DEVELOPMENT OF A TEMPORARY BARRIER SYSTEM FOR OFF-ROAD APPLICATIONS

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The safety shape portable concrete barrier (PCB) has been approved for use when placed on a bituminous or concrete pad. Construction personnel would like to use PCBs in temporary situations along roadways where the use of a bituminous or concrete pad is impractical and costly. However, when PCBs are placed on soil foundations with no anchorage, they tend to dig into the soil, causing the barrier sections to rotate or overturn.

The objective of this research was to develop a device which will allow temporary PCBs placed on soil foundations to translate without significant rotation when impacted by errant vehicles. This device was developed and successfully tested to Test Level 3 of the National Cooperative Highway Research Program (NCHRP) Report No. 350.

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1 INTRODUCTION

1.1 Problem Statement

The safety shape portable concrete barrier (PCB) has been approved for use when placed on a bituminous or concrete pad. Construction personnel would like to use PCBs in temporary situations along roadways where the use of a bituminous or concrete pad is impractical and costly. However, when PCBs are placed on soil foundations with no anchorage, they tend to dig into the soil, causing the barrier sections to rotate or overturn.

1.2 Background

Portable concrete barriers (PCBs) located along the roadside are typically placed on concrete or bituminous surface pads. However, this practice is often impractical and costly. Therefore, the member states of the Midwest States Regional Pooled Fund Program hypothesized that it would be economical to develop a system which would allow PCBs to be placed on soil foundations or on native fill where side-slopes typically are 10:1 or flatter.

One suggestion from the states was to use soil screws placed vertically through the lower base on both sides of the PCB. This concept was intended to prevent the temporary PCBs from rotating when impacted by an errant vehicle. However, a significant number of screws would be required on each side of the PCB in order to prevent barrier rotation, making this option impractical and costly. In addition, it is anticipated that the soil screws would translate and rotate in the soil, allowing the PCBs to dig into the soil foundation and rotate or overturn. Past research has shown that even permanent precast concrete barriers doweled into concrete often rotate excessively (1). Variability in soils, ranging from compacted clay fills to sandy loams and saturated soils, would further complicate the soil screw concept.

An alternative to fixing the barrier to the ground is to allow the barriers to slide laterally along the surface of the soil without rotating. The problem with this concept lies in the fact that the PCBs will not translate adequately unless barrier-soil friction is reduced and/or barrier-soil gouging is prevented. Methods that were considered to prevent this undesirable behavior included placing the temporary PCBs on sheets of plywood or developing a skid device which attaches to the PCB base and allows the barrier to slide rather than rotate. The second alternative appeared to be more practical based upon life cycle cost factors, ease of installation, and aesthetics.

1.3 Objective

The objective of this research was to develop a device that will allow temporary PCBs placed on soil foundations to translate without significant rotation when impacted by errant vehicles. The safety performance of the device will be evaluated according to Test Level 3 of the National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* (2).

1.4 Scope

The Midwest Roadside Safety Facility (MwRSF) developed a device which can be attached to standard PCBs to allow them to slide on a soil foundation. During this process static component tests and one compliance test was performed on the system. The full-scale vehicle crash test was performed using a Chevrolet pickup truck, weighing approximately 2,000 kg (4,409 lbs). The target impact speed and angle were 100 km/h (62.1 mph) and 25 degrees, respectively. The design components were instrumented with strain gages to determine the loads which they were subjected to during impact.

2 PERFORMANCE EVALUATION CRITERIA

In order to be considered acceptable under Test Level 3 (TL-3) of NCHRP Report No. 350, longitudinal barriers must be subjected to two full-scale vehicle crash tests: (1) a 2,000-kg pickup truck impacting at a speed of 100 km/hr and at an angle of 25 degrees; and (2) an 820-kg small car impacting at a speed of 100 km/hr and at an angle of 20 degrees. However, the 820-kg small car crash test was considered unnecessary for several reasons. First, rigid New Jersey safety shape barriers have been shown to meet safety standards when impacted by small cars (3,4). Second, small car crash tests conducted on temporary New Jersey safety shape PCBs have also resulted in little barrier movement (5). Third, computer simulation modeling of safety shape barriers has suggested that the F-shape PCB offers a slight improvement in safety performance over the New Jersey safety shape (6). Finally, a small car test was successfully conducted on a rigid, F-shape bridge rail, which was reasoned to be a valid indicator of the safety performance of the PCB (7).

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 barrier to contain and redirect an impacting vehicle. The occupant risk criteria 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 all vehicles to undue hazard. These three evaluation criteria are defined in Table 1. The full-scale vehicle crash tests were conducted and reported in accordance with the procedures provided in NCHRP Report No. 350 (2).

Table 1. NCHRP Report 350 Evaluation Criteria for 2000P Pickup Truck Crash Test.

Category		Criteria
Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.
Occupant Risk	D.	Detached elements. fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.
	F.	The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.
	L.	The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 G's.
	M.	The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.

3 SKI DESIGN

Various design concepts were investigated with the conclusion that the most promising alternative was an apparatus that would allow the barriers to slide laterally, as opposed to one that holds the barrier in its original place. The initial concept involved placing flat sheets at one or more location under each rail segment. Spacer blocks between the sheets and the barrier would allow the barrier to be installed in a vertical position on modest slopes. Unfortunately, this concept relies on the moment capacity of the sheeting to prevent the barrier from rotating or tipping during a severe impact. The required moment capacity to prevent this behavior was found to be unreasonably high and therefore the sheeting concept was rejected.

In an effort to increase the moment capacity, a truss system was developed that would attach the barrier to a smaller piece of sheeting placed behind the barrier. In this design the ski plate was located approximately four feet from the barrier, as shown in Appendix A. The basic design called for two ski systems on each barrier segment. Based on preliminary estimates of the impact forces measured during impacts with safety shaped barriers (3) the maximum overturning moment during a crash test of a temporary barrier was estimated to be 4.5 kN-m (3.3 kip-ft). Each ski system was then designed to resist half of this moment. The truss system incorporated in the ski system utilizes a single compression member that carries the lateral load on top of the barrier down to the ground. Soil forces provide vertical support for the ski and two tensile members carry the lateral loads back to the base of the barrier segment, as shown in Figure 1. A 2 ft square piece of 3/4 in. plywood is placed under the ski to prevent it from gouging into the soil. This is attached by placing a 1/4 in wood screw through the ski and into the plywood. The wood screw is designed to restrain the plywood prior to impact and then shear off during an accident. The plywood also elevates the ski so that soil erosion is not as likely to cause the ski to become embedded in the soil. The compression tube is designed to be adjustable so that the ski can be used on level ground or on a slope.

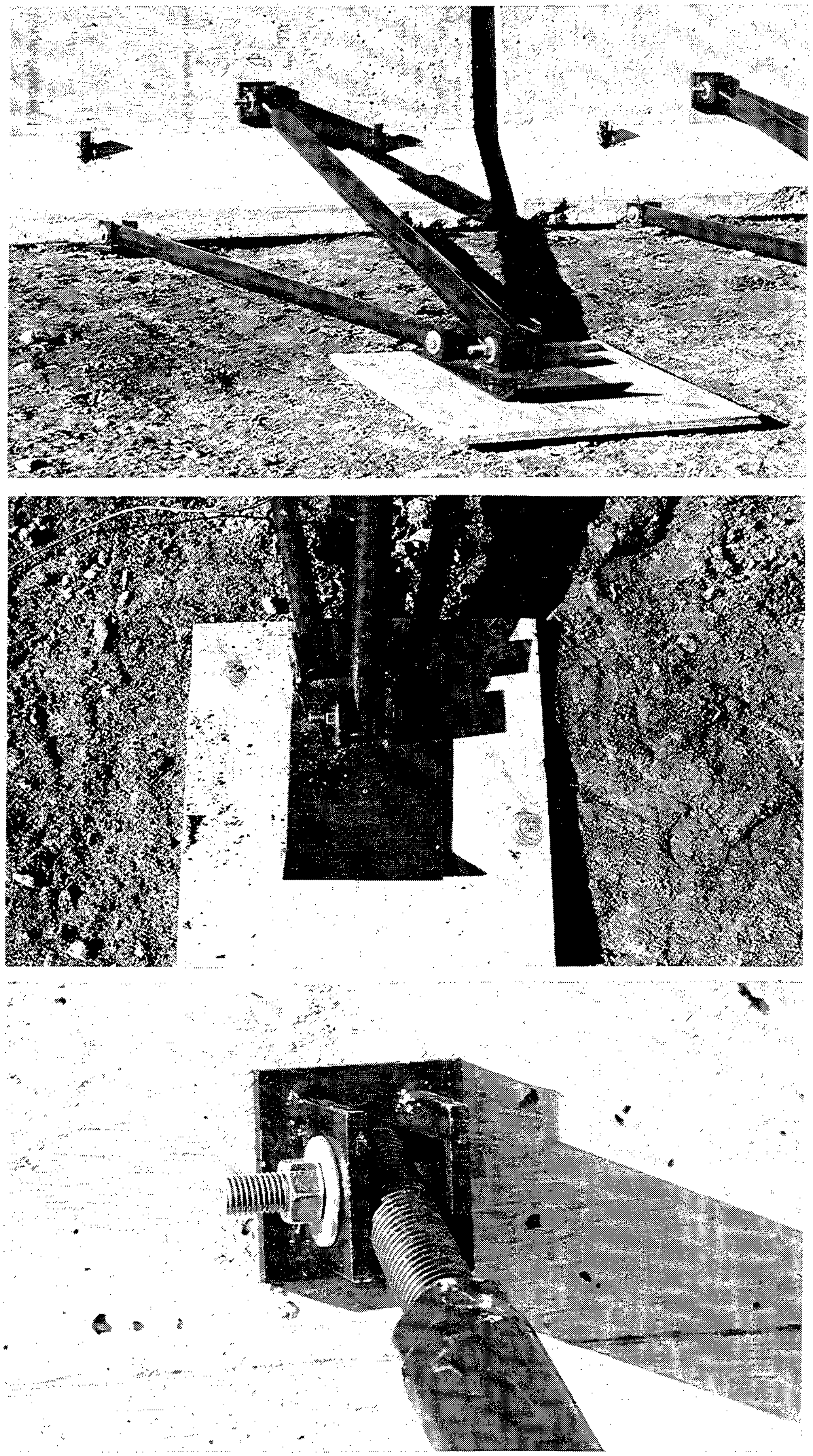


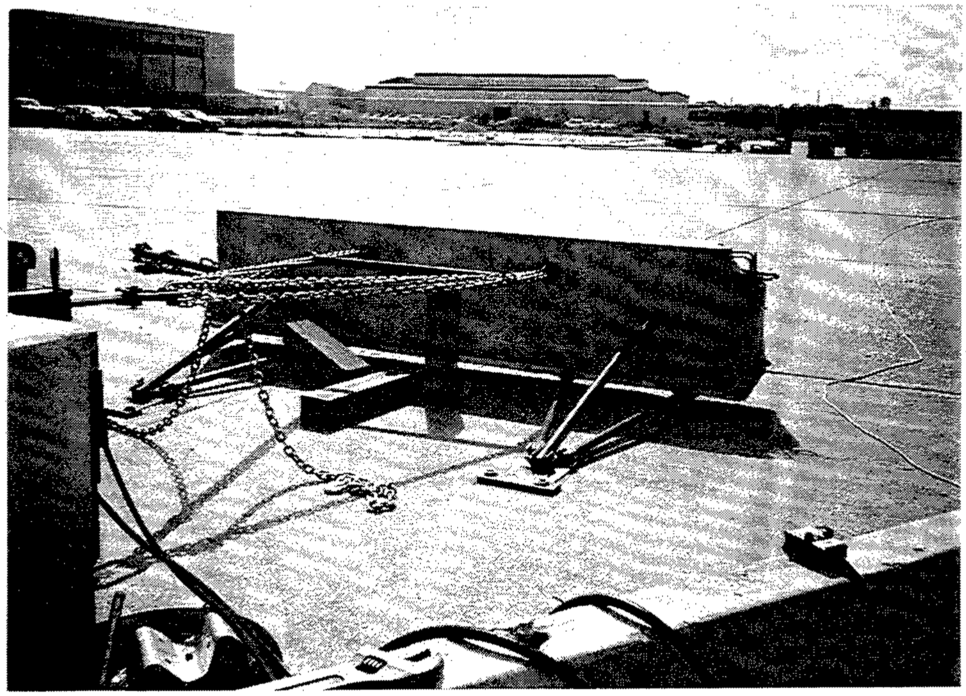
Figure 1. Ski Design

4 STATIC TESTING

Two static tests were conducted to test the performance of the ski components when subjected to a high load. The tests were designed to evaluate the interaction between the barrier and the ski. The value of the test load was determined by the maximum capacity of the loading ram and pump, which was 15,000 lbs. This load correlates with a 19 kN-m (14.1 kip-ft) overturning moment compared to the design value of 39.7 kN-m (29.3 kip-ft). For static testing the ski plate was bolted to the concrete and additional anchor plates were set to keep the ski plate from moving, as shown in Figure 2. Two holes were drilled in the test barrier 1267 mm from each end in order to attach the ram to the barrier. This test set-up, along with all required attachment hardware are shown in Figure 3.

The first test was assembled with the barrier located perpendicular to the loading ram and a load of 15,000 lbs was applied to the barrier, 7,500 lbs through each chain. The only yielding that took place occurred in the ski plates, as shown in Figure 2. This yielding was anticipated since the plates, which are only 1/4 in. thick, were fixed to the concrete apron for this test.

The second test was assembled with the barrier located 30 degrees off perpendicular to the loading ram, as shown in Figure 3, and a load of 15,000 lbs was again applied to the barrier. The ski plates yielded similiar to the first static test. The barrier began to spall where the lower structural members of the ski are connected to the barrier. Concrete breakout at this location was not a great concern since longitudinal steel reinforcement is located between the steel attachment of the ski and the edge of the barrier. This testing showed that the ski apparatus upheld the high load and that barrier-ski damage was minimal.



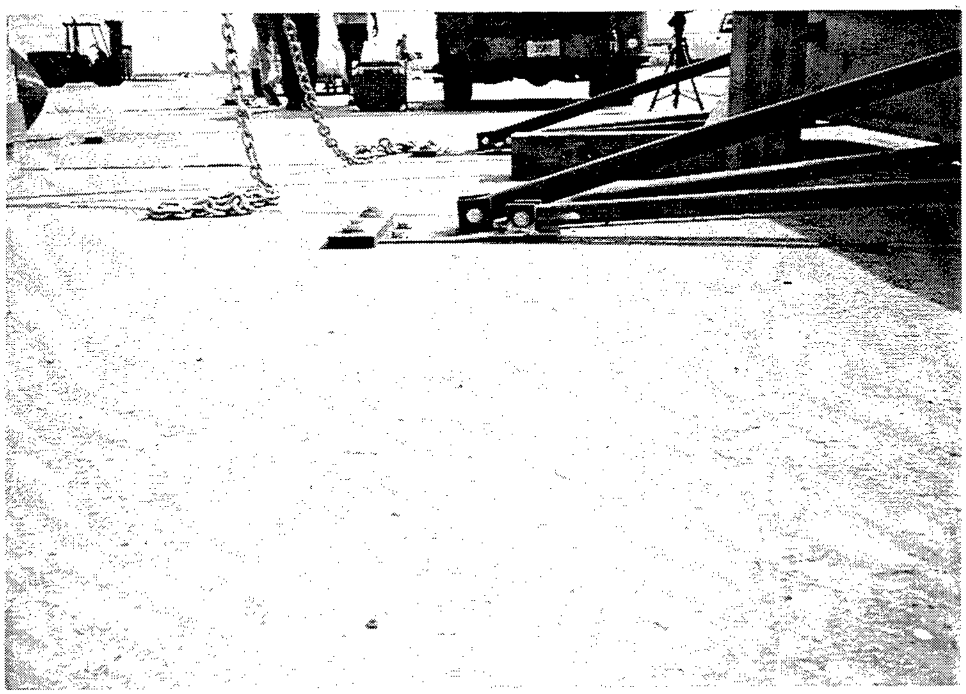


Figure 2. Perpendicular Load Static Test

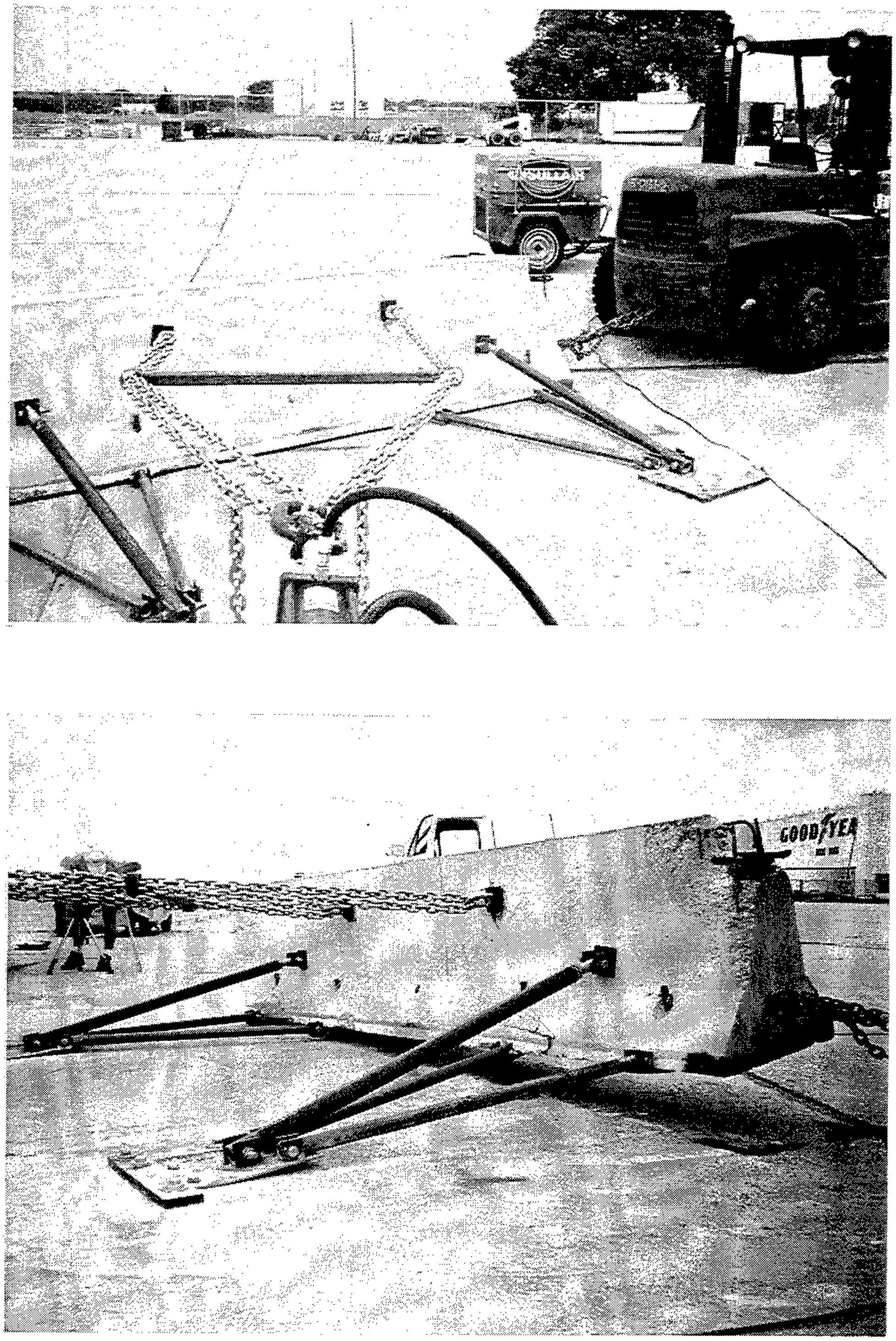


Figure 3. Angled Load Static Test

5 TEST CONDITIONS

5.1 Test Facility

The Midwest Roadside Safety Facility's (MwRSF's) outdoor testing site is located at the Lincoln Air-Park on the northwest corner of the Lincoln Municipal Airport. The test facility is approximately 5-mi (8-km) northwest of the University of Nebraska-Lincoln. The site is surrounded and protected by an 8-ft (2.44-m) high chain-link security fence.

5.2 Vehicle Tow 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 are one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the barrier system. A fifth wheel, built by the 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.

5.3 Vehicle Guidance System

A vehicle guidance system developed by Hinch (8) 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 (3/8-in) diameter guide cable was tensioned to approximately 13.3-kN (3,000-lbs), and supported laterally and vertically every 30.5-m (100-ft) 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 460-m long.

5.4 Test Vehicle

The test vehicle used for test KTS-1 was a 1990 Chevy 2500 Series 3/4-ton pickup truck. The test inertial and gross static weights were 1998-kg (4404-lbs). The test vehicle is shown in Figure 4, and its dimensions are shown in Figure 5.

Black and white checkered targets were placed on the test vehicle for use in the high-speed film analysis, as shown in Figure 6. Two targets were located on the center of gravity, one on the top and one on the driver's side of the test vehicle. Additional targets, visible from external high-speed cameras, were placed on the vehicle for reference during 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 the hood of the vehicles to pinpoint the time of impact with the 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 remotely controlled brake system was installed in the test vehicle so that it could be brought safely to a stop after the test.

5.5 Data Acquisition Systems

5.5.1 High Speed Photography

Five 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 a field of view perpendicular to the ground. A Red Lake Locam with a 76-mm lens was placed downstream of the impact point and had a field of view parallel to the barrier. A Red Lake Locam with a 12.5 to 75-mm zoom lens was placed on the traffic side of the barrier and had a field of view perpendicular to the barrier. A Red Lake Locam with a 12.5-mm lens was placed upstream and behind the barrier. A Red Lake Locam with a 12.5 to 75-mm zoom lens was placed on the back side of the bridge rail and had a field of view perpendicular to the barrier.

5.5.2 Accelerometers

Two triaxial piezoresistive accelerometer systems with a range of ±200 G's was used to measure the acceleration in the longitudinal, lateral, and vertical directions. The environmental shock and vibration sensor/recorder system, Models EDR-3 and EDR-4, were developed by Instrumented Sensor Technology (IST) of Okemos, Michigan. The EDR-3 was configured with 256 Kb of RAM memory and a 1,120 Hz filter and was set to sample data at 3200 samples/sec. The EDR-4 is the next generation of the EDR-3, and was set to sample data at 10,000 samples/sec. Computer software, "DynaMax 1 (DM-1)" and "DADiSP" were used to digitize, analyze, and plot the accelerometer data.

5.5.3 Pressure Tape Switches

Five pressure tape switches spaced at 2-m intervals were used to determine the speed of the vehicle before impact. Each tape switch fired a strobe light and sent an electronic timing mark to the data acquisition system as the front tire of the test vehicle passed over it. Test vehicle speeds were determined from recorded electronic timing mark data. Strobe lights and high-speed film analysis are used only as a backup in the event that vehicle speeds cannot be determined from the electronic data.

5.5.4 Strain Gages

Ten weldable LWK-06-W250B-350 strain gages were installed on the skis upstream and downstream from impact to determine the loads in the members. Four were installed on the tension members and six were installed on the compression members, as shown in Figure 7.

The nominal resistance of the gages was 350.0±1.4 ohms with a gauge factor equal to 2.02. The operating temperature limits of the gages was -195 to +260 degrees Celsius. The strain limits of the gages were 0.5% in tension or compression (5000 $\mu\epsilon$). The strain gages were manufactured by the Micro-Measurements Division of Measurements Group, Inc. of Raleigh, North Carolina.

The installation procedure required that the metal surface be clean and free from debris and oxidation. Once the surface had been prepared, the gauges were spot welded to the test surface.

A Measurements Group Vishay Model 2310 signal conditioning amplifier was used to condition and amplify the low-level signals to high-level outputs for multichannel, simultaneous dynamic recording on "EGAA" software. After the signal was amplified it was sent to a ComputerScope ISC-16 data acquisition board before being sent to the computer software. The sample rate for all gages was 200 samples per second, and the duration of sampling was 10 seconds.

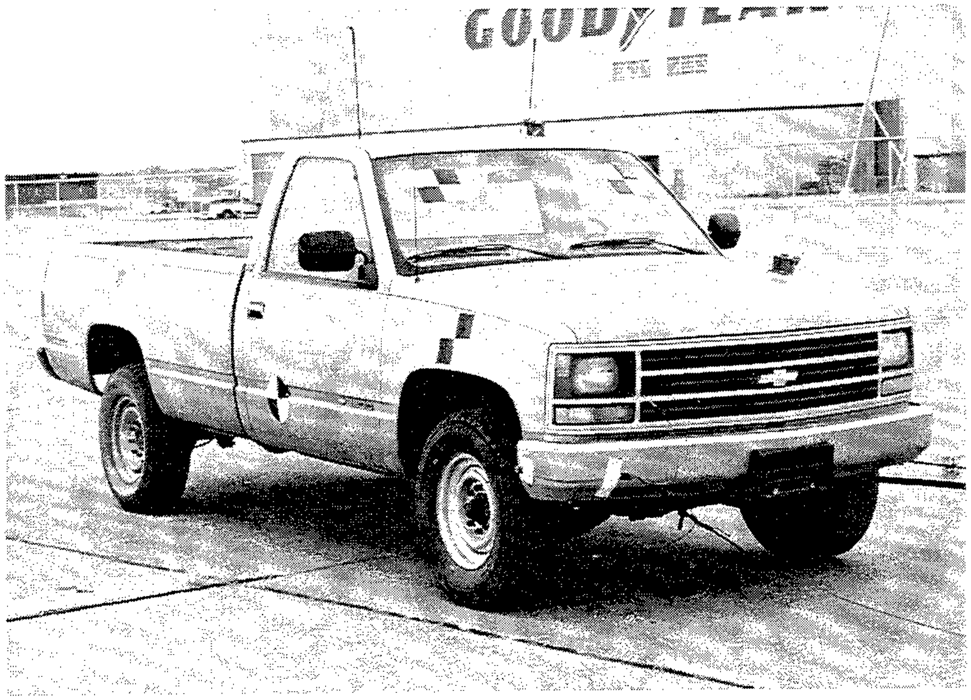


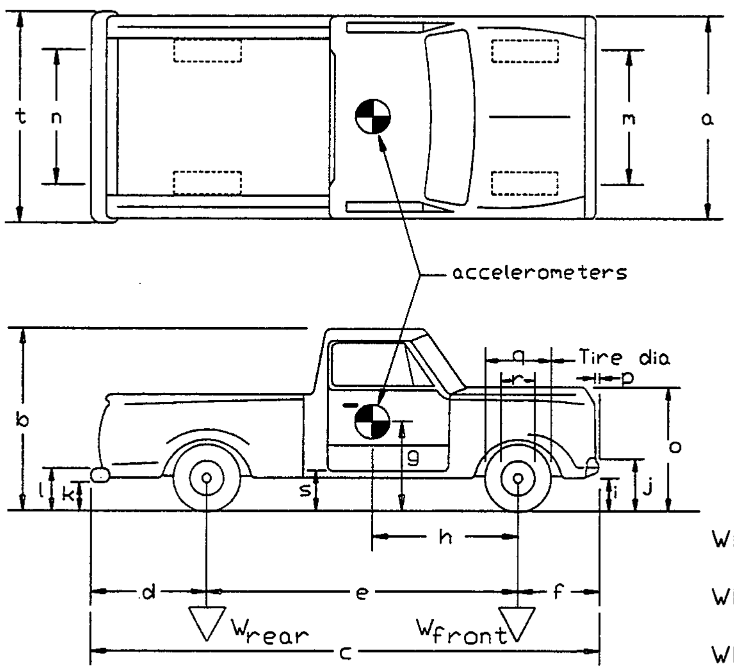
Figure 4. Test Vehicle, Test KTS-1

Date: 12/12/96 Test Number: KTS-1 Model: 2500/BLUE

Make: Chevrolet Vehicle I.D.#: 1GCGC24K8LE134999

Tire Size: 245/75 R16 Year: 1990 Odometer: 203877

*(All Measurements Refer to Impacting Side)



Vehicle Geometry - in.

a	74	b	73.5
c	217.5	d	51.5
e	131.5	f	34.5
g	27.5	h	57.5
i	18.25	j	26.625
k	23.0	l	30.75
m	63.125	n	63.75
o	42.25	p	3.5
q	29.25	r	17.5
s	18.625	t	73.5

Wheel Center Height Front 14.5

Wheel Center Height Rear 14.75

Wheel Well Clearance (FR) 35.5

Wheel Well Clearance (RR) 37.75

Engine Type 8 cyl.

Engine Size 350 (5.7L)

Transmission Type:

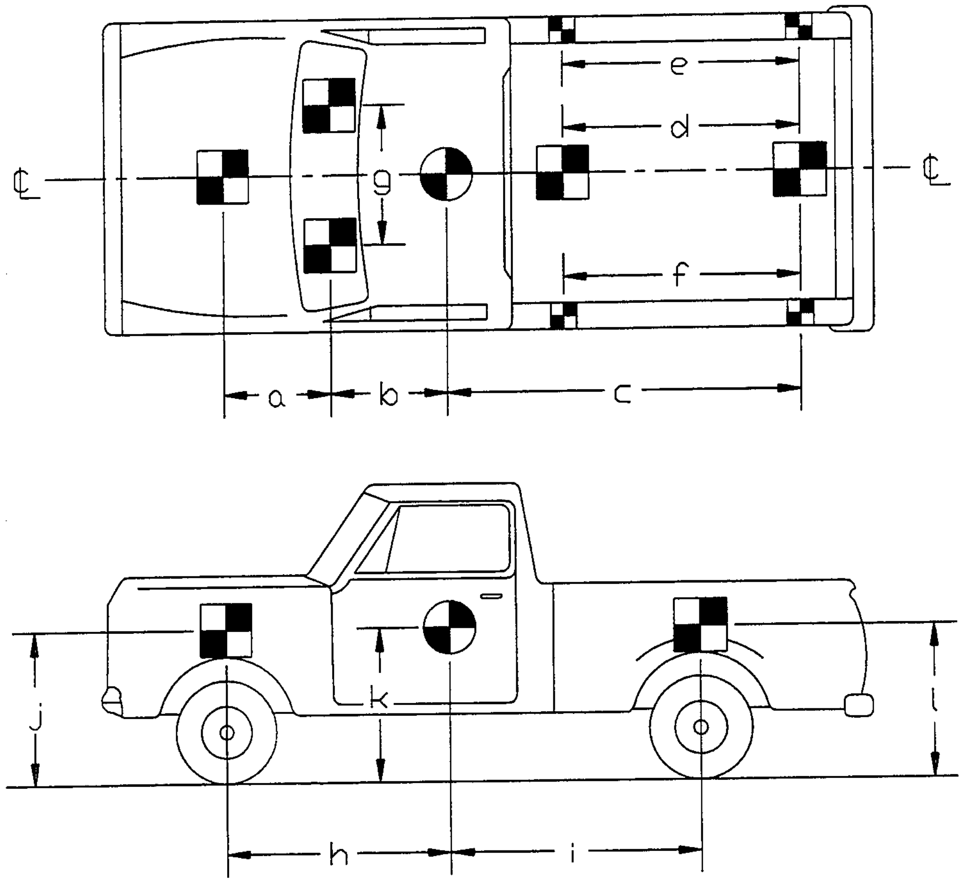
Automatic or Manual

FWD or RWD or 4WD

Weights - lbs	Curb	Test Inertial	Gross Static
W_{front}	2508	2463	2463
W_{rear}	2097	1956	1656
W_{total}	4605	4404	4404

Note any damage prior to test: Diagonal crack in windshield, Non impact side-fender crease where door meets

Figure 5. Vehicle Dimensions, Test KTS-1



TEST #: KTS-1

TARGET GEOMETRY (in)

a 30.25	b 26.75	c 108	d 77.75
e 72.75	f 72.75	g 38.5	h 57.5
i 75.5	j 40.50	k 27.375	l 44.75

Figure 6. Vehicle Target Locations, Test KTS-1

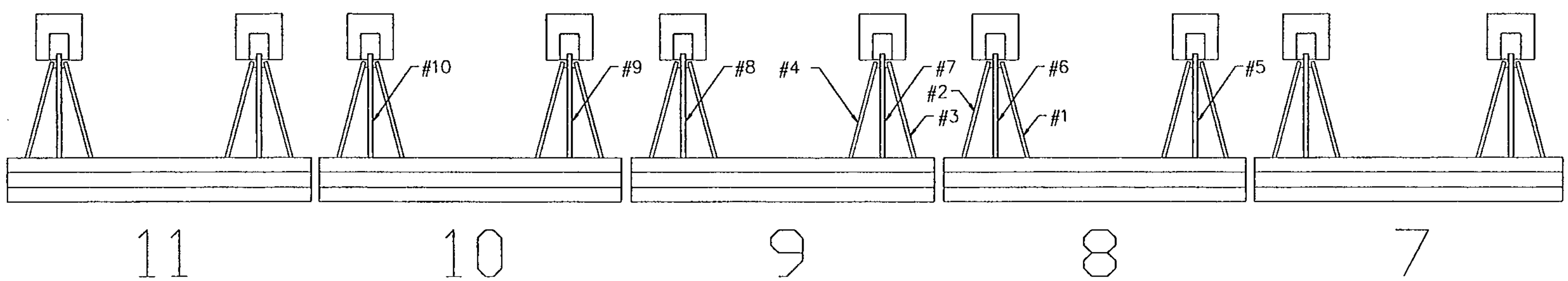


Figure 7. Strain Gage Locations, Test KTS-1

6 CRASH TEST RESULTS

6.1 Test KTS-1

A 62.0-m long barrier system was constructed on soil at the MwRSF outdoor test site, as shown in Figure 8. The barrier system consisted of 17 PCBs, each measuring 3,800 mm. The ski configuration discussed earlier was connected to the impact barrier, as well as three additional barriers upstream from impact, and six barriers downstream from impact. Design details for the joint connections and steel reinforcement are shown in Appendix B. It is noted that five additional barrier sections were connected to the upstream end of the installation to better represent an actual field installation.

The 1,998-kg pickup truck impacted the concrete barrier 1.20 m upstream from the centerline of the gap between barrier nos. 8 and 9 at a speed of 99.6 km/h and at an angle of 26.9 degrees, as shown in Figure 9. A summary of the test results and the sequential photographs are shown in Figure 10. Additional sequential photographs are shown in Figure 11. Documentary photographs of the crash test are shown in Figures 12 and 13.

6.2 Test Description

After impact, the right-front tire of the vehicle became airborne as it began to climb the face of the barrier, and the right-front corner of the vehicle was crushed inward. The right-front tire deflated as it contacted the gap between barrier nos. 8 and 9, and the right-front corner continued to crush inward and extend over the top of the barrier. As the right-front tire continued to climb the face of the barrier, the left-front tire lost contact with the ground just before the vehicle contacted the gap between barrier nos. 9 and 10. The right-front tire continued to climb until it was on top of the rail and then the right-rear tire came into contact with barrier no. 9. The left-rear tire lost contact with the ground as the vehicle impacted the gap between barrier nos. 10 and 11, so the entire vehicle was airborne, with the exception of the right-front tire which was still in contact with the top of the rail. The right-front tire then came off the top of the rail followed by the left-front tire returning to the ground. The other three tires returned to the ground, the right-front, then the right-rear, and finally the left-rear. All four tires subsequently left the ground again as the vehicle recontacted the wall. The vehicle then came back down on all four tires and slid sideways until coming to a stop downstream of impact as shown in Figure 10.

6.3 Vehicle Damage

Vehicle damage was acceptable, as shown in Figure 14. The right-front quarter panel was crushed in and the right door was deformed outward at the top. The right-front rim was bent in two different places and the tire was torn. There was no major undercarriage damage or disengagements and there was also no box contact. There was only a slight amount of occupant compartment damage with a small crease in the back portion of the passenger side. The deformations were judged to be insufficient to cause serious injury to the vehicle occupants.

6.4 Barrier and Ski Damage

Barrier damage was minor, as shown in Figures 15 through 17. Concrete damage was mostly cosmetic, consisting of tire marks, scrapes, gouges, and minor spalling. Eleven steel pins were also deformed, with the damage ranging from slight to extensive. The maximum permanent set deflection of the barrier was 1.16 m. No damage was done to the skis with the exception of slight ski plate damage, as shown in Figure 18.

6.5 Occupant Risk Values

The normalized occupant impact velocities in the longitudinal and lateral directions were determined to be 7.0 m/sec and 4.8 m/sec, respectively. The maximum 10 ms average occupant ridedown decelerations in the longitudinal and lateral directions were 3.5 g's and 10.7 g's, respectively. It is noted that the occupant impact velocities and occupant ridedown decelerations were within the suggested limits provided in NCHRP Report No. 350 (2). The results of the occupant risk, determined from accelerometer data, are summarized in Figure 10. Results are shown graphically in Appendix C.

6.6 Discussion

The analysis of the test results for test KTS-1 showed that the barrier contained and redirected the vehicle with controlled lateral displacement of the barrier. The vehicle remained upright both during and after the collision and with significant vehicle yaw and pitch movements occurring during the impact. The maximum roll angle during this test was 18.1 degrees, which compares well with tests of other temporary barrier systems (1). Strain gage measurements showed a maximum load of 66,060 N, (14,850 lbs), in one of the compression members and a maximum load of 27,360 N, (6,150 lbs) in one of the tension members. These values correlate to an overturning moment of 32.6 kN-m (24.1 kip-ft) which is very close to the design loads. All strain gage data is summarized in Table 2.

Based on the results of this test, it was determined that this system was acceptable according to the criteria presented in NCHRP Report 350 (2).

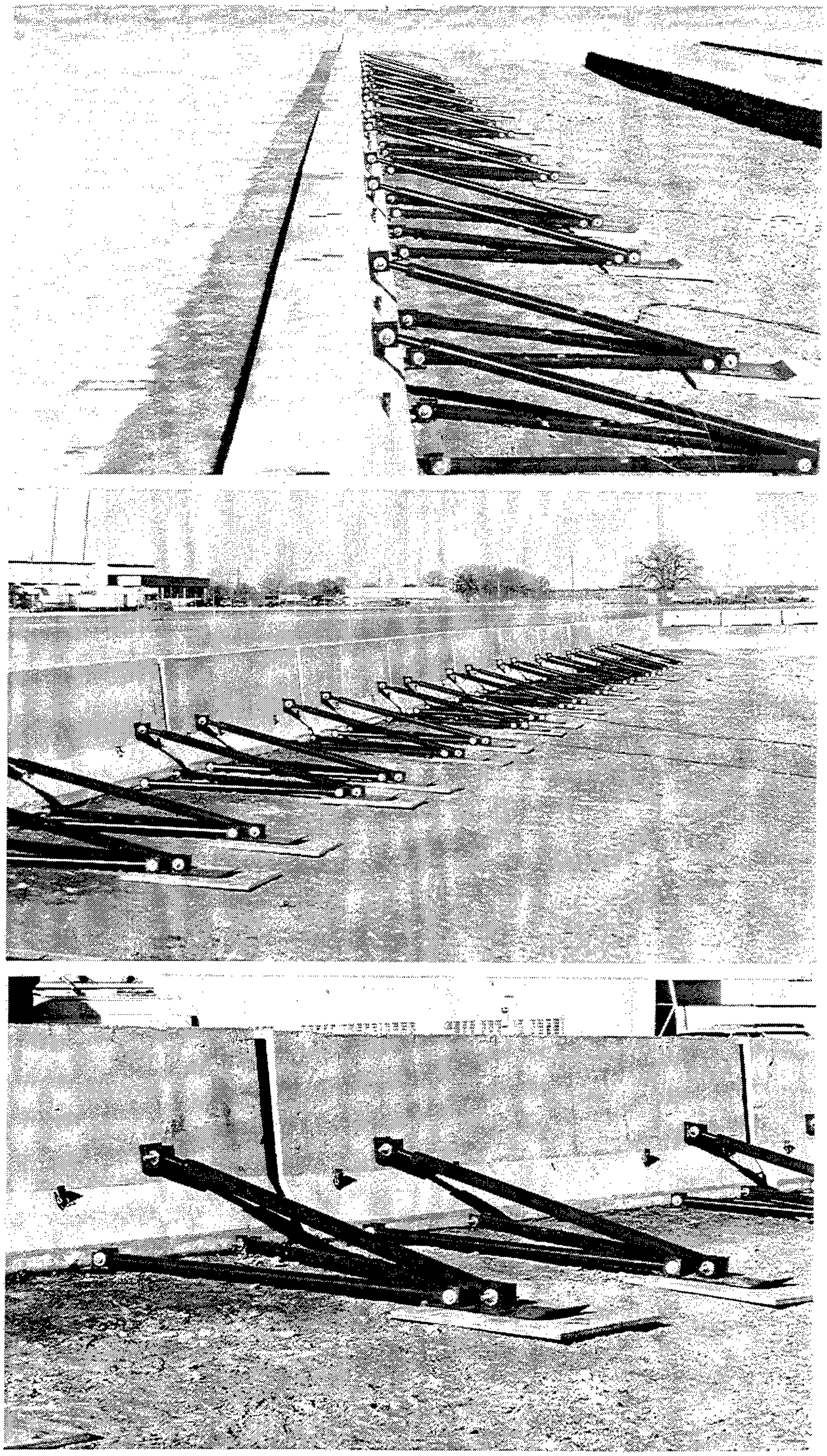


Figure 8. Portable Concrete Barrier System with Ski Design, Test KTS-1

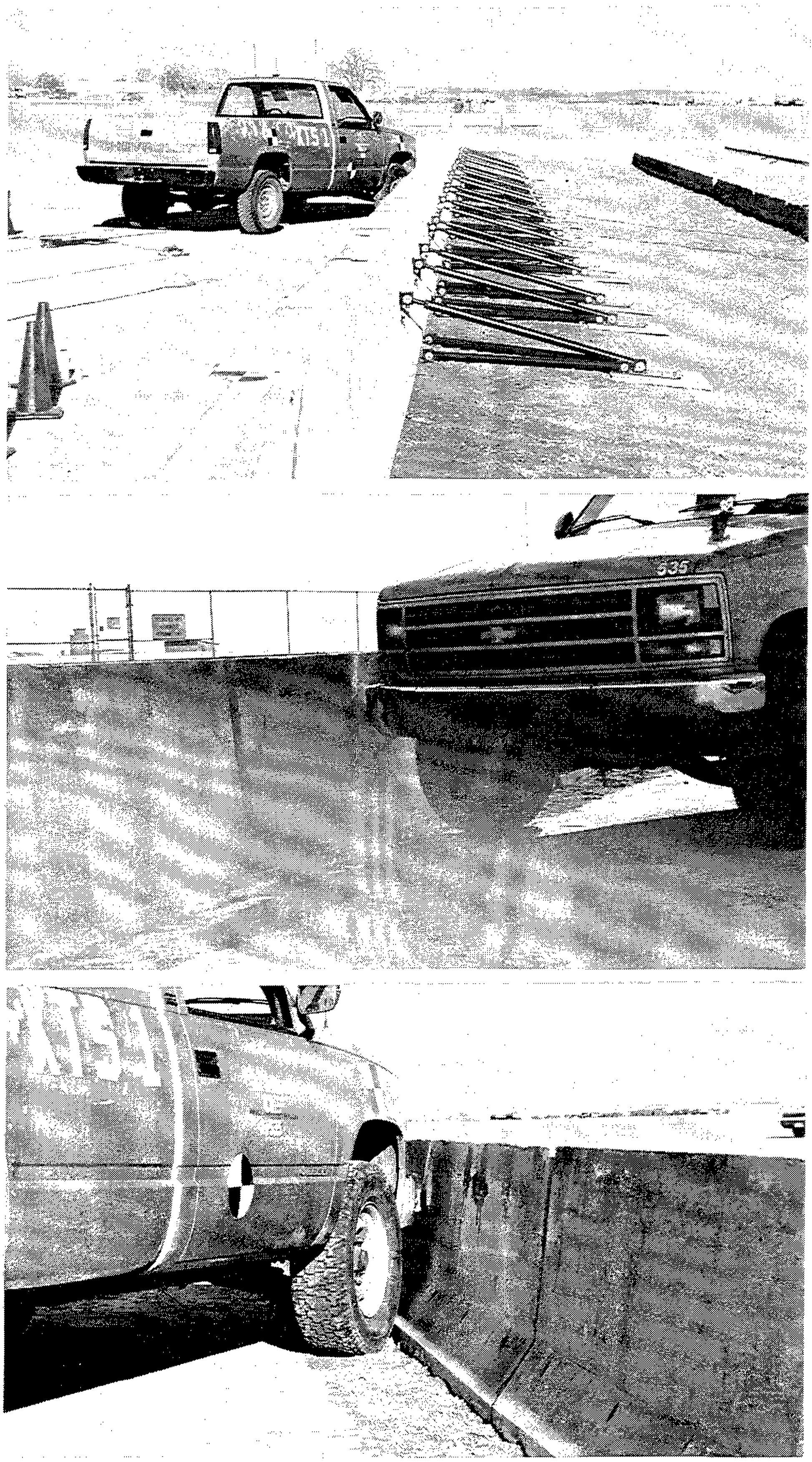
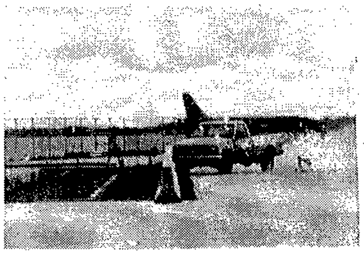
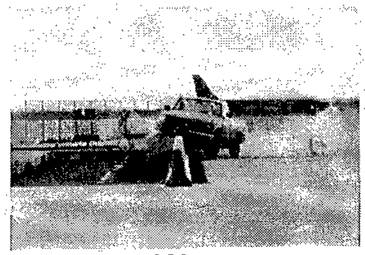


Figure 9. Impact Location, Test KTS-1



Impact



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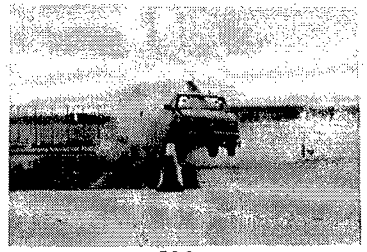
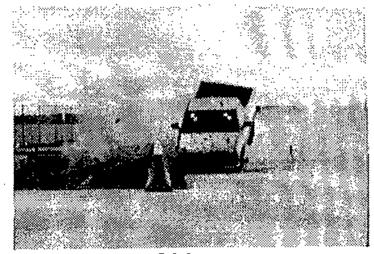
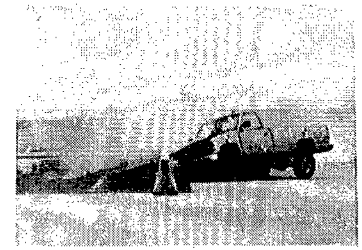


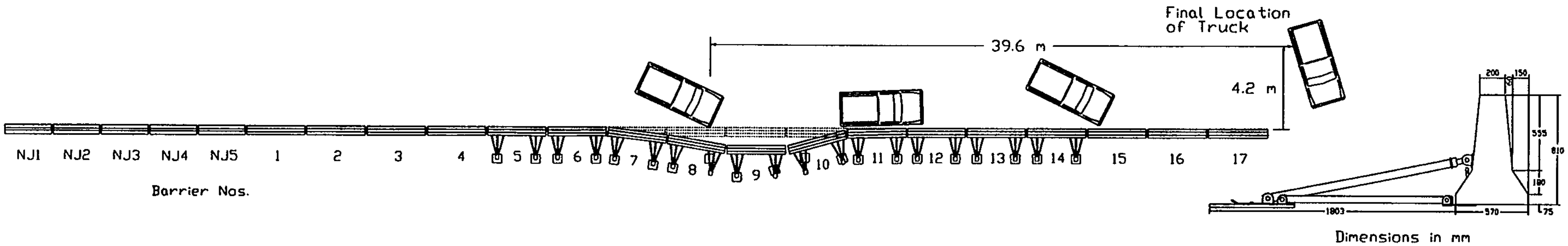
522 ms



890 ms



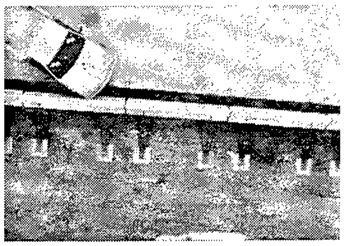
1286 ms



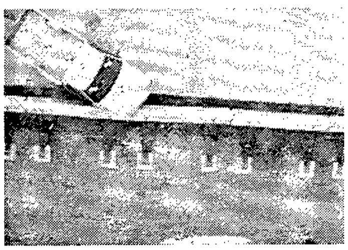
Test Number	KTS-1
Date	12/12/96
Appurtenance	F-Shape Concrete Median Barrier
Total Length	81.52 m
Barrier	
Length	3800 mm
Height	810 mm
Base Width	570 mm
Top Width	200 mm
Connection	
Type	Constrained Pin and Rebar
Pin Diameter	31.8 mm
Rebar Diameter	20 mm
Constraint Type	13 mm bolt and nut
Vehicle Model	1990 Chevrolet 2500
Curb Weight	2,089 kg
Test Inertial Weight	1,998 kg
Gross Static Weight	1,998 kg
Vehicle Speed	
Impact	99.6 km/hr

Vehicle Angle	
Impact	26.9 deg
Exit	8.8 deg
Vehicle Snagging	None
Vehicle Stability	Satisfactory
Occupant Ridedown Deceleration	
Longitudinal	3.5 G's < 20 G's
Lateral (not required)	10.7 G's
Occupant Impact Velocity (Normalized)	
Longitudinal	7.0 m/s < 12 m/s
Lateral (not required)	4.8 m/s
Vehicle Damage	Moderate
TAD[9]	1-RFQ-4
SAE[10]	01RFES2
Vehicle Stopping Distance	39.62 m downstream 4.22m lateral
Barrier Damage	Minimal
Maximum Permanent Set Deflections	1.16 m

Figure 10. Summary of Test Results, Test KTS-1



Impact



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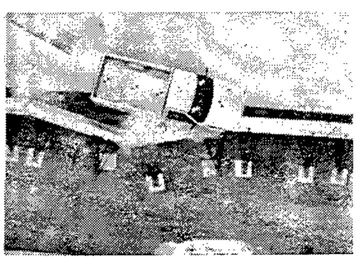
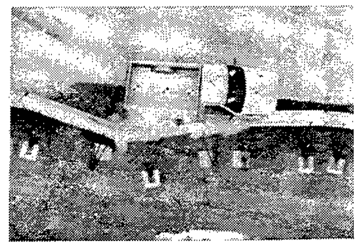
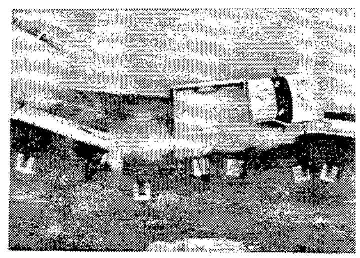


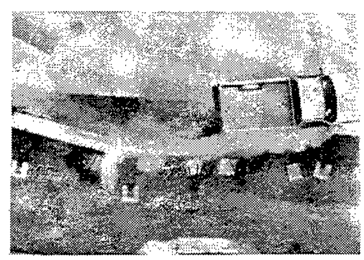
209 ms



274 ms



372 ms



473 ms

Figure 11. Additional Sequential Photographs, Test KTS-1

Figure 12. Documentary Photographs, Test KTS-1

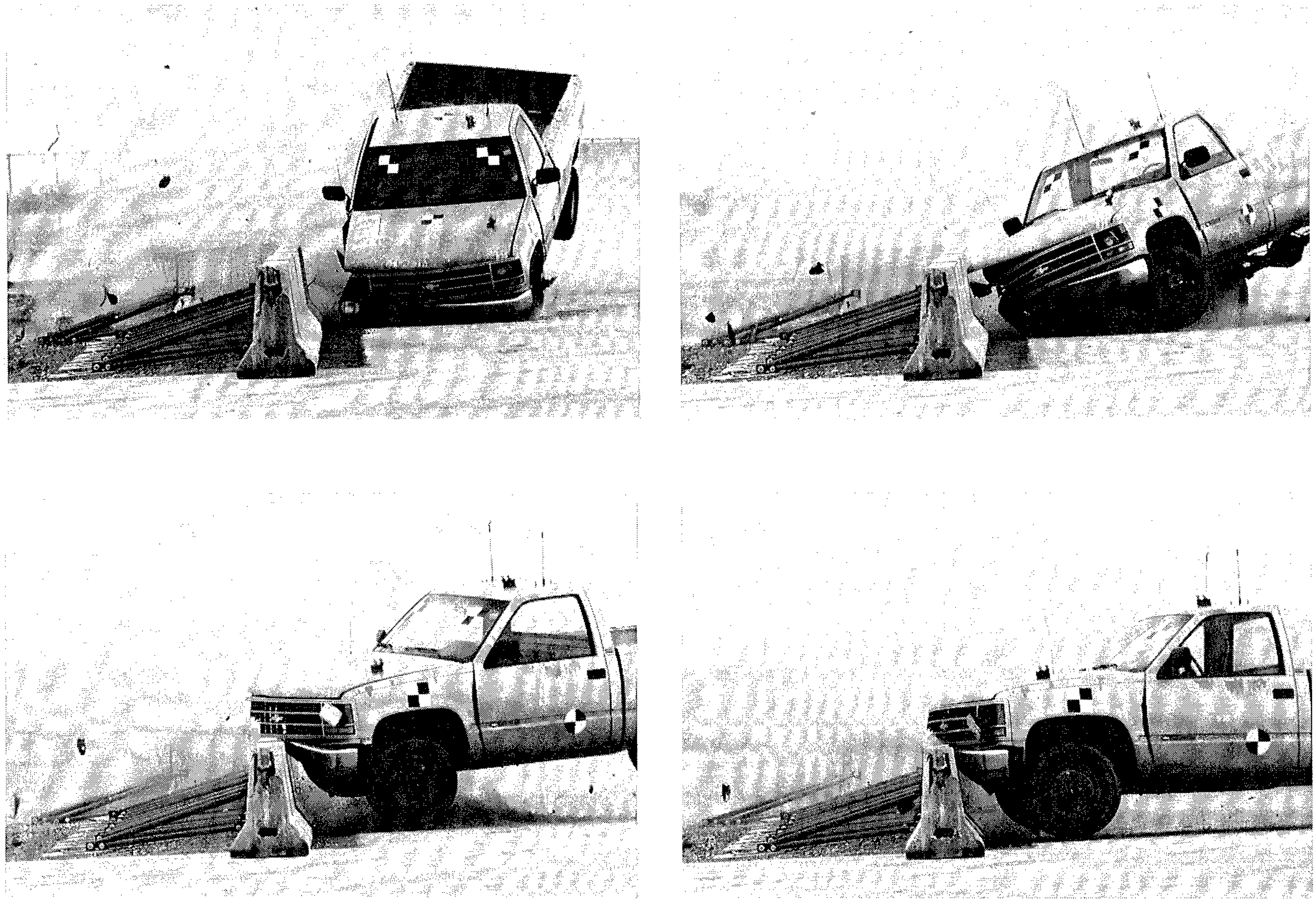


Figure 13. Documentary Photographs, Test KTS-1

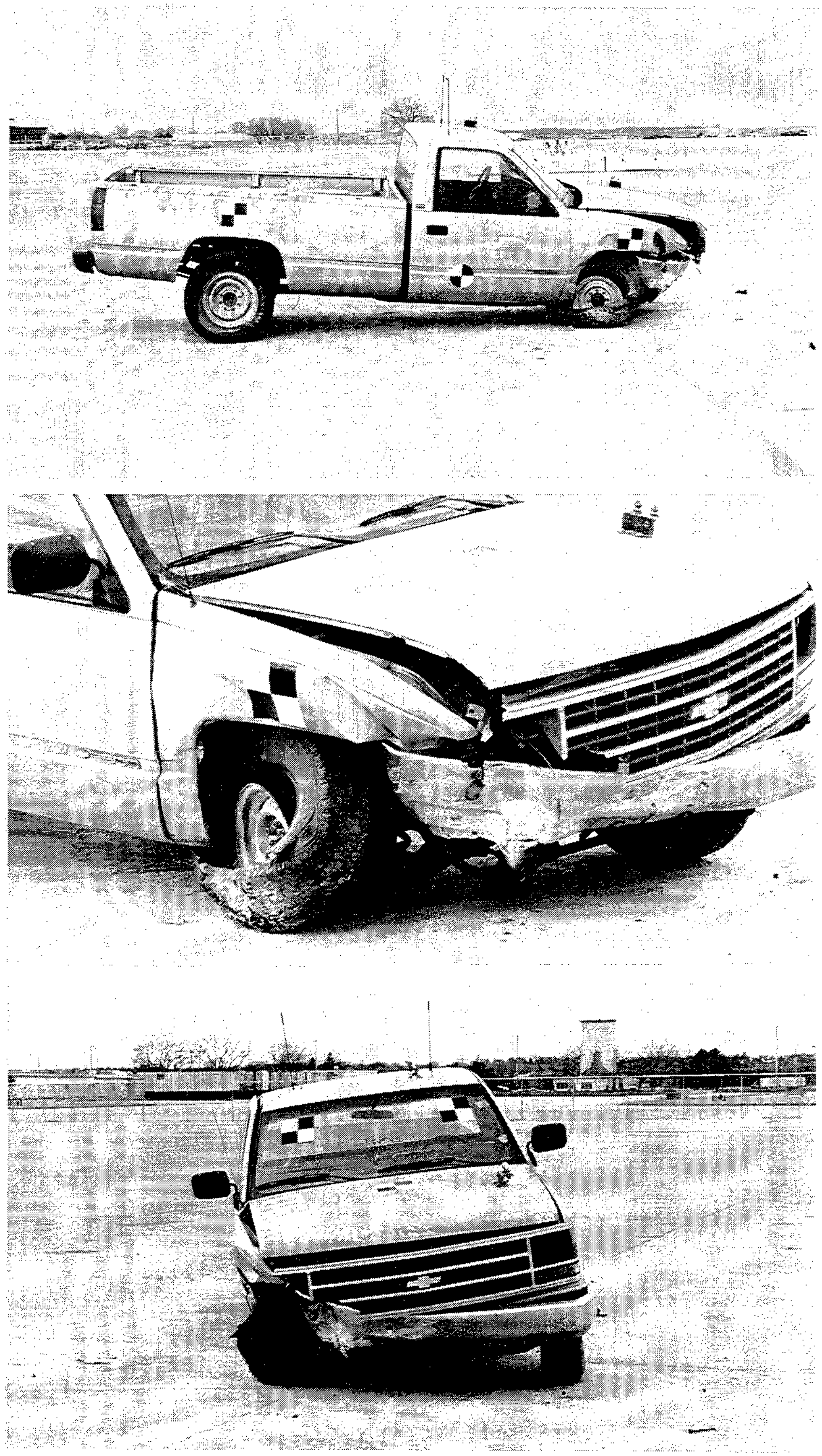


Figure 14. Vehicle Damage, Test KTS-1

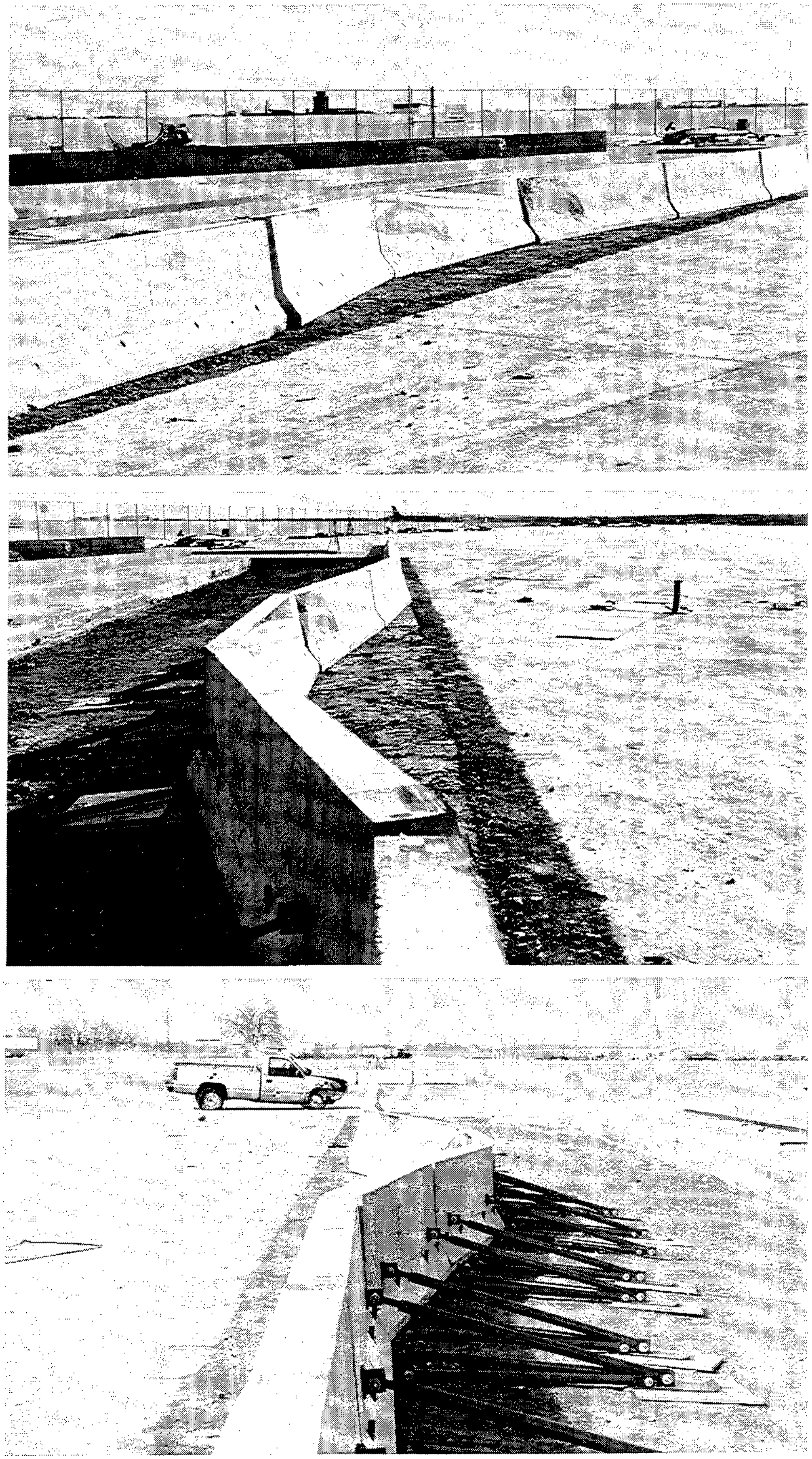


Figure 15. Barrier Damage, Test KTS-1

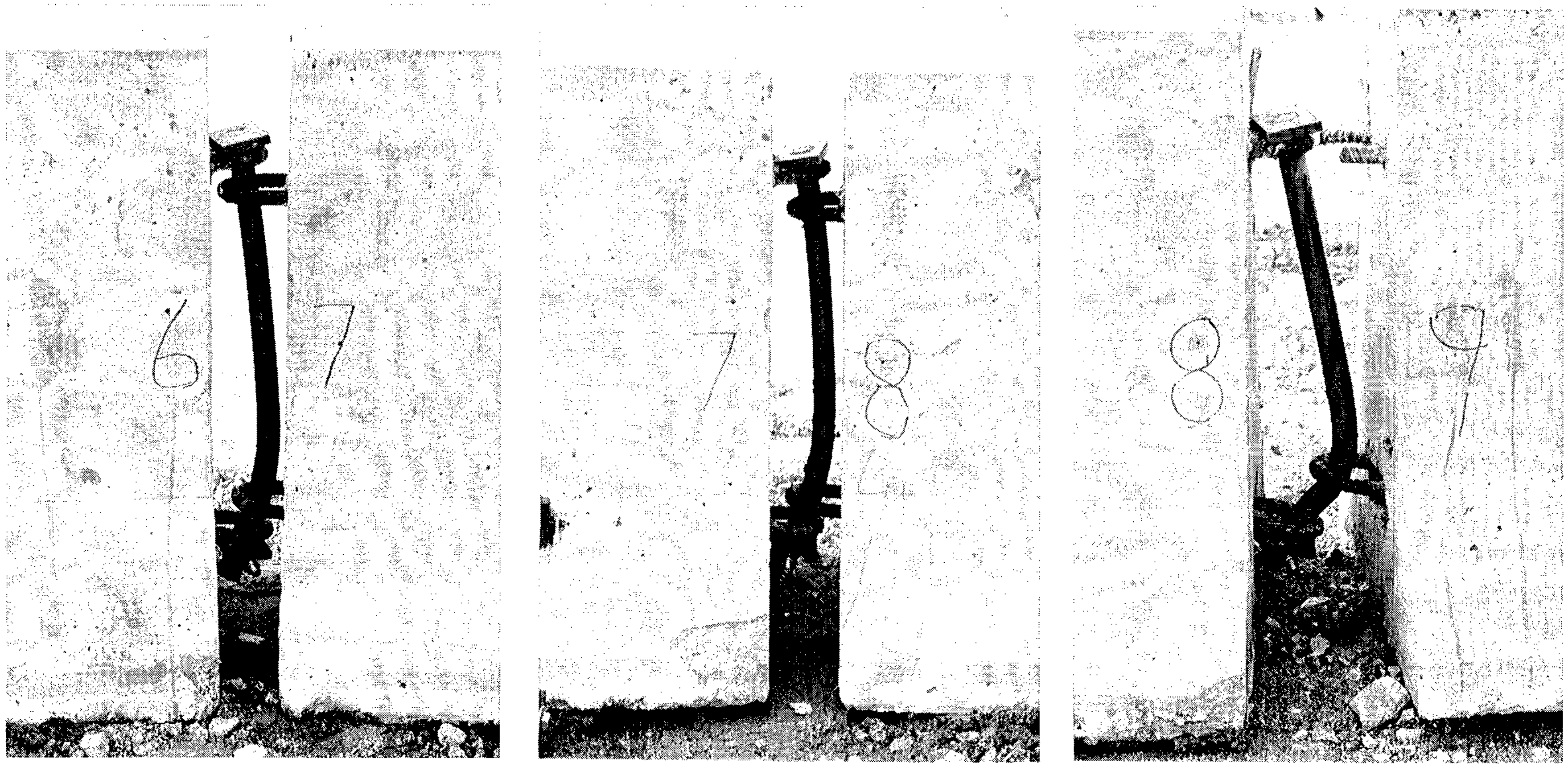


Figure 16. Damage of Barrier Ends (Back Side), KTS-1

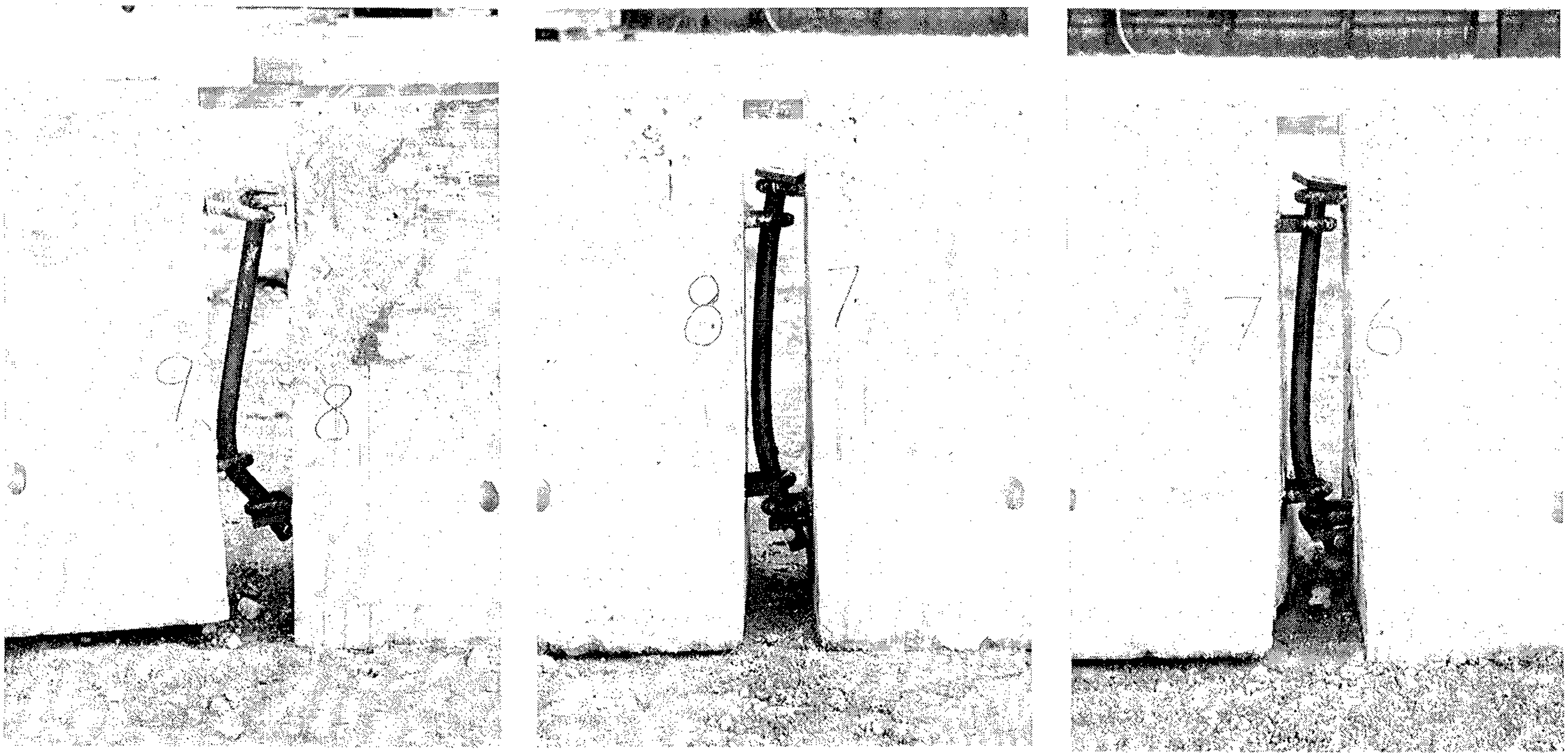


Figure 17. Damage of Barrier Ends (Traffic Side), KTS-1

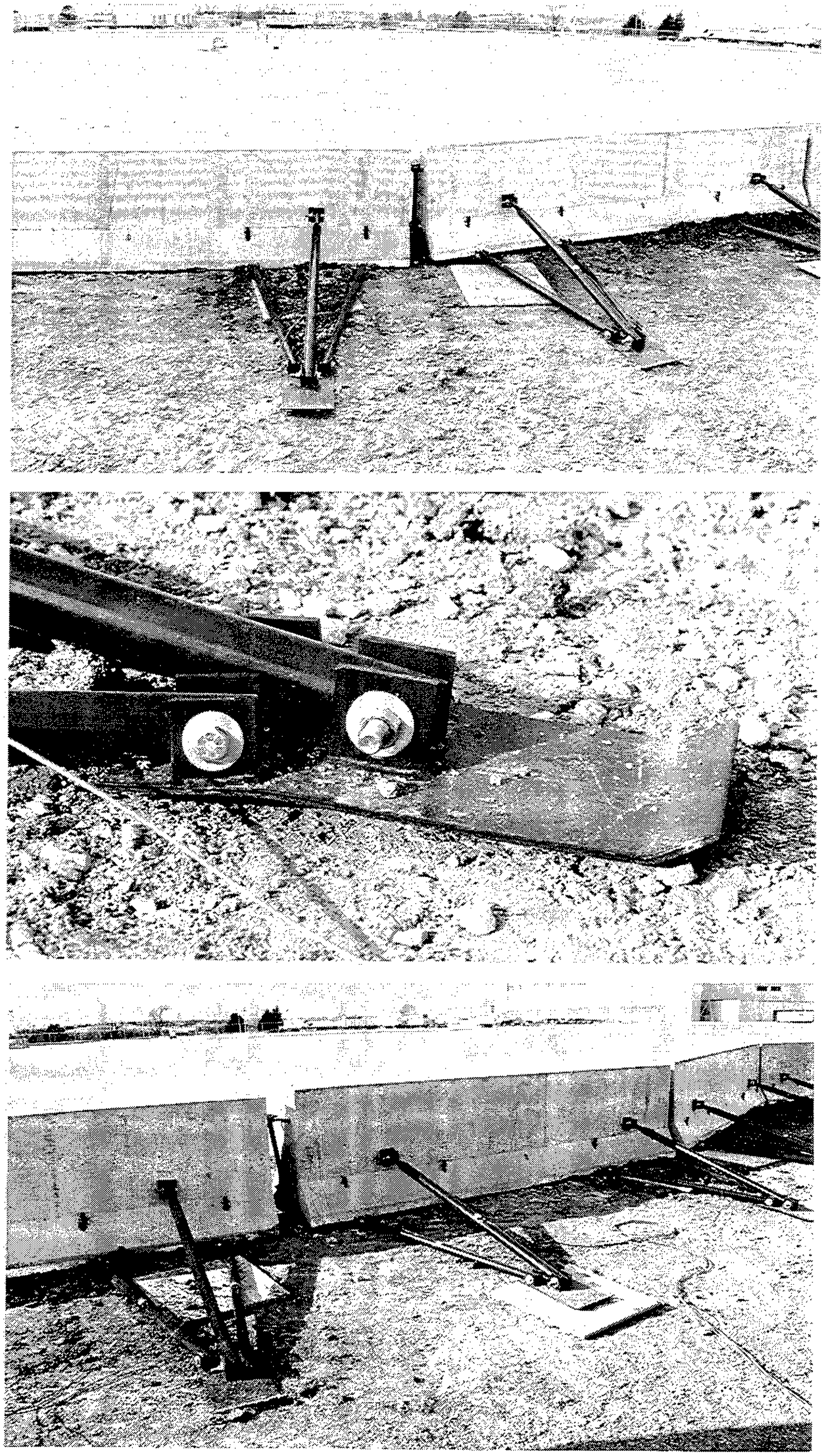


Figure 18. Ski Damage, KTS-1

Table 2. Summary of Loads Obtained from Strain Gages

Strain Gage No.	Tension or Compression	Maximum Force (lbs)
1	Tension	5440
2	Tension	3950
3	Tension	6150
4	Tension	5940
5	Compression	4250
6	Compression	14850
7	Compression	7885
8	Compression	5865
9	Compression	5095
10	Compression	4460

7 SUMMARY AND CONCLUSIONS

A concrete barrier system for off-road applications was developed and subjected to full-scale vehicle crash testing. The design of this system addressed concerns for safety, economy, structural integrity, constructability, ease of installation, and maintenance.

One crash test was conducted according to Test Level 3 of NCHRP Report 350 (2). This test successfully passed the required criteria, although significant vehicle pitch and yaw motions were encountered during the test. The behavior witnessed, however, is typical of this type of test. Vehicle roll was minimal, however, which is unusual for this type of test. This concrete barrier system proved to be capable of preventing the concrete barriers from digging into the soil, a behavior which could cause the barrier sections to rotate considerably or even overturn. A summary of the safety performance evaluation is provided in Table 3.

Based on the results of this research, it was determined that the performance of this system was acceptable according to the criteria presented for Test Level 3 of NCHRP Report 350 (2).

Table 3. Summary of Safety Performance Evaluation Results

Evaluation Factors	Evaluation Criteria	Test KTS-1
Structural Adequacy	A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	S
Occupant Risk	D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.	S
	F. The vehicle should remain upright during and after collision although moderate roll, pitching and yawing are acceptable.	S
Vehicle Trajectory	K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	S
	L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 G's.	S
	M. The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.	S

S - (Satisfactory)
M - (Marginal)
U - (Unsatisfactory)

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10. *Collision Deformation Classification - Recommended Practice J224 March 1980*, Handbook Volume 4, Society of Automotive Engineers (SAE), Warrendale, Pennsylvania, 1985.

11. Faller, R.K., Rohde, J.R., Rosson, B.T., Smith, R. P., Addink, K.A., *Development of a TL-3 F-Shape Temporary Concrete Median Barrier*, Research Report TRP- 03-64-96, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska 68588-0531.

9 APPENDICES

APPENDIX A - SKI SYSTEM DESIGN DRAWINGS

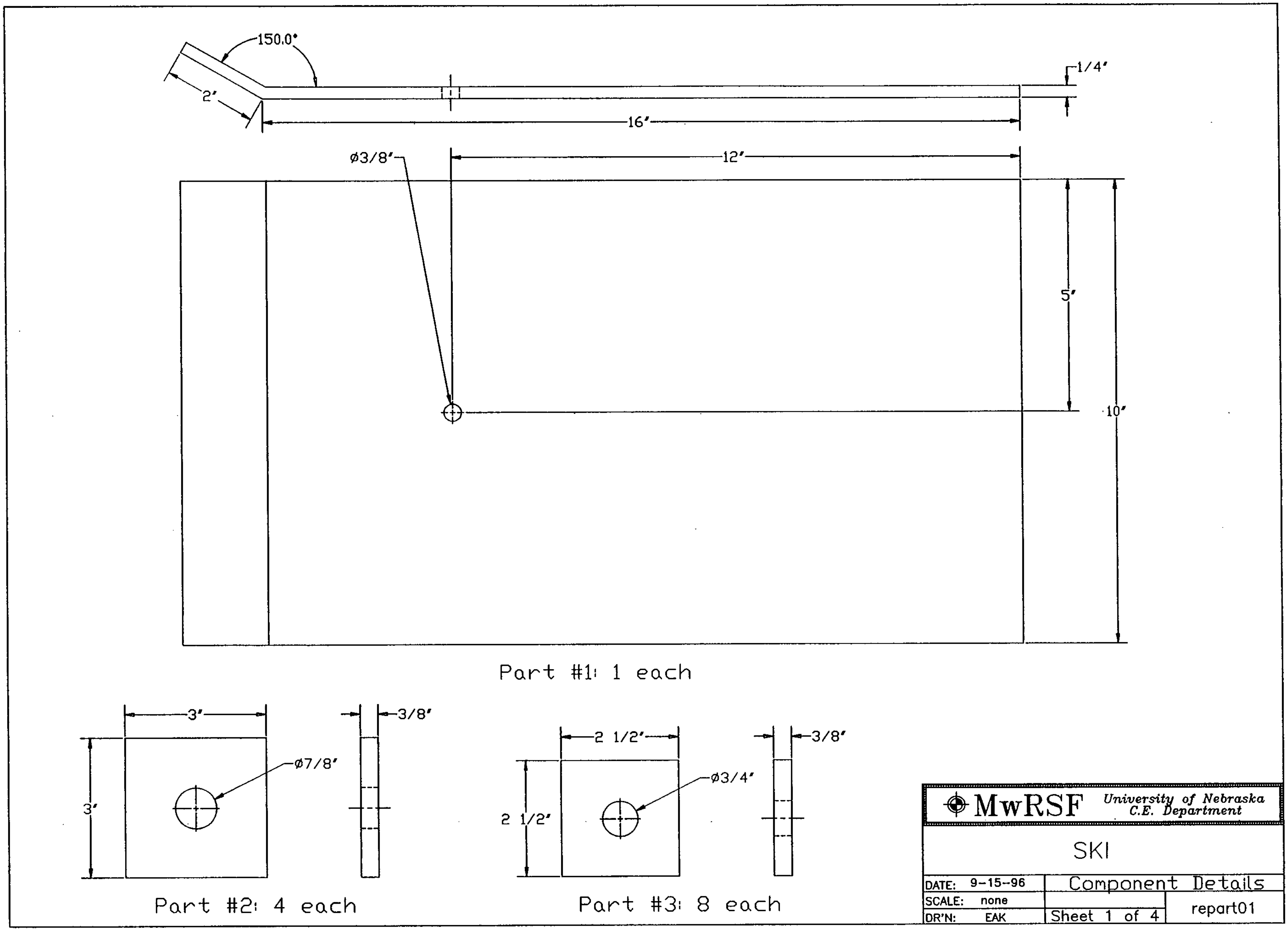

Figure A-1. Component Details

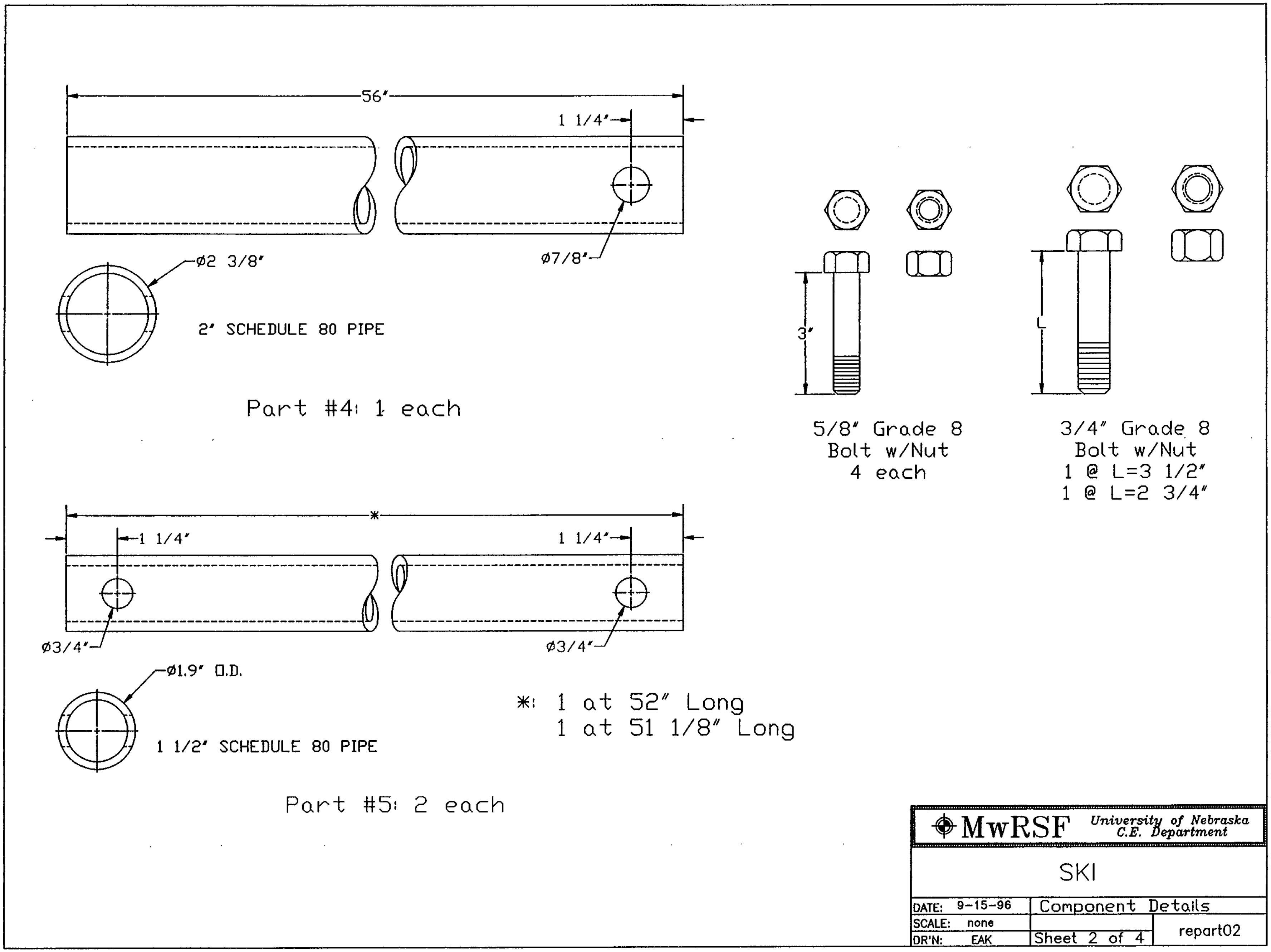

Figure A-2. Component Details (cont)

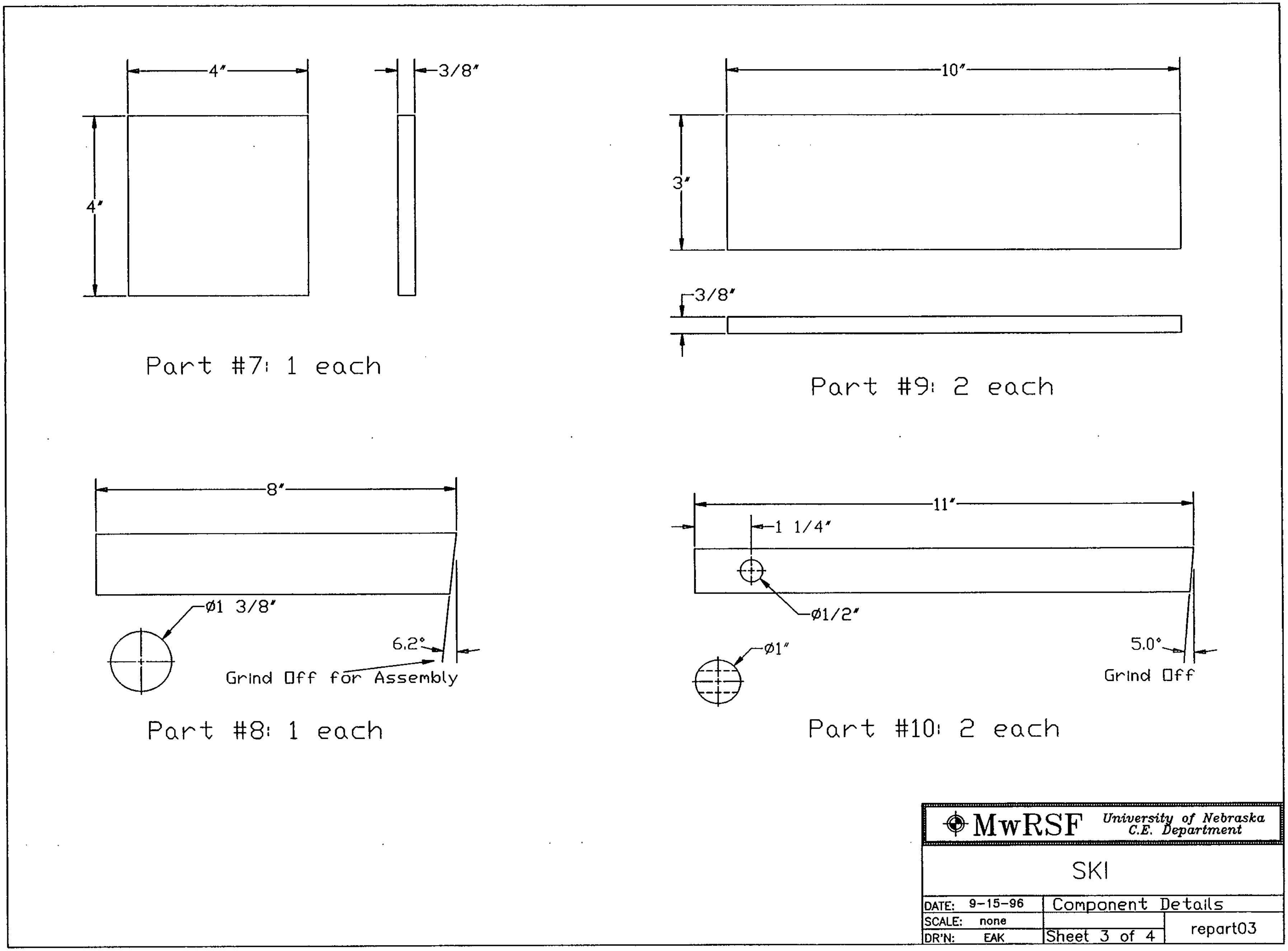

Figure A-3. Component Details (cont)

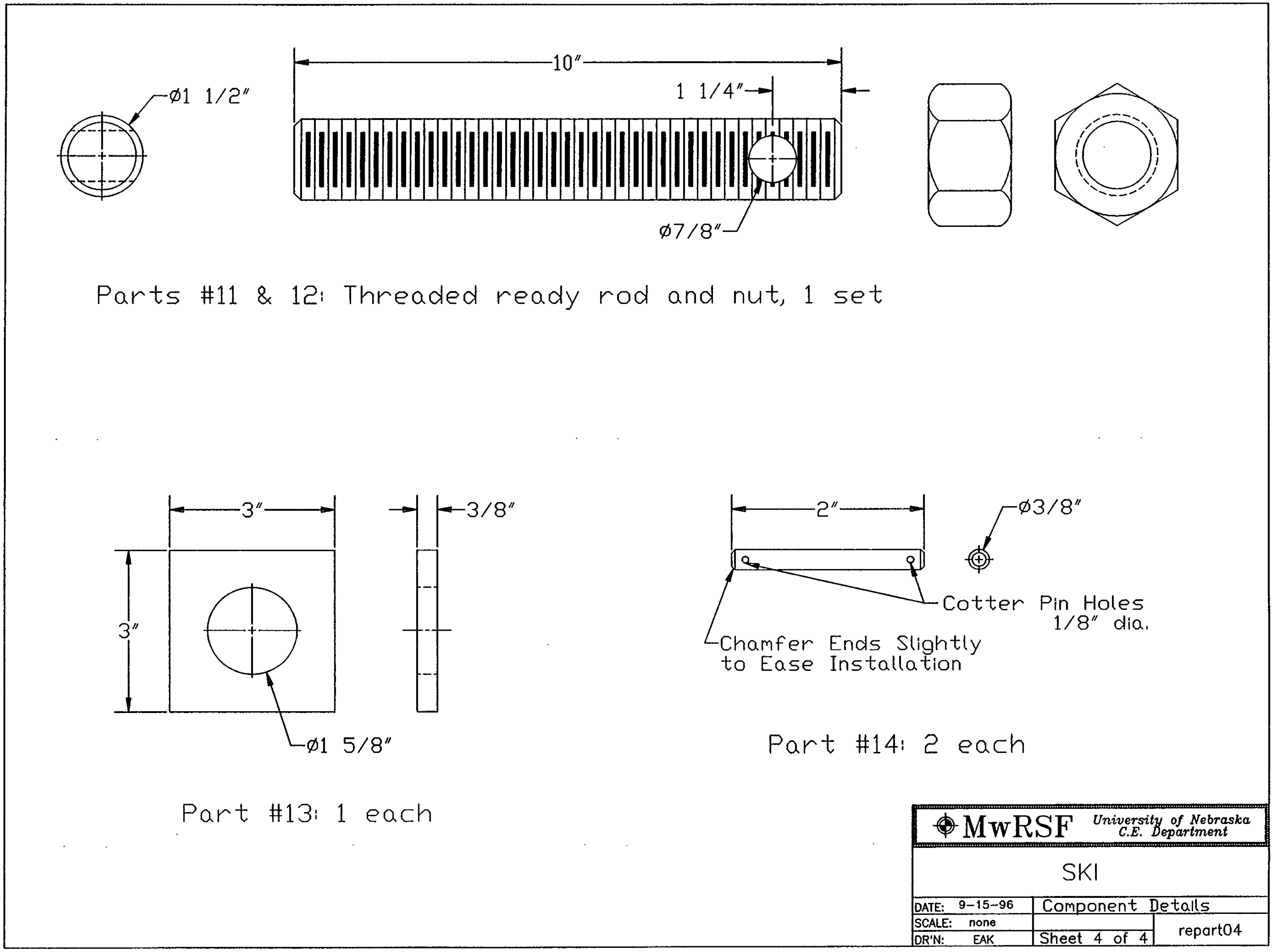

Figure A-4. Component Details (cont)

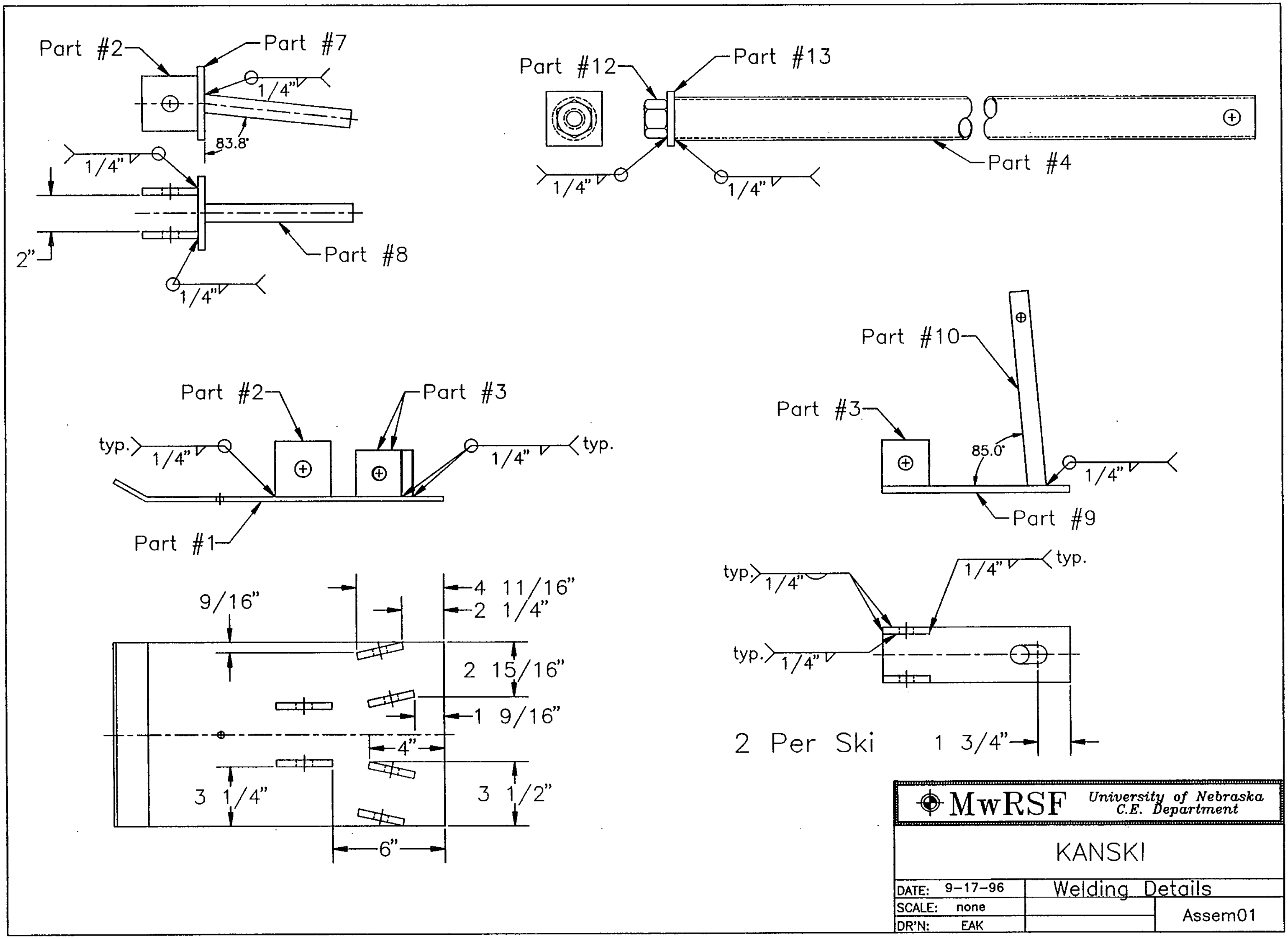

Figure A-5. Welding Details

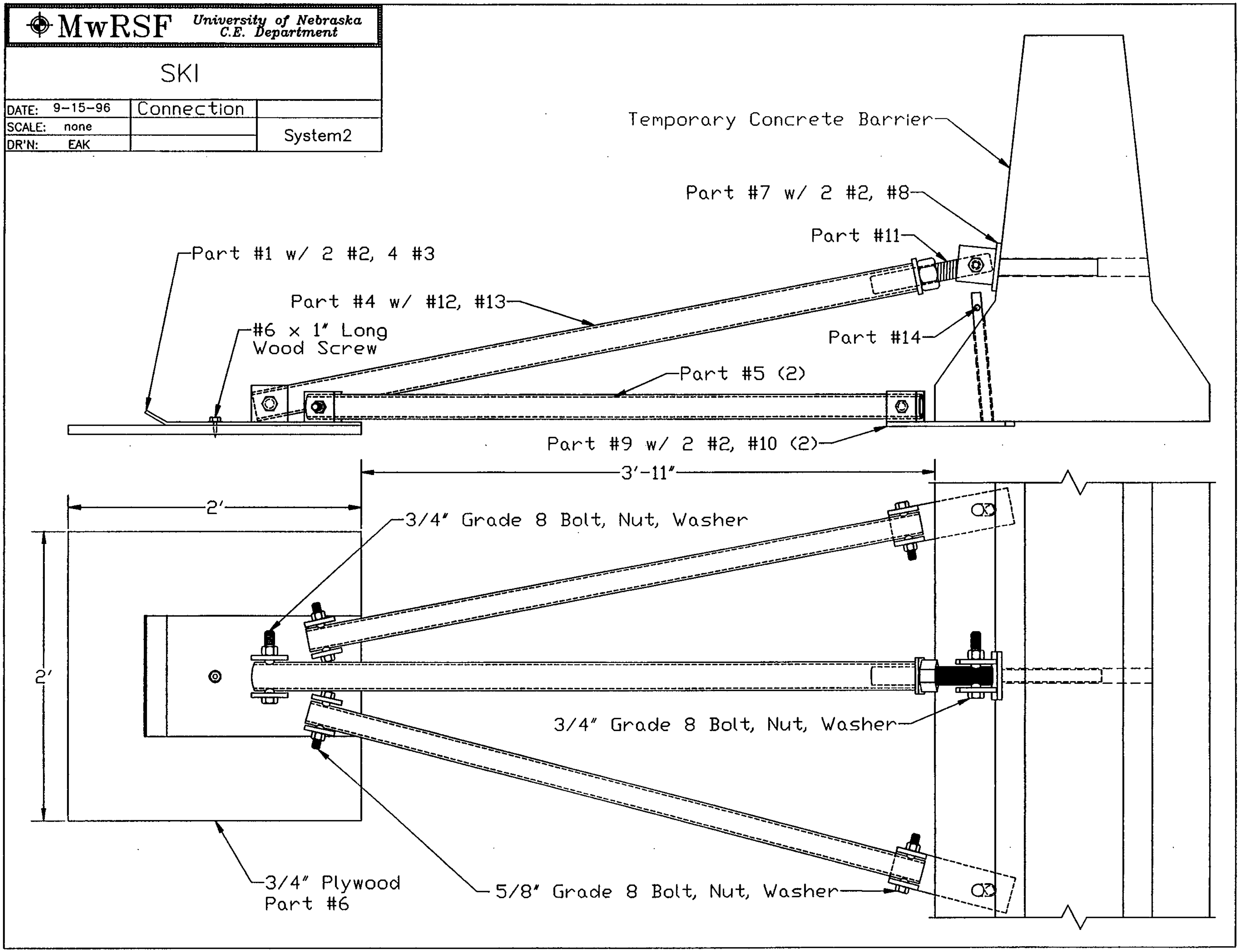

Figure A-6. Ski Connection to Barrier

APPENDIX B - BARRIER SYSTEM

A concrete median barrier was developed and subjected to full scale crash testing by MwRSF in 1996 for the Midwest State's Regional Pooled Fund Program (11). The concrete median barrier developed, shown in Figures B-1 and B-2, was first tested with unsatisfactory results. The barrier did not adequately contain and redirect the vehicle, so the concrete barrier connections were modified as shown in Figure B-3. A retest was performed on the modified barrier system and the results were acceptable according to the TL-3 crash test conditions of NCHRP Report No. 350 (2). This modified barrier system was used for the off-road application test described in this report, as shown in Figures B-4 and B-5. Following the successful completion of this testing, it is recommended that the barrier details shown in Figures B-6 and B-7 be used for future construction.

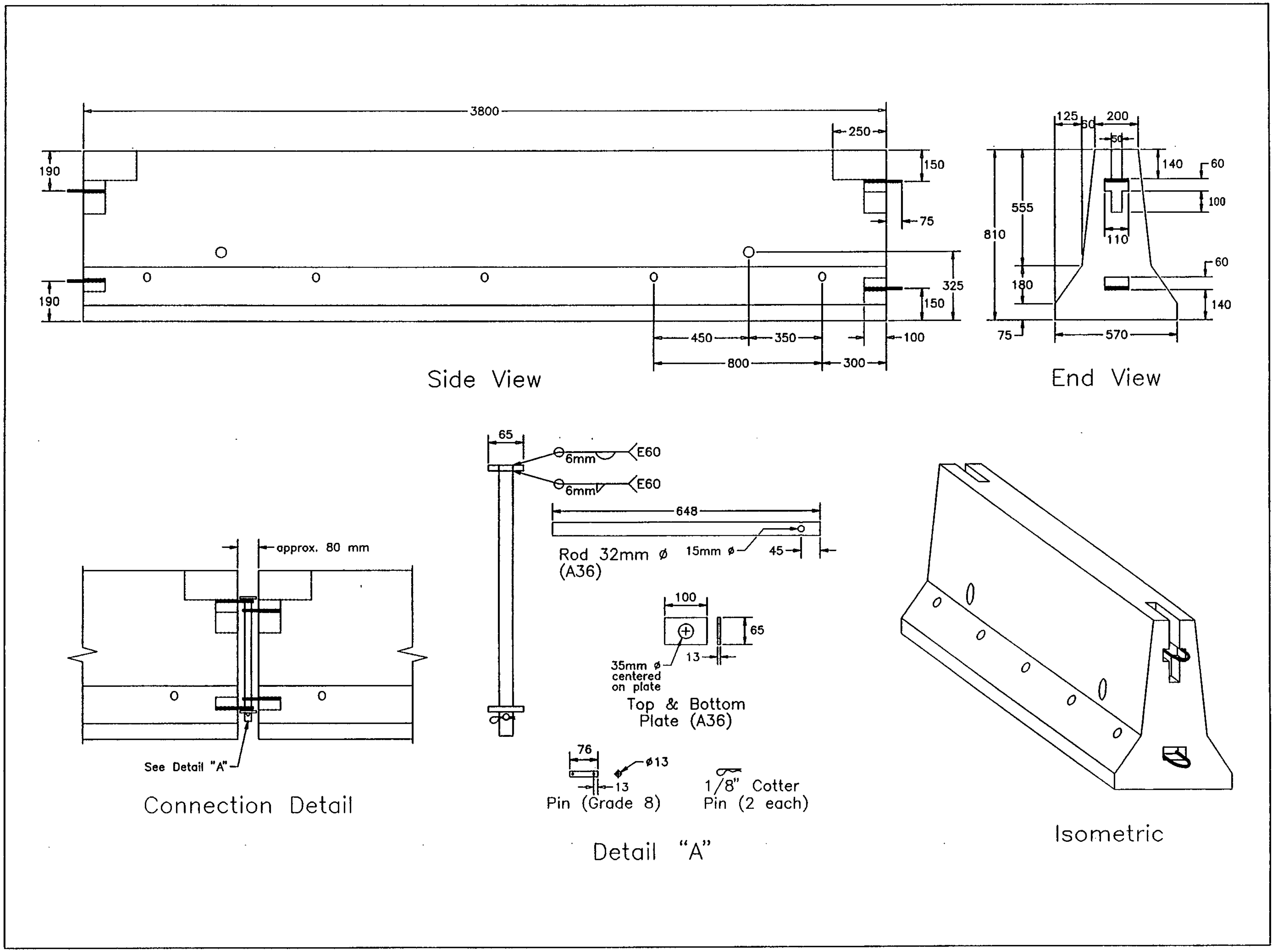

Figure B-1. Original Barrier Design

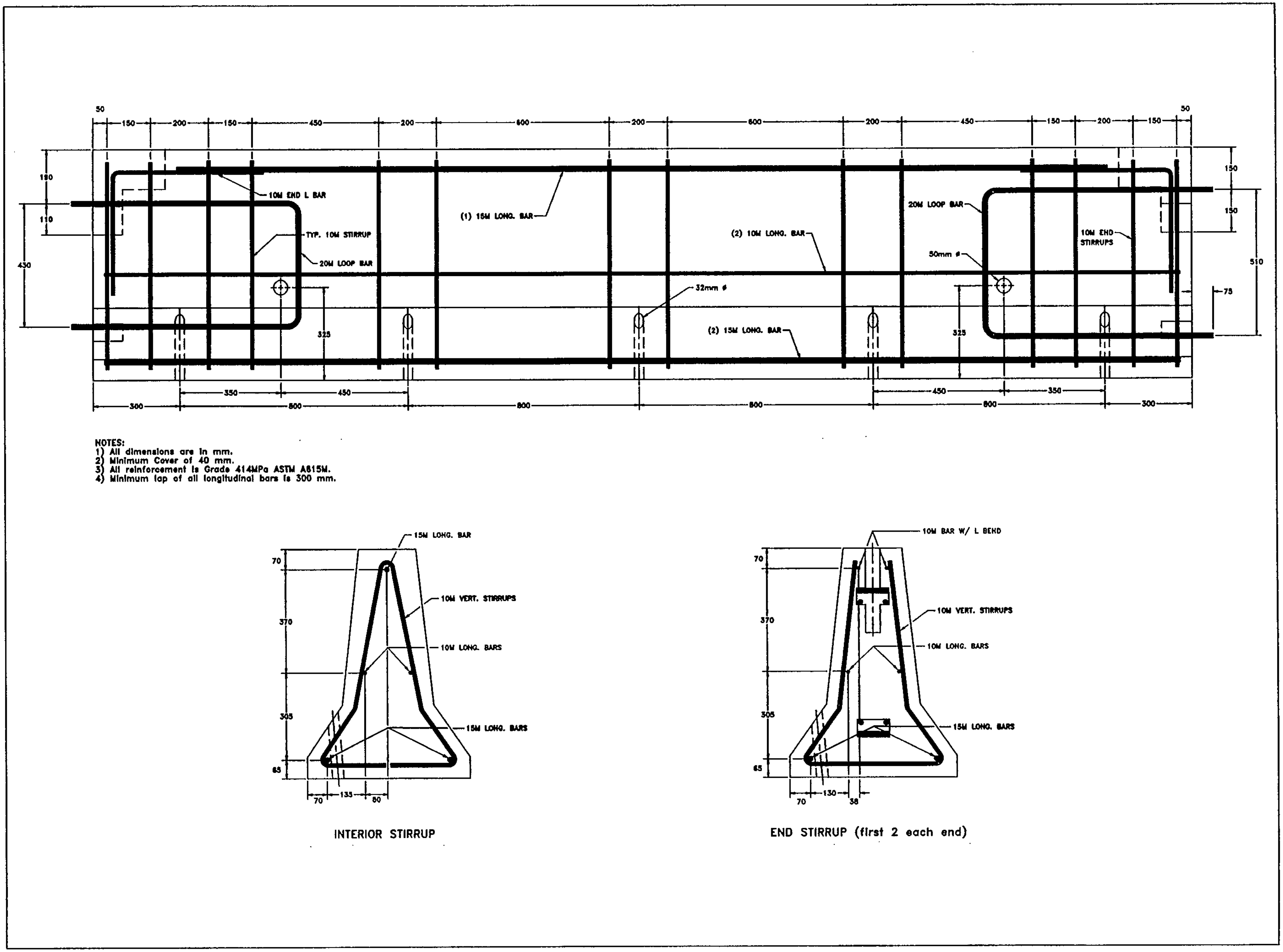

Figure B-2. Original Barrier Reinforcement Details

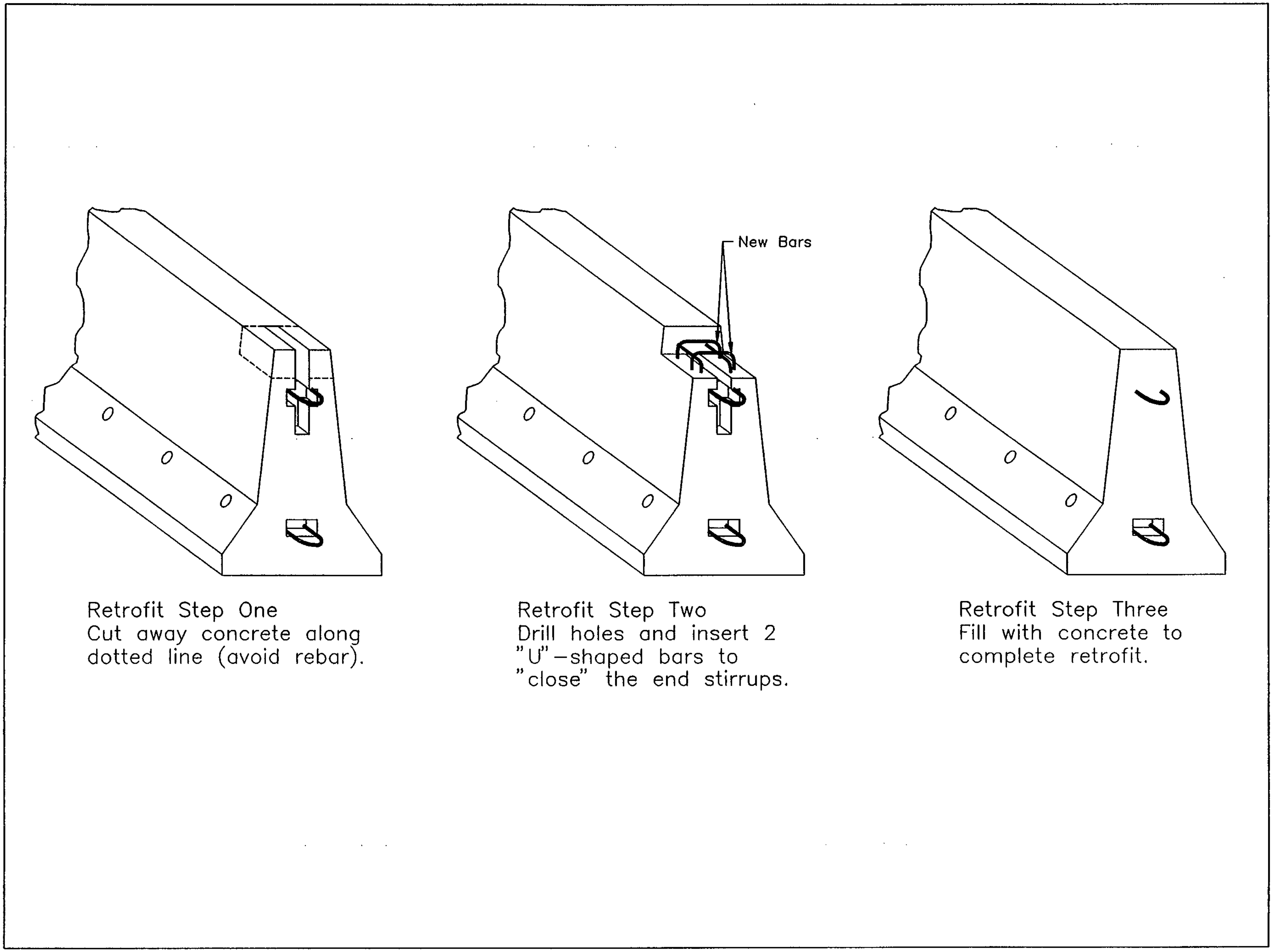

Figure B-3. Barrier Retrofit Details

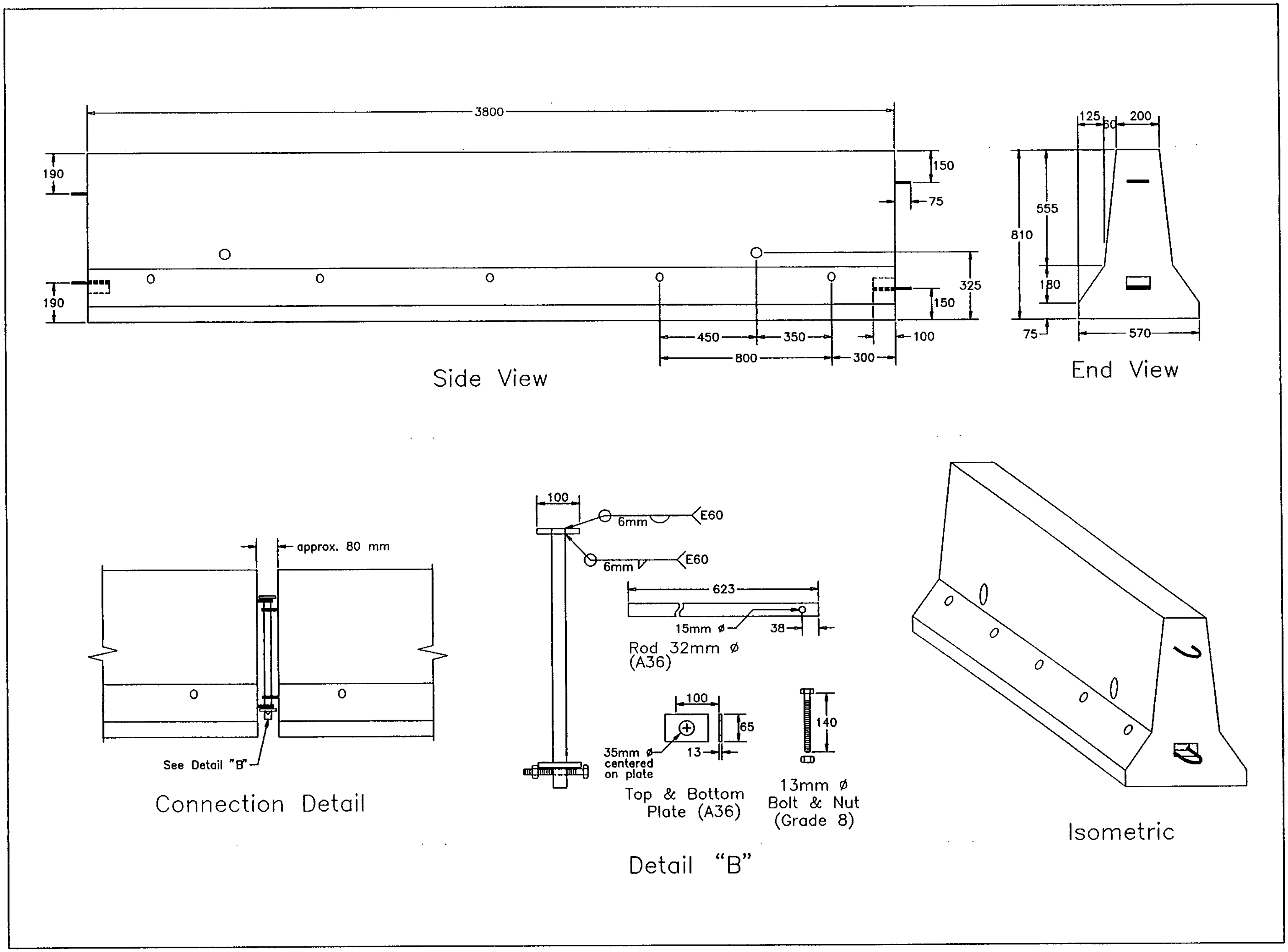

Figure B-4. Barrier Design for KTS-1

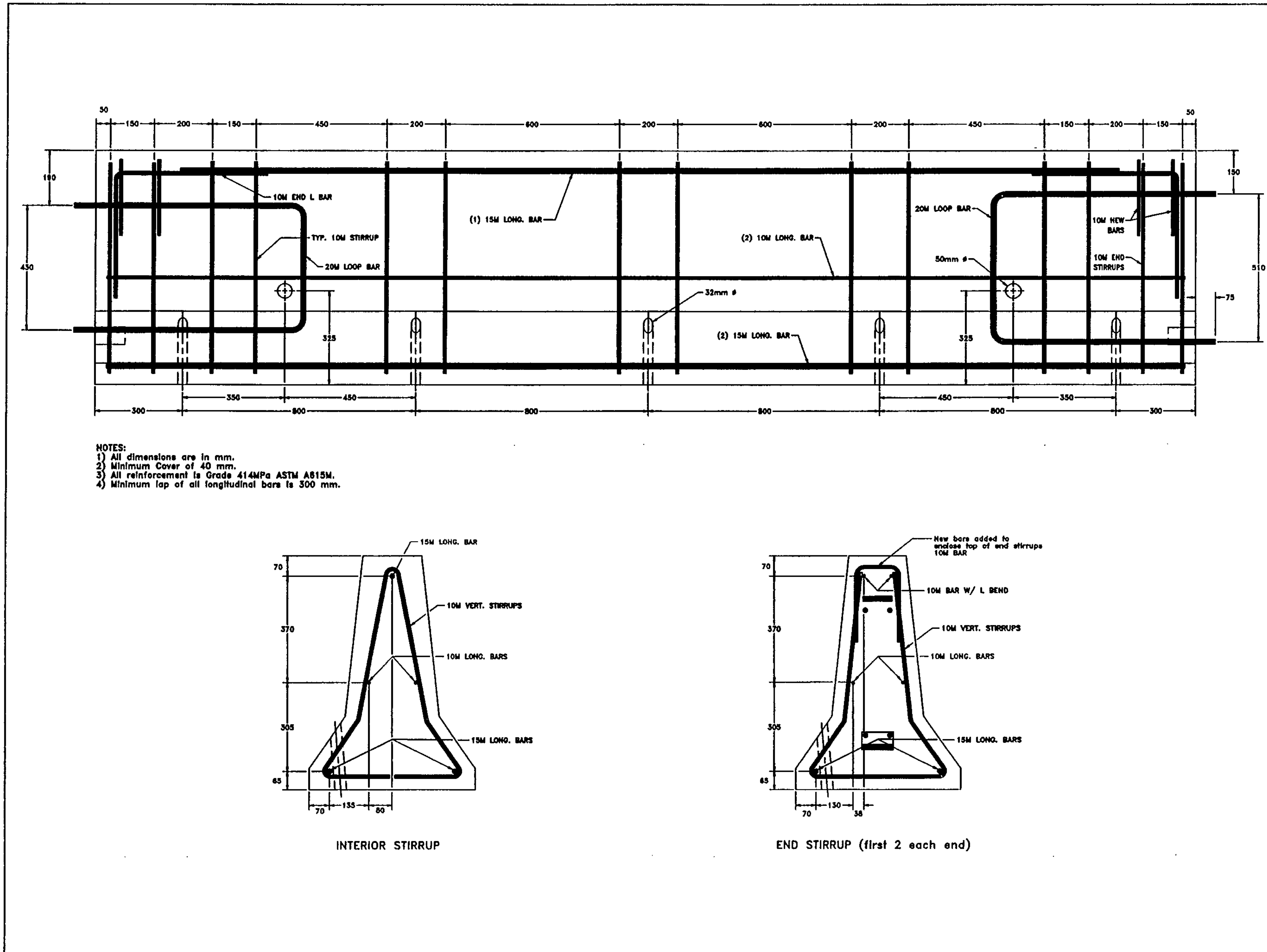

Figure B-5. Reinforcement Details for KTS-1

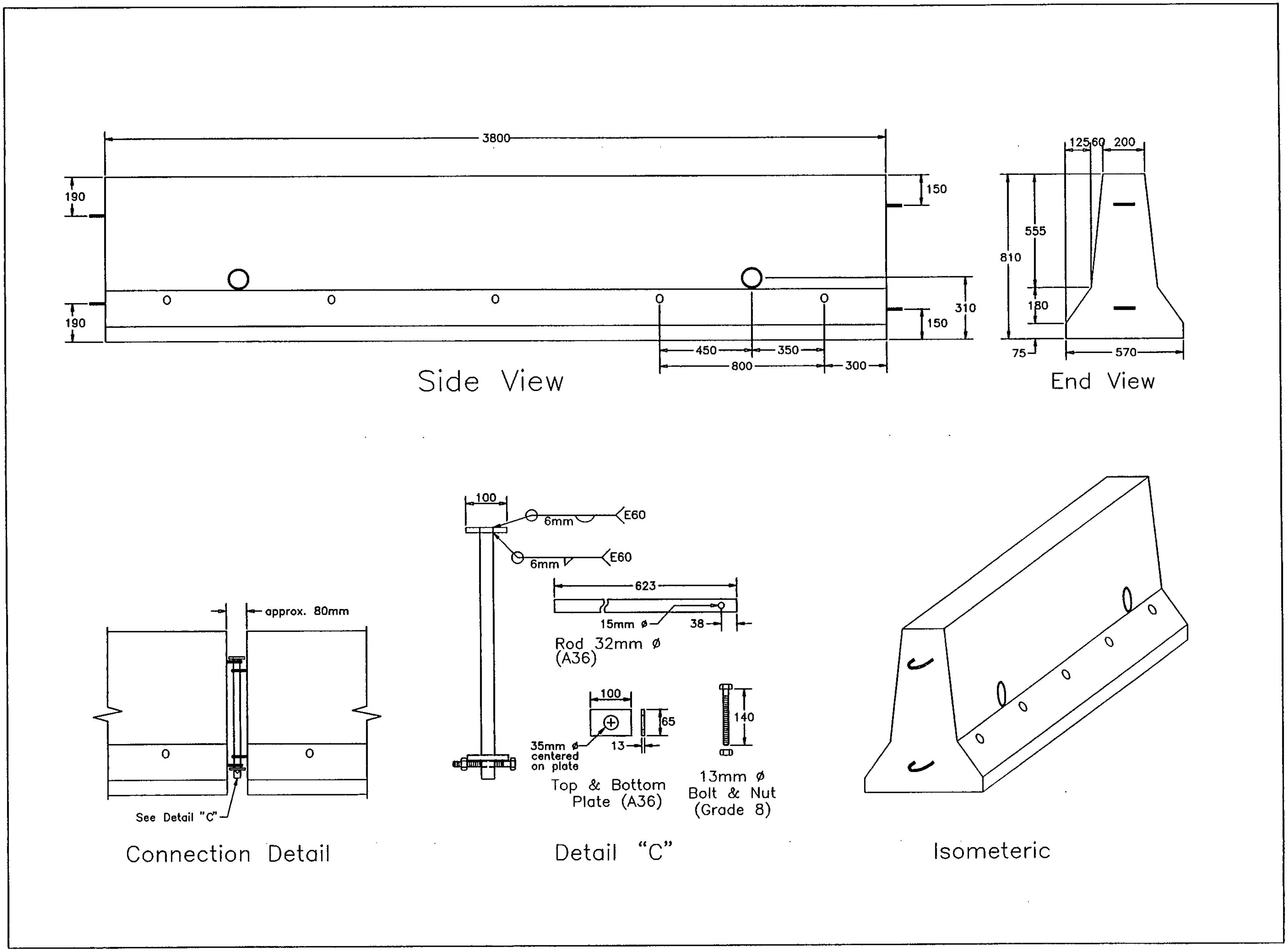

Figure B-6. Barrier Design for Future Construction

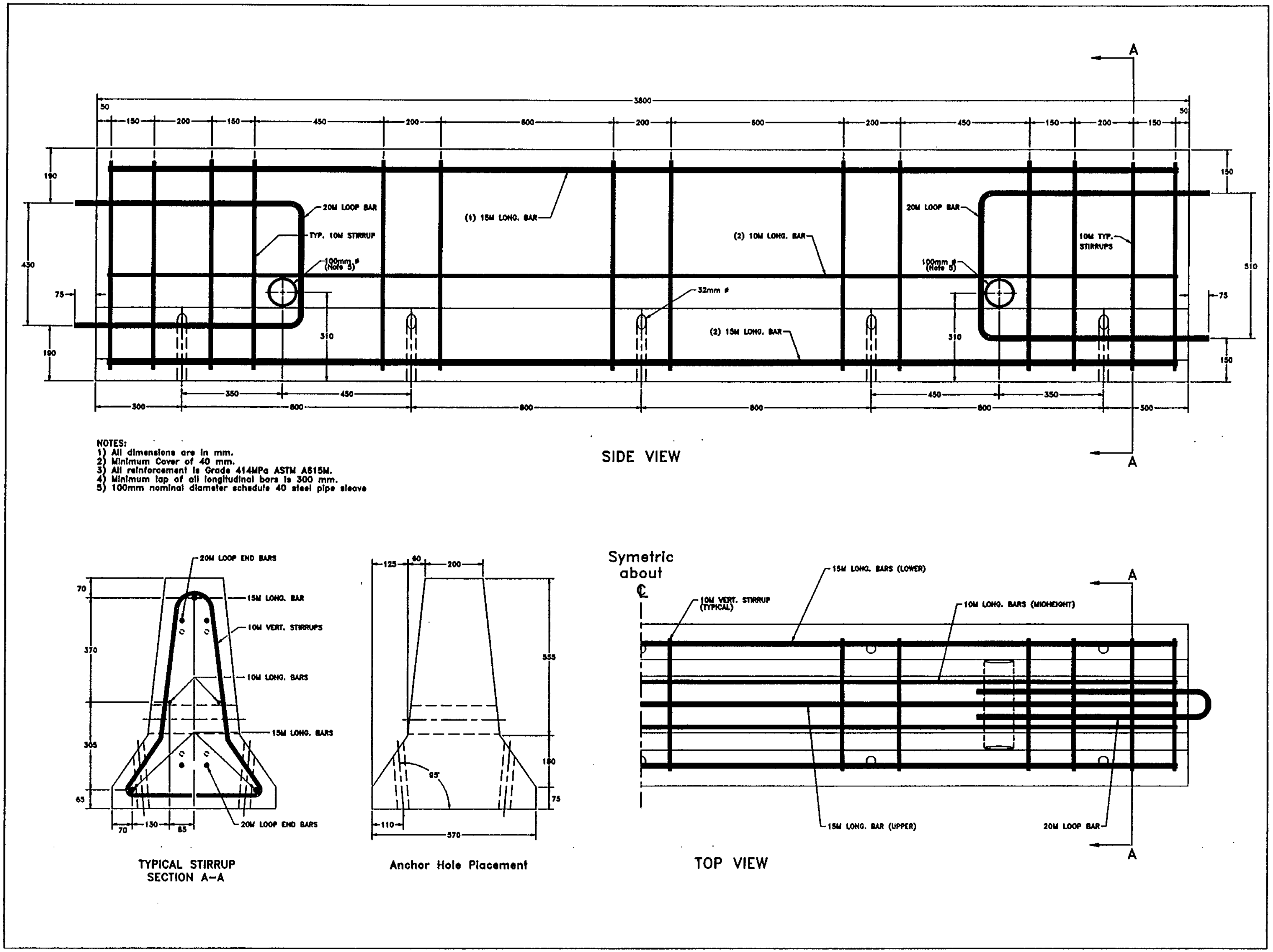

Figure B-7. Reinforcement Details for Future Construction

APPENDIX C - ACCELEROMETER DATA ANALYSIS

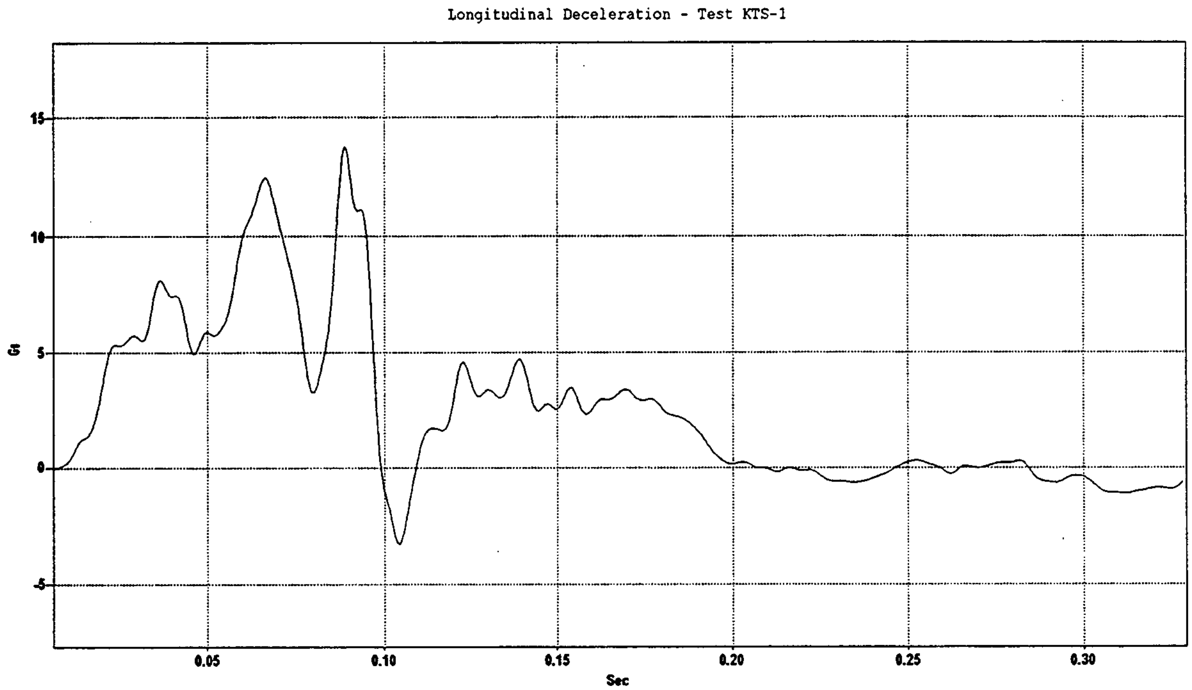

Figure C-1. Graph of Longitudinal Deceleration, Test KTS-1

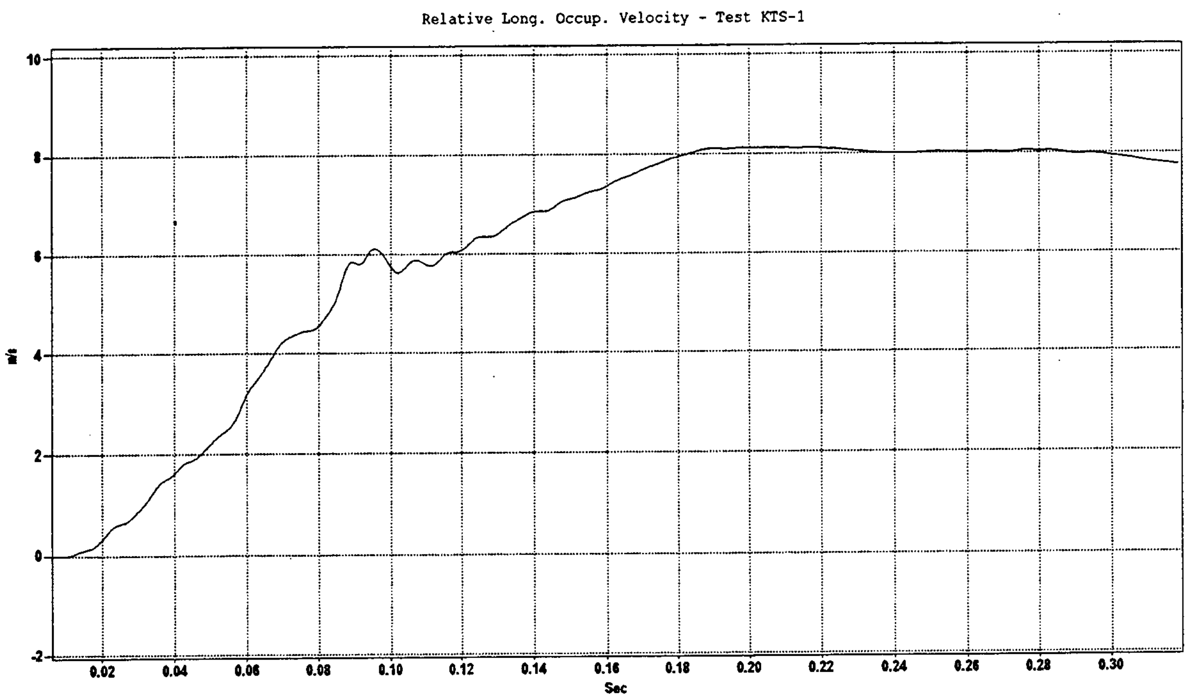

Figure C-2. Graph of Longitudinal Occupant Impact Velocity, Test KTS-1

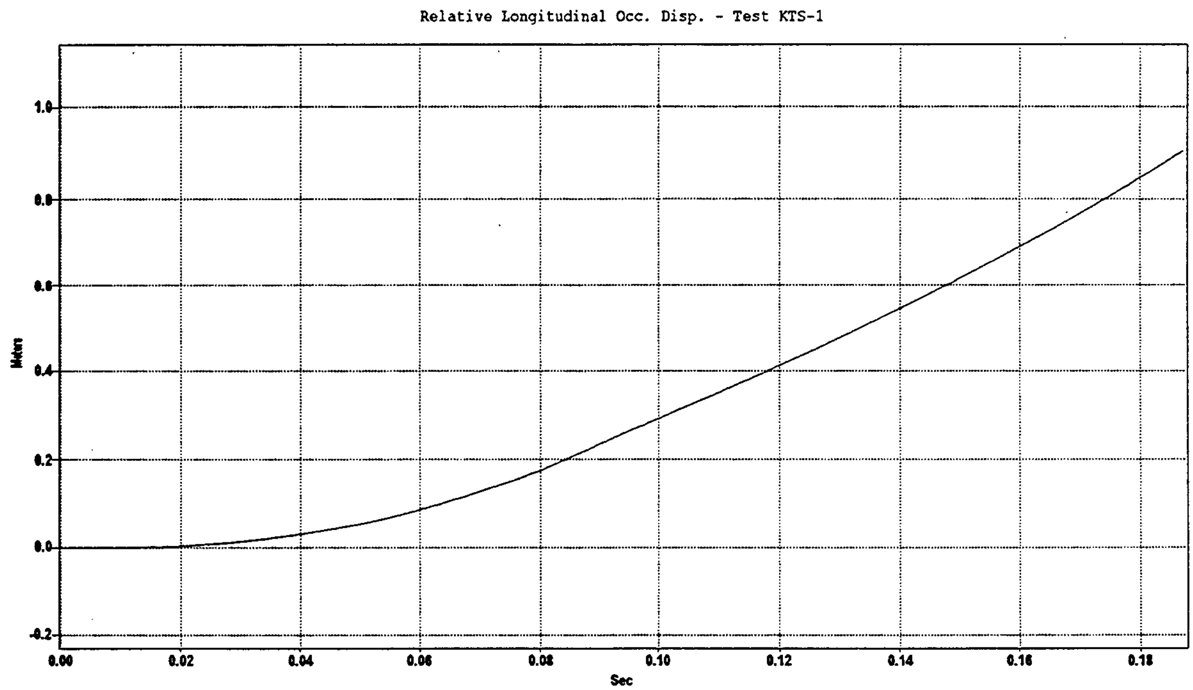

Figure C-3. Graph of Longitudinal Occupant Displacement, Test KTS-1

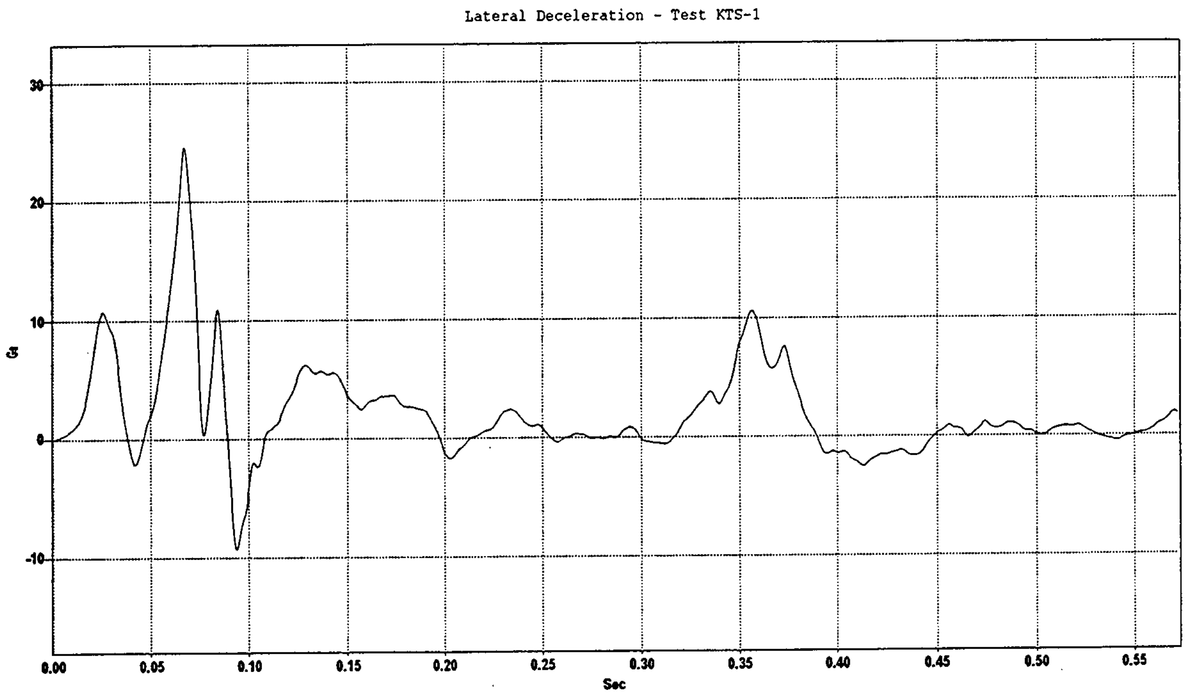

Figure C-4. Graph of Lateral Deceleration, Test KTS-1

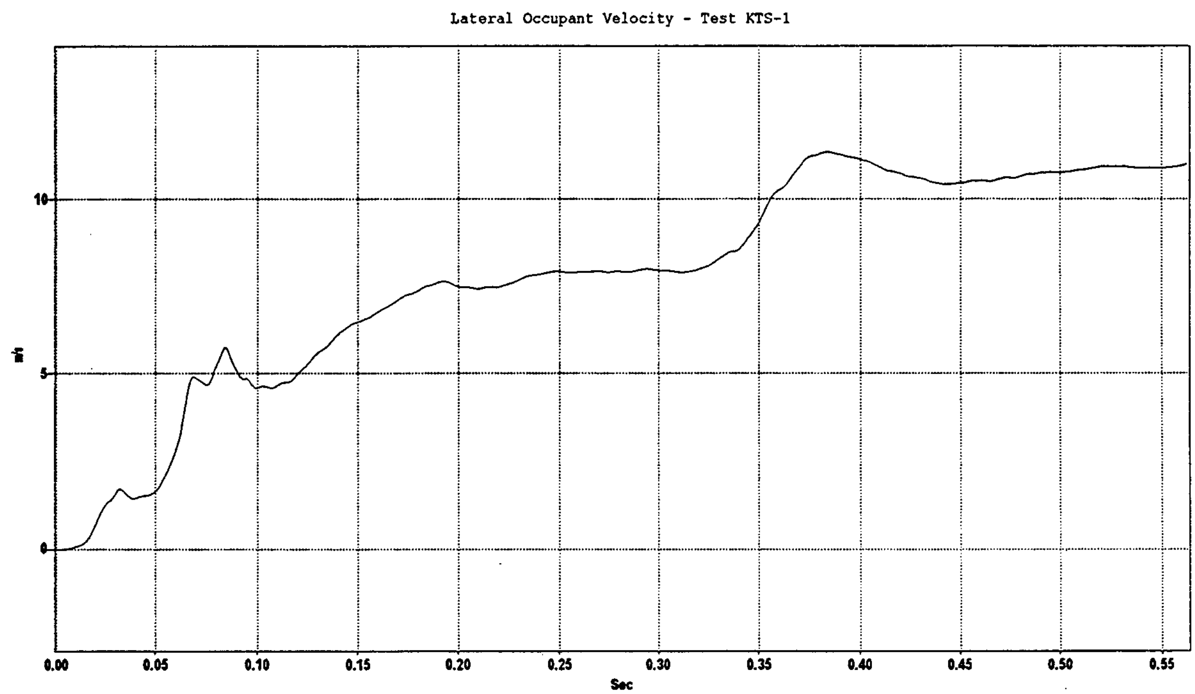

Figure C-5. Graph of Lateral Occupant Impact Velocity, Test KTS-1

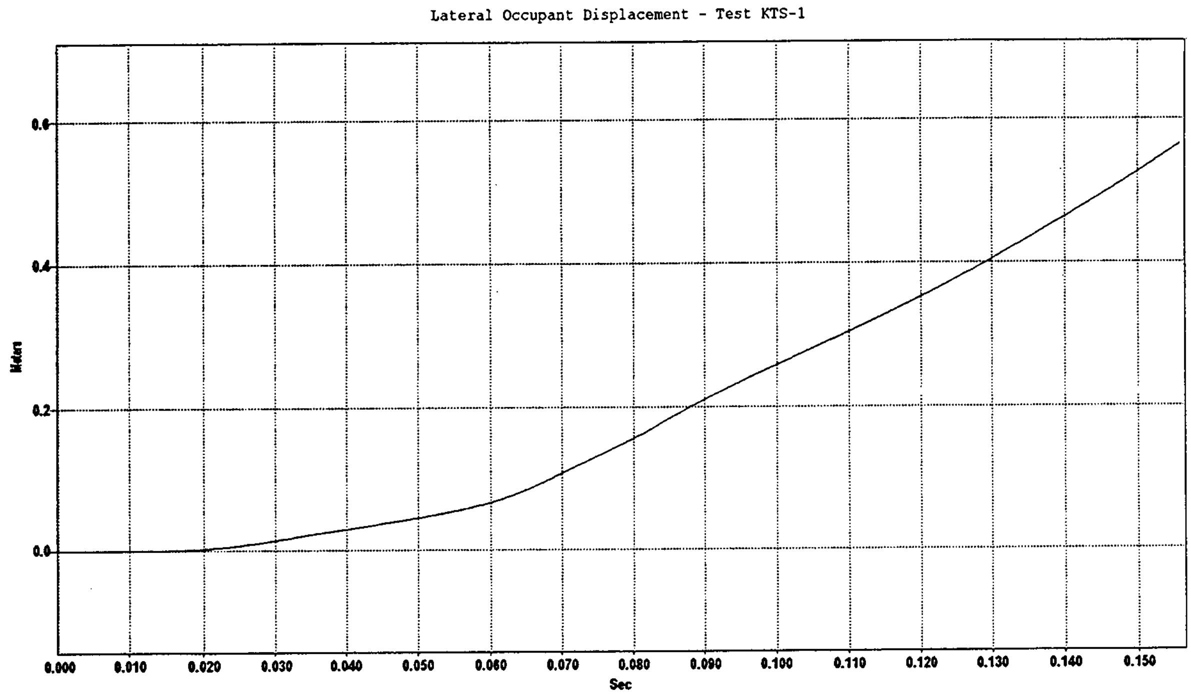

Figure C-6. Graph of Lateral Occupant Displacement, Test KTS-1