through 17. The test installation consisted of three major structural components: (1) a TBC-8000 bridge railing with an attached simulated anchorage device; (2) a longitudinal glulam timber deck; and (3) an approach guardrail transition with an attached simulated anchorage device. The TBC-8000 bridge railing consists of four major components: (1) structural steel posts and spacer blocks; (2) steel thrie beam rail; (3) structural steel channel rail; and (4) structural steel mounting plates.

Fifteen galvanized ASTM A36 W152x22.3 structural steel posts measuring 933-mm long were used to support the steel railing, as shown in Figures 2 through 4. The steel posts were attached to the longitudinal glulam timber deck with ASTM A36 structural steel mounting plates, as shown in Figure 5. Fifteen steel mounting plates measuring19-mm thick x 273-mm deep x 610-mm long were attached to the deck with two ASTM A722 25-mm diameter x 1372-mm long high-strength bars spaced at 406 mm and located 76 mm below the top surface of the deck, as shown in Figure 2. Design details for the bearing plates located at the other end of the rods are included in a study by Ritter et al., a study by Ritter, and in AASHTO's *LRFD Bridge Design Specifications* (5,7,8). Each steel post was bolted to a steel mounting plate with four ASTM A325 22-mm diameter galvanized hex head bolts which were welded to the deck side of the steel plate, as shown in Figure 3. Four recessed holes were cut into the edge of the timber deck so that the steel mounting plates would bolt flush against the vertical deck surface. The lower rail consisted of 3.42-mm thick thrie beam mounted 785 mm above the timber deck surface, as shown in Figure 2. The thrie beam rail was offset 152 mm away from the posts with galvanized, ASTM A36 W152x22.3 structural steel spacer blocks measuring 587-mm long, as shown in Figures 2 and 6.

The upper rail consisted of galvanized, ASTM A36 C200x17 structural steel channel sections attached to the top of the steel spacer blocks, as shown in Figure 2. The distance from the bridge deck to the top of the channel rail was 845 mm. Design details of the channel railing sections are shown in Figure 7. The channel rail sections were attached to the spacer blocks with ASTM A36 structural steel angles measuring 89 mm x 89 mm x 8 mm, as shown in Figure 8. Each channel rail section was spliced together with ASTM A36 structural steel splice plates, as shown in Figure 8. The layout of the channel sections is shown in Figure 1.

An approach guardrail transition was constructed on the upstream end of the TBC-8000 bridge railing, as shown in Figure 1. Design details for the approach guardrail and transition are shown in Figures 9 through 15. The approach guardrail transition consisted of the following components: (1) thrie beam rail sections; (2) a W-beam to thrie beam transition section; (3) standard W-beam; (4) structural steel posts; (5) timber posts; (6) structural steel channel rail; and (7) a breakaway cable terminal end anchorage system.

The approach guardrail and transition was supported by twelve posts, as shown in Figure 1. Post no. 1A was fabricated from galvanized, ASTM A36 W152x22.3 structural steel measuring 2,134-mm long, as shown in Figure 15. Post nos. 2A through 5A were also W152x22.3 structural steel sections but measured 2,083-mm long, as shown in Figure 15. Post nos. 6A and 7A were fabricated from galvanized, ASTM A36 W152x13.5 structural steel measuring 1,829-mm long. Post nos. 8A through 12A were timber posts measuring 152-mm wide x 203-mm deep x 1,829-mm long. Post nos. 11A and 12A were also embedded in concrete footings. The timber posts and concrete footings were part of a standard W-beam breakaway cable terminal (BCT) end anchorage system used to develop the required tensile capacity of the guardrail at the upstream end of the system. The BCT end anchorage system incorporated a steel cable and anchor assembly and a 3.42-mm thick terminal connector was located at post no. 12A.

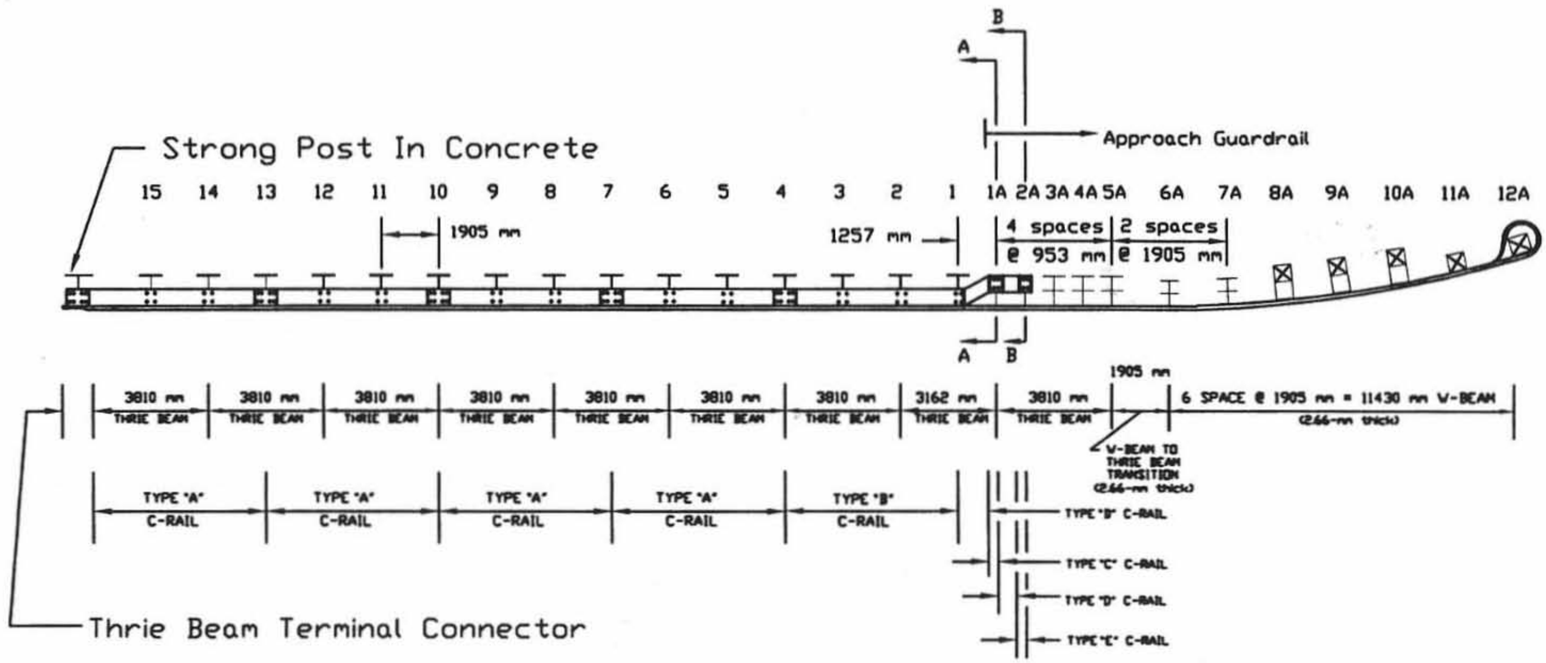
For post nos. 1A through 5A, a galvanized, ASTM A36 W152x22.3 structural steel spacer blocks was used to support the thrie beam section, as shown in Figures 13 through 15. At post nos. 6A and 7A, galvanized, ASTM A36 W152x13.5 structural steel spacer blocks were used, as describe in AASHTO's *A Guide to Standardized Highway Barrier Rail Hardware* (9). For post nos. 8A through 10A, timber spacer blocks measuring 152-mm wide x 203-mm deep x 356-mm long were used to support the W-beam rail.

The spacing between post nos. 1A through 5A was 953 mm, as shown in Figure 1. The spacing between post nos. 1 and 1A was 1,257 mm. Post nos. 5A through 12A were spaced on 1,905-mm centers, as shown in Figure 1. The soil embedment depth for post nos. 1A through 5A was 1,326 mm. The posts were embedded in a strong S-1 soil specified by NCHRP 230 (2).

A standard, 3.42-mm thick thrie beam rail was used in the approach guardrail transition from post nos. 1 through 5A. The height from the ground to the top of the thrie beam was 784 mm, as shown in Figures 13 and 14. A standard W-beam to thrie beam transition section 2.66-mm thick measuring 1,905-mm long was constructed between post nos. 5A and 6A. The approach guardrail was constructed with standard, 2.66-mm thick W-beam rail between post nos. 6A through 12A, as shown in Figure 1. The standard mounting height from the ground to the top of the W-beam was 686 mm, as specified by 1977 AASHTO Barrier Guide (10).

The approach guardrail transition was also constructed with an upper rail section from post nos. 1 through 2A, as shown in Figures 1 and 9. The upper rail sections were fabricated from galvanized, ASTM A36 C200x17 structural steel channel, as shown in Figures 9 through 12.

The TBC-8000 bridge rail was anchored at the downstream end with an ASTM A36 W305x107.3 structural steel section embedded in a reinforced concrete footing measuring 914-mm wide x 914-mm long x 914-mm deep.



NOTES:

(1) Post Nos. 1A through 7A: Steel Sections W152x22.3 (W6x15) with Spacers
(2) Post Nos. 8A through 10A: Timber Posts 152 mm x 203 mm with Spacers
(3) All Thrie Beam sections between post nos. 5A and 15 are 3.42-mm thick

Figure 1. Installation Layout of the TBC-8000 Bridge Rail and Approach Transition

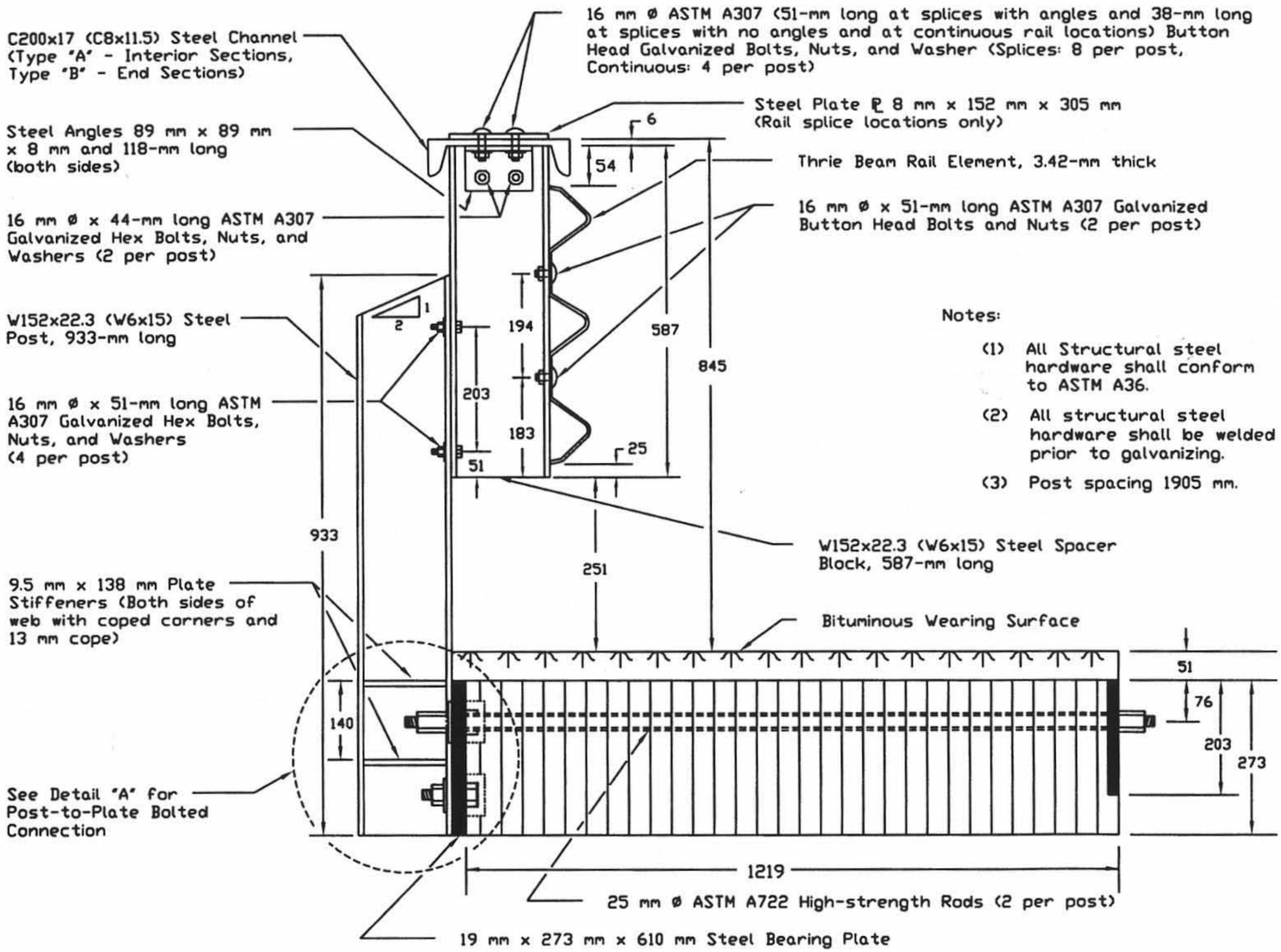


Figure 2. Schematic of the TBC-8000 Bridge Rail

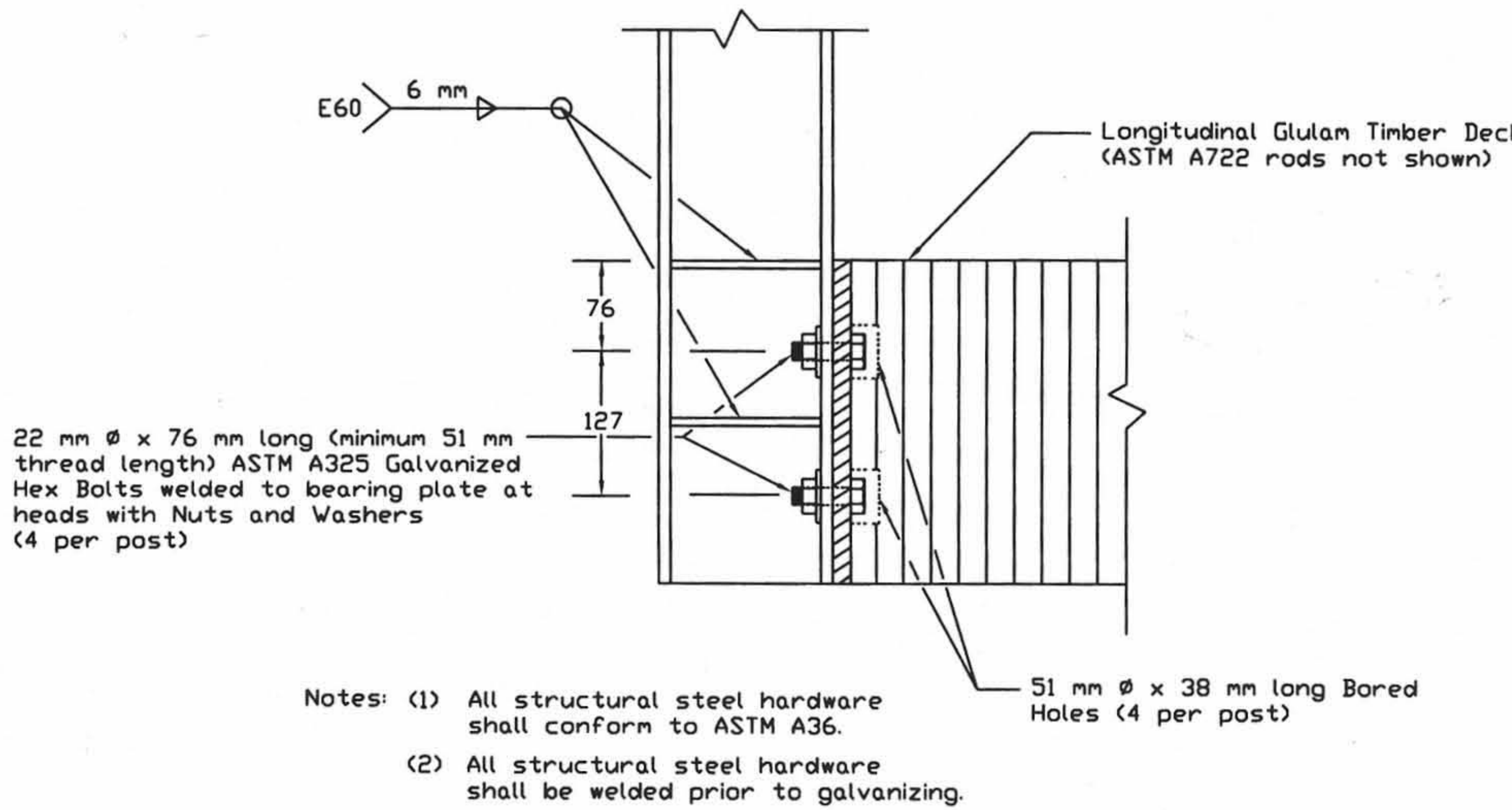


Figure 3. Detail "A": Post-to-Plate Bolted Connection

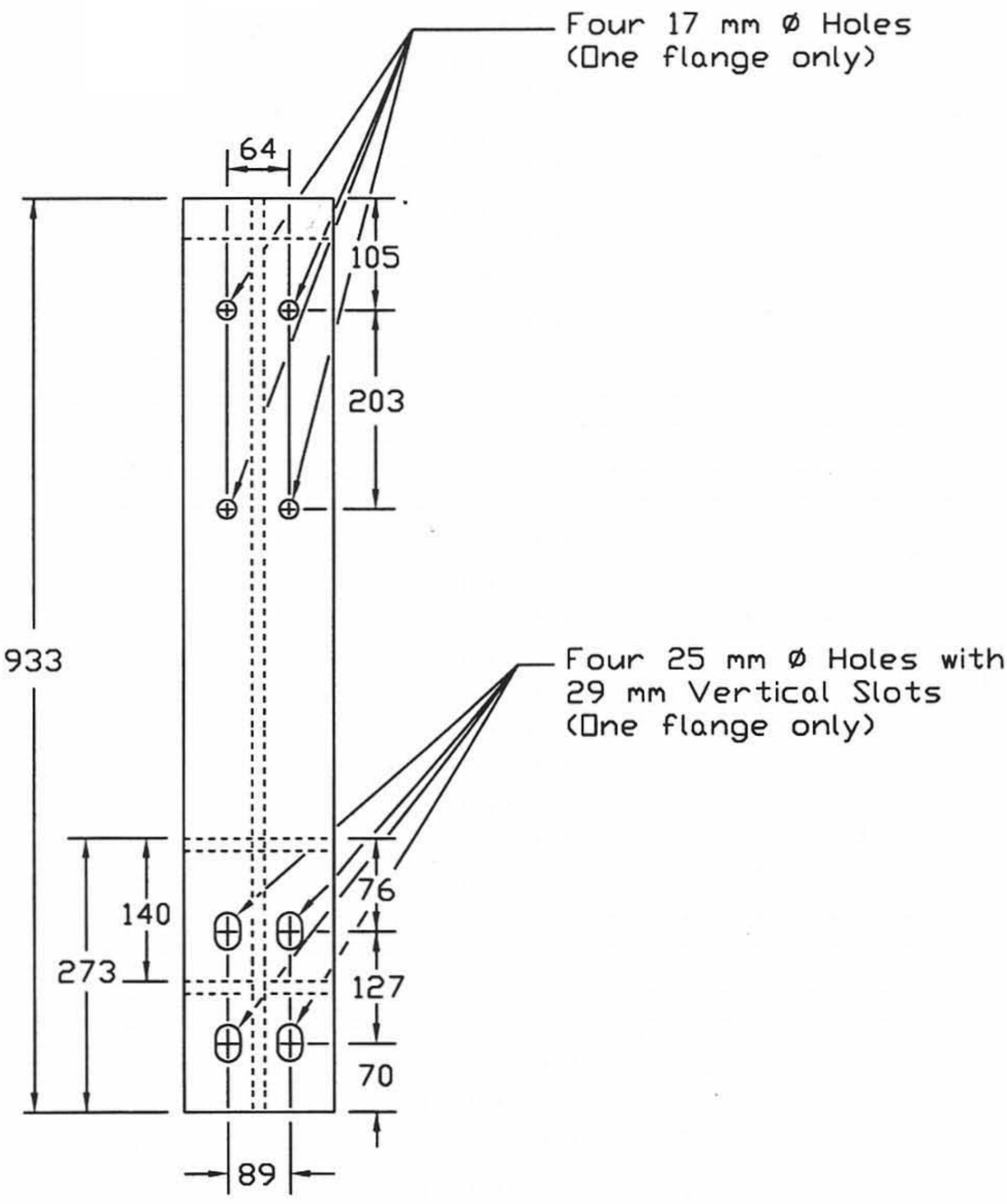


Figure 4. Steel Bridge Post Details

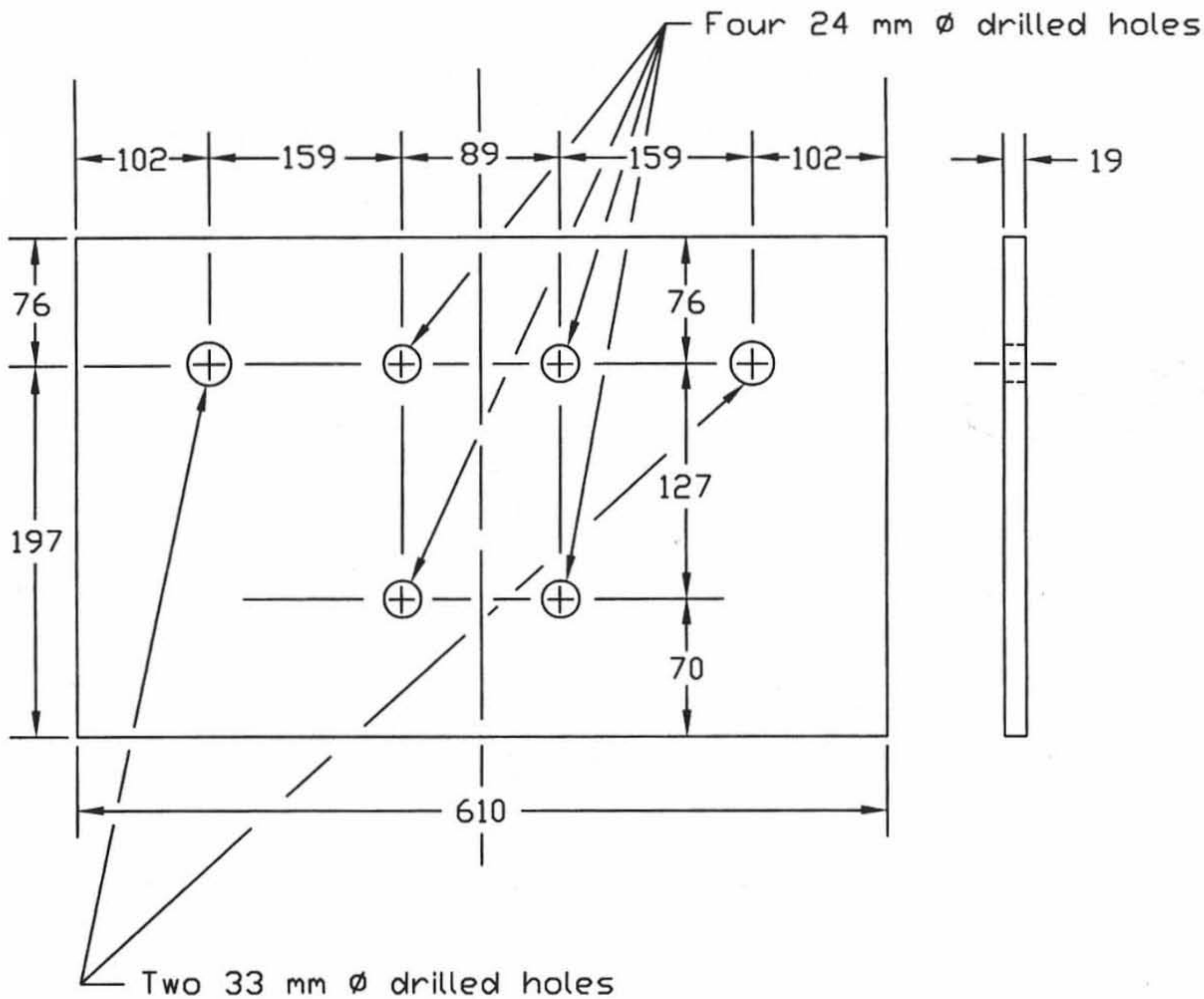


Figure 5. Outside-edge Bearing Plate Detail

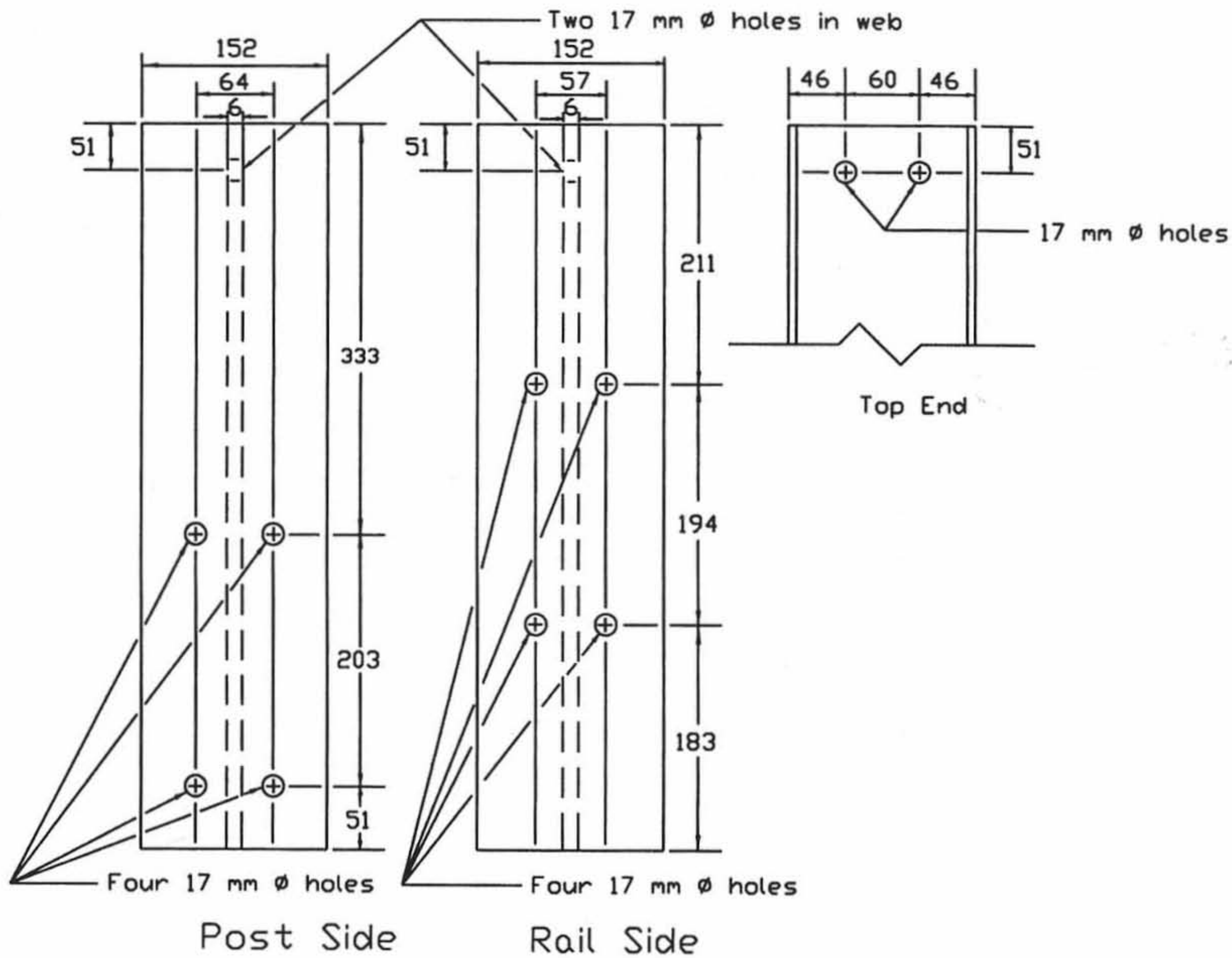


Figure 6. Spacer Block for Bridge Post Details

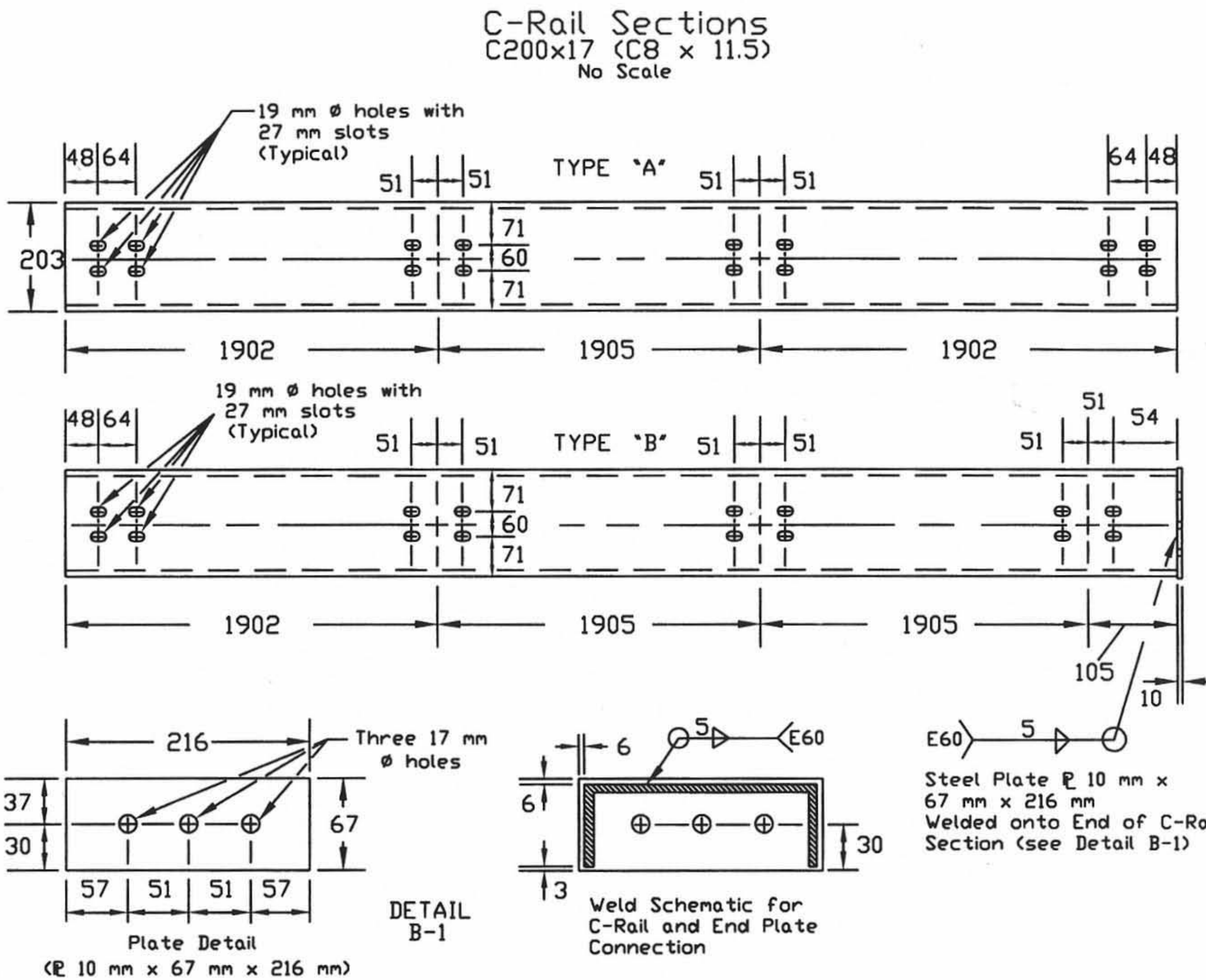


Figure 7. Channel Rail Section Details

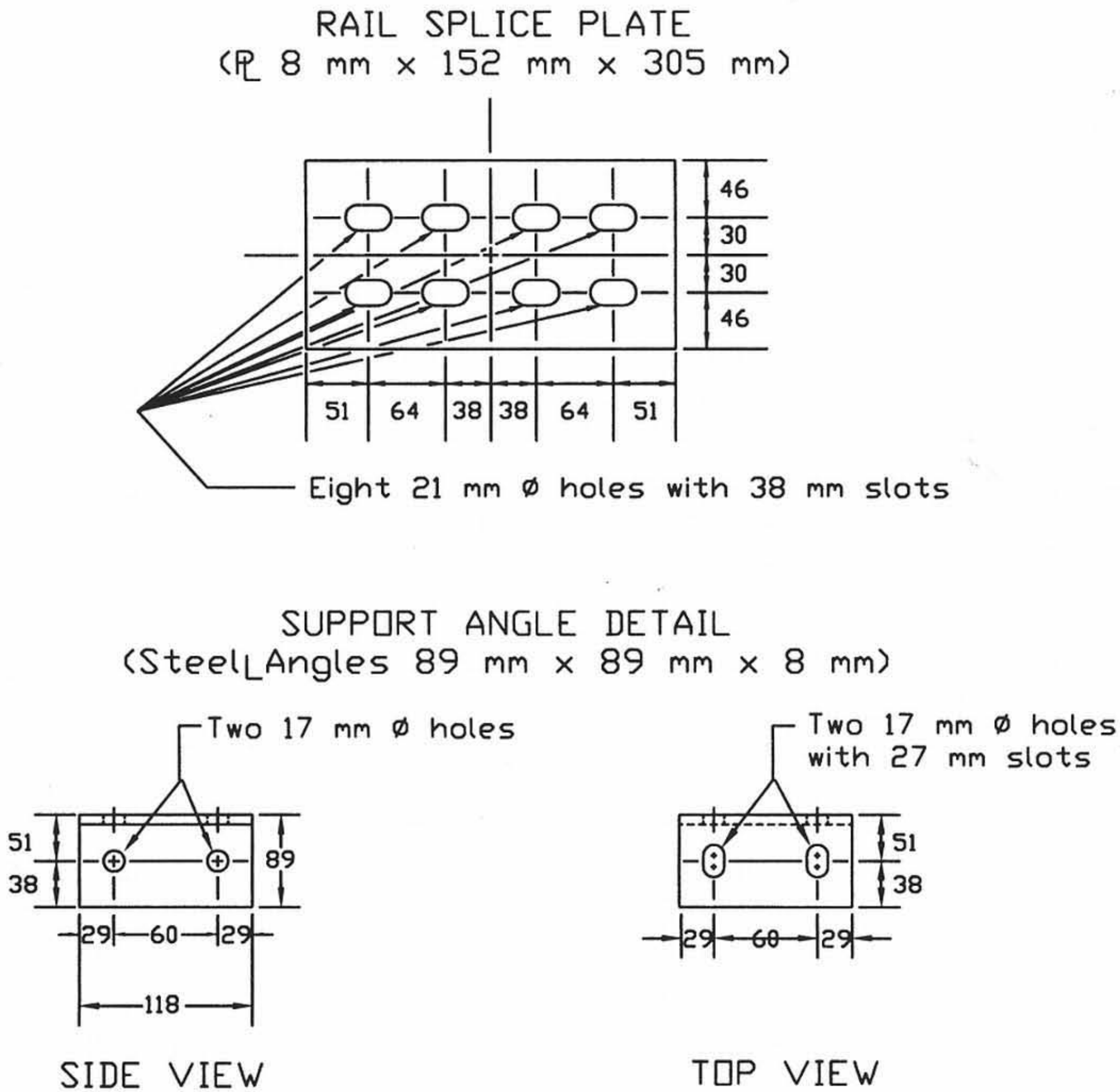


Figure 8. Channel Rail Splice Connection Hardware

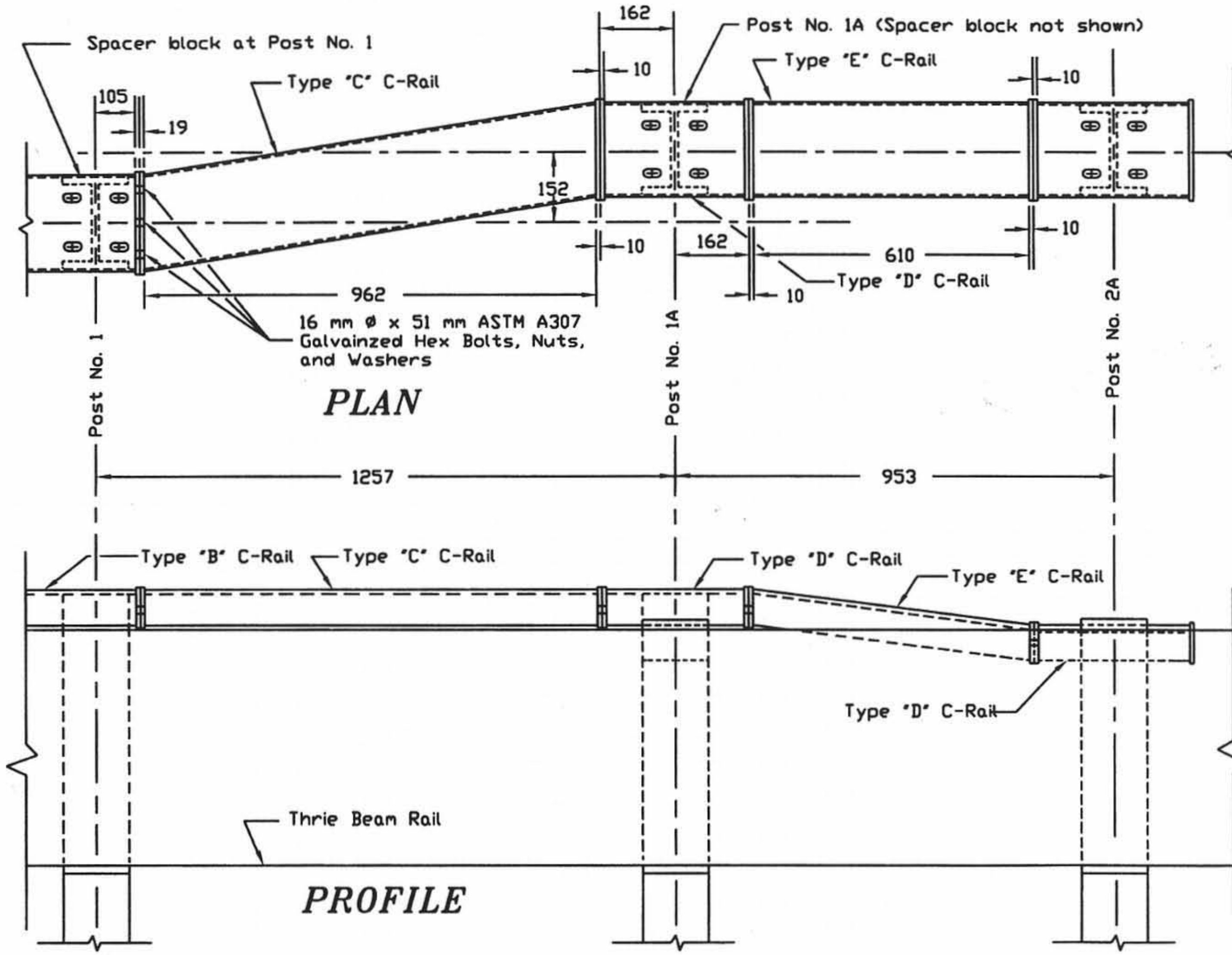


Figure 9. Approach Transition Channel Rail Section Connection Details

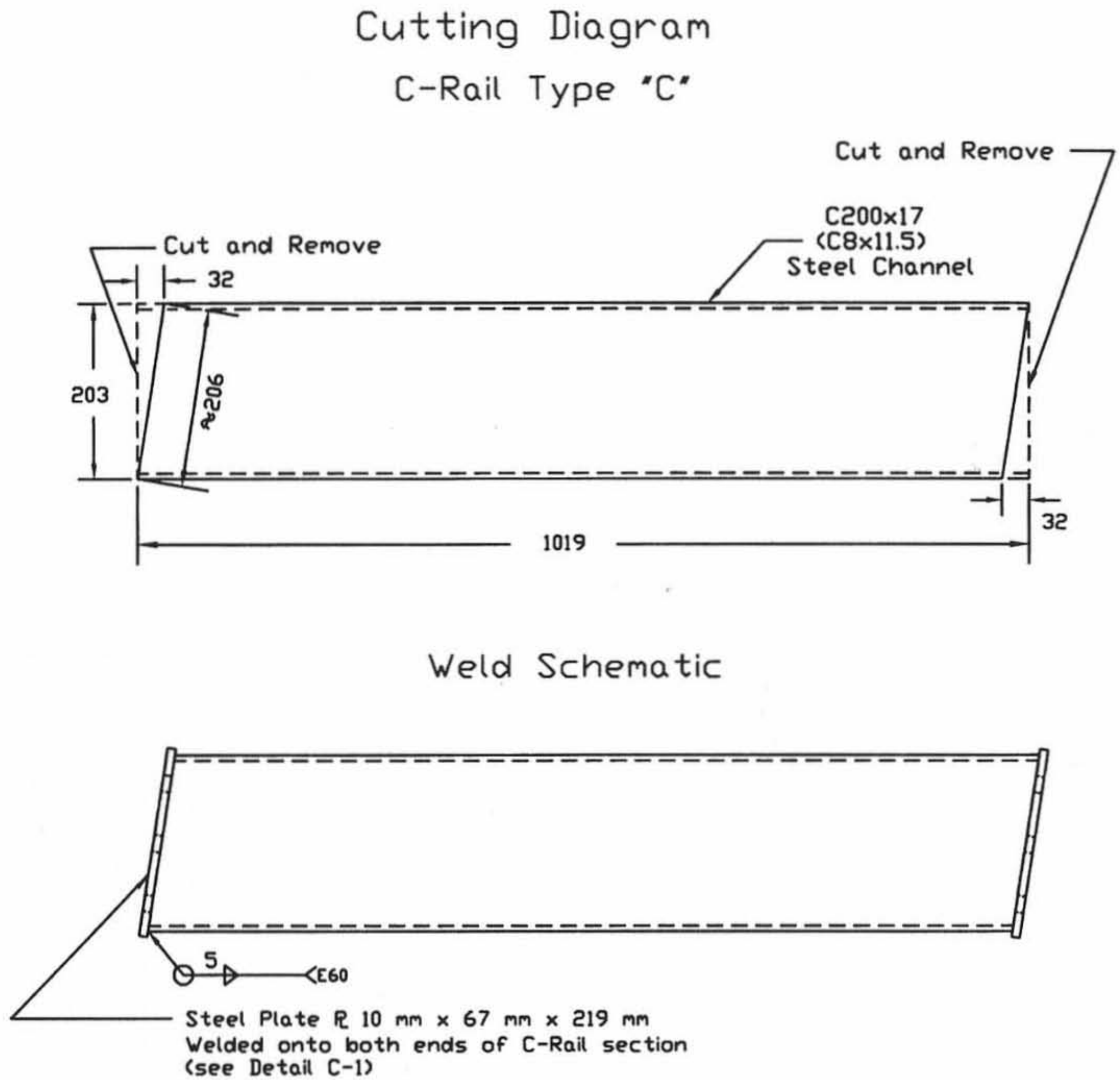


Figure 10. Type "C" Channel Rail Section Design Details

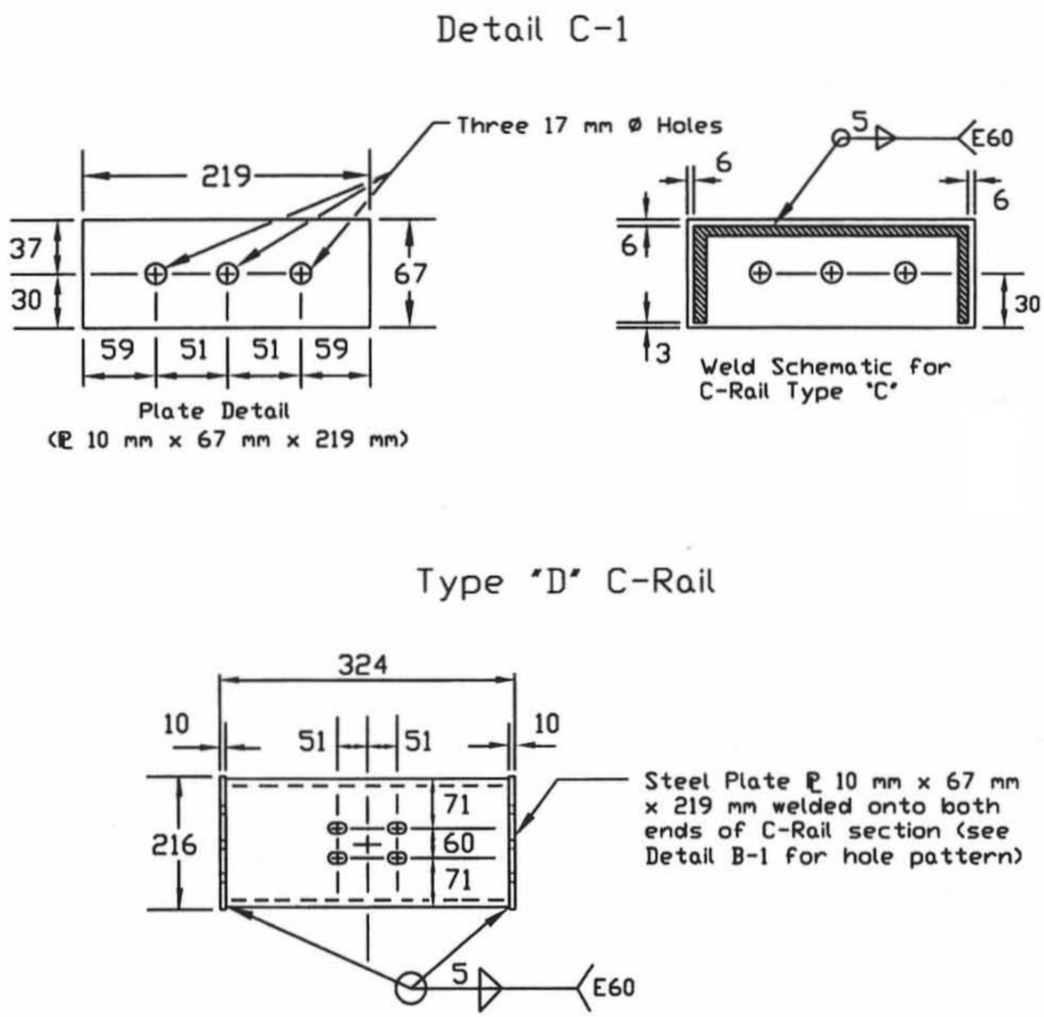


Figure 11. Detail C-1 and Type "D" Channel Rail Section Design Details

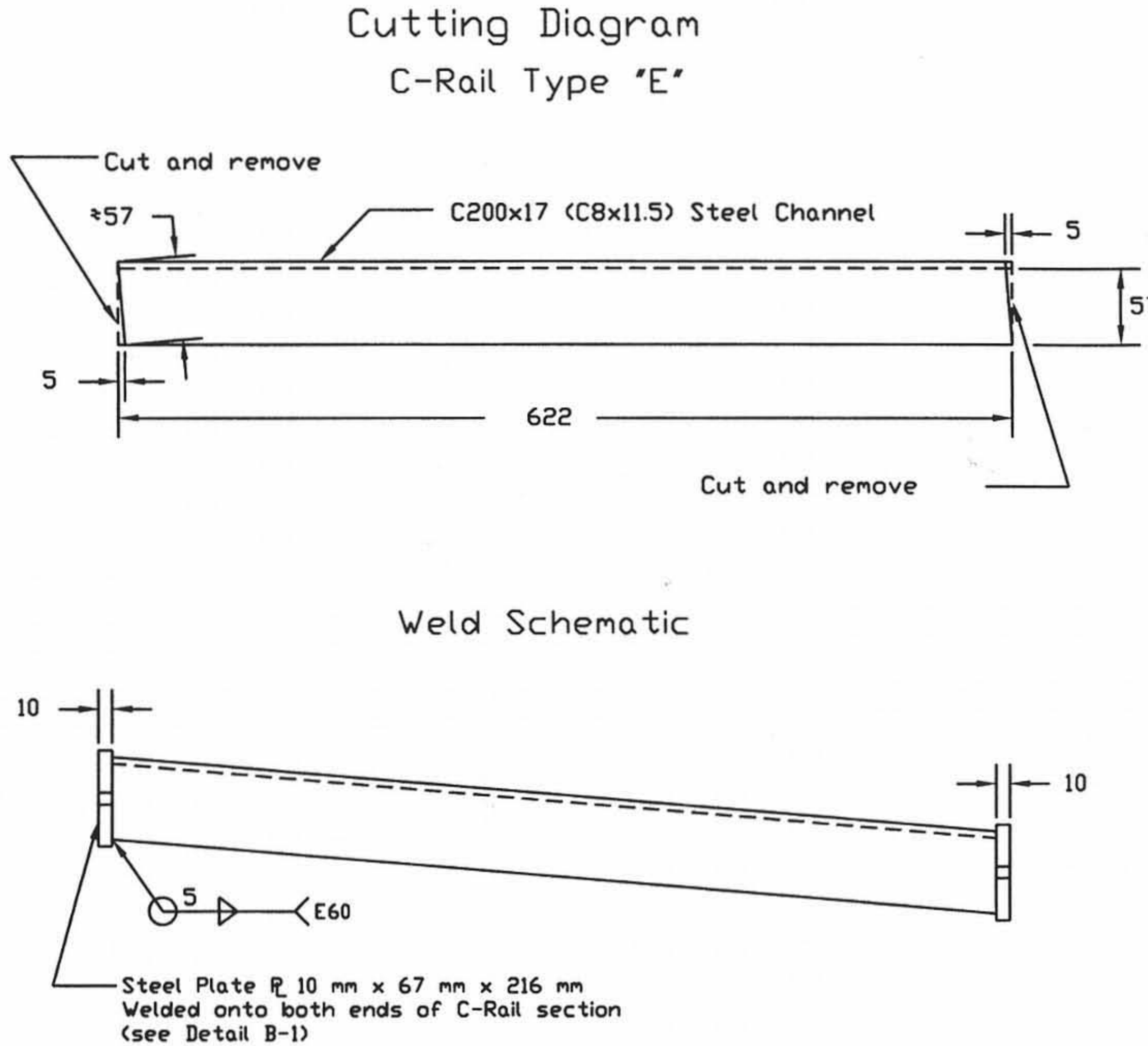
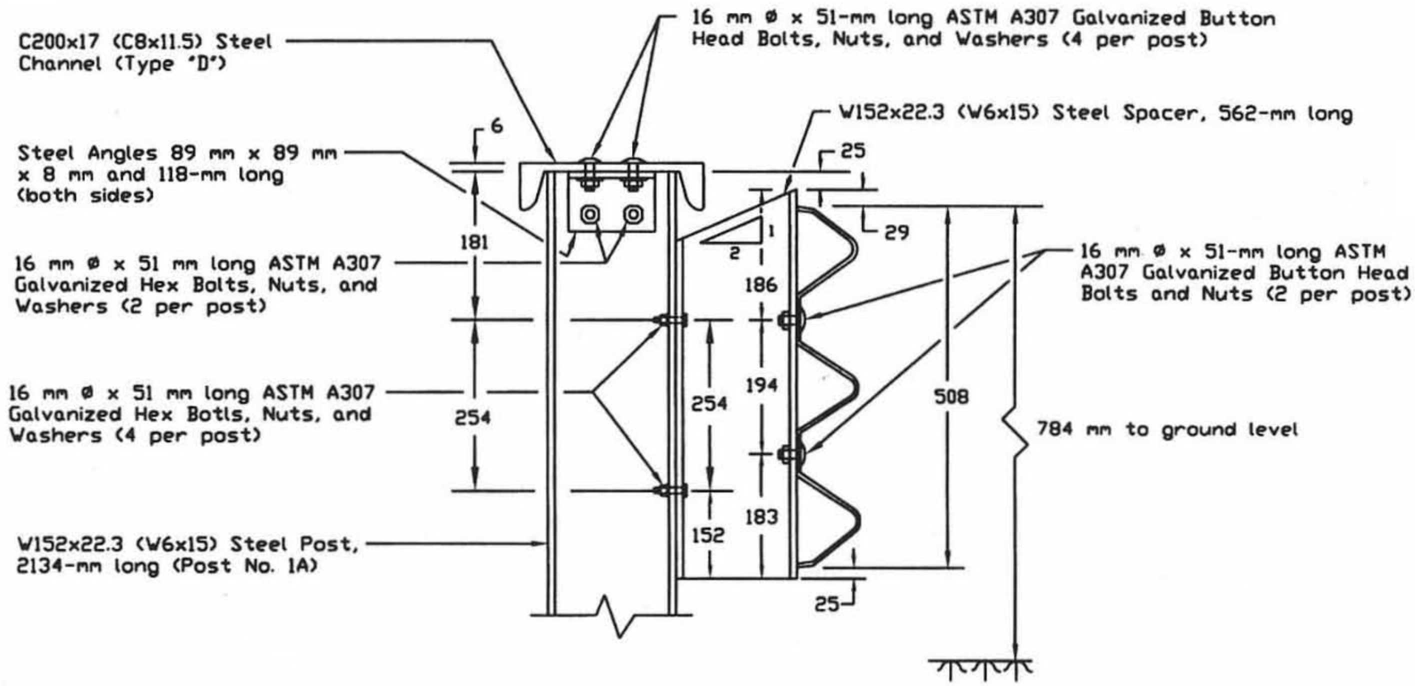
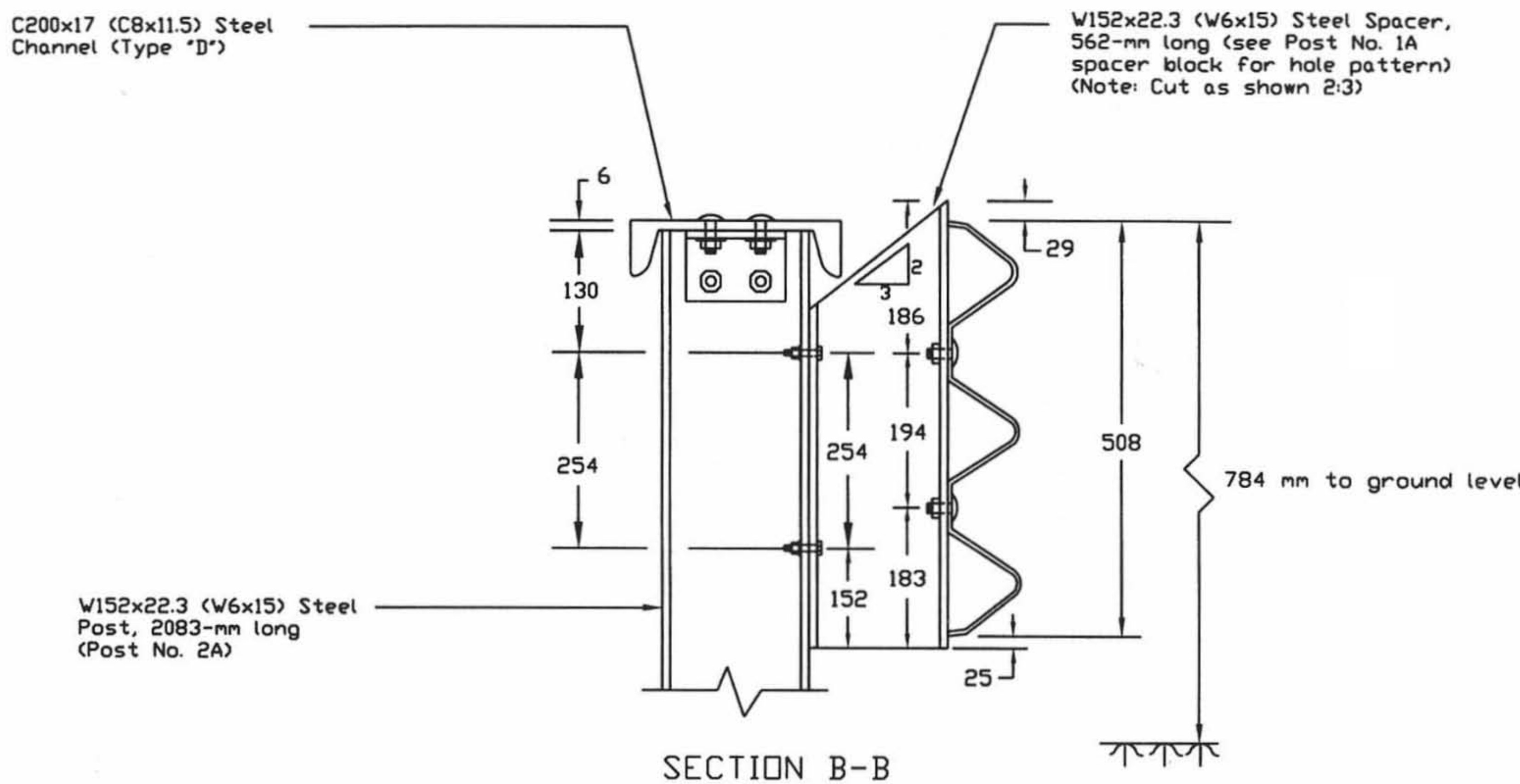


Figure 12. Type "E" Channel Rail Section Design Details



SECTION A-A

Figure 13. Post and Spacer Block Detail for Post No. 1A



Note:

(1) See Post 1A and attached spacer block for details on bolts, nuts, and washers.

Figure 14. Post and Spacer Block Detail for Post Nos. 2A through 5A

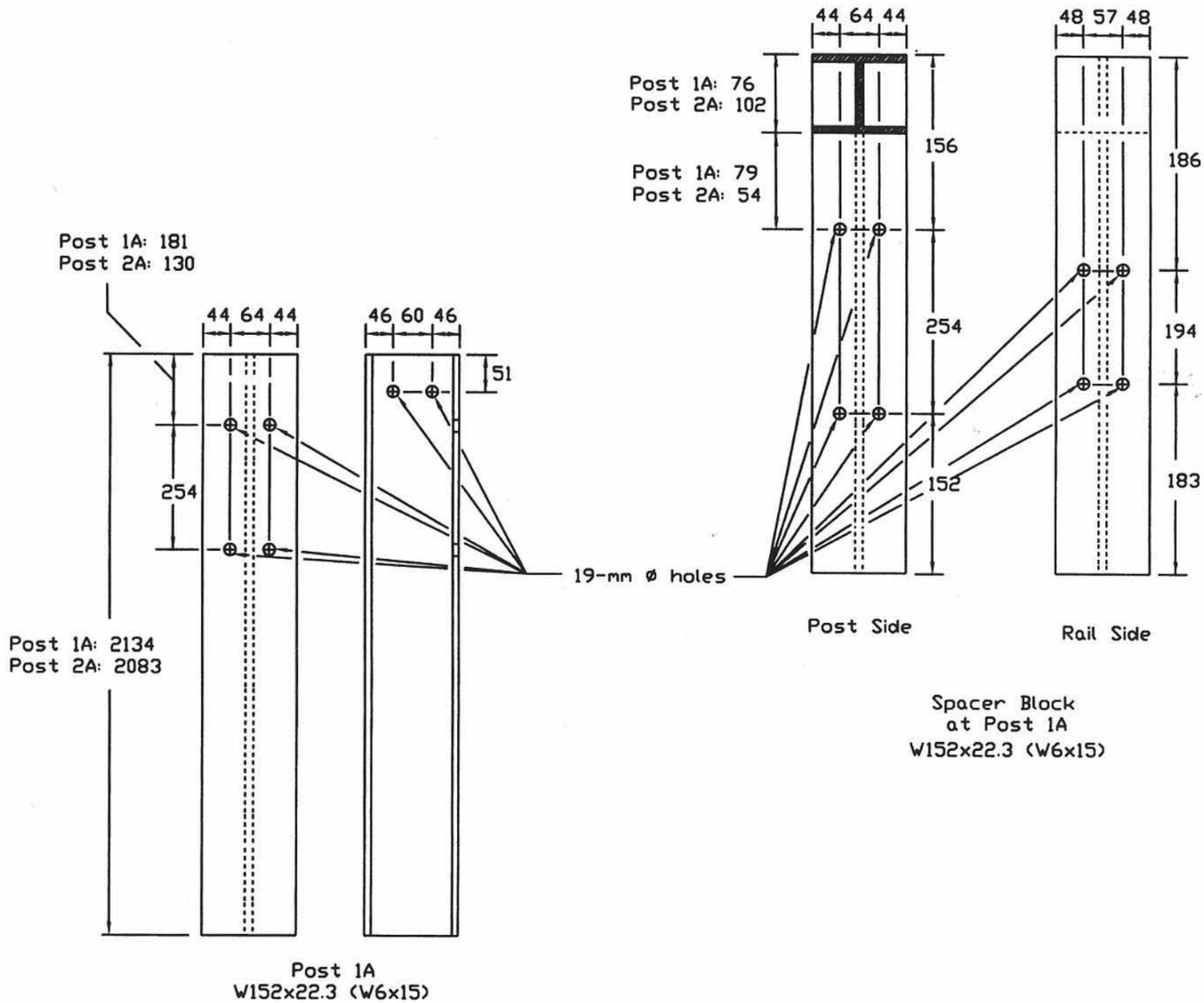


Figure 15. Design Details for Post Nos. 1A and 2A through 5A and Attached Spacer Blocks

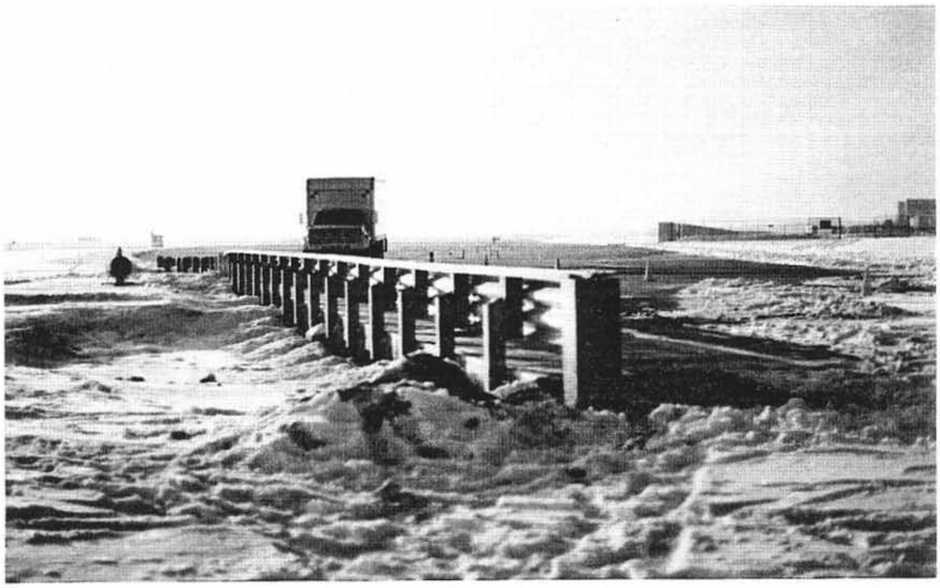


Figure 16. **TBC**-8000 Bridge Rail

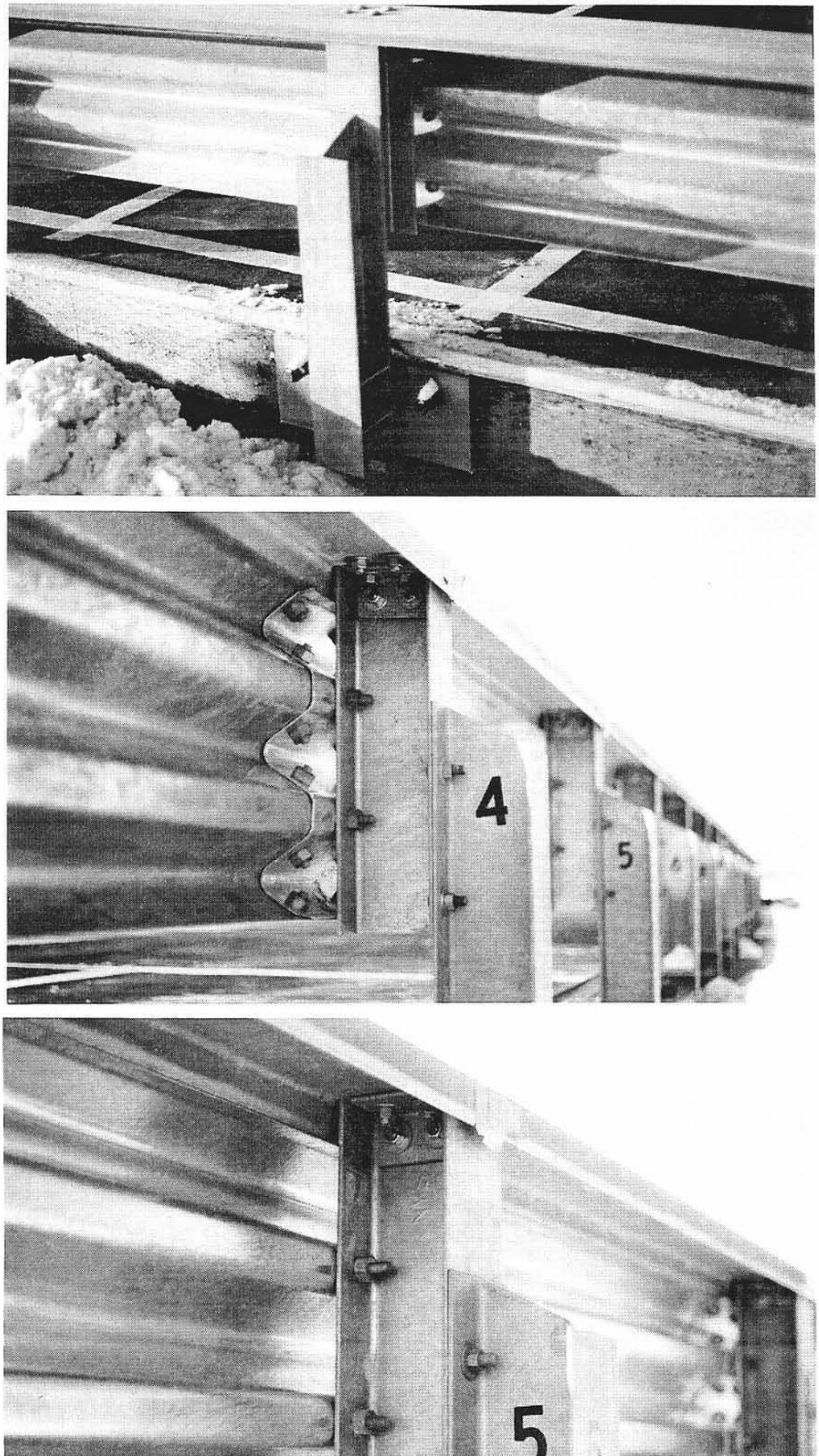


Figure 17. **TBC**-8000 Bridge Rail

5 TEST CONDITIONS

5.1 Test Facility

The testing facility is located at the Lincoln Air-Park on the NW side of the Lincoln Municipal Airport and is approximately 8.0 km NW of the University of Nebraska-Lincoln.

5.2 Vehicle Tow and Guidance System

A reverse cable tow system with a 1:2 mechanical advantage was used to propel the test vehicle. The distance traveled and the speed of the tow vehicle were one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the bridge rail. A fifth wheel, built by Nucleus Corporation, was located on the tow vehicle and used in conjunction with a digital speedometer to increase the accuracy of the test vehicle impact speed.

A vehicle guidance system developed by Hinch (11) was used to steer the test vehicle. A guide-flag, attached to the front-left wheel and the guide cable, was sheared off before impact. The 9.5-mm diameter guide cable was tensioned to approximately 13.3 kN, and supported laterally and vertically every 30.48 m by hinged stanchions. The hinged stanchions stood upright while holding up the guide cable, but as the vehicle was towed down the line, the guide-flag struck and knocked each stanchion to the ground. The vehicle guidance system was approximately 610-m long.

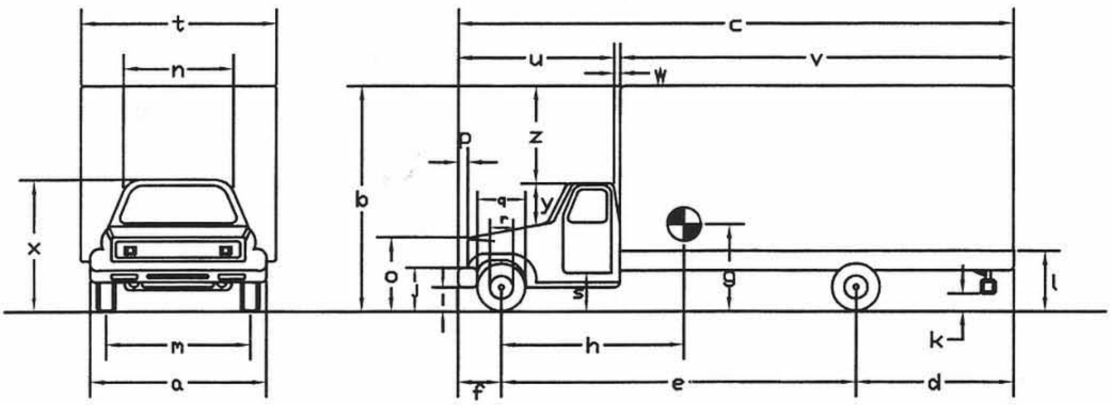
5.3 Test Vehicle

For test FSTC-1, a 1986 GMC 7000 series single unit truck, was used as the test vehicle. The test inertial and gross static weights were 8,165 kg. The test vehicle is shown in Figure 18, and vehicle dimensions are shown in Figure 19.

The Elevated Axle Method (12) was used to determine the vertical component of the center of gravity for the test vehicle. This method converts measured wheel weights at different elevations

Figure 18. Test Vehicle, Test FSTC-1

Date:	12/9/92	Test Number:	FSTC-1	Model:	7000 Series
Tire Sz FR:	---	Odometer:	---	Make:	GMC
Tire Sz RR:	---	V.I.N. #:	---	Year:	1986



Vehicle Geometry (mm)

a> fr. bump. width	2261	J> fr. bump. top	---	s> bot. door height	---
b> overall height	3353	k> rr. bump. bot.	343	t> overall width	2426
c> overall length	10056	l> rr. frame top	1232	u> cab length	2426
d> rear overhang	3251	m> fr. track width	1937	v> trler/box length	7516
e> wheel base	6068	n> roof width	1473	w> gap width	114
f> front overhang	737	o> hood height	1664	x> overall fr. height	2210
g> C.G. height	1245	p> bump. extension	---	y> roof–hood dist.	546
h> C.G. hor. dist.	3165	q> fr. tire width	1003	z> roof height dif.	1143
I> fr. bump. bot.	521	r> fr. wheel width	---	wheel center height front	---

wheel center height rear	---
wheel well clearance (FR)	---
wheel well clearance (RR)	---
Engine Type	---
Engine Size	---

Transmission Type:
Automatic or Manual
FWD or RWD or 4WD

Weights (kg)

	Curb	Test Inertial	Gross Static
$W_{front\ axel}$	2094	3906	3906
$W_{rear\ axel}$	2981	4259	4259
W_{TOTAL}	5075	8165	8165

Ballast 2976

Note any damage prior to test:

Figure 19. Vehicle Dimensions, Test FSTC-1

to the location of the vertical component of the center of gravity. The longitudinal and vertical components of the center of gravity were determined using the measured axle weights. The location of the final centers of gravity are shown in Figures 18 and 19.

Square, black and white-checkered targets were placed on the vehicle to aid in the analysis of the high-speed film, as shown in Figure 20. Round, checkered targets were placed on the center of gravity on the driver's side, the passenger's side, and on the roof of the vehicle. The other square targets were located at convenient reference locations for viewing from the high-speed cameras for film analysis.

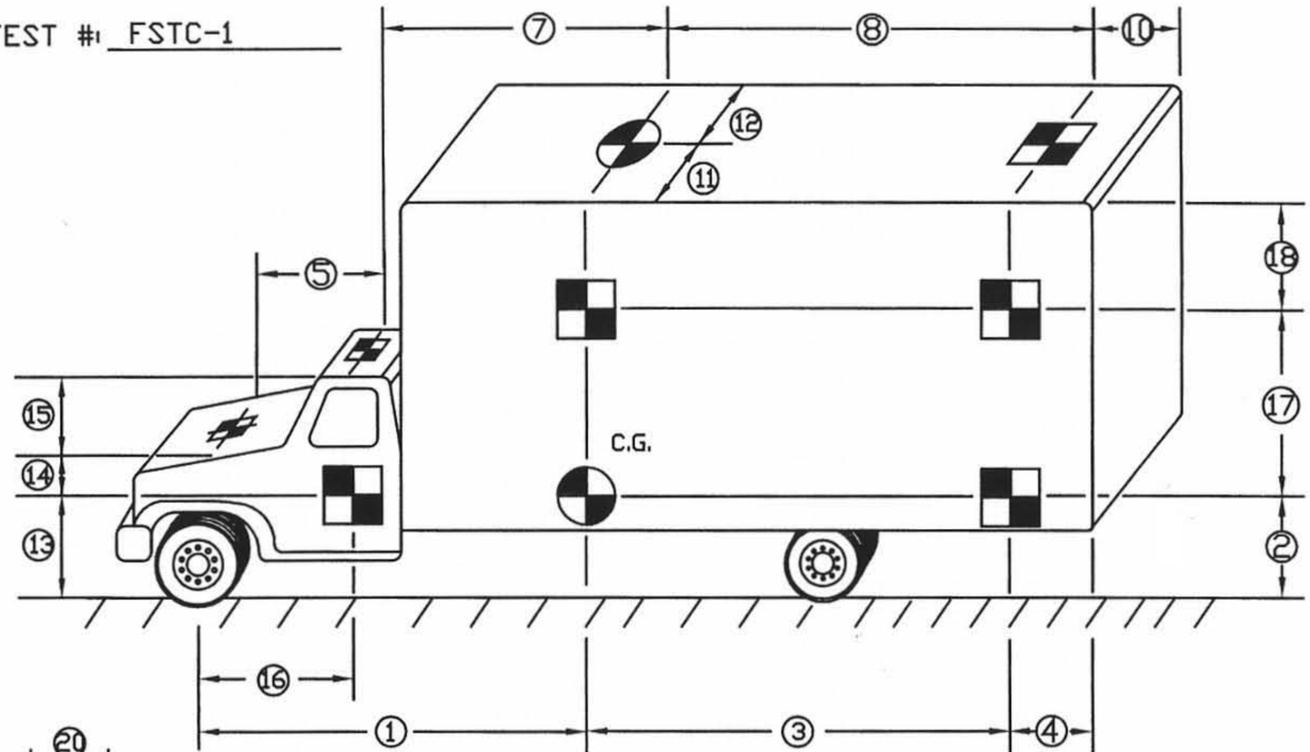
The front wheels of the test vehicle were aligned for camber, caster, and toe-in values of zero so that the vehicle would track properly along the guide cable. Two 5B flash bulbs were mounted on both the hood and roof of the vehicles to pinpoint the time of impact with bridge railing on the high-speed film. The flash bulbs were fired by a pressure tape switch mounted on the front face of the bumper. A remote controlled brake system was installed in the test vehicle so the vehicle could be brought safely to a stop after the test.

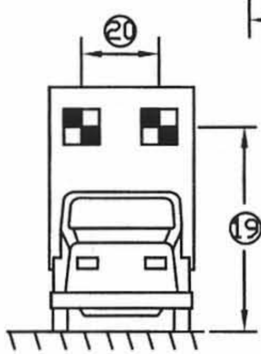
5.4 Data Acquisition Systems

5.4.1 Accelerometers

Two triaxial piezoresistive accelerometer systems with a range of ±200 G's (Endevco Model 7264), were used to measure the acceleration in the longitudinal, lateral, and vertical directions. The accelerometers were rigidly attached to an aluminum block mounted near the vehicle's center of gravity. Accelerometer signals were received and conditioned by an onboard Series 300 Multiplexed FM Data System built by Metraplex Corporation. The multiplexed signal was then transmitted to a Honeywell 101 Analog Tape Recorder. Computer software, "EGAA" and "DADiSP", were used

TEST #: FSTC-1





TARGET GEOMETRY (mm)

①	3165	⑦	2134	⑬	1245	⑱	635
②	1245	⑧	4572	⑭	419	⑲	2762
③	4572	⑩	1422	⑮	546	⑳	1803
④	1422	⑪	1210	⑯	1041		
⑤	1219	⑫	1210	⑰	1524		

Figure 20. Vehicle Target Locations, Tests FSTC-1

to digitize, analyze, and plot the accelerometer data.

5.4.2 High-Speed Photography

For test FSTC-1, three high-speed 16-mm cameras, with operating speeds of approximately 500 frames/sec, were used to film the crash test. A Red Lake Locam, with a wide-angle 12.5-mm lens, was placed above the test installation to provide an overhead field of view perpendicular to the ground. A Photec IV, with an 80-mm lens, was placed downstream from the impact point and had a field of view parallel to the barrier. Another Photec IV, with a 55-mm lens, was placed on the traffic side of the barrier and had a field of view perpendicular to the barrier. A schematic of all three camera locations for test FSTC-1 is shown in Figure 21. A white-colored 1.5-m by 1.5-m grid was painted on the concrete in front of the rail near the impact point. This grid was in the view of the overhead camera, and provided a visible reference system to use in the analysis of the overhead high-speed film. The film was analyzed using the Vanguard Motion Analyzer. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed film.

5.4.3 Pressure Tape Switches

For test FSTC-1, four pressure-activated tape switches, spaced at 1.52-m intervals, were used to determine the speed of the vehicle before impact. Each tape switch fired a strobe light which sent an electronic timing signal to the data acquisition system as the left-front tire of the test vehicle passed over it. Test vehicle speed was determined from electronic timing mark data recorded on "EGAA" software. Strobe lights and high-speed film analysis are used only as a backup in the event that vehicle speed cannot be determined from the electronic data.

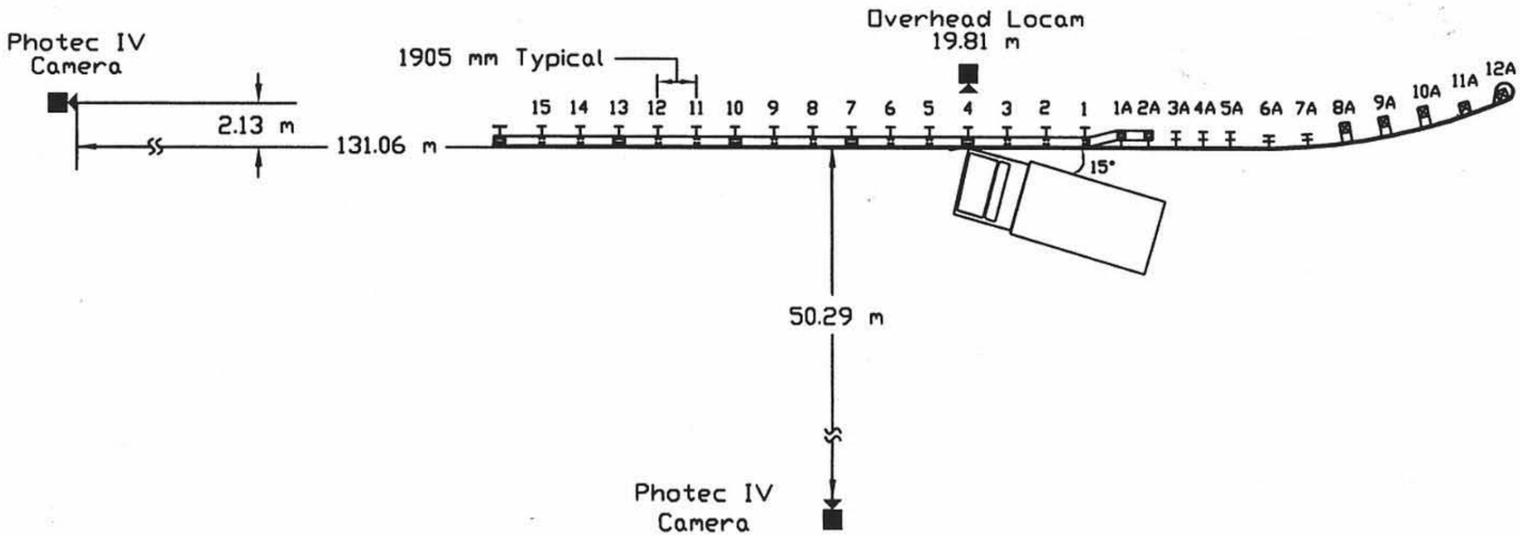


Figure 21. Location of High-Speed Cameras, Test FSTC-1

6 COMPUTER SIMULATION

6.1 Background

Computer simulation modeling with BARRIER VII (13) was performed to analyze and predict the dynamic performance of the preliminary TBC-8000 design prior to full-scale vehicle crash testing. The simulation was conducted modeling a 8,165-kg straight truck impact at a speed of 80.5 km/hr and at an angle of 15 degrees.

6.2 Vehicle Model Calibration

A vehicle model of an 8,165-kg straight truck was not readily available for use with BARRIER VII. Therefore, a vehicle model was developed based upon an actual crash test with an instrumented rigid concrete wall conducted at TTI (14). The vehicle model was based upon a 1982 GMC 7000 Series straight truck with a test inertial weight of 8,187 kg (14). Equations for calculating the yaw moment of inertia were found in a technical paper by Garrott et al. and a study by Fancher et al. (15,16). A BARRIER VII model of the TTI instrumented wall was also necessary to calibrate the vehicle model. The BARRIER VII finite element model of the instrumented wall is shown in Appendix A.

Vehicle model calibration was performed by an iterative process of adjusting the vehicle crushing stiffness at the vehicle contact points. The vehicle model was properly calibrated when the simulated 0.050-sec average normal impact forces exerted on the instrumented wall and the yaw motion of the simulation vehicle compared favorably to that of the actual test. The idealized finite element, 2-dimensional vehicle model for the 8,187-kg single-unit truck used in BARRIER VII is shown in Appendix A.

6.3 Design Option

BARRIER VII computer simulation modeling was performed on only one design option. The TBC-8000 bridge railing design was constructed with a 3.42-mm thick thrie beam rail supported by fifteen W152x22.3 steel posts, a channel rail, and an approach guardrail transition. Post nos. 1 through 15 were 933-mm long and were spaced at 1,905 mm on centers. The BARRIER VII finite element model of the TBC-8000 bridge railing is shown in Appendix A. The structural properties used for the rail and post elements are shown in Appendix B. A typical computer simulation input data file is shown in Appendix C.

6.4 BARRIER VII Results

The simulation results indicated that the TBC-8000 bridge railing satisfactorily redirected the 8,165-kg single-unit truck. In addition, all structural hardware remained functional during the impact (i.e., failure was not predicted for any posts or rails elements). The maximum permanent set deflections of the C-rail and thrie beam were 178 mm and 152 mm, respectively. The maximum dynamic deflections of the C-rail and thrie beam were 348 mm and 292 mm, respectively. The maximum 0.001-msec average lateral and longitudinal decelerations were 2.8 g's and 2.0 g's, respectively. The peak 0.050-msec average impact force perpendicular to the bridge railing was approximately 222 kN. The truck became parallel to the bridge railing at 0.350 sec. At 0.68 sec, the truck exited the bridge railing at an angle of 11.4 degrees.

7 CRASH TEST NO. 1

7.1 Test FSTC-1

The 8,165-kg single-unit truck impacted the bridge railing at a speed of 76.3 km/hr and an angle of 16.1 degrees. A summary of the test results and sequential photographs are shown in Figure 22. Additional sequential photographs are shown in Figure 23. Documentary photographs of the crash test are shown in Figures 24 through 27.

7.2 Test Description

Initial impact occurred at post no. 4, as shown in Figure 28. After the initial impact with the bridge railing, the right-front corner of the bumper and quarter panel crushed inward. At 0.064 sec, the truck cab began to rotate clockwise toward the rail. At 0.180 sec, the truck box began to rotate clockwise toward the rail. At 0.399 sec, the truck became parallel with the rail with a velocity of 66.6 km/hr. At 0.523 sec, the front-end of the truck began to yaw away from the rail. At 0.622 sec, the truck box reached a maximum clockwise roll angle of approximately 18 degrees, while the rear tires of the truck were positioned vertically above the bridge deck surface. At 0.828 sec, the rear of the truck box began to yaw away from the rail as the box descended. At 0.864 sec, the left-front tire contacted the surface. The truck exited the bridge rail at approximately 1.504 sec and 1.8 degrees. The vehicle's post-impact trajectory is shown in Figure 22.

7.3 Bridge Rail Damage

Damage to the bridge rail was moderate, as shown in Figures 29 through 39. Bridge railing damage consisted mostly of deformed thrie beam sections, C-rail sections, and steel posts. The length of vehicle contact along the top of the C-rail was approximately 11.4 m. Physical evidence revealed that lateral buckling of the C-rail occurred between post nos. 4 and 5. The physical damage to the thrie beam rail revealed that approximately 7.6 m of rail was damaged. Vehicle contact or scrubbing marks on the thrie beam rail were evident at two locations: (1) between Post Nos. 3 through 8; and (2) from the midspan between Post Nos. 10 and 11 through Post No. 15. This can be explained by the vehicle exiting at an angle virtually parallel to the bridge railing. On the traffic-side face of the thrie beam rail, evidence showed that there was intense vehicle contact at the mid-height of the thrie beam. This intense vehicle contact is also shown by the spalling of the galvanized coating on the back-side of the thrie beam rail.

Six steel posts, post nos. 2 through 7, were permanently deformed during the test, as shown in Figures 33 through 39. The flange on the traffic-side face of post nos. 2 through 7 was deformed. Post nos. 3 through 6 also encountered buckling of the web at the base of the posts. The attached bearing plate was also deformed at post nos. 3 through 6, with the maximum deformation occurring to the plate at post no. 5.

The permanent set deflections of thrie beam and C-rail are shown in Appendix D. The maximum lateral permanent set deflections of the C-rail and thrie beam rail were 193 mm and 208 mm at the centerline of post no. 4, respectively, as measured in the field.. The effective coefficient of friction was determined to be 0.31.

7.4 Vehicle Damage

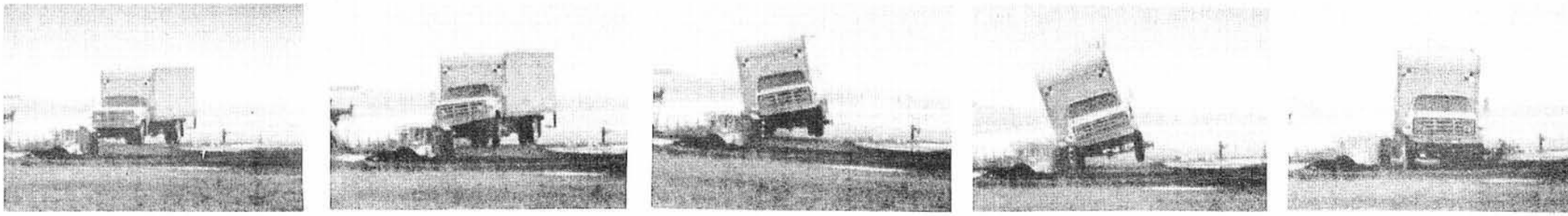
Exterior vehicle damage was relatively minor, as shown in Figures 40 through 43. Interior occupant compartment deformations did not occur. Most of the minor damage was limited to the right-front corner of the truck cab, box, and front bumper. Following the test, all the tires remained inflated. The bottom-side edge of the right-front corner of the box was indented upward due to the contact between the bottom of the truck box and the top of the C-rail. In addition, the truck box shifted to the right of the longitudinal centerline of the truck cab and steel frame. Minor dents were also evident in the right-side gas tank and running board. There was no intrusion nor deformation of the occupant department. No other damage to the vehicle was observed.

7.5 Occupant Risk Values

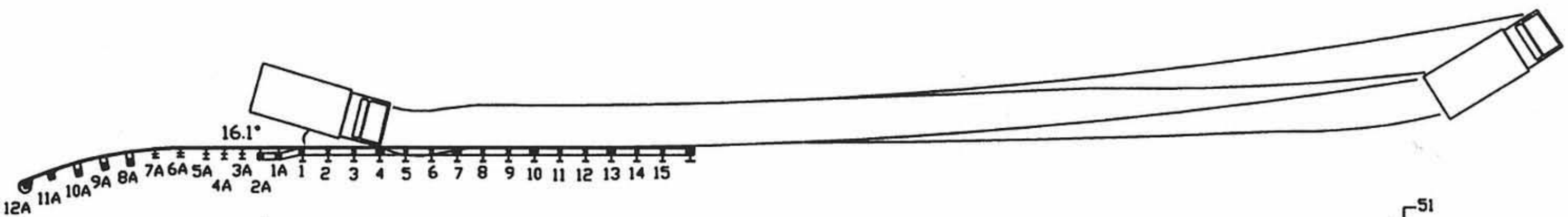
The normalized longitudinal and lateral occupant impact velocities were determined to be 3.3 m/s and 4.8 m/s, respectively. The maximum 0.010-sec average occupant ridedown decelerations in the longitudinal and lateral directions were 1.8 g's and 6.1 g's, respectively. It is noted that the occupant impact velocities (OIV) and occupant ridedown decelerations (ORD) values were were within the suggested limits provided in AASHTO. The results of the occupant risk assessment, as determined from high-speed film, are summarized in Figure 22.

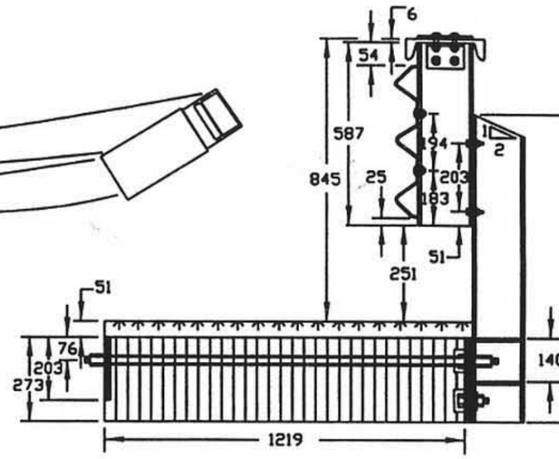
7.6 Discussion

The analysis of the test results for test FSTC-1 showed that the bridge railing adequately contained and redirected the vehicle with controlled lateral displacements of the bridge rail. There were no detached elements or fragments which showed potential for penetrating the occupant compartment or presented undue hazard to other traffic. Deformations of, or intrusion into, the occupant compartment that could have caused serious injury did not occur. The test vehicle did not penetrate or ride over the bridge rail and remained upright during and after the collision. Vehicle roll, pitch, and yaw angular displacements were noted, but they were deemed acceptable because they did not adversely influence occupant risk safety criteria nor cause rollover. After collision, the vehicle's trajectory revealed minimum intrusion into adjacent traffic lanes. In addition, the vehicle's exit angle was less than 60 percent of the impact angle. Therefore, test FSTC-1 conducted on the bridge railing was determined to be acceptable according the AASHTO PL-2 safety performance criteria.



0.000 sec 0.118 sec 0.341 sec 0.702 sec 1.504 sec





- Test Number FSTC-1
- Date 12/9/92
- Appurtenance .... Steel Thrie and Cannel Bridge Rail System
- Total Length .... 28.57 m
- Steel Thrie Beam Rail
  - Type .... AASHTO M180
  - Thickness .... 3.42 mm
  - Top Mounting Height ..... 784 mm
- Steel Channel Rail (C-Rail)
  - Type .... C200x17 - ASTM A36
  - Top Mounting Height ..... 845 mm
- Steel Post Nos. 1 -15
  - Dimensions .... W152x22.3 by 933-mm long
  - Material .... ASTM A36
- Steel Spacer Block Nos. 1 - 15
  - Dimensions .... W152x22.3 by 587-mm long
  - Material .... ASTM A36
- Vehicle Model .... 1986 GMC 7000 Series Straight Truck
  - Curb .... 5,075 kg
  - Test Inertial .... 8,165 kg
  - Gross Static .... 8,165 kg
- Vehicle Speed
  - Impact .... 76.3 km/hr
  - Exit .... NA
- Vehicle Angle
  - Impact .... 16.1 deg
  - Exit .... 1.8 deg
- Vehicle Snagging .... None
- Vehicle Stability .... Satisfactory
- Effective Coefficient of Friction (μ) 0.31
- Occupant Ridedown Deceleration (10 msec avg.)
  - Longitudinal (not required) .... 1.8 G's < 15 G's
  - Lateral (not required) .... 6.1 G's < 15 G's
- Occupant Impact Velocity (Normalized)
  - Longitudinal (not required) .... 3.3 m/s < 9.1 m/s
  - Lateral (not required) .... 4.8 m/s < 7.6 m/s
- Vehicle Damage .... Minor
  - TAD[17] 1-RFQ-2
  - SAE[18] 01-RYEW1
- Bridge Rail Damage .... Moderate
- Maximum Vehicle Rebound Distance ..... 178 mm @ 40.54 m
- Maximum Permanent Set Deflections
  - Thrie Beam .... 208 mm
  - Channel Rail .... 193 mm

Figure 22. Summary of Test Results and Sequential Photographs, Test FSTC-1

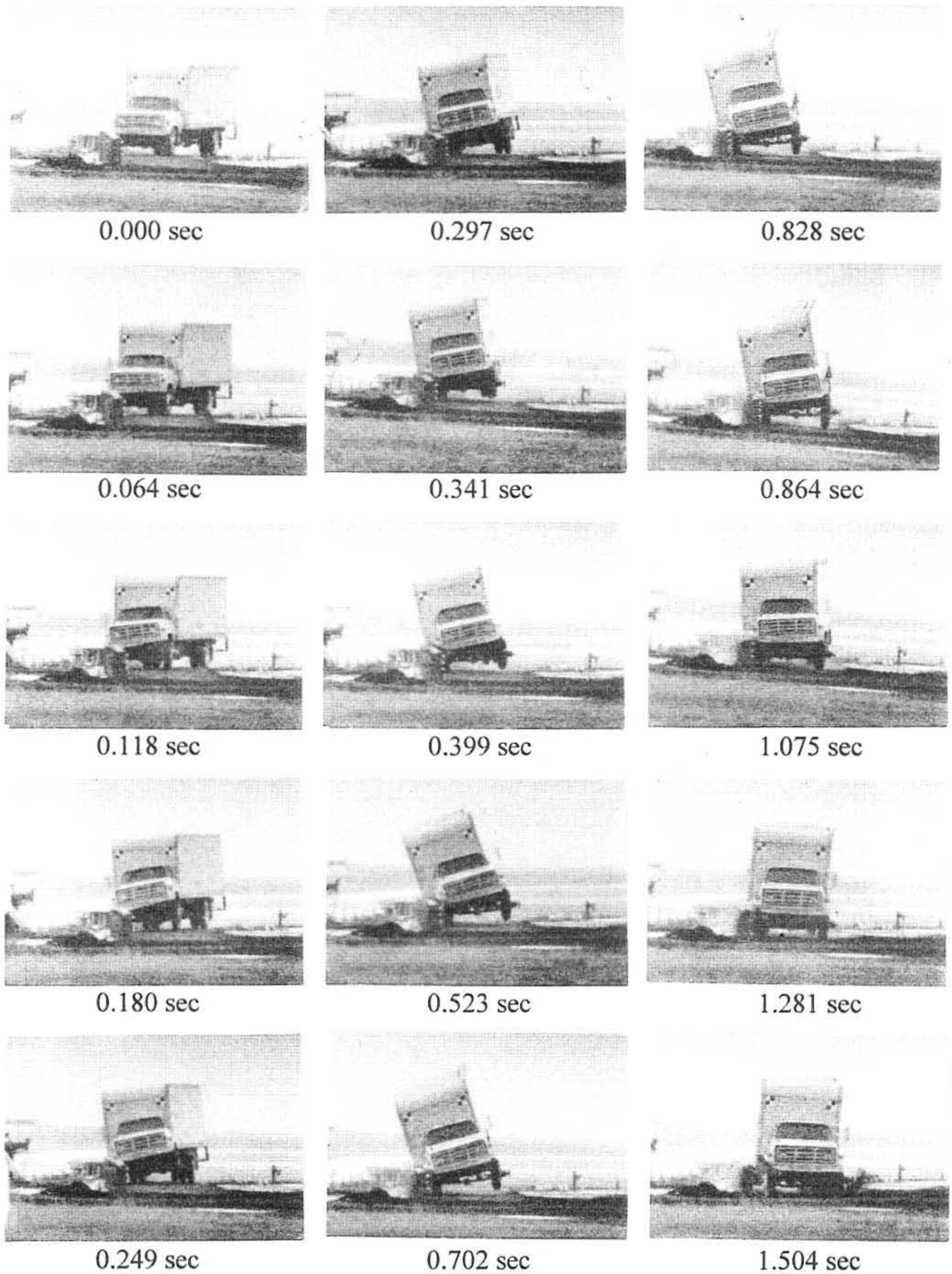


Figure 23. Additional Sequential Photographs, Test FSTC-1

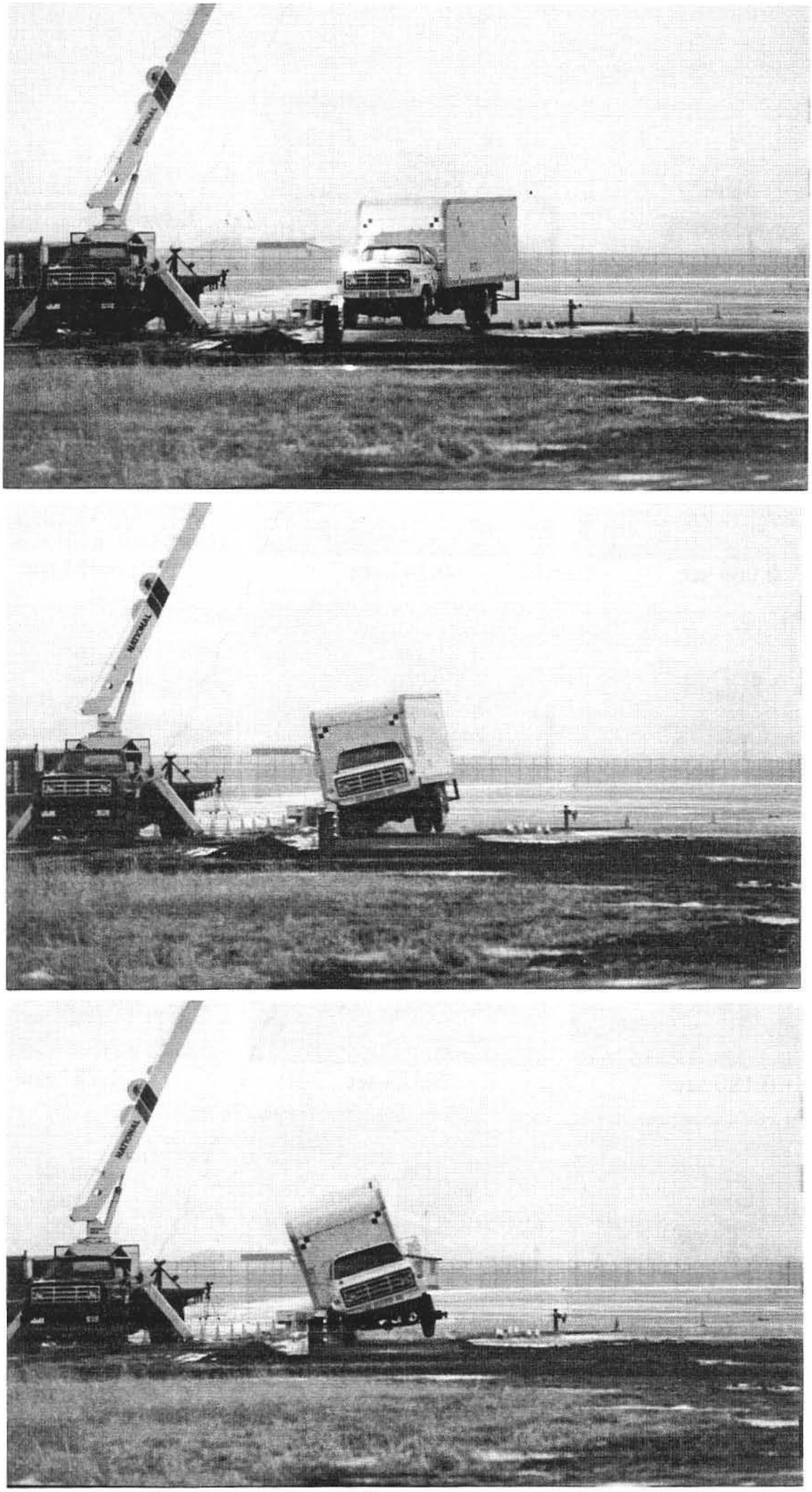


Figure 24. Documentary Photographs, Test FSTC-1

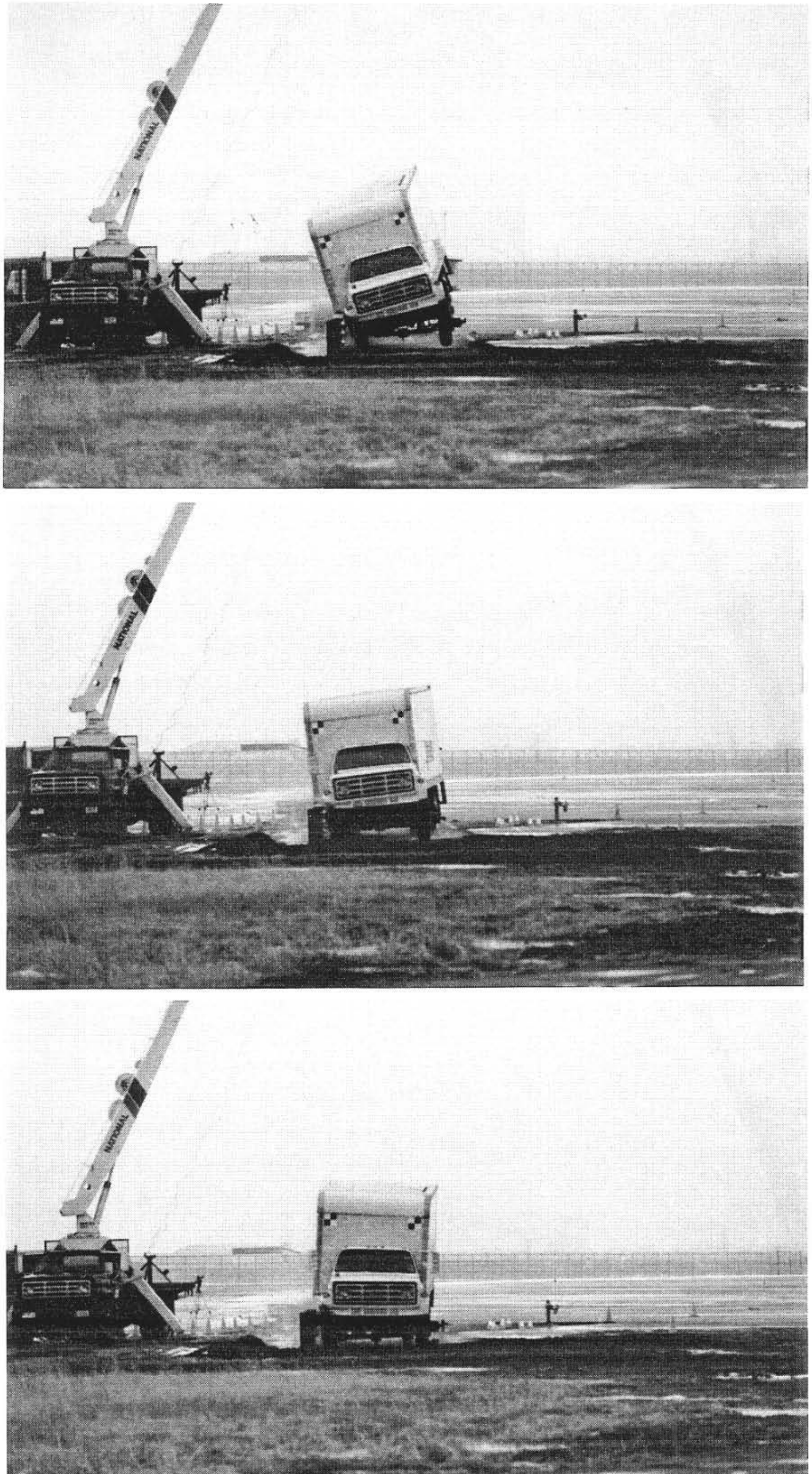


Figure 25. Documentary Photographs, Test FSTC-1

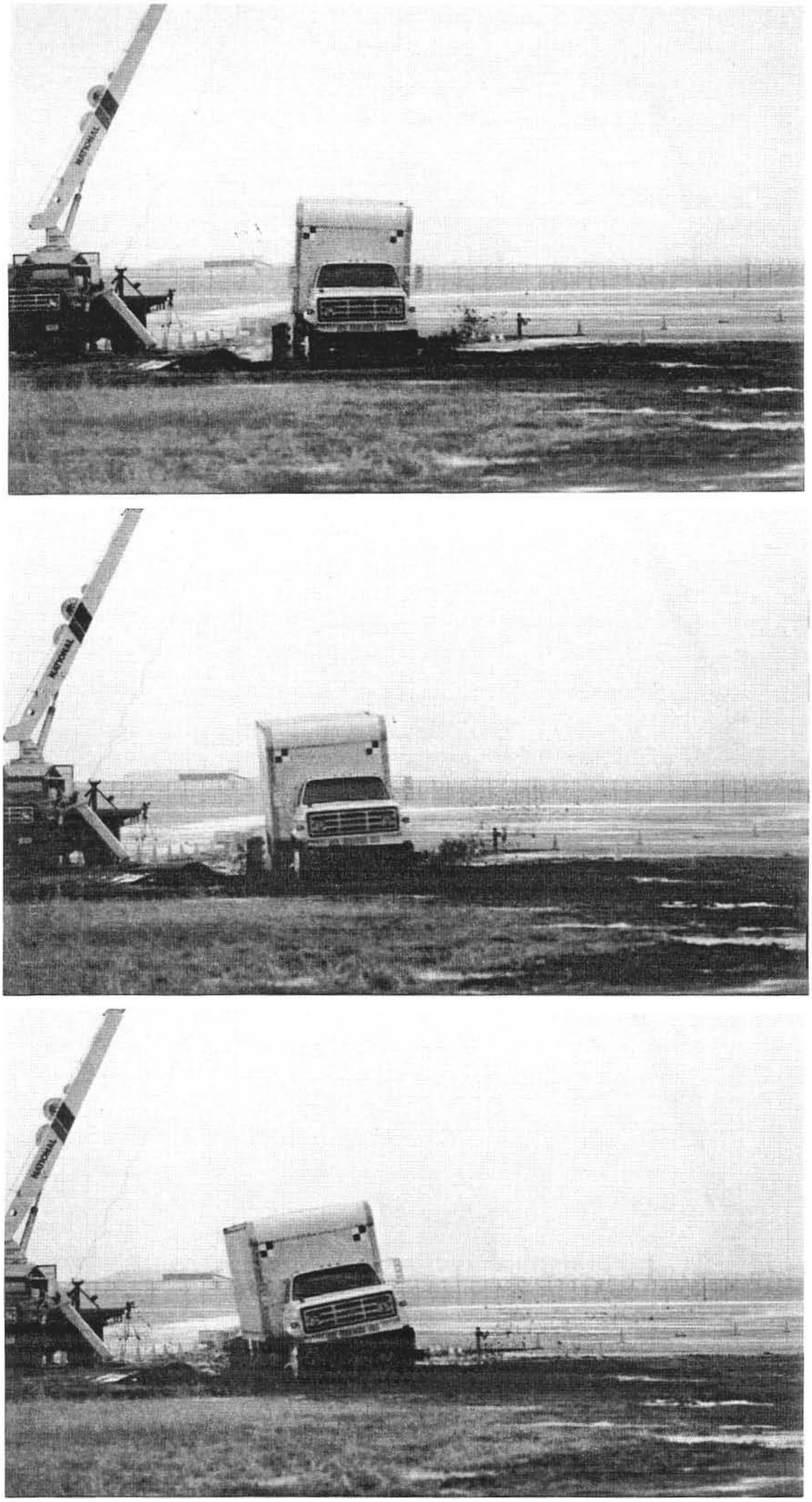


Figure 26. Documentary Photographs, Test FSTC-1

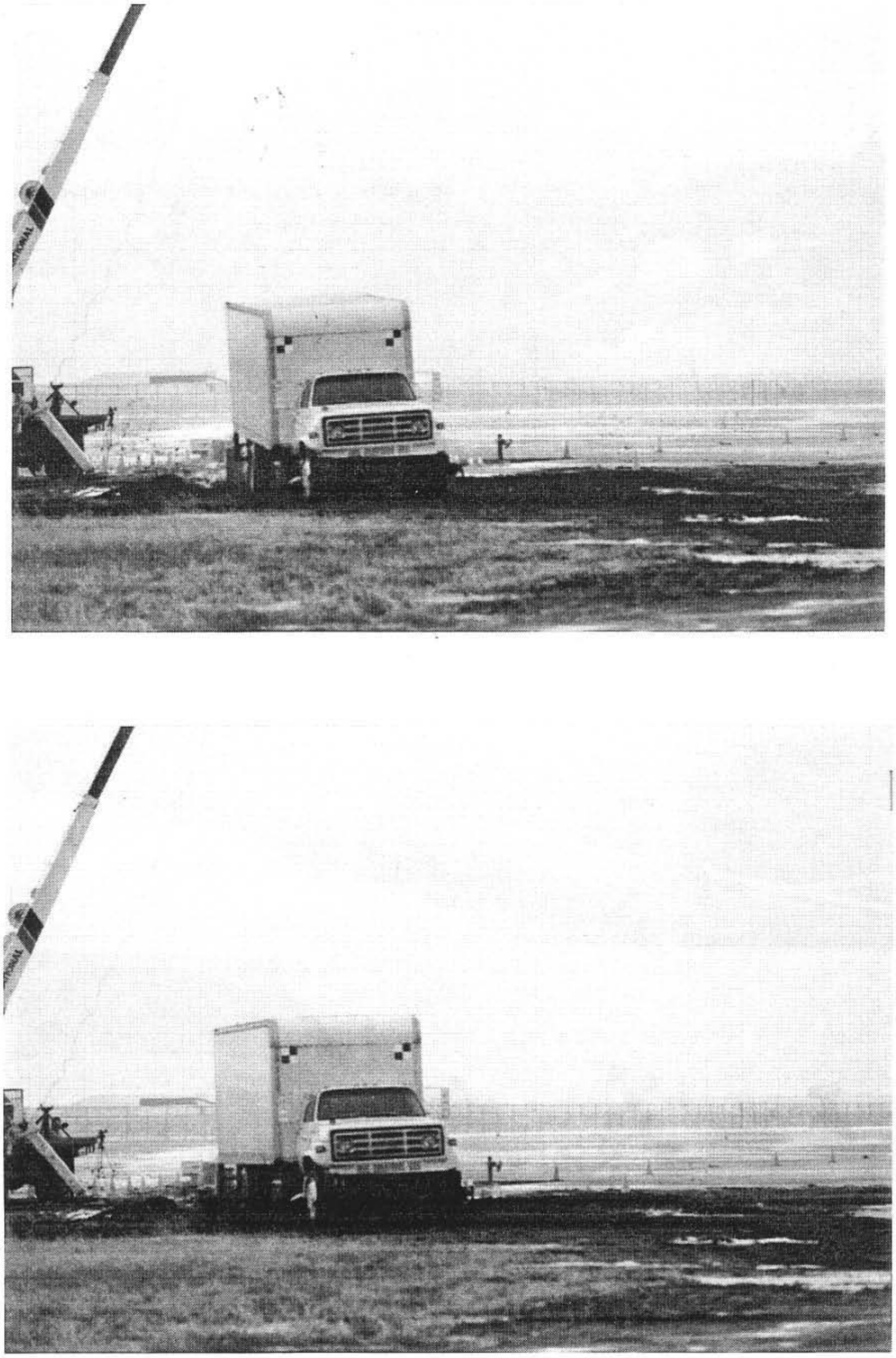


Figure 27. Documentary Photographs, Test FSTC-1

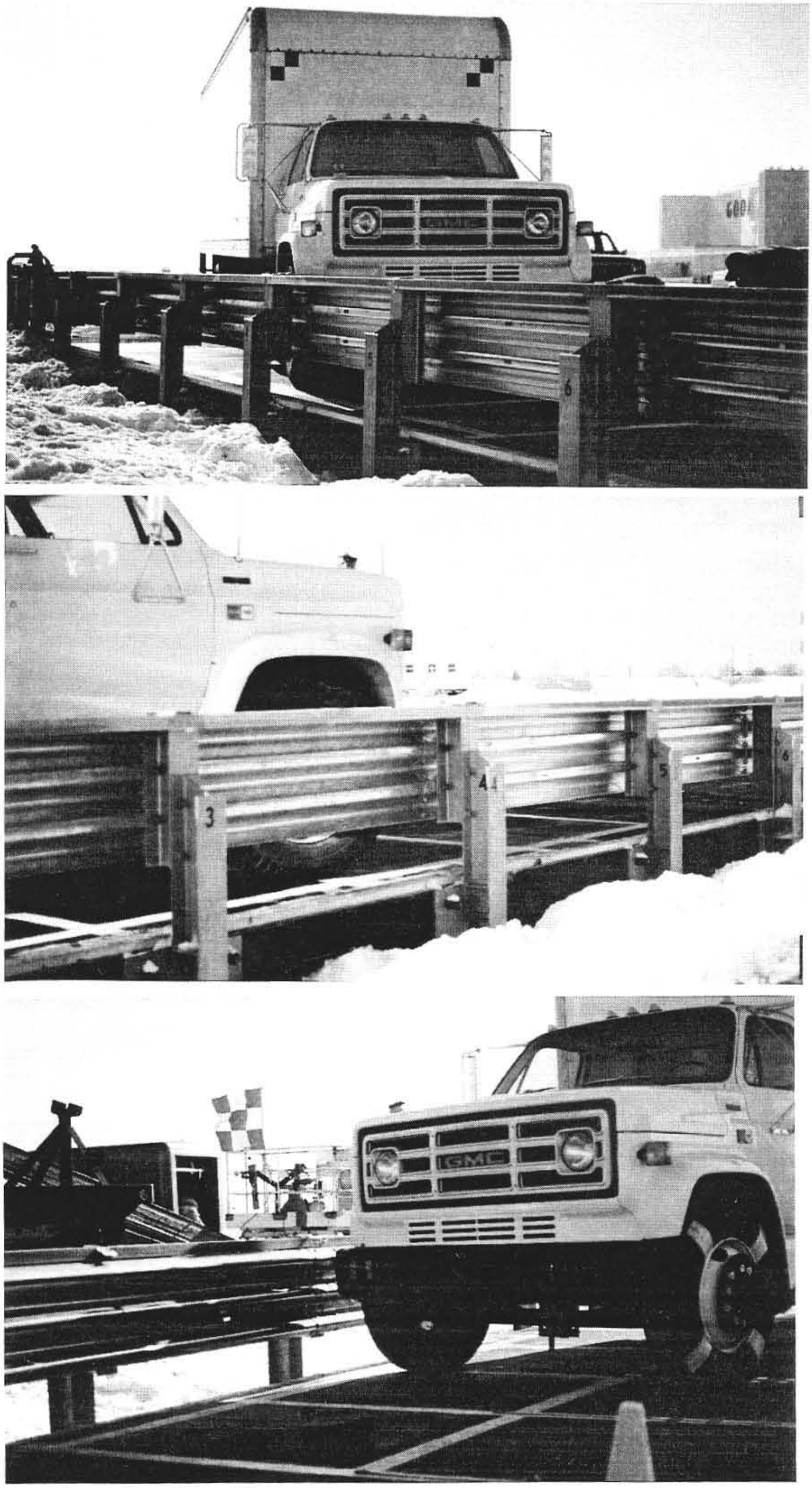


Figure 28. Impact Locations, Test FSTC-1

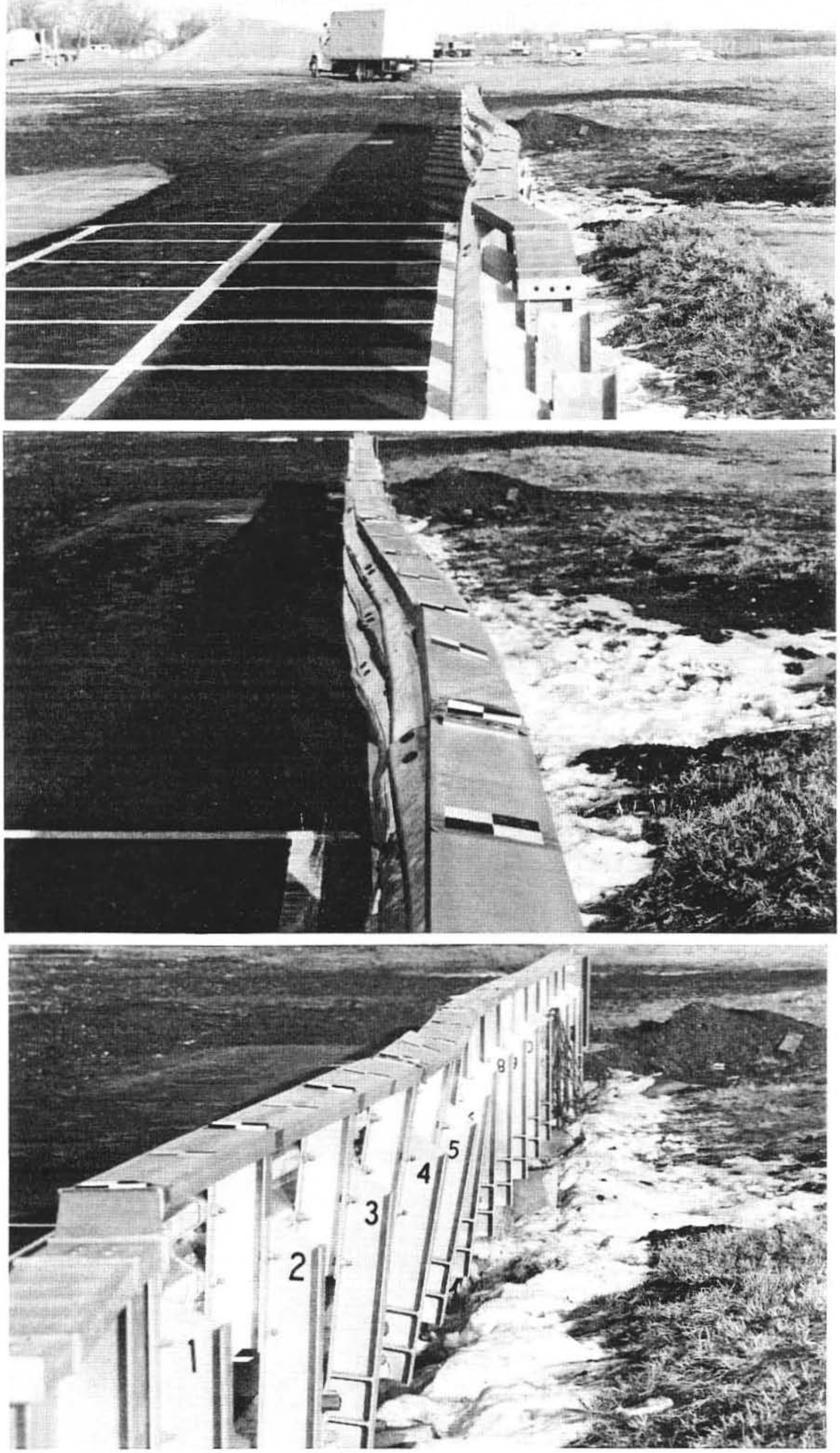


Figure 29. Bridge Rail Damage, Test FSTC-1

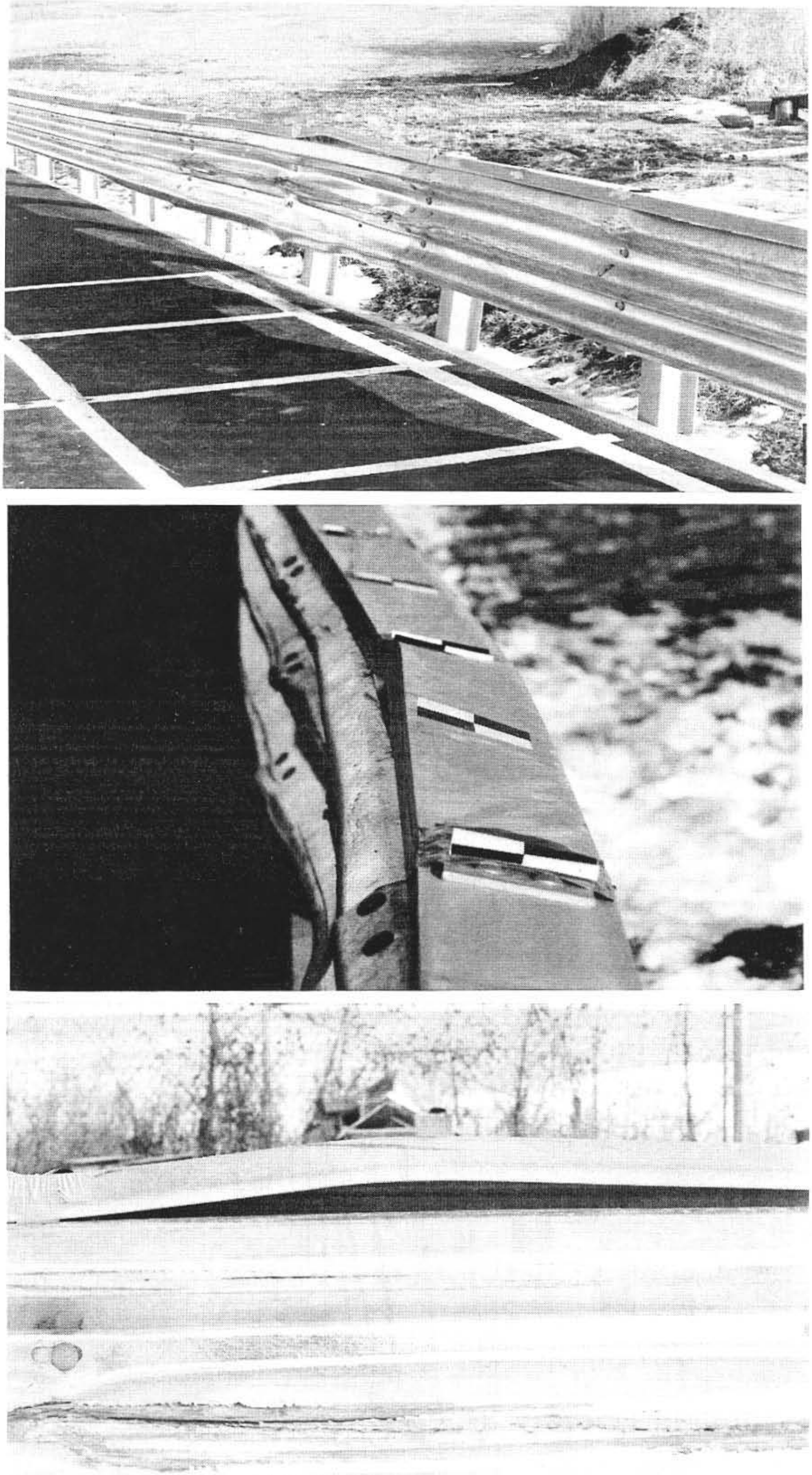


Figure 30. Buckling of C-rail Between Post Nos. 4 and 5, Test FSTC-1

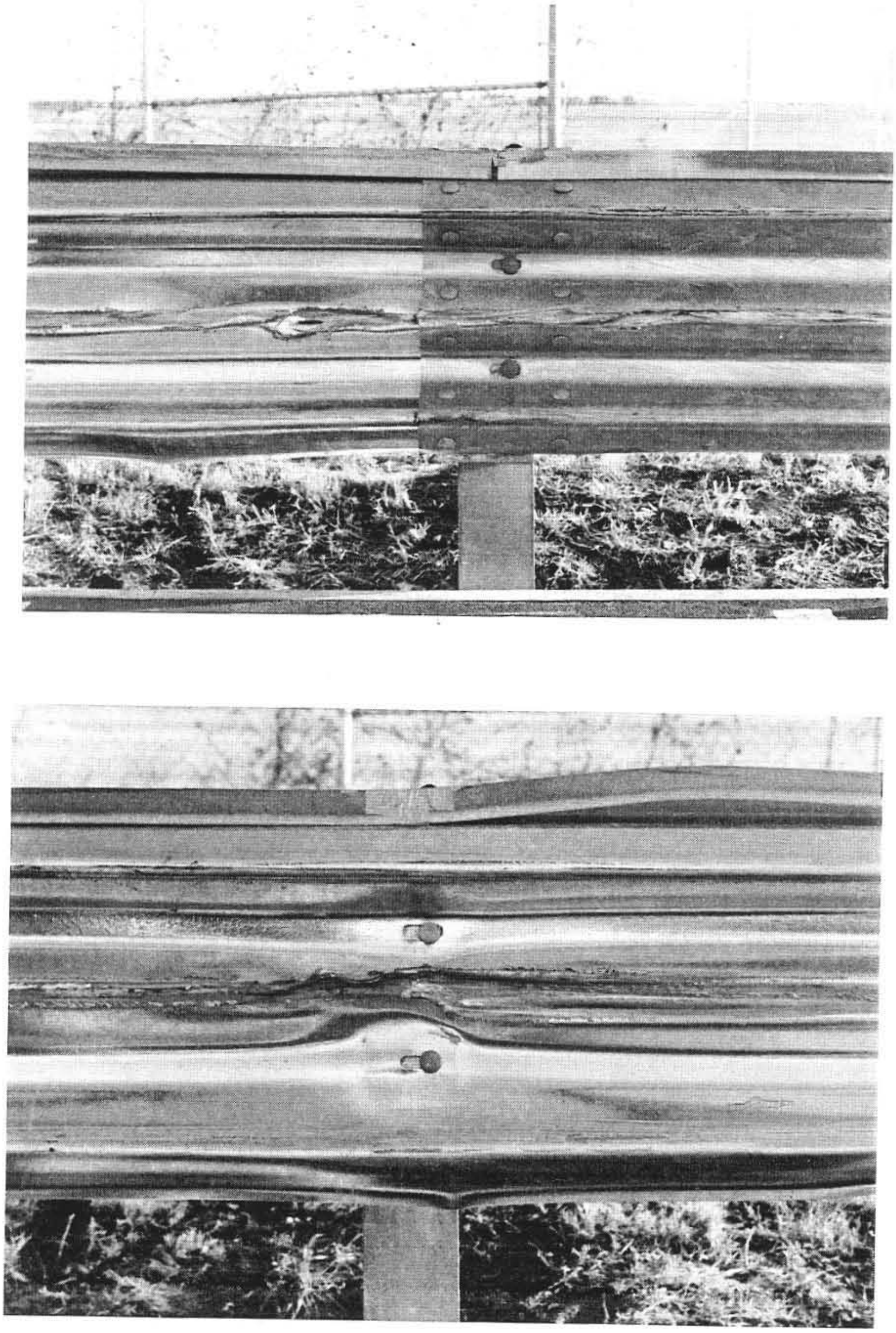


Figure 31. Thrie Beam Rail Damage, Test FSTC-1

Figure 32. Thrie Beam Rail Damage, Test FSTC-1

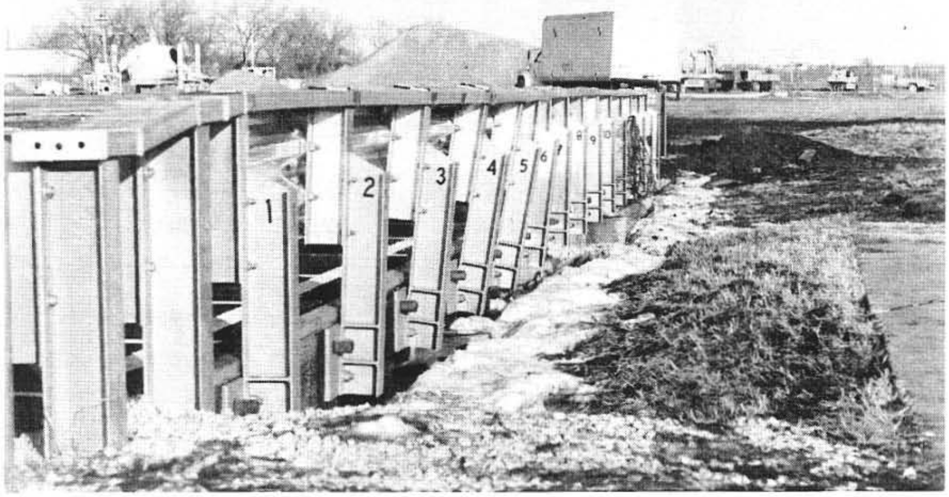


Figure 33. Overall Steel Post Damage, Test FSTC-1

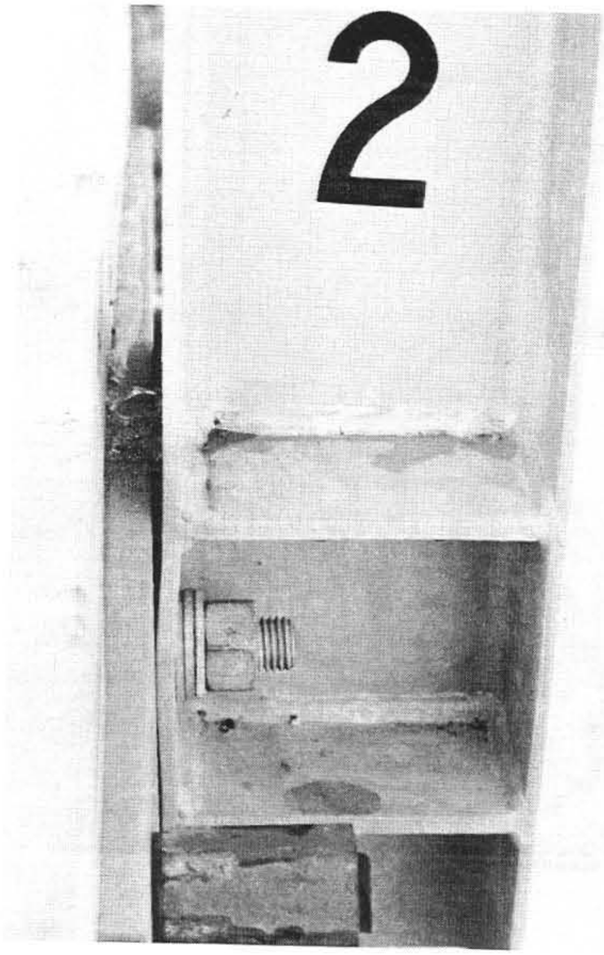


Figure 34. Post No. 2 Damage, Test FSTC-1

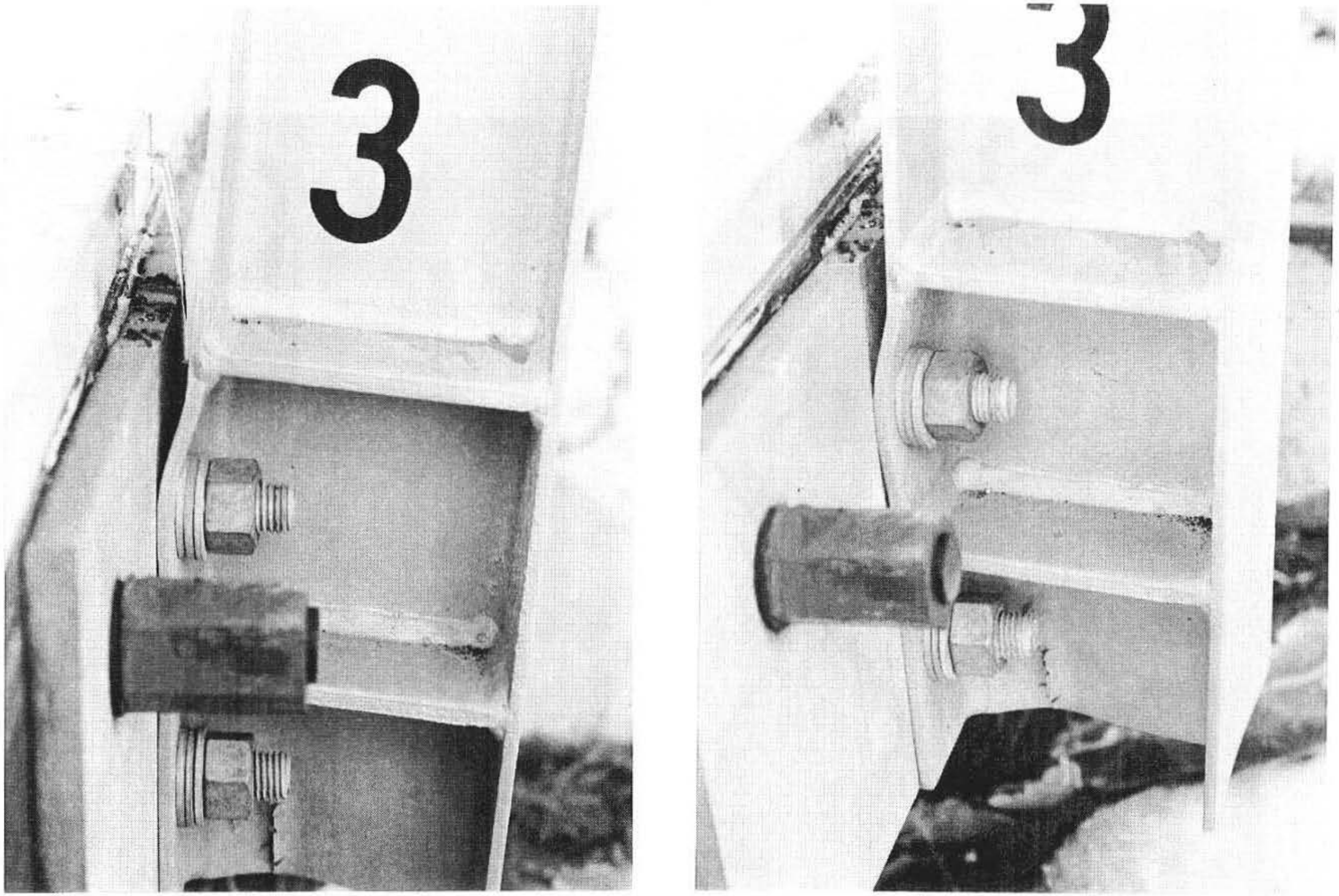


Figure 35. Post No. 3 Damage, Test FSTC-1

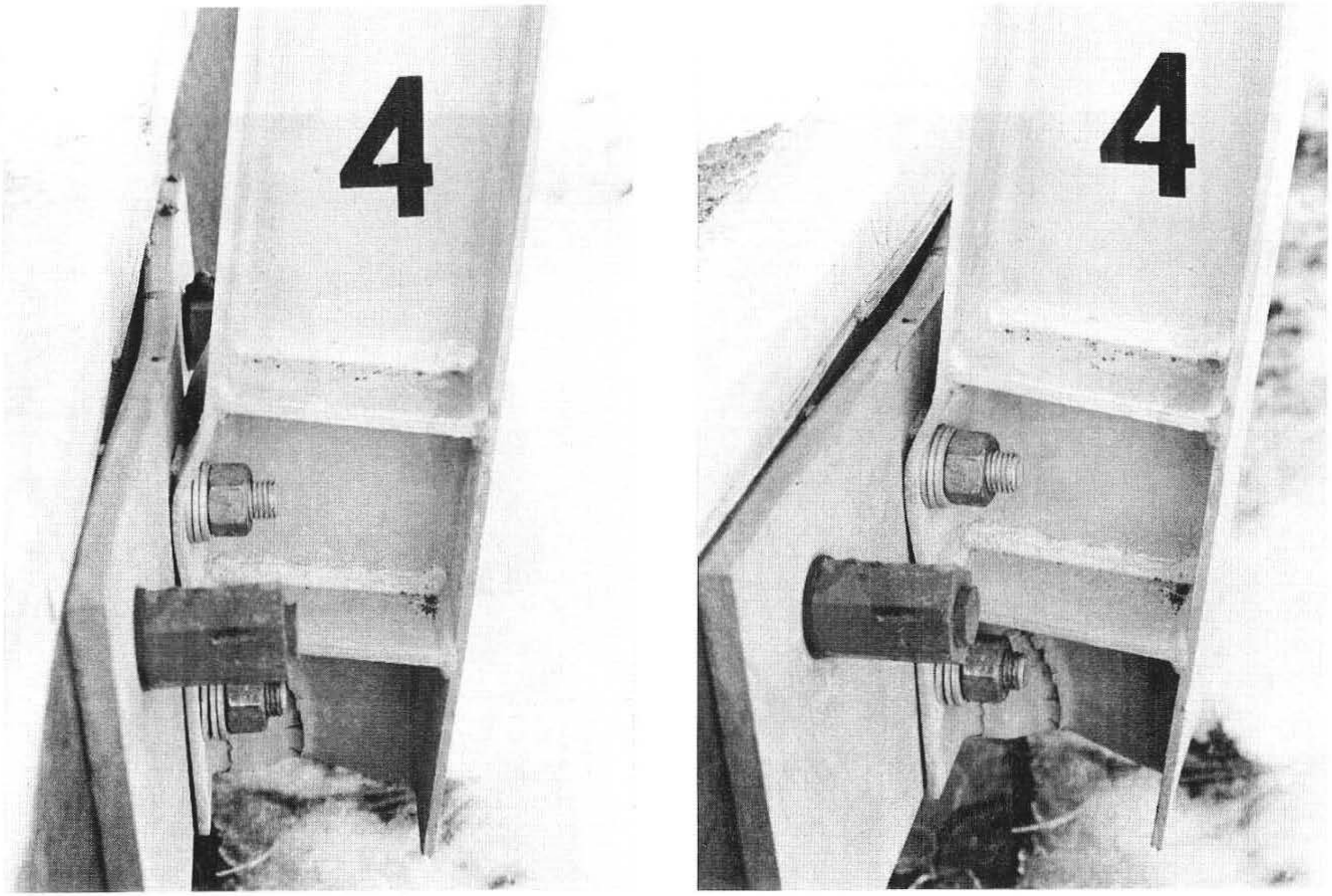


Figure 36. Post No. 4 Damage, Test FSTC-1

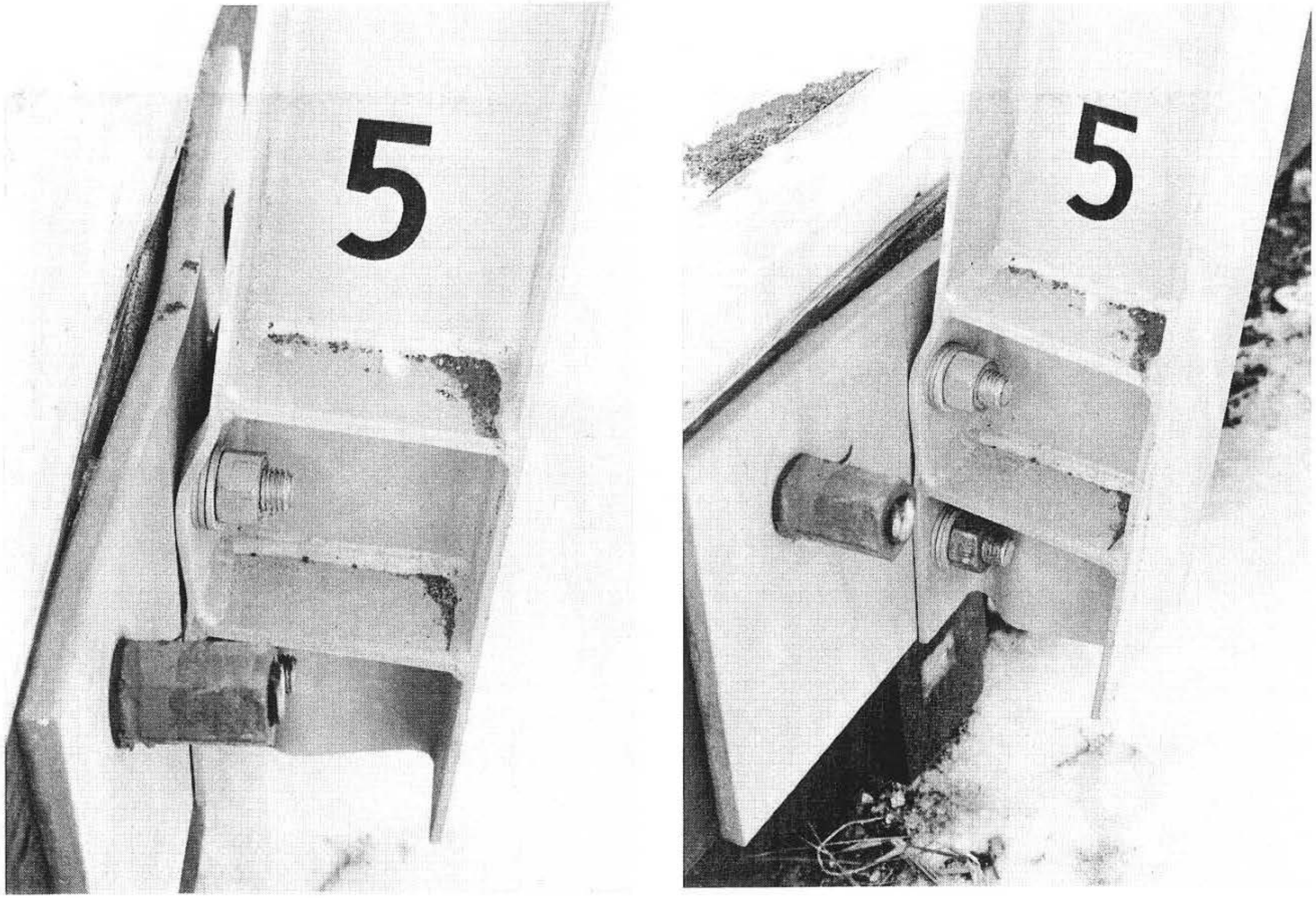


Figure 37. Post No. 5 Damage, Test FSTC-1

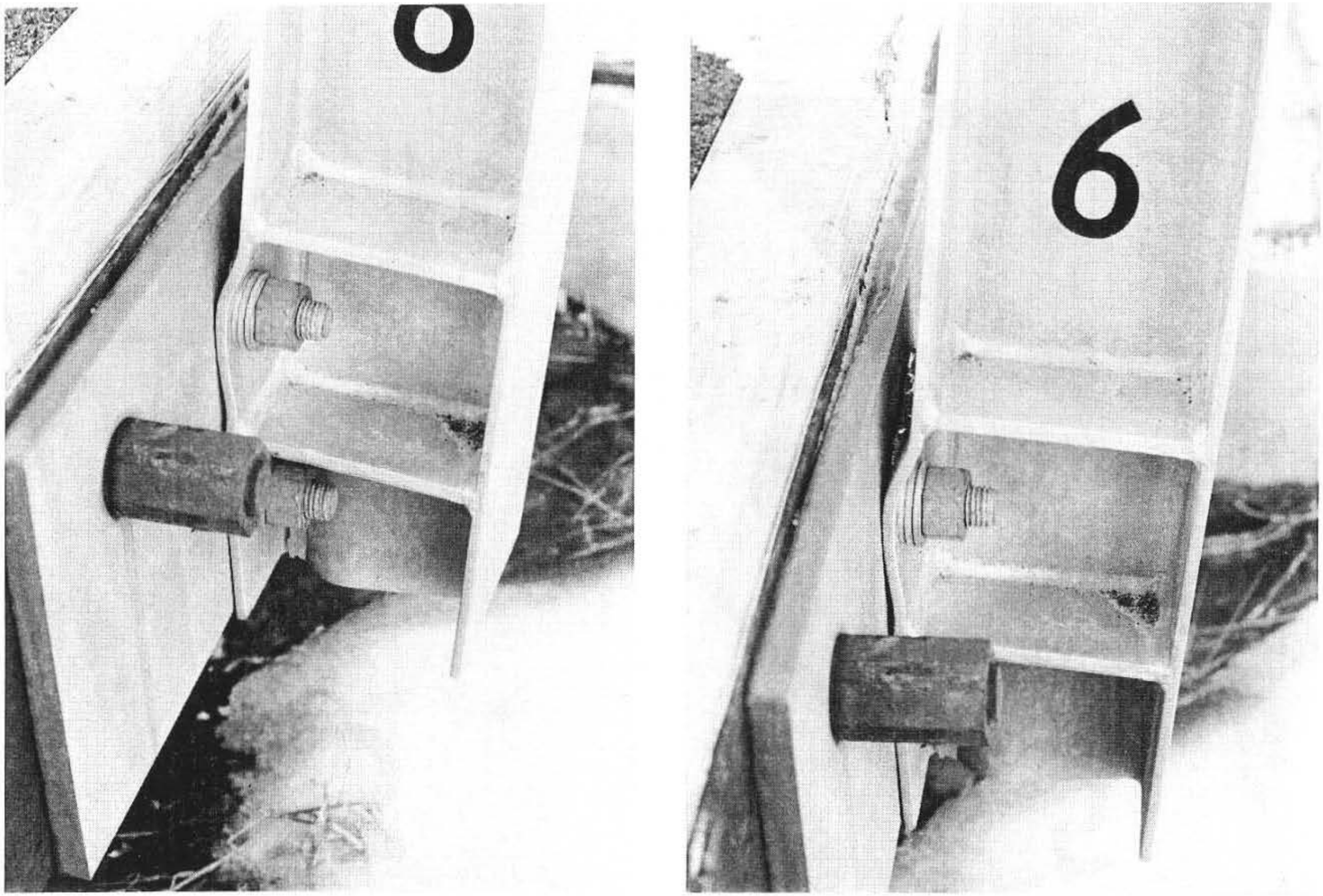


Figure 38. Post No. 6 Damage, Test FSTC-1

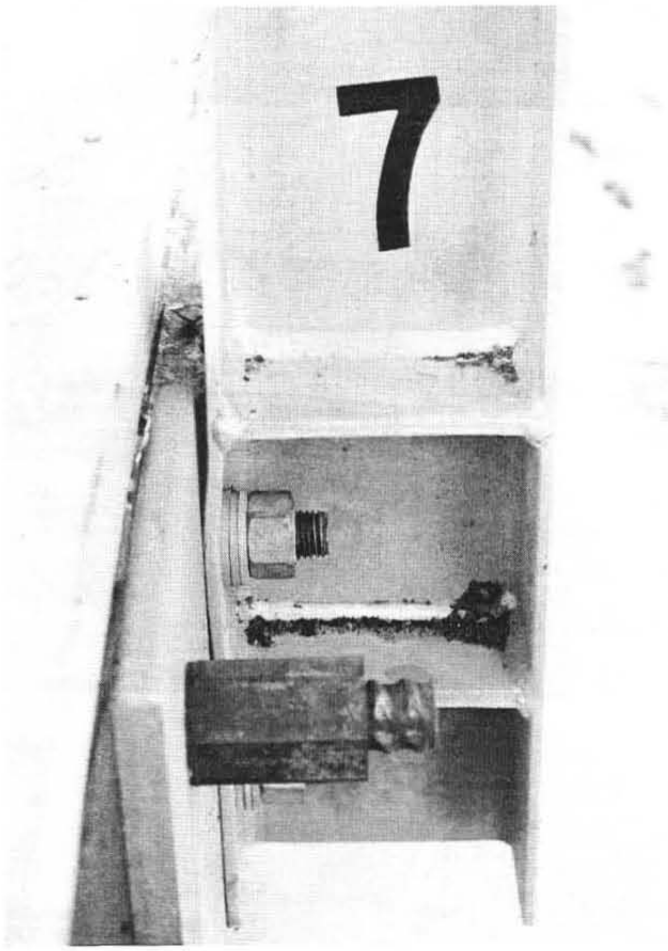


Figure 39. Post No. 7 Damage, Test FSTC-1

Figure 40. Vehicle Damage, Test FSTC-1

Figure 41. Vehicle Damage, Test FSTC-1

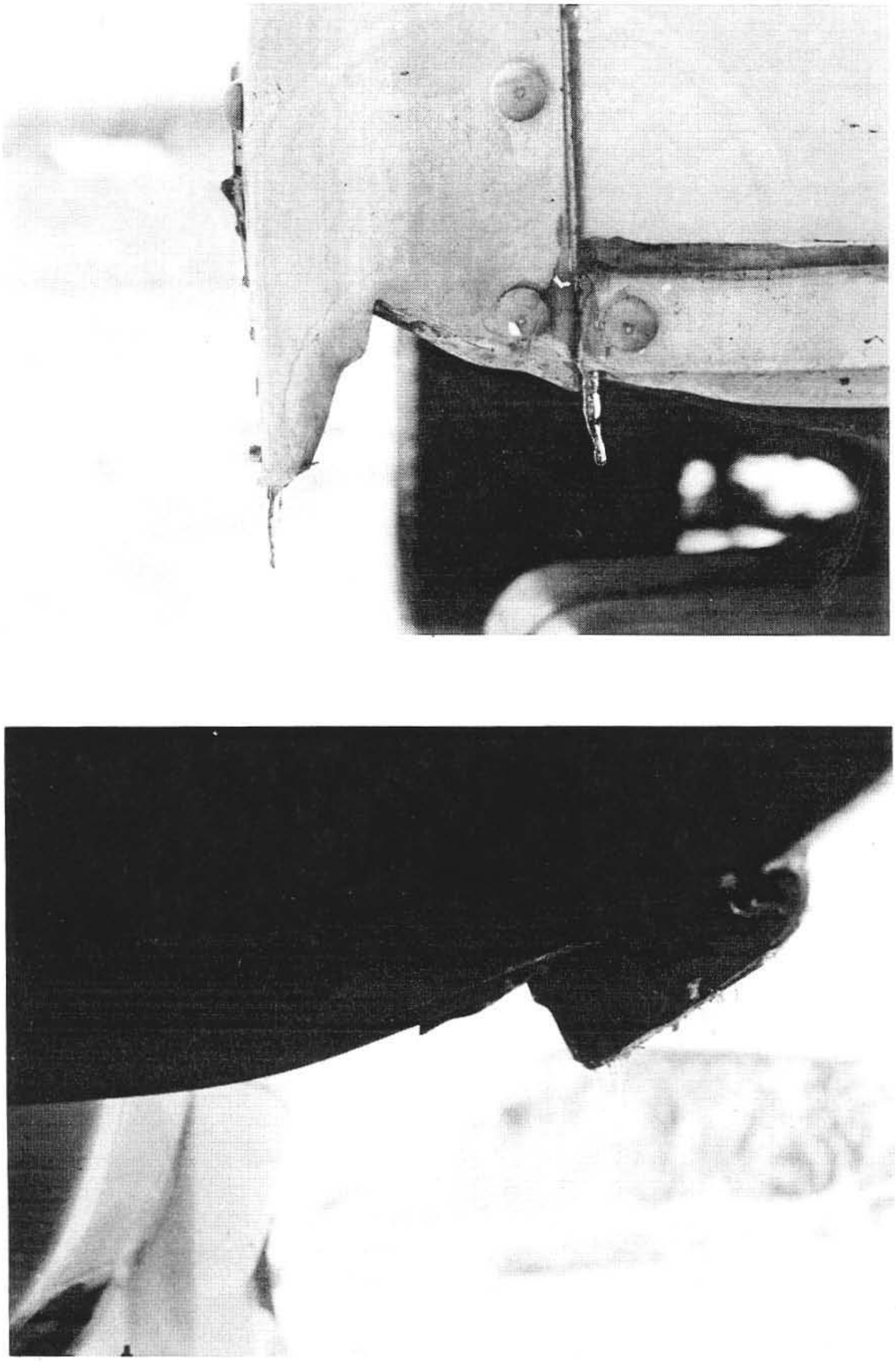


Figure 42. Undercarriage Damage to Truck Box, Test FSTC-1

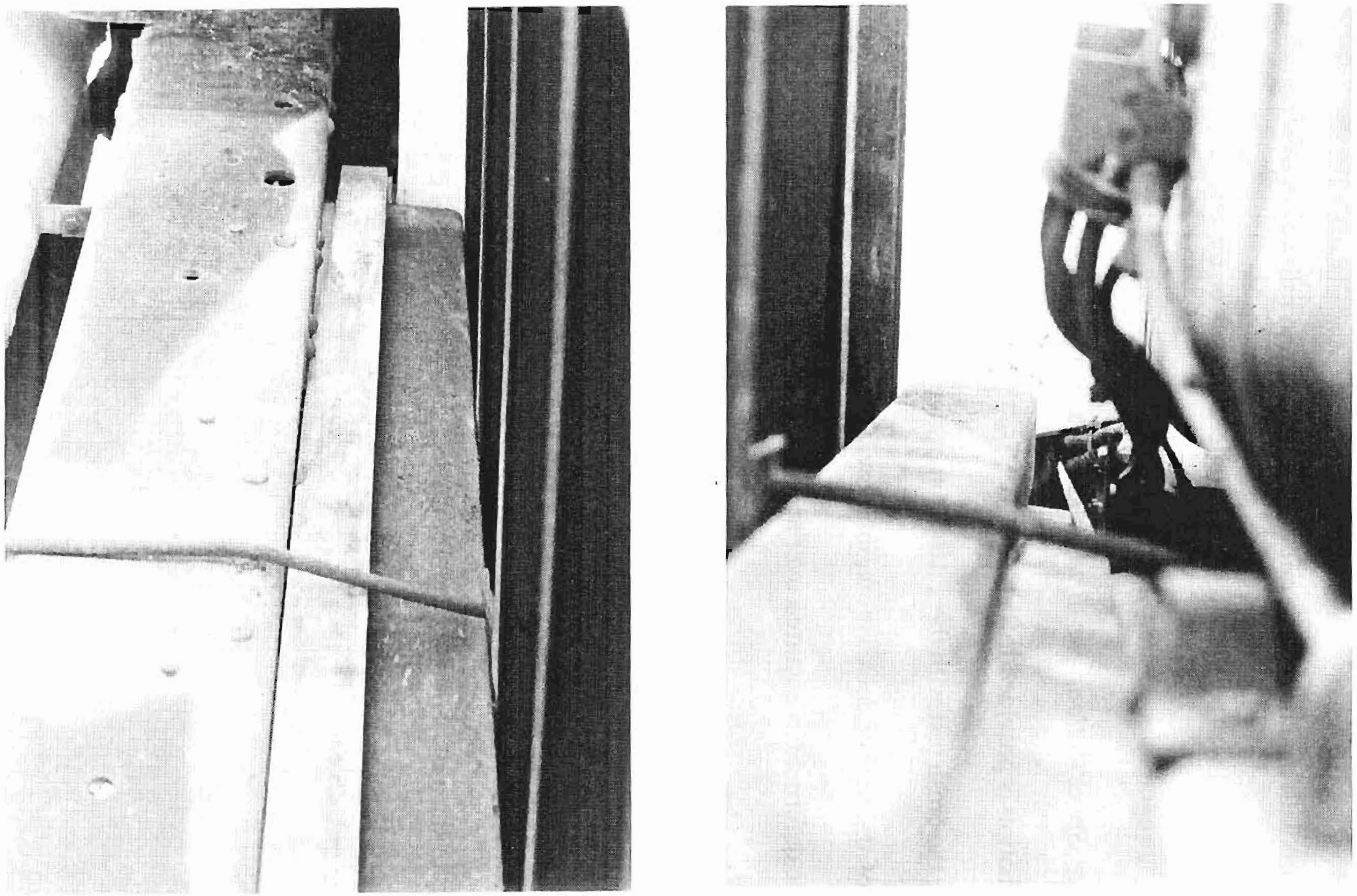


Figure 43. Shifted Truck Box Damage, Test FSTC-1

8 SUMMARY AND CONCLUSIONS

A thrie beam with channel bridge rail was developed and full-scale vehicle crash tested. A full-scale vehicle crash test was performed with a single-unit truck on the bridge rail system and was determined to be acceptable according to the PL-2 safety performance guidelines presented in AASHTO's *Guide Specifications for Bridge Railings*. A summary of the AASHTO safety performance evaluation is provided in Table 3.

Following the crash test with the TBC-8000 bridge railing, the examination of the top and bottom surfaces of the timber deck laminations revealed that there was no physical damage or separation. Plastic deformation occurred over approximately 7.6 m of thrie beam rail and six steel posts and mounting plates.

The development of the TBC-8000 bridge railing satisfied the concern for economy while also providing a crashworthy bridge railing system for timber bridge decks on higher performance level roadways. The TBC-8000 was easy to install; therefore, it should have low construction costs. The material cost for the TBC-8000 was approximately $174/m.

Table 3. Summary of AASHTO Safety Performance Results

AASHTO Evaluation Criteria	Test FSTC-1
3.a. The test article shall contain the vehicle; neither the vehicle nor its cargo shall penetrate or go over the installation. Controlled lateral deflection of the test article is acceptable.	S
3.b. Detached elements, fragments, or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	S
3.c. Integrity of the passenger compartment must be maintained with no intrusion and essentially no deformation.	S
3.d. The vehicle shall remain upright during and after collision.	S
3.e. The test article shall smoothly redirect the vehicle. A redirection is deemed smooth if the rear of the vehicle does not yaw more than 5 degrees away from the railing from time of impact until the vehicle separates from the railing.	S
3.f. The smoothness of the vehicle-railing interaction is further assessed by the effective coefficient of friction μ, where $\mu = (\cos\theta - V_p/V)/\sin\theta$. Assessment is described as either good (0.0 - 0.25), fair (0.26 - 0.35), or marginal (> 0.35).	Fair (0.31)
3.g. The impact velocity of a hypothetical front-seat passenger against the vehicle interior, calculated from vehicle accelerations and 0.6-m longitudinal and 0.3-m lateral displacements shall be less than 9.1 m/s longitudinally and 7.6 m/s laterally and for the vehicle highest 10-ms average longitudinal and lateral occupant ridedown accelerations subsequent to the instant of hypothetical passenger impact should be less than 15 g's.	S
3.h. Vehicle exit angle from the barrier shall not be more than 12 degrees. Within 30.5-m plus the length of the test vehicle from the point of initial impact with the railing, the railing side of the vehicle shall move no more than 6.1-m from the line of the traffic face of the railing	S

S - Satisfactory
M - Marginal
U - Unsatisfactory
NA - Not Available

9 RECOMMENDATIONS

A thrie beam with channel bridge rail, as described in this report, was successfully crash tested according to the criteria found in AASHTO (1). The results of this test indicate that this design is a suitable design for use on higher performance roadways. It is suggested that the research described herein could be further developed using the data collected from testing to modify future designs. However, any design modifications made to the bridge railing system may require verification through the use of full-scale vehicle crash testing.

The thrie beam with channel bridge rail is recommended for use on longitudinal timber bridges. Although the bridge rail was tested on a longitudinal glulam timber bridge deck, it could be adapted for use on other longitudinal timber bridge decks.

Following this research study, FPL and MwRSF engineers prepared a set of standard bridge railing plans for use on timber deck bridges (19). As a result, design details for the TBC-8000 bridge railing system are provided in the set of plans for both English and SI units.

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11 APPENDICES

APPENDIX A

BARRIER VII Computer Models

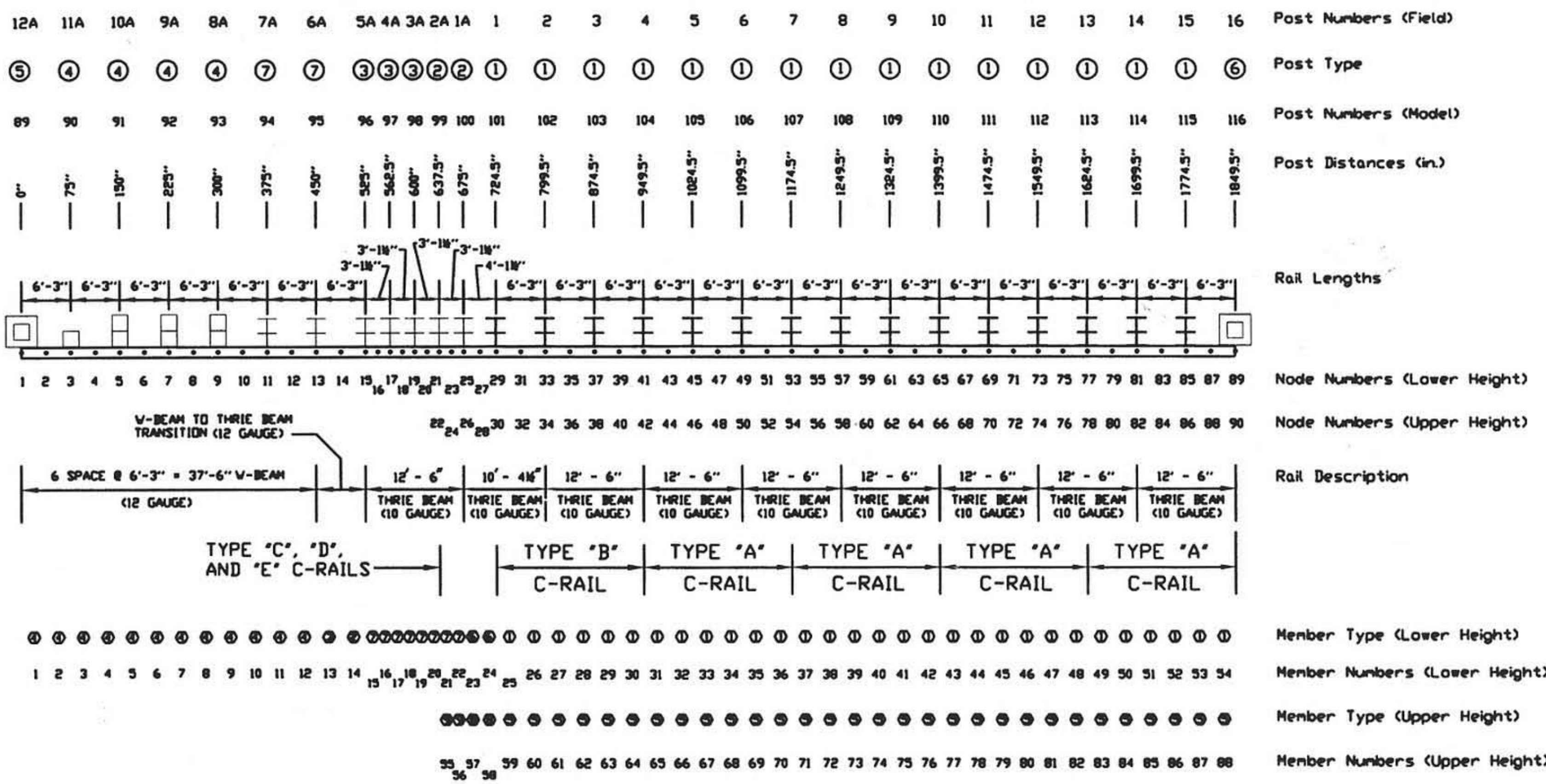

Figure A-1. Model of the TBC-8000 Bridge Railing System

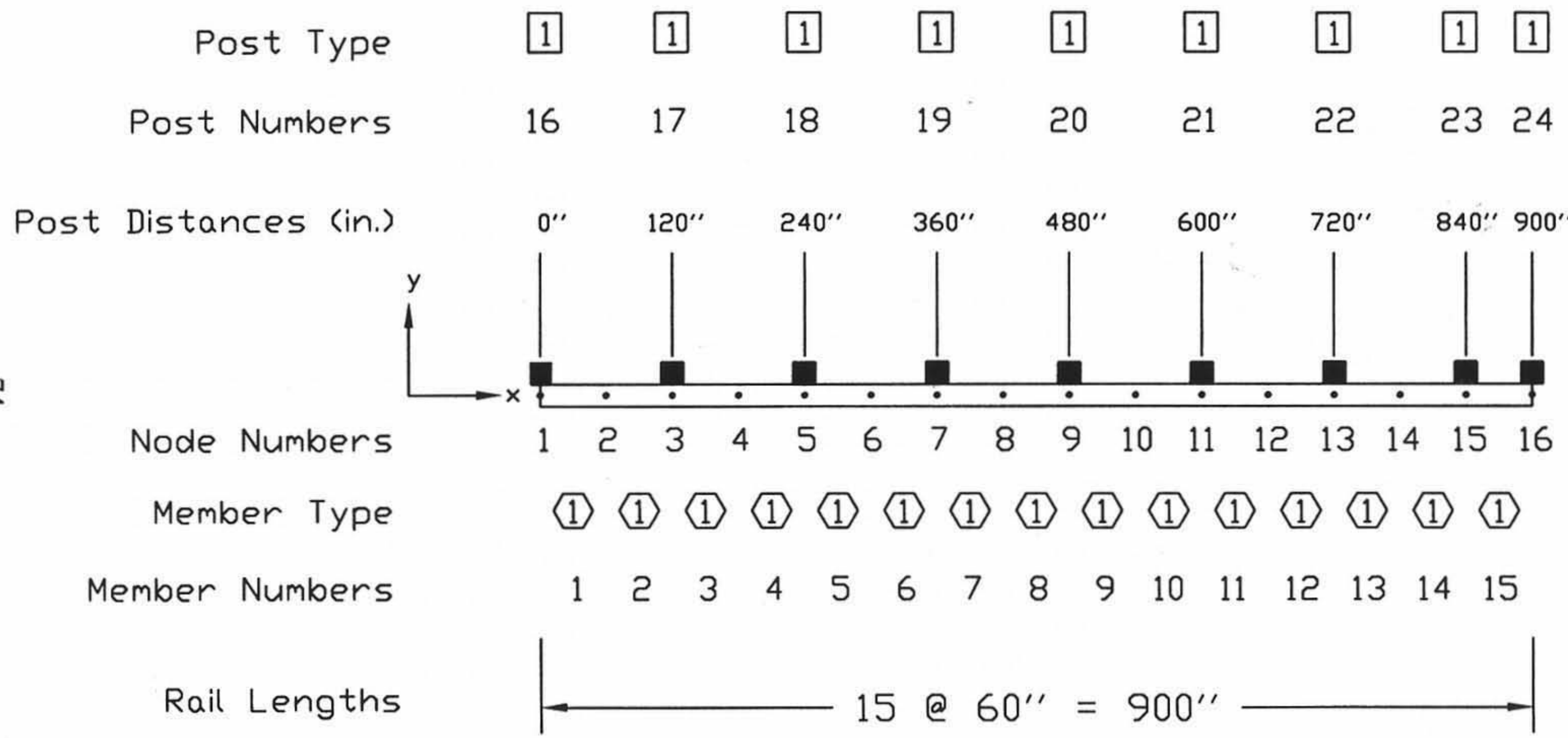

Figure A-2. Model of the Instrumented Wall

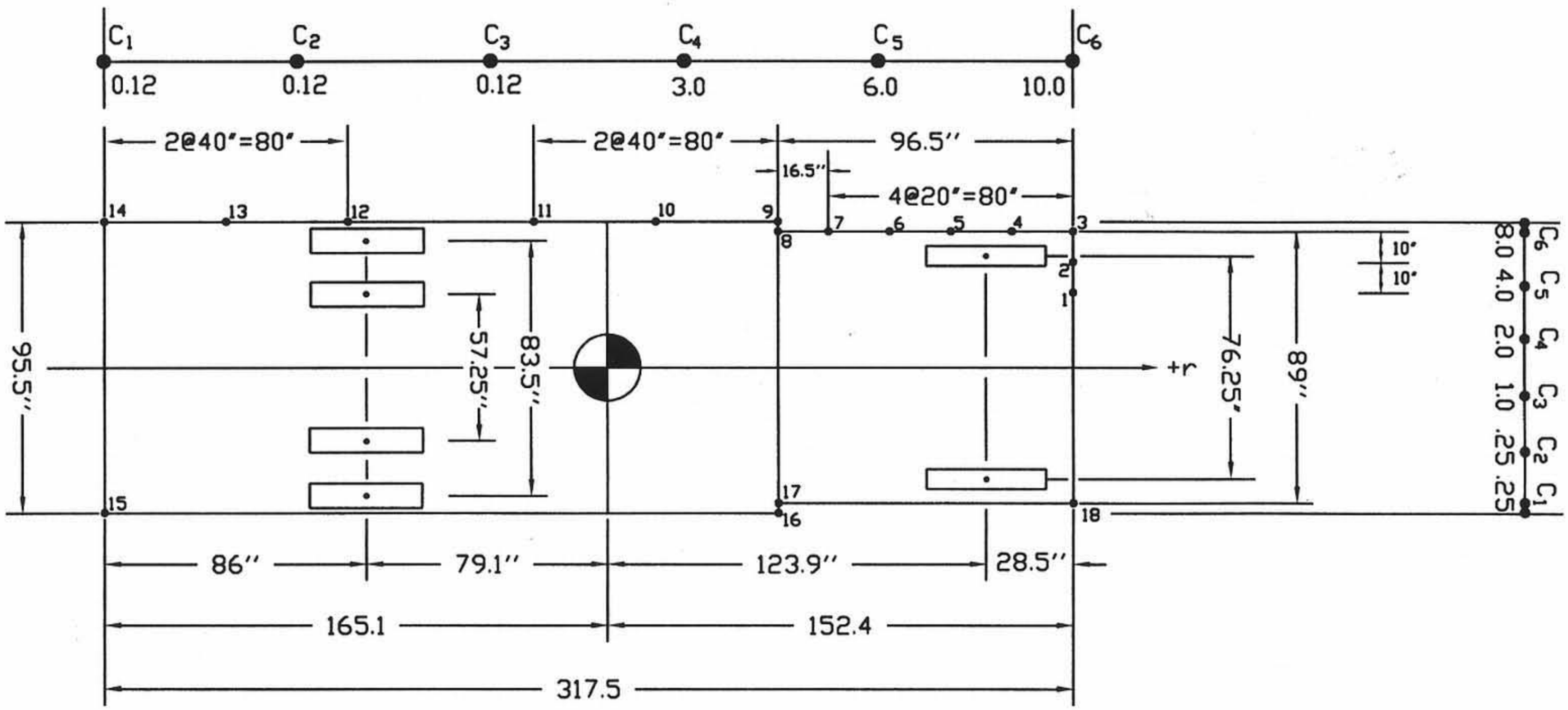

Figure A-3. Idealized Finite Element, 2 Dimensional Vehicle Model for the 8,165-kg Straight Truck

APPENDIX B

BARRIER VII Structural Quantities

Table B-1. Structural Quantities for Railing Elements of TBC-8000 Bridge Railing

Table B-2. Structural Quantities for Post Elements of TBC-8000 Bridge Railing

Table B-1. Structural Quantities for Railing Elements of TBC-8000 Bridge Railing

Member Type	Member Size	Area (in.^{2})	Moment of Inertia (in.^{4})	Modulus of Elasticity (ksi)	Weight (lbs/ft)	Nominal Yield Stress (ksi)	Nominal Yield Force (kips)	Section Modulus (in.^{3})	Nominal Yield Moment (kip-in.)	Plastic Modulus (in.^{3})	Nominal Plastic Moment (kip-in.)
W-Beam	12-Gauge	1.99	C-axis: 2.29	30,000	6.92	50	99.5	1.37	68.5	1.93	96.5
Thrie Beam	10-Gauge	4.00	C-axis: 4.82	30,000	13.95	36	200.0	2.80	140.0	3.92	196.0
Channel Rail	C8 x 11.5	3.38	C-axis: 32.6	30,000	11.5	36	121.68	8.14	293.04	9.55	343.8

Table B-2. Structural Quantities for Post Elements of TBC-8000 Bridge Railing

Member Type	Member Size	Top Node Height (in.)	Bottom Node Height (in.)	Stiffness Along (kips/in.)	Effective Weight (lbs)	Plastic Modulus (in.^{3})	Nominal Yield Stress (ksi)	Nominal Plastic Moment[1] (kip-in.)	Nominal Yield Moment (kip-in.)	Failure Shear Force (kips)	Failure Deflection (in.)
Bridge Post	W6 x 15 (Steel)	32.12	20.90	A-axis: 33.95 B-axis: 3.5	40.0	A-axis: NA B-axis: 4.75	36	A-axis: 292.25 B-axis: 256.5	NA	A-axis: 50.0 B-axis: 50.0	A-axis: 5.0 B-axis: 8.98
Guardrail Post	W6 x 15 (Steel)	32.12 20.90	20.90 0.0	A-axis: 30.56 B-axis: 94.31	102.5	A-axis: 10.8 B-axis: 4.75	36	A-axis: 571.49 B-axis: 251.19	NA	A-axis: 12.03 B-axis: 27.37	A-axis: 5.0 B-axis: 12.0
Guardrail Post	W6 x 9 (Steel)	20.90	0.0	A-axis: 4.44 B-axis: 12.17	54.0	A-axis: 6.23 B-axis: 1.72	36	A-axis: 254.35 B-axis: 92.80	NA	A-axis: 4.44 B-axis: 12.17	A-axis: 16.0 B-axis: 16.0
Guardrail Post	6" x 8" (Timber)	20.90	0.0	A-axis: 14.64 B-axis: 10.98	67.3	NA	NA	NA	A-axis: 229.26 B-axis: 305.68	A-axis: 14.64 B-axis: 10.98	A-axis: 20.0 B-axis: 20.0

NA - Not Applicable.
[1] - Includes dynamic impact factor (DF=1.5).

APPENDIX C

Typical BARRIER VII Input File

Note that the example BARRIER VII input data file included in Appendix C corresponds with the critical impact point for test FSTC-1.

```
USFS PL-2 STEEL RAIL-THRIE BEAM WITH CHANNEL (18000 LB, 50 MPH, 15 DEG, POST #4)
   90   10     8     2   116    17     2     0
    0.0010      0.0010       0.80  150     0        1.0     1
    1     5     5     5     5     5     1
    1       0.0         0.0
   15     525.0         0.0
   21     637.5         0.0
   22     637.5         0.0
   25     675.0         0.0
   26     675.0         0.0
   29     724.5         0.0
   30     724.5         0.0
   89    1849.5         0.0
   90    1849.5         0.0
    1    15    13     1         0.0
   15    21     5     1         0.0
   21    25     1     2         0.0
   22    26     1     2         0.0
   25    29     1     2         0.0
   26    30     1     2         0.0
   29    89    29     2         0.0
   30    90    29     2         0.0
    1    55       0.35
   89    87    85    83    81    79    77    75    73    71
   69    67    65    63    61    59    57    55    53    51
   49    47    45    43    41    39    37    35    33    31
   29    27    25    23    21    20    19    18    17    16
   15    14    13    12    11    10     9     8     7     6
    5     4     3     2     1
    2    35       0.35
   90    88    86    84    82    80    78    76    74    72
   70    68    66    64    62    60    58    56    54    52
   50    48    46    44    42    40    38    36    34    32
   30    28    26    24    22
  100     9
    1      4.82        4.00       37.50   30000.0       13.95       200.0        140.0 0.10
    2      3.39        2.82       37.50   30000.0        9.84       141.0         99.0 0.10
    3      2.66        2.26       37.50   30000.0        7.89       113.0         79.0 0.10
    4      2.29        1.99       37.50   30000.0        6.92       99.50        68.50 0.10
    5      32.6        3.38       37.50   30000.0        11.5      121.68        343.8 0.10
    6      4.82        4.00       24.75   30000.0       13.95       200.0        140.0 0.10
    7      4.82        4.00       18.75   30000.0       13.95       200.0        140.0 0.10
    8      32.6        3.38       24.75   30000.0        11.5      121.68        343.8 0.10
    9      32.6        3.38       18.75   30000.0        11.5      121.68        343.8 0.10
  300     7
    1     20.90       32.12       33.95      3.50       40.00       256.5       292.25 0.10
    50.00       50.00       5.0        8.98
    2     20.90       32.12       30.56     94.31      102.50      251.19       571.49 0.10
    12.03       27.37       5.0        12.0
    3     20.90         0.0       30.56     94.31      102.50      251.19       571.49 0.10
    12.03       27.37       5.0        12.0
    4     20.90         0.0       14.64     10.98       67.30      305.68       229.26 0.10
    18.30       13.72      20.0        20.0
    5     20.90         0.0      1927.9    5902.4       216.0      2500.0       3888.0 0.10
    125.0       186.2       1.0        1.0
    6     20.90       32.12      1000.0    2500.0       216.0      2500.0       3888.0 0.10
    125.0       146.7       1.0        1.0
    7     20.90         0.0        4.44     12.17        54.0        92.8       254.35 0.10
```

```
   4.44       12.17        16.0        16.0
  1    1    2   12    1  104          0.0        0.0        0.0
 13   13   14    0    0  103          0.0        0.0        0.0
 14   14   15    0    0  102          0.0        0.0        0.0
 15   15   16   20    1  107          0.0        0.0        0.0
 21   21   23   22    2  107          0.0        0.0        0.0
 23   25   27   24    2  106          0.0        0.0        0.0
 25   29   31   54    2  101          0.0        0.0        0.0
 55   22   24   56    2  109          0.0        0.0        0.0
 57   26   28   58    2  108          0.0        0.0        0.0
 59   30   32   88    2  105          0.0        0.0        0.0
 89    1    0    0    0  305          0.0        0.0        0.0
 90    3    0   93    2  304         0.0        0.0        0.0        0.0        0.0
 94   11    0   95    2  307         0.0        0.0        0.0        0.0        0.0
 96   15    0   98    2  303         0.0        0.0        0.0        0.0        0.0
 99   21   22  100    4  302         0.0        0.0        0.0        0.0        0.0
101   29   30  115    4  301         0.0        0.0        0.0        0.0        0.0
116   89   90    0    0  306         0.0        0.0        0.0        0.0        0.0
 18050.0  561483.4    20    7     6     0     1
  1      0.082        0.21        1.5       18.0
  2      0.063        0.19        2.0       12.0
  3      0.045        0.17        3.0        4.0
  4      0.800        0.95        2.5        2.5
  5      0.900        1.05        3.5        2.0
  6       0.35        0.25       10.0        3.0
  7        2.5         3.5        4.5        3.0
  1      152.4        24.5    1      10.0    1    1    0    0
  2      152.4        34.5    1      10.0    1    1    0    0
  3      152.4        44.5    1      15.0    1    1    0    0
  4      132.4        44.5    1      20.0    1    1    0    0
  5      112.4        44.5    2      20.0    1    1    0    0
  6       92.4        44.5    2      20.0    1    1    0    0
  7       72.4        44.5    2     18.25    1    1    0    0
  8       55.9        44.5    2      11.5    1    1    0    0
  9       55.9       47.75    3     23.25    0    0    0    0
 10       15.9       47.75    4      40.0    0    0    0    0
 11      -24.1       47.75    5      40.0    0    0    0    0
 12      -85.1       47.75    5      40.0    0    0    0    0
 13     -125.1       47.75    5      40.0    0    0    0    0
 14     -165.1       47.75    5      20.0    0    0    0    0
 15     -165.1      -47.75    5       1.0    0    0    0    0
 16       55.9      -47.75    3       1.0    0    0    0    0
 17       55.9       -44.5    2       1.0    0    0    0    0
 18      152.4       -44.5    1       1.0    0    0    0    0
 19      -79.1       45.75    7       1.0    1    1    0    0
 20      123.9       42.12    6       1.0    1    1    0    0
  1      123.9       38.12        0.0      2214.
  2      123.9      -38.12        0.0      2214.
  3      -79.1       41.75        0.0      1157.
  4      -79.1      -41.75        0.0      1157.
  5      -79.1       28.62        0.0      1157.
  6      -79.1      -28.62        0.0      1157.
  1        0.0         0.0
  3      949.5         0.0       15.0       50.0        0.0        0.0       10.0
```

APPENDIX D

Permanent Set Deflections - Test FSTC-1

Figure D-1. Graph of Permanent Set Deflections, Test FSTC-1

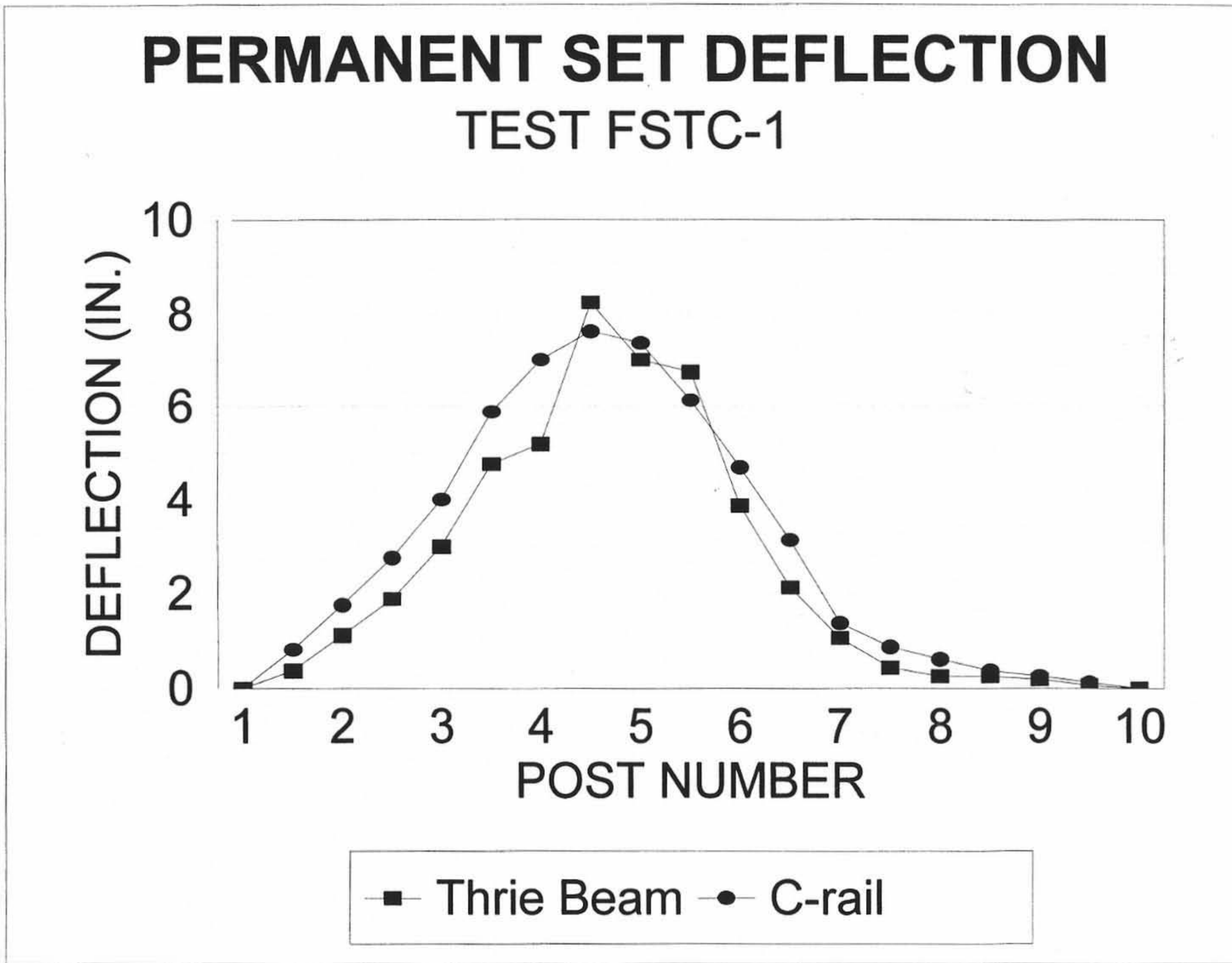

Figure D-1. Graph of Permanent Set Deflections, Test FSTC-1