TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TX-91/990-1		

4. Title and Subtitle	5. Report Date
ADIEM Development of a Low Cost High Performance Terminal for Concrete Median Barriers and Portable Concrete Barriers	August 15, 1991
	6. Performing Organization Code
7. Author(s) Don L. Ivey and Mark A. Marek	8. Performing Organization Report No. Research Report 990-1
9. Performing Organization Name and Address Texas Transportation Institute Texas A&M University System College Station, TX 77843-3135	10. Work Unit No. 11. Contract or Grant No. Study No. 2-8-90/1-990
12. Sponsoring Agency Name and Address Texas Department of Transportation Transportation Planning Division P.O. Box 5051 Austin, TX 78763	13. Type of Report and Period Covered Final - May 24, 1988 (2-8-88-942) August 1, 1991 14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the state of Texas. Research Study Title: Development of a Low Cost High Performance Terminal for Concrete Median Barriers and Portable Concrete Barriers.

16. Abstract

Presented here are the results of a research and compliance testing program to develop a low-cost, high-performance terminal for portable concrete barriers (PCBs) and permanent concrete median (CMB) and roadside barriers. The result is the Advanced Dynamic Impact Extension Module (ADIEM). The energy absorption elements of this terminal are lightly reinforced, ultra low strength Perlite concrete modules. The redirection element of this terminal is a heavily reinforced conventional concrete variable height curb with automobile hub-height pipe rail. ADIEM meets the requirements of NCHRP 230 at a cost of approximately $100 per foot. This translates into a projected cost for a 60 mph class, 30 foot barrier of $3000.00. This appears to represent a major cost reduction for PCB and CMB terminals.

17. Key Words	18. Distribution Statement
ADIEM, terminal, crash cushion, end treatment, low-cost, low strength lightweight concrete, crushable, modules, barrier, Perlite, NCHRP 230, acceleration	No restrictions. This document is available to the public through the National Technical Information Service 5285 Port Royal Road Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	70	

Form DOT F 1700.7 (8-69)

FINAL REPORT

Project 9901E

Development of a Low Cost High Performance Terminal
for Concrete Median Barriers and Portable Concrete Barriers

by

Don L. Ivey and Mark A. Marek

Prepared for

Highway Design Division
Texas State Department of Highways
and Public Transportation

August 15, 1991

Texas Transportation Institute
Texas A&M University System
College Station, Texas 77843

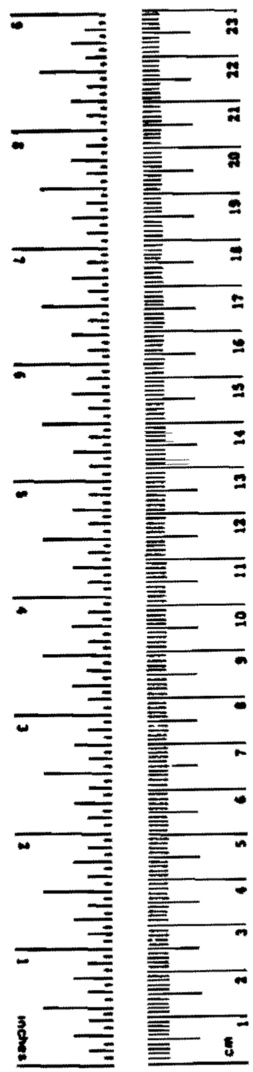
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

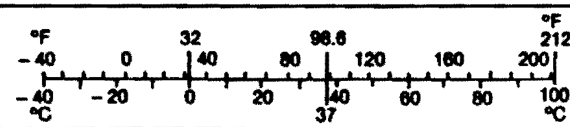
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

Acknowledgement

The authors are grateful for the cooperation and support of the following individuals and organization:

Mr. Harold D. Cooner, Resident Engineer

Mr. Frank D. Holzmann, Deputy Director Project Development

Mr. William A. Lancaster, Chief Engineer, D-8

of the Texas Department of Transportation.

The ADIEM was developed under Texas DOT Project 2-8-90/1-990, "Standards, Policies, Guidelines and Designs."

Disclaimer Statement

TABLE OF CONTENTS

INTRODUCTION

In the field of roadside safety, transportation entities have always been handicapped by severe limitations in the public funds available for improvements. While the public demand for mobility has always been strong, the demand for greater levels of safety has been both limited and sporadic. This is the underlying reason for normally severe funding limitations for roadside safety improvements. Due to these economic constraints, the achievement of cost-effectiveness has been and is of critical importance.

The ends of concrete median barriers (CMB's) and portable concrete barriers (PCB's) are a troublesome safety problem. Some solutions such as the sloping concrete wedge have been low-cost, but effectiveness in reducing injuries is questionable. Sand filled barrels and the steel barrel cushions are fairly low-cost, but maintenance is difficult. Further, they require a wide median or roadside which is often not available, especially in constrained construction areas. The excessive width of these two cushions greatly increases the target size of the protective device, resulting in more collisions than would be produced when compared to a narrow cushion. Finally, there are narrow cushions for end treatments in narrow zones that perform quite well in collision circumstances. These, however, are extremely costly. The motivating situation for this work is the fact that there existed no low-cost, high performance, easily maintained end treatments for CMB's and PCB's. This report describes the development and final performance verification of such a terminal. Figure 1 and Table 1 show the final results of this development.

Chronological Development

During the early 70's TTI developed a vermiculite concrete crash cushion with good collision performance characteristics (1,2). While vermiculite concrete was shown to have good

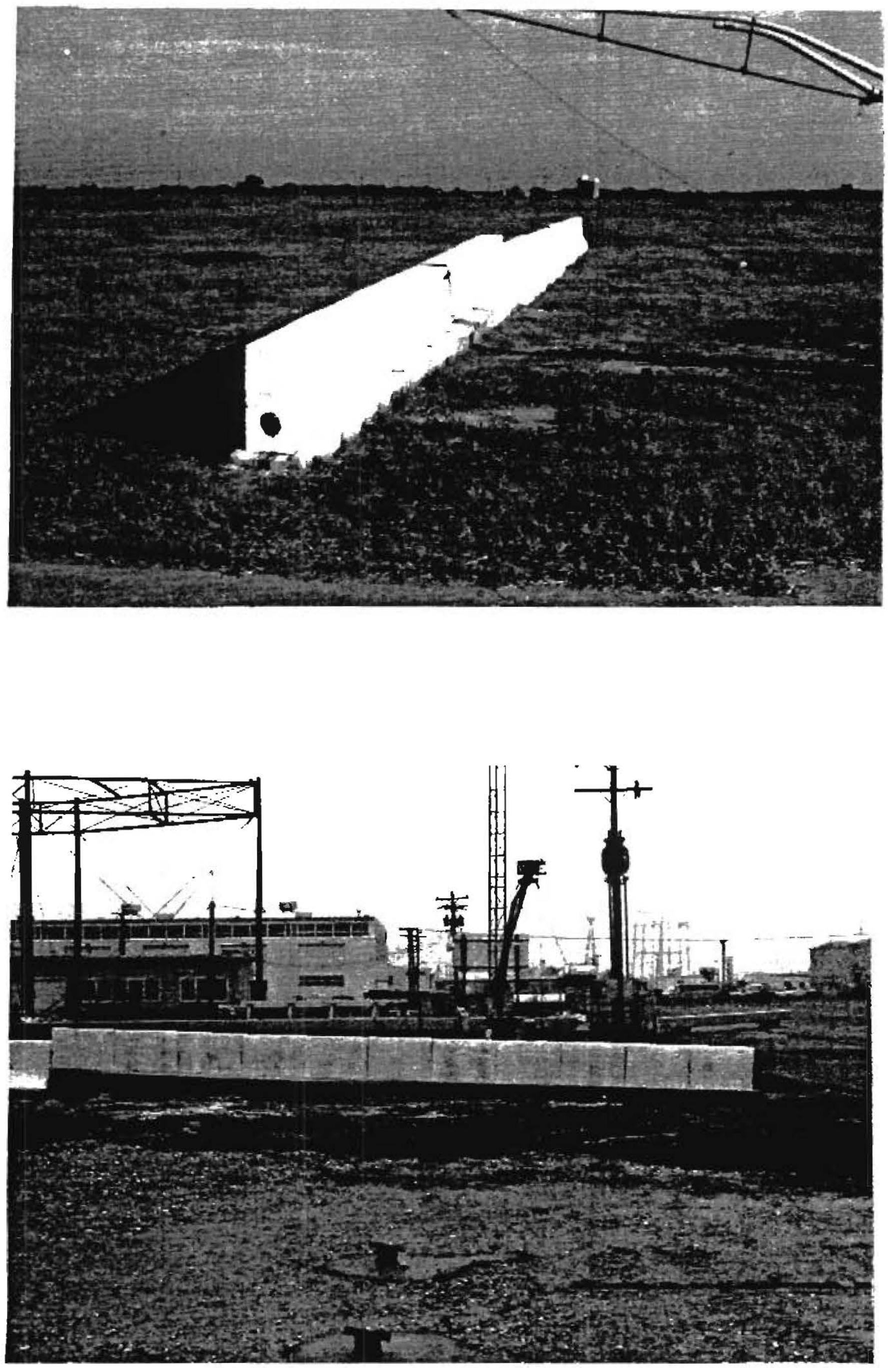


Figure 1. ADIEM terminal for concrete barriers.
(Concrete median barriers, portable concrete barriers and toll road collection zones.)

Table 1

Development of
PCC terminal for CMB's and PCB's
Results

PROJECTED* COST	$3000.00
INSTALLATION TIME	< 1 hour
EFFECTIVE DIMENSIONS	Length - 30 ft. Width - 2 ft.
AFTER A MAJOR COLLISION	
• Cost of replacement modules	$1500.00
• Time to clear crushed modules	< 20 min.
• Time to install new modules	< 20 min.
NCHRP 230 COMPLIANCE	Exceeds requirements of this guide by significant margins. (See Table 3.)

* Includes 50% profit for the manufacturer. This does not include a profit estimate for the contractor.

energy absorption characteristics, the design suffered from several drawbacks. Cardboard column forms were used to form the interior voids of the cushion. These cardboard elements deteriorated rapidly under many conditions. The cushion required extensive "fish scale" plywood side panels to affect redirection during side impacts. This requirement complicated installation procedures, increased cost, and made maintenance difficult. These cushions were used experimentally in Wisconsin and Florida but never became popular.

The concept of using low-strength, lightweight concrete as an energy absorbing material for crash cushions lay dormant until 1986. At that time it was clear that a cost effective end treatment for PCB's was badly needed. TTI, in an internal program, developed a design called ADIEM (Advanced Dynamic Impact Extension Module), a low strength concrete crash cushion. The Texas A&M University System, in following a new policy couched to help secure cost reducing competition into the field, sought patent protection for the device, and was subsequently issued such a patent (Number 4,822,208). In 1987 TTI approached engineers of the State Department of Highways and Public Transportation (SDHPT) with the ADIEM design and asked SDHPT to consider it for further development. That development under SDHPT sponsorship was carried out in three phases. Those phases can in part be illustrated by Figures 2, 3, and 4. The first concept was a simple modification of a fifteen foot segment of PCB using soft concrete (concrete weighing less than 40 lb/ft^3 with a compressive strength less than 200 psi).

In Phase 1, the original design was modified significantly to improve installation and maintenance characteristics. Material strength testing was conducted and individual modules of reinforced Perlite were tested at low speed using a 5000 lb. ram. From these tests a module was selected for vehicle crash testing. Finally, a complete end treatment was fabricated as illustrated by the "1st Prototype" in Figure 3. The complete ADIEM consisted of two elements. The first

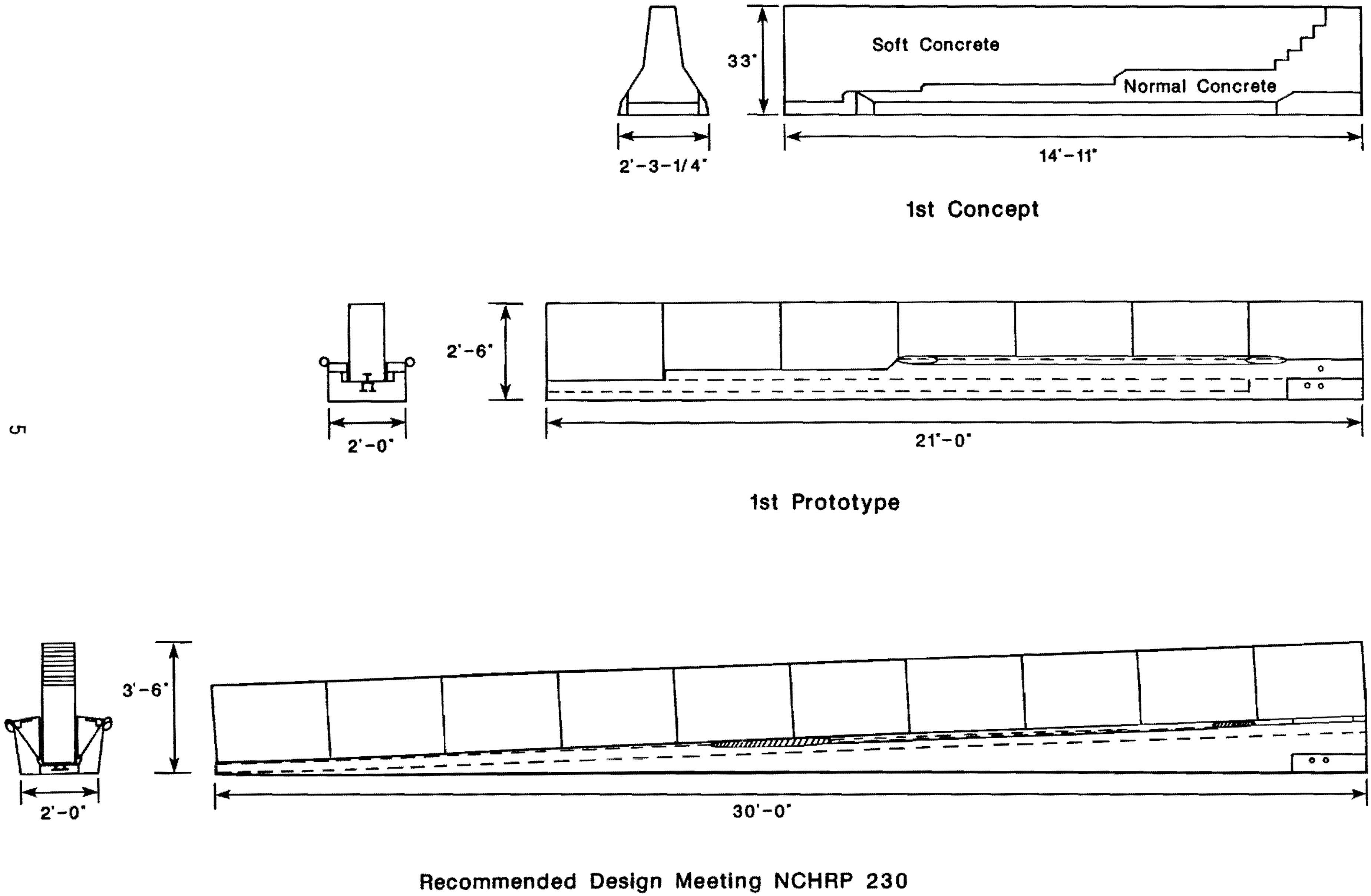


Figure 2. Evolution of ADIEM design.

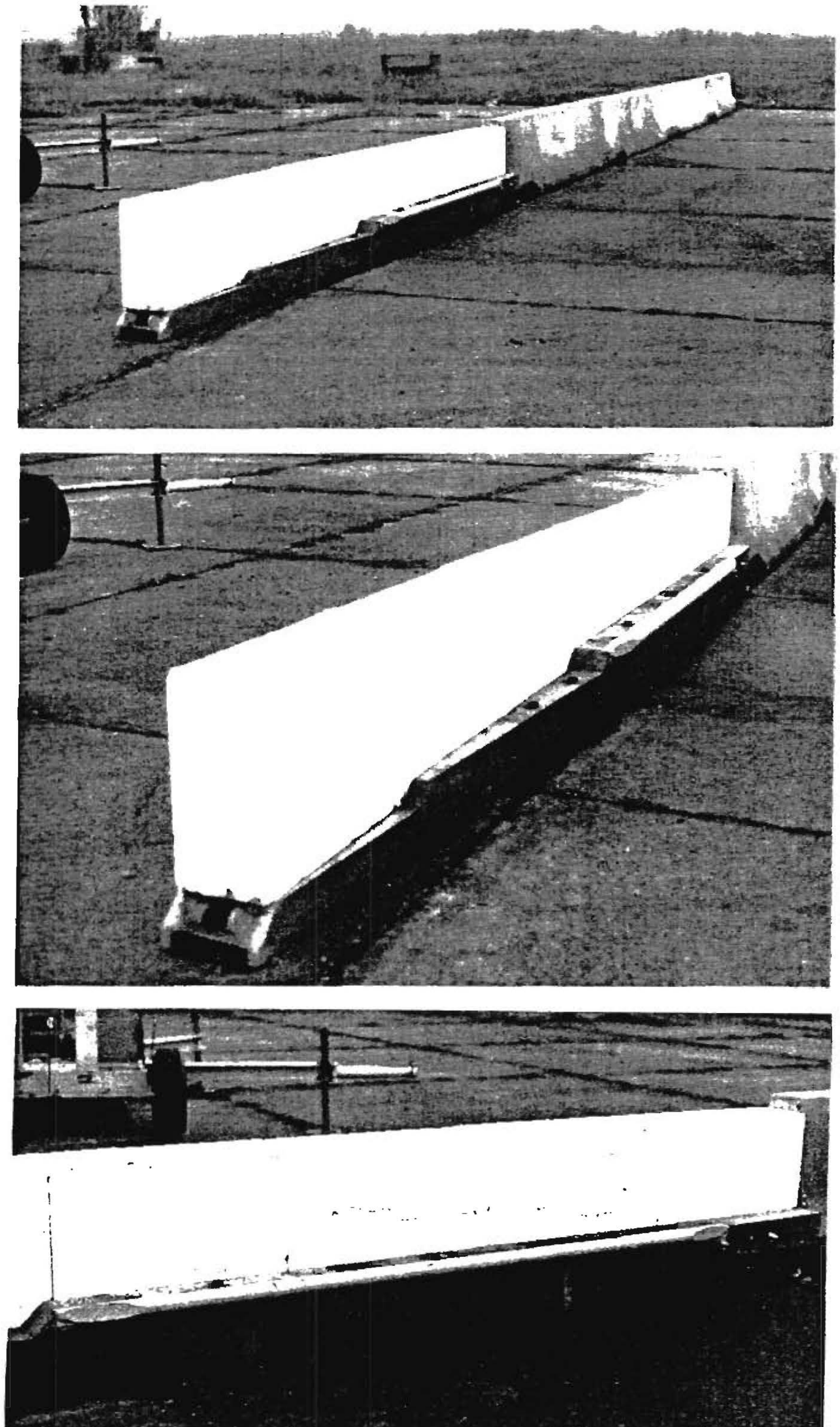
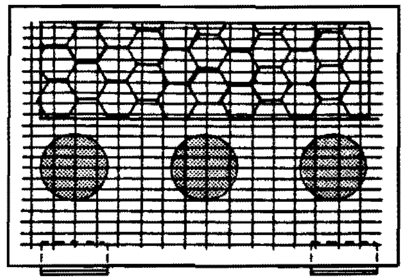


Figure 3. First prototype.

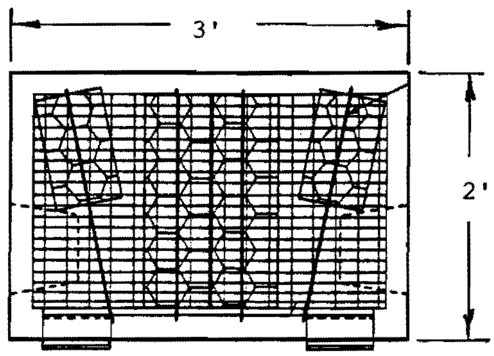
(a)



Side Views

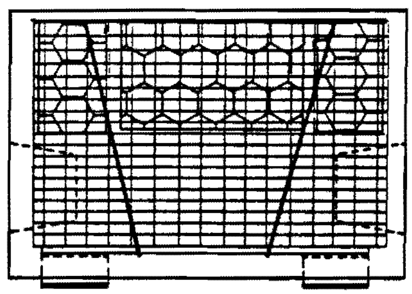
Early Concept

(b)



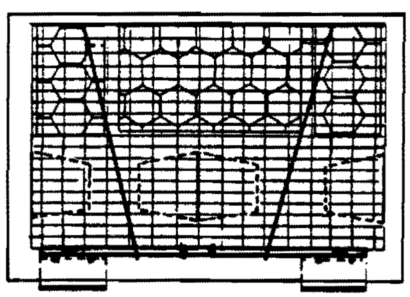
1st Prototype

(c)



Intermediate Prototype

(d)



Recommended Design Meeting NCHRP 230

Figure 4. Evolution of crushable module.

was a reinforced concrete carrier base. The base was tapered from a six inch frontal height to a 13 inch height in the rear half of the 21 foot terminal. Into the carrier base were keyed seven low strength concrete modules. Each module was three feet long, two feet in height, and eleven and one-half inches wide. Each module weighed about 200 lbs. The evolution of the module is shown in Figure 4. Modules "a" and "b" were tested in Phase 1. At the completion of Phase 1 engineers of the SDHPT decided the potential of the prototype was such that full scale crash testing was warranted.

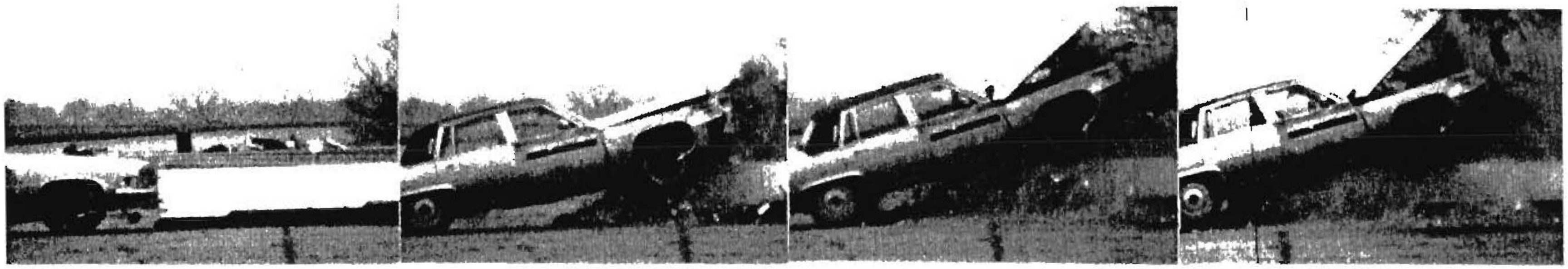
In Phase 2 five crash tests were conducted. These tests are summarized by Table 2. Further details of each crash test are given in Figures 5 through 9. These tests were presented in detail in an interim report (4, Vol. 2)

NCHRP 230 (3) gives the crash tests which should be conducted on a barrier end treatment (or barrier terminal) in order for it to be accepted for use by the highway community. The appropriate table from NCHRP 230 is shown by Figure 10. The three tests applicable are 41, 44, and 45 shown under "terminal" tests. Tests number 42 and 43 are not needed because tests 44 and 45, using the smaller automobile, are more critical from the vehicle stability and acceleration standpoints. Test 40 is not needed since the ADIEM terminal joins a conventional PCB at the "beginning of length of need". Thus, conducting this test would simply be testing a PCB, which has been done many times.

The tests conducted in Phase 2 are described in the following paragraphs along with a discussion of what was learned from each test and changes that were made to improve performance.

Table 2. Summary of developmental crash tests.

Test Type	Test No.	NCHRP* 230 No.	Test Date	Results	Comments:
Developmental (4500 lb./43.1 mph head on)	1	NA	03/03/89	Poor	Excessive deceleration, poor module failure pattern, vehicle ramped and rolled over. Redesign of modules was necessary.
Compliance (1800 lb./15°, mid-size)	2	44	03/03/89	Excellent	Passed 230-Vehicle was appropriately redirected. All aspects of 230 were met. Barrier performance was ideal. No maintenance would have been necessary. Barrier totally undamaged.
Developmental (4500 lb., 37.1 mph, head on)	3	NA	05/25/89	Good	Vehicle was smoothly decelerated. Deceleration rates were very low indicating module crushing strength was ideal. Vehicle damage was slight. All modules would need to be replaced.
Developmental (1800 lb./58.4 mph, head on, 15 inches off center)	4	45	08/01/89	Marginal	Did not pass 230. Deceleration rates were too high. Vehicle stability was good, but damage severe. Concrete strength determined to be 60% too high. Some failure in module reinforcement noted. Small change in module reinforcement was necessary.
Developmental (4500 lb., 57.6 mph, head on)	5	41	09/28/89	Good	Passed 230. Deceleration rates excellent. All aspects of 230 were met. Vehicle damage reasonable. Some modules did not clear as preferred resulting in modest vehicle ramping at end of interaction with barrier and after speed had been reduced to below 20 mph. Modest changes in module reinforcement should improve interaction.

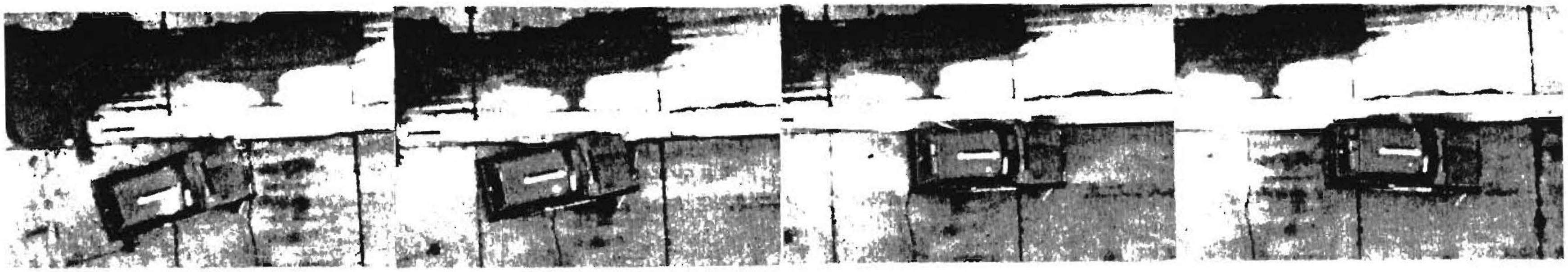


0.000 s 0.247 s 0.494 s 0.740 s

Test No.	9429G-1
Date	03/03/89
Test Installation.	Adiem Impact Attenuator
Length of Installation . .	21.0 ft (6.4 m)
Vehicle	1979 Cadillac Sedan DeVille
Vehicle Weight	
Test Inertia	4,500 lb (2,041 kg)
Vehicle Damage Classification	
TAD	12FC-5
CDC	12FCEN2

Impact Speed	43.1 mi/h (69.4 km/h)
Impact Angle.	0 deg - center
Exit Speed.	Not Available
Vehicle Accelerations (Max. 0.050-sec Avg)	
Longitudinal.	-14.6 g
Lateral	-1.3 g
Occupant Impact Velocity	
Longitudinal.	37.7 ft/s (11.5 m/s)
Lateral	7.5 ft/s (2.3 m/s)
Occupant Ridedown Accelerations	
Longitudinal	-9.2 g
Lateral.	-1.2 g

Figure 5. Summary of results for test 9429G-1.



0.000 s 0.074 s 0.146 s 0.222 s

Test No. 9429G-2
Date 03/03/89
Test Installation. . . . . Adiem Impact Attenuator
Length of Installation . . 21.0 ft (6.4 m)
Vehicle. . . . . 1980 Honda Civic
Vehicle Weight
  Test Inertia . . . . 1,800 lb (816 kg)
Vehicle damage Classification
  TAD. 11LFQ-3
  CDC. 11FFEW3

Impact Speed . . . . 61.2 mi/h (98.6 km/h)
Impact Angle. . . . . 15.1 deg
Exit Speed. . . . . 54.5 mi/h (87.7 km/h)
Exit Angle. . . . . 2.5 deg
Vehicle Accelerations
  (Max. 0.050-sec Avg)
  Longitudinal. . . . . . . -6.3 g
  Lateral . . . . -13.1 g
Occupant Impact Velocity
  Longitudinal. . . . . . . 16.6 ft/s (5.1 m/s)
  Lateral . . . . 24.7 ft/s (7.5 m/s)
Occupant Ridedown Accelerations
  Longitudinal. . . . . . . -1.8 g
  Lateral . . . . -5.0 g

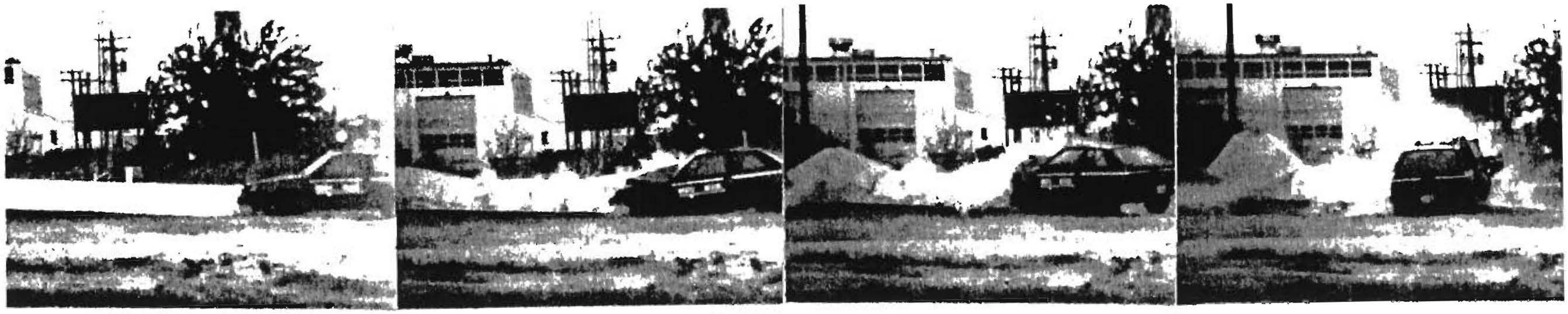
Figure 6. Summary of results for test 9429G-2.

0.000 s　　0.100 s　　0.210 s　　0.310 s

Test No.	9429G-3
Date	05/25/89
Test Installation.	Adiem Impact Attenuator
Length of Installation . .	21.0 ft (6.4 m)
Vehicle.	1979 Oldsmobile Ninety-Eight
Vehicle Weight	
Test Inertia.	4,500 lb (2,041 kg)
Vehicle damage Classification	
TAD.	12FC-1
CDC.	12FCEN1

Impact Speed	37.1 mi/h (59.6 km/h)
Impact Angle.	0 deg - center
Exit Speed.	Not Available
Vehicle Accelerations	
(Max. 0.050-sec Avg)	
Longitudinal.	-6.9 g
Lateral	-2.1 g
Occupant Impact Velocity	
Longitudinal.	24.9 ft/s (7.6 m/s)
Lateral	7.7 ft/s (2.4 m/s)
Occupant Ridedown Accelerations	
Longitudinal.	-8.4 g
Lateral	-1.6 g

Figure 7. Summary of results for test 9429G-3.

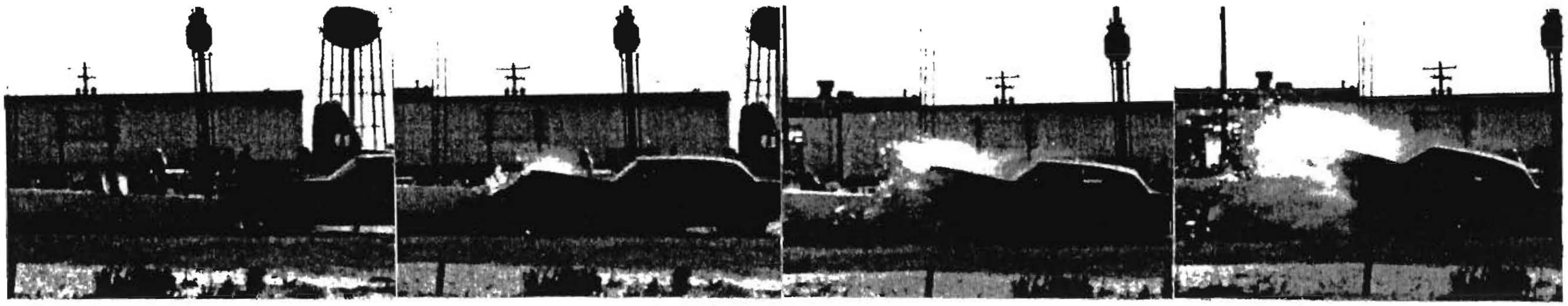


0.000 s | 0.120 s | 0.239 s | 0.419 s

Test No. 9429G-4
Date 08/01/89
Test Installation. . . . . Adiem Impact Attenuator
Length of Installatiton. . 24.0 ft (7.3 m)
Vehicle. . . . . 1983 Plymouth Colt
Vehicle Weight
  Test Inertia . . . . 1,800 lb (816 kg)
  Gross Static . . . . 1,969 lb (893 kg)
Vehicle Damage Classification
  TAD. 12FR6
  CDC. 12FRAN8

Impact Speed . . . . 58.4 mi/h (93.9 km/h)
Impact Angle. . . . . 0 deg - center
Exit Speed. . . . . Not Available
Vehicle Accelerations
  (Max. 0.050-sec Avg)
  Longitudinal. . . . . . . -21.3 g
  Lateral . . . . -6.8 g
Occupant Impact Velocity
  Longitudinal. . . . . . . 47.9 ft/s (14.6 m/s)
  Lateral . . . . 9.3 ft/s (2.8 m/s)
Occupant Ridedown Accelerations
  Longitudinal. . . . . . . -11.7 g
  Lateral . . . . -3.9 g

Figure 8. Summary of results for test 9429G-4



0.000 s 0.114 s 0.229 s 0.343 s

Test No. 9429G-5
Date 09/28/89
Test Installation. . . . . Adiem Impact Attenuator
Length of Installatiton. . 24.0 ft (7.3 m)
Vehicle. . . . . 1979 Oldsmobile Ninety-Eight
Vehicle Weight
  Test Inertia . . . . . . 4,500 lb (2,041 kg)
Vehicle Damage Classification
  TAD. 12FC4
  CDC. 12FCEN2

Impact Speed . . . . . . 57.6 mi/h (92.7 km/h)
Impact Angle. . . . . . . 0 deg - center
Exit Speed. . . . . Not Available
Vehicle Accelerations
  (Max. 0.050-sec Avg)
  Longitudinal. . . . . . -9.1 g
  Lateral . . . . -2.0 g
Occupant Impact Velocity
  Longitudinal. . . . . . 29.7 ft/s (9.1 m/s)
  Lateral . . . . 4.9 ft/s (1.5 m/s)
Occupant Ridedown Accelerations
  Longitudinal. . . . . . -9.5 g
  Lateral . . . . 1.4 g

Figure 9. Summary of results for test 9429G-5.

CRASH TEST CONDITIONS FOR MINIMUM MATRIX

Appurtenance	Test Designation	Vehicle Type[d]	Impact Speed (mph)	Impact Angle[e] (deg)	Target Impact Severity[f] (ft-kips)	Impact Point[g]	Evaluation Criteria[h]
Longitudinal Barrier[a] Length-of-Need	10	4500S	60	25[i]	$97^{-9,+17}$	For post and beam systems, midway between posts in span contianing railing splice	A,D,E,H,I
	11	2250S	60	15[i]	$18^{-2,+3}$	For post and beam systems, vehicle should contact railing splice	A,D,E,F,(G),H,I
	12	1800S	60	15[i]	$14^{-2,+2}$	For post and beam system, vehicle should contact railing splice	A,D,E,F,(G),H,I
Transition	30	4500S	60	25[i]	$97^{-9,+17}$	15 ft upstream from second system	A,D,E,H,I
Terminal	40	4500S	60	25[i]	$97^{-9,+17}$	At beginning of lenth-of-need	A,D,E,H,I
	41	4500S	60	0[i]	$541^{-53,+94}$	Center nose of device	C,D,E,F,(G),H,J
	42	2250S	60	15[i]	$18^{-2,+3}$	Midway between nose and lenth-of-need	C,D,E,F,(G),H,I,J
	43	2250S	60[o]	0[i]	$270^{-26,+47}$	Offset 1.25 ft from center nose of device	C,D,E,F,(G),H,J
	44	1800S	60	15[i]	$14^{-2,+2}$	Midway between nose and length-of-need	C,D,E,F,(G),H,I,J
	45	1800S	60[o]	0[i]	$216^{-21,+37}$	Offset 1.25 ft from center nose of device	C,D,E,F,(G),H,J
Crash Cushion[b]	50	4500S	60	0[j]	$541^{-53,+94}$	Center nose of device	C,D,E,F,(G),H,J
	51	2250S	60[o]	0[j]	$270^{-26,+47}$	Center nose of device	C,D,E,F,(G),H,J
	52	1800S	60[o]	0[j]	$216^{-21,+37}$	Center nose of device	C,D,E,F,(G),H,J
	53[l]	4500S	60	20[j]	$63^{-6,+11}$	Alongside, midlength	C,D,E,H,I,J
	54	4500S	60	10-15[j]	$541^{-53,+94}$	0-3 ft offset from center of nose of device	C,D,E,F,(G),H,J
Breakaway or Yielding Support[c]	60	2250S	20	[k]	$30^{-4,+4}$	Center of bumper[m,n]	B,D,E, F,(G),H,J
	61	2250S	60	[k]	$270^{-26,+47}$	At quarter point of bumper[n]	B,D,E,F,(G),H,J
	62	1800S	20	[k]	$24^{-3,+3}$	Center of bumper[m,n]	B,D,E,F,(G),H,J
	63	1800S	60	[k]	$216^{-21,+37}$	At quarter point of bumper[n]	B,D,E,F,(G),H,J

(a) Includes guardrail, bridgerail, median and construction barriers.
(b) Includes devices such as water cells, sand containers, steel drums, etc.
(c) Includes sign, luminaire, and signal box supports.
(d) See Table 2 for description.
(e) + 2 degrees
(f) $IS = 1/2\, m\, (v \sin \theta)^2$ where m is vehicle test inertial mass, slugs; v is impact speed, fps; and θ is impact angle for redirectional impacts or 90 deg for frontal impacts, deg.
(g) Point on appurtenance where initial vehicle contact is made.
(h) See Table 6 for performance evaluation factors; ( ) denotes supplementary status.
(i) From centerline of highway.
(j) From line of symmetry of device.
(k) Test article shall be oriented with respect to the vehicle approach path to a position that will theoretically produce the maximum vehicle velocity change; the orientation shall be consistent with reasonably expected traffic situations.
(l) See Commentary, Chapter 4 Test Conditions for devices which are not intended to redirect vehicle when impacted on the side of the device.
(m) For base bending devices, the impact point should be at the quarter point of the bumper.
(n) For multiple supports, align vehicle so that the maximum number of supports are contacted assuming the vehicle departs from the highway with an angle from 0 to 30 deg.
(o) For devices that produce fairly constant or slowly varying vehicle accelerations; an additional test at 20 mph (32 kph) is recommended for staged devices, those devices that produce a sequence of individual vehicle deceleration pulses (i.e. "lumpy" device) and/or those devices comprised of massive components that are displaced during dynamic performance (see commentary).

Figure 10. Table 3, page 9 of NCHRP 230

Test 9429G-1 (Developmental Test)

The 4500 lb. vehicle impacted the cushion head-on at 43 mph. The vehicle ramped and rolled over after stopping momentarily on the top of the cushion. The module performance was poor. The basic 2 ft. x 3 ft. x 1 ft. geometry was maintained, but the module reinforcement and concrete strength were redesigned before the third test was conducted. Details of this first test are given in reference 4, Volume 2. (See Test Report 9429G-1.)

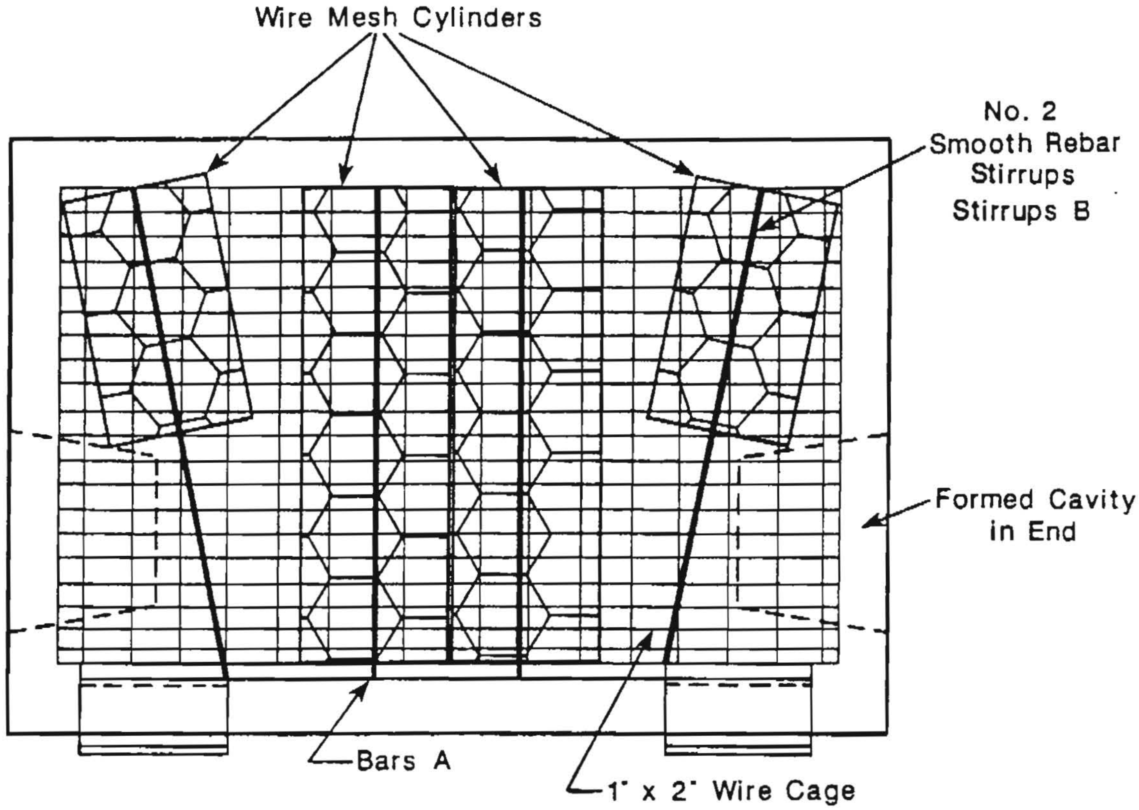
Test 9429G-2 (Developmental Test)[1]

The same cushion used in Test 1 was used. The modules damaged in Test 9429G-1 were replaced. Since this test indicated the performance of the structural concrete carrier base curb and rail, the crushable modules which clearly required redesign were expected to exert no influence. The cushion was impacted on the left side 10.5 feet from the front and 10.5 feet from where the carrier base was bolted to the PCB. Performance was excellent. The 1800 lb. vehicle was redirected in a stable manner. No significant damage to the cushion occurred. The requirements of NCHRP 230 were satisfied. Details of this test are given in reference 4, Volume 2 and also in the appendix to this report. (See Test Report 9429G-2.) It should be noted for later discussion that the vehicle's left front wheel impacted the rounded part of the pipe rail in contrast with the flattened, tapered segment.

Test 9429G-3 (Developmental Test)

This was a repeat of Test 1 after the modules had been redesigned. The modules were constructed as shown in Figure 4(b) and 11 with three levels of Perlite concrete strength as shown in Figure 12. Performance was ideal. The 4500 lb. vehicle impacted at 37 mph and decelerated in a stable and smooth manner. At this stage it was believed a good module design

[1] In final performance summary this test is NCHRP 230 Compliance Test No. 44.



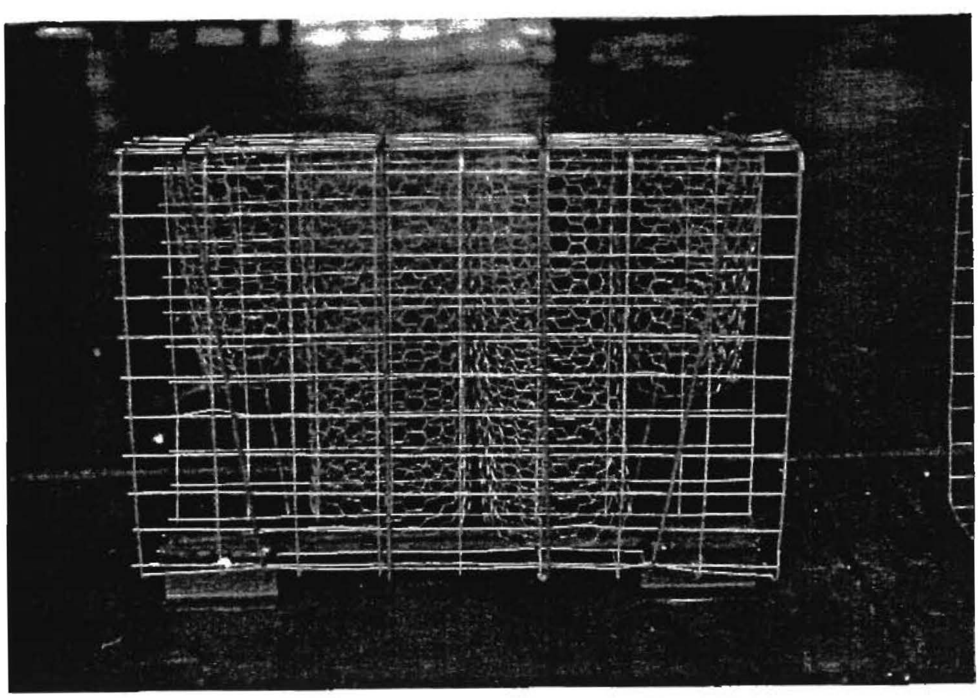
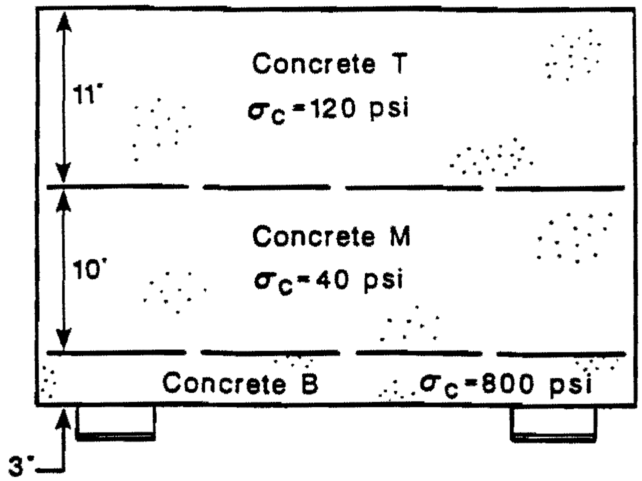


Figure 11. First revision of module reinforcement (Tests 9429G-3 and 4).



ELEVATION SINGLE MODULE

	Concrete T	Concrete M	Concrete B
Cement	340 lbs.	180 lbs.	520 lbs.
Water	425 lbs.	350 lbs.	520 lbs.
Perlite	205 lbs.	225 lbs.	240 lbs.
Air Agent	1000 cc.	1300 cc.	1000 cc.
Unit Weight	36 lbs./ft.^{3}	28 lbs./ft.^{3}	47 lbs./ft.^{3}
Compressive Strength	120 psi	40 psi	800 psi

Figure 12. Batch Designs* and placement of concrete within module for tests 9429G-3 and 4.

* For 1 cubic yard of concrete

had been achieved. Details of this test are given in reference 4, Volume 2. (See Test Report 9429G-3.)

<u>Test 9429G-4</u> (Compliance Test No. 45)

All modules were replaced after test 3. There had been some difficulty with unit weights during the batching of these modules and the penetrometer shown in Figure 13 was nearing completion. It was not available for quality control on the modules used in this test. The vehicle weighed 1800 lbs. and impacted head-on but was offset from center by 1.25 feet. The test speed was 58 mph. The vehicle reaction to the barrier was a stable spin-out as is characteristic of this type of test. The deceleration rates were about 60% too high and some module elements became detached from the carrier base and came to rest where they were considered to be a potential hazard to other traffic. It was clear the modules had not crushed at the design force level. Several days later the large penetrometer was completed (Figure 13) and the strength of the Perlite concrete was determined. Based on those penetrometer tests of concrete elements from the broken modules, it was found the concrete strength on the top two levels of each module was about 60% higher than designed. The decelerations were also found to be about 60% too high when compared to those suggested by NCHRP 230. Since the vehicle reaction was stable during the test it was concluded that reducing the concrete strength to the appropriate level would have only made that reaction better. It was also concluded that test (No. 45), if re-run on a cushion of appropriate concrete strength, would probably result in an interaction which complied with NCHRP 230.

When the cushion was tested at these elevated levels of concrete strength some failures in the reinforcement cage occurred. This allowed large module segments to become detached from the carrier base. To preclude the possibility of this occurring in the next proposed test,

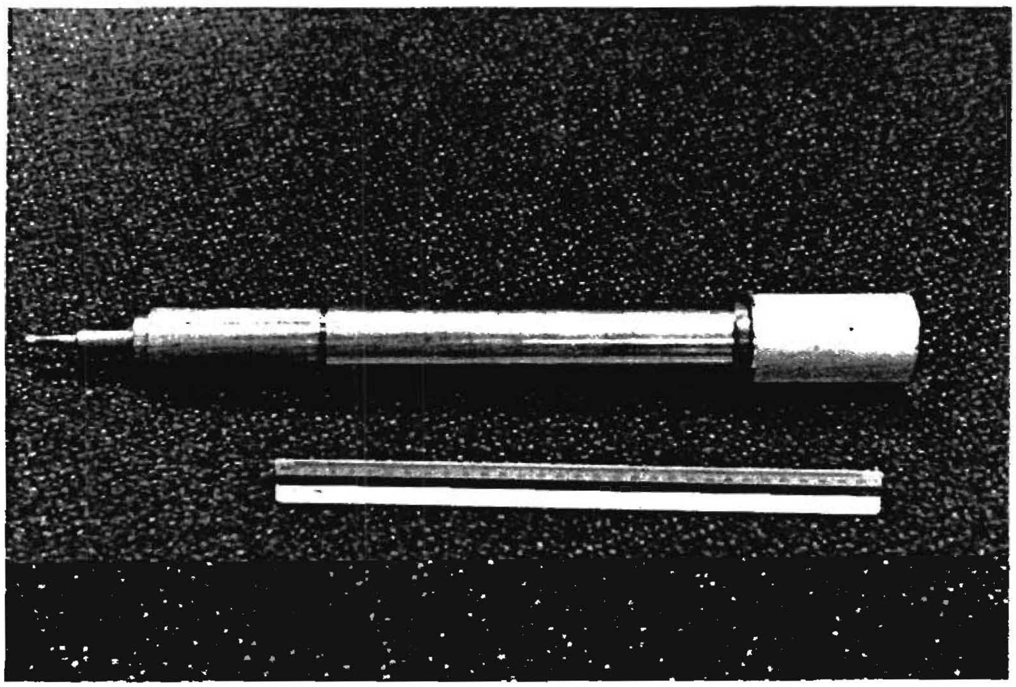


Figure 13. Penetrometer developed to test concrete strengths between 20 and 250 psi.

the 60 mph large automobile head-on, changes were made in the module reinforcement cage. Referring to Figure 11, the change was to the two reinforcing bars that extend longitudinally between the top flanges of the 3 x 5.7 x 5" S beam segments. These are the beam segments that fit in the carrier base keyway. Up until this time those longitudinal bars (Bars A) were No. 3 deformed re-bars. These No. 3 bars were changed to one-half inch smooth square bars. This cross sectional area is roughly twice that of a No. 3 bar and should prevent the failure of those elements under high energy loadings. The four rectangular stirrups that extend from the bottom to the top of the module (Stirrups B) wrap around Bars A. Changing to the smooth square bars should also allow Stirrups B to slide along Bars A as the module is crushed with less resistance. Details of this test are given in reference 4, Volume 2. (See Test Report 9429G-4.)

Test 9429G-5 (Compliance Test No. 41)

In this final test of the Phase 2 development work a 4500 lb. vehicle was directed head-on into the cushion at a speed of 58 mph. The result was good. The vehicle was brought smoothly to a stop in a distance of 20 ft. It stayed in an extremely stable condition for the first nine feet (through three modules), then began to ride up as the fourth module was penetrated and rode up higher on the fifth module. The vehicle came to rest with its front end elevated about three feet above the ideal level. (See Figure 9.) Throughout the vehicle cushion interaction the vehicle was stable. The velocity change during the first part of the collision was 29.7 feet per second (fps). (NCHRP 230 suggests an allowable value of 40 fps and a design value of 30 fps.) The ridedown acceleration was 9.5 g's. (NCHRP 230 suggests an allowable value of 20 g's and a design value of 15 g's.)

In summary, all requirements of NCHRP 230 were met. The ramping toward the end of the interaction, however, was not the preferred vehicle reaction. Investigation showed a combination of two unfavorably interacting factors produced this reaction. First and most importantly, elements of the first three modules did not disintegrate and clear adequately as they were crushed. These elements were partially pulled down by the stirrups and were concentrated just above the carrier base as shown in Figure 14. The second factor was the way the ½" square bars (Bars A) within the module deformed. As the S beam segments on each end of a module are forced together during crushing the two connecting ½" square bars (Bars A) are bent into a hair pin shape which contributes to vehicle ramping. (See figure 14b.)

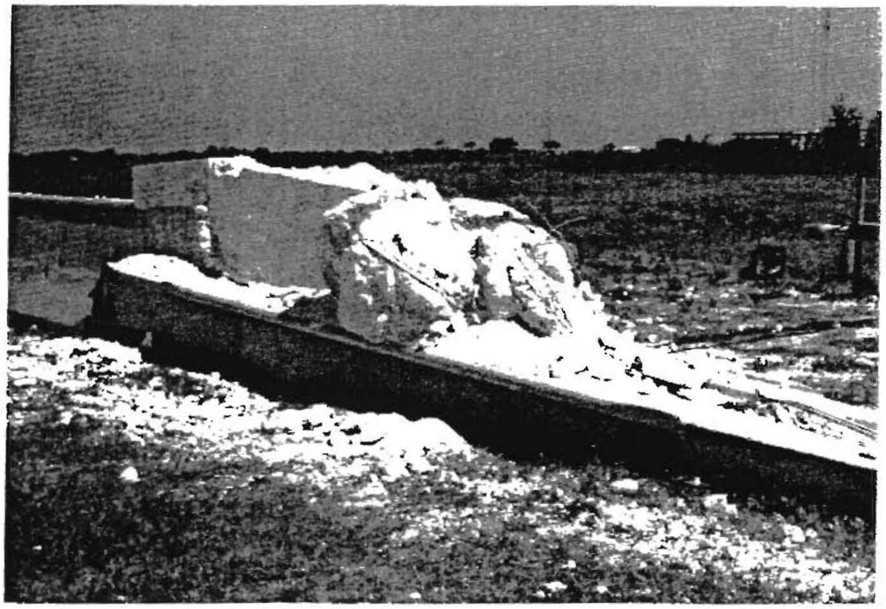
At the conclusion of Phase 2 it was determined that significant changes to improve performance should be made and that a final phase (Phase 3) should be used to perform the three pertinent NCHRP 230 compliance tests.

Phase 3 Re-design and Final Compliance Testing

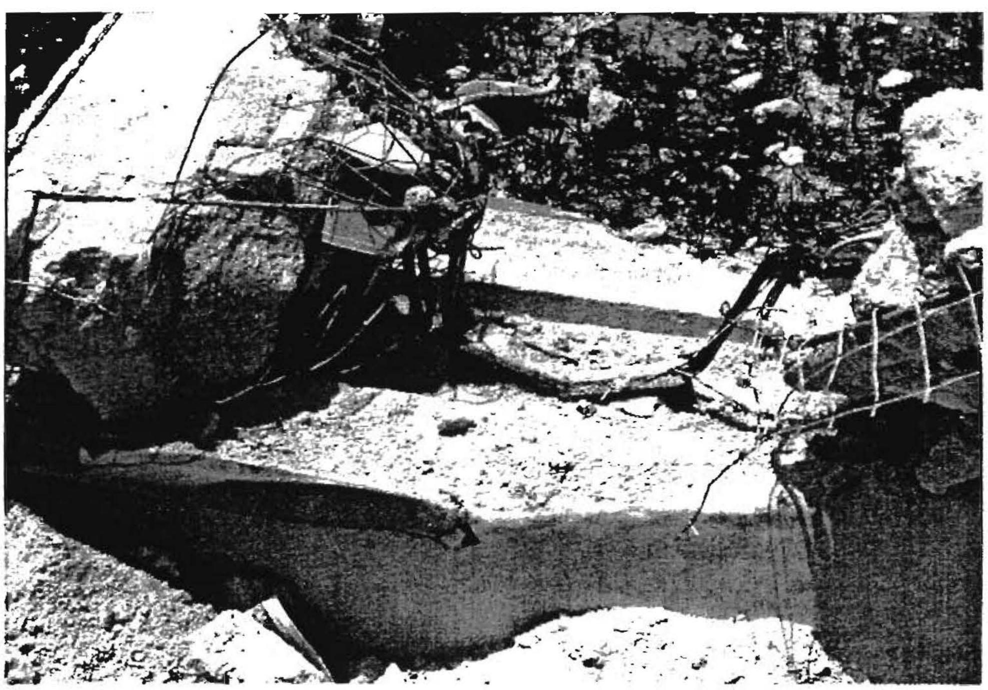
A complete analysis of the tests performed in Phase 2 was performed. Based on this analysis the changes were as follows.

1. Changes to the carrier beam.

This beam was increased from twenty-four to thirty-three feet in length. Eleven three ft. modules would then be needed to fill the carrier beam. The average deceleration level, a function of module crushing force, could thus be further reduced. This would also result in more of the carrier beam available to "stack" the crushed modules that would be carried down the beam track as a vehicle advanced. This stacking of the crushed modules at the end of the 21 ft. beam had played a part in the ramping which occurred in the 60 mph head-on test, No. 9429G-5. The top of the carrier beam was also redesigned to be one smooth slightly rising surface throughout the length of the beam. This was done to preclude any discontinuities which might contribute to ramping.



(a)



(b)

Figure 14. ADIEM impact attenuator after test 9429G-5.

2. Changes to the module.

The reinforcement of the module was changed as follows. a.) The two longitudinal ½" x ½" square steel bars (Bars A, Figure 11) were replaced by two No. 2 round steel bars and a loop of ¼" wire rope secured by cable clamps. The new design of reinforcement is shown in Figures 15 & 16. In earlier tests the square steel bars were deformed into a relatively rigid "hair pin" shape which contributed to ramping. The combination of thin bars and cable would deform easily under a horizontal load from a bumper or frame without forcing the front of the vehicle to climb. b.) An additional void was cast in the center of the middle, lowest strength level of the Perlite concrete and that middle level was extended to within seven inches of the module top. The bottom level of perlite concrete (three inches) was reduced in strength to 120 psi, the same strength as the top layer. This redesign of the module concrete is shown in Figure 17.

The final three compliance tests are summarized by Table 3 and by Figures 18, 19 and 20. In addition, Test 9429G-2 (Figure 6) is shown to provide verification of improvement resulting from the modification of the side rail pipe taper. These tests are documented by test reports 9901E-1, 2 and 3 and 9429G-2, which are located in the appendix.

In the following paragraphs these tests are described together with a discussion of the single change that was required to achieve ideal performance and unqualified compliance with NCHRP 230. The terminal used in tests 9901E-1, 2 and 3 is shown in Figures 21, 22 and 23.

Test 9901E-1

A 1979 Lincoln Continental impacted the ADIEM terminal at 60.3 mph (97.1 km/h). The vehicle weight was 4,500 lbs. (2,041 kg).

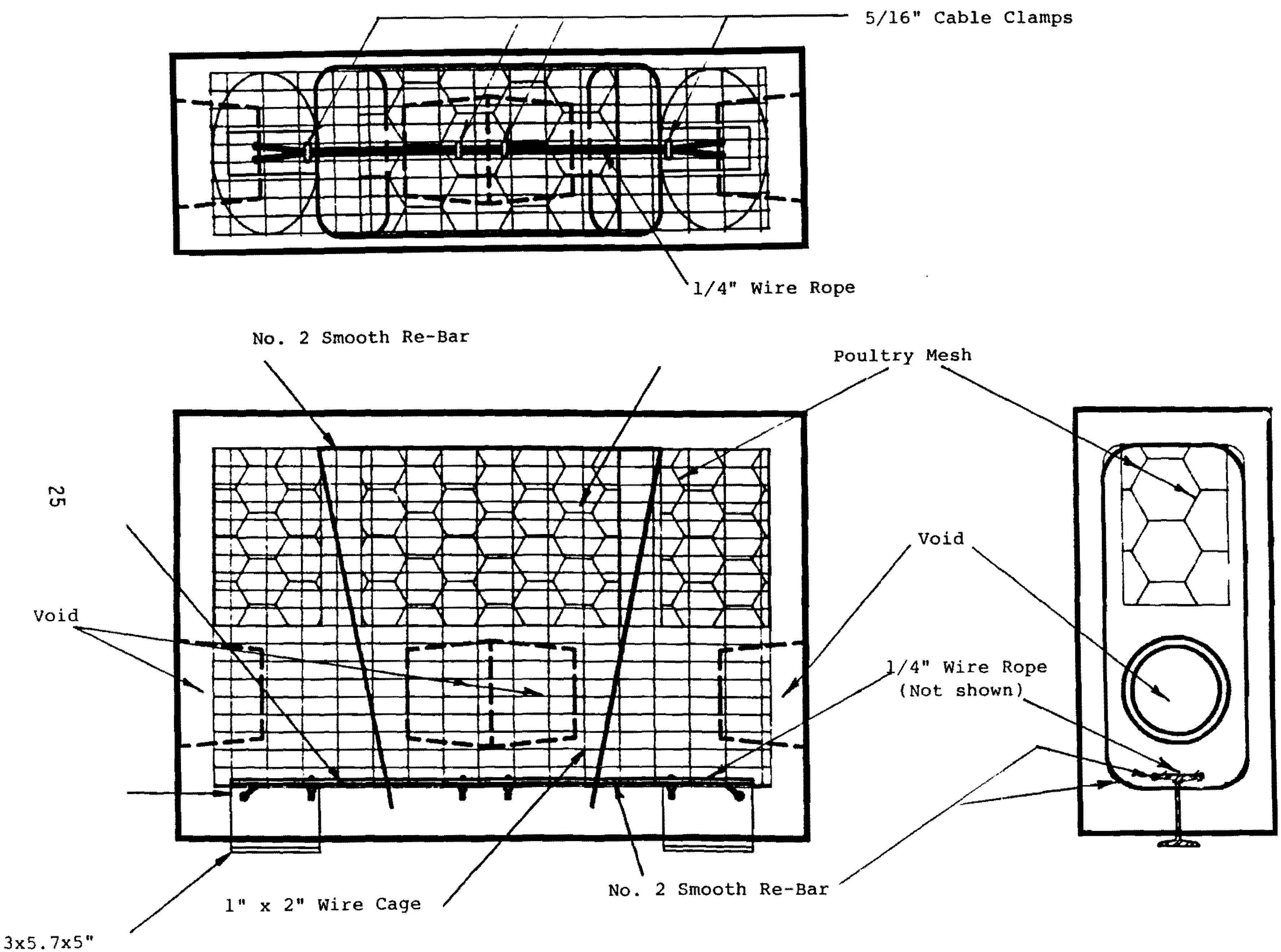


Figure 15. Final design of crushable module.

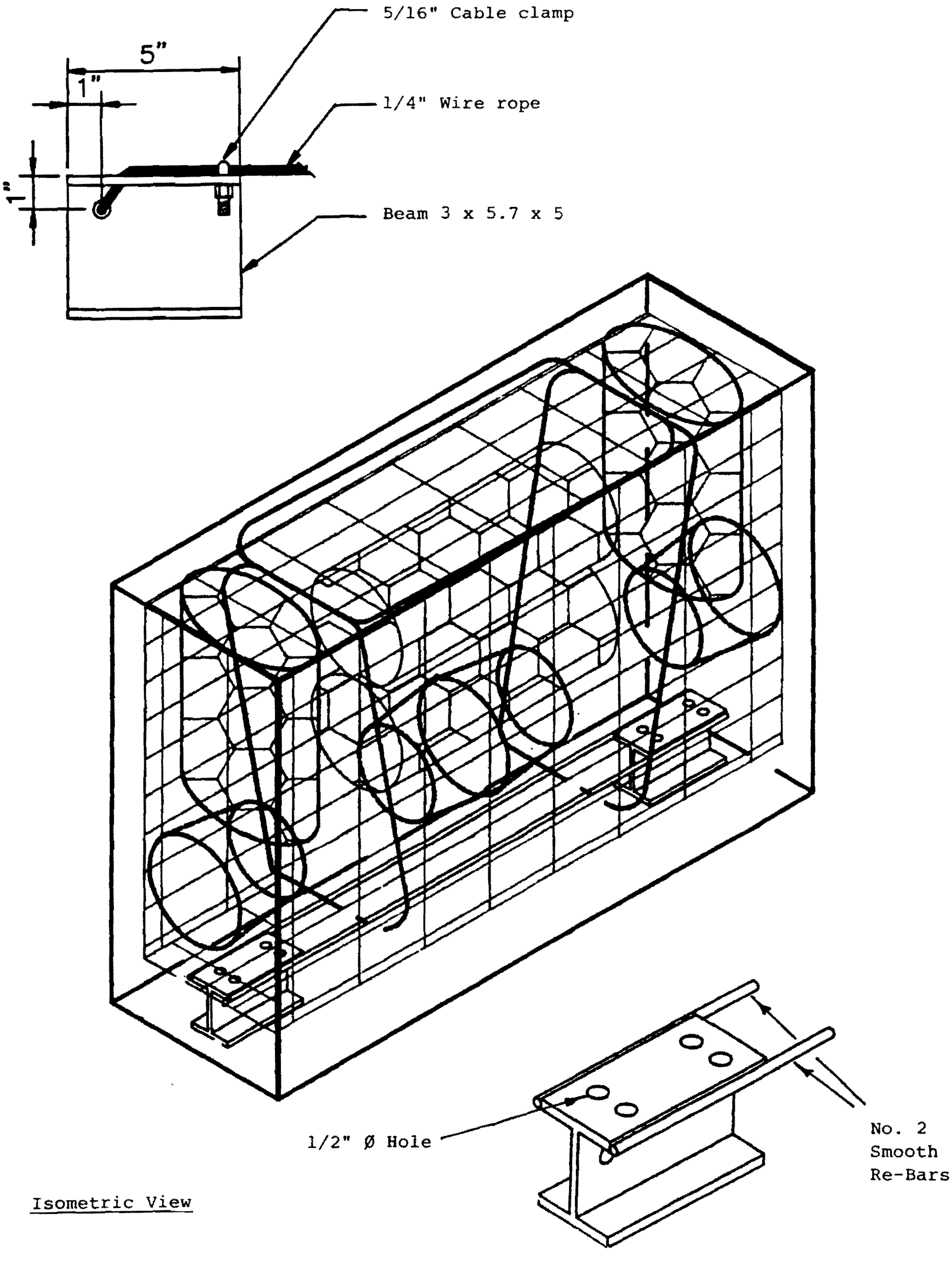
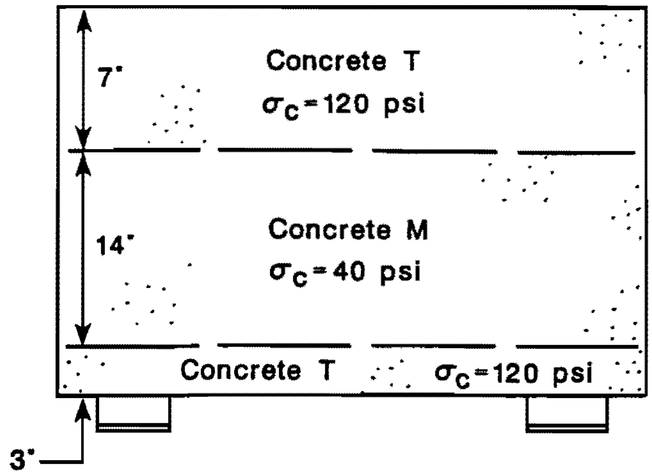


Figure 16. Isometric view of module reinforcement.



Note: Reinforcement is not shown.

ELEVATION SINGLE MODULE

	Concrete T	Concrete M
Cement	340 lbs.	180 lbs.
Water	425 lbs.	350 lbs.
Perlite	205 lbs.	225 lbs.
Air Agent	1000 cc	1300 cc
Unit Weight	36 lbs./ft.^{3}	28 lbs./ft.^{3}
Compressive Strength	120 psi	40 psi

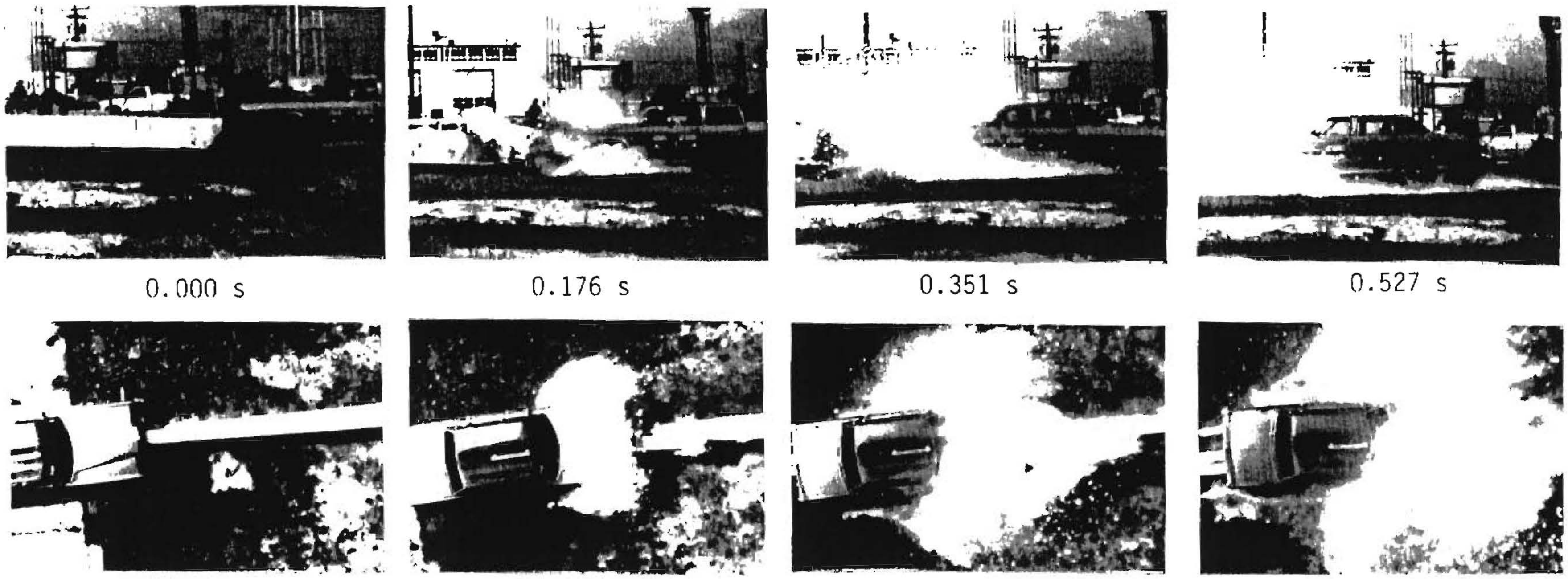
Note: These batch designs are applicable for the brand of Perlite used in this program. Trial batch designs to verify appropriate strength will be necessary when other brands are used and possibly when the Perlite provided by a particular supplier varies from shipment to shipment. Unit weight is a good early warning of product variability.

Figure 17. Final concrete placement recommended for modules.

Table 3. Summary of Compliance Test Data and NCHRP 230 Requirements

Test No. (Wt., Angle, Position)	NCHRP* 230 No.	Change in Velocity (longitudinal/lateral)	Acceleration (longitudinal/lateral)	Remarks:
1 (4500 lb./0°/head on)	41	29.8 fps / NA (30)*	-6.3 g's / No Contact (15)	Performance excellent.
2 (1800 lb./0°/15" offset)	45	37.4 fps / 8.9 fps (40)	-10.6 g's / -1.6 g's (15)	Performance excellent.
3 (1800 lb./15°/Side)	44	11.8 fps / -26.3 fps (30)	-4.9 g's / -7.3 g's (15)	Performance fair. Pitch larger than preferred. (Rail modification to correct problem verified by test 3^1.)
3^1 (1800 lb./15°/Side)	44	16.6 fps / 24.7 fps (30)	-1.8 g's / -5.0 g's (15)	Test verifies performance of rail modification described on page 49.

* Numbers in parenthesis are NCHRP 230 Requirements (See Table 8 of Reference 3)



Test No. 9901E-1
Date 10/16/90
Test Installation . . . . Adiem Impact Attenuator

Installation Length . . . 33.0 ft (10.1 m)
Vehicle . . . . 1979 Lincoln

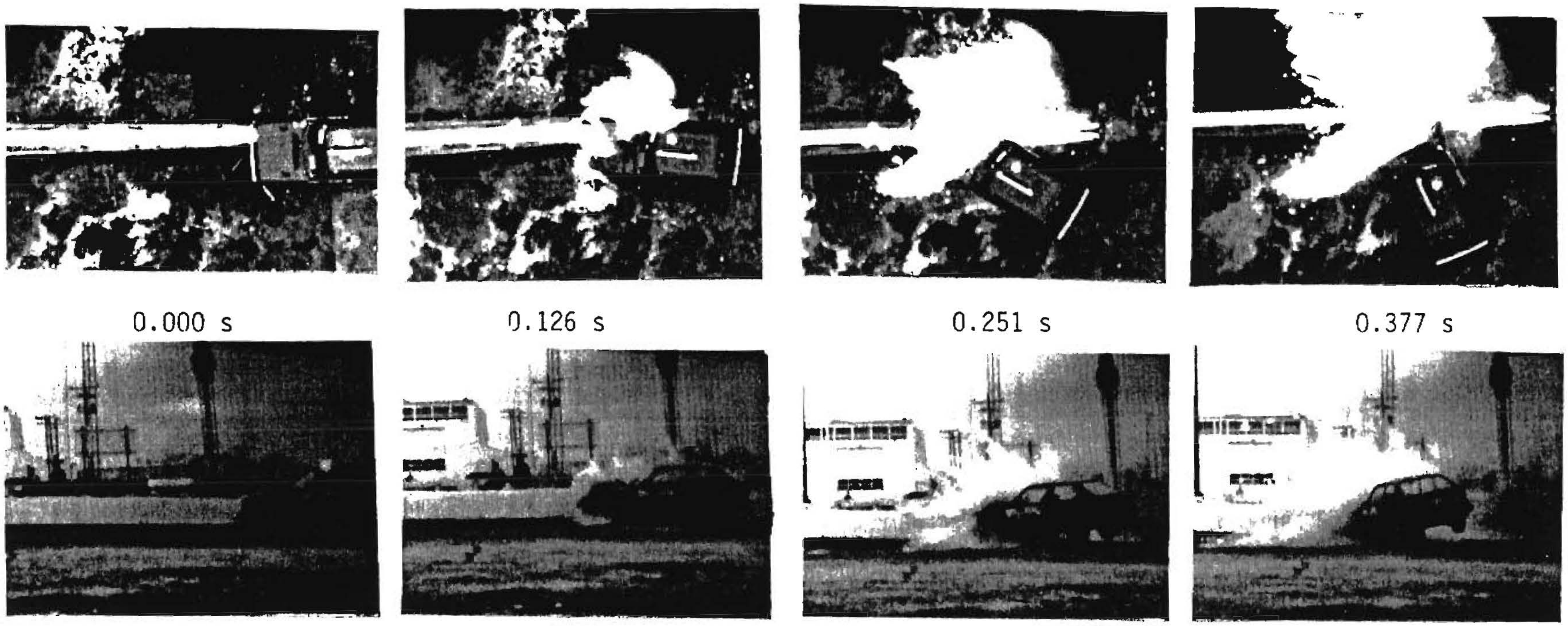
Vehicle Weight
Test Inertia . . . . 4,500 lb (2,041 kg)

Vehicle Damage Classification
TAD 12FC-3
CDC 12FCEN1

Impact Speed . . . . . . 60.3 mi/h (97.1 km/h)
Impact Angle . . . . . . 0 deg - center
Exit Speed . . . . Not Applicable

Vehicle Accelerations
(Max. 0.050-sec Avg)
Longitudinal . . . . . -7.9 g
Lateral . . . . -0.8 g
Occupant Impact Velocity
Longitudinal . . . . . 29.8 ft/s (9.1 m/s)
Lateral . . . . N/A
Occupant Ridedown Accelerations
Longitudinal . . . . . -6.3 g
Lateral . . . . No Contact

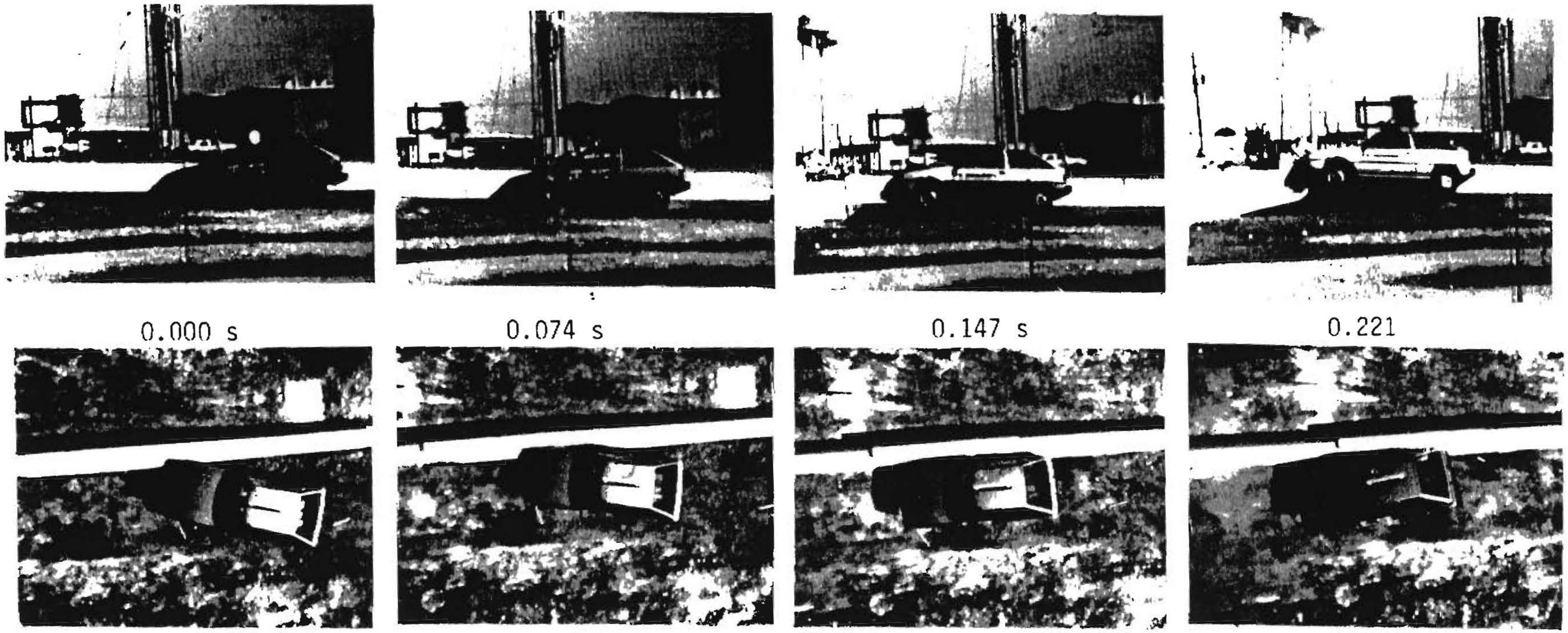
Figure 18. Summary of results for test 9901E-1.



Test No. 9901E-2
Date 01/29/91
Test Installation . . Adiem \Impact Attenuator
Installation Length . 33.0 ft (10.1 m)
Vehicle . . . . 1981 Honda Civic
Vehicle Weight
  Test Inertia . . . . 1,800 lb (816 kg)
Vehicle Damage Classification
  TAD 12FR-4
  CDC 12FREN2

Impact Speed. . . 58.6 mi/h (94.3 km/h)
Impact Angle. . . 0 deg (15 in. right side offset)
Exit Speed. . . . Not Applicable
Vehicle Accelerations
  (Max. 0.050-sec Avg)
    Longitudinal. . -11.7 g
    Lateral . . . . -3.1 g
Occupant Impact Velocity
  Longitudinal. . 37.4 ft/s (11.4 m/s)
  Lateral . . . . 8.9 ft/s (2.7 m/s)
Occupant Ridedown Accelerations
  Longitudinal. . -10.6 g
  Lateral . . . . -1.6 g

Figure 19. Summary of results for test 9901E-2.



Test No. 9901E-3
Date 02/08/91
Test Installation . . . . . Adiem Impact Attenuator
Installation Length . . . . 33.0 ft (10.1 m)
Vehicle . . . . 1985 Dodge Colt

Vehicle Weight
  Test Inertia . . . . 1,800 lb (816 kg)
Vehicle Damage Classification
  TAD 01RFQ-2
  CDC 01RFEW1

Impact Speed. . . . . 58.8 mi/h (94.6 km/h)
Impact Angle. . . . . 15.9 deg
Exit Speed. . . . . 57.2 mi/h (92.1 km/h)
Vehicle Accelerations
  (Max. 0.050-sec Avg)
  Longitudinal. . . . .- 5.4 g
  Lateral . . . . 15.7 g
Occupant Impact Velocity
  Longitudinal. . . . . 11.8 ft/s (3.6 m/s)
  Lateral . . . .-26.3 ft/s (8.0 m/s)
Occupant Ridedown Accelerations
  Longitudinal. . . . . -4.9 g
  Lateral . . . .- 7.3 g

Figure 20. Summary of results for test 9901E-3.

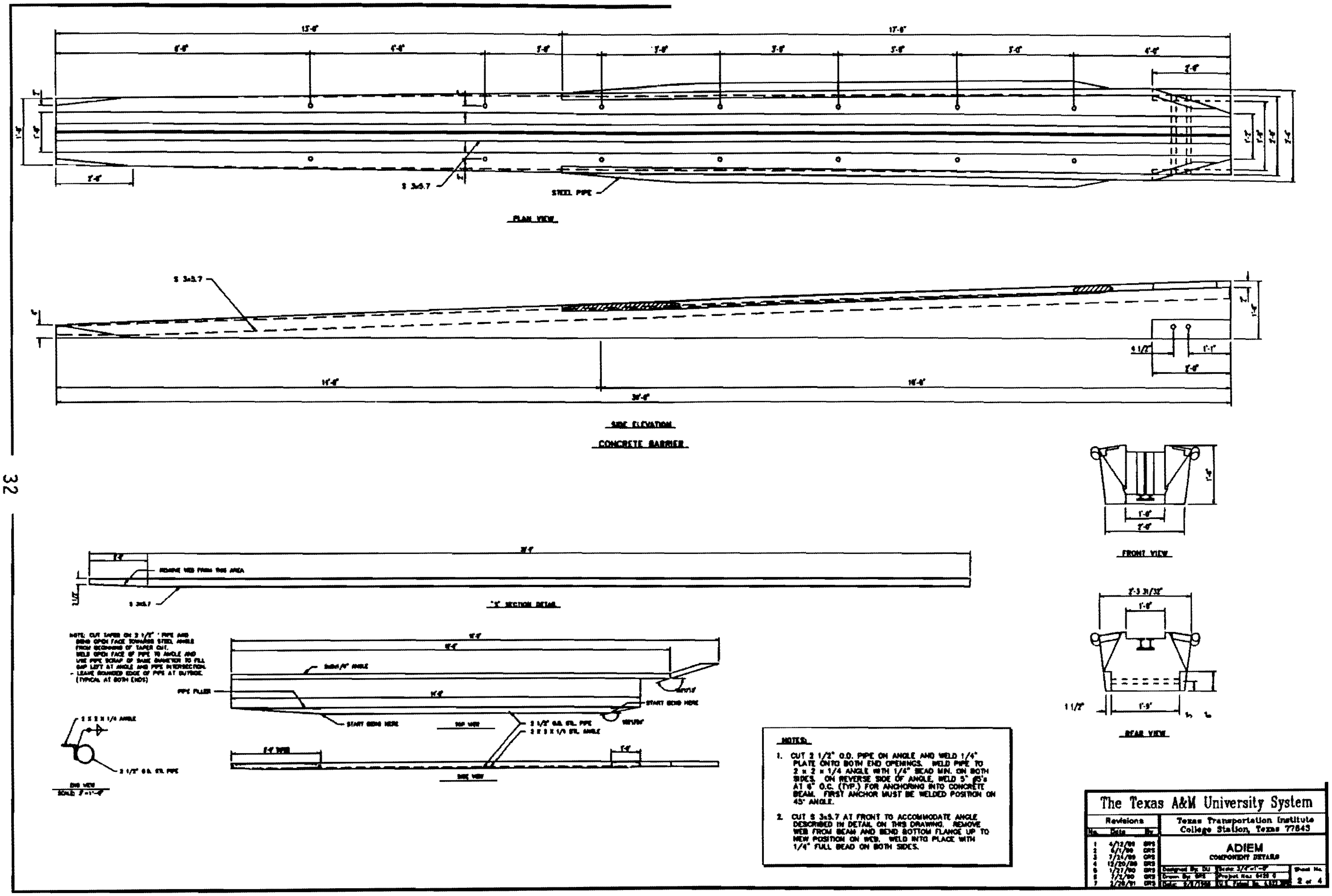


Figure 21. Final design of carrier beam.

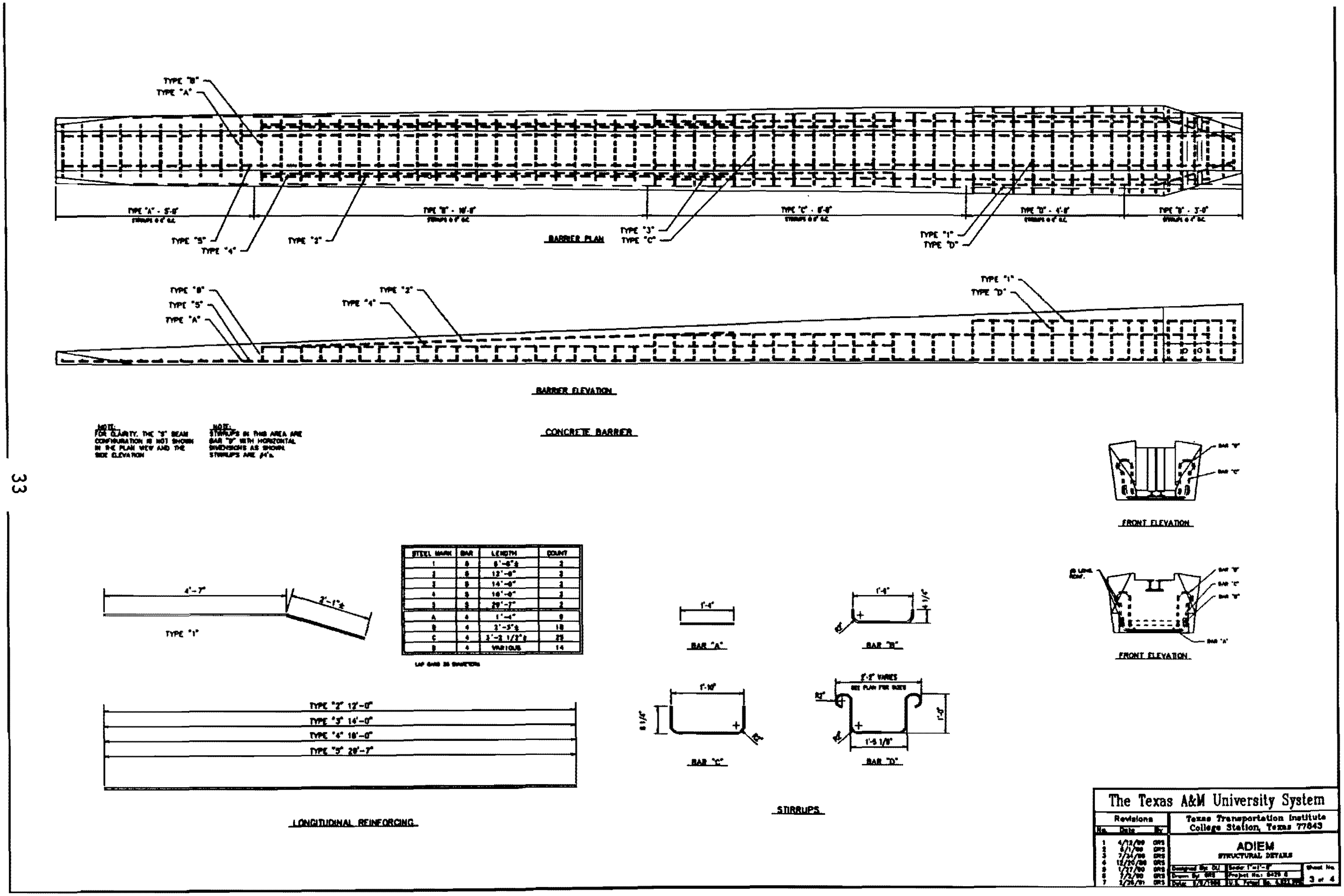


Figure 22. Final design of carrier beam reinforcement.

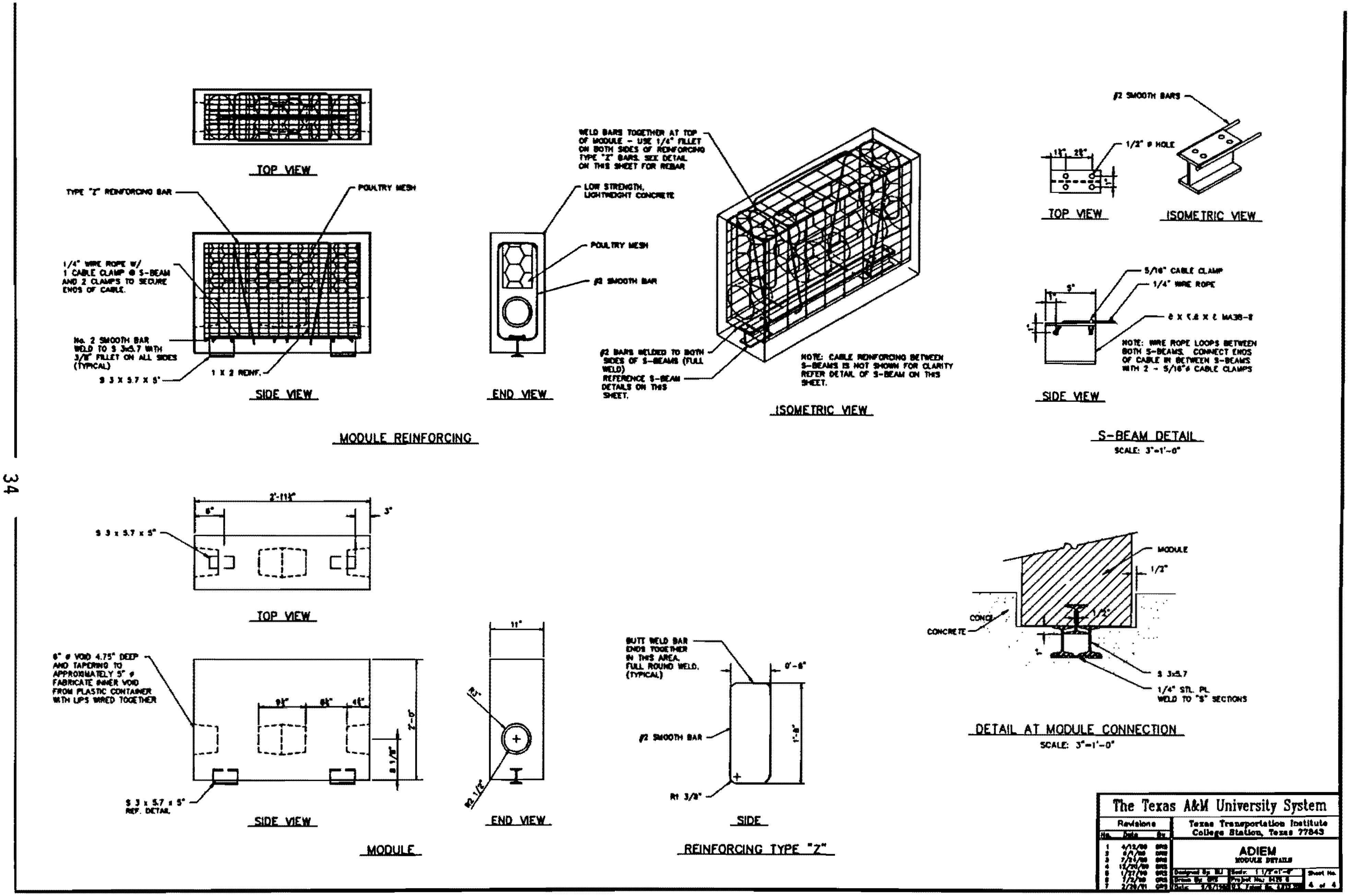


Figure 23. Final design of modules.

Upon impact, the modules began to crush at the design level of resistance. The vehicle remained extremely stable and level as it penetrated the modules. The vehicle penetrated 25.6 ft. (7.8 m) into the terminal. Sequential photographs of the test are shown in Figure 24.

The modules were all crushed to varying degrees. There was no damage to the carrier beam. Minimal amounts of debris and detached pieces of soft concrete remained around the installation after the collision. The carrier beam remained firmly attached to the ground surface and to the PCB.

The vehicle received minimal damage. Maximum permanent deformation was 10 in. (25.4 cm) at the center of the front end of the vehicle. In addition, the vehicle sustained damage to the bumper, grill, and radiator. There was no intrusion into the occupant compartment.

A summary of the test results and other information pertinent to this test are given in Figure 18 along with sequential photographs of the collision. The maximum 0.050 second average acceleration imposed on the vehicle was -7.9 g in the longitudinal direction. Occupant impact velocity in the longitudinal direction was 29.8 fps (9.1 m/s). The highest 0.010 second occupant ridedown acceleration was -6.3g (longitudinal).

In summary, the terminal smoothly arrested the forward motion of the vehicle. The vehicle sustained minimal damages and did not present a significant hazard to other traffic. (See Figure 25.) Occupant impact velocities and ridedown accelerations were within the recommended limits of NCHRP Report 230 (i.e. 30 fps). In addition, the maximum 0.050 second averages were also well below the recommended limit of 20 g. These test results meet the evaluation criteria recommended in NCHRP Report 230.

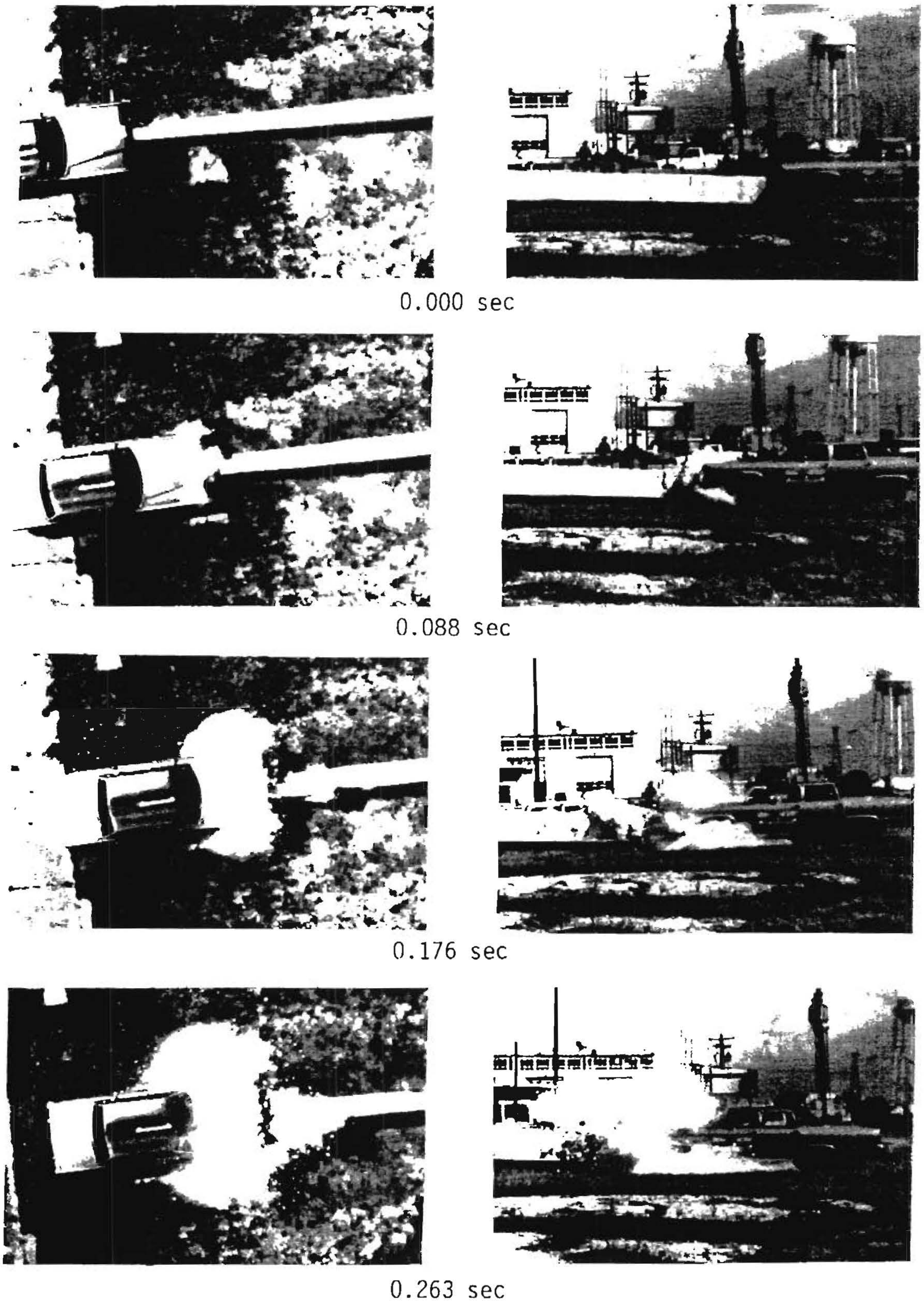
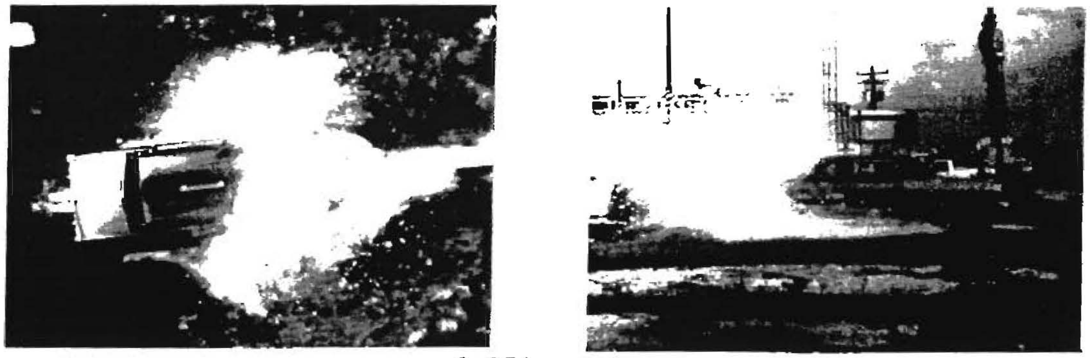
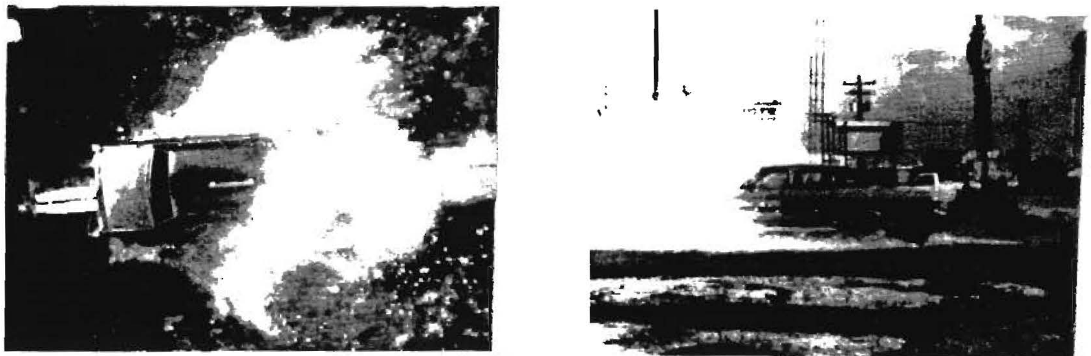


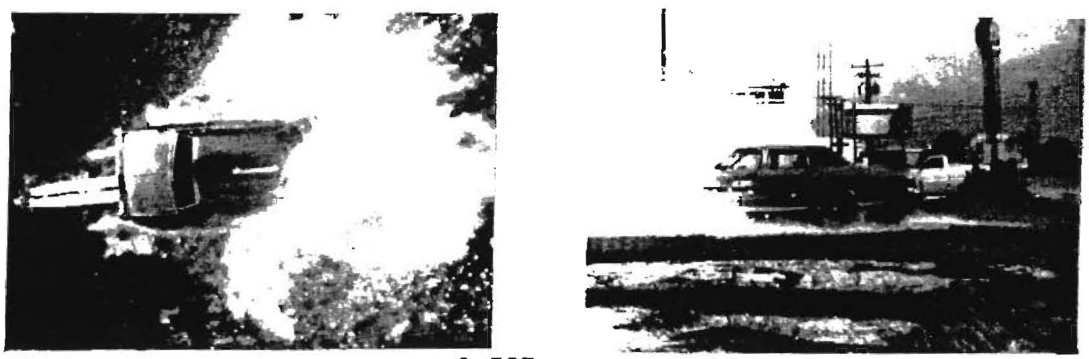
Figure 24. Sequential photographs of test 9901E-1.



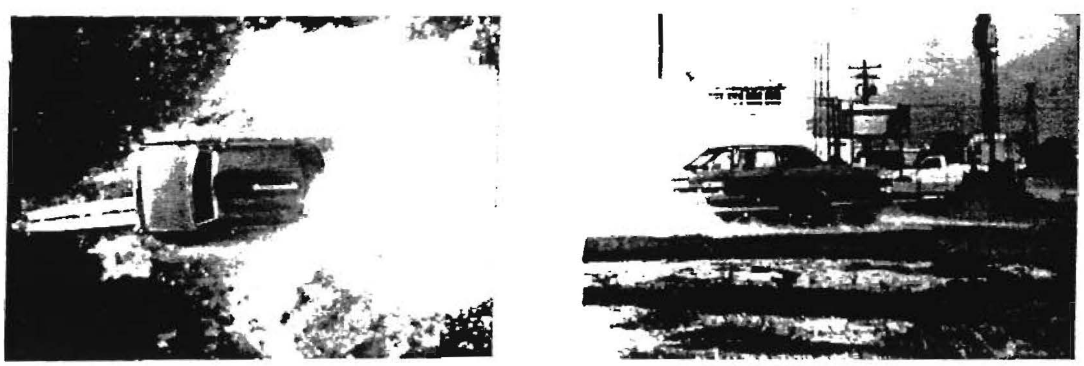
0.351 sec



0.439 sec

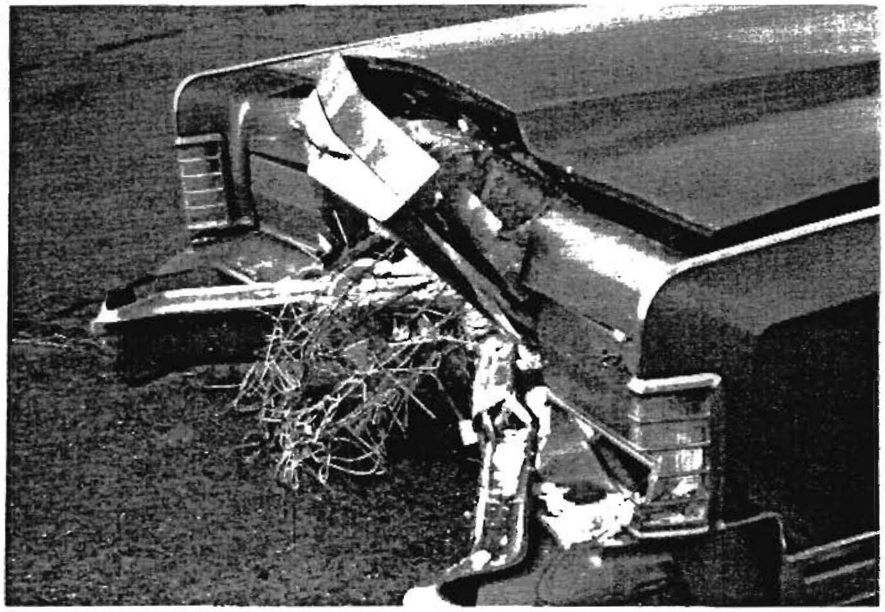


0.527 sec



0.614 sec

Figure 24. Sequential photographs of test 9901E-1. (Continued)



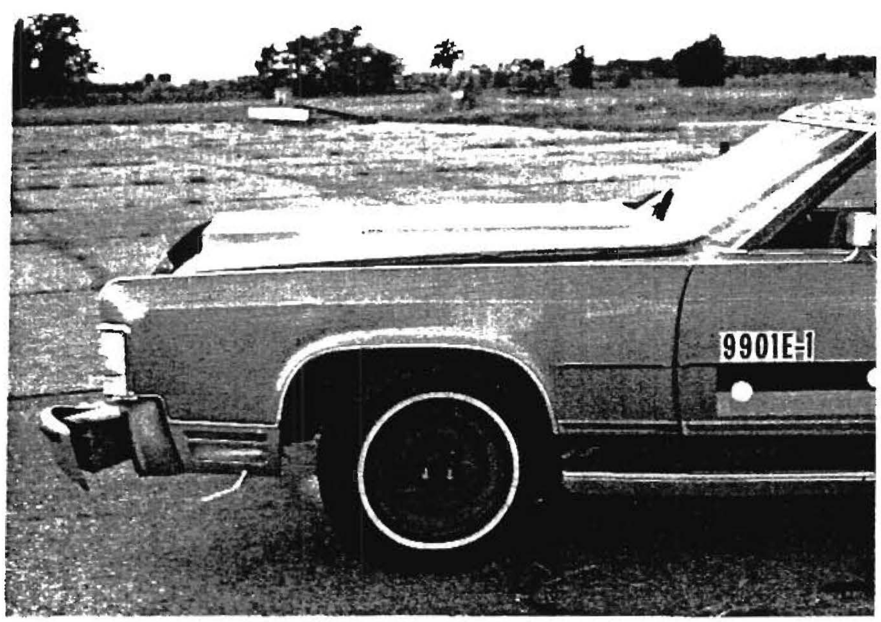


Figure 25. Vehicle after test 9901E-1.

Test 9901E-2

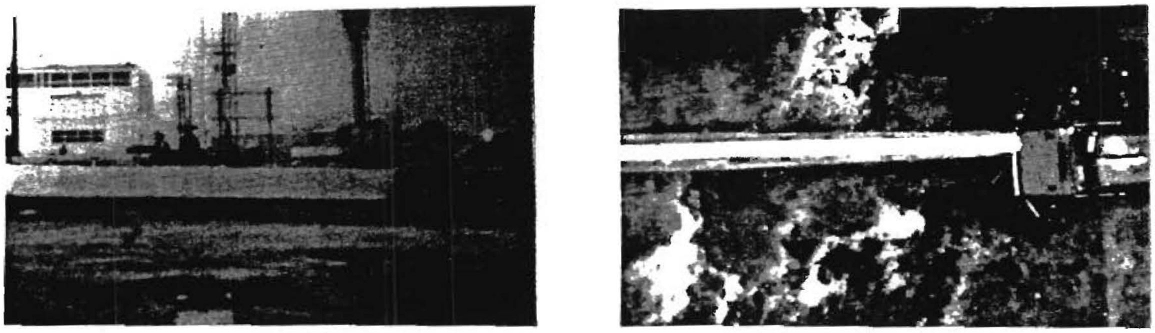
A 1981 Honda Civic impacted the ADIEM terminal at 58.6 mph (94.3 km/h). The vehicle weight was 1,800 lbs. (816 kg).

Upon impact, the modules began to crush as designed. The vehicle remained stable and level as it penetrated the first module. As the vehicle penetrated the second module, it began to yaw clockwise. The vehicle continued to yaw clockwise as module crush continued. The vehicle yawed to about ninety degrees as loss of contact between the Honda and the crushed modules occurred. The vehicle penetrated 9.9 ft. (3.0 m) into the attenuator. Sequential photographs of the test are shown in Figure 26.

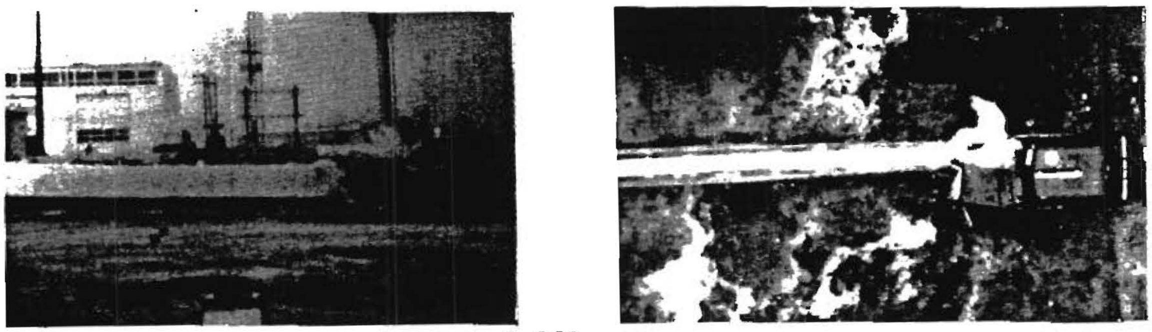
All terminal modules were crushed to varying degrees. There was no damage to the terminal carrier beam, the base structure. Minimal amounts of debris and small pieces of soft concrete were distributed around the installation. The modules yielded appropriately and the carrier beam remained firmly attached to the ground surface and to the PCB.

The vehicle received minimal damage. Maximum permanent deformation was 9 in. (22.9 cm) at the right front corner of the vehicle. (See Figure 27.) In addition, the vehicle sustained damage to the bumper, grill, radiator, front fenders and left front strut assembly. There was no intrusion into the occupant compartment. Post test photographs of the vehicle are shown in Figure 27.

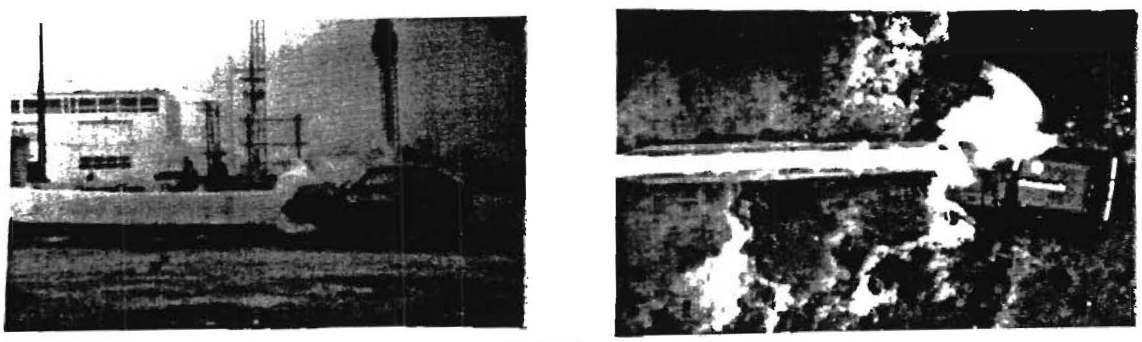
A summary of the test results and other information pertinent to this test is given in Figure 19. The maximum 0.050 second average acceleration experienced by the vehicle was -11.7 g in the longitudinal direction. Occupant impact velocity in the longitudinal direction was 37.4 fps (11.4 m/s). Although this is above the preferred level of 30 fps it is generally observed that there are no terminals that do better than the 40 fps requirement for small car head-on tests.



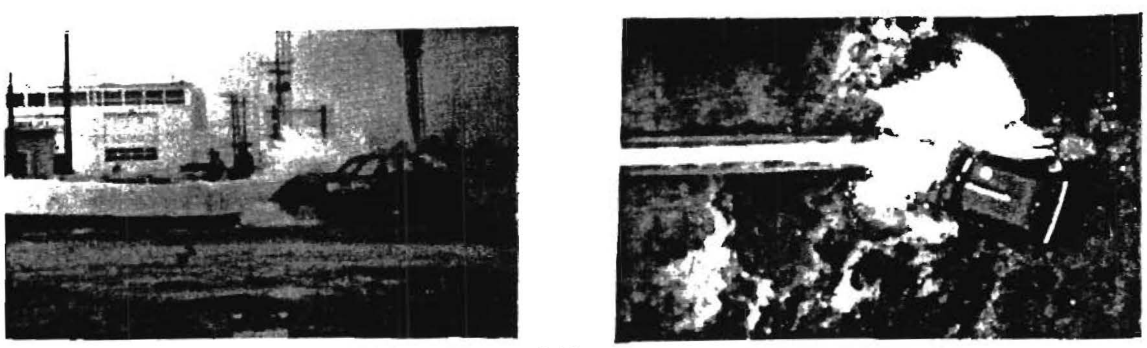
0.000 sec



0.063 sec

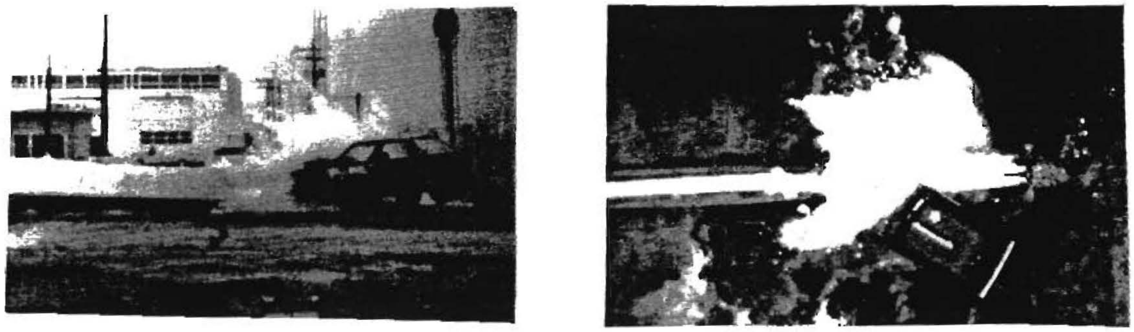


0.126 sec

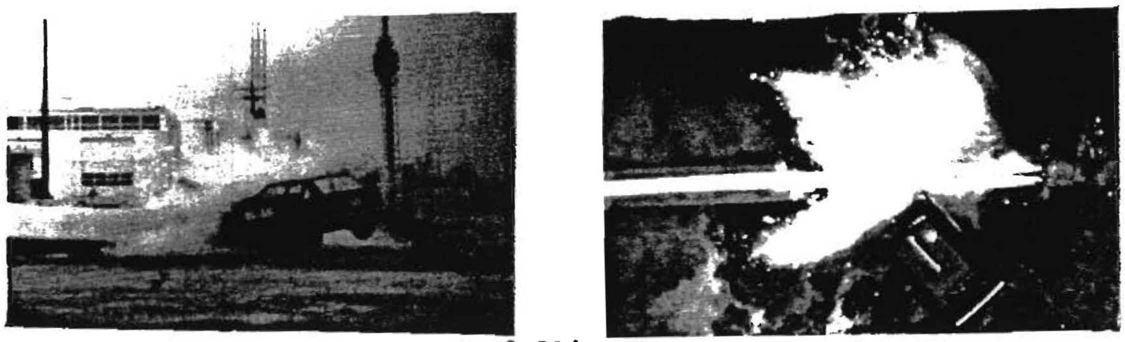


0.188 sec

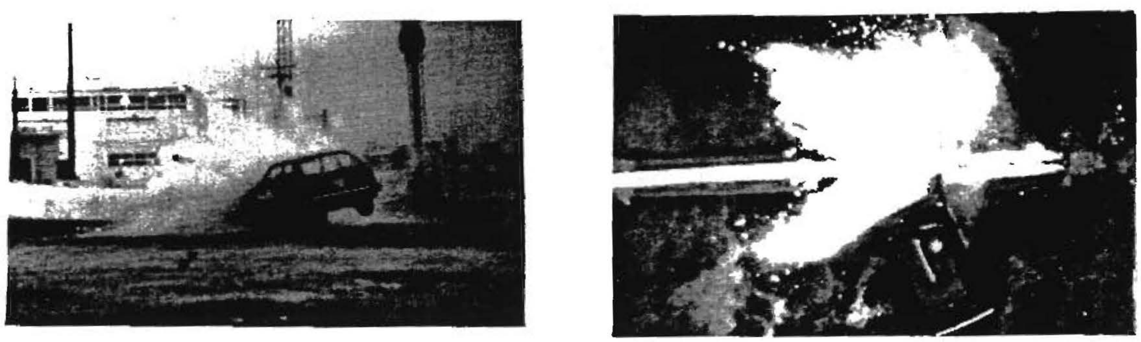
Figure 26. Sequential photographs of test 9901E-2.



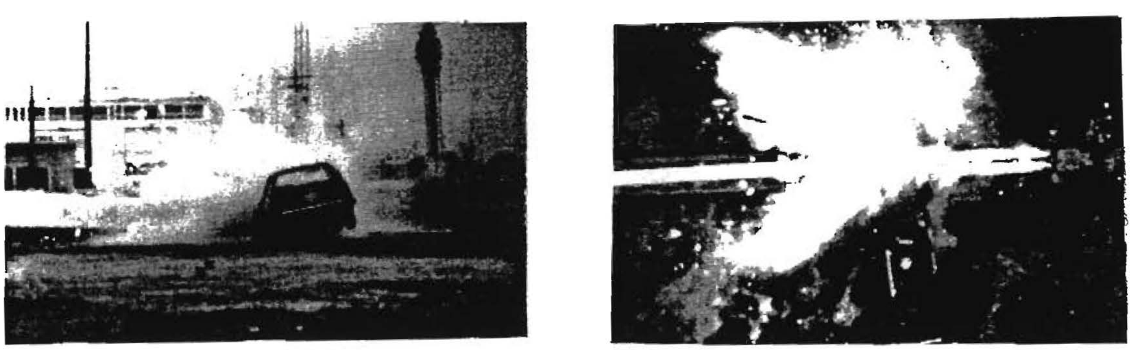
0.251 sec



0.314 sec



0.377 sec



0.439 sec

Figure 26. Sequential photographs of test 9901E-2 (Continued).

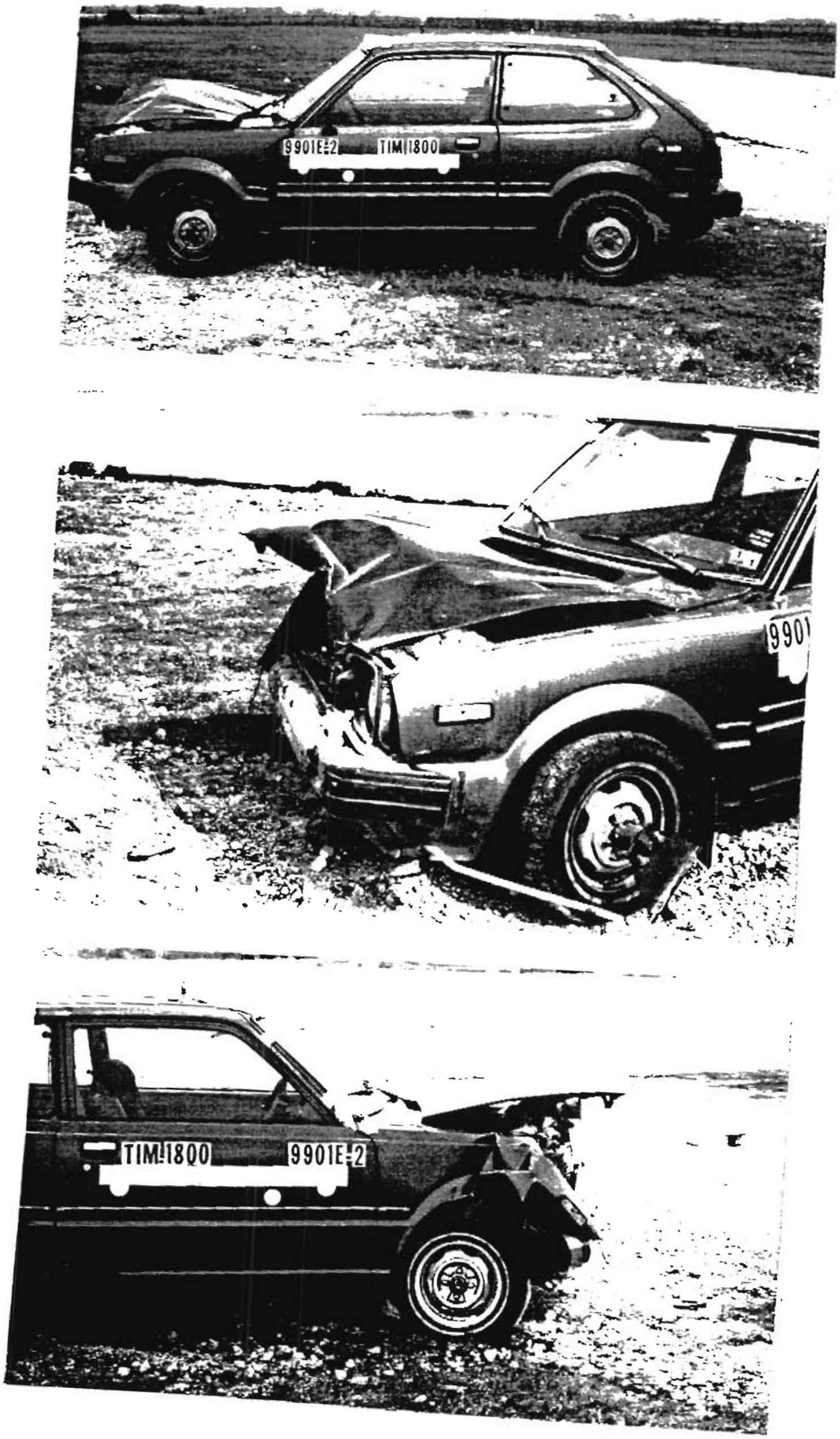


Figure 27. Vehicle after test 9901E-2.

(See Figure 8 of reference 3.) The highest 0.010 second occupant ridedown acceleration was -10.6 g (longitudinal).

In summary, the terminal functioned precisely as designed. The vehicle sustained minimal damages and did not present undue hazard to other traffic. Occupant impact velocities and ridedown accelerations were within the recommended limits of NCHRP Report 230. In addition, the maximum 0.050 second averages were also well below the recommended limit of 20 g. These test results meet the evaluation criteria recommended in NCHRP Report 230.

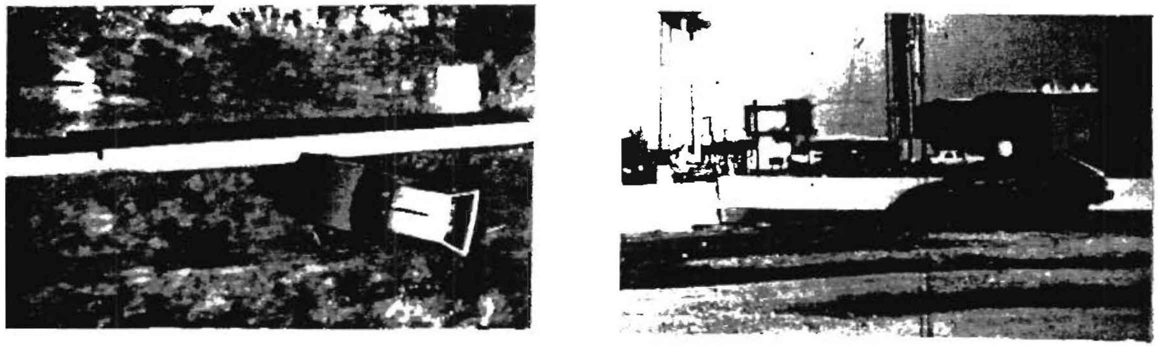
<u>Test 9901E-3</u>

A 1985 Dodge Colt impacted the ADIEM terminal at 58.8 mph (94.6 km/h) at an angle of fifteen degrees. The vehicle weight was 1,800 lbs. (816 kg).

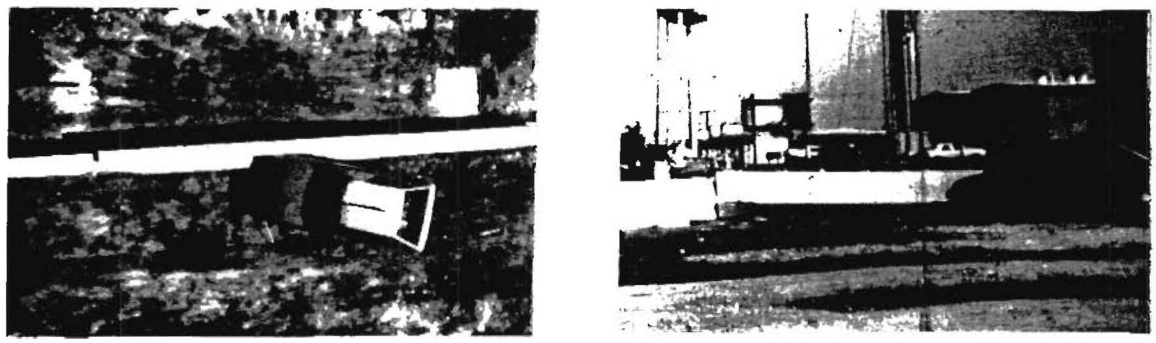
Upon impact, the vehicle began to redirect. As the vehicle redirected, the left wheels lost contact with the roadway. At approximately 0.140 second, at a vehicle speed of 55.9 mph (89.9 km/h), the rear of the vehicle came into contact with the attenuator. The vehicle began to yaw counter-clockwise and pitch forward as it became parallel to the terminal. The vehicle lost contact with the rail at approximately 0.245 second travelling 53.9 mph at an angle of 2.4 degrees. The brakes were applied to the vehicle as it exited the installation. The vehicle came to rest in a stable and upright condition 140 feet downstream from the point of impact. Sequential photographs of the test are shown in Figure 28.

The soft concrete modules were scraped but did not sustain any structural damage. There was no damage to the terminal carrier beam. There was no debris or any detached elements around the installation. The base structure remained firmly attached to the roadway and PCB.

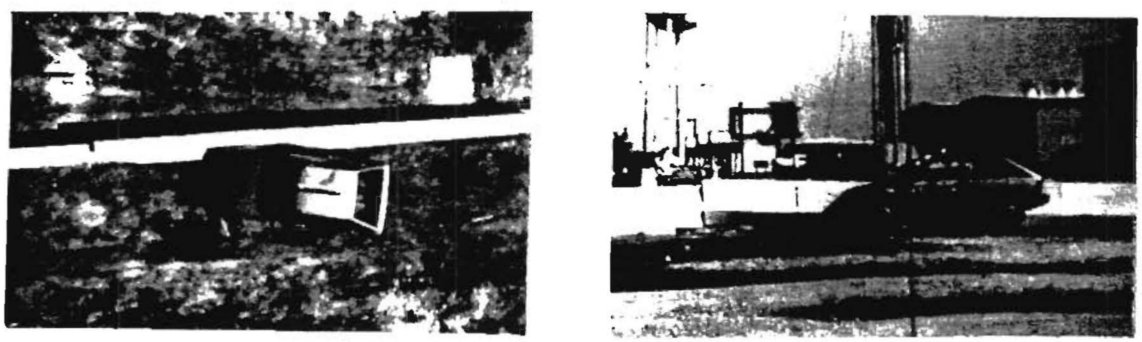
The vehicle received minimal damage. Primary damage was sustained to the right front control arm assembly, and wheel. The subframe and floor pan was bent. There was no



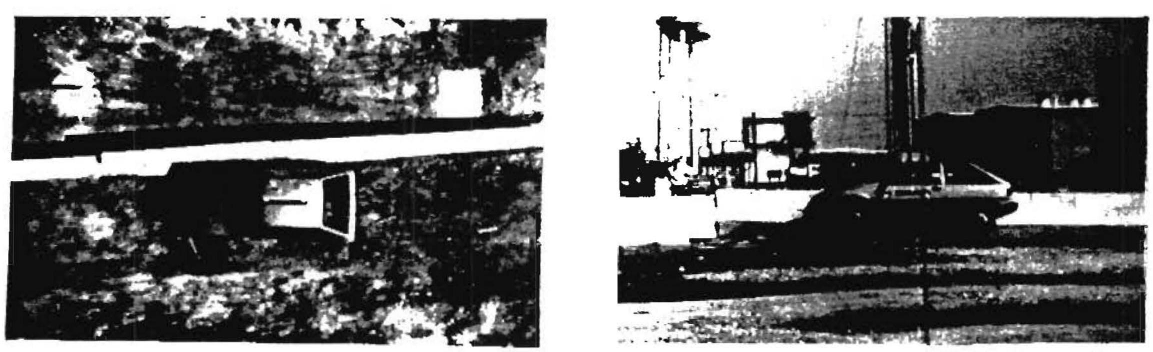
0.000



0.037

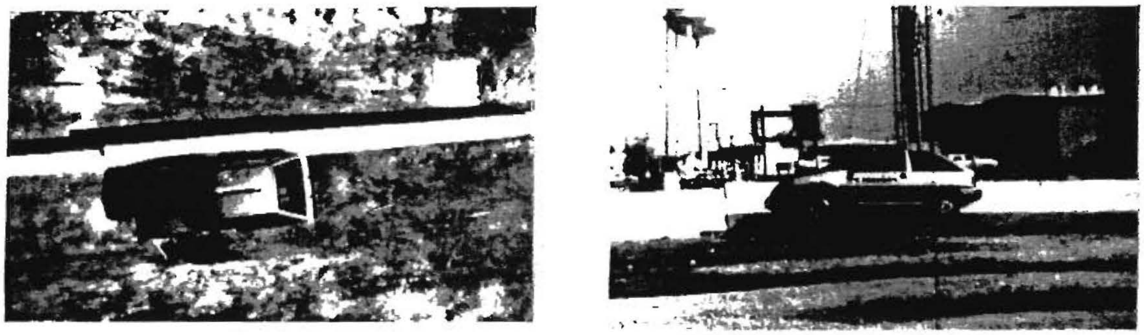


0.074

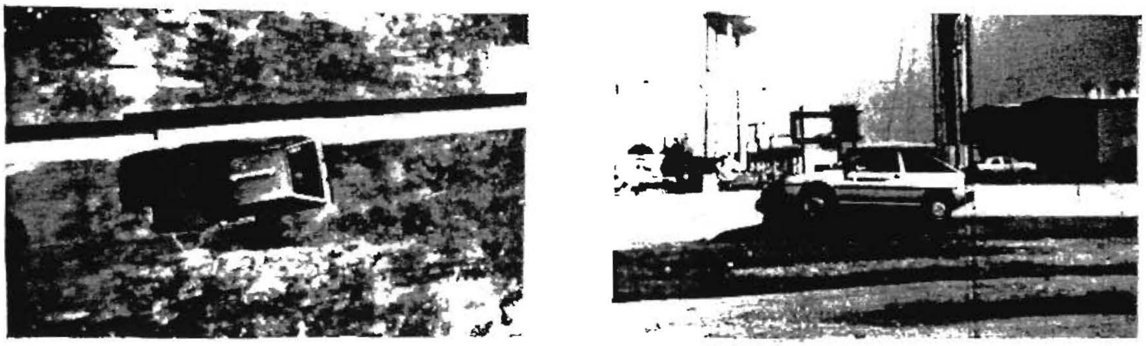


0.110

Figure 28. Sequential photographs of test 9901E-3.

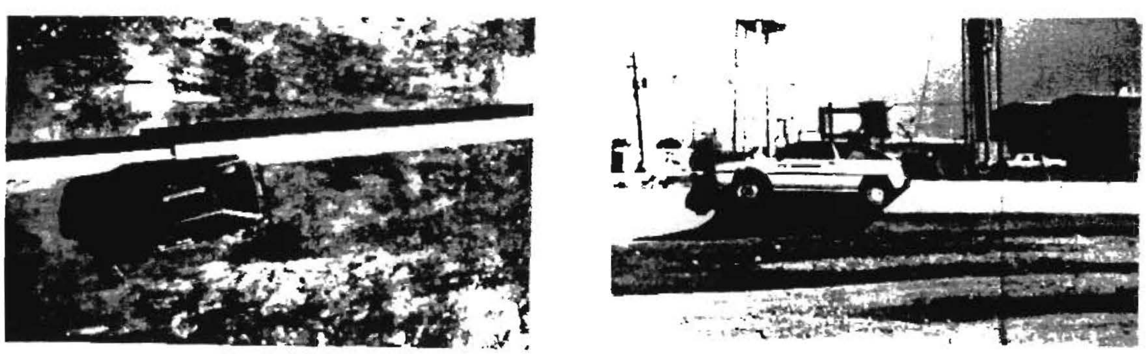


0.147



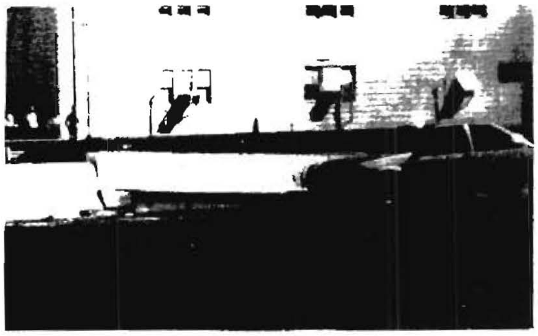
0.184

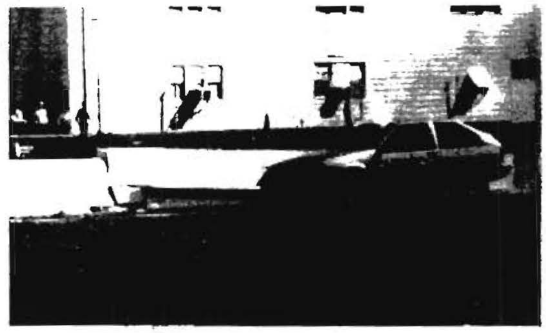
0.221



0.258

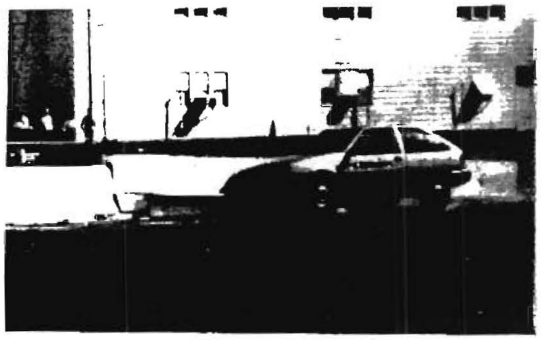
Figure 28. Sequential photographs of test 9901E-3. (continued).

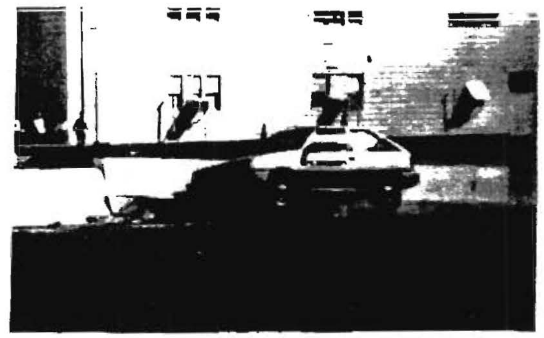




0.000

0.037



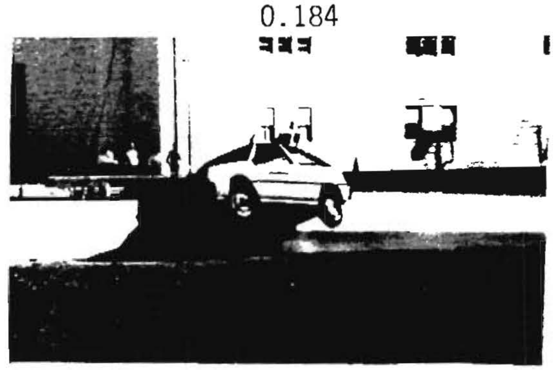


0.074

0.110

0.147

0.184



0.221

0.258

Figure 28. Sequential photographs of test 9901E-3 (continued).

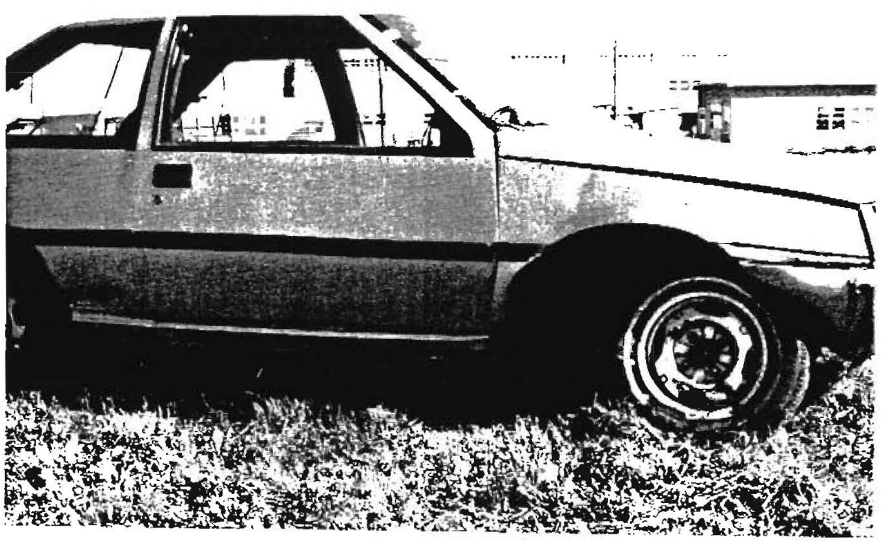


Figure 29. Vehicle after test 9901E-3.

intrusion into the occupant compartment. Post test photographs of the vehicle are shown in Figure 29.

A summary of the test results and other information pertinent to this test is given in Figure 20. The maximum 0.050 second average acceleration experienced by the vehicle was -5.4 g in the longitudinal direction and 15.7 g in the lateral direction. Occupant impact velocity in the longitudinal direction was 11.8 fps (3.6 m/s) and 26.3 fps (8.0 m/s) in the lateral direction. The highest 0.010 second occupant ridedown accelerations were -4.9 g (longitudinal) and 7.3 g (lateral).

In summary, the terminal safely redirected the vehicle. The vehicle sustained minimal damage and did not present undue hazard to other traffic. Occupant impact velocities and ridedown accelerations were within the recommended limits of NCHRP Report 230. In addition, the maximum 0.050 second averages were also well below the recommended limit of 20 g. These test results fundamentally meet the evaluation criteria recommended in NCHRP Report 230, but did not meet the expectations of the designers. There was more pitch of the vehicle than was expected. A careful examination of the terminal and the vehicle and comparison of this test to test 9429G-2 yielded the reason.

In test 9429G-2 the 1,800 lb vehicle impacted a similar side rail on an earlier ADIEM terminal at a speed of 60 mph and an angle of 15 degrees. The result was an extremely smooth and safe redirection. (See Test Report 9429G-2 in the appendix.) A quick comparison of the acceleration traces in these two tests showed that the 9429G-2 test vehicle lost only 5 mph during the first 100 ms while the 9901E-3 test vehicle lost about 12 mph. Clearly there was much more retarding force in the E test on the front wheel than in the G test. Inspection of the right front wheel rim and the point on the ADIEM side rail where the major re-directive load was applied yielded the answer. In the E test the wheel rim impacted on the three foot tapered part of the side rail. The way the taper was produced was by simply slicing away a portion of the pipe and replacing it with a flat plate as shown in Figure 30. The pipe was then welded to the angle section with the flat part of the taper out, or facing the impacting wheel. At the bottom of the taper section replacing the cut off section of pipe with a flat plate results in an edge with a blunt radius of about ¼ inch facing down and another edge facing up. As the wheel rim applied force to the tapered section during initial impact the lower edge of the taper cut into the rim on the trailing side of the rim. This gouge in the rim is shown in Figure 31. The rotation of the wheel and friction with the ground forced the wheel down about the pivot point at the place the side rail edge cut into the rim. The result was a tire that was squashed down almost to the rim with the resulting vertical force translating into a friction (retarding) force on the right front tire that was at least ten times what could normally be produced by a tire that was simply braked on the same surface. Thus, the right front was forced down by the edge and a large force to the rear occurred at the tire/ground interface. The result was the unexpected pitch that occurred in test E. The solution to this minor problem was simple. In test 9429G-2 the wheel impacted a curved pipe surface and an ideal redirection occurred. Thus the only change in the design needed was to put the flat surface of the pipe taper flush with the carrier beam side and have the curved surface of the taper facing out to accommodate the impact of the wheel. This was done as shown in Figure 32. With this small design modification it is clear the ADIEM terminal will perform ideally under all required NCHRP 230 tests.

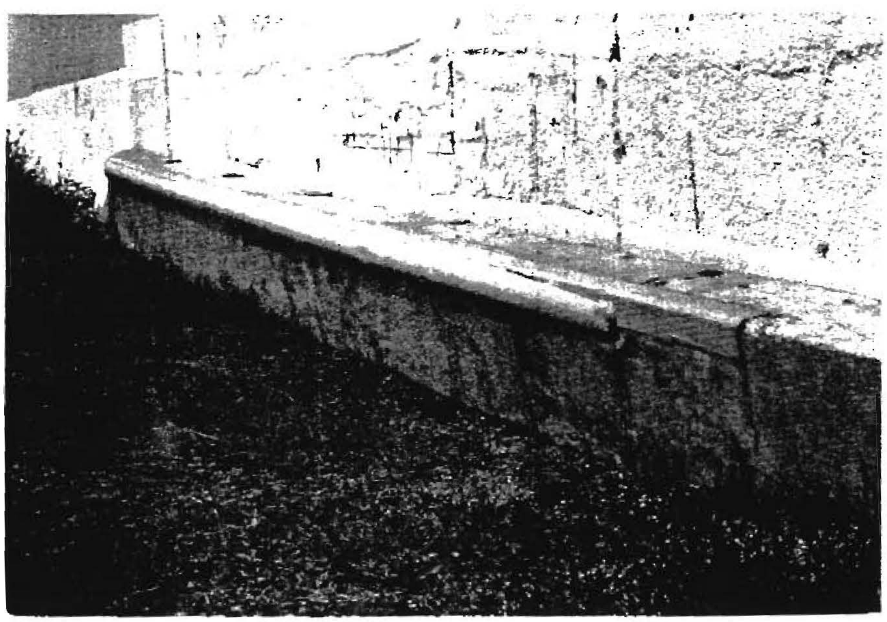
Final Design

In this section the final design of the ADIEM terminal is discussed. The final design functions ideally for vehicle speeds up to 60 mph and for vehicle weights up to 4,500 lbs.. It

Figure 30. Taper as tested in 9901E-2, E test. (The arrow points to the lower edge of the taper. The rim is shown as it was deformed and gouged by the taper during impact.)

Figure 31. Right front wheel rim from test 9901E-2, E test. (The ruler is pointing to the gouge in the rim from the lower edge of the pipe taper.)

Top View



Side view

Figure 32. Final design of pipe side rail taper.

is composed of a thirty foot carrier beam or base structure which accommodates ten Perlite concrete crushable modules. Details of this design were shown by plan sheets 2/4, 3/4 and 4/4.

The carrier base of ADIEM shown in Figure 33 is composed of standard class A five sack concrete. Longitudinal reinforcement is predominately No. 5 bars. Transverse reinforcement is all No. 4 bars. This base is shown in plan sheets 2/4 and 3/4. (Figures 21 and 22.)

There are ten modules required for an installation. These are shown in plan sheet 4/4. (Figure 23.) Figure 34 shows a single module. These modules are cast in three layers of varying strength. This is shown in Figure 17. The lowest three inches is concrete T (Oc=120 psi). The next fourteen inches is concrete M (Oc=40 psi). The final top seven inches is Concrete T (Oc=120 psi). The constituents of these three levels of Perlite concrete are also shown in Figure 17. Perlite is an expanded inert mineral soil filler normally used for soil aeration. It weighs only about 7.5 lbs per ft^3 in bulk form and single particles are not usually more than 1/8 inch in diameter. When concrete is made of Perlite, white portland cement, water, and an air entraining agent it is extremely light in weight and has a white color. Wet unit weights are given between 25 and 40 lbs per ft^3, but these unit weights decrease as the concrete hydrates and dries, approaching 80% of the wet unit weights. The average dry weight of the module concrete is only about 30 lbs per ft^3. A complete module after curing weighs about 190 pounds, and can be installed by two men. (See Figure 35.)

Both the strength and durability of the Perlite crushable modules is of great importance. If the strength levels are not controlled during the precasting phase within reasonable boundaries the resisting forces during collisions and thus accelerations on impacting vehicles could vary significantly from those observed in the compliance testing. Unit weight of wet Perlite is the

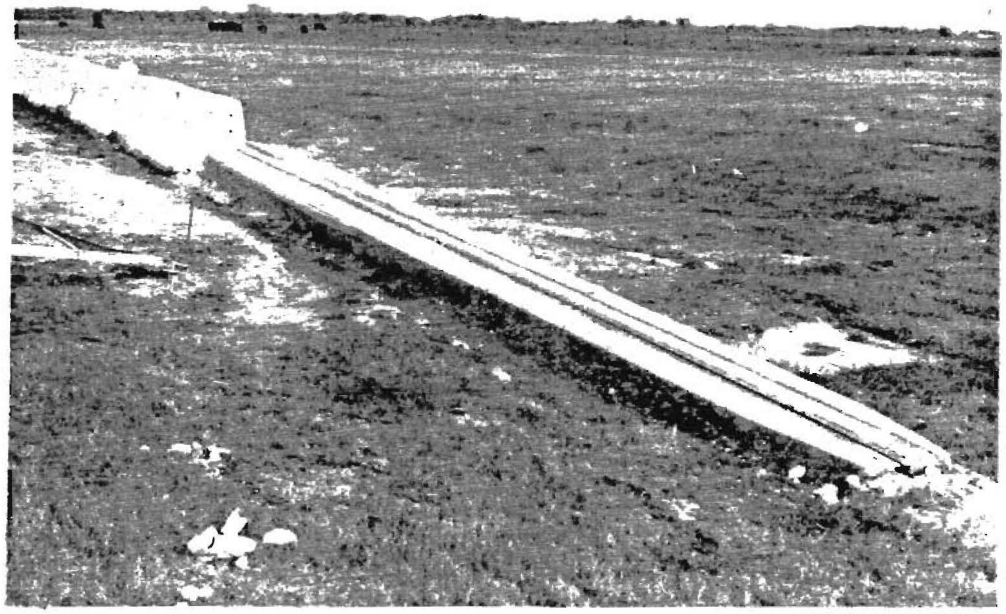


Figure 33. Carrier base before installation of modules.

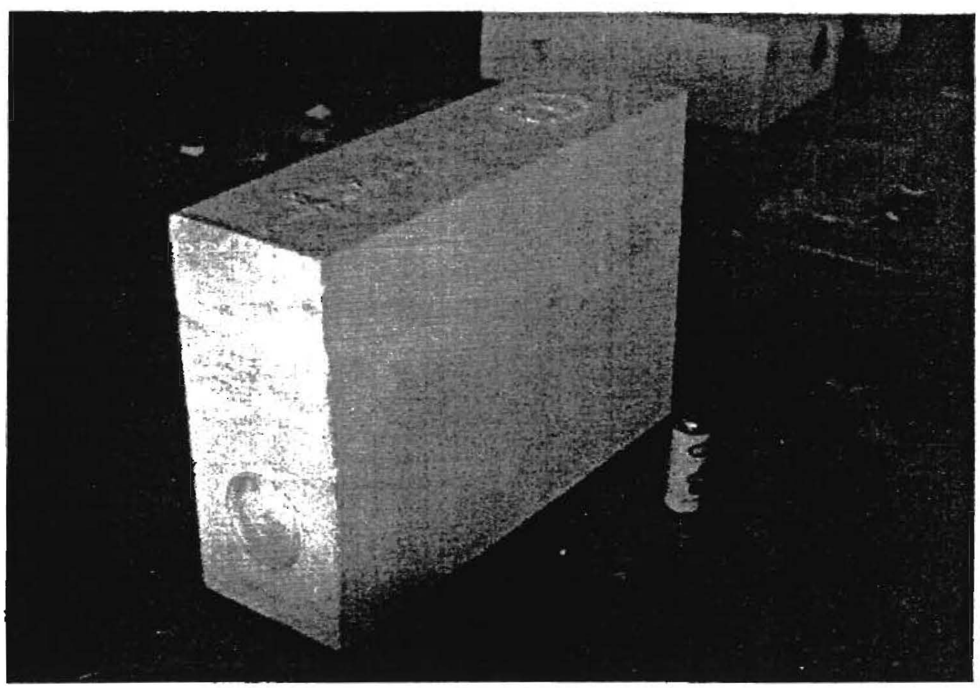
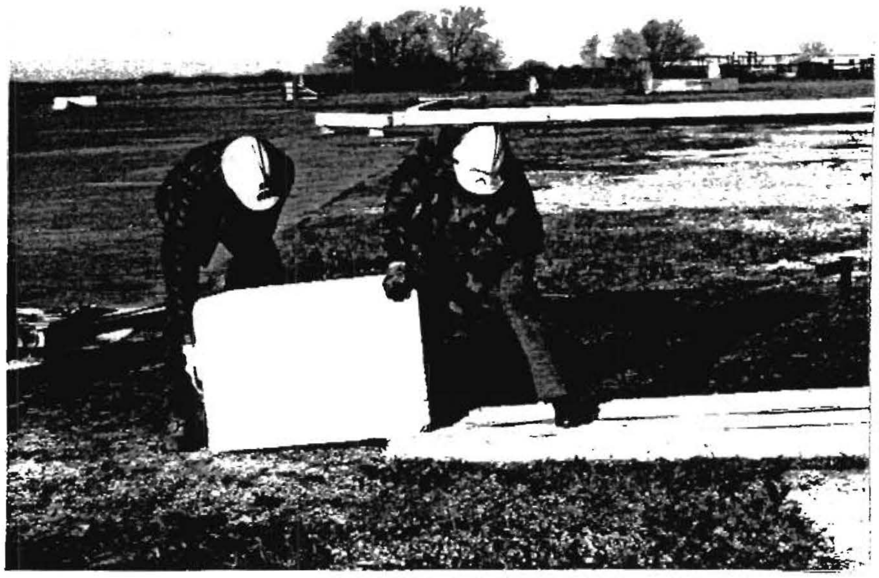


Figure 34. Single perlite concrete module.



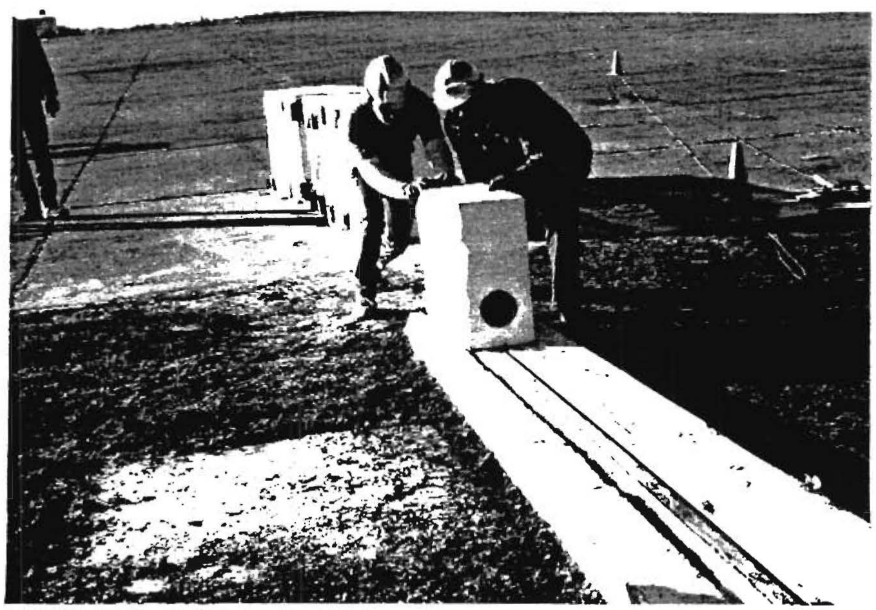


Figure 35. Installation of ADIEM terminal modules.

best way found to date to predict strength after curing. The penetrometer shown in Figure 13 is an appropriate way to determine strength after curing. Figure 36 shows the tolerance limits which should be achieved for the 40 and 120 psi concrete levels. These levels are from 30 to 60 psi for the low strength concrete and 100 to 150 psi for the higher strength concrete. These observations can be made at any time after twenty-one days of curing. The average of six penetrometer tests should be compared to these limits. Note, if the penetrometer is placed directly over an element of wire reinforcement the reading will be invalid. It will also be arbitrarily high. With a little practice the individual running the penetrometer test can tell immediately if a wire element interferes with a reading. The difference is normally great.

Durability of a low strength concrete, especially the 40 psi portion of the modules is required. The problem and solution are this simple. The uncoated concrete will absorb great volumes of water. It is highly porous. If that water then freezes the 40 psi material will soon have all the strength of a cake left out in the rain. The solution? Coat the modules to keep their surfaces impermeable. Two products have been found to perform well in the laboratory. They are two coats of Alkyd Traffic Marking Paint (in white or yellow), and Plasti-Dip #11602[2], an elastomeric rubber. During the manufacturing process the coating should only be applied after the individual modules have passed the penetrometer test. The coatings should also be applied so that the surface is fully covered, leaving no avenue for water intrusion. It is the view of the researchers that these modules will remain effective under all weather conditions for an indefinite period of time as long as the coating is effective in preventing water intrusion.

---

[2] PDI, Inc. (612) 785-2156

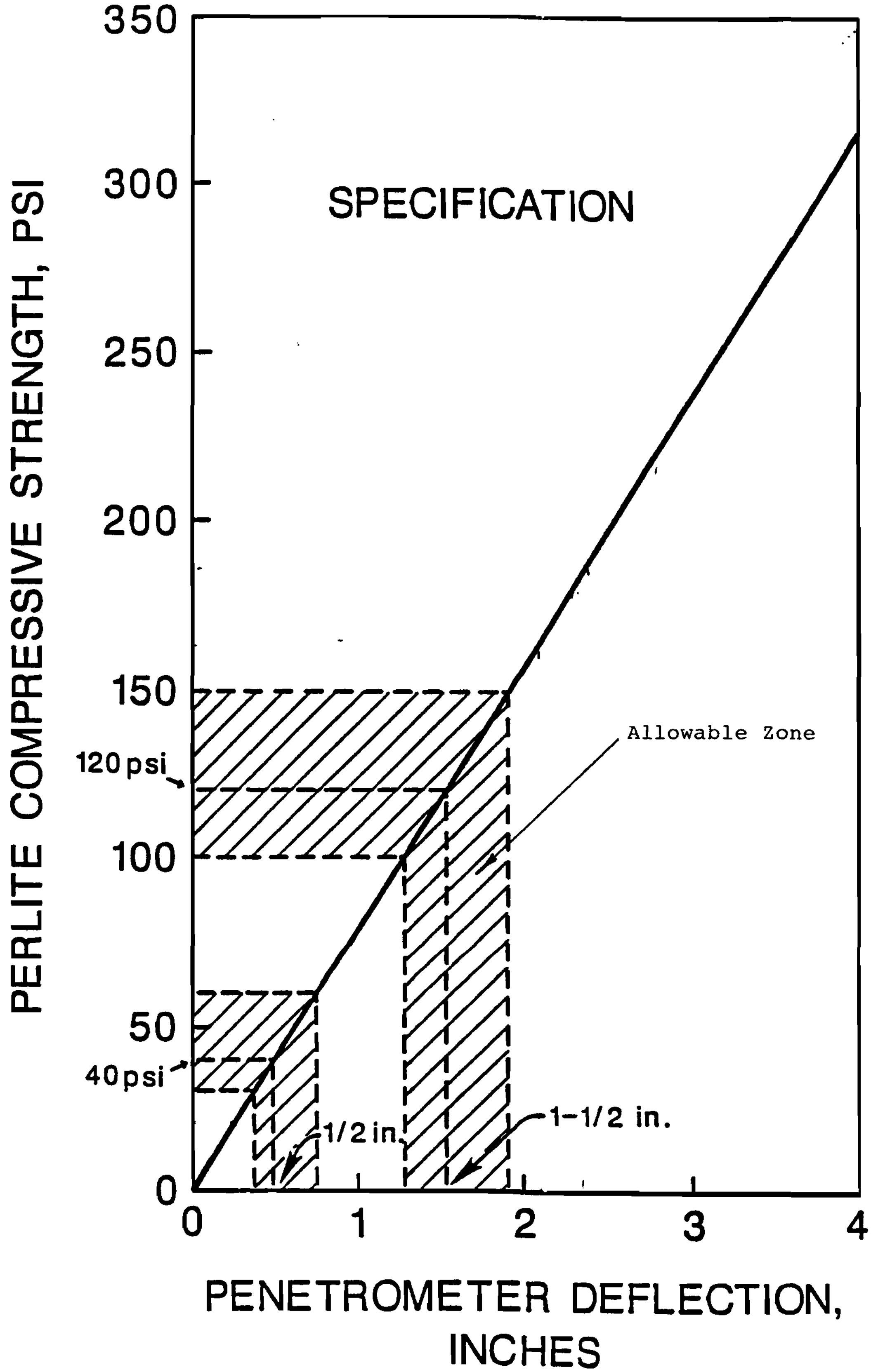


Figure 36. Penetrometer strength compliance chart for perlite concrete module.

TABLE 4
COST ESTIMATES

(Based on invoice costs of small quantities during construction of one barrier.)

BASE (1) (Carrier beam for modules and redirection rails.)

Re-Bar	#4 & #5	$800.00
Concrete	2.5 yds. @ $46.00	115.00
3" S Beams	(70' @ $1.65/ft.)	115.00
3" Pipe	(30' @ $1.80/ft.)	54.00
	Sub-total	$1084.00

MODULES (8)

2" x 4" welded wire (60' @ $0.30/ft.)	$ 18.00
Poultry Wire (44' @ $0.40/ft.)	18.00
Re-Bar, No. 2 250 ft.	25.00
Perlite (25 bags @ $9.50/bag)	238.00
White Cement (10 bags @ $10.40/bag)	104.00
¼" Wire Rope and cable clamps	80.00
Sub-total	$ 483.00
Total of Materials	$1567.00

TABLE 4 (Continued)

BASE (1) (Does not include cost of form.)

Assembly of forms
5 man-hours

Placing and tying reinforcement
14 man-hours

Placing Concrete (Redi-Mix Truck)
1 man-hour

Breaking out base
2 man-hours

Sub-total 21 man-hours @ $15.00/hr. = $ 315.00

MODULES (8) (Does not include cost of forms.)

Assembly of forms
8 man-hours

Fabrication of reinforcement
36 man-hours

Placing concrete
12 man-hours

Breaking out modules
5 man-hours

Sub-total 61 man-hours @ $15.00/hr. = $ 915.00

Total Labor $1230.00

Grand Total* Labor and Material $2797.00

* In a research oriented non-production environment.

Costs

The cost of an ADIEM terminal is illustrated by Table 4. These costs were based on construction of three carrier bases and some seventy modules in a prototype development environment. Table 4 shows material costs of $1,567.00, labor costs of $1,380.00 and a total cost of $2,947.00. It is likely that complete cushions could be fabricated in a production environment for two thirds of this cost. This would yield a production cost per barrier of $2,000.00. Allowing 50% for profit margins it is estimated this cushion could be placed in the field for $3,000.00 plus a reasonable cost of installation. Since current commercially marketed devices of similar performance cost approximately $15,000.00 per unit, ADIEM appears to offer a 5 to 1 cost advantage. Similar advantages will be noted relative to installation and maintenance. In construction zones, due to the completely pre-cast portable construction, it is estimated the complete end treatment can be installed in less than one hour. A two man crew was timed to determine the time necessary to clear a terminal which had been completely crushed. That time was seventeen minutes. Extraordinary efforts to do the job quickly were not made. The same crew then retrieved ten modules from a truck bed and replaced those in the carrier beam in fifteen minutes. In most cases it is estimated a collision site could be restored in about thirty minutes by a two man crew with the use of a straight or dump truck. It is also advisable to sweep the site since small elements of debris will be distributed about the collapsed modules.

Conclusion

ADIEM, the low-cost end treatment for PCB's and CMB's has been subjected to eight full scale crash tests. Four of these tests were developmental and four were the compliance tests suggested by NCHRP 230. The results of the four compliance tests are shown in Table 5.

These results show the final terminal design clearly meets the requirements of NCHRP 230. What is also shown is that this terminal is by far the most economical of the terminals now in use which have NCHRP 230 performance characteristics. It is believed the cost effectiveness of this design will be demonstrated as field experience is gained. ADIEM is now ready for experimental field application as a portable terminal for construction zones and as a permanent terminal for concrete barriers.

Table 5. Results of Compliance Crash Tests

Test Type	Test No.	NCHRP* 230 No.	Results	Comments:
Compliance	1	41	Excellent	Met all requirements of NCHRP 230. Barrier performance ideal.
Compliance	2	45	Excellent	Met all requirements of NCHRP 230. Barrier performance ideal.
Compliance	3	44	Fair*	Met all requirements of NCHRP 230 except that vehicle pitch was more than would be preferred. (See footnote *.)
Compliance	3[1]	44	Excellent	Met all requirements of NCHRP 230. Barrier performance ideal.

* Simple rail modification required to produce excellent performance verified by test 9429G-2.

References

1. Ivey, D.L., with C.E. Buth and T.J. Hirsch. "Feasibility of Lightweight Cellular Concrete for Vehicle Crash Cushions". Highway Research Record No. 306, 1970, pp. 50-57. Presented at the 49th Annual Meeting of the Highway Research Board, Washington, D.C., January, 1970.

2. Ivey, D.L., with C.E. Buth, T.J. Hirsch, and J.G. Viner. "Evaluation of Crash Cushions Constructed of Lightweight Cellular Concrete". Highway Research Record No. 386, 1972, pp. 10-18. Presented at the 51st Annual Meeting of the Highway Research Board, Washington, D.C., January, 1972.

3. Michie, Jarvis D. "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances", NCHRP 230, Transportation Research Board, March 1981.

4. Ivey, D.L. "Development of a Low-Cost High Performance Terminal for Concrete Median Barriers and Portable Concrete Barriers", Progress Reports, Volumes 1 and 2. Texas Transportation Institute, December, 1989.