U.S. Department
of Transportation

**Federal Highway
Administration**

Portable Concrete Barrier Connectors

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

Publication No. FHWA-TS-88-006
November 1987

FOREWORD

This state of the practice report includes a description of the various types of portable concrete barrier connectors being used by highway agencies, an analytical analysis of connector strength, review of previous crash tests and recommendations for additional testing. This report should be of interest to design and safety engineers responsible for the design and installation of portable concrete barrier systems.

Research, development and technology transfer for improving construction zone safety are included in the National Coordinated Program of Research, Development and Technology in Program Area A1 "Traffic Control for Safety"

Additional copies of this report can be obtained from the National Technical Information Service, Springfield, Virginia 22161.

Stanley Byington

Stanley R. Byington
Director, Office of Implementation

NOTICE

Technical Report Documentation Page

1. Report No.
FHWA-TS-88-006

2. Government Accession No.
PB88-218854/AS

3. Recipient's Catalog No.

4. Title and Subtitle
PORTABLE CONCRETE BARRIER CONNECTORS

5. Report Date
November 1987

6. Performing Organization Code

7. Author(s)
J.L. Graham, J.R. Loumiet and J. Migletz

8. Performing Organization Report No.

9. Performing Organization Name and Address
Graham - Migletz Enterprises, Inc.
P.O. Box 348
Independence, MO 64050

10. Work Unit No. (TRAIS)
3A9A0043

11. Contract or Grant No.
DTFH61-86-C-00084

12. Sponsoring Agency Name and Address
Federal Highway Administration
Office of Implementation
6300 Georgetown Pike
McLean, VA 22101

13. Type of Report and Period Covered
Final Report
September 1986 - June 1987

14. Sponsoring Agency Code

15. Supplementary Notes

Charles Niessner was the FHWA COTR, (HRT-10)

16. Abstract Portable concrete barriers (PCB) keep traffic from entering work areas, protect workers, separate two-way traffic and protect construction such as falsework for bridges. The barrier connector is normally regarded as the weakest part of the barrier system. Recently, a number of chronic problems have been observed in the use of PCB, mainly related to the connector system.

This report contains the results of a survey of PCB use, an analytical analysis of connector strengths, review of crash test results and narratives on visits to highway agencies to learn about current application and performance.

The pin and loop variety of connector is used in 46 agencies, however, design specifications even within this connector variety vary widely. The tongue and groove and plate insert connectors are the next most widely used connectors.

The most widely used connectors are the least crash tested, and a number of connectors presently being used have never been tested. Analysis of connector strengths reveals that pins in pin and loop connectors should be anchored to prevent pins from jumping or bending out of connector loops. Some connectors currently used have major application and performance problems.

17. Key Words
portable concrete barrier
worker safety
crash tests
work zone traffic control
PCB connector design

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	161	A08 [redacted]

Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^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)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
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)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
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

Symbol	When You Know	Multiply By	To Find	Symbol
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)

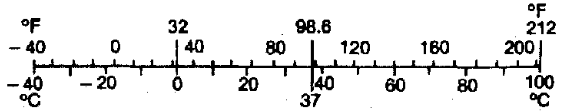
Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
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)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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

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* SI is the symbol for the International System of Measurements

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I. Introduction

The Traffic Control Devices Handbook states that there are four primary functions of barriers:

- Keep traffic from entering work areas, such as excavations or material storage sites.
- Protect workers.
- Separate two-way traffic.
- Protect construction, such as falsework for bridges, and other exposed objects. (1)

Barrier use has become increasingly popular in recent years for protecting highway workers and for containing and redirecting errant vehicles.

Are these barriers affording all the protection for which they were designed? Are they performing as intended?

The barriers are usually concrete precast in lengths from 8 to 30 ft. Barrier segments are connected to form a continuous barrier system. The barrier connector is normally regarded as the weakest part of the barrier system. The types of connectors used to hold together barrier segments vary widely.

Recently a number of chronic problems have been observed in the use of portable concrete barriers (PCB). Most of these problems are related to the strength, application, and maintenance of the PCB connector.

A. History of the Portable Concrete Barrier

The development of portable precast concrete barriers was a response to the need for an effective means to protect highway work zones. Construction of or maintenance work on highways requires traffic control in order to separate the work activity from traffic moving through the work zone.

An early barrier, called the timber barricade, consisted of a large (10-in by 10-in) timber base and horizontal railings at 22 in and 34 in above the base. Evaluating the performance of timber barricades used on I-495 near Washington D.C. in the late 70's, the Virginia Highway and Transportation Research Council found that 45.3 percent of the vehicles that came into contact with the barriers penetrated the work area. (2) The horizontal railings also were hazardous to the vehicles striking the barriers. Concrete barriers eventually replaced the ineffective and unsafe timber barricade.

The design of the portable concrete barrier was based on that of the concrete median barrier. Use of a concrete median barrier in Louisiana in 1942 and in California in 1946 provided initial insight into the barrier's performance capabilities. (3) New Jersey officials used the Louisiana and

California experience to design a barrier that would redirect a vehicle after it strikes the barrier system. The earliest design used barriers that were 18 in high, but because vehicles climbed to the top of the barrier the height had to be increased.

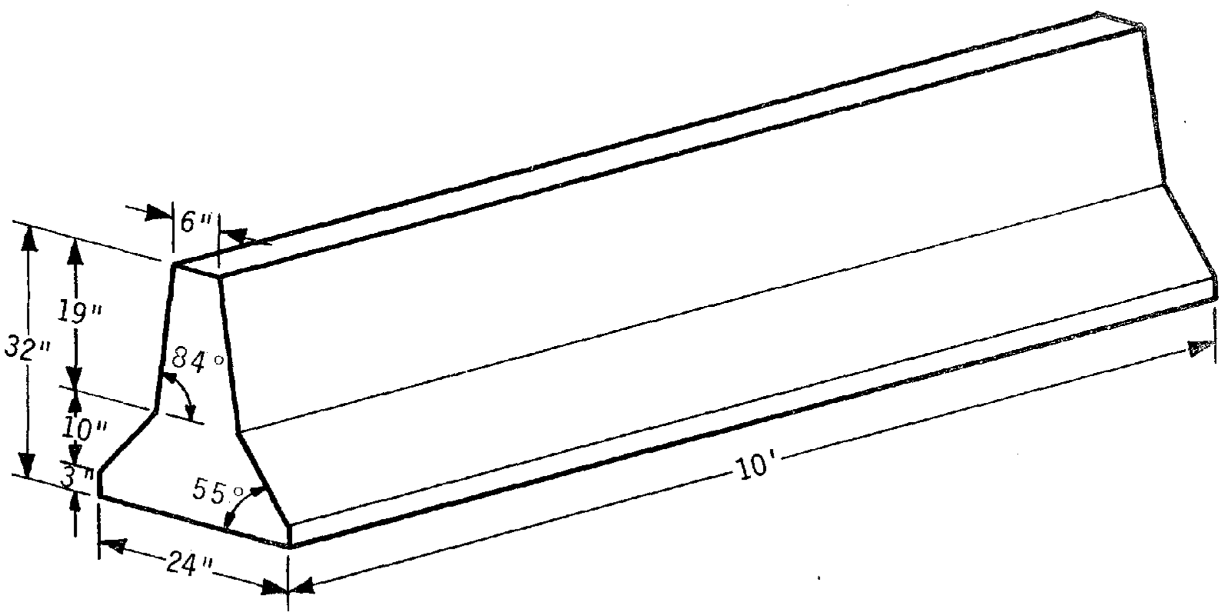
The barrier commonly used today (figure 1), referred to as the New Jersey barrier, is 32 in high and has a 24-in base width and a 6-in top width. It incorporates a 55 degree batter-curb face and an upper portion that is at 84 degrees from the horizontal. Another design, called the General Motors, or GM, shape, is also used in both a permanent and temporary capacity. Research has shown, however, that the GM shape produces excessive roll in impacting vehicles.(3) GM-shape barriers are generally being retired from use. A more recent design, the F shape, is considered the most efficient barrier design in terms of redirection and preventing rollover. A modified F shape is being used in the field in at least one State at this time.

The theory on which the New Jersey barrier performs is relatively simple. Referring to figure 1, when a vehicle strikes the barrier at an angle less than 15 degrees, the initial contact is between the 3-in vertical curb and the vehicle tire. This contact deforms the tire, tending to slow the vehicle. The front wheel then climbs up the 55 degree batter-curb face causing the vehicle to be lifted from the roadway. The lifting of the vehicle dissipates some of its kinetic energy of motion and places it in a position such that the redirecting forces perpendicular to the barrier can be applied to the vehicle's suspension system. At a low angle of impact (less than 15 degrees) there is usually no contact between the side of the car and the barrier.

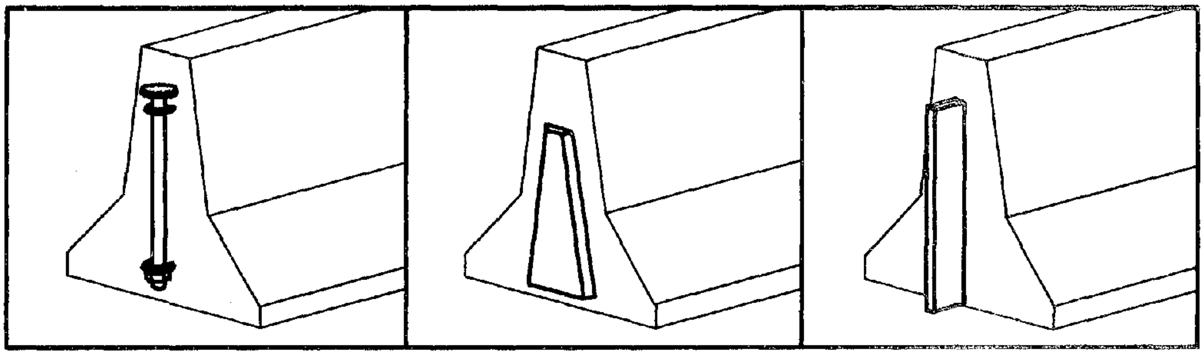
If the vehicle's impact speed is high (for example 60 mi/h) and its impact angle is more than a few degrees, the vehicle may climb up the 55-degree angled face to where the angle changes to 84 degrees (the upper portion of the barrier). As the front portion of the vehicle wheel contacts the upper (near vertical) portion of the barrier, the wheel is turned parallel to the barrier's longitudinal axis and the vehicle is redirected. Depending on the impact speed and angle, the vehicle may continue to climb the near vertical portion of the barrier before returning to the roadway.

Permanent concrete barriers were used in medians to separate traffic or to replace older, less effective designs. In some phases of highway construction, the barrier also was used in work zone traffic control. Although most of the concrete median barrier was cast in place, some precast barrier was also used. This precast concrete barrier led to the development of a barrier that could be moved from one location to another and could be placed in a position temporarily while work was completed.

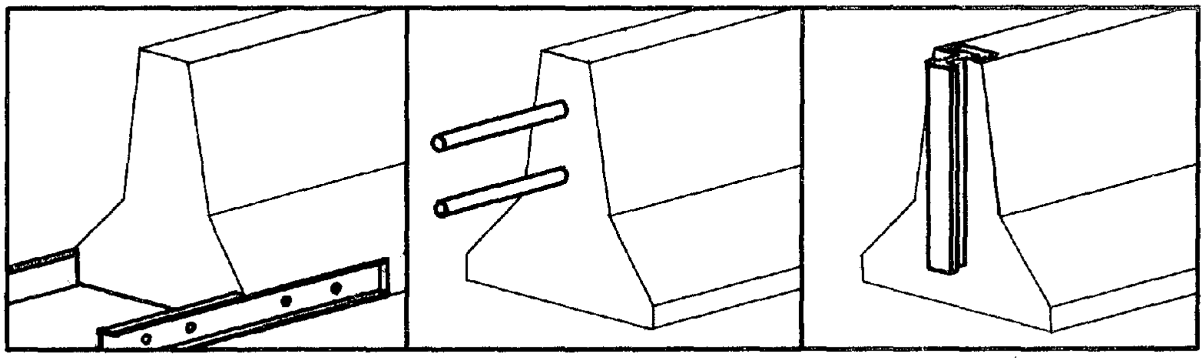
In its early history the segments of the PCB were sometimes simply butted end-to-end. It soon became evident, however, that the segments needed to be connected in order to be effective. While the use of PCB spread rapidly in the 1970s, various agencies developed a number of different methods for connecting the barrier segments. Two statements from different reports illustrate the variety in connector design. One report stated that "there are at least as many variations in PCB design as there are states in which it is used".(4) The second report stated, "Although



New Jersey Barrier



Pin and Loop Tongue and Groove Plate Insert



Channel Splice Double Dowell I-Beam

Figure 1. New Jersey barrier and typical connectors

the PCB is used from coast to coast, its design features vary from State to State.... It is in the method of joining these segments that the widest design variation takes place". (5)

For the PCB system to perform properly and redirect vehicles it must be capable of withstanding the kinetic energy exerted by a vehicle striking it. The weakest point in the PCB system is its connectors, which include the physical connection and mating faces of adjoining barriers.

Figure 1 also shows a number of methods of connecting barrier segments. Although the strength of these connectors varies widely, published research has shown that barriers with the tongue and groove connector, one of the weakest, had 49 vehicle contacts for every reported accident in which the barrier was involved. (2)

B. Present Use of Portable Concrete Barrier Connectors

The wide variety of connector types is reflected in the results (table 1) of a survey of PCB use. In a 1985 telephone survey, the Federal Highway Administration (FHWA) asked the States what type of connectors they were using. The results of this earlier survey were sent to the principal construction engineer of each State highway agency, including Puerto Rico and the District of Columbia with a letter asking each engineer to verify the type of connector used in his/her State, send copies of the State's standard plan(s) on portable concrete barriers, and designate a contact person in the event that interviews would be sought.

Forty-eight of the fifty-two agencies responded to the survey and confirmed the type of PCB connector used. For each State, the primary connector type and approved alternates are listed in the table. Some States specified a number of acceptable connectors with no preference. For these States all the connectors are listed under Primary Connector. Other States allowed more than one type of connector but preferred one or more types. In these States the preferred types(s) are listed under Primary Connector and the others are listed under Alternate Connector. The length of the barrier segments used in each State is also given.

The most commonly used connector is the pin and loop connector. It consists of steel loops cast in each end of the barrier segment. The barriers are connected by inserting a pin through the loops of two adjacent barrier segments. (Detailed descriptions of each connector type are given in chapter II.) Forty-six of the agencies use some variation of the pin and loop connector.

The pin and loop connector category can be subdivided by the types of material used to form the loops. Loops are commonly formed from reinforcing steel bars (rebar), wire rope, eye bolts, or steel plates. Twenty-seven agencies specify the pin and rebar connections, fourteen agencies specify the pin and wire rope, two agencies specify the eye bolt, and one agency specifies the pin and plate connector. (Two agencies using pin and loop connectors did not respond to the survey and, therefore, could not be categorized.)

Table 1
Usage Survey Results

State	Primary Connector	Alternate Connector	Barrier Segment Length	Confirmed By Engineer
Alabama	Pin & Rebar		10 ft ± 1/2 in	Yes
Alaska	Pin & Rebar		10 ft	Yes
Arizona	Pin & Wire Rope		12 ft 6 in, and 20 ft	Yes
Arkansas	Pin & Wire Rope		10 ft	Yes
California	Pin & Rebar		19 ft 10 in	Yes
Colorado	Pin & Rebar		10 ft	Yes
Connecticut	Pin & Rebar		20 ft	Yes
Delaware	Plate Insert		12 ft	Yes
Dist. of Columbia	Pin & Rebar	Plate Insert	12 ft	Yes
Florida	Flaring Tongue & Groove, Straight Tongue & Groove, Pin & Wire Rope, Pin & Rebar	Side Plate	12 ft min	Yes
Georgia	Pin & Rebar		10 ft	Yes
Hawaii	Pin & Rebar		19 ft 9 1/4 in	Yes
Idaho	Pin & Wire Rope		Unknown	No
Illinois	Pin & Wire Rope		10 ft	Yes
Indiana	Pin & Rebar		10 ft	Yes
Iowa	Pin & Wire Rope		10 ft	Yes
Kansas	Straight Tongue & Groove with Steel Dowels	Straight Tongue & Groove with Side Plates	10 ft	Yes
Kentucky	Straight Tongue & Groove With Side Plates,		20 ft ± 1/2 in	Yes
	Pin & Rebar		10 ft ± 1/2 in	
	Slotted Triple Dowel		20 ft, 30 ft	
Louisiana	Pin & Wire Rope		15 ft	Yes
Maine	Pin & Rebar		10 ft	Yes
Maryland	Plate Insert		Unknown	No
Massachusetts	Pin and Loop		Unknown	No
Michigan	Pin & Eye Bolt	Double Dowel	10 ft	Yes
Minnesota	Pin & Wire Rope		10 ft	Yes
Mississippi	Pin & Rebar		10 ft ± 1/2 in	Yes
Missouri	Straight Tongue & Groove with Continuous Cable		10 ft	Yes
Montana	Pin & Wire Rope		10 ft	Yes
Nebraska	Pin & Rebar		10 ft	Yes
Nevada	Pin & Rebar		19 ft 10 in	Yes
New Hampshire	Pin & Rebar		10 ft	Yes
New Jersey	Straight Tongue & Groove, Straight Tongue & Groove with Side Plate	Welsbach	20 ft	Yes
New Mexico	Pin & Rebar	Straight Tongue & Groove	10 ft	Yes
New York	Vertical I-Beam		8 ft, 10 ft, 12 ft, 14 ft, 16 ft, 18 ft, 20 ft	Yes
North Carolina	Pin & Rebar		10 ft	Yes
North Dakota	Pin & Wire Rope		10 ft	Yes
Ohio	Pin & Rebar	Straight Tongue & Groove Flaring Tongue & Groove	10 ft, 12 ft	Yes

Table 1 (concluded)

State	Primary Connector	Alternate Connector	Barrier Segment Length	Confirmed By Engineer
Oklahoma	Pin & Rebar		10 ft	Yes
Oregon	Pin & Wire Rope		12 ft 6 in	Yes
Pennsylvania	Plate Insert			
	Flaring Tongue & Groove		30 ft max	Yes
Puerto Rico	Pin and Loop		Unknown	No
Rhode Island	Pin & Rebar		10 ft	Yes
South Carolina	Pin & Rebar		12 ft	Yes
South Dakota	Pin & Twin Double Rebar		10 ft	Yes
Tennessee	Pin & Triple Rebar		8 ft to 12 ft	Yes
Texas	Channel Splice		14 ft 11 in to 25 ft	Yes
		Grid Slot, Lapped Joint & Bolt		
		Flaring Tongue & Groove		
		Steel Dowel	30 ft ± 4 in	
Utah	Pin & Plate	Pin & Wire Rope	10 ft, 12 ft, 12 ft 6 in, 20 ft	Yes
Vermont	Pin & Rebar		10 ft	Yes
Virginia	Flaring Tongue & Groove	Plate Insert	12 ft	Yes
Washington	Pin & Wire Rope		10 ft and 12 ft 6 in	Yes
West Virginia	Flaring Tongue & Groove	Pin & Eye Bolt	12 ft and 10 ft 10 ft	Yes
Wisconsin	Pin & Rebar with Wire Rope		10 ft	Yes
Wyoming	Pin & Rebar Pin & Wire Rope		10 ft	Yes

Total:	Unspecified Pin and Loop	2 agencies
	Pin and Rebar	27 agencies
	Pin and Wire Rope	14 agencies
	Pin and Eye Bolt	2 agencies
	Pin and Plate	1 agency
	Tongue and Groove	8 agencies
	Plate Insert	5 agencies
	Channel Splice	1 agency
	Side Plates	1 agency
	I-Beam	1 agency
	Continuous Cable	1 agency
	Dowel Rods	2 agencies
	Grid Slot	1 agency

After the pin and loop category, the next most commonly used connector is the tongue and groove connector. It consists of a vertical protrusion, or tongue, cast into the end of a barrier segment that is inserted into the groove of an adjacent segment. Eight agencies specify the tongue and groove connector as their primary or alternate connector.

The plate insert connector consists of a steel plate inserted in a vertical slot located in the lower center of each barrier end. This connector is specified by five agencies.

Eight agencies specify connectors other than the three types mentioned. The channel splice, I-beam, grid slot, side plates, top T lock, Welsbach, lapped joint and bolt and continuous cable connectors are each specified by one agency. The dowel connector is specified by two agencies. (See chapter II for descriptions of these connectors.)

The review of each State's standard plans for portable concrete barriers reveals even greater variability in connector types than the survey results shown in table 1. Even though twenty-seven agencies use the pin and rebar connector, their specifications for pin diameter, loop diameter, depth of loop embedment in the barrier end, and gap width between barrier segments differ. Virtually no two States have identical specifications for PCB connectors.

C. Problems Observed in FHWA Field Reviews

A 1985 memorandum (6) covering portable concrete barrier connectors was sent to FHWA Regional Administrators from the Directors of the Offices of Highway Operations and Traffic Operations. This memorandum stated that in field reviews by FHWA headquarters personnel, recurring problems involving PCB connectors had been observed. These problems were serious enough to make the barriers ineffective in protecting both workers and motorists.

Some of the most serious recurring problems observed were as follows:

* In pin and loop connections, contractors often failed to install the vertical steel pin. The pin also was prone to removal by vandals. The loops were structurally inadequate because of design deficiencies or previous damage.

* Tongue and groove systems were not adequately interlocked. At times the barrier sections were not butted flush against each other. The tongue or groove was damaged to the point of being ineffective.

* Some systems, such as the plate insert connector, might not have enough connection slack to be installed on sharp curves or flares.

* A number of systems were difficult to realign if they shifted as a result of a vehicular impact.

- Some of the systems being used have not been properly tested using accepted crash test criteria.
- Improper placement or position of the barrier constituted at times a hazard to motorists.

D. Project Objectives

The objectives of this contract were to develop:

- A report on the state-of-the-art of portable concrete barrier connectors.
- Recommendations for additional work to fill gaps in the technology.

The work in the contract involved (a) a literature review of research that has been done on PCB, (b) contacts with and visits to highway agencies to discuss PCB use, and (c) analytical determination of connector strengths. The key task of the project was to compare the research that has been done on PCB with the present application of PCB in actual work zones.

E. Report Organization

This final report describes the state-of-the-art in PCB connector design and presents an evaluation of the PCB design capabilities with present application in actual work zone situations.

After this introductory chapter, Chapter II details the various connector designs used in the United States. Chapter III discusses the forces involved when a barrier is hit, a method for measuring the strength of a connector system, and the results of an analytical determination of the strengths of State connector systems. Chapter IV summarizes the crash tests that have been conducted on portable concrete barriers and compares the crash test results and current field applications. Chapter V presents information gathered in the State visits. Advantages and disadvantages of PCB systems, performance of the barrier during accidents, anchoring methods, and connections to other barriers also are discussed. Chapters VI and VII present the conclusions and recommendations developed from the literature review, analytical determination of connector strengths, and the field visits. Finally, Chapter VIII presents the recommendations of the study that address additional crash tests needed and other research that should be performed. There are three appendixes. Appendix A presents connector design details, appendix B gives individual crash test descriptions and appendix C describes information gathered in each State visit.

II. Types of Portable Concrete Barrier Connectors

A variety of types of portable concrete barrier (PCB) connectors are in use in the United States. This chapter describes these connectors, lists the States or agencies that use the connectors, gives specifications important to the performance of the subject connector, and discusses the structural advantages and disadvantages of the subject design. Next is a brief description of how the connector is applied and replaced in the field. Last, if applicable, are crash test performances of the connector and any special features a particular type may have which sets it apart from other connectors in its category.

The connectors are described by category, such as pin and loop or tongue and groove, and divided into types, such as pin and rebar or flaring tongue and groove connector. The categories are discussed in the order of most to least used connectors. Some of the latter categories are experimental connectors used only in crash tests. The last category of connectors is hybrid connectors. They incorporate features of more than one connector type (usually the tongue and groove in combination with another connector). Although experimental connector types are included, connectors that have been determined to be obsolete are not included. A total of 24 types of connectors are described.

Specifications on the various PCB connector types described in this chapter are given in appendix A. This appendix is an extensive table that lists dimensions of the connectors and their respective PCB segments, the States or agencies using these connectors, and notes on crash tests performed on given connectors. The connector types and their dimension symbols used in the table are keyed to those used in the figures that will be presented in this chapter illustrating the various types of connectors. Details of the crash tests noted in the appendix table are given in chapter IV.

All specifications given in appendix A for State connector designs were taken directly from State specification sheets acquired through a mail survey of the States. Non-State connector specifications were taken from various publications written by the testing agency. The information on the States or agencies which use the specific types of connectors also was taken from State specification sheets, or in the case of agencies, from various publications.

A. Pin and Loop

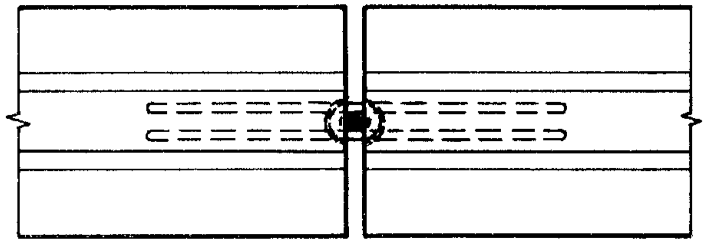
In this category of connector the joint is constructed by casting either rebar, wire rope, eye bolt, or plate into each end of the barrier segments. Loops are then positioned such that they overlap and a steel pin is inserted in the loops. Forty-six States and agencies now use this connector variety. There are several varieties of the pin and loop connector, and they differ according to gap width, pin diameter, loop embedment length, and material used to form the loops. While all these factors are important, the most important is the gap width. The gap width directly determines the amount of rotational slack that can be expected in a given connection. Rotational slack is the angle through which two connected barriers can rotate freely relative to each other before their connector begins resisting rotation. Excessive rotational slack is undesirable in a barrier, since it usually results in excessive lateral displacement of the barrier when impacted. Presently, only 15 States directly specify a gap width for this connector and some of those are excessive (greater than 3 in). Other States indirectly imply a nominal gap width as a result of other dimensions, but do not specify gap width as such. Generally speaking, this joint can develop moderate strength in tension, shear, and torsion. Barriers with these connectors are generally easy to install. The one exception is when anchoring nuts are required on the connecting pins, since access to the threaded portion of the pin is difficult for barriers with a small gap width.

1. Pin and Rebar

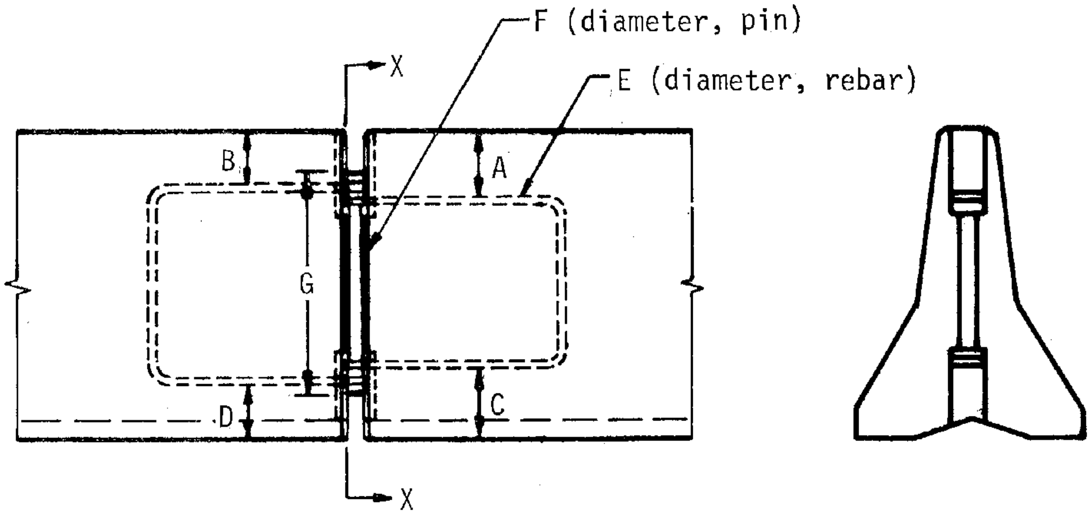
The pin and rebar connector (see figure 2) is a variety of the pin and loop connector which uses steel rebar to form four loops (two loops in each barrier end). Twenty-five States use this connector at this time. Gap width varies anywhere from 1 in to 3 in; however, most users do not specify the gap width. One State, Georgia, has a rotational slack of 18 degrees, due to an excessively large gap width. Pin diameters vary from 7/8 in to 1 1/4 in. Rebar diameters vary from 5/8 in to 1 in. Segment lengths vary from 10 ft to 19 ft 10 in, with intermediate sizes specified. Wisconsin specifies a pin and loop type connector which uses wire rope loops that are spliced onto rebars which are cast in the barrier. This splice gives the connector characteristics of both the pin and rebar, and pin and wire rope connectors. To date, four crash tests have been conducted on pin and rebar connectors. In one test, the unanchored pin was bent out of the loops and allowed a barrier segment to overturn. In another test, unanchored pins were bent out of the loops, and the barrier broke in two because of impact with the vehicle. This illustrates the importance of the pin in the performance of this connector. Permanent deflection for the remaining two tests was relatively low, measuring 0.46 and 0.52 ft.

2. Pin and Triple Rebar

The pin and triple rebar connector (see figure 3), a variety of the pin and loop connector, has three rebar loops cast into each barrier end rather than the usual two. However, all these loops are cast in the bottom half of the barrier, putting them very close together. At this time only Tennessee uses this connector. This loop configuration promotes an increase in torsional rotation slack due to lack of adequate anchoring near the top of the barrier. Since torsional rotation promotes the ramping of vehicles upon impact, this connector could be considered inferior to other pin and loop varieties in this respect. It has a gap width of 2 in, a segment length from 8 ft to 12 ft, a 1-in-diameter pin, and a 1/2-in-diameter rebar used for the connectors. To date no crash tests have been performed on this connector.



TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL

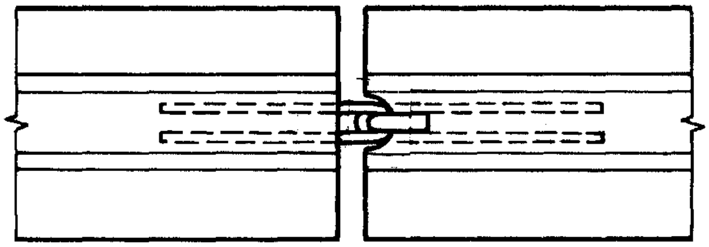


TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL

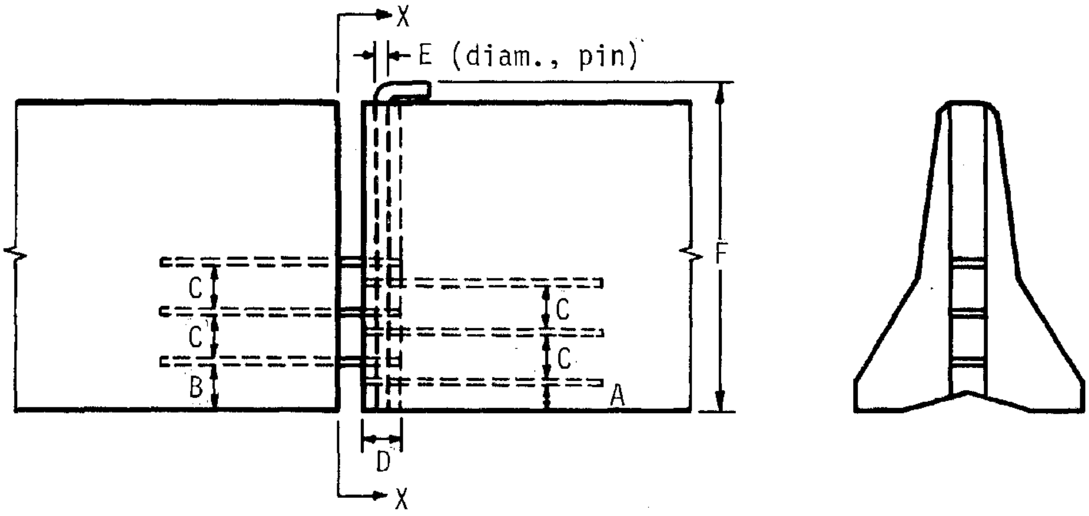
VIEW X-X

(see pages 88 and 89 for values of lettered dimensions)

Figure 2. Pin and rebar



TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL



TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL

VIEW X-X

(see page 89 for values of lettered dimensions)

Figure 3. Pin and triple rebar

3. Pin and Twin Double Rebar

The pin and twin double rebar connector (see figure 4), a variety of the pin and loop connector, has four rebar loops cast into each barrier end rather than the usual two. Only South Dakota uses this connector at this time. The advantage of this configuration is the decreased probability of connector failure due to loop rupture or rebar loops coming out of the barrier ends. It has a segment length of 10 ft, a rebar diameter of 5/8 in, a pin diameter of 1 3/8 in, and no specification of gap width. To date, no crash tests have been performed on this connector.

4. Pin and Wire Rope

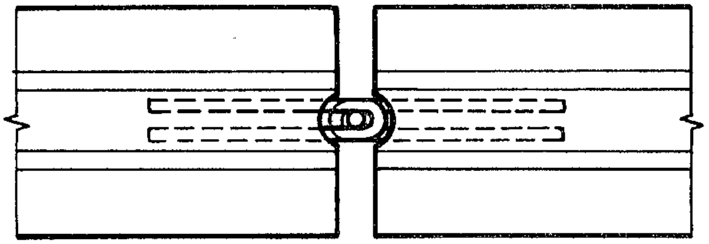
The pin and wire rope connector (see figure 5), a variety of the pin and loop connector, uses wire ropes to form the loops. Fourteen States now use the pin and wire rope connector. Differences in pin diameters vary from 7/8 in to 1 1/4 in. Differences in gap width are anywhere from 1/4 in to 3 1/2 in; however, most users do not specify the gap width for this connector. Also, segment lengths vary from 10 ft to 25 ft, with several intermediate lengths between. There is little difference, however, in wire rope diameters, the dimensions being either 1/2 in or 5/8 in. To date, no crash tests have been performed on the pin and wire rope connector.

5. Pin and Eye Bolt

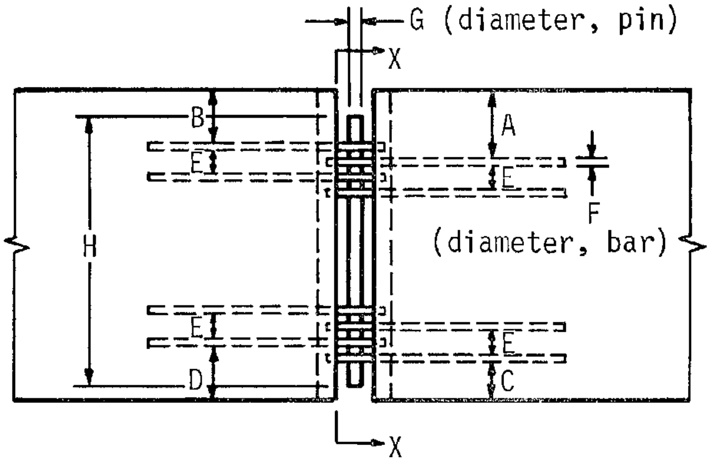
The pin and eye bolt connector (see figure 6), a variety of the pin and loop connector, consists of two eye bolts cast into each barrier end to form the loops. West Virginia and Michigan use this connector at this time, although Michigan is in the process of changing their connector design to the pin and wire rope connector. A major reason for Michigan changing from the pin and eye bolt connector is that the eye-bolt would break off in shear during handling of the barriers. Another State, Minnesota, in the past had the experience of eye-bolts pulling out of barrier ends on impact, and therefore changed their connector design. West Virginia specifies a segment length of 10 ft, a pin diameter of 7/8 in, and a 3/4-in-eye bolt, but does not specify a gap width. To date, no crash tests have been performed on this connector.

6. Pin and Plate

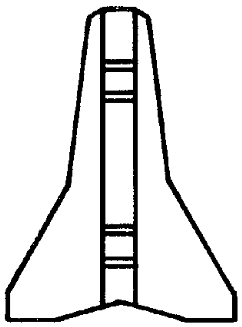
The pin and plate connector (see figure 7), a variety of the pin and loop connector, uses steel tongues cast longitudinally into the barrier ends to form the loops. Holes are cut into the tongues to form the loops through which the pin goes. Utah is the only State which uses this connector at this time. The connector has the same basic performance characteristics as the pin and rebar connector. It has segment lengths of 10 ft, 12 1/2 ft, and 20 ft; a pin diameter of 1 in; and a plate thickness of 1/2 in. No gap width is specified. To date, no crash tests have been performed on this connector.



TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL



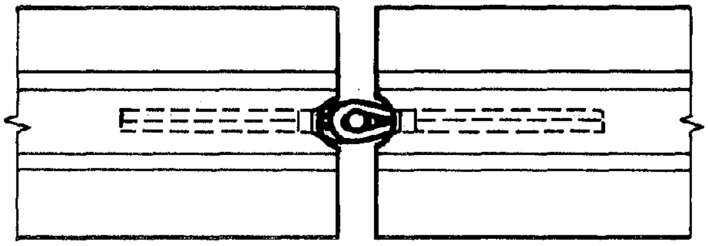
TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL



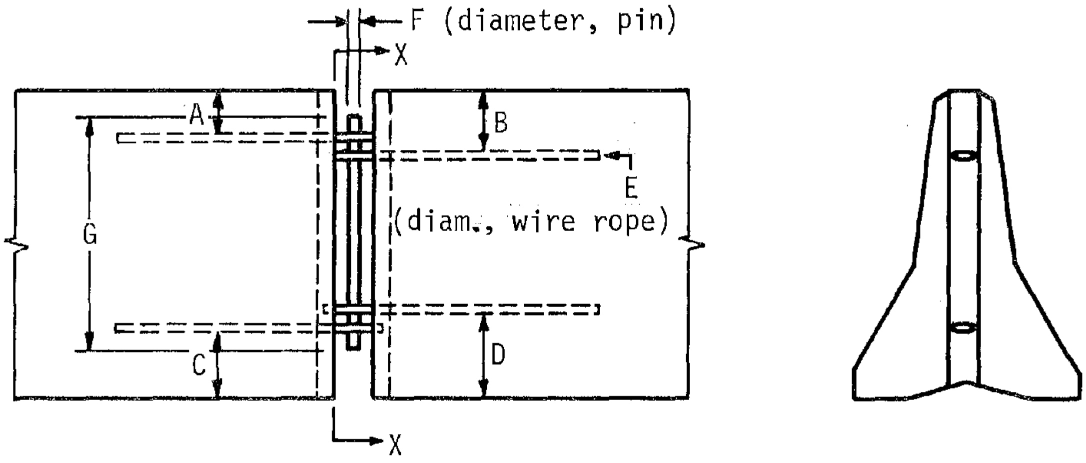
VIEW X-X

(see page 89 for values of lettered dimensions)

Figure 4. Pin and twin-double rebar



TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL

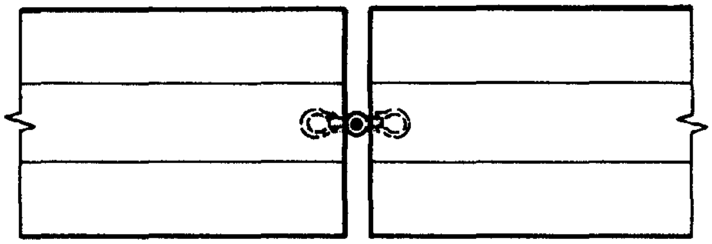


TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL

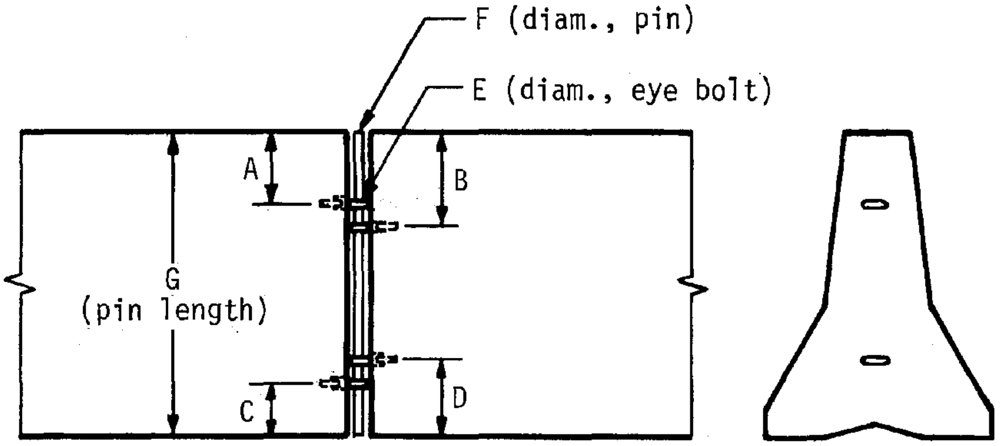
VIEW X-X

(see page 90 for values of lettered dimensions)

Figure 5. Pin and wire rope



TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL

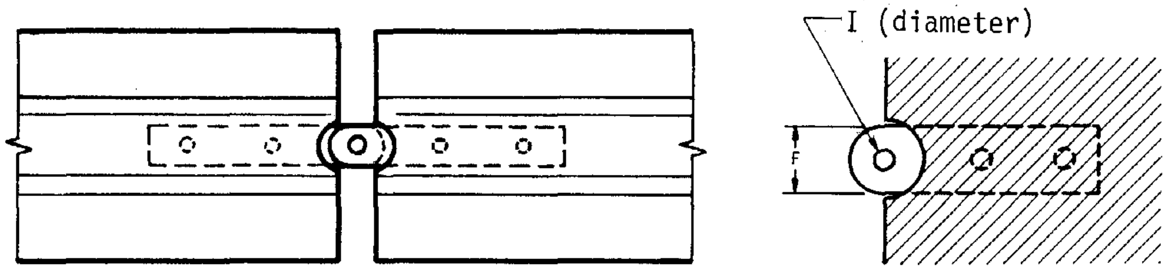


TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL

TYPICAL END VIEW

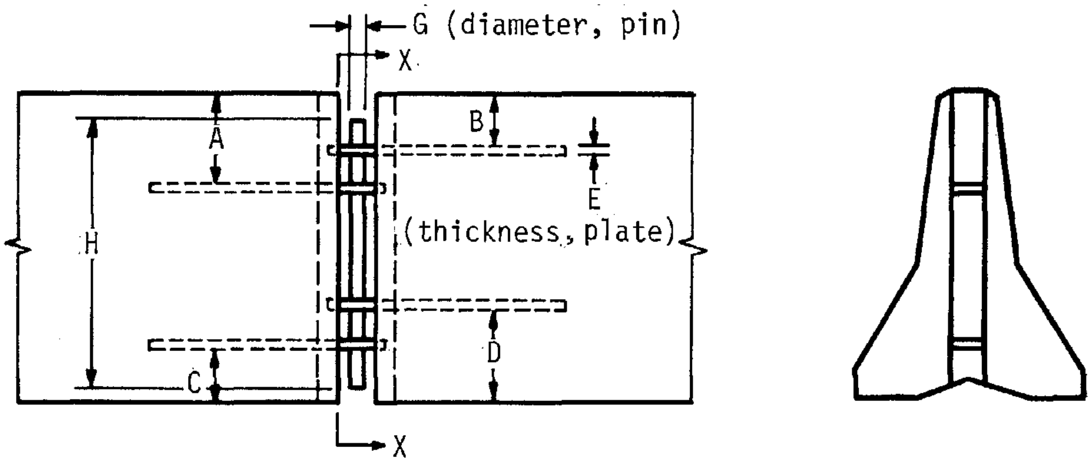
(see page 90 for values of lettered dimensions)

Figure 6. Pin and eye bolt



TYPICAL PANEL PLAN WITH A VIEW OF CONNECTION DETAIL

PLATE DETAIL



TYPICAL PANEL ELEVATION WITH A VIEW OF CONNECTION DETAIL

VIEW X-X

(see page 91 for values of lettered dimensions)

Figure 7. Pin and plate

B. Tongue and Groove

In this category of connector, the connector is formed by casting male tongues and/or female grooves in portable concrete barrier end. The tongues are then fitted in the grooves to form a connection. This connector has two basic shapes (as viewed from the barrier end): straight and flaring. At this time, eight States use some type of tongue and groove connector. The important factor for this connector is the cross-sectional area of the tongue because that area determines the shear and torsion strength of the connector. The connector has no capacity to transfer tension or moment from one segment to the next.

1. Flaring Tongue and Groove

The flaring tongue and groove connector (see figure 8) consists of a trapezoid-shaped tongue or groove cast in the end of a barrier segment. The tongue is inserted into a like-shaped groove cast into an adjacent barrier segment. Six States now use the flaring tongue and groove. This connector generally has no capacity to transfer tension or moment from one segment to the next, and can transfer only small torsion and shear loads between segments.

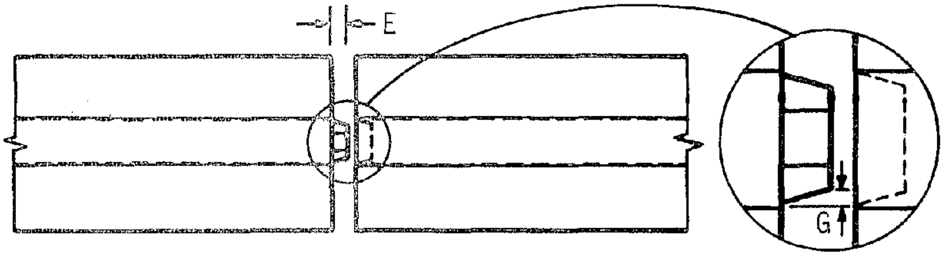
This barrier connector is easy to install initially, and replacement of a segment requires simply that a double female end segment be lifted out of the system; there is no disruption to other segments of the system. One crash test has been performed on this connector by ENSCO, Inc. For a 4240 lb vehicle impacting at 58 mi/h and 25 degrees, the connector failed since one barrier segment overturned.

2. Straight Tongue and Groove

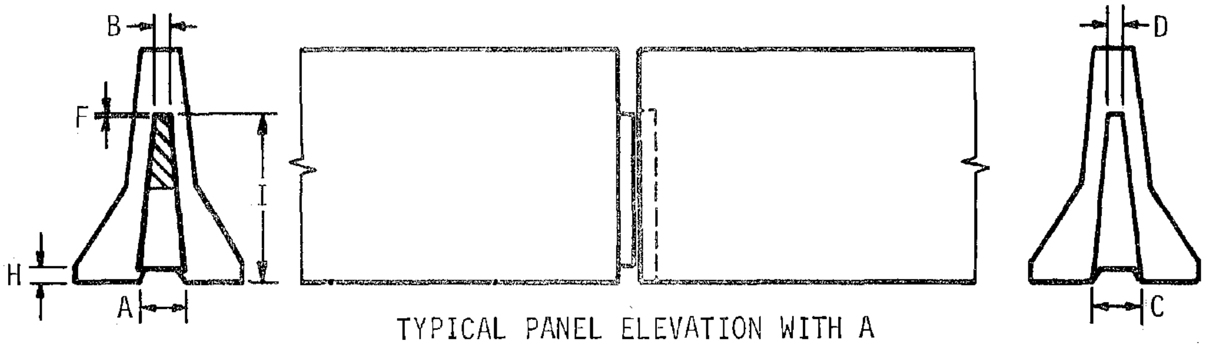
The straight tongue and groove connector (see figure 9) is the same as the flaring tongue and groove except that it is approximately as wide at the top as it is at the bottom. Four States specify this connector at this time. Like the flaring tongue and groove, this connector has no ability to transfer tension or moment between segments, and can transfer only small torsion and shear loads. It differs in design from the flaring tongue and groove in that it's tongue and groove runs the full height of the barrier face. A segment can be lifted and lowered into place within the barrier system without the adjacent barriers on either end being moved. To date, no crash tests had been performed on this connector.

C. Plate Insert/Grid Slot

In this category of connector, the connector consists of either a rectangular, steel plate (plate insert), or a welded rebar grid (grid slot) inserted into vertical slots in each barrier end. Five States specify the plate insert, and one State (Texas) specifies the grid slot. The most important factors for this category are either plate thickness or rebar diameter, since these dimensions determine the moment, torsion, and shear capacities.



TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL

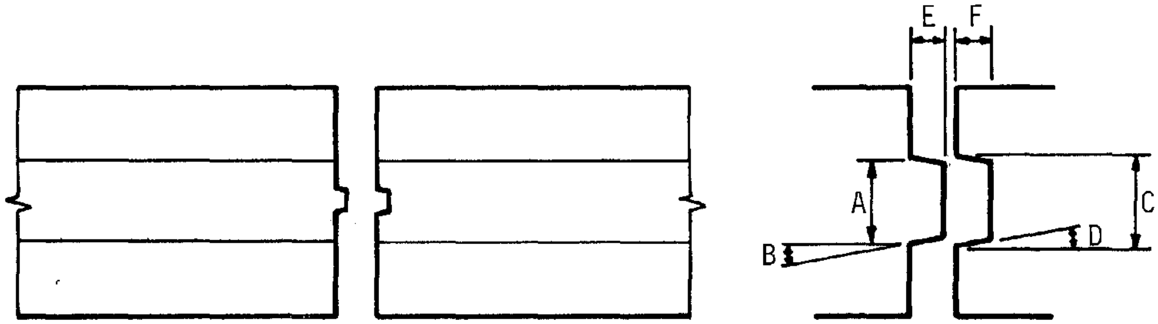


TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL

TYPICAL END VIEW

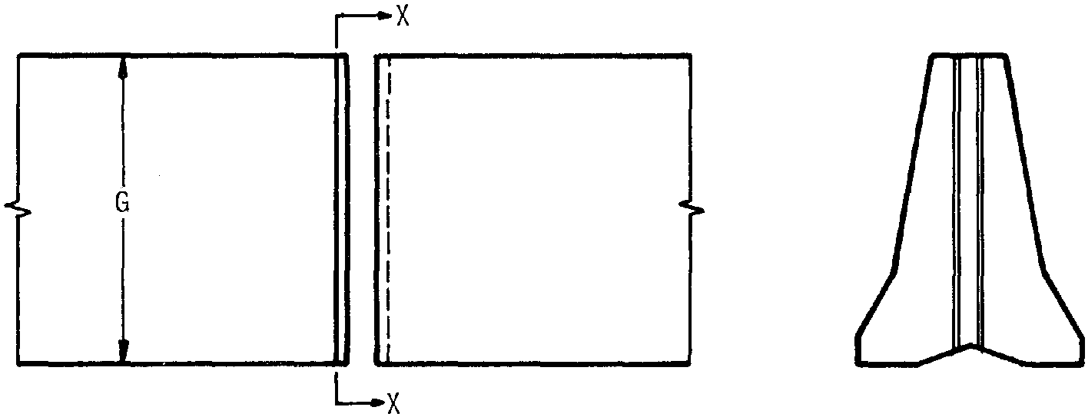
(see page 91 for values of lettered dimensions)

Figure 8. Flaring tongue and groove



TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL

CONNECTION DETAIL



TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL

VIEW X-X

(see page 91 for values of lettered dimensions)

Figure 9. Straight tongue and groove

1. Plate Insert

The plate insert connector (see figure 10) consists of a rectangular steel plate inserted in vertical slots in each barrier end. This connector is popular in the eastern mid-Atlantic States. Important dimensions for this connector are plate width, height, thickness, and slot width. This connector has no tensile capacity, and low moment, shear, and torsion capacities. Structural performance is also hindered by the fact that the vertical slots cast in the barrier end reduce barrier cross section. This creates a tendency for the plates to "break out" of the barrier upon impact before they actually fail. Replacement of segments involves lifting the desired segment out of the barrier system and lowering a new segment back into the system. To date, no crash tests have been performed on this connector.

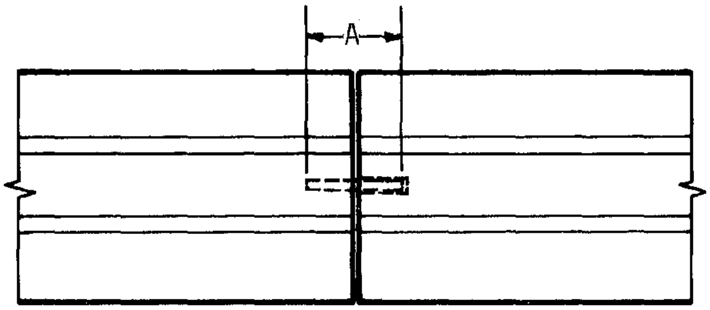
2. Grid Slot

The grid slot connector (see figure 11) involves placing a rectangular grid of welded rebar into vertical slots cast into each barrier end. To date, only Texas specifies the grid slot connector. Important dimensions for this connector are overall grid width and length, rebar diameter, welding requirements, and slot widths. This connector has no tensile capacity, and low torsion, shear, and moment capacities. The structural capacity of the connector is hindered by the fact that vertical slots at each barrier end reduce the barrier cross section by approximately one half, thereby causing the grid to break out of the barrier upon impact before actually failing itself. Since the vertical slots extend to the top of the barrier, application and maintenance of this system are rather simple, requiring no more than aligning the barrier segments and dropping the grid slot into position. To date, no crash tests have been performed on this connector.

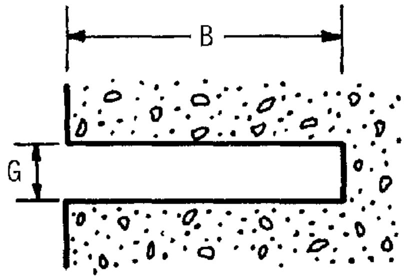
D. Steel Dowel

The steel dowel connector (see figure 12) uses either two or three steel dowels set longitudinally between barrier ends. Only three States, Texas, Kentucky, and Michigan now use this connector. Important factors for this connector are the number of dowels used, dowel diameter, dowel length, whether the gap is grouted or not, gap width, segment length, and the vertical spacing between the dowels (the dowels should be spread out vertically to inhibit torsional rotation slack). Michigan uses two dowels, and Texas and Kentucky use three dowels. Texas and Kentucky specify 1/2 in gap width; use anywhere from 20 ft to 30 ft segments; have good, even vertical distributions of the connectors in the barriers, leading to moderate torsional capacity; and have similar dowel diameters.

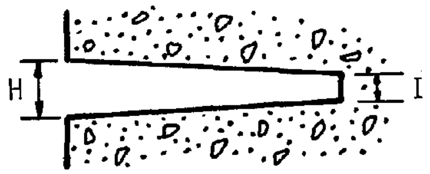
The only major difference between the three connectors is the way in which they are applied. Since Texas and Michigan have holes in the barrier ends to accommodate the dowels, replacement of a segment requires that the barrier system on either side of this segment be spread out and subsequently moved back in once the replacement has been made. Kentucky has the dowels cast in one end of a barrier, and the other barrier end has vertical slots into which the dowels are placed and subsequently grouted in. This enables Kentucky to simply lower segments into place within the barrier system.



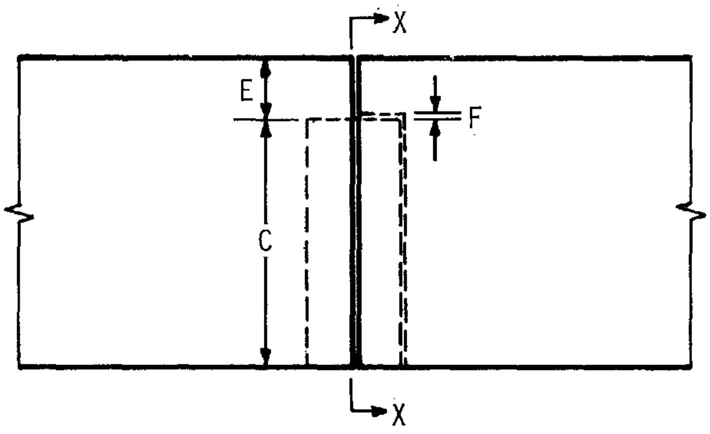
TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL



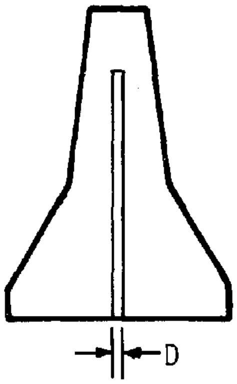
SLOT DETAIL



PERMISSIBLE TAPER



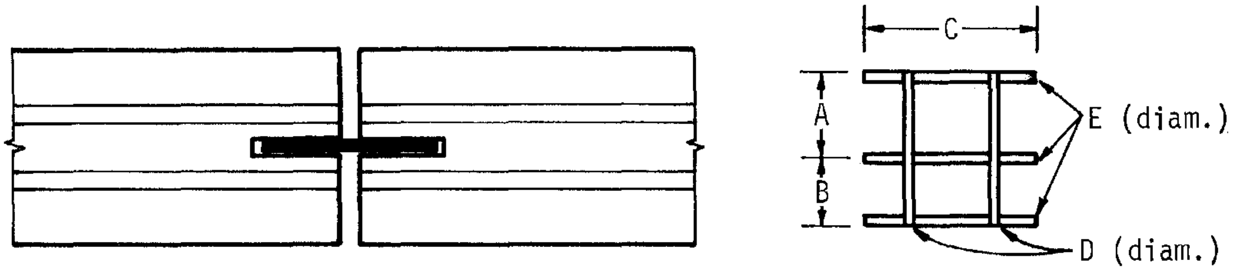
TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL



VIEW X-X

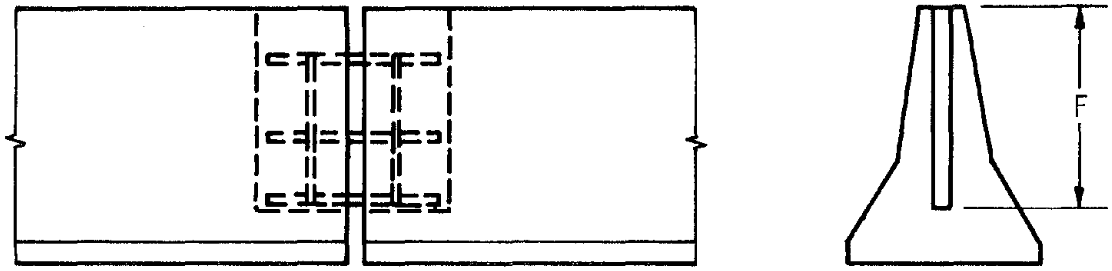
(see page 92 for values of lettered dimensions)

Figure 10. Plate insert



TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL

REBAR GRID

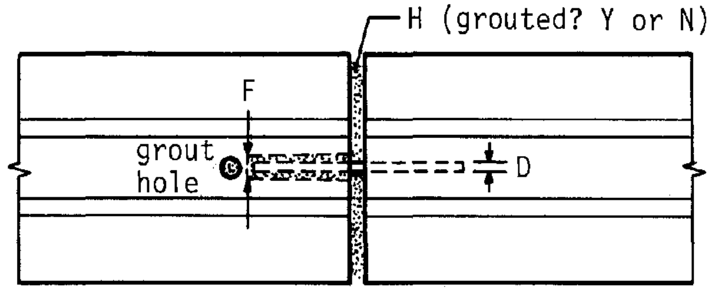


TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL

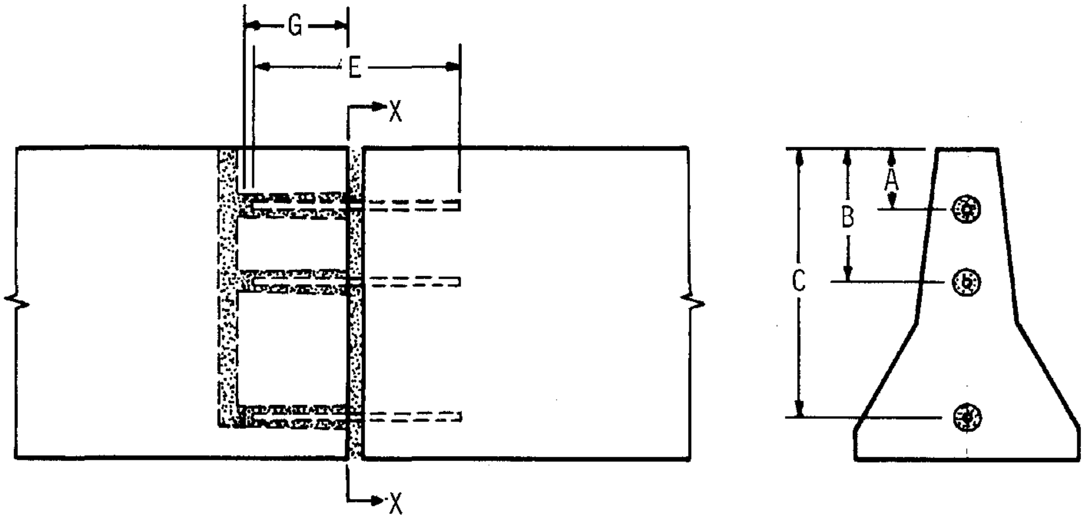
TYPICAL END VIEW

(see page 92 for values of lettered dimensions)

Figure 11. Grid slot



TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL



TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL

VIEW X-X

(see page 92 for values of lettered dimensions)

Figure 12. Steel dowel

This connector type has no tensile capacity, very low moment capacity, and moderate torsion and shear capacity. Only one crash test has been performed on this connector, and it performed satisfactorily with a 4,540-lb vehicle impacting at 60 mi/h and 25 degrees, giving a maximum permanent displacement of 1.1 ft.

E. Channel Splice/Side Plates

In this category of connector, the connector consists of either a steel channel or a steel plate bolted longitudinally, at the base, between two barriers. At this time, only Texas specifies the channel splice, and only Florida specifies the side plates. The most important factor for this connector is the type of splice used, either channel or plate. Channel splices give greater shearing, torsional, and moment capacity.

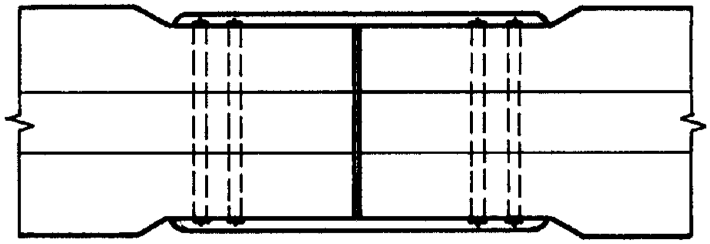
1. Channel Splice

Barrier segments utilizing the channel splice (see figure 13) are cast with two bolt holes at each end passing through the base of the barrier. Channel splices are then bolted to the sides of each adjoining segment. Only one State, Texas, uses this connector at this time. Important factors for this connector are the type of channel used, channel length, number of bolts used, bolt diameter, bolt hole diameter, spacing between bolt holes, and segment length. Using a C5 by 9 by 42 in long channel 5 in wide by 1.885 in high and anywhere from a 15 ft to 25 ft segment length, this connector generates moderately high tensile, moment, and shear strength and does not allow significant joint deflection before the moment resistance is generated. Texas has no gap width specifications for this connector, but gap width is not considered critical to this design.

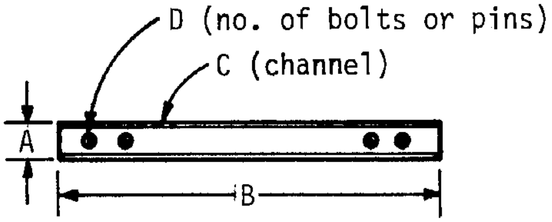
Only one crash test, Texas Transportation Institute's (TTI) 2262-2, has been performed on this connector. The connector successfully tested with a full-sized sedan impacting at approximately 60 mi/h and 25 degrees giving a maximum permanent displacement of 1.33 ft. Application and maintenance of this barrier are relatively easy, requiring only that barrier segments be set in place, channels aligned, and bolts inserted and tightened.

2. Side Plates

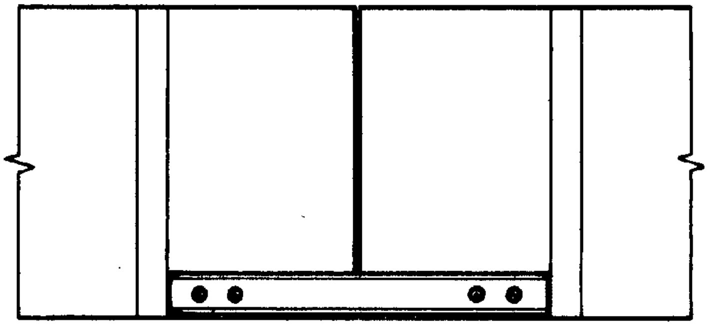
Barrier segments utilizing the side plate connector (see figure 14) are cast with either two or four bolt holes at each end passing through the base of the barrier. Rectangular side plates are then bolted to the sides of each adjoining segment. Only one State, Florida, uses this connector at this time. Also, TTI has crash-tested a connector of this design. Important factors for this connector are plate length, plate width, plate thickness, number of bolts used, bolt diameter, bolt hole diameter, spacing between bolt holes, and segment length. While the TTI and Florida connector both specifiy 1/2-in-thick plate, the TTI plate connector is wider, is longer, uses four bolts rather than two, and uses a wider bolt, making it a stronger connector than the Florida connector. The side plate connector is comparable to the channel splice connector in design, but it is generally weaker, the difference being the cross-sectional difference



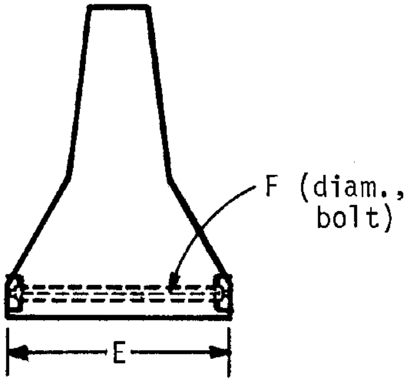
TYPICAL PANEL PLAN WITH A VIEW OF CONNECTION DETAIL



CHANNEL SPLICE



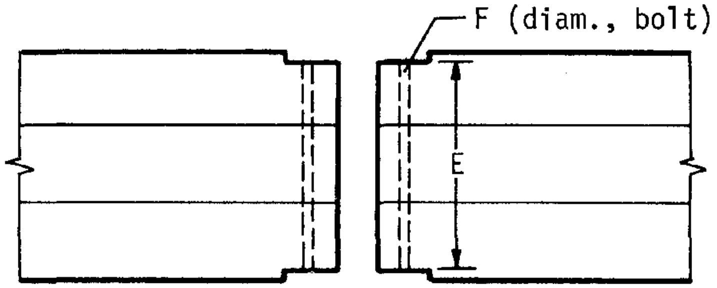
TYPICAL PANEL ELEVATION WITH A VIEW OF CONNECTION DETAIL



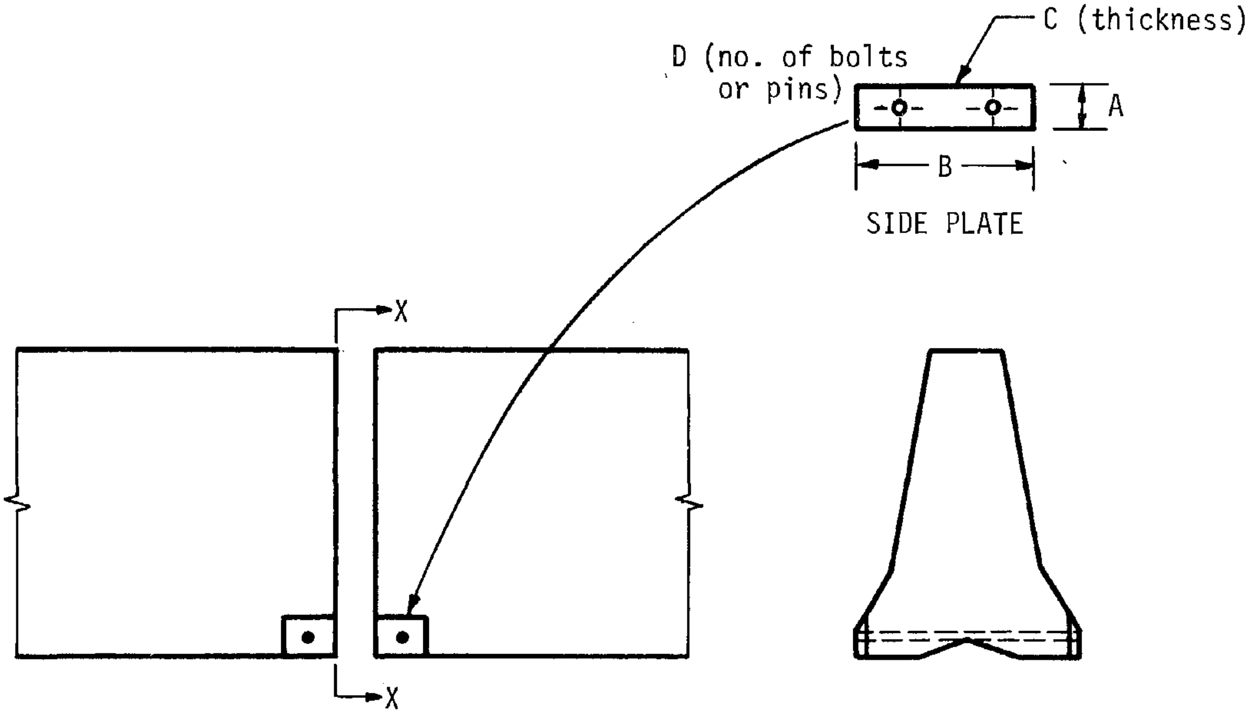
TYPICAL END VIEW

(see page 93 for values of lettered dimensions)

Figure 13. Channel splice



TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL



TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL

VIEW X-X

(see page 93 for values of lettered dimensions)

Figure 14. Side plates

between a channel and plate. Installation and maintenance on this connector are relatively easy, requiring no more than aligning the barrier into position, aligning the plates with the barrier holes, and fastening and tightening the bolts. To date, only one crash test has been performed on the TTI connector: TTI's 2262-1. This connector successfully tested with a 4500-lb vehicle impacting at 60 mi/h and 15 degrees, giving a maximum permanent displacement of 0.9 ft.

F. Vertical I-Beam

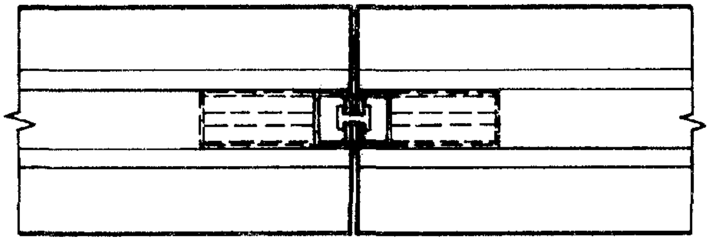
For the vertical I-beam connector (see figure 15), barrier segments are constructed with slotted steel tubes cast into each end of the barrier. The segments are then linked by passing a steel I-beam down adjoining slotted tubes. New York is the only State which now specifies this connector. Important factors for this connector are I-beam length, I-beam cross-sectional area, tubing thickness, gap width, and anchoring of the tubing in the barrier ends. This connector can develop relatively high tensile, moment, shear, and torsion capacities. To date, four crash tests have been conducted on New York's current version of this connector. The barrier system successfully crash tested with either a 2,175-lb or a 4,500-lb vehicle impacting at 60 mi/h and either 15 degrees or 25 degrees, with maximum permanent displacements ranging from 0.23 ft to 1.4 ft. Interesting to note was that in one crash test rotational slack was reduced by grouting the connection, thereby reducing permanent barrier deflection.

G. Top T-Lock

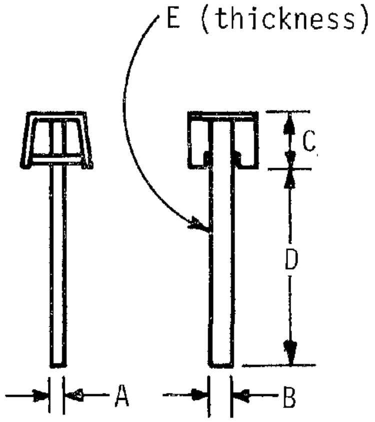
The top T-lock connector (see figure 16) consists of vertical steel tubes welded to the ends of an upright steel T. Barrier segments are cast with vertical holes at the top, near the ends, which mate with the vertical tubes of the upright T. The connection is accomplished by placing the barriers into position and lowering the T onto the barrier, placing the tubes into the holes. Only Texas now uses this connector. Important factors for this connector are welding requirements and cross-sectional areas of the members which form the T. The Texas connector uses channel and structural tubing to form the T, thereby giving it relatively high tensile, moment, shear, and torsion strength. Installation of this connector is relatively simple, requiring no more than aligning the barrier segments and dropping the T connector into place. To date, no crash tests have been performed on this connector.

H. New Jersey Welsbach Interlock

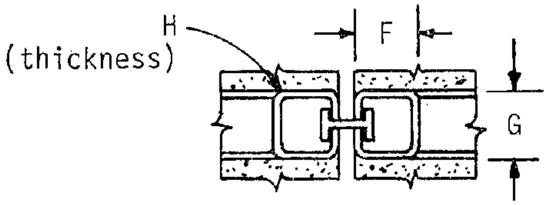
The New Jersey Welsbach connector (see figure 17) consists of two I-beam segments protruding from one barrier end and interlocking into steel-lined slots cast into the other barrier end. New Jersey is the only State which specifies this connector, and only as an alternate to preferred designs. Important factors for this connector are I-beam cross-sectional area, and slot specification. This connector has very high tension, shear, moment, and torsion capacities, comparable with those of a permanent barrier connector. Replacement of a segment is complicated by the fact that barrier segments on either end of the replacement must be spread out



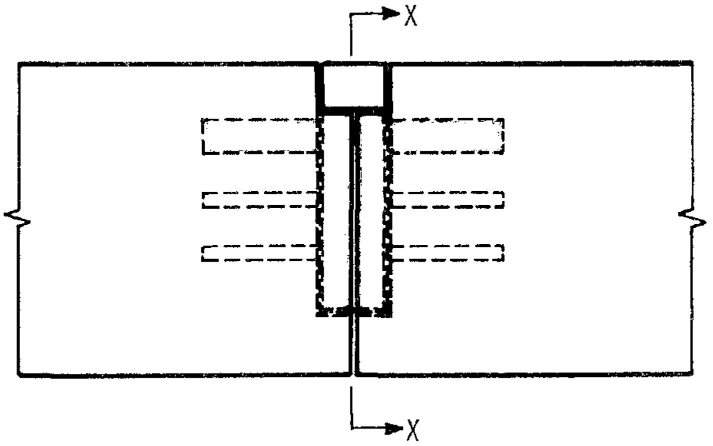
TYPICAL PANEL PLAN WITH A VIEW OF CONNECTION DETAIL



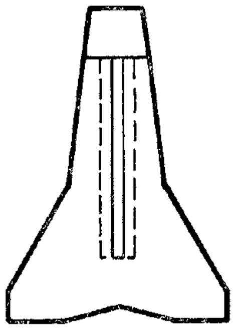
CONNECTION KEY



CONNECTION DETAIL



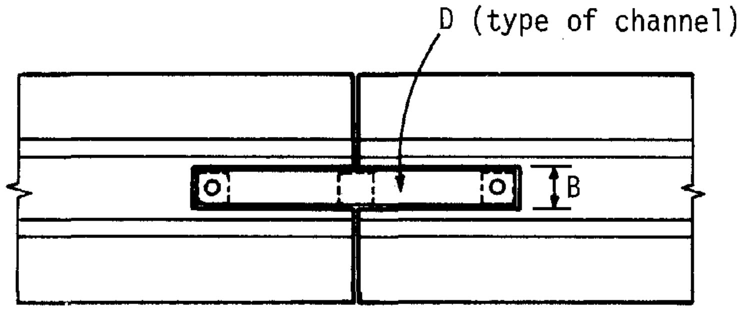
TYPICAL PANEL ELEVATION WITH A VIEW OF CONNECTION DETAIL



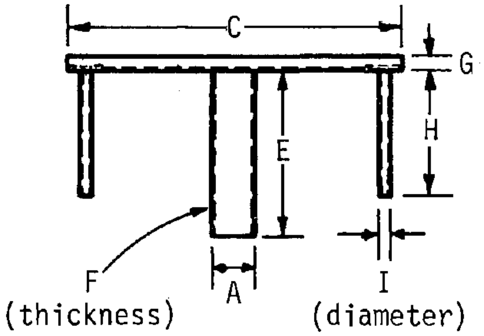
VIEW X-X

(see page 93 for values of lettered dimensions)

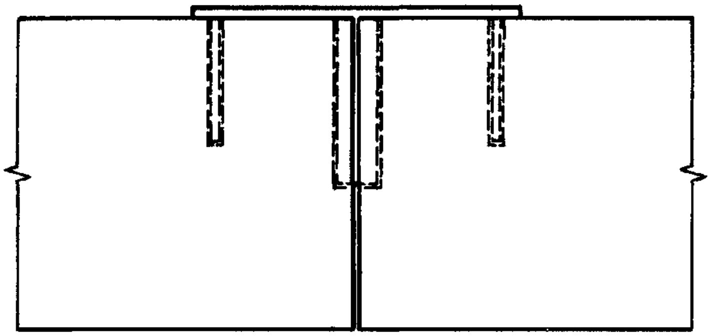
Figure 15. Vertical I-beam



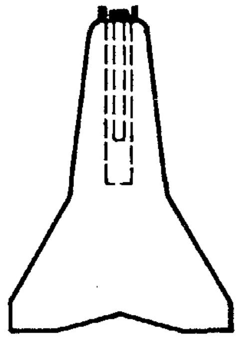
TYPICAL PANEL PLAN WITH A VIEW OF CONNECTION DETAIL



CONNECTOR DETAIL



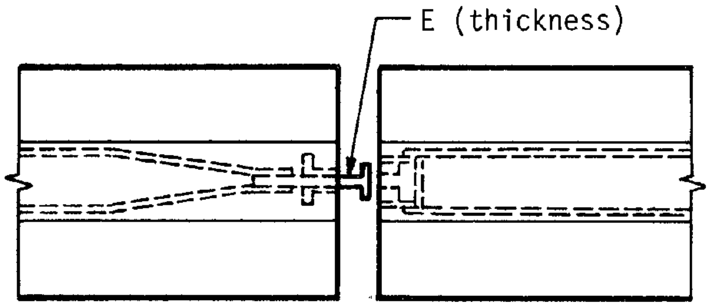
TYPICAL PANEL ELEVATION WITH A VIEW OF CONNECTION DETAIL



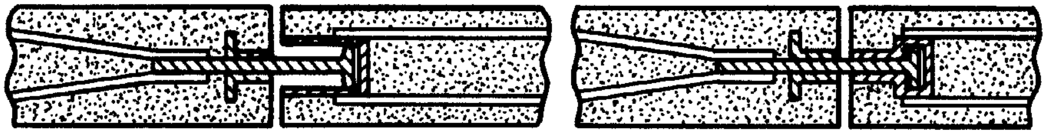
TYPICAL END VIEW

(see page 93 for values of lettered dimensions)

Figure 16. Top T-lock

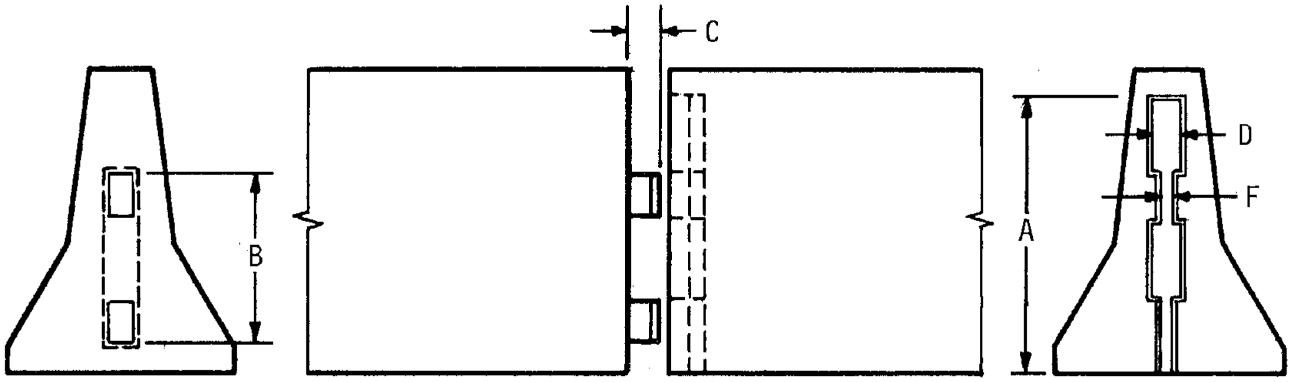


TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL



CONNECTION DETAIL 1

CONNECTION DETAIL 2



MALE END VIEW

TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL

FEMALE END VIEW

(see page 94 for values of lettered dimensions)

Figure 17. New Jersey Welsbach interlock

and subsequently moved back once the replacement has been made. To date, two crash tests have been performed on this connector. The connector performed well in both tests, the most severe being a 2,250-lb. vehicle impacting at 60 mi/h and 15 degrees. There was no permanent deflection of the barrier for either test.

I. Bottom T-Lock

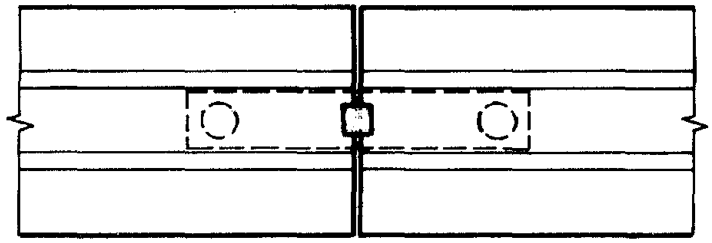
The bottom T-lock connector (see figure 18) consists of vertical steel tube welded to the ends of an inverted steel T. Barrier segments are cast with vertical holes at the bottom near the ends, which mate with the vertical tubes of the inverted T. The connection is accomplished by placing the inverted T into position and lowering the barrier over the vertical steel tubes. Important factors of this connector are welding requirements, and cross-sectional area of members forming the T. This connector is not specified by any State highway agency; however, it has been tested by TTI. TTI's specification for channel, structural tubing, and large diameter steel tubes gives this connector very high tensile, moment, shear, and torsion strength. To date, TTI has conducted eight crash tests on this connector. All tests were conducted with atypical vehicles (ex. trucks, 4-w drives, etc.), one being a 2-1/2-ton truck weighing 18,240 lb. In all tests at speeds of 60 mi/h and angles anywhere from 7 degrees to 22 degrees, the connector performed satisfactorily, with maximum permanent displacement ranging from 0 ft to 0.08 ft.

J. Lapped Joint and Bolt

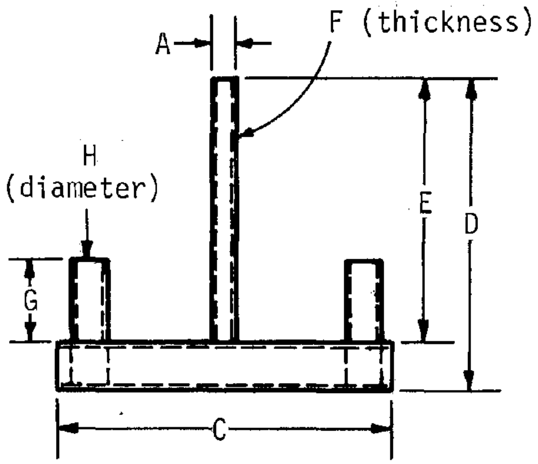
In the lapped joint and bolt connector the ends of the lapped joint barrier segments (see figure 19) are fabricated such that they overlap in a vertical plane. The joint is then secured with a single steel bolt that passes through the overlapping segments. To date, only Texas specifies this connector, and only as an alternate. Important factors for this connector are bolt diameter, overlapping area between barrier segments and cross-sectional area of the lapped portion. This connector provides moderate moment and tensile capacity, with relatively low shear and torsion strengths. Application and replacement of this connector are relatively simple, requiring only that barrier segments be aligned and the bolt subsequently fastened. To date, no crash tests have been performed on this connector.

K. Hinge Plate

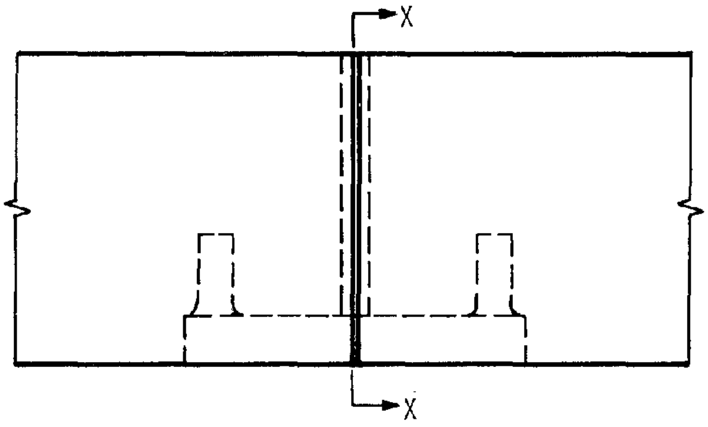
The hinge plate connector (See figure 20) consists of two steel plates anchored by bolts on each barrier end. The plates are positioned so that they overlap, and a steel pin is inserted through holes in the plates. Important factors for this connector are gap width, plate thickness, and pin diameter. This connector is similar to pin and loop connectors, however, there are some differences. First, overlapping plates are flush with one another, rather than having a gap between them. Second, the segment length, being only 39 inches, is very short. Third, the barrier has a cross-sectional shape quite different from the New Jersey shape. Thirteen crash tests have been performed on this connector, all by the proprietor, Barrier Systems Incorporated (BSI). No agencies specify this connector at this time.



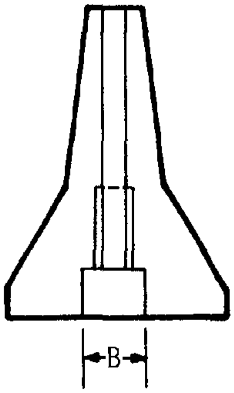
TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL



CONNECTOR DETAIL



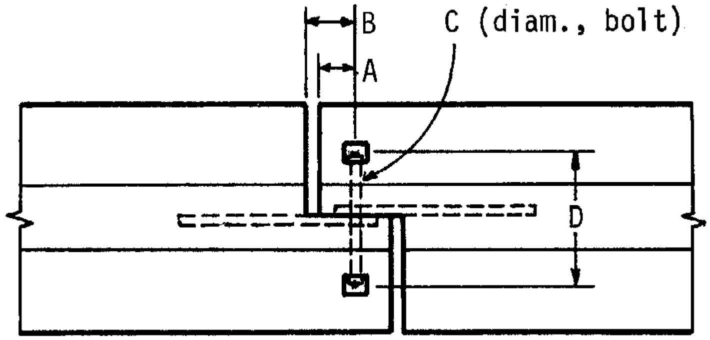
TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL



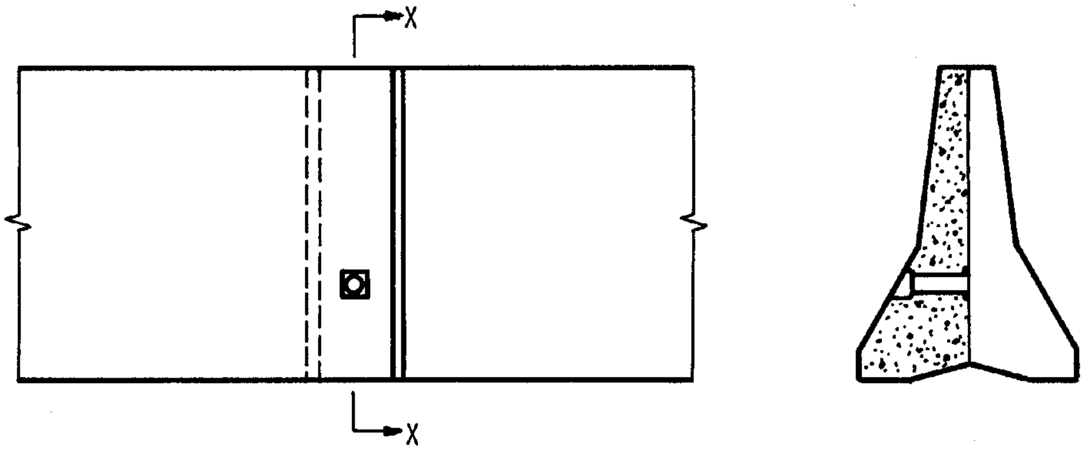
VIEW X-X

(see page 94 for values of lettered dimensions)

Figure 18. Bottom T-lock



TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL

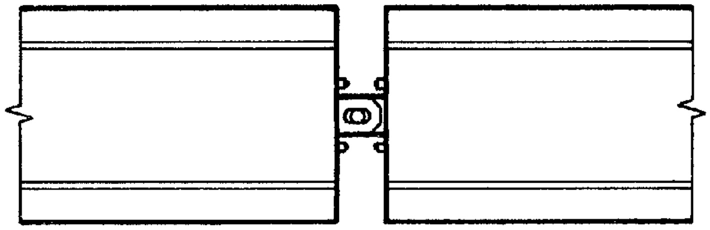


TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL

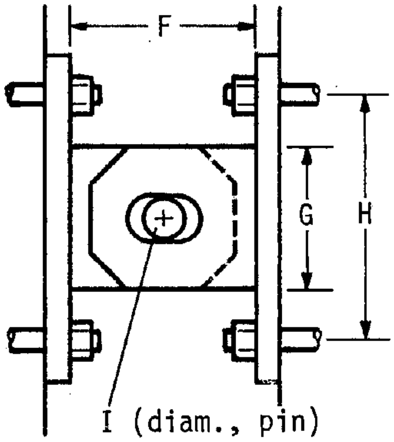
VIEW X-X

(see page 94 for values of lettered dimensions)

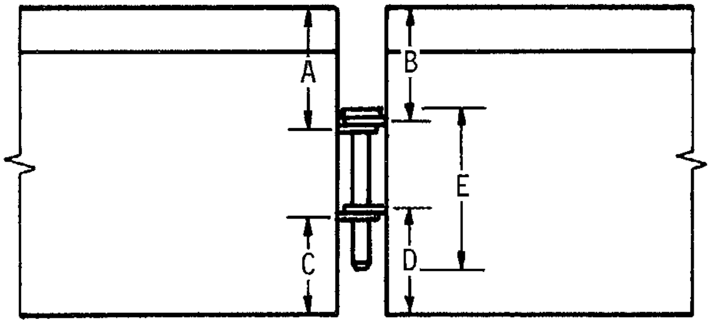
Figure 19. Lapped joint



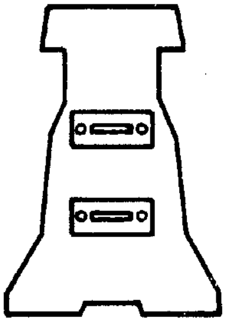
TYPICAL PANEL PLAN WITH A VIEW
OF CONNECTION DETAIL



CONNECTION DETAIL



TYPICAL PANEL ELEVATION WITH A
VIEW OF CONNECTION DETAIL



TYPICAL END VIEW

(see page 94 for values of lettered dimensions)

Figure 20. Hinge plate

L. Hybrid Connectors

Hybrid connectors incorporate two or more different connector types into one connection system. Some examples of hybrid connectors are straight tongue and groove with steel dowels, and flaring tongue and groove with side plates. The advantage of a hybrid connector is that it incorporates the best features of each connector type. Furthermore, application and maintenance of this system is usually no more difficult than application and maintenance of one of the component connectors. To date, four States use one variety or another of a hybrid connector.

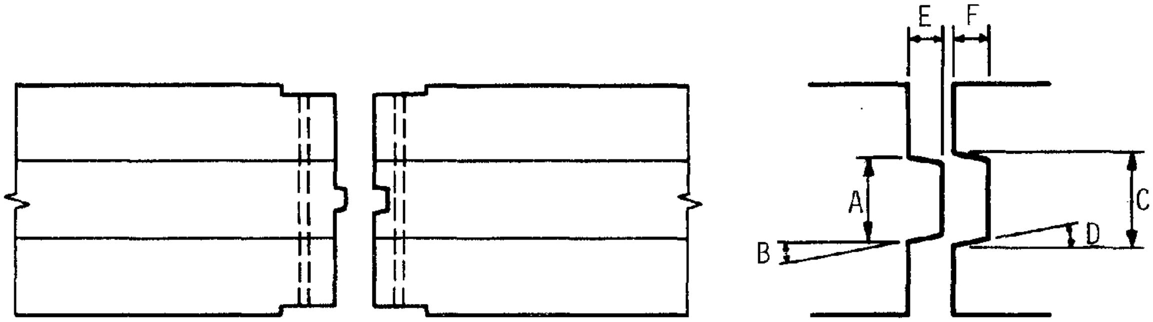
1. Straight Tongue and Groove With Side Plates

This connector consists of a concrete vertical tongue or groove cast into the barrier end, along with side plates bolted longitudinally to the barrier base (see figure 21). Three States now use this connector. Important factors for this connector are plate length, plate width, plate thickness, bolt diameter, number of bolts, bolt hole diameter, bolt hole spacing, tongue cross-sectional area, and tongue protrusion length. The structural capacities of this connector are superior to either a simple straight tongue and groove or a side plate connector, since the structural capacities of the respective component connectors are simply added to achieve the structural capacities of the hybrid connector. This gives this connector relatively moderate tensile, shear, moment, and torsion capacities. Plate thickness for this connector ranges from 1/4 in to 1/2 in, plate length ranges from 12 in to 126 in, and tongue height ranges from 32 in to 38 in. The number of bolts used is usually two, and plate width ranges only from 3 in to 4 in. Segment lengths are specified as either 10 ft or 20 ft.

To date, two crash tests have been performed on this hybrid connector, by the Southwest Research Institute. In these tests, a 4500-lb vehicle impacted the barrier at approximately 62 mi/h and 25 degrees, causing barrier failure in both tests. It should be noted here that the plate thickness for the connectors used in these tests was only 1/4 in, the bottom of the range. It is difficult to assess what the performance of a connector using thicker plate would be under similar impact conditions.

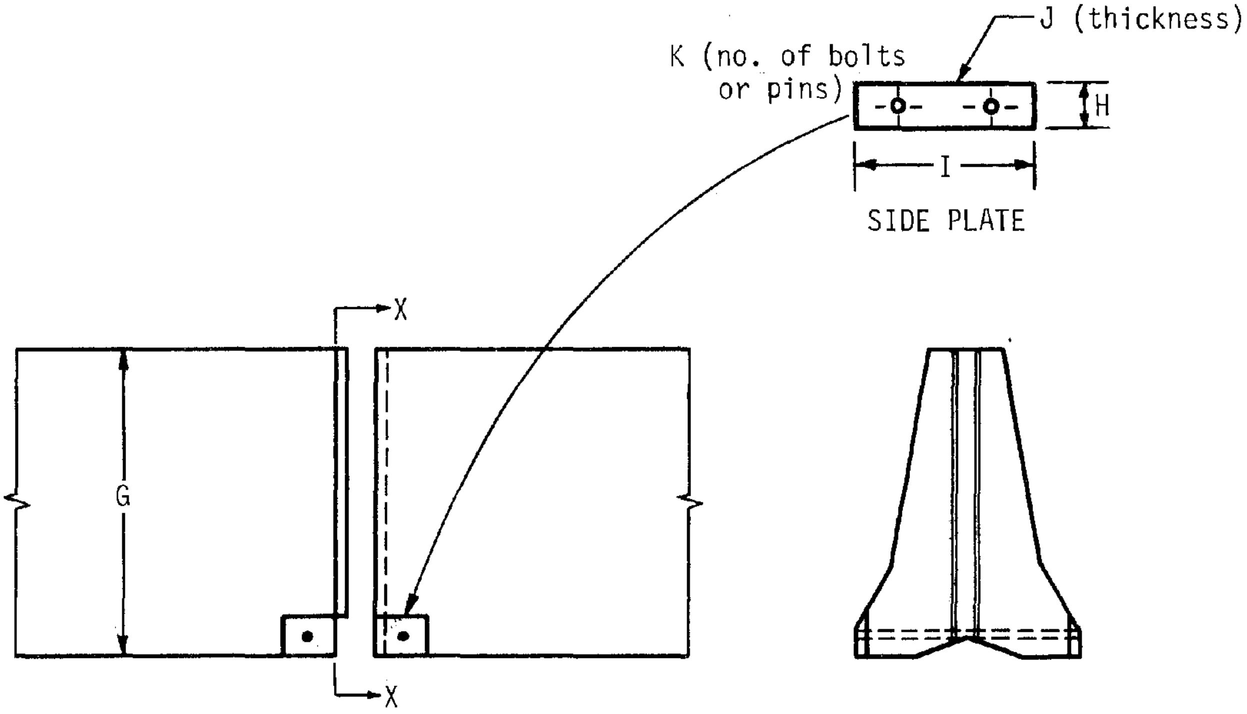
2. Flaring Tongue and Groove With Side Plates

This connector consists of a trapezoid-shaped tongue or groove cast into the barrier end and the addition of side plates bolted longitudinally at the barrier base (see figure 22). Only TTI has tested this connector. Important factors for this connector are plate length, plate width, plate thickness, bolt diameter, number of bolts, bolt hole diameter, spacing between holes, tongue area, and tongue protrusion length. Sensitivity analysis reveals that plate thickness is the most important consideration in this connector. Therefore, structural capacities range from relatively moderate to relatively high, depending upon the plate thickness used. However, this configuration is superior in structural capacity to either of its component connectors, having the capacities of the component connectors added to give the capacities of the new connector.



TYPICAL PANEL PLAN WITH A VIEW OF CONNECTION DETAIL

CONNECTION DETAIL

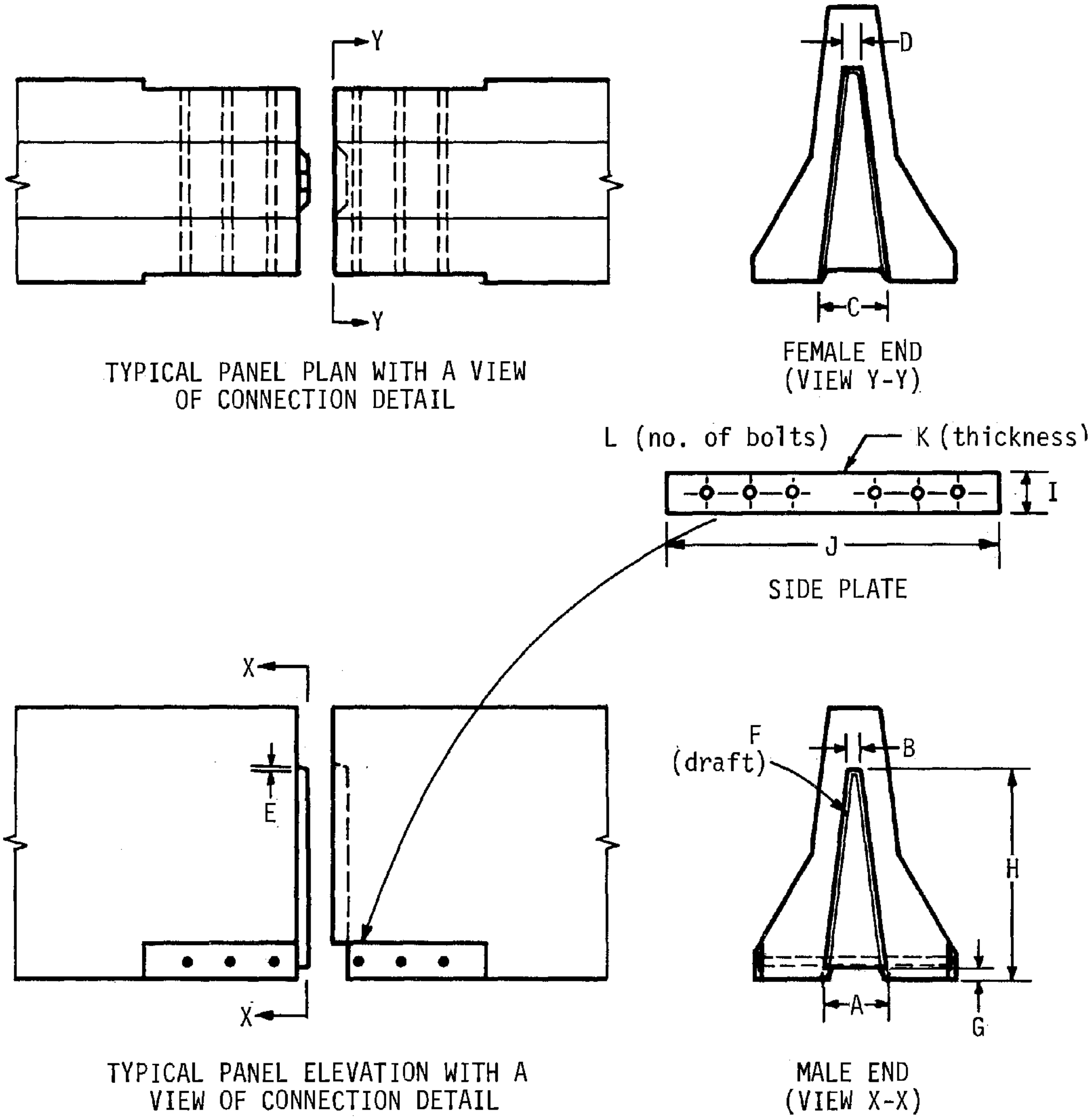


TYPICAL PANEL ELEVATION WITH A VIEW OF CONNECTION DETAIL

VIEW X-X

(see page 95 for values of lettered dimensions)

Figure 21. Straight tongue and groove with side plates



TYPICAL PANEL PLAN WITH A VIEW OF CONNECTION DETAIL

FEMALE END (VIEW Y-Y)

SIDE PLATE

TYPICAL PANEL ELEVATION WITH A VIEW OF CONNECTION DETAIL

MALE END (VIEW X-X)

(see page 95 for values of lettered dimensions)

Figure 22. Flaring tongue and groove
with side plates

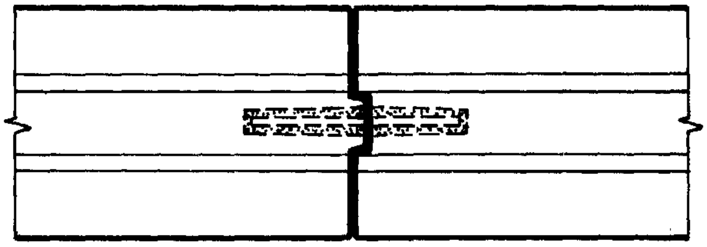
To date, four crash tests have been conducted on this connector. All four tests used approximately 4500-lb vehicles impacting at approximately 60 mi/h and at an angle of 25 degrees. The only major difference in all these tests was in the plate thickness used, which ranged from 1/8 in to 1/2 in, increasing in 1/8-in-increments. Only in the test using the 1/4-in-plate did the connector fail upon impact. In all other tests with thicker plate, the connectors were successful, with maximum permanent displacement ranging from 1.6 ft to 1.8 ft. No agencies specify this connector at this time.

3. Straight Tongue and Groove With Steel Dowel

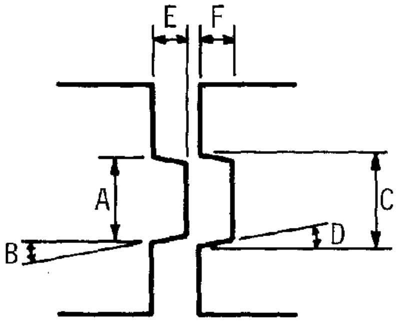
The straight tongue and groove with steel dowel connector has the same configuration as the straight tongue and groove connector, with the addition of one steel dowel placed across each barrier segment interface, aligned normal to the barrier end (See figure 23). Only one State, Kansas, now uses this connector. Important factors for this connector are dowel length, dowel diameter, tongue cross-sectional area, and protrusion length of tongue. This connector has the structural characteristics of the straight tongue and groove, plus the additional strength characteristics of the dowel, which gives the connector a moment capacity. However, this connector still has no tensile capacity, and relatively low moment, shear, and torsion capacities. While initially easy to apply, replacement of segments in a barrier system is complicated by the fact that the segments on either side of a replacement segment must be spread out in order to accommodate the placing of the steel dowels. To circumvent this, Kansas uses a different type of connector (the side plate which is easier to replace) for replacement of segments rather than go through the replacement procedures associated with the steel dowel. To date, no crash tests have been performed on this connector.

4. Straight Tongue and Groove with Continuous Cable

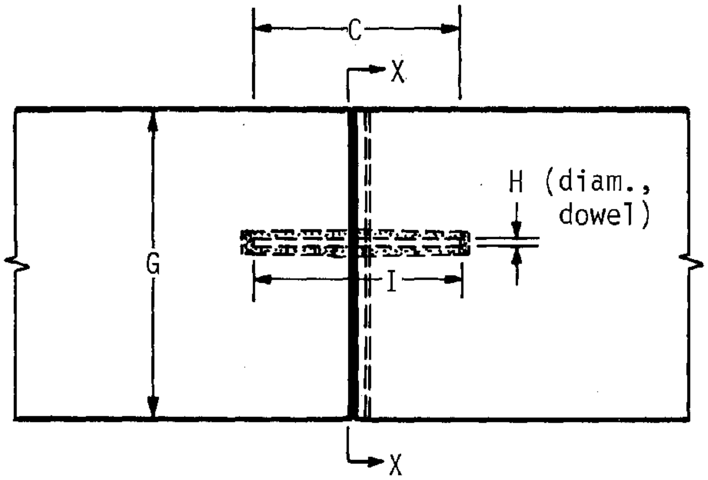
The straight tongue and groove with continuous cable connector involves mating tongue and groove segments and then threading a cable throughout the entire barrier system via longitudinal holes cast in each barrier segment (See figure 24). The cables are subsequently pulled in tension and locked into position once the threading has been accomplished. Only one State, Missouri, now uses this connector. Important factors for this connector are cable diameter, cable tension, and tongue cross-sectional area. This system has low torsion, tensile, shear, and moment capacities. Maintenance of this system is made difficult by the fact that damage to the cable requires that it be repaired and retensioned. To date, no crash tests have been performed on this hybrid connector.



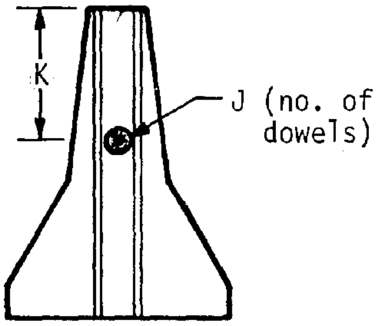
TYPICAL PANEL PLAN WITH A VIEW OF CONNECTION DETAIL



CONNECTION DETAIL



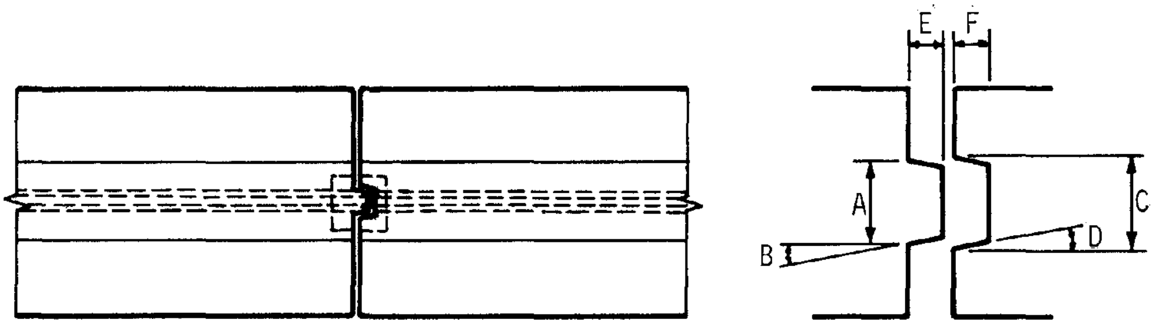
TYPICAL PANEL ELEVATION WITH A VIEW OF CONNECTION DETAIL



VIEW X-X

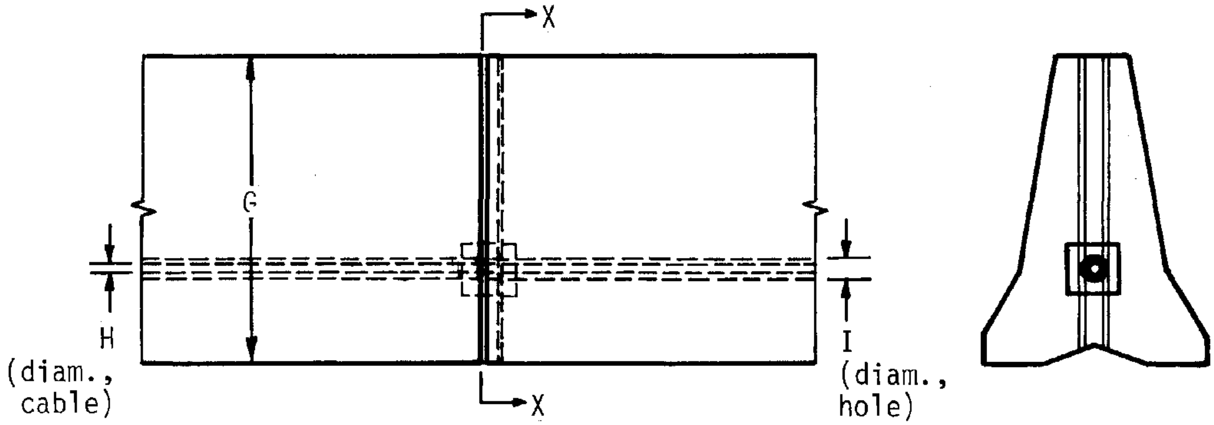
(see page 95 for values of lettered dimensions)

Figure 23. Straight tongue and groove with steel dowels



TYPICAL PANEL PLAN WITH A VIEW OF CONNECTION DETAIL

CONNECTION DETAIL



TYPICAL PANEL ELEVATION WITH A VIEW OF CONNECTION DETAIL

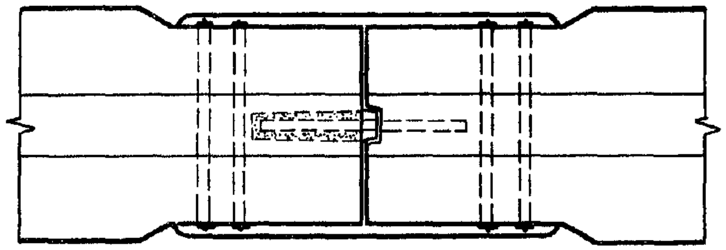
VIEW X-X

(see page 96 for values of lettered dimensions)

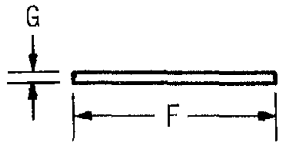
Figure 24. Straight tongue and groove with continuous cable

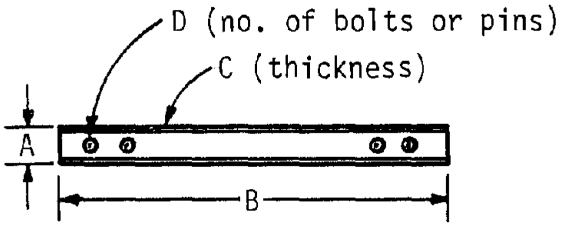
5. Flaring Tongue and Groove with Channel Splice and Double Dowels

This connector is a composite of the dowel, flaring tongue and groove, and channel splice connectors. It consists of a trapezoid-shaped tongue or groove in the barrier end, two dowels across the barrier interface, and a steel channel mounted longitudinally at the barrier base (see figure 25). Only one agency, TTI, has tested this connector. Structurally, it has the characteristics of the three composite connectors summed together, giving it relatively high tensile, shear, moment, and torsion capacities. Important factors for this connector are number of dowels, dowel diameter, dowel length, tongue area, tongue protrusion length, channel cross-sectional area, channel length, number of bolts used, bolt hole diameter, spacing of holes, and bolt diameter. Replacement of a segment in a barrier system is complicated by the fact that the segments on either side of the segment to be replaced must be spread and subsequently moved back to accommodate the replacement of a segment. To date, one crash test has been performed on this hybrid connector. For an impact of a 20,000-lb bus at 60 mi/h and 15 degrees, the connector was successful, having a maximum permanent displacement of 1.8 ft.

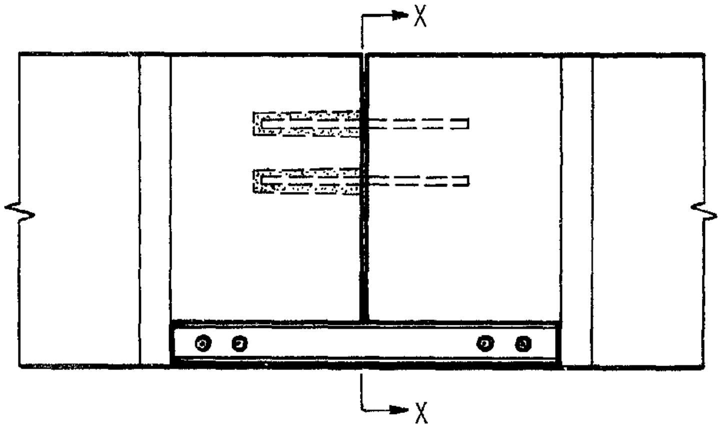


TYPICAL PANEL PLAN WITH A VIEW OF CONNECTION DETAIL

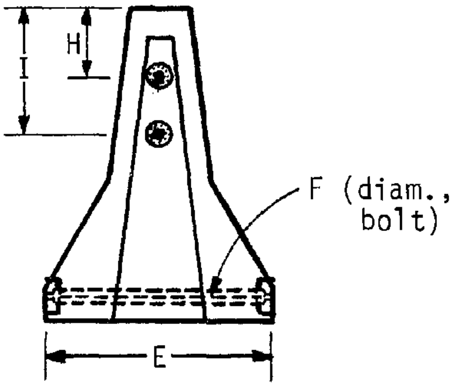




CHANNEL SPLICE



TYPICAL PANEL ELEVATION WITH A VIEW OF CONNECTION DETAIL



VIEW X-X

(see page 96 for values of lettered dimensions)

Figure 25. Flaring tongue and groove with channel splice and double dowels

III. Determination of Connector Strength

This section examines the characteristics of pin and loop and tongue and groove connectors and analyzes how these characteristics determine the structural capacity of the connectors. Pin and loop connectors and tongue and groove connectors were singled out for analysis because of their widespread use in the field; 43 States presently specify some type of the pin and loop connector and 8 States specify some type of the tongue and groove connector for temporary concrete barriers. Analysis of these connectors is important since the connector is usually the weakest part of the portable concrete barrier (PCB) system.

This chapter is divided into three sections. The first section describes the reference coordinate system for the barrier and, with respect to these coordinates, defines the type of forces that must be resisted in a connector. The capacity of a connector to withstand these forces is measured in terms of tensile strength, moment strength, shear strength, and torsion strength. The second section lists the strengths for various connectors that have been published in past reports. Connector strengths are given in terms of tensile, moment, shear, and torsion strengths. In the third section, a sample analysis of a pin and wire rope connector, a pin and rebar connector, and a flaring tongue and groove connector are given. Two tables list all the strengths of the connectors analyzed by GME. The values in the table for pin and loop connectors were determined using a GME in-house BASIC program modeled after the sample analysis mentioned above.

A. Forces Involved

Figure 26 shows the right-hand coordinate system used to define the tensile, moment, shear, and torsion load capacities of a barrier connector. The X-axis in the system is coincident with the longitudinal barrier

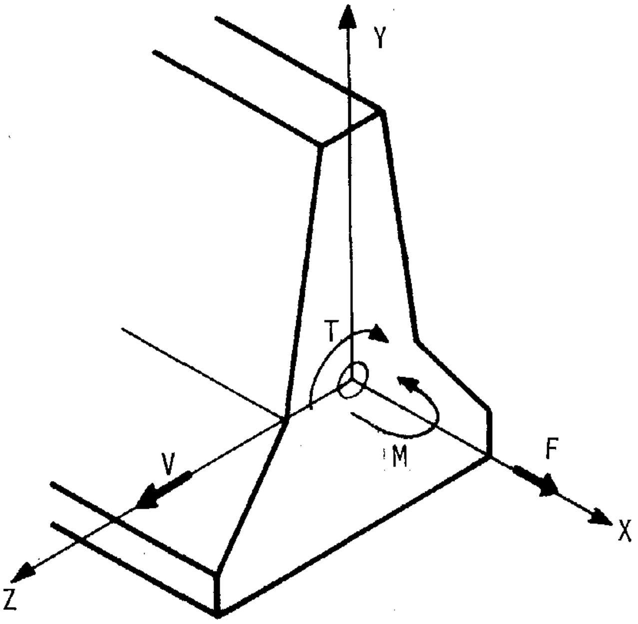


Figure 26. Coordinate system for portable concrete barrier

centroidal axis. The Y-axis is vertical and forms a right angle with the X-axis. The Z-axis is orthogonal to the X and Y axes, and is in a right-hand sense.

The four loading conditions analyzed are the ultimate tensile strength (F), the ultimate moment (M), the ultimate shear strength (V), and the ultimate torsion (T). For this analysis, pin and loop, and tongue and groove connectors will be considered. In general, barrier systems will usually be subjected to moment or torsion dynamic loading due to an impact. For this reason, moment and torsion capacities are the most important gauge of connector strength. Tensile capacity is also important, however, since it directly determines the moment capacity. Moment capacity is the distance between the barrier center of gravity and extreme fibers of the barrier crossed into the tensile capacity of the connector.

Shear capacity is the least important loading condition, since barriers are usually not loaded in shear, and since the shear capacity does not necessarily determine the torsion capacity of the connector. However, shear capacity has been included in the analysis since it does give some gauge of connector strength. Torsion capacity, T, is the vertical distance between the loops on one barrier end crossed into the failure force for torsion loading conditions.

In general, a pin and loop connector under tensile loading conditions will fail due to any one of the following reasons:

- Pin fails due to transverse loading. If the pin is not anchored on both top and bottom, then failure is due to yielding, since yielding would allow the pin to bend and slip out of the loops. While the pin may not actually come out of the loops when it begins to yield, it is certainly in danger of doing so. If the pin is anchored, however, then pin failure is due to rupture.

- Loops fail in tension.

- Loops pull out of barrier (only if top and bottom loops are not physically connected.

- Concrete shears due to force on loops.

The tensile capacity of the connector is then the minimum force required to cause failure for any one of the above-stated reasons.

Second, a pin and loop connector under moment loading will fail for the same reason that it does for tensile loading. Moment capacity then is the distance between the pin center and the extreme fibers of the barrier crossed into the tensile capacity of the connector.

Third, a pin and loop connector under shear loading conditions will fail due to any one of the following reasons:

- Pin fails due to transverse loading.

- Loops fail in tension.

- Loops pull out of barrier (this occurs for wire rope loops only).
- Concrete shears laterally due to forces on loops (this occurs for rebar loops only).
- For wire rope, concrete shears longitudinally (if top and bottom loops are physically connected) due to forces on loops. This is because forces on wire rope always resolves into tensile forces.

The shear capacity of a pin and loop connector is then the minimum force required to cause failure for any one of the above-stated reasons.

Fourth, a pin and loop connector under torsion loading conditions has the same possible modes of failure as does a pin and loop connector under shear loading conditions. The only difference is that the pin analysis will change due to the change in loading conditions on the pin itself. The torsion capacity of the connector is then the vertical distance between the loops in one barrier end crossed into the minimum force required to cause failure for any of the above-stated reasons.

B. Strengths Cited in Published Reports

Given below are three tables (2 to 4) submitted in published reports, which list the strengths of various PCB connectors. The three tables, taken from different publications, are referenced accordingly.

As can be seen, some of the same connectors have different structural capacities listed in the different tables. For example, one report (7) gives the tensile capacity of the Idaho pin and rebar as 61 kips, whereas another study (4) gives this same capacity as 23 kips. Even within the same study, results do not appear consistent. For example, table 4 has the capacity of side plates and side channels as being exactly equal, which is not true. It was impossible to tell why these discrepancies occurred, since only one report, (7) actually showed the computations which yielded the capacities.

C. Analytical Determination of Connector Strengths

An analysis of the Arkansas pin and wire rope, the California pin and rebar, and the Virginia tongue and groove connectors is given in this section. The following assumptions were used for the analysis:

- Connector strengths are analyzed using the mechancial properties of the actual materials in the connector. Mechanical properties are assumed only when actual properties are unknown (Steel was assumed to be ASTM-A36 and concrete was assumed to be 3000 psi).
- Concrete is an integral part of the connector system, and is therefore taken into account in the failure analysis.
- The ultimate shear strength (v_c) of concrete is governed by the equation $v_c = 2\sqrt{f'_c}$ where f'_c is the compressive strength of the concrete,

Table 2. Strengths cited in "Barriers in Construction Zones" (7)

Connection	Tensile Capacity (k)	Shear Capacity (k)	Moment Capacity (ft-k)	Torsion Capacity (ft-k)
Welsbach Interlock (NJ)	208	156	139	94
I-Lock (NY)	92	208	61	87
Pin and Rebar (CA)	85	85	57	60
Corrugation and Cable (CA)	41	23	27	19
Lapped Joint and Bolt (TX)	27	47	22	24
Pin and Eye Bolt (MN)	20	12	13	9
Pin and Wire Rope (ID)	61	61	41	41
Pin and Rebar (GA)	46	46	31	31
Dowel (TX)	0	60	0	37
Tongue and Groove (OR)	0	27	0	9
Tongue and Groove (VA)	0	32	0	7
Hook and Rebar (CO)	7	5	5	0
Channel Splice	96	67	80	21
T-Lock (Base)	46	588	97	375
T-Lock (Top)	16	193	11	56
Grid-Slot (TX)	0	60	0	30

Table 3. Strengths cited in TRR 769 (4)

Connection	Tensile Force P (kips)	Shear Force V (kips)	Moment M (kip-ft)	Torsion T (kip-ft)
Welsbach	270	160	135	95
New York I-Lock	115	180	96	75
California pin and rebar(b)	44	44	37	19
California cable posttension	36	20	20	10
Texas lapped with bolt	31	22	21	11
Minnesota pin and eye bolt	23	23	20	15
Idaho pin and rebar	23	23	19	17
Georgia pin and rebar	15	15	12	11
Texas dowel Calculated	0	51	0	22
As tested	60	51	50	--
Oregon tongue and groove	0	41	0	12
Virginia tongue and groove	0	54	0	12
Colorado latch	8	6	7	0

Table 4. Strengths cited in TRR 1024 (8)

Connection	Connection Capacity Shear (kips)	 Moment (kip ft)	 Torsion (kip-ft)
Side plates (3ft 6 in x 5 in x 1/2 in, steel)	90	117	53
Side channels (C5 x 9 x 3 ft 6 in, steel)	90	117	53
Partial tongue and groove and side plates (3 ft 0 in x 4 in x 1/2 in steel)	76	103	67
Partial tongue and groove and side plates (3 ft 0 in x 4 in x 3/8 in steel)	57	77	52
Partial tongue and groove and side plates (3 ft 0 in x 4 in x 1/4 in steel)	38	52	37
Partial tongue and groove and side plates (3 ft 0 in x 4 in x 1/8 in steel)	19	26	22
Side channels (C5 x 9 x 3 ft 6 in steel) plus three no. 8 x 18 in steel rebar dowels	135	117	73
Three grouted dowels (no. 8 x 18 in)	60	50	37
Vertical steel pin (7/8 in diameter x 26 in)	46	31	35
Vertical steel pin (1 in diameter x 25 in)	46	31	35

Table 4. Strengths cited in TRR 1024 (8) (concluded)

Connection	Connection Capacity (concluded) Shear (kips)	Moment (kip-ft)	Torsion (kip-ft)
Tongue and groove and side plates (12 in x 3 in x 1/2 in steel)	27	9	16
Tongue and groove and side plates (12 in x 3 in x 1/4 in steel)	27	9	16
Vertical I-beam (3 1/4 in x 2 in)	208	61	87
Vertical I-beam (3 1/4 in x 2 in) (grouted joints)	208	61	87

- The development length (L_d) for rebar in the concrete is governed by the equation $L_d = \frac{0.04A_bf_y}{\sqrt{f'_c}}$ where A_b is the area of the rebar, and f_y is the yield strength of the rebar.

- Barriers are pulled tight at the connectors for pin and loop connectors.

- All structural hardware is the same material unless otherwise specified.

- All structural steels are considered ductile.

- Connectors are to be evaluated for catastrophic failure.

- The masses of the various components of the connector will be disregarded.

- Forces on anchor nuts that are induced by transverse loading on the pin are assumed to be of insufficent magnitude to cau failure in the threaded portion of the pin.

1. Arkansas Pin and Wire Rope

The Arkansas pin and wire rope is shown in figure 27. It has a pin diameter of 1.25 in and a wire rope diameter of 5/8 in.

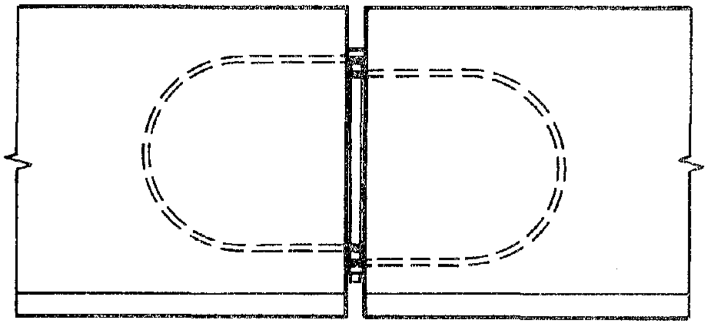


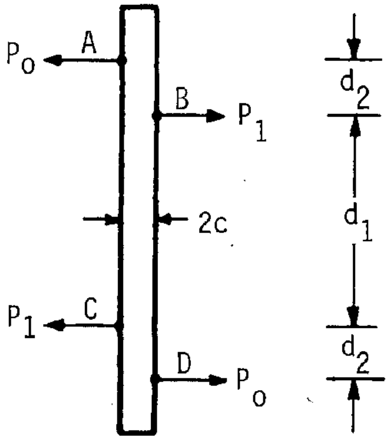
Figure 27. Arkansas pin and wire rope connector

a. Tensile Capacity

The possible modes of failure of this connector in tension are: (1) pin fails in transverse loading, (2) loops fail in tension, (3) loops pull out of the barrier, or (4) concrete shears due to forces on loops.

(1) Tensile Capacity of Connector for Pin Failure

The pin is under the loading condition shown in figure 28:



P_o, P_1: maximum allowable forces
$2c = 1\frac{1}{4}$ in.
$d_1 = 14\frac{1}{2}$ in.
$d_2 = 1$ in.

Figure 28. Free body diagram (FBD) of pin of Arkansas connector (tensile)

Letting $F = P_1 + P_o$ (Eq.1) and summing forces in the X direction yields:

$$\sum F_x = P_1 + P_o - P_1 - P_o = 0$$

Now summing moments about D yields:

$$\sum M_D = 0 = d_2P_1 - (d_2 + d_1)\, P_1 + (d_1 + 2d_2)\, P_o$$

$$P_1 = \frac{(d_1 + 2d_2)\, P_o}{d_1} = 1.138\, P_o$$

Analysis of shear and bending moment diagrams reveals that the critical points on the pin are points B and C, where the maximum shearing force is P_o/A and the maximum moment is $d_2 \times P_o$.

Since the pin is anchored at both ends, it must be ruptured in order to break the connection. A conservative method to find the force (F) required to rupture the pin is simply to calculate the shearing force required to rupture the pin. Solving for P_o :

$$P_o = (\sigma_f)(A) = (60 \text{ ksi})\frac{\Pi}{4}(1.25)^2$$

$$P_o = 73.6 \text{ kips}$$

Now solving for the tensile capacity of the connector for pin failure:

$$F = P_o + P_1 = 73.6 \text{ kips} + (1.138)(73.6 \text{ kips})$$

$$F = 157.4 \text{ kips}$$

The tensile capacity of the connector for pin failure is 157.4 kips.

(2) Tensile Capacity of Connector for Loop Failure

For loop failure to occur, those loops loaded with P_0 must fail before the connection will fail. Each loop of the barrier system loaded by P_0 is shown in figure 29:

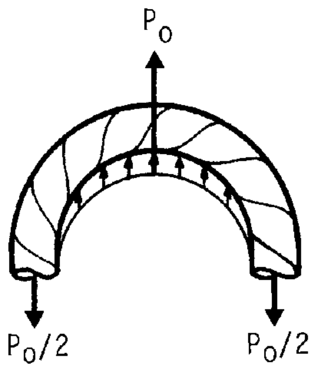


Figure 29. FBD of loop of Arkansas connector (tensile)

Arkansas specifies a 5/8-in-diameter wire rope with a minimum breaking strength of 17.9 tons = 35,800 lb.

Therefore, for P/2 = 35,800 lb:

$$P_0 = (2)(35{,}800 \text{ lb}) = 71.6 \text{ kips}$$

$$F = 71.6 + (1.138)(71.6 \text{ kips})$$

$$F = 153.1 \text{ kips}$$

(3) Tensile Capacity of Connector for Loop Pullout

Since the top and bottom loops in each barrier section are comprised of one continuous length of wire rope, loop pullout is not an issue for the analysis of this connector.

(4) Tensile Capacity of Connector for Concrete Shear

The concrete is in the loading condition shown in figure 30:

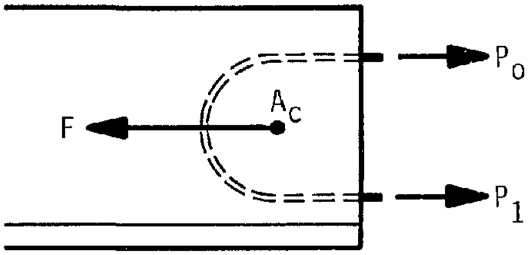


Figure 30. FBD of concrete of Arkansas connector (tensile)

Therefore, for the tensile loading condition shown, the concrete is in shear, with a shear area of $2A_c$ (for both sides of the cable). For a concrete compressive strength of 2,500 psi, the shear strength of the concrete is determined by

$$v_c = 2\sqrt{f'_c}$$

where v_c is the shear strength of the concrete and 2,500 psi is the compressive strength of the concrete.

Therefore,

$$v_c = 2\sqrt{2500} = 100\text{psi}$$

For Ac = 466.35 in^2 , 2Ac = 932.7 in^2

Solving for F:

$$F = (100\ \text{psi})(932.7\ \text{in}^2)$$

$$F = 93.3\ \text{kips}$$

Therefore, the concrete is the failure mechanism for the connector.

Therefore, the tension capacity of the Arkansas pin and wire rope connector is 93.3 kips and is determined by the capacity of the concrete in shear.

b. Moment Capacity

The moment capacity, M, of the Arkansas pin and wire rope connector is the distance (r) between the pin center and the extreme fibers of the barrier crossed into the tension capacity of the connector. Therefore,

$$M = r \times F$$

$$M = (1\text{ft}) \times (93.3 \text{ kips})$$

$$\underline{M = 93.3 \text{ kip - ft}}$$

The moment capacity of the connector is 93.3 kip-ft

c. Shear Capacity

The possible modes of failure of this connector in shear are: (1) pin fails in transverse loading, (2) loops fail in tension (3) loops pull out of the barrier, or (4) concrete shears due to forces on loops. Since these modes of failure capacity are the same as those for tensile capacity, the shear capacity (V) is equal to the tensile capacity (F). Therefore, the shear capacity of the Arkansas pin and wire rope connector is 93.3 kips.

d. Torsion Capacity

The failure modes for the connector in torsion are the same as the failure modes for the connector in shear. However, the pin analysis changes since the loading on the pin changes. For the torsion mode, the pin is under the loading condition shown in figure 31:

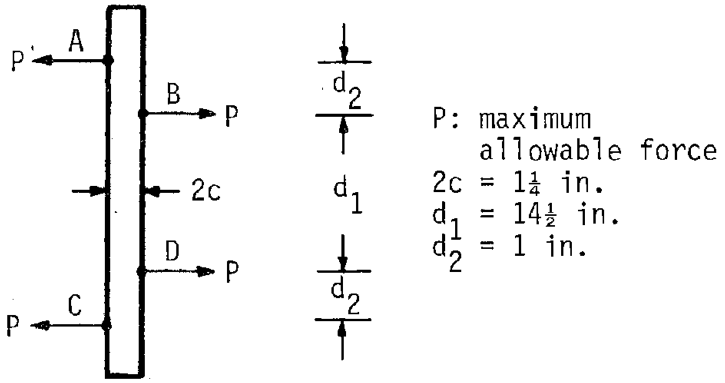


Figure 31. FBD of pin of Arkansas connector (torsion)

Equilibrium of moments and forces dictates that F = 2P.

Solving for P yields:

$$P = (\sigma_f)(A) = (60 \text{ ksi}) \frac{\Pi}{4} (1.25)^2 \doteq 73.6 \text{ kips}$$

Now solving for F:

$$F = (2)(73.6 \text{ kip})$$

$$\underline{F \doteq 147.2 \text{ kips}}$$

Since this value of V (=147.2 kips) is greater than the force V associated with concrete failure, then concrete failure is still the failure mechanism for this connector in torsion. Therefore, the torsion capacity of this connector is given by

$$T = r_2 \times V$$

where r_2 is the vertical distance between loops on one barrier end.

Therefore,

$$T = (1.3 \text{ ft}) \times (93.3 \text{ kips})$$

$$\underline{T \doteq 121.3 \text{ kip ft}}$$

The torsion capacity, T, of this connector is 121.3 kip ft.

2. California Pin and Rebar

The California pin and rebar is shown in figure 32. This connector has a pin diameter of 1.25 in, and a rebar diameter of 3/4 in. The pin is unanchored in this connection.

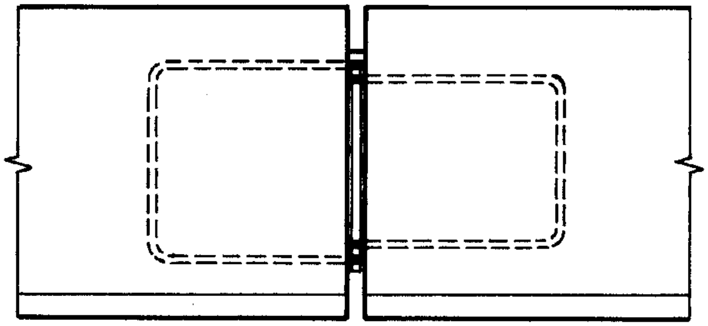


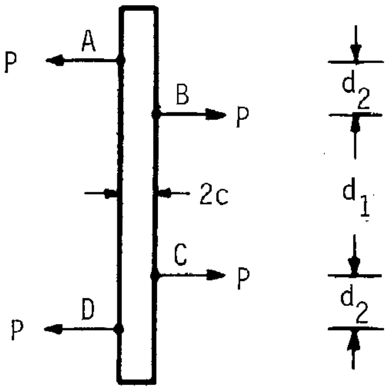
Figure 32. California pin and rebar connector

a. Tensile Capacity

The possible modes of failure of this connector in tension are: (1) pin fails in transverse loading, (2) loops fail in tension, (3) loops pull out of concrete barrier, or (4) concrete shears due to forces on loops.

(1) Tensile Capacity of Connector for Pin Failure

The pin is under the loading condition shown in figure 33:



P: maximum allowable force
$2c = 1\frac{1}{4}$ in.
$d_1 = 17$ in.
$d_2 = 1\frac{1}{2}$ in.

Figure 33. FBD of pin of California connector (tensile)

The critical points in this member are B and C. This configuration is the same as for the pin of the Arkansas pin and wire rope in torsion loading mode except the distances d_1 and d_2 are different. Therefore, solving for the stresses σ_x produced by bending and τ_{xz} produced by pure shear:

$$\sigma_x = \frac{Mc}{I} = \frac{4d_2P}{\Pi c^3} = \frac{4(1.5)P}{\Pi(0.625)^3} = 7.823P$$

$$\tau_{xz} = \frac{P}{A} = \frac{P}{\Pi c^2} = \frac{P}{\Pi(.625)^2} =0.815P$$

Now using the values of σ_x and τ_{xz} to solve for the principal stresses σ_1 σ_2 and σ_3 yields:

$$\sigma_1 = \frac{\sigma_x}{2} + \sqrt{\left(\frac{\sigma_x}{2}\right)^2 + (\tau_{xz})^2} = \frac{7.823P}{2} + \sqrt{\left(\frac{7.823P}{2}\right)^2 + (0.815P)^2} = 7.908P$$

$$\sigma_2 = 0$$

$$\sigma_3 = \frac{\sigma_x}{2} - \sqrt{\left(\frac{\sigma_x}{2}\right)^2 + (\tau_{xz})^2} = \frac{7.823P}{2} - \sqrt{\left(\frac{7.823P}{2}\right)^2 + (0.815P)^2} = -0.085P$$

The Von Mises (Distortion Engergy) Theory (9) will be used to evaluate for the strength of the pin, since this theory best agrees with experimental results. This theory states that failure is predicted to occur if:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \geq 2\,\sigma_f^2$$

Solving for P:

$$(7.908P)^2 + (0.085P)^2 + (7.993P)^2 = 2\sigma_f^2$$

Because the pin is not anchored on both ends, failure occurs at yielding. Therefore, for σ_f = 36,000 psi, P = 4.5 kips. Letting F = 2P:

F = (2)(4.5 kips)

F = 9.0 kips

The tensile capacity of the connector for pin failure is 9.0 kips.

(2) Tensile Capacity of Connector for Loop Failure

Each loop in the barrier system is loaded as shown in figure 34:

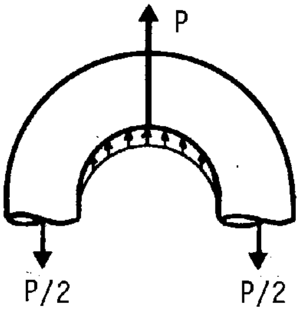


Figure 34. FBD of loop of California connector (tensile)

California specifies a 3/4-in-diameter rebar with an ultimate strength of 60,000 psi.

Solving for P yields:

$$P/2 = (60\text{ ksi})\frac{\Pi}{4}(0.75)^2 \longrightarrow P = 53.0\text{ kips}$$

Now solving for F:

F = 2P = 2(53.0 kips) = 106.0 kips

Since this value of F is higher than the F for pin failure (= 9.0 kips), loop failure is not the failure mechanism for this connector.

(3) Tensile Capacity of Connector for Loop Pullout

The force which pulls the loops out of the barrier end must be sufficiently large to break the adhesive bond between the steel and the concrete and bend the rebar around the curved portion of the slot in which it is cast. The rebar is loaded as shown in figure 35:

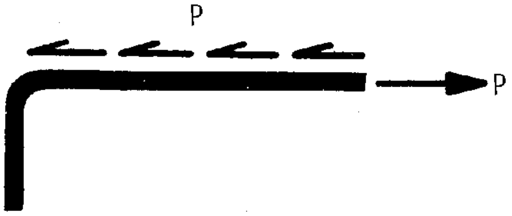


Figure 35. FBD of rebar of California connector (tensile)

To analyze the anchoring of the loop, we need to determine the development length required to prevent loop pullout. This is governed by the equation:

$$L_d = \frac{0.04 A_b f_y}{\sqrt{f'_c}}$$

where A_b is the rebar cross-sectional area, L_d is the development length of the straight portion of the bar, and f_y is the failure stress of the bar.

$$L_d = \frac{(0.04)(0.44)(36,000)}{3000} = 12 \text{ in}$$

Hence, the length of rebar required to prevent pullout is 12 inches. Since the straight portion of the California rebar is approximately 24 in, the rebar will not pull out of the barrier for any load (it would fail in tension before doing so).

(4) Tensile Capacity of Connector for Concrete Shear

The concrete is loaded as shown in figure 36:

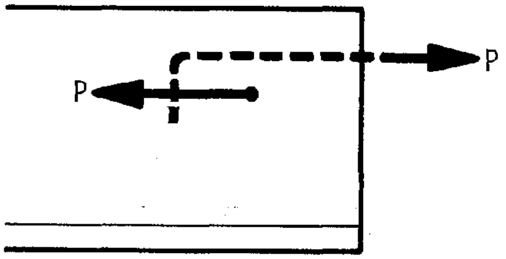


Figure 36. FBD of concrete of California connector (tensile)

The shear strength of the concrete v_c is equal to $2\sqrt{f'_c}$. Therefore,

$$v_c = 2\sqrt{3000}\ \text{psi} = 109.5\ \text{psi}$$

Solving for P:

$$P = (4)(109.5\ \text{psi})(204\ \text{in}^2) = 89.4\ \text{kips}$$
$$F = (2)P = (2)(89.4) = 178.8$$

Since this value of F is well above the 9.0 kips associated with pin failure, concrete shear is not the failure mechanism.

The tensile capacity of the California pin and rebar connector is 9.0 kips, and is governed by the capacity of the pin in transverse loading.

b. Moment Capacity

The moment capacity, M, of the California pin and rebar is the distance (r) between the pin center and the extreme fibers of the barriers crossed into the tensile capacity of the connector. Therefore,

$$M = r \times F$$

$$M = (1\text{ft}) \times (9.0\ \text{kips})$$

$$\underline{M = 9.0\ \text{kip ft}}$$

c. Shear Capacity

The possible modes of failure of this connector in shear are: (1) pin fails in transverse loading, (2) loops fail in transverse loading, or (3) concrete shears laterally due to rebar rotation inside the concrete. Mode (1) for shear failure is the same as for tensile failure. Therefore, we will examine only modes (2) and (3) and compare them with failure mode (1).

(1) Shear Capacity of Connector for Loop Failure

The loops are loaded as shown in figure 37:

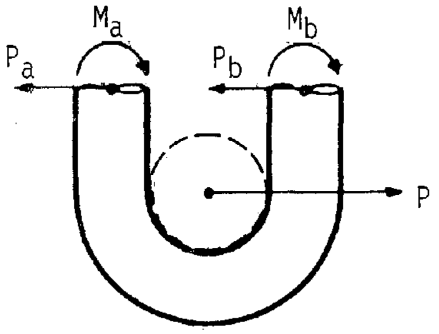


Figure 37. FBD of loop of California connector (shear)

This is a statically indeterminate component. However, assuming the loop will fail in tension, then the shear capacity for loop failure equals the tensile capacity for loop failure.

Since the 106.0 kips for loop failure is greater than the V associated with failure of the pin, loop failure is not the failure mechanism for this connector in shear.

(2) Shear Capacity of Concrete

The concrete in shear is loaded as shown in figure 38:

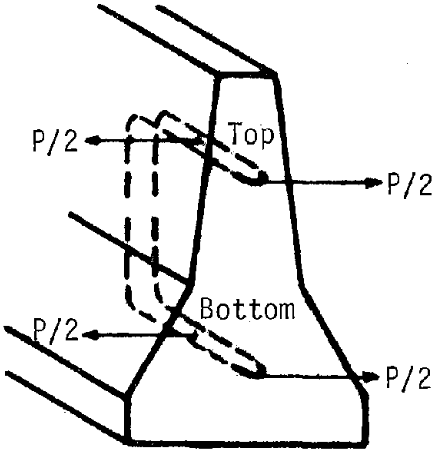


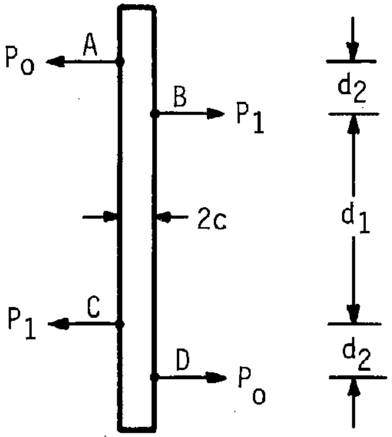
Figure 38. FBD of concrete of California connector (shear)

Since the force V required to shear the concrete in a shearing mode is roughly on the same order of magnitude as the F required to shear the concrete in a tension mode (F = 178.8 kips), concrete shear is not the failure mechanism for this connector in shear.

The shear capacity (V) of the California pin and rebar connector is 9.0 kips, and is governed by the capacity of the pin in transverse loading.

d. Torsion Capacity

The failure modes for the connector in torsion are the same as the failure modes for the connector in shear. However, the pin analysis changes since the loading on the pin changes. For the torsion mode, the pin is under the loading condition shown in figure 39:



P_o, P_1: maximum allowable forces

$2c = 1\frac{1}{4}$ in.

$d_1 = 17$ in.

$d_2 = 1\frac{1}{2}$ in.

Figure 39. FBD of pin of California connector (torsion)

Letting $V = P_o + P_1$, summing forces in the X-direction, and summing moments about D yields the following relations:

$$\sum F_x = P_o + P_1 - P_o - P_1 = 0$$

$$\sum M_D = d_2 P_1 - (d_2 + d_1)P_1 + (d_1 + 2d_2)P_o = 0$$

$$P_1 = \left(\frac{d_1 + 2d_2}{d_1}\right)P_o = 1.176P_o$$

The principal stresses σ_1 σ_2 and σ_3 are

$$\sigma_1 = 7.908P_o$$

$$\sigma_2 = 0$$

$$\sigma_3 = -0.085P_o$$

Solving for P_o :

$$(7.908P_o)^2 + (0.085P_o)^2 + (7.993P_o)^2 = 2.6 \times 10^9$$

$$P_o = 4.5 \text{ kips}$$

$$V = P_o + P_1 = 4.5 \text{ kips} + (1.176)(4.5 \text{ kips})$$

$$V = 9.8 \text{ kips}$$

Since this value of V is the limiting force for torsion loading, the torsion capacity of the connector in given by:

$T = r_2 \times V$, where r_2 is the minimum vertical distance between loops on one barrier end.

Therefore,

$$T = (1.42 \text{ ft}) \times (9.8 \text{ kips})$$

$$\underline{T = 14.0 \text{ kip ft}}$$

The torsion capacity, T, of this connector is 14.0 kip ft

3. Virginia Tongue and Groove

The Virginia tongue and groove connector is shown in figure 40. It has a 2.5 in (top) x 7.5 in (bottom) x 21.25 in (high) tongue. Tongue and groove connectors in general have no tensile or moment capacities because they have no mechanism for resisting tensile forces.

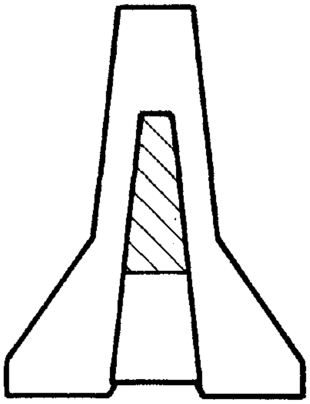


Figure 40. Virginia flaring tongue and groove connector

a. Shear Capacity

The shear capacity of this connector is the product of the cross-section area of the tongue and the shear strength of the concrete.

Solving for V, the shear capacity is

$$V = (A)(2\sqrt{f_c'})$$

$$V = (106.3)(2\sqrt{4000})$$

$$V = 13.5 \text{ kips}$$

The shear capacity of the connector is 13.5 kips.

b. Torsion Capacity

The torsion capacity of the connector is the product of the distance between the resultant forces acting on the tongue and the resultant forces, as shown in figure 41:

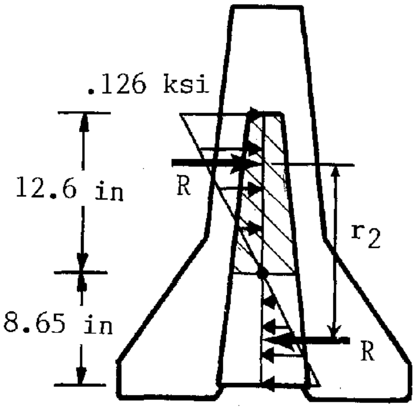


Figure 41. FBD of tongue for Virginia connector (torsion)

Solving for the torsion capacity, T:

$$T = r_2 \text{ x } R$$

$$T = 1.13 \text{ ft x } 3.0 \text{ kips}$$

$$T = 3.4 \text{ kip-ft}$$

The torsion capacity of the connector is 3.4 kip ft.

4. Summary of Analytical Determination of Connector Strengths

The results of the complete structural analysis are shown below in tables 5 and 6. Table 5 contains the structural capacities of the pin and rebar, pin and wire rope, and pin and eye-bolt connectors. The structural capacities for these connectors we calculated using the GME in-house

Table 5. Structural capacities of pin and loop connectors

Connector Type State	Tensile (kips)	Shear (kips)	Moment (kip-ft)	Torsion (kip-ft)	Failing Component	Pin Anchored?
Pin and Rebar						
Alabama	3.9	3.9	3.9	5.2	pin	N
Alaska	81.8	81.8	81.8	122.7	loop	Y
California	9.1	9.1	9.1	14.0	pin	N
Colorado	2.6	2.6	2.6	3.5	pin	N
Dist. of Columbia	106.0	106.0	106.0	163.5	loop	Y
Florida	7.6	7.6	7.6	10.1	pin	N
Georgia	6.6	6.6	8.2	8.5	pin	N
Hawaii	76.6	76.6	76.6	113.5	loop	Y
Indiana	2.9	2.9	2.9	3.1	pin	N
Kentucky	88.4	88.4	88.4	132.5	loop	Y
Maine	2.6	2.6	2.6	3.5	pin	N
Mississippi	106.0	106.0	106.0	159.0	loop	Y
Nebraska	3.5	3.5	3.5	5.2	pin	N
Nevada	8.8	8.8	8.8	13.6	pin	N
New Hampshire	3.5	3.5	3.5	5.2	pin	N
New Mexico	2.6	2.6	2.6	3.5	pin	N
N. Carolina	3.9	3.9	3.9	5.2	pin	N
Ohio	6.7	6.7	6.7	8.4	pin	N
Oklahoma	3.9	3.9	3.9	5.2	pin	N
Rhode Island	3.9	3.9	3.9	6.0	pin	N
South Carolina	13.4	13.4	13.4	19.0	pin	N
Vermont	3.9	3.9	3.9	4.6	pin	N
Wisconsin	3.9	3.9	3.9	5.2	pin	N
Wyoming	2.6	2.6	2.6	3.5	pin	N
Pin and Wire Rope						
Arizona	3.9	3.9	3.9	4.9	pin	N
Arkansas	93.3	93.3	93.3	121.3	concrete	Y
Florida	7.6	7.6	7.6	10.1	pin	N
Illinois	2.6	2.6	2.6	3.5	pin	N
Iowa	6.5	6.5	6.5	9.2	pin	N
Louisiana	4.5	4.5	4.5	7.0	pin	N
Minnesota	7.7	7.7	7.7	9.0	pin	N
Montana	5.2	5.2	5.2	4.5	pin	N
N. Dakota	7.7	7.7	7.7	9.0	pin	N
Oregon	4.7	4.7	4.7	6.5	pin	N
Utah	3.4	3.4	3.4	3.0	pin	N
Washington	4.5	4.5	4.5	7.0	pin	N
Wyoming	2.6	2.6	2.6	3.5	pin	N
Pin and Eye Bolt						
West Virginia	2.6	2.6	2.6	3.1	pin	N
Michigan	1.7	1.7	2.0	1.9	pin	N

Table 6. Structural capacities of tongue and groove connectors

Connector Type State	Tensile (kips)	Shear (kips)	Moment (kip-ft)	Torsion (kip-ft)
<u>Flaring Tongue and Groove</u>				
Florida	0	11.6	0	2.9
Ohio	0	13.5	0	3.4
Pennsylvania	0	11.6	0	2.9
Texas	0	10.9	0	2.7
Virginia	0	13.5	0	3.4
West Virginia	0	11.2	0	2.8
<u>Straight Tongue and Groove</u>				
Florida	0	10.6	0	6.3
New Jersey	0	10.4	0	6.2
New Mexico	0	6.7	0	4.1
Oregon	0	9.5	0	5.7

program PINLOOP, which is modeled after the analysis just performed. Table 6 contains the structural capacities of the flaring tongue and groove and straight tongue and groove connectors. Capacities for these last two connectors were calculated by hand.

The most interesting result of the analysis of pin and loop connectors is the large differences in the capacities of connectors with anchored pins versus the capacities of connectors with unanchored pins. In general, the capacities of anchored pin connectors are an order of magnitude greater than the capacities of unanchored pin connectors. For example, the tensile capacities of unanchored pin connectors range from 3 kips to 9 kips, whereas the tensile capacities of anchored pin connectors ranged from 77 kips to 106 kips. This discrepancy is because the mode of failure changes from yielding to rupture when going from unanchored to anchored pins. To date, only six States specify anchoring for their pins.

Invariably, the pin is the critical component of unanchored pin connectors, since the pin needs only to be pulled and bent out of the loops to destroy the integrity of the connection. This makes the structural capacity of the pin an order of magnitude less than other structural components of the connector. One critical factor which determines bending on the pin is the distance between the two top loops or the two bottom loops of the connector. The greater the distance between these loops, the greater the moment arm on the pin, and hence the lower the capacity of the pin to resist bending. The structural capacity of the pin is also very sensitive to the pin diameter since the pin diameter gets squared or cubed in strength calculations. For example, doubling the pin diameter will increase the strength of the pin by a factor of 4.

On the other hand, the structural capacity of the components of anchored pin connectors are in the same general range, being somewhere between 77 kips to 160 kips. This is because the anchored pin must now be ruptured to destroy the integrity of the connection, which raises the pin's structural capacity an order of magnitude. While unanchored pin capacities range from 3 kips to 13 kips, anchored pin capacities range from 94 kips up to 160 kips.

One last interesting feature of pin and loop connectors is the loop configuration when barriers are connected. In general, the loop configuration of the California connector is preferable to the loop configuration of the Arkansas connector. This is because the former configuration will prevent barriers from vertically displacing relative to one another, whereas the latter configuration will not.

The shear capacities of flaring tongue and groove connectors are generally higher than the shear capacities of straight tongue and groove connectors. This is because the shear areas for flaring tongue and groove connectors are larger than the shear areas for straight tongue and groove connectors. Shear areas for flaring tongue and groove connectors range from 99 sq in to 107 sq in, whereas shear areas for straight tongue and groove connectors range from 62 sq in to 96 sq in.

On the other hand the torsion capacities of flaring tongue and groove connectors are smaller than the torsion capacities of straight tongue and groove connectors. This is because the torsion moment arm for straight tongue and groove connectors is greater than the torsion moment arm for flaring tongue and groove connectors. Torsion capacities for flaring tongue and groove connectors range from 2.7 kips to 3.4 kips, whereas torsion capacities for straight tongue and groove connectors range from 4.1 kips to 6.3 kips.

Of all the connectors analyzed, the pin and loop connectors with anchored pins are by far the most structurally sound connectors. Generally, pin and loop connectors with unanchored pins and tongue and groove connectors have about equal shear and torsion capacities. However, the pin and loop connectors with unanchored pins are superior to tongue and groove connectors because of the latters inability to generate any tensile or moment capacity.

As stated earlier, only one report, TTI's "Barriers In Construction Zones," (7) actually showed the computations which yielded the structural capacities for the connectors that they analyzed. Comparing GME's results to TTI's results shows that for several connectors, GME's calculated strengths are lower than TTI's calculated strengths. The main reason for these differences is that TTI generally used higher material constants than GME did for analysis. For example, TTI used 60 ksi for steel yield strength in some calculations, whereas GME used 36 ksi for several calculations. Other differences included different specifications used, different analytical techniques, and round-off errors.

IV. Crash Test Results

To date, 45 valid crash tests are known to have been performed on portable concrete barriers (PCB) and their connectors. Details concerning individual tests are given in appendix B. While more than 45 crash tests have been performed on portable concrete barriers, not all of these tests are a true test of the connector. For example, Southwest Research Institute (SWRI) performed crash tests on concrete barriers that had back-up structures attached to prevent barrier displacement on impact. The reason for this was that SWRI was testing the barrier shape and vehicle reaction, not the connector design. However, by adding this back-up structure to the barrier system, the barrier connectors were effectively under a non-loaded condition at impact. Therefore, it was impossible to tell how the connector would have reacted in a field situation. For this reason, crash tests of this nature are not included in this report.

The crash testing of portable concrete barriers and their connectors is the best way to estimate connector performance in the field. This is because crash testing is the closest simulation of the actual conditions to which a connector is exposed.

Perhaps the most important result crash tests give is the lateral displacement of a barrier system on impact. Lateral displacement of a barrier system is dependent on, among other things, the stiffness of the connection. The stiffer the connection, the less the barrier system will displace. Connectors which allow large lateral displacement (say, 3 ft) are a danger to personnel working behind the barrier and a hazard to equipment behind the barrier. Crash testing is useful in determining whether a connector will sufficiently prevent a barrier from laterally displacing or not.

Crash testing also reveals connector characteristics that do not show up in static analysis. For example, unanchored pins in pin and loop connectors have a tendency to "jump out" of loops during vehicle impact, thereby destroying the integrity of the connection.

Crash tests were performed by the following six agencies or proprietors: California Department of Transportation (CALTRANS), Texas Transportation Institute (TTI), Southwest Research Institute (SWRI), New York State Department of Transportation (NYDOT), Barrier Systems Inc. (BSI) and ENSCO, Inc. Caltrans performed four tests between 1972 and 1974. All four tests were performed on the pin and rebar connector with unanchored pin. The first two tests were run using 7/8-in-diameter pins, and the second two tests were run using 1-in-diameter pins. In three of the four tests the pins were severely bent. In two of these tests (one with a 7/8-in-pin and one with a 1-in-pin), the pins actually came out of the loops, the 7/8 in-pin being pulled out and the 1-in-pin jumping out due to impact. The 1-in-pin jumping out caused a barrier segment to roll over. In the two tests that had pins come out of the loops, the lateral displacement was not an issue since the integrity of the connection was destroyed and the vehicles penetrated the barrier system. In the two tests where the pin did not come out of the loops (one with a 7/8-in-pin and the other with a 1-in-pin), the maximum permanent lateral displacement was 0.52 ft.

The Texas Transportation Institute performed sixteen crash tests between 1980 and 1984. Connectors tested were the steel dowel (one test), flaring tongue and groove with side plates (four tests), flaring tongue and groove with channel splice and steel dowels (one test), the bottom T-lock (eight tests) side plates (one test), and channel splice (one test). All the connectors performed adequately for these tests except one test of the flaring tongue and groove with side plates. In this test, (number 3825-9), at an impact speed and angle of 63.4 mi/h and 25 degrees, respectively, and with a vehicle weight of 4510 lb, several side plates were broken and the barrier was displaced 6.5 ft.

Southwest Research Institute performed five crash tests between 1974 and 1975 and include test numbers CMB-1, CMB-8, CMB-9, CMB-18, and CMB-24. Although the purpose of these tests was to test barrier shape and vehicle reaction to impact with a barrier, these tests yielded information pertinent to connector performance. The connectors tested in these five tests were dowels with top plate (one test), the New Jersey Welsbach (two tests), and the straight tongue and groove with side plates (two tests). The dowels with top plate connector and the New Jersey Welsbach connector sustained the impacts without damage. The straight tongue and groove with side plates connector, however, was tested twice and failed both times. The cracking of female joints on the impact side was the mode of connector failure. For both tests, nominal impact speed and impact angle were 60 mi/h, 25 degrees, respectively, and vehicle weight was 4500 lb.

The New York State Department of Transportation performed six crash tests on the I-beam connector. The I-beam connector used in the last four tests had some slight modifications from the I-beam connectors used in the first two tests. In all six tests, the connectors performed well, and had a maximum permanent displacement of 1.4 ft among the six tests.

Barrier Systems Incorporated performed thirteen crash tests, all on the hinge plate connector. Vehicle mass, impact speed, and impact angle were varied over these tests to determine the limitations of the connector. In one of these tests (number 031986-1) the connector failed. This test used a vehicle weight of 4850 lb, and had an impact speed and angle of 50 mi/h and 25 degrees, respectively. Three tests (numbers 031486-1, 032586-1, and 032686-1) had excessive lateral displacements ranging from 3.125 ft to 5.0 ft. The vehicle weights for these three tests ranged from 4020 lb to 5100 lb, impact speeds ranged from 45 mi/h to 60 mi/h, and impact angles ranged from 15 degrees to 25 degrees.

ENSCO, Inc. performed one test of the flaring tongue and groove connector in 1978. For a vehicle impact of 58 mi/h and 25 degrees, and a vehicle weight of 4240 lb, the connector failed due to one of the barrier segments being overturned.

In general, those connectors that have been tested are not being used in the field, and those connectors that are in the field have not been tested. For example, no crash tests have been performed on the pin and wire rope connector with anchored pin. Also, while several connector types performed well in crash tests, not all of these tests were severe. For example, the New Jersey Welsbach connector was tested with a maximum impact angle of 15 degrees, while other connectors were tested with impact angles as high as 40 degrees.

V. Application and Maintenance of Portable Concrete Barriers

Although most of the portable concrete barrier (PCB) connectors in use in the United States have not been crash tested, they have been used extensively in countless work zones over the last 10 to 15 years. Performance of the various PCB connector systems has been observed in a number of ways. State highway engineers and other work zone personnel have observed the effectiveness and efficiency of different PCB connectors in use. Accident reports also are a valuable source of information. This performance record has pointed out the advantages and disadvantages of various connectors, thereby completing the picture of the state of the PCB connector technology.

This chapter documents visits made to highway agencies to determine the field performance of PCB connectors. Problems in the application of various connectors and in their field performance are summarized. Information about anchoring portable concrete barriers is also presented as are methods of connecting portable concrete barriers to other barrier systems.

A. State Visits

Thirteen State agencies were visited between December 1986 and May 1987 to determine the field performance of their PCB connector systems. Seven of the agencies visited included office visits and visits to field sites. The remaining six agencies visited included office visits only. Table 7 lists the State agencies visited, the connector types used by the respective agencies visited, and the type and date of visits.

Some States were chosen based on information received in the connector use survey. Since the pin and loop category of connector was used by more agencies than any other type, States that use this category of connector are over-represented. Other States were selected based on the number of different connectors they used. When information was sought on a connector little used, the one or two States that used it also were selected. Because some of the northern States were visited in January or February, work zones with portable concrete barriers were not yet set up and, therefore, were not visited.

A questionnaire was developed for the State visits. This questionnaire consisted of basic questions to ask about connectors used in the State and included areas to check during field visits. The interviews varied widely based on the type of connector used and on the number and experience of the people interviewed. A brief description of each State visit and the information learned are given in appendix C.

Table 7. Agencies visited

Agency	Connector Types	Type of Visit	Dates of Visit
1. Colorado	Pin and Rebar	Office	1/21/87
2. District of Columbia	Tongue and Groove, Plate Insert, Pin and Rebar	Office and 1 Site	5/07/87
3. Illinois	Pin and Wire Rope	Office and 2 Sites	2/10/87
4. Iowa	Pin and Wire Rope	Office	1/22/87
5. Kansas	Tongue and Groove w/Dowels, Tongue and Groove w/Side Plates	Office and 1 Site	5/28/87
6. Maine	Pin and Rebar	Office	1/16/87
7. Michigan	Pin and Eye Bolt and Dowel	Office	2/11/87
8. Minnesota	Pin and Wire Rope	Office	3/13/87
9. Missouri	Tongue and Groove w/Continuous Cable	Office and 2 Sites	2/9 and 5/27/87
10. Ohio	Pin and Rebar, Tongue and Groove	Office and 1 Site	2/12/87
11. Texas (Houston Area)	Triple Dowel, lapped Joint, Channel Splice, Top-T	Office and 3 Sites	12/30 and 31/86
12. Virginia	Tongue and Groove, Plate Insert	Office and 4 Sites	5/05/87
13. Wisconsin	Pin and Wire Rope w/Rebar	Office	2/02/87

B. Problems in Application of PCB Connectors

Even the strongest connector is not effective if it has not been fabricated or installed as designed. The following problems in field application are summarized from the State visits discussed in appendix C.

* Inspectors do not have specific criteria against which to reject a barrier segment being installed, or on when to require that a barrier segment be replaced. Illinois does specify that the offset between segments be not greater than 1 in.

* Pin and loop connectors that are too close-fitting do not allow for installation on curves or at angles. As a result, smaller pins are being used or pins are being left out of connectors.

* It is not possible to replace a segment in the middle of barrier run with doweled connectors, male-female tongue and groove connectors, or tongue and groove with continuous cable connections.

* Tongue and groove and doweled connectors are difficult to inspect once they are installed.

* Segments that are 30 ft in length are too long, too heavy, and too cumbersome for most agencies to handle with currently available equipment.

* Rebars used for loops sometimes crack during fabrication or moving.

* Channel splice and plate insert connectors are not easy to curve or angle. Some part of the connector is more likely to be left off where it may be most needed.

* Barriers are sometimes not connected where the barrier has to be moved for access to the work area.

* Barriers can be hard to align vertically when they are extended across shoulders.

* When the gap between segments in connectors such as the grid slot or dowel is not controlled by specification or design, the barriers tend to be spread farther apart in order to make it easier to replace a segment or to make up small gaps near permanent barriers.

* Agencies with more than one accepted connector or barrier design sometimes find two or more types of connector or barrier intermixed at one site.

* Changes in connector requirements would make the existing barrier obsolete.

- Pin and rebar connectors in many cases are not stiff enough to be used on bridges or near drop-offs where deflection distances are limited.

C. Problems in Field Performance of PCB Connectors

Performance of barrier in controlled crash tests can be measured in terms of the lateral deflection of the barrier, and in terms of damage to the impacting vehicle and barrier system. Of course, the size, speed, and angle of the impacting vehicle in crash tests are controlled. Also, the barriers are installed in a manner completely in agreement with the barrier specifications; for example, joints are pulled tight and barriers are placed on styrofoam pads.

Information on incidents of vehicles striking barriers was gathered during the State visits. In most of these incidents, the speed and angle of the impacting vehicles were not known, and in some cases the vehicle type was not known. The information does give, however, an idea of what barrier systems are being knocked out of place or penetrated. Field performance problems found from the State visits are summarized below. The States where the problem was observed are given in parentheses after the problem.

- Barriers connected with the grid slot overturned and rolled down a side slope when struck by a semi-trailer truck. (Texas)
- Numbers 4 and 5 rebars used as pins bent when the barrier was impacted. (Maine)
- Barriers connected with the tongue and groove with continuous cable deflected 3 ft to 5 ft after a high-angle (45 degree) impact but did not overturn. (Missouri)
- Large chunks of concrete were knocked into opposing lanes and one of these concrete missiles struck a maintenance worker (Virginia)
- When struck by a loaded semi-trailer truck, #6 pins on pin and eyebolt connectors "bent like pretzels." The truck had struck a parallel run of guardrail on a bridge approach prior to hitting the barrier. (Minnesota)
- Two incidents involving barriers with pin and eyebolt connectors were observed in which no accident occurred. In the first, an empty grain truck used the barrier as a braking rail to avoid a rear-end collision. The truck was in contact with the barrier for 60 ft. The barrier deflected 1 in. In the second incident, a semi-trailer truck climbed the barrier to within 3 in of the top of the barrier. The barrier deflected 6 in and the truck was undamaged. (Minnesota)
- Two accidents involving loaded semi-trailer trucks were observed at barriers connected with pin and eyebolt. In the first accident, a truck rebounded from the guardrail and went through a barrier run. "Inserts and pins on all affected segments either

broke off or were pulled out of concrete." (10) In the second accident, pins and eyebolts failed and one barrier segment flew 30 ft and hit an adjacent bridge. (Minnesota)

- In two accidents involving trucks hitting barrier connected with pin and wire rope, lateral deflection was 8 ft., which is too large for most applications. The trucks did not penetrate the barriers, however. (Minnesota)

- Eleven accident reports were obtained where the barrier has been connected with the tongue and groove with a single dowel. Work zone roadway was comprised of an S curve with barrier on both sides of the roadway and in the median. In one accident a pickup truck and a car hit the barrier at different points. Both vehicles knocked the barrier into opposing lanes of traffic. In another accident, the car hit the barrier and overturned one segment. The car then went over the barrier into opposing lanes. In other accidents, vehicles flew over the barrier or overturned after hitting the barrier. (Kansas)

D. Anchoring

Anchoring is the fastening of portable concrete barriers to the surface upon which the barriers rest. Several States require some sort of anchoring for portable concrete barriers, and specify anchoring for a variety of reasons. Some reasons for using anchoring are as follows:

- Anchoring minimizes or negates lateral movement of the barrier when impacted by a vehicle. Minimizing lateral displacement is necessary when the work zone behind the barrier is narrow, such as on bridge decks or near drop-offs.

- Anchoring is necessary for a PCB system if it is to be converted to a permanent barrier system. In general permanent barriers must not allow lateral displacement, and anchoring of precast barriers is the best way to ensure this.

- Anchoring can prevent barrier overturn. Not all anchoring methods will prevent barriers from overturning, but some methods will. Preventing barriers from overturning is important, because barrier overturning tends to induce ramping of a vehicle during its impact with a barrier.

Anchoring methods fall into two categories: anchoring by pins or dowels, and anchoring by splice plates combined with pins. The first method involves driving steel stakes through precast holes in the barrier base into the surface. The stakes are 1/2 in to 2 1/2 in in diameter, and are embedded in the ground from 5 in to 36, in depending on whether the surface is paved or unpaved (the greater embedment lengths are specified for unpaved surfaces). New York uses anchoring of this category. One variation of this method is the use of short dowels (6 in to 12 in in length) which are not driven through holes in the barrier base, but rather are aligned with slots, or short length holes, in the bottom surface of the barrier, and aligned with holes in the surface. Colorado uses dowels for anchoring. Another variation of pin and dowel anchoring is driving the pin used in pin and loop connectors into the surface. Indiana is a State which uses this method of anchoring.

The second anchoring method involves splice plates, typically angle iron, which both connects barrier segments and anchors the barriers to the ground. Florida is an example of a State that specifies splice plate anchoring. Iowa specifies anchoring straps which are anchored to the ground on one end and are connected with the pin in the loops on the other end.

Another method which is not true anchoring but which should be mentioned is the use of back-up embankments placed behind barriers. Back-up embankments prevent lateral displacement of the barrier, and are typically either earth berms or short-height asphalt curbs which run the length of the barrier system on the work zone side of the system. Sometimes the barrier will straddle an embankment through use of longitudinal keyways cast into the barrier bottom. Short-height back-up curbs, however, will not eliminate the possiblity of barrier overturn.

E. Connections to Other Barriers

Connections to other barriers involve the fastening of other highway appurtenances to portable concrete barriers. Such appurtenances include permanent concrete barriers, impact attenuators, and guardrails such as the W-beam. In all observed cases, highway appurtenances are connected only to the ends of PCB systems. Impact attenuators are generally used as head-on crash cushions on the entrance end of PCB systems. W-beam rails, on the other hand, are used as flared end segments on both ends of PCB systems. Permanent concrete barriers are used as a continuation of the PCB system.

The various appurtenances are connected by two methods: bolting and butting. W-beam rails are generally bolted to portable concrete barriers. The W-beam rail overlaps with the PCB for approximately 4 ft and is flush with the side of the barrier. Bolts, which run through the width of the PCB segment, fasten the W-beam to the barrier. In some States, the W-beam rail is mounted to the barrier segment with wooden offset blocks placed between the W-beam rail and the barrier segment. This allows the W-beam rail to protrude out into the traffic side of the barrier as far as the barrier base, thus reducing snagging potential in the barrier system. Other States shave the base of the barrier on the approach end to make the base narrower and reduce snagging potential.

Impact attenuators, on the other hand, are butted against the head-on end of the PCB system. In some cases, the impact attenuator may also be bolted to the barrier in a fashion similar to W-beam rails, as well as being anchored to the ground. Portable concrete barriers are butted against the sides of permanent barriers at a slight angle. A concrete transition segment is then cast between the permanent and portable barriers to provide a smooth transition between the two barrier systems on the traffic side. Georgia specifies most of the methods described above.

VI. Conclusions

This chapter presents the study conclusions drawn from the connector use survey, strength analysis, crash tests, and State visits. The conclusions are presented in the order of most to least important. At the end of each conclusion is the page number of the report where supporting information can be found.

- There is a wide variety both in the types of connectors used for portable concrete barriers and in the design specifications of any one barrier type. For example, within the basic pin and loop category loops are constructed with reinforcing steel (rebar), wire rope, eye bolts, and steel plates. (9)

- Most catastrophic accidents with barrier involve heavy trucks or vehicles striking the barrier at high speeds and at high angles. High-angle impacts are most likely when barrier is on both sides of the road or when barrier is placed in curves. (74)

- The types of connectors most used in the field are generally those which have had the least crash testing. The California pin and rebar had four crash tests conducted in 1972-74. These four tests have been the extent of crash testing of pin and loop connectors. Moreover, although the bottom T-lock connector has been crash tested eight times, the connector use survey revealed no agency that currently specifies this connector. (70)

- Crash tests are still the best method of estimating connector performance because crash testing is the closest simulation of the actual conditions to which a connector is exposed. Crash testing also reveals dynamic performance of connectors which does not show up in static analysis. For example, in Caltrans crash test 293, unanchored pins in the connectors "jumped out" of loops during vehicle impact, thereby destroying the integrity of the connection. (69)

- Some varieties of the pin and loop connector have strength characteristics that are sufficient for most highway situations and approach the requirements of permanent barriers (4500 lb vehicle impacting at 25 degrees at a speed of 60 mi/h) They are not always installed in the field, however, so that their full capabilities can be utilized. (73)

- Even low strength connectors such as the tongue and groove used in Virginia, are effective in redirecting many of the vehicles impacting a barrier. (4)

- Generally, pin and loop connectors with unanchored pins and tongue and groove connectors have about equal shear and torsion capacities. However, the pin and loop connectors with unanchored pins are superior to tongue and groove connectors because of the latters inability to generate any tensile or moment capacity. (68)

- Review of a limited number of accident reports shows that high-angle impacts are most likely when the barrier is on both sides of a roadway or when there is guardrail on one side and barrier on the other. (75)

- The most commonly used type of connector is the pin and loop connector. The next most commonly used types of connector are the tongue and groove and the plate insert. (4)

- Retrofitting and modifying of connectors to make them stiffer and stronger are attractive options due to the amount of barrier already cast with certain connectors. (73)

- Some States stiffen and use stronger barriers for situations where high-angle impacts are possible, high speeds are likely, or there is a limited distance for barrier deflection. (75)

- Not all connector designs are based on standardized design practices as specified by authoritative organizations. For example, Michigan does not provide for sufficient anchoring of eyebolts in their pin and eyebolt connector to prevent the eyebolts from breaking out of the concrete as specified by American Concrete Institute (ACI) codes ACI-12.2.2 and ACI-12.5.3. as cited by Wang and Salmon. (11) (67)

- Static structural analysis is valid only in that it compares one connector's strength with that of another connector. In application static loads do not occur to barrier systems. (69)

- Static structural analysis usually will determine the weakest component in a connector system. This does not always indicate what actually happens when a barrier is impacted. For example, static analysis of a flaring tongue and groove connector showed the failing component to be the male tongue. Crash tests performed on flaring tongue and groove connectors with side plates, however, had the female groove fail, not the male tongue. This was because impact was on the side of the groove. (70)

- Unanchored pins in pin and loop connectors have the danger of "jumping out" of the loops during vehicle impacts, thereby destroying the structural integrity of the connector. (69)

* In the field barriers are not always installed according to standard plans. For example, smaller pins are substituted, gaps are excessive, and broken or chipped barriers are used. (73)

* Loops made of wire rope generally are stronger than those made of rebar. Rebar loops also are more prone to breaking during fabrication and handling. (73)

* Published reports give conflicting figures for some connector strengths. For example, one study (7) gives the tensile capacity of the Idaho pin and rebar as 61 kips, whereas another study (4) gives this same capacity as 23 kips. (47, 48)

* Some connectors, such as dowel or plate inserts, cannot be inspected easily to see if all connector hardware is being used. (73)

* For pin and loop connectors with unanchored pins, the pin is the critical structural element, its structural capacity being an order of magnitude less than that of other components of the connector. This is because the pin need only be bent rather than ruptured in order to destroy the integrity of the connection. (67)

* Inspectors need guidance on when to replace a barrier due to excessive spalling or damaged loops. (73)

* Pin and loop connectors are more prone to sloppy installation than other types of connectors. Pins smaller than standard and loose loops can significantly affect field performance. (73)

* The larger the gap between either the top two or bottom two opposing loops in a pin and loop connector, the smaller the pin's structural capacity. This is because the moment arm between opposing forces on the pin is increased. (67)

* Most users of pin and loop connectors do not specify gap width. To date, only 15 of the 46 pin and loop connector users specify a gap width.(10)

* In pin and loop connectors, larger gap widths mean greater rotational slack in the connector, which increases the estimated lateral displacement of a barrier system using this connector.(10)

* The pin and loop connector can be strengthened and stiffened by putting a nut on the pin, by using shims, or by adding side plates. (74)

- Connector systems in which the gap is controlled as a part of the connector are preferable to those in which gaps are variable and can vary from one location to another. (73)

- In agencies where two types of connectors or barriers are specified, intermixing of designs on one job is common. For instance, in Virginia tongue and groove and plate insert connectors are mixed, and in Michigan 6 in top and 10 in top barriers are mixed. (73)

- The loop configuration of the California pin and rebar connector is preferable to the loop configuration of the Arkansas pin and wire rope connector. This is because the former configuration will prevent barriers from vertically displacing relative to one another, whereas the latter configuration will not.(67)

- Results for connector strength analyses are lower than those given in previous reports mainly because of different material constants. (68)

- Some States are using metal guardrail behind barriers to connect segments when the normal connector does not work. (appendix C)

- Excessive gaps between barrier segments create snag points on which impacting vehicles may get caught. This defeats the "safety shape" design of the barrier. (appendix C)

- The strength of pins in anchored pin and loop connectors generally matches the strength of other components in the connector. (67)

- Some States bevel the corners of barriers to prevent snagging of snow plows and to allow placement of the barrier sections in curves. (appendix C)

- Several States specify the same precast barrier design for temporary and permanent installations. (75)

VII. Recommendations

The following recommendations cover items that the project staff feel are implementable based on the state of portable concrete barrier technology. Further research and crash tests that are recommended are covered in the next chapter. Recommendations are listed in descending order of importance:

- Agencies should specify strengthening or stiffening of connectors for conditions where minimal deflection distances are available, where high speeds or high impact angles are possible, or where there is a large proportion of truck traffic. Candidate sites include bridges, bridge approaches, lateral shifts or crossovers, or any roadway where there are two or three parallel runs of barrier.

- Inspectors should use the checklist given in table 8 for determining the adequacy and condition of PCB connectors. Inspection of the connectors during installation is particularly important for tongue and groove, plate insert, and doweled connectors.

- Pins in pin and loop connectors should be anchored at both ends of the barrier segment. Anchoring by drilled hole with cotter pin or slotted end with driven pin will prevent pins from jumping out on impact. Only nut and washer anchoring will prevent pins from being bent out of the loop when the pin is loaded, and is therefore the recommended anchoring method.

- Plan sheets covering the pin and loop type of connector should specify the permissible gap width between barrier segments. The plan sheets are clearer concerning the connection if two segments of barrier are shown.

- The permissible gap between barrier segments should be specified for tongue and groove, plate insert, and doweled connectors. For plate insert and doweled connectors it is preferable to have a minimum gap of at least 1/4 in to allow for verification that all connector hardware is present.

- Wire rope is generally preferable to steel rebar for forming loops in pin and loop connectors. Also, loop configurations should be like the California pin and rebar connector, to prevent vertical displacement between barriers.

- The goal in design of connectors is to match the strength of all components of the connector.

Table 8. Inspectors checklist

General

1. Check for segments that have chipped or broken places that could create snag points. Broken places are critical near joints when the gap adds to the distance between segments. Total gaps of 5 in or greater should be considered critical.

2. Check for cracks near lifting points and around drainage channels.

3. Focus on the condition of connectors at angles, curves, or where segments have been replaced.

4. Check for acceptable width between barrier segments.

For Pin and Loop Connectors

1. Check that pins are installed and are the proper design and diameter.

2. Check for cracked, broken, or bent loops.

Other

1. Check that tongue on tongue and groove connector has at least two-thirds of its length in good condition.

2. Check for presence of dowel bars and plates in connection.

- States should use PCB connectors only if they have been structurally analyzed and sucessfully crash tested (see chapter VIII for needed crash tests).

- States should adopt a regional connector design, as Illinois, Minnesota, and Wisconsin have to decrease the number of different designs that fabricators and contractors must stock.

- Crash tests of PCB connectors should use a point of impact near the PCB connector.

VIII. Additional Research Needed

Additional research is needed to resolve some issues related to portable concrete barrier (PCB) connectors. A major conclusion of this study was that the most used connectors are the least crash tested. It is unlikely, however, that enough crash tests could be conducted that would resolve all issues of connector design. Additional accident data also should be analyzed.

Needed research on PCB connectors, comes under four categories: (1) computer simulation (2) impact tests, (3) crash tests, and (4) accident studies.

A. Computer Simulation

Computer simulation involves the programming of static and dynamic properties of portable concrete barriers and their connectors and using these properties to simulate and predict barrier reactions for certain impact conditions. This is an attractive research tool since it is relatively inexpensive and since sensitivity analysis can be performed on various components of the barrier at no extra cost. Also, much of the undesirable randomness of actual crash tests is eliminated in simulation programs.

While work has been done in the simulation area for portable concrete barriers, however, no comprehensive effort to use these models for analyzing barrier connectors is known. It is recommended that previous simulation research on portable concrete barriers be reviewed to locate the most promising results and software. This software should be used to predict estimated barrier displacement for those connectors that are specified by the State. Sensitivity analysis should also be performed on these barrier systems for different ground or surface conditions, different segment lengths, and various dimensions of connector components.

B. Impact Testing

Impact testing involves connecting several barriers and impacting them with a bogie in order to determine the connector's reaction on impact. One suggested configuration for a test of this sort is shown in figure 42.

To test the moment capacity of the connector, the bogie would strike the barrier system at point 1, on a level with the center of gravity (C.G.) of the barrier system. Back-up structures would be added as shown in the figure. To test the shear capacity, the bogie would strike the barrier system at point 2, on a level with the C.G. of the barrier system. To test torsion capacity, the bogie would again strike the barrier system at point 2, but this time at a level well above the C.G. of the barrier system. Back-up structures for these last two tests would be added as shown in the figure.

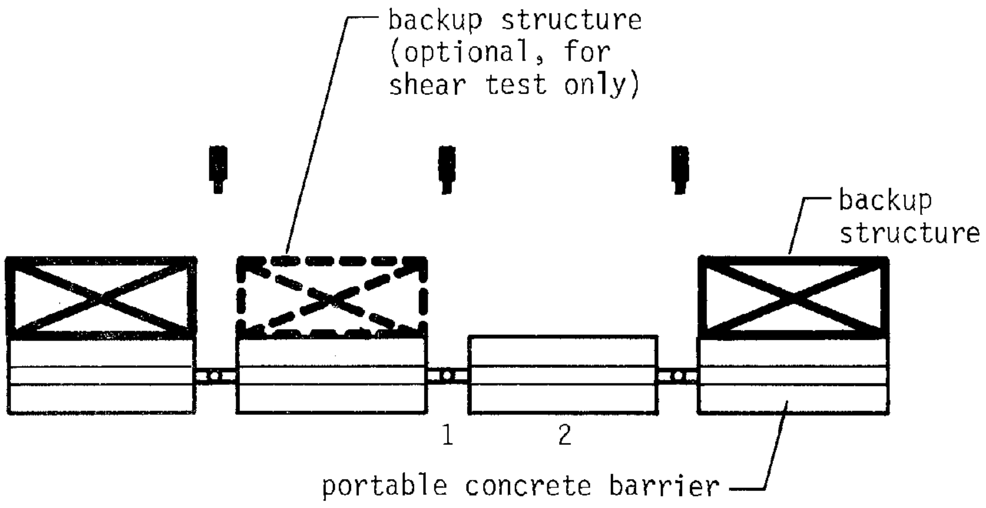


Figure 42. Impact testing configuration

The main advantage of impact testing is that it tests the connector's reaction to moment, shear, and torsion dynamic loading all on an individual basis. Crash tests have several other variables involved, and connector reaction is often a secondary consideration. Since most of the present connectors used in the field have not been crash tested, it is recommended that impact tests be performed on some of these connectors. Of particular interest is the pin and loop connector. Tests should be run using unanchored pins, pins anchored with cotter keys, and pins with nuts on the threaded portion to determine how the connector's reaction changes with different pin configurations. Impact testing could also be used to screen out undesirable connectors, with only promising connectors being fully crash tested.

C. Crash Testing

Crash testing is still the best method to test connector design, since crash testing is still the closest approximation of conditions to which connectors are exposed in the field. Crash tests in the past have yielded valuable information on connector performance that neither static nor dynamic analysis was able to predict. However, as mentioned in the Conclusions chapter, the most used connectors are also the least tested ones. Crash testing is recommended, therefore, for these connectors.

Foremost among these connectors is the pin and wire rope connector, since it is so widely used. Pin configuration for this test (whether anchored or unanchored) could be determined through analysis of impact tests. At least one test should be run on a pin and loop connector which has a stiffener in the gap, such as the Ohio shim shown in figure 46 or the GME pinned spacer as shown in figure 43, to see how stiffening the connector affects the performance of the barrier system. Other connectors which need testing are the pin and eyebolt, and plate insert connectors. It is also recommended that a run of unconnected barriers with both 6-in and 10-in tops be tested to determine what part the mass of the barrier itself plays in redirecting vehicles and protecting the work zone.

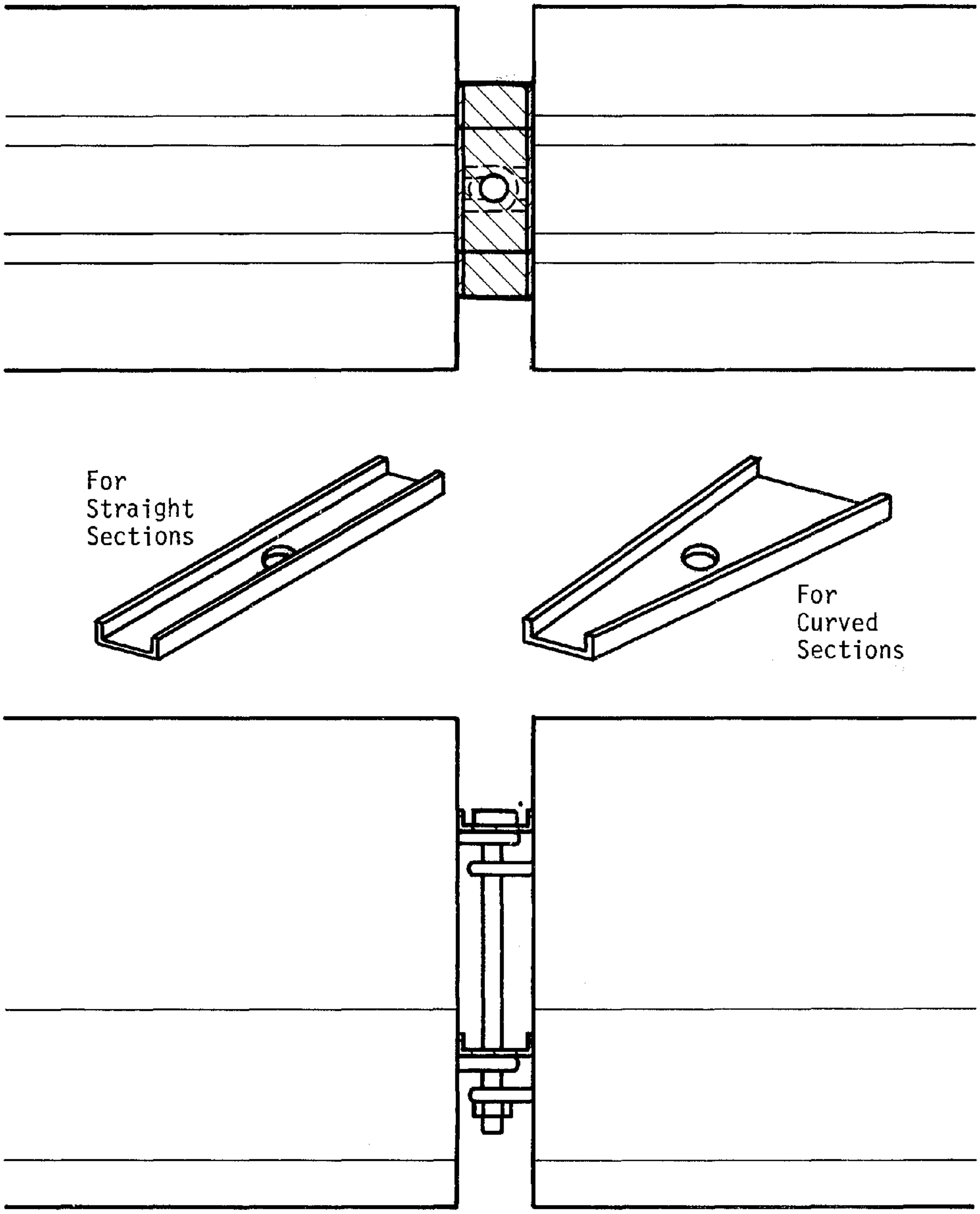


Figure 43. GME pinned spacer

D. Accident Studies

Because of the alarming number of severe barrier-related accidents which took place in Kansas (see appendix C), it is recommended that an accident study of barrier-related accidents throughout the States be performed. While GME did receive some information on this topic, this project's budget only allowed a limited number of State visits. Of particular interest should be connector structural performance in the field and how connector performance affects barrier lateral deflection and overturn.

It is difficult to sort barrier-related accidents from a statewide computerized accident records system. An alternate approach would be to review all accidents for projects that employ PCB. Another step would be to supplement information on barrier accidents in a manner similar to information obtained by NASS teams (for example, estimated speed, impact angle, vehicle damage, injury and connector damage).

APPENDIX A – Connector Design Details

Connector Type

Pin and Rebar
(Figure 2)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	8	6	6	8	3/4	1	24	Alabama		10 ± 1/2	NS	
2	8	6	8	6	5/8	1 1/4	25	Alaska		10	NS	
3a	7 1/2	6	7 1/2	6	3/4	1 1/4	26	California		19-10	2	
3b	7	5	7	9	0	7/8	26	California	291,292	NS	NS	has been modified to 3a
3c	7	5	7	9	0	1	26	California	293,294	NS	NS	has been modified to 3a
4	8	6	6	8	5/8	7/8	28	Colorado		10	0 to 1 (Taper)	
5	7	5	5	7	5/8	1	32	Connecticut		20	NS	loops formed from two bars
6	7 1/2	6	7 1/2	6	3/4	1 1/4	24	Dist. of Columbia		12	2	
7	8	6	6	8	3/4	1-1/4	30	Florida		12 min	NS	Type 3
8	7	5	7	9	5/8	7/8	26	Georgia		10	NS	
9	7-1/2	6	7-1/2	6	5/8	1	26	Hawaii		19-9 1/4	2-3/4	
10	9	6	6	9	3/4	1	31	Indiana		10	NS	
11a	8	6	10	8	3/4	1-1/4	25	Kentucky		10 ± 1/2	NS	34 in high PCB, Type J
11b	8	6	8	6	3/4	1-1/4	25	Kentucky		10 ± 1/2	NS	32 in high PCB, 9 or 12 in wide top, Types 9k, 12k
12	8	6	6	8	5/8	7/8	27	Maine		10	NS	
13	8	6	8	6	3/4	1-1/4	25	Mississippi		10 ± 1/2	NS	
14	8	6	8	6	3/4	1	30	Nebraska		10	NS	
15	7-1/2	6	7-1/2	6	3/4	1-1/4	26	Nevada		19-9 1/4	1-1/2	
16	8	6	8	6	5/8	1	31	New Hampshire		10	NS	
17	8	6	6	8	5/8	7/8	28	New Mexico		10	0 to 1 (Taper)	

NS – Not Specified

Connector Type

Pin and Rebar
(Figure 2, continued)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
18a	8	6	6	8	3/4	1	24	North Carolina		10	NS	32 in high PCB
18b	8	6	8	10	3/4	1	24	North Carolina		10	NS	34 in high PCB
19	10	8	9	7	3/4	1-1/4	27	Ohio		10, 12	NS	
20	8	6	7	9	3/4	1	24	Oklahoma		10	NS	
21	7	5	5	7	5/8	1	35	Rhode Island		10	3	
22	8	7	6	7	1	1-1/4	NS	South Carolina		12	4	
23	10	8	6	8	5/8	1	32	Vermont		10	NS	
24	8	6	6	8	1/2	1	30	Wisconsin		10	NS	
25	8	6	6	8	5/8	7/8	26	Wyoming		10	0 to 1 (Taper)	

Connector Type

Pin and Triple Rebar
(Figure 3)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	3	5	5	3	1	38	Tennessee		8 to 12	2	

Connector Type

Pin and Twin Double Rebar
(Figure 4)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	H(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	9	7	5	7	4	5/8	1-3/8	24	South Dakota		10	NS	

NS - Not Specified

Connector Type

Pin and Wire
Rope
(Figure 5)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	8	6	7	9	1/2	1	29	Arizona		12-6 or 20	NS	
2	8-1/4	7-1/4	9-1/4	10-1/4	5/8	1-1/4	21	Arkansas		10	2 max.	
3	8	6	6	8	1/2	1 1/4	30	Florida		12 min	NS	Type 4
4	specifications not available							Idaho				
5	8	6	6	8	1/2	7/8	32	Illinois		10	NS	
6	7	6	9	8	1/2	1	26	Iowa		10	3 ± 1/2	
7	7-1/2	6	7-1/2	6	1/2	1	29	Louisiana		15	1/4	
8	10	8	6	8	1/2	1-1/4	24	Minnesota		10	NS	
9	10	8-1/2	10	11-1/2	1/2	1	26	Montana		10	NS	
10	10	8	6	8	NS	1 1/4	24	North Dakota		10	NS	
11	8	6	5	7	5/8	7/8	25-1/2	Oregon		12 6, 25	1	
12	9	6-1/2	7	9-1/2	1/2	1	29	Utah		10, 12 6, 20	NS	alternate
13	7-1/2	6	7-1/2	6	5/8	1	26	Washington		10, 12-6	NS	
14	8	6	6	8	1/2 5/8	7/8	26	Wyoming		10	0 to 1 (Taper)	

Connector Type

Pin and Eye Bolt
(Figure 6)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	10	8	6	8	3/4	3/4	32	Michigan		10	NS	
2	8	6	8	10	3/4	7/8	30	W. Virginia		10	NS	alternate

NS - Not Specified

Connector Type

Pin and Plate
(Figure 7)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	H(in)	I(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	9	6-1/2	7	9-1/2	1/2	3	1	29	1-1/2	Utah		10, 12, 12-6 , 20	NS	

Connector Type

Flaring Tongue
and Groove
(Figure 8)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	H(in)	I(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	7-1/2	2-1/2	8	2-1/2	2	1/2	1/8	1-3/4	23	Florida		12 min	NS	Type 1
2	7-1/2	2-1/2	8	2-1/2	2	1/2	1/8	1-3/4	23	Ohio		10, 12'	NS	alternate, Type B
3	7-1/2	2-1/2	8	2-1/2	2	1/2	1/4	1-3/4	23	Pennsylvania		30 max	NS	
4	7-7/8	2-1/4	8	2-1/4	1-1/4	1/2	1/8	4-3/4	26	Texas		30 ± 4	NS	alternate
5	7-7/8	2-1/2	8	2-1/2	1	1/8	1/8	1-3/4	23	Virginia		12	1 max.	gap width is specified for curves only
6	7-7/8	2-1/4	8	2-1/4	2	1/2	1/8	1-3/4	23	W. Virginia		12	NS	

Connector Type

Straight Tongue
and Groove
(Figure 9)

No.	A(in)	B(deg)	C(in)	D(deg)	E(in)	F(in)	G(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	3	4.5	3	4.0	1-1/8	1-1/8	32	Florida		12 min	NS	Type 2
2	NS	NS	1-7/8	14.0	NS	1-1/4	31	New Jersey		20	NS	2 in wider at bottom than top, Type Z
3	2	5.4	2-3/4	5.1	2	2-1/8	32	New Mexico		12 - 6	NS	alternate
4	3	4.5	3	4.0	1-1/8	1-1/8	32	Ohio		10, 12	NS	alternate, Type A

NS - Not Specified

Connector Type

Plate Insert
(Figure 10)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	H(in)	I(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	specifications not available									Delaware				
2	specifications not available									Dist. of Columbia				alternate
3	specifications not available									Maryland				
4	7	4	25-1/2	5/16	6	1/2	7/16	9/16	5/16	Pennsylvania		30 max	NS	
5	7	NS	25-1/2	5/16	5	1-1/2	NS	7/8	1/2	Virginia		20	NS	alternate

Connector Type

Grid Slot
(Figure 11)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	8	10	18	1/2	1	24	Texas		30 ± 4	1/2	alternate

Connector Type

Steel Dowel
(Figure 12)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	H(Yes or No)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	6	14	28	1	18	2	10	N	Kentucky		20, 30	1/2	35 in high barrier; 9 in, 12 in, or 14 in wide top, Types L, M, 9M, 12M
2	6	14	28	1	18	2-1/2	10	N	Texas	CMB-2	30 ±	1/2	alternate
3	specifications not available								Michigan				alternate

NS - Not Specified

Connector Type

Channel Splice
(Figure 13)

No.	A(in)	B(in)	C (channel)	D(no)	E(in)	F(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	5	42	C5x9	4	27-1/4	1-1/8	Texas	2262-2	14 - 11	25 max.	

Connector Type

Side Plates
(Figure 14)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	3	18	1/2	2	27	5/8	Florida		12 min	NS	alternate
2	5	42	1/2	4	26	1-1/8	Texas Transportation Institute (TTI)	2262-2	15	NS	

Connector Type

Vertical I-Beam
(Figure 15)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	H(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1a	2	2-1/4	0	26	1/2	4	4	1/2	New York	NY-17 NY-18	20	NS	has been modified to 1b
1	2	3-1/4	6	20	1/2	4	4	1/2	New York	NY-44 NY-45 NY-46 NY-47	8,10,12, 14,16,18, 20	NS	

Connector Type

Top T-Lock
(Figure 16)

No.	A(in)	B(in)	C(in)	D (Channel)	E(in)	F(in)	G(in)	H(in)	I(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	3	4	27	C4 x5.4	18	1/4	1-5/8	NS	NS	Texas		12	NS	

NS - Not Specified

Connector Type

New Jersey Welsbach Interlock (Figure 17)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	specifications not available						New Jersey				alternate

Connector Type

Bottom T-Lock (Figure 18)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	H(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	2	6	36	31-1/2	27-1/2	1/4	8	3	TTI	3825-10 thru 3825-17	12	NS	

Connector Type

Lapped Joint (Figure 19)

No.	A(in)	B(in)	C(in)	D(in)	State or Agency	Crash Test	Segment Length(ft-in)	Gap Width	Notes
1	5-1/2	7-1/2	1	16	Texas		30 ± 4	2	alternate

Connector Type

Hinge Plate (Figure 20)

No.	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	H(in)	I(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	NS	NS	NS	NS	NS	6-1/2	4	6	1-1/8	Barrier Systems Inc.	13 different tests	3-3	2-3/8	all tests conducted by manufacturer, see Table 4

NS - Not Specified

Connector Type

Straight Tongue and
Groove with Side Plates
(Figure 21)

No.	A(in)	B(deg)	C(in)	D(deg)	E(in)	F(in)	G(in)	H(in)	I(in)	J(in)	K(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1a	2	9-1/2	2-1/2	9-1/2	1-1/2	1-1/2	32	4	66	1/2	2	Kansas		10	1/4 to 1/2	alternate
1b	2	9-1/2	2-1/2	9-1/2	1-1/2	1-1/2	32	4	126	1/2	2	Kansas		10	1/4 to 1/2	alternate
2	3	4-1/2	3	4	1-1/8	1-1/3	32	4	12	1/8	2	Kentucky		20 ±1/2	NS	9 or 12 in 12 wide
3	NS	NS	1-7/8	14	NS	1-1/4	31	top 3	12	1/4	2	New Jersey		20	NS	Type 3
4	3	14.5	3	NS	1-1/4	1-1/4	32	3	12	1/4	2	Southwest Research Institute (SWRI)	CMB-18 CMB-24	20	1/4 max	

Connector Type

Flaring Tongue
and Groove with
Side Plates
(Figure 22)

No.	A(in)	B(deg)	C(in)	D(deg)	E(in)	F(in)	G(in)	H(in)	I(in)	J(in)	K(in)	L(no)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	7-7/8	2-1/4	8	2-1/4	1/8	1/8	1-3/4	23	4	36	1/2	6	TTI	3925-7	12	NS	
2	7-7/8	2-1/4	8	2-1/4	1/8	1/8	1-3/4	23	4	36	3/8	6	TTI	3825-6	12	NS	
3	7-7/8	2-1/4	8	2-1/4	1/8	1/8	1-3/4	23	4	36	1/8	6	TTI	3825-9	12	NS	
4	7-7/8	2-1/4	8	2-1/4	1/8	1/8	1-3/4	23	4	36	1/4	6	TTI	3825-5	12	NS	

Connector Type

Straight Tongue
and Groove with
Steel Dowels
(Figure 23)

No.	A(in)	B(deg)	C(in)	D(deg)	E(in)	F(in)	G(in)	H(in)	I(in)	J(no)	K(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	2	9-1/2	2-1/2	9-1/2	1-1/2	1-1/2	32	1	24	1		Kansas		10	1/4 to 1/2	

NS - Not Specified

Connector Type

Straight Tongue and Groove with Continuous Cable (Figure 24)

No.	A(in)	B(deg)	C(in)	D(deg)	E(in)	F(in)	G(in)	H(in)	I(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	2	9-1/2	2-1/2	9-1/2	1-1/2	1-1/2	32	1/2	2	Missouri		10	1/4	

Connector Type

Flaring Tongue and Groove with Channel Splice and Double Dowels (Figure 25)

No.	A(in)	B(deg)	C(in)	D(no)	E(in)	F(in)	G(in)	H(in)	I(in)	State or Agency	Crash Tests	Segment Length(ft-in)	Gap Width(in)	Notes
1	5	42	0.325	4	27-1/4	24	1	6	12	TTI	3825-8	15	NS	

NS - Not Specified

Appendix B

CRASH TEST DETAILS

This appendix describes crash tests performed on portable concrete barriers in the past. A summary of these crash tests is given in table 9. The ENSCO,Inc. crash test on the flaring tongue and groove connector is not included in the descriptions, since the only available information on that test is already given in table 9.

Table 9 is modeled after the NCHRP 230 format for reporting crash test results. Some of the parameters in NCHRP 230 were left out of table 9, however, because the information was not available from the literature, or because these parameters were not considered important to the evaluation of connector performance. The parameters used in table 9 are: date the test was performed, connector type, installation length, segment length, profile type, maximum dynamic deflection, maximum permanent deflection, vehicle model, gross vehicle weight, nominal impact speed, nominal impact angle, actual impact speed, actual impact angle, exit speed, exit angle, impact point, vehicle reaction, vehicle damage, barrier damage and reaction, connector damage, and soil type and condition. Connector types are followed by numbers in parenthesis which correspond to numbers listing the connectors in appendix A.

The following detailed descriptions of each crash test performed are presented by conducting agency. It should be noted that some crash test descriptions have more information than others. This is because some references give more information in their accounts of crash tests than others. These descriptions from other references were left basically intact in this appendix so that the reader would have a thorough description for any given crash test. Hence, there is information in the descriptions that is not in table 9. The most important of these is the narration and time sequence of the crash events.

A. Southwest Research Institute

1. Test CMB-1

The connector used in test CMB-1 was dowels with top plate. The barrier segments were freestanding and connected by shear keys at the bottom and by steel plates at the top. Barrier segment length was 10 ft, and the total system length was 150 ft. A 4,370 lb vehicle impacted the barrier at an actual speed of 60.3 mi/h and at an actual impact angle of 7.5 degrees. The vehicle was smoothly redirected. Lateral translation of 1 in was observed at the juncture of segments 5 and 6; no other joint locations showed evidence of barrier movement.

Damage to the installation was limited to scarring of the concrete surface due to vehicle contact. The left side of the vehicle's front bumper was bent and some local damage to its left fender was noted. Otherwise, the vehicle was undamaged and drivable.

Table 9. Crash test summary

Agency	Southwest Research Institute (SWRI)			
Test No.	CMB-1	CMB-8	CMB-9	CMB-10	CMB-24
Date of Test	2/74	7/74	7/74	1975	1975
Connector Type*	Dowels w/ top plate	NJ Welsbach (1)	NJ Welsbach (1)	ST&GW/SP(5)	ST&GW/SP(4)
Install. Length(ft)	150	180	180	100	100
Segment Length(ft)	10	30	30	20	20
Profile Type	N.J.	N.J.	N.J.	F	F
Max. Dynamic Defl.(ft)	0.08	0	0	NA	
Max. Perm. Defl.(ft)		0	0	NA	3.42
Vehicle Model		71 Vega Hatchback	71 Vega Hatchback	1971	74 Ambassador
Gross Veh. Wt.(lbs)	4370	2250	2250	4500	4500
Nom. Impact Sp.(mph)	60	55	57		60
Nom. Impact Ang.(deg)	7	7	15		15
Actual Impact Sp.(mph)	60.3	55.9	58.9	62	56.4
Actual Impact Ang.(deg)	7.5	8.0	15.5	25	24.1
Exit Speed(mph)					
Exit Angle(deg)					
Impact Point	4'-10" down from joint 5-6	11.6' up from joint 2	14.2' up from joint 2	5' up from joint 3	4.7' up fro joint 2
Vehicle Reaction	Smoothly redirected	Smoothly redirected	Smoothly redirected	Redirected	Redirecte
Vehicle Damage	Slight	Slight	Moderate	Severe	Severe on left side
Barrier Damage and Reaction	Scarring of barrier	Slight scraping	Slight scraping	Failure; 11 ft barrier section dislodged	Significant; concrete failed at jt. 1, 2, and 3
Connector Damage	None	None	None	NA	Failure; joints 1, 2, and 3
Soil Type and Condition	Concrete pad			Styrofoam pad on asphalt	Styrofoam pad on asphalt

Legend

* Specific dimensions of the connectors can be found in Appendix A. The numbers in parenthesis by the connector type in this table correspond to numbers listing the connectors in Appendix A.
ST&GW/SP - Straight tongue and groove with side plates
ST&G - Straight tongue and groove
SD Steel Dowel
FT&GW/SP&DD - Flaring tongue and groove with side plates and double dowels
BT-Lock-Bottom T-Lock
SP-Side Plate
CS - Channel splice
P&R - Pin and rebar

Table 9. Crash test summary (cont.)

Agency	New York State Department of Transportation (NYSDOT)					
Test No.	NY-44	NY-45	NY-46	NY-47	NY-17	NY-18
Date of Test	7/27/81	7/31/81	8/11/81 or(3)	8/25/81	9/7/78	9/19/78
Connector Type*	I-Beam(Ib)	I-Beam(Ib)	I-Beam(Ib)	I-Beam (Ib)	I-Beam (Ia)	I-Beam (Ia)
Install. Length(ft)	160	160	160	160	160	160
Segment Length(ft)	8	8	8	20	20	20
Profile Type	NJ	NJ	NJ	NJ	NJ	NJ
Max. Dynamic Defl.(ft)					1.33	0.92
Max. Perm. Defl.(ft)	1.4	0.23	0.56	0.3	1.33	0.92
Vehicle Model	70 Plymouth Fury	71 Chevy Vega	71 Chevy Impala	72 Chevy Vega	75 Plymouth Sedan	73 AMC Matador Station Wagon
Gross Veh. Wt.(lbs)	4300	2175	4350	2175	4250	4230
Nom. Impact Sp.(mph)	60	60	60	60		
Nom. Impact Ang.(deg)	25	15	25	15		
Actual Impact Sp.(mph)	64.9	65.5	61.1	61.4	52.0	54.0
Actual Impact Ang.(deg)	27.1	16.1	25.2	15.2	25.0	25.0
Exit Speed(mph)	30.8	55.4	45.3	53.2		
Exit Angle(deg)	10	5	8	5	5	15
Impact Point	2′ down from joint 7-8	2′ up from joint 7-8	1.5′ up from joint 7-8	3′ up from joint 7-8	Center of Fourth Section	Center of Fourth Section
Vehicle Reaction	Redirected then rollover	Redirected could have rolled over	Redirected	Smoothly redirected	Redirected	Violently redirected then rollover
Vehicle Damage	TAD-/RT-7 SAE-012DA09	TAD-RFQ-4 SAE-12RFEW5	TAD-RFQ-4 SAE-01RYAW6	TAD-RFQ-4 SAE-01RFEW5	TAD-RFQ-3 SAE-01RFEW5	TAD-R+T-7 SAE-01RDA09
Barrier Damage and Reaction	Spalling, cracked base Sec. 7 hairline cracks sec. 8,9	Cosmetic	Moderate, Scratches, gouges, hair-line cracks	Light Scratches	Moderate spalling	Light spalling
Connector Damage	None	None	None	None	None	None
Soil Type and Condition	Dry compacted granular	Dry compacted granular	Dry compacted granular	Dry compacted granular	Dry asphalt pavement	Dry asphalt pavement

Legend

* Specific dimensions of the connectors can be found in Appendix A.
The numbers in parenthesis by the connector type in this table correspond to numbers listing the connectors in Appendix A.
ST&GW/SP - Straight tongue and groove with side plates
ST&G - Straight tongue and groove
SD Steel Dowel
FT&GW/SP&DD - Flaring tongue and groove with side plates and double dowels
BT-Lock-Bottom T-Lock
SP-Side Plate
CS - Channel splice
P&R - Pin and rebar

Table 9. Crash test summary (con.)

Agency		Texas Transportation Institute (TTI)			
Test No.	Test 2	3025-5	3025-6	3025-7	3025-8
Date of Test		1/10/80	1/9/80	1/8/80	4/3/80
Connector Type*	SD(2)	FT&GW/SP(4)	FT&GW/SP(2)	FT&GW/SP(1)	FT&GW/CS&DD(1)
Install. Length(ft)	90	120	120	120	100
Segment Length(ft)	30	12	12	12	15
Profile Type	modified NJ	NJ	NJ	NJ	Mod. of NJ(6)
Max. Dynamic Defl.(ft)		1.6	2.0	2.3	-----
Max. Perm Defl.(ft)	1.1	1.6	1.8	1.8	1.8
Vehicle Model	65 Oldsmobile	74 Plymouth Fury	74 Plymouth Fury	74 Plymouth Fury	70 IH School Bus
Gross Veh. Wt.(lbs)	4540	4500	4500	4500	20,000
Nom. Impact Spd.	60				
Nom. Impact Ang.(deg)	25				
Actual Impact Spd.	60	60.7	60.1	59.2	57.7
Actual Impact Ang.(deg)	24	25	24	25	15
Exit Speed(mph)		NA	NA	---	NA
Exit Angle(deg)	3	NA	6	13	NA
Impact Point	7' up from Joint 1-2	Center, Sec. 4	5.9'down from jt. 3-4	5.8'down from jt. 3-4	1.2'down from jt. 4-5
Vehicle Reaction	Smoothly redirected	Rode top of system	Rode top of system	Rode top of system	Rollover
Vehicle Damage	TAD-FL-4-5 SAE-11FLEW2	TAD-11FL4 SAE-11FLME1	TAD-10L&T5 10FLEW2	TAD-10FL3 10FLEW2 10LDES1 SAE-00ULXW1	Slight SAE-101DES1
Barrier Damage and Reaction	Cracked both sides around joint, groove joint fractured	Minor, flexural cracking & spalling	Flexural cracking & spalling	Slight due to smooth defl. as a unit; minor crack. & spall	Flexural crack. on back, light spalling
Connector Damage	None	Spalling near tongue & groove conn.	Spalling at tongue & groove joints that had large rot	Tongue & groove damage minor crack & spall. at side plates	None
Soil Type & Condition		Dry level concr. surf.	Dry level concr. surf.	Level conc. surf.(PCC)	Level conc. surface

Legend

* Specific dimensions of the connectors can be found in Appendix A.
The numbers in parenthesis by the connector type in this table correspond to numbers listing the connectors in Appendix A.

ST&GW/SP - Straight tongue and groove with side plates
ST&G - Straight tongue and groove
SD Steel Dowel
FT&GW/SP&DD - Flaring tongue and groove with side plates and double dowels
BT-Lock-Bottom T-Lock
SP-Side Plate
CS - Channel splice
P&R - Pin and rebar

Table 9. Crash test summary (cont.)

Agency	Texas Transportation Institute (TTI)			
Test No.	3825-9	3825-10	3825-11	3825-12
Date of Test	7/17/80	1/11/84 (4)	1/11/84	1/17/84
Connector Type*	FT&GW/SP(3)	BT-LOCK(1)	BT-LOCK(1)	BT-LOCK(1)
Install. Length(ft)	120	120	120	120
Segment Length(ft)	12	12	12	12
Profile Type	NJ	NJ	NJ	NJ
Max. Dynamic Defl.(ft)	6.5	0.05	0.11	0
Max. Perm Defl.(ft)	6.5	0.02	0	0
Vehicle Model	76 Plymouth Fury	66 Ford Bronco	66 Ford Bronco	74 Datsun Pickup
Gross Veh. Wt.(lbs)	4510	3598	3598	2434
Nom. Impact Spd.		60	60	60
Nom. Impact Ang.(deg)		7	15	15
Actual Impact Spd.	63.4	60.6	60.7	61
Actual Impact Ang.(deg)	25	6.5	14.5	15
Exit Speed(mph)		52.6	52	54
Exit Angle(deg)	8	0	1.2	2
Impact Point	6.8' down from jt. 3-4	1' up from jt. 3-4	2' down from jt. 3-4	3' down from jt. 3-4
Vehicle Reaction	Violently redirected	Smoothly redirected	Smoothly redirected	Smoothly redirected
Vehicle Damage	TAD-01RFQ6 SAE-01FREW9	TAD-11LFQ1 SAE-11FLEN1	TAD-11LFQ3 11FLEX2 SAE-11LFES2	TAD-11LFQ3 11FLEK2 SAE-11LFES2
Barrier Damage and Reaction	Severe damage most at jt. 4-5	Minor cosmetic damage	Upper corners of jts. 3-4 & 4-5 broken	Minimal cracking at jts. 3-4 & 4-5
Connector Damage	Side plates broken at jts. 4-5, 5-6, 6-7	None	None	None
Soil Type & Condition	Dry level concr surf.			

Legend

* Specific dimensions of the connectors can be found in Appendix A. The numbers in parenthesis by the connector type in this table correspond to numbers listing the connectors in Appendix A.

ST&GW/SP - Straight tongue and groove with side plates
ST&G - Straight tongue and groove
SD Steel Dowel
FT&GW/SP&DD - Flaring tongue and groove with side plates and double dowels
BT-Lock-Bottom T-Lock
SP-Side Plate
CS - Channel splice
P&R - Pin and rebar

Table 9. Crash test summary (cont.)

Agency	Texas Transportation Institute (TTI)			
Test No.	3825-13	3825-14	3825-15	3825-16
Date of Test	1/13/84	1/13/84	1/26/84	1/24/84
Connector Type*	BT-lock(1)	BT-Lock(1)	BT-Lock(1)	BT-Lock(1)
Install. Lengt(ft)	120	120	120	120
Segment Length(ft)	12	12	12	12
Profile Type	NJ	NJ	NJ	NJ
Max. Dynamic Def.(ft)	0.11	0.12	0.63	0.14
Max. Perm Def.(ft)	0	0	0.08	0.03
Vehicle Model	77 Ford F250 P/U	77 Ford F250 P/U	74 Ford F250	72 Chevy 4WD P/U
Gross Veh. Wt.(lb)	4490	4490	4540	4760
Nom. Impact Sp.(mph)	60 mph	60	60	60
Nom. Impact Ang.(deg)	7 deg	15	22	15
Actual Impact Sp.(mph)	57.3 mph	58.1	60.2	59.7
Actual Impact Ang.(deg)	7 deg	15	22	15
Exit Speed(mph)	50.6 mph	46.8	NA	51.7
Exit Angle(deg)	4 deg	4	NA	0.5
Impact Point	2' down from jt. 3-4	4' down from jt. 3-4	3.5' down from jt. 3-4	3' down from jt. 3.4
Vehicle Reaction	Smoothly Redirected	Smoothly Redirected	Rollover	Smoothly Redirected
Vehicle Damage	TAD-11FLEN1 SAE-11FLEN1	TAD-11LFQ4 11FLEK1 SAE-11LFES3	TAD-11FQ5 11FLEK2 SAE-11LFES3	TAD-11LFQ3 11FLEK1 SAE-11LFES3
Barrier Damage and Reaction	Upper corners of jts. 3-4 & 4-5 cracked & broken	Upper corners of jts. 3-4 & 4-5 cracked & broken	Segment 4 tilted; breakage at jts. 3-4, 4-5, 5-6	Jts. 3-4, 4-5 chipped & broken
Connector Damage	None	None	Joints 3-4, 4-5, 5-6, exposed	None
Soil Type & Condition				

Legend

* Specific dimensions of the connectors can be found in Appendix A. The numbers in parenthesis by the connector type in this table correspond to numbers listing the connectors in Appendix A.

ST&GW/SP - Straight tongue and groove with side plates
ST&G - Straight tongue and groove
SD Steel Dowel
FT&GW/SP&DD - Flaring tongue and groove with side plates and double dowels
BT-Lock-Bottom T-Lock
SP-Side Plate
CS - Channel splice
P&R - Pin and rebar

Table 9. Crash test summary (cont.)

Agency	Texas Transportation Institute (TTI)			Barrier Systems Inc. (BSI)		
Test No.	3825-17	2262-1	2262-2	022686-1	022786-1	022886-1
Date of Test	2/24/84		8/22/82			
Connector Type*	(5) BT-Lock(1)	SP(2)	CS(1)	Hinge Plate(1)	Hinge Plate(1)	Hinge Plate(1)
Install. Lengt(ft)	120		180	200	200	200
Segment Length(ft)	12	15	15	3.1	3.1	3.1
Profile Type	NJ		NJ	F(7)	F(7)	F(7)
Max. Dynamic Def.(ft)	0		1.94			
Max. Perm Def.(ft)	0	0.9	1.33	0.35	0.10	0.44
Vehicle Model	73 Ford 2 1/2 Ton Trk.		74 Plymouth Fury	72 Plymouth Scamp-2 dr.	77 Honda Civic CVCC-2dr.	66 AMC Station Wagon
Gross Veh. Wt.(lb)	18,240	4500	4510	3200	1800	3180
Nom. Impact Sp.(mph)	60	60	60	45	45	
Nom. Impact Ang.(deg)	15	15	25	7	7	7
Actual Impact Sp.(mph)	60.1	60.9	56	45	47	52
Actual Impact Ang.(deg)	15	15	26	7	7	7
Exit Speed(mph)	NA		NA			
Exit Angle(deg)	NA		NA	2	2	1
Impact Point	1' down from jt. 3-4		Sec. 4			
Vehicle Reaction	Slide off end and Rollover	Smoothly Redirected	Smoothly Redirected	Smoothly Redirected	Smoothly Redirected	Smoothly Redirected
Vehicle Damage	Severe	Moderate	TAD-LFQ-5 SAE-10FLEQ3	Slight	Slight	Slight
Barrier Damage and Reaction	Jts. 3-4, 4-5, 5-6, 6-7, chipped & cracked	Superficial scarring	Surface scarring	Slight spalling at corners of several bases	No damage	No damage
Connector Damage	None	Major deformation in 3 splice plates	Light	None	None	None
Soil Type & Condition						

Legend

* Specific dimensions of the connectors can be found in Appendix A.
The numbers in parenthesis by the connector type in this table
correspond to numbers listing the connectors in Appendix A.
ST&GW/SP - Straight tongue and groove with side plates
ST&G - Straight tongue and groove
SD Steel Dowel
FT&GW/SP&DD - Flaring tongue and groove with side plates and double dowels
BT-Lock-Bottom T-Lock
SP-Side Plate
CS - Channel splice
P&R - Pin and rebar

Table 9. Crash test summary (cont.)

Agency	Barrier Systems Inc. (BSI)					
Test No.	022886-2	030386-1	030486-1	030686-1	030686-2	030686-3
Date of Test						
Connector Type*	Hinge Plate(1)	Hinge Plate(1)	Hinge(1)	Hinge(1) Plate	Hinge (1) Plate	Hinge(1) Plate
Install. Lengt(ft)	200	200	200	200	200	200
Segment Length(ft)	3.1	3.1	3.1	3.1	3.1	3.1
Profile Type	F(7)	F(7)	F(7)	F(7)	F(7)	F(7)
Max. Dynamic Def.(ft)						
Max. Perm Def.(ft)	1.28	0.94	1.88	1.33	2.60	2.48
Vehicle Model	69 Ford Ranch Wagon	77 Honda Civic CVCC-2dr	72 Plymouth Scamp-2dr	77 Honda Civic CVCC-2dr	74 Ford Gran Torino	70 Plymouth Fury
Gross Veh. Wt.(lb)	4240	1800	3200	1800	4320	3650
Nom. Impact Sp.(mph)		45	45		45	
Nom. Impact Ang.(deg)	7	15	15	15	15	15
Actual Impact Sp.(mph)	58	47	46	57	43	56
Actual Impact Ang.(deg)	7	15	15	15	15	15
Exit Speed(mph)						
Exit Angle(deg)	2	8	6	4	3	4
Impact Point						
Vehicle Reaction	Smoothly Redirected	Smoothly Redirected	Smoothly Redirected	Smoothly Redirected	Smoothly Redirected	Smoothly Redirected
Vehicle Damage	Moderate	Slight	Moderate	Moderate	Slight	Severe
Barrier Damage and Reaction	No damage	No damage	No damage	No damage	Horizontal, longitudinal crack in downstream half of Sec. 26 neck	Slight spalling one corner
Connector Damage	None	None	None	None	None	None
Soil Type & Condition						

Legend

* Specific dimensions of the connectors can be found in Appendix A.
The numbers in parenthesis by the connector type in this table correspond to numbers listing the connectors in Appendix A.

ST&GW/SP - Straight tongue and groove with side plates
ST&G - Straight tongue and groove
SD Steel Dowel
FT&GW/SP&DD - Flaring tongue and groove with side plates and double dowels
BT-Lock-Bottom T-Lock
SP-Side Plate
CS - Channel splice
P&R - Pin and rebar

Table 9. Crash test summary (cont.)

	Barrier Systems Inc. (BSI)			
Agency				
Test No.	031486-1	031986-1	032586-1	032686-1
Date				
Connector Type*	Hinge(1) Plate	Hinge(1) Plate	Hinge(1) Plate	Hinge(1) Plate
Install. Length(ft)	200	200	200	200
Segment Length(ft)	3.1	3.1	3.1	3.1
Profile Type	F(7)	F(7)	F(7)	F(7)
Max. Dynamic Defl.(ft)				
Max. Perm Defl.(ft)	4.11		3.125	5.06
Vehicle Model	61 Olds 88 Sedan	68 Cadillac Coupe Deville	71 Plymouth Fury	69 Chrysler Station Wagon
Gross Veh. Wt.(lbs)	4280	4850	4020	5100
Nom. Impact Sp.(mph)	60		45	
Nom. Impact Ang.(deg)	15	25	15	25
Actual Impact Sp.(mph)	60	50	44	57
Actual Impact Ang.(deg)	15	25	15	25
Exit Speed(mph)				
Exit Angle(deg)	10		0	15
Impact Point				
Vehicle Reaction	Smoothly Redirected	Smoothly Redirected	Smoothly Redirected	Smoothly Redirected
Vehicle Damage	Severe	Moderate	Moderate	Severe
Barrier Damage and Reaction	Slight corner spalling; Sec. 47, 1 ft crack	Moderate spalling near failed joint	No damage	Moderate spalling
Connector Damage	None	Failed at joint 27-28	None	3 pins Moderately bent, 1 pin severely bent
Soil Type & Condition				

Legend

* Specific dimensions of the connectors can be found in Appendix A. The numbers in parenthesis by the connector type in this table correspond to numbers listing the connectors in Appendix A.
ST&GW/SP - Straight tongue and groove with side plates
ST&G - Straight tongue and groove
SD Steel Dowel
FT&GW/SP&DD - Flaring tongue and groove with side plates and double dowels
BT-Lock-Bottom T-Lock
SP-Side Plate
CS - Channel splice
P&R - Pin and rebar

Table 9. Crash test summary (cont.)

Agency	California Department of Transportation (Caltrans)				ENSCO, Inc
Test No.	291	292	293	294	
Date	3/72	3/72	5/73	11/74	12/78
Connector Type*	P&R (3b)	P&R (3b)	P&R (3c)	P&R (3c)	FT&G(5)
Install. Length(ft)					108
Segment Length(ft)	12	12	20	20	12
Profile Type	N.J.	N.J.	N.J.		N.J.
Max. Dynamic Defl.(ft)		NA	NA		
Max. Perm Defl.(ft)	0.52	NA	NA	0.46	4-5
Vehicle Model	69 Dodge Polara	69 Dodge Polara	69 Dodge Polara	1968	72 Ford 4 dr.
Gross Veh. Wt.(lbs)	4860	4860	4860	4509	4240
Nom. Impact Sp.(mph)	65		65		60
Nom. Impact Ang.(deg)	7			25	25
Actual Impact Sp.(mph)	64	68	66	39	58
Actual Impact Ang.(deg)	7	23	40	25	25
Exit Speed(mph)			NA		
Exit Angle(deg)	18		NA		8
Impact Point					segments
Vehicle Reaction	Redirected	Airborne and Penetrated	Airborne rollover	Redirected, but airborne for 16 ft	Redirected
Vehicle Damage					
Barrier Damage and Reaction	Cosmetic Scarring, slight spalling	Failure one section cracked in half	Failure one seg. knocked over	slight spalling	one segment rolled over
Connector Damage	None	pins pulled out	Connections bent	Pins bent severely	
Soil Type & Condition					

Legend

* Specific dimensions of the connectors can be found in Appendix A. The numbers in parenthesis by the connector type in this table correspond to numbers listing the connectors in Appendix A.

ST&GW/SP - Straight tongue and groove with side plates
ST&G - Straight tongue and groove
SD Steel Dowel
FT&GW/SP&DD - Flaring tongue and groove with side plates and double dowels
BT-Lock-Bottom T-Lock
SP-Side Plate
CS - Channel splice
P&R - Pin and rebar

2. Test CMB-8

The connector used in test CMB-8 was the New Jersey Welsbach (1). Barrier segment length was 30 ft, and the total system length was 180 ft. In this test a 2,250-lb vehicle impacted the barrier 11.6 ft upstream from joint 2 at an actual speed of 55.9 mi/h and an actual impact angle of 8.0 degrees. The vehicle was smoothly redirected with a maximum roll angle of 20 degrees. A second impact occurred after the vehicle lost initial barrier contact.

Damage to the installation was minimal; some scraping of the concrete surface resulted from rim contact with the barrier. No translation of the barrier occurred. The vehicle's left front tire lost pressure and some rim damage was noted, otherwise, the vehicle was undamaged, and no evidence of sheet metal/barrier contact was noted.

3. Test CMB-9

The connector used in test CMB-9 was the New Jersey Welsbach (1). The vehicle used in this test was the same as that used in test CMB-1. A new tire and rim replaced the damage left front wheel. In this test a 2,250-lb-vehicle impacted the barrier 14.2 ft upstream from joint 2 at an actual speed of 58.9 mi/h and an actual impact angle of 15.5 degrees. The vehicle was smoothly redirected with a maximum roll angle of 20 degrees.

Some scraping of the concrete surface occurred, but no translation of the barrier was noted. The vehicle damage was limited to the front and left quadrant. The left front tire remained inflated and moderate front end damage was noted in driving the vehicle after the test.

4. Test CMB-18

The connector used in test CMB-18 was the straight tongue and groove with side plates (4). Barrier segment length was 20 ft, and the total system length was 100 ft. The barriers were placed on styrofoam pads for the purpose of establishing a mechanical interlock with the asphalt surface to maximize sliding resistance. Such a concept has been employed in Oregon for several years. In this test a 4,500-lb vehicle impacted the barrier 5 ft upstream from joint 3 at an actual speed of 62 mi/h and an actual impact angle of 25 degrees. The barrier failed when a crack 5 1/2 ft upstream of joint 3 was detected at 0.07 second after impact. A second crack 5 1/2 ft downstream of joint 3 was detected at 0.1 second after impact. Although the barrier sustained structural failure, the vehicle was redirected. Considerable vehicle damage occurred when the vehicle's underside contacted the downstream exposed end of the barrier at the failure location.

An 11-ft-long barrier segment was dislodged from the barrier system. These flexual failures occurred at the stress concentration point created by the 12-in by 12-in-lifting voids cast in the barriers. It could not be readily determined if failure of the joint precipitated the barrier failure; however, the diagonal cracking of the female joint on the impact side of barrier element four (between joints 3 and 4) could have initiated the failure. The area of the joint was obscured from camera coverage by the overhang of the impacting vehicle. Concrete strength of test cylinders for the two failed barrier segments was 3995 psi and 4220 psi; concrete testing was accomplished one day before crash testing.

5. Test CMB-24

The connector used in test CMB-24 was the straight tongue and groove with side plates (2). Barrier segment length was 20 ft, and the total system length was 100 ft. Each barrier segment was placed on styrofoam pads on grade. The original 3/4-in-thick pads were crushed approximately 50 percent by the weight of the barrier. The purpose of the pads was to establish a mechanical interlock with the asphalt surface to maximize sliding resistance.

In this test a 4,500 lb vehicle impacted the barrier 4.7 ft upstream from joint 2 at an actual speed of 56.4 mi/h and an actual impact angle of 24.1 degrees. The barrier segments remained attached by the steel plates although failure occurred at joints 1, 2, and 3. The vehicle was redirected with a maximum roll angle of 26 degrees away from the barrier. Redirection of the vehicle occurred with a total barrier contact of 44.5 ft.

Installation damage consisted of severe damage to joints 1, 2, and 3. The concrete at the base of these three joints failed around the connecting steel plates. Diagonal cracking of the female joint on the impact side of segment 2 at joint 2 and the back side of segment 4 at joint 3 also occurred. No cracking of the concrete along any other segments was noted. Lateral translation of the barrier measured a maximum of 41 in at joint 2.

Vehicle damage was considerable. Major damage was sustained by the left front quadrant of the vehicle. Extensive frame damage resulted. The left front wheel was deflated and the rim deformed.

B. New York State Department of Transportation

1. Test NY-17

The connector used in test NY-17 was I-beam (1a). Barrier segment length was 20 ft, and the total system length was 160 ft. The barrier system was placed on a dry asphalt pavement. In this test, a 4250 lb, 1975 plymouth sedan impacted the barrier at the center of the fourth segment, at 52.8 mi/h and 25 degrees. On impact, the vehicle climbed to the top of the barrier, and within 15 ft was redirected parallel to the barrier. Upon initial redirection, while the right side tires were up on the barrier, the left side was airborne. When the vehicle left the barrier, the front end pitched forward, dragging on the pavement, while the rear was still airborne for some time. The vehicle remained in contact with the barrier for 34 ft, leaving it just beyond the joint between the fifth and sixth segments. Because its right front suspension was severly damaged and the tire flattened, the vehicle turned back into the barrier, again striking the bottom 3 in high vertical barrier face about 6 ft into the seventh segment. The bumper rode about halfway up the slope barrier face, and the vehicles right side was in contact with the barrier for the entire length of the eighth segment. The vehicle came to rest about 40 ft beyond and perpendicular to the barrier.

The vehicle sustained heavy damage to the front end sheet metal, right front suspension, and along the entire right side. Barrier damage was minor and maximum deflection was 1.33 ft. The third, fourth, and fifth segments were displaced laterally, but there was no barrier overturn. Segment 4, where impact occurred, sustained three vertical hairline cracks on the backside. Corners on the barrier base were spalled slightly at joints 2, 3, and 6 on the front, moderately at joint 4 on the front, and extensively on the back at joints 2 and 5.

2. Test NY-18

The connector used in test NY-18 was I-beam (1a). Barrier segment length was 20 ft, and the total system length was 160 ft. The barrier system was placed on a dry asphalt pavement. The first barrier segment was pinned to the ground, joints were pulled tight, and each joint was packed with a stiff portland cement mortar to a height of 6 in, about 6 in into the joint. In this test, a 4230-lb, 1973 AMC Matador station wagon impacted the barrier at the center of the fourth segment, at 54.8 mi/h and 25 degrees. On impact, the right side tires quickly climbed to the barrier top, and on redirection, both tires were well above its top. At 26 ft after impact, the vehicle had rolled 36 degrees to the left and was airborne with the left side about 8 in off the ground, and the right side about 5 ft off the ground. The vehicle's rear yawed right so that the right rear wheel was about 3 ft above and 2 ft behind the barrier. The vehicle recontacted the barrier 63 ft downstream of impact with the right rear wheel on top of the barrier, the right front and left rear wheels on the barrier face, and the left front wheel and bumper dug into the pavement. When it returned to the pavement 71 ft after impact, the rear of the vehicle yawed sharply right and it rolled over, coming to rest on its wheels about 60 ft beyond and perpendicular to the barrier.

The vehicle suffered extensive damage during both impact and rollover. There was heavy damage to all of the front end and right side sheet metal and to all right side wheels and suspension parts. Also, the frame was bent and the windshield broken. The rollover popped out the windshield, dented the roof, and crushed the engine compartment.

The barrier moved laterally a maximum of 0.92 ft at the downstream end of the impacted (fourth) segment, with less movement of the second, third, and fifth segments. Again, there was no barrier overturn. The only significant barrier damage was confined to some base corner spalling and some cracks in the impacted section ranging from hairline fractures to 1/8 in wide. Joint spalling in this test was noticeably less than in the previous test because the mortar helped transfer impact forces across the joints more uniformly.

3. Test NY-44

The connector used in NY-44 test was I-beam (Ib). Barrier segment length was 8 ft, and the total system length was 160 ft. The barrier system was placed on a dry compacted granular surface. In this test, a 4300-lb vehicle impacted the barrier 58.0 ft from the beginning at an actual speed of 64.9 mi/h and an actual angle of 27.1 degrees. On impact the vehicle's right side immediately climbed to the barrier top, the hood opened and the vehicle pitched up 8 degrees while deflecting the barrier about 17 in. The vehicle was redirected, but because it was at a high roll angle of 54 degrees left and had its underside against the barrier, redirection was not smooth. It contacted the barrier a number of times, and the right rear tire caught behind the barrier top when its right side came down. The left front tire initially directed the vehicle's front away from the barrier with a 10 degree left exit angle, but when the damaged right front tire recontacted the ground, the front end pitched down to a maximum of 23 degrees and increased its deceleration. The rear end lifted and rolled right 180 degrees and yawed 90 degrees left about its front end, coming to rest on its roof.

Vehicle damage was severe. The roof and hood were dented, front suspension was heavily damaged, there was frame damage, the right side sustained sheet metal damage, and both right tires had blown out. Roof crush was probably exaggerated because the target concentrated the impact in the center of the roof. Barrier damage was moderate, consisting mostly of scratches and spalled areas. Segment 7 had a cracked base and segments 8 and 9 had hairline cracks in the back side surfaces.

4. Test NY-45

The connector used in test NY-45 was I-beam (Ib). Barrier segment length was 8 ft, and the total system length was 160 ft. The barrier system was placed on a dry compacted granular surface. In this test, a 2,175-lb vehicle impacted the barrier 54.0 ft from the beginning at 65.5 mi/h and 16.1 degrees. The vehicle's right side immediately climbed the barrier top and pitched up 2 degrees while deflecting the barrier 2.75 in. The right front tire blew out and the steering and suspension were damaged on impact. It was redirected with an exit angle of 5 degrees left and maximum pitch down of 8 degrees, with a maximum roll left of 64 degrees. It appears that the vehicle would have rolled over had the 1-in-square data cable bar mounted on the rear not contacted the ground and acted as a counterforce to its roll. After leaving the barrier, the vehicle's full weight came down on its left side, its right side recontacted the ground, and the damaged front end caused it to swerve to the left, where it was stopped by a cable and safety fence.

Vehicle damage was moderate, consisting of steering and front suspension damage, a blown right front tire, sheet metal damage to the front end and right side, and cracking of the right hand edge of the windshield. Barrier damage was only cosmetic with scratches and tire marks.

5. Test NY-46

The connector used in test NY-46 was I-beam (1b) with grouted joints. Barrier segment length was 8 ft, and the total system length was 160 ft. The barrier system was placed on a dry compacted granular surface. In this test, a 4,350-lb vehicle (sedan) impacted the barrier at 54.5 ft from the beginning at 61.1 mi/h and 25.2 degrees. Upon impact, the vehicle's right side climbed to the barrier top and pitched up 5 degrees while deflecting the barrier 6.75 in. The vehicle was redirected with an exit angle of 8 degrees left and a maximum roll of 42 degrees left. The right rear tire caught behind the barrier as the vehicle lost roll angle, causing its weight to be shifted to the left front tire with a maximum pitch down of 10 degrees and yawing to the left. Its rear end remained on the barrier while yaw increased and the roll changed to the right, bringing the damaged right front tire and suspension down to the ground, further decelerating the vehicle, and causing an increase in yaw. Its rear end reached the end of the barrier installation and came off the barrier, and then bounced on the ground and continued to yaw until it was stopped by the cable and safety fence at a maximum yaw of 270 degrees left.

Vehicle damage was severe, with front and rear suspension particularly affected. Both right tires were blown, there was front sheet metal and bumper damage, and the windshield was cracked. Barrier damage was moderate with scratches, gouges, hairline cracks, and broken corners.

6. Test NY-47

The connector used in test NY-47 was an I-beam (1b). Barrier segment length was 20 ft, and the total system length was 160 ft. The barrier system was placed on a dry compacted granular surface. In this test, a 2,175-lb vehicle (the same that was used in test NY-45) impacted the barrier 53.0 ft from the beginning at 61.4 mi/h and at 15.2 degrees. On impact, the vehicle climbed half way up the barrier, and pitched up less than 3 degrees. Maximum roll was 11 degrees right, and the vehicle was redirected quite smoothly. A maximum pitch of 3 degrees down preceded its losing contact with the barrier. It left the barrier 82 ft from the beginning with an exit angle of 5 degrees left. No yaw was observed and it continued its exit until stopped by safety cables.

Vehicle damage was moderate, mostly involving sheet metal and the front suspension and steering. Except for scratches and tire marks, the barrier was not damaged. Maximum barrier deflection was 3 1/2 in.

C. Texas Transportation Institute (TTI)

1. Test 3825-5

The connector used in test 3825-5 was the flaring tongue and groove with side plates (4). Barrier segment length was 12 ft, and the total system length was 120 ft. The system was placed on a dry level concrete surface. In this test, a vehicle weighing 4,500 lb (including telemetry equipment) impacted the barrier at an actual speed of 60.7 mi/h and an actual angle of 25 degrees.

The vehicle impacted the barrier initially at the center of segment 4. The force of the impact disengaged the hood, causing it to fly up and become folded back against the windshield. The left front wheel contacted the barrier 1.2 ft downstream from impact and began to ramp, causing the vehicle to roll and yaw to the right and the barrier to deflect. By 0.331 second the left front wheel was up and over the barrier with the vehicle continuing to roll and yaw. As this yaw continued, the left rear tire swung into the barrier 4.8 ft downstream from joint 3-4 and also cleared the barrier. The motion of the vehicle became parallel to barrier by 0.264 second as the vehicle skidded along the top of the barrier and continued to yaw to the right. The vehicle exited when it slid off the end of the barrier and skidded sideways to a stop 253.0 ft downstream from the initial impact point. During the test the vehicle penetrated a maximum of 4.6 ft into the construction zone as measured from the initial center line of the barrier. This occurred when the rear of the vehicle went over the top of the barrier. The maximum dynamic deflection of the barrier was 1.6 ft, as was the maximum permanent deflection, both occuring at joint 4-5.

Minor damage occurred due to flexural cracking and concrete spalling at the base of the joints near the impact area. Major spalling occurred at some of the joints due to the tongue and groove connector undergoing large deflections.

2. Test 3825-6

The connector used in test 3825-6 was the flaring tongue and groove with side plates (2). Barrier segment length was 12 ft, and the total system length was 120 ft. The system was placed on a dry level concrete surface. In this test, a vehicle (the same that was used in test 3825-5) weighing 4500 lb (the same that was used in test 3825-5) impacted the barrier at an actual speed of 60.1 mi/h and an actual angle of 24 degrees.

The vehicle impacted the barrier initially 5.9 ft downstream from joint 3-4 on segment 4. The force of the impact buckled the hood and crushed the left front fender back to the wheel. The left front wheel ramped on the barrier, and by 0.225 second was over the top of the barrier. During this time, the barrier was deflecting laterally and rotating while the vehicle began to yaw to the right and redirect. As this yaw continued, the rear of the vehicle swung into the barrier 5.7 ft downstream from joint 3-4 and also moved over the top of the barrier. The motion of the vehicle became parallel to the barrier 0.243 second after impact as the vehicle settled on the barrier, with both the left front and rear wheels over the barrier, and skidded along the top. The vehicle exited when it slid off the end of the system at approximately 6 degrees to the barrier and continued to yaw to the right. After sliding off, the vehicle then rolled one and a half times, eventually ending upside down 178.0 ft downstream from the initial impact point.

The testing agency felt that although the vehicle did roll after losing contact with the barrier, that this test alone should not be used to disqualify this connector, since several factors contributed to the vehicle rollover. (12)

During the test, the vehicle penetrated a maximum of 2.9 ft into the simulated construction zone. The maximum dynamic deflection of the barrier system was 2.0 ft, occurring 12.3 ft downstream from the impact at joint 4-5. The maximum permanent deflection was 1.8 ft, also at joint 4-5.

Minor damage to the barrier occurred due to flexural cracking and concrete spalling near the base of the joints in the vicinity of the impact point. Most damage occurred at the joints that underwent the largest rotation due to the tongue and groove connector interaction.

3. Test 3825-7

The connector used in test 3825-7 was the flaring tongue and groove with side plates (1). Barrier segment length was 12 ft, and the total system length was 120 ft. The system was placed on a level concrete surface. In this test, a 4,500-lb vehicle (the same that was used in test 3825-5 and 3825-6) impacted the barrier at an actual speed of 59.2 mi/h and an actual angle of 25 degrees.

The vehicle first contacted the barrier at a distance 5.8 ft downstream from joint 3-4 on segment 4. The force of the impact caused the hood to disengage and open, and eventually to fold back against the windshield. The left front tire rode up the barrier, and by 0.172 second was over the top of the barrier. During this time, the vehicle was yawing to the right and eventually became parallel to the barrier system at 0.24 seconds. As this yaw continued, the rear of the vehicle swung into the barrier 8.3 ft downstream from joint 3-4, causing the left rear tire to be sheared off and the entire car to undergo moderate counterclockwise roll. The loose tire continued on a course behind the barrier roughly parallel to it and penetrating 5.4 ft into the construction zone while the vehicle settled and skidded along the top of the barrier and continued to yaw to the right. The vehicle exited at approximately 13 degrees to the barrier system. The maximum dynamic deflection of the barrier system was 2.3 ft, occurring 11.9 ft downstream from the impact point at joint 4-5, while the maximum permanent deflection remaining in the barrier was 1.8 ft at joint 4-5. However, the vehicle penetrated a maximum of 5.6 ft into the construction zone when the rear of the vehicle went over the top of the barrier.

Damage to the barrier was slight due to the smooth deflection of the barrier segment acting as a unit. The major portion of the damage that occurred was due to the tongue and groove interaction at the joints. Minor cracking and spalling occurred near the initial impact point at the base of the joints where the side plates were bolted. The side plates were all intact, and no tensile yielding was apparent.

4. Test 3825-8

The connector used in test 3825-8 was the flaring tongue and groove with channel splice and double dowels (1). Barrier segment length was 15 ft, and the total system length was 180 ft. The barrier system was placed on a level concrete surface.

In this test, a school bus weighing 20,000 lb, including telemetry equipment, anthropomorphic dummies, and sandbags, impacted the barrier at an actual speed of 57.7 mi/h and an actual angle 15 degrees.

Impact occurred 1.2 ft downstream of joint 4-5 on segment 5. The right front wheel impacted initially, and the right fender rode up onto the barrier. The vehicle began to roll while its rear impacted the barrier. The vehicle continued to roll as it slid off the barrier and came to a rest on its side 168.0 ft beyond the downstream end of the test installation.

The maximum permanent deflection of the barrier was 1.8 ft and occurred in segment 5 adjacent to joint 5-6. Damage to the barrier consisted primarily of flexural cracking on the back bases. Some spalling occurred on the top end of segment 5 adjacent to segment 6. A crack from the top of the dowel in segment 4 (joint 4-5) also formed.

The testing agency believes that this test illustrates the structural capacity of portable concrete barriers to redirect vehicles as large as school buses. The reaction of the bus was not ideal, but this relates to the geometry of the barrier rather than to structural capacity. Modification of barrier geometry will improve the reaction of large vehicles during redirection. (12)

5. Test 3825-9

The connector used in test 3825-9 was the flaring tongue and groove with side plates (3). In addition, a block out W-beam rail was installed on the simulated traffic face of the barrier system. Barrier segment length was 12 ft, and the total system length was 120 ft. The barrier system was placed on a dry level concrete surface. In this test 4510-lb-vehicle impacted the barrier at an actual speed of 63.4 mi/h and an actual angle of 25 degrees.

The vehicle impacted the barrier 6.8 ft downstream from joint 3-4 on barrier segment 4. The force of the impact crushed the right front fender back to the wheel and caused the hood to begin to fly up. Due to the W-beam segment rail blockout attached to the barrier system, there was no tendency for the vehicle to ramp on to the barrier. As the vehicle yawed and redirected, its motion became parallel to the rail 0.247 seconds after impact. The vehicle exited the barrier system at approximately 8 degrees. Due to severe damage to the right part of the vehicle, it skidded and yawed 180 degrees, ending up 138.0 ft downstream from the initial impact point. The maximum vehicle penetration into this simulated construction zone was 2.0 ft. The maximum dynamic deflection of the barrier was 6.5 ft.

Damage to the barrier segments was significant, with the most severe damage occurring at joint 4-5. This was due to the large deflection causing large rotation of the tongue and groove joints. The 1/8-in-base plates were broken at joints 4-5, 5-6, and 6-7.

The testing agency believes that this test illustrates the inadequacy of the 1/8 in base plates due the large deflections and failure of several joints. The concept of mounting the W-beam on the CMB segment was shown to be quite effective in preventing the vehicle from ramping onto the CMB segments. (12)

6. Test 3825-10

The connector used in test 3825-10 was the bottom T-lock (1). Barrier segment length was 12 ft, and the total system length was 120 ft. In this test, a 3,598-lb vehicle impacted the barrier at an actual speed of 60.6 mi/h and an actual angle of 6.5 degrees. The vehicle was free-wheeling and unrestrained at impact.

The vehicle impacted the barrier 1.0 ft upstream of the joint between segments 3 and 4. The tire path moved up the side of the barrier, reaching a maximum height of 2.1 ft, approximately 12.0 ft from impact. Total length of contact was approximately 24.0 ft. The vehicle was redirected and exited the barrier at 0.305 second with exit angle of 0 degrees. Subsequently, the vehicle impacted the barrier again at 0.727 second, rode off the end of the barrier, and spun around. The vehicle sustained slight damage to the left front quarter. The left end of the bumper was bent back slightly.

The barrier received minor cosmetic damage to segments 3 and 4. There were also tire marks on segments 9 and 10 where the vehicle impacted the barrier a second time. The top of the barrier moved 0.05 ft during the test but was permanently displaced only 0.02 ft.

7. Test 3825-11

The connector used in test 3825-11 was the bottom T-lock (1). Barrier segment length was 12 ft, and the total system length was 120 ft. In this test, a 3,598-lb vehicle (the same as that was used in test 3825-10) impacted the barrier at an actual speed of 60.7 mi/h and an actual angle of 14.5 degrees. The vehicle was free-wheeling and unrestrained at impact.

The vehicle impacted the barrier approximately 2 ft downstream of the joint between segments 3 and 4. The top of the path reached the top of the barrier approximately 2.0 ft downstream of the impact point. Tire marks extended to the upper edge of the barrier for a distance of about 7.0 ft and the bottom of the tire marks formed a curved path. Total length of contact was approximately 13.8 ft. The vehicle was redirected and exited the barrier at 0.286 second with an exit angle of 1.2 degrees. The speed of the vehicle at loss of contact was 52.0 mi/h.

The barrier received damage to segment 4. The upper corners of joints 3-4 and 4-5 were cracked and broken. The top of the barrier moved 0.11 ft during the test but returned to its original position afterwards. The vehicle sustained minimal damage to its left front quarter. Its left front tire was deflated and the rim was bent. The left corner of the rear bumper was also pulled back. The barrier redirected the vehicle, and detached elements did not penetrate the occupant compartment. The vehicle remained upright during and after impact. Exit angle was 1.2 degrees and vehicle change in speed at loss of contact was 8.7 mi/h.

8. Test 3825-12

The connector used in test 3825-12 was the bottom T-lock (1). Barrier segment length was 12 ft, and the total system length was 120 ft. In this test, a 2434-lb vehicle impacted the barrier at an actual speed of 51 mi/h and an actual angle of 15 degrees. The vehicle was freewheeling and unrestrained at impact.

The vehicle impacted the barrier approximately 3 ft downstream from the joint between segments 3 and 4. The tire path on the face reached the top of the barrier approximately 0.5 ft downstream of the impact point. Tire marks extended to the upper edge of the barrier a distance of about 7.5 ft before fading out. Total length of contact was approximately 10.5 ft. The vehicle was redirected and exited the barrier at 0.284 second with an exit angle of 2.0 degrees. The speed of the vehicle at loss of contact was 54 mi/h.

The barrier received damage to segments 3 and 4 with minimal cracking at joints 3-4 and 4-5. The barrier showed no measurable movement during the test. The vehicle sustained minimal damage to its left front quarter. Its left front tire was deflated, and the rim was slightly bent.

9. Test 3825-13

The connector used in this test was 3825-13 the bottom T-lock (1). Barrier segment length was 12 ft, and the total system length was 120 ft. In this test, a 4490-lb vehicle impacted the barrier at an actual speed of 57.3 mi/h and an actual angle of 6.5 degrees. The vehicle was freewheeling and unrestrained at impact.

The vehicle impacted the barrier approximately 2 ft downstream of the joint between segments 3 and 4. The tire path on the barrier face reached a maximum height of 2.2 ft at 11.6 ft downstream of the impact point. Total length of contact was 16.8 ft. The vehicle was redirected and exited the barrier at 0.363 second with an exit angle of 4.0 degrees. The speed of the vehicle at loss of contact was 50.6 mi/h.

The barrier received damage to segments 3 through 5. The upper corners of joints 3-4 and 4-5 were cracked and broken. The top of the barrier moved 0.11 ft during the test but returned to its original position afterwards. The vehicle sustained minimal damage to its left front quarter. The left front corner of the bumper was pushed back.

10. Test 3825-14

The connector used in this test 3825-14 was the bottom T-lock (1). Barrier segment length was 12 ft, and the total system length was 120 ft. In this test, a 4490 lb vehicle (the same that was used in test 3825-13) impacted the barrier at an actual speed of 58.1 mi/h and an actual angle of 5 degrees. The vehicle was freewheeling and unrestrained at impact.

The vehicle impacted the barrier approximately 4 ft downstream of the joint between segments 3 and 4. The vehicle's tire path on the barrier face reached the top of the barrier 6.5 ft downstream of the impact point. Tire marks extended to or near the upper edge of the barrier for a distance of about 6.0 ft. Total length of contact was 17 ft. The vehicle was redirected and exited the barrier at 0.418 second with an exit angle of 4.0 degrees. The speed of the vehicle at loss of contact was 46.8 mi/h.

The barrier received damage to segments 3 through 5. The upper corners of joints 3-4 and 4-5 were cracked and broken. The top of the barrier moved 0.12 ft during the test but returned to its original position afterwards. The vehicle sustained damage to its left side. Its left front and left rear tires were deflated and the rims were bent.

11. Test 3825-15

The connector used in 3825-15 test was the bottom T-lock (1). Barrier segment length was 12 ft, and the total system length was 120 ft. In this test, a 4540 lb vehicle impacted the barrier at an actual speed of 60.2 mi/h and an actual angle of 21.5 degrees. The vehicle was freewheeling and unrestrained at impact.

The vehicle impacted the barrier 3.5 ft downstream of the joint between segments 3 and 4. The vehicle rode up the face of the barrier and started rolling away from the barrier. The vehicle left the barrier at about 0.370 second after impact and had rolled approximately 30 degrees. As the vehicle left the barrier it continued to roll and subsequently touched ground on its right side and slid approximately 150 ft.

The vehicle's tire path on the barrier face reached the top of the barrier 3 ft downstream of the impact point. Tire marks extended to the upper edge of the barrier for a distance of over 12.0 ft. Total length of contact was 16 ft.

Segment 4 had tilted back during impact, causing the concrete at the joints on each end to break off, exposing the channel in the T-lock. The segment came to rest on some of these pieces of concrete, elevating it approximately 2 in. The T-lock was also exposed at joint 5-6. The top of the barrier (segment 4) moved 0.63 ft during impact and retained a permanent deflection of 0.08 ft. The vehicle sustained damage to the undercarriage. The left I-beam (axle) was bent back, the left strut attachment bracket was sheared from the frame, and both main frame rails were bent. The left front tire was deflated and the rim was bent.

12. 3825-16

The connector used in test 3825-16 was the bottom T-lock (1). Barrier segment length was 12 ft, and the total system length was 120 ft. In this test, a 4,760 lb vehicle impacted the barrier at an actual speed of 59.7 mi/h and an actual angle of 14.5 degrees. The vehicle was freewheeling and unrestrained at impact.

The vehicle impacted the barrier 3 ft downstream of the joint between segments 3 and 4. The vehicle's tire path on the barrier face reached the top of the barrier 2 ft downstream of the impact point. Tire marks extended to the upper edge of the barrier for a distance of over 14.0 ft and the bottom of the tire marks formed a curved path. Total length of contact was 18 ft. The vehicle was redirected and exited the barrier at 0.40 second with an exit angle of 0.5 degrees toward the barrier. The speed of the vehicle at loss of contact was 51.7 mi/h.

The barrier received damage to segment 4. Joints 3-4 and 4-5 were chipped and broken. The top of the barrier moved 0.14 ft during the test and retained a permanent set of 0.03 ft. The vehicle sustained damage to its left front quarter. Its left front tire was deflated and the rim was bent. The front axle and wheel assembly also were damaged.

13. Test 3825-17

The connector used in test 3825-17 was the bottom T-lock (1). A steel backup structure was added to the rear side of the barrier to prevent significant deflection of the barrier when impacted by the heavy vehicle. Barrier segment length was 12 ft, and the total system length was 120 ft. In this test, a vehicle weighing 18,240 lb impacted the barrier at an actual speed of 60.1 mi/h and an actual angle of 15 degrees. The vehicle was freewheeling and unrestrained at impact.

The vehicle impacted the barrier 1 ft downstream of the joint between segments 3 and 4. The vehicle's tire path on the barrier face reached the top of the barrier approximately 5.0 ft downstream of the impact point. Tire marks extended to the upper edge of the barrier for a distance of over 6 ft. Marks were also made on the rear of the barrier. Total length of contact was approximately 86 ft. The vehicle was redirected, but it rolled onto the barrier and slid off the end at about 1.224 seconds. Maximum roll was approximately 94 degrees. The speed of the vehicle at 1.000 second (end of data processing) was 54.1 mi/h.

The barrier received damage extending from the downstream end of segment 3 to the downstream end of the barrier (approximately 86 ft). Joints 3-4, 4-5, 5-6, and 6-7 were chipped and cracked. The top rear of segment 6 and the steel framework were scraped. Vehicle tire marks started on the top rear of segment 7, moved along the rear of segment 8, and ended up near the ground 1.8 ft upstream of joint 9-10. The rear of segment 10 was scraped. The barrier showed no measurable sign of movement.

The vehicle was severely damaged. The U-bolts attaching the axle to the frame were broken and the frame was bent. The motor mounts, springs, and shackles were severely damaged.

14. Test 2262-1

The connector used in test 2262-1 was the side plate (2). Barrier segment length was 15 ft, and the total system length was 180 ft. In this test a 4,500 lb vehicle impacted the barrier at an actual speed of 60.9 mi/h and an actual angle of 15 degrees. The vehicle was smoothly redirected and was not severely damaged. The vehicle's projectory after impact would not have been a hazard to other traffic.

The barrier was displaced only 0.9 ft and was not damaged significantly. Damage to the barrier installation was limited to superficial scarring of the concrete surface and measured deformations in three splice plates. However, there was significant differential horizontal movement between barriers. At large impact angles, this differential movement can prove to be a snag point for impacting vehicles. The testing agency considered this test very successful since the test vehicle was safely redirected and both barrier and vehicle were lightly damaged. (12)

15. Test 2262-2

The connector used in test 2262-2 was a channel splice (1). Barrier segment length was 15 ft, and the total system length was 180 ft. In this test a 4500-lb vehicle impacted the barrier at an actual speed of 56 mi/h and at an actual angle of 26 degrees. The test vehicle which was redirected smoothly, and was not badly damaged for a test of this severity.

The maximum deflection of the barrier was only 1.33 ft. Damage to concrete barrier segments was again limited to surface scarring. The channel splices were lightly damaged, and only six channels required replacement. There was no differential motion between barrier ends. The testing agency considered this test very successful due to the safe redirection of the test vehicle and limited damage to the barrier. (12)

D. Barrier Systems Incorporated (BSI)

1. Test 022686-1

The connector used in test 022686-1 was the hinge plate (1). Barrier segment length was 3.1 ft, and the total system length was 200 ft. In this test, a 3200-lb vehicle impacted the barrier at an actual speed of 45 mi/h and an actual angle of 7 degrees. The car was smoothly redirected. The only roll during the collision was the gradual lean away from the barrier as the vehicle's left front and rear tires climbed up the lower sloping face of the barrier. Tire scuff marks indicate that the maximum vertical rise of the left tires was approximately 8 in. The right tires maintained contact with the pavement.

There was longitudinal movement in the barrier in hinges 32 through 37, and was due to longitudinal slip in the hinges. The unanchored end of the barrier did not move in any direction. There was no physical damage to the barrier other than the very slight spalling at the corner of the base of several concrete segments. Other than bending of the left end of the front bumper and moderate bending of the left front fender, the vehicle was undamaged and was used again in a later crash.

2. Test 022786-1

The connector used in test 022786-1 was the hinge plate (1). Barrier segment length was 3.1 ft, and the total system length was 200 ft. In this test, an 1800-lb vehicle impacted the barrier at an actual speed of 47 mi/h and an actual angle of 7 degrees. The vehicle was smoothly redirected. The only rolls of the vehicle during the collision were its lean away from the barrier as the left front and rear tires rode up the lower sloping face of the barrier and its lesser reverse roll when its rebounded and the left wheels landed back on the pavement. Tire scuff marks on the face of the barrier indicated that the vertical rise of the left tires was approximately 9 in. The right tires maintained contact with the pavement throughout the event.

There was no longitudinal movement in the barrier at either any of the hinges or the unanchored end. There was no physical damage or distress to the concrete segments, to the steel hinge pins, or to the welded plate hinges. Other than minor scuff marks and scratches on the left corner of the front bumper and several light scratches on the left side, the vehicle was undamaged and was used again in a later test.

3. Test 022886-1

The connector used in test 022886-1 was the hinge plate (1). Barrier segment length was 3.1 ft, and the total system length was 200 ft. In this test a 3180-lb vehicle impacted the barrier at an actual speed of 52 mi/h and at an actual angle of 7 degrees. The vehicle was smoothly redirected. The only roll of the vehicle during the collision was its gradual lean away from the barrier as the front and rear left tires mounted the lower slope of the barrier face. Tire scuff and rub marks on the barrier face indicate that the maximum vertical rise of the left tires was approximately 10 in. The right tires maintained contact with the pavement throughout the collision. There was no visual evidence that any of the barrier segments tilted during the impact.

There was no more than 1/8 in of longitudinal movement in the hinges in the primary impact area or at the ends of the barrier. Nor was there any physical damage or signs of distress to any of the concrete segments, steel hinge pins, or welded steel plate hinges. Except for minor bending at the left end of the front bumper and minor scratches on the left side of body, the vehicle was undamaged and scheduled for use in a later test, which was aborted because of collision with the barrier.

4. Test 022886-2

The connector used in test 022886-2 was the hinge plate (1). Barrier segment length was 3.1 ft, and the total system length was 200 ft. In this test a 4,240 lb vehicle impacted the barrier at an actual speed of 58 mi/h and at an actual angle of 7 degrees. The vehicle was smoothly redirected. The only roll of the vehicle during the collision was the gradual lean away from the barrier as the left front and rear tires mounted the lower sloping face of the barrier. Tire scuff and rub marks on the barrier face indicated the maximum vertical rise was about 10 in. The right tires maintained contact with the pavement throughout the collision. There was no visual evidence that any of the barrier segments tilted during the impact.

There was longitudinal movement in the barrier, due to longitudinal slip in hinges 28 through 35. The unanchored ends of the barrier did not move in any direction. There was no physical damage or signs of distress to the concrete segments, the steel hinge pins, or the welded steel plate hinges. There was a long scratch or narrow groove along the lower left side of the vehicle body and some scratches on the left end of the front bumper. There was also some upward distortional bending of the vehicle body above and forward of the front wheels, but this was on both sides and developed after the barrier impact when the car nosed into the earth and boulder mound and came to a stop on it.

5. Test 030386-1

The connector used in test 030386-1 was the hinge plate (1). Barrier segment length was 3.1 ft, and the total system length was 200 ft. In this test, an 1800-lb vehicle (the same that was used in test 022786-1) vehicle impacted the barrier at an actual speed of 47 mi/h and an actual angle of 15 degrees. The vehicle was smoothly redirected. The vehicle rolled to the right as the left front and rear wheels climbed the lower sloped face of the barrier. Tire scuff and rub marks on the face of the barrier indicated that the maximum vertical rise of the left front tire was about 10 in. The right tires maintained contact with the pavement throughout the collision. Although the vehicle yawed first to the right and then to the left on the pavement after it left the barrier, it never exhibited any serious rolling. There was no visual evidence that any of barrier segments tilted during the impact.

There was longitudinal movement in the barrier due to longitudinal slip in hinges 25 through 32 The unanchored end of the barrier did not move in any direction. There was no physical damage or signs of distress to any of the concrete segments, steel hinge pins, or welded steel plate hinges. Other than slight bending of the left end of the front bumper and minor lower body scratches, the left side of the vehicle was undamaged. It was used again for the third time in a later impact test in this series.

6. Test 030486-1

The connector used in test 030486-1 was the hinge plate (1). Barrier segment length was 3.1 ft, and the total system length was 200 ft. In this test, a 3200-lb vehicle (the same that was used in test 030386-1) impacted the barrier at an actual speed of 46 mi/h and an actual angle of 15 degrees. The vehicle was smoothly redirected. The vehicle rolled to the right as its left front and rear wheels climbed the lower slope of the barrier face. Tire scuff and rub marks on the barrier face indicated that the maximum vertical rise of the left tires was about 12 in in the primary impact area. The left end of the front bumper rose almost to the top of the barrier for the first time in this test series. In the preceding test (number 030386-1), the projecting cap restrained the rise of the bumper and the vehicle. The right front and rear tires maintained contact with the pavement throughout the collision. The vehicle never showed any serious roll difficulties. Nor was there any visual evidence that any of the barrier segments tilted during impact.

There was longitudinal movement of the barrier due to longitudinal slip in hinges 23 through 33 in the primary contact area, and in hinges 48 through 54 in the secondary impact area. The unanchored ends of the barrier did not move in any direction. Nor was there any physical damage or signs of distress to any of the concrete segments, steel hinge pins, or welded steel plate hinges. The left end of the front bumper was bent and the left corner of the vehicle was moderately crushed. The left front tire was flat and the left front wheel suspension was damaged.

7. Test 030686-1

The connector used in test 030686-1 was the hinge plate (1). Barrier segment length was 3.1 ft, amd the total system length was 200 ft. In this test, an 1800-lb vehicle (the same that was used in tests 022786-1 and 030386-1) impacted the barrier at an actual speed of 57 mi/h and an actual angle of 15 degrees. The vehicle was smoothly redirected. The only roll of the vehicle during the collision was its lean away from the barrier as the left front and rear tires mounted the lower sloping face of the barrier. Tire scuff and rub marks on the face of the barrier indicated that the maximum vertical rise of the left tires was approximately 10 in. Abrasion marks under the projecting cap of the concrete segments in the impact area and the left end of the front bumper indicated that the cap did restrict the climb of the vehicle in this high speed 15 degree impact. The right front and rear tires of the vehicle maintained contact with the pavement and the vehicle exhibited no serious roll throughout the collision. There was no visual evidence that any of the concrete segments tilted during impact.

There was longitudinal movement in the barrier due to longitudinal slip in hinges 19 through 33. The unanchored ends of the barrier did not move in any direction. There was no physical damage or signs of distress in any of the concrete segments, steel hinge pins, or welded steel plate hinges.

Although this 1800-lb vehicle had now been through three impact tests (namely 7 degrees/47 mi/h, 15 degrees/47 mi/h, and 15 degrees/57 mi/h), it was still judged to be drivable except for a flat left front tire. The left front corner of the vehicle was moderately crushed and the left end of the bumper was bent. There were also some minor dents and scratches on the left side of the body.

8. Test 030686-2

The connector used in test 030686-2 was the hinge plate (1). Barrier segment length was 3.1 ft, and the total system length was 200 ft. In this test, a 4,320-lb vehicle impacted the barrier at an actual speed of 43 mi/h and at an actual angle of 15 degrees. The vehicle was smoothly redirected. The only roll of the vehicle during the impact was its lean away from the barrier as the left front and rear tires mounted the lower sloping surface of the barrier. Tire scuff and rub marks on the barrier face indicated that the maximum vertical rise of the left tire was about 9 in. Scraping marks under the projecting cap of concrete segments 26 through 30 and abrasion marks on the top of the left end of the front bumper indicated the cap had restricted the climb of the vehicle. The right front tire of the vehicle maintained contact with the pavement throughout the collision. However, the right rear tire rose above the pavement when the right end of the vehicle rebounded from its secondary impact with the barrier. There was no serious rolling situation throughout the collision. Nor was there any visual evidence that any of the concrete segments tilted during the impact.

Longitudinal movement in the barrier was in hinges 17 through 35. The unanchored ends of the barrier did not move in any direction. There was a horizontal longitudinal crack in the front face at the bottom of the 5 1/8 in thick neck of the downstream half of module number 26. This was the concrete module where the cap received the initial upward thrust of the relatively heavy, rigid bumper end of the impacting vehicle. The high combined forces caused the bending crack at the critical moment. There was no other damage or signs of distress in any of the concrete segments, steel hinge pins, or welded steel hinge plates.

There was very little damage to the vehicle other than a light crushing at the left front corner above the bumper, abrasion on the left end of the front bumper, and light scratches and damaged molding on the left side of the vehicle.

9. Test 030686-3

The connector used in test 030686-3 was the hinge plate (1). Barrier segment length was 3.1 ft, and the total system length was 200 ft. In this test, a 3,650-lb vehicle impacted the barrier at an actual speed of 56 mi/h and an actual angle of 15 degrees. The vehicle was smoothly redirected. Its only roll was when the left front and rear tires climbed up the lower sloping face of the barrier. Tire scuffs and rub marks and bumper scrape marks on the barrier face and under the cap indicated that the maximum vertical rise of the left tires was about 9 in. Scraping marks under the projecting cap on concrete segments 28 through 33 and abrasion marks on the left end of the bumper clearly showed that the module cap limited the vertical rise of the vehicle was similarly restricted in the secondary impact area. The right front tire of the vehicle maintained contact with pavement throughout the entire collision. The right rear tire left the pavement only when the rear end of the vehicle rebounded in the primary impact area. There was no serious car roll at any time during the test. Nor was there any visual evidence that any of the concrete segments had tilted during the impact.

The unanchored stream end of the barrier did not move in any direction. There was longitudinal movement in the barrier from hinges 21 through 38 in the primary impact area and between hinge 48 and the downstream end of the barrier in the secondary impact area. There was no physical damage to the concrete segments except that a triangular-prism-shaped chunk of concrete 6 in by 6 in by 6 in was knocked off the downstream corner of the cap on module 54. The horizontal longitudinal crack that developed in the preceding test (number 030686-2) in the downstream half of the lower neck of module 26 did not enlarge. There was no damage to any of the steel hinge pins or to the welded steel plate hinges.

The left front corner and the left front end of the front bumper of the vehicle were crushed and bent in. The left side of the body was scraped and grooved, the left end of the rear bumper was bent away from the body of the car and the left front tire was flat.

10. Test 031486-1

The connector used in test 031486-1 was the hinge plate (1). Barrier segment length was 3.1 ft, and the total system length was 200 ft. In this test, a 4280-lb vehicle impacted the barrier at an actual speed of 60 mi/h and at an actual angle of 15 degrees. The vehicle was smoothly redirected. The only roll of the vehicle during the collision was its lean away from the barrier as the left front and rear wheels climbed up the lower sloping face of the barrier. Tire scuff and rub marks on the face of the barrier indicated that maximum vertical rise of the left tires was about 13 in. The right front tire maintained contact with the pavement throughout the collision. The right rear tire lost pavement contact only when the rear end of the vehicle rebounded off the barrier face. There was no visual evidence that any of the concrete segments tilted during the impact.

The unanchored upstream end of the barrier did not move in any direction. The unanchored downstream end was laterally displaced 1/4 in. There was longitudinal movement in hinges 7 through 41 in the primary impact area and between hinges 43 through 56 in the secondary impact area. There was no damage or signs of distress in any of the steel hinge pins or welded steel plate hinges. All the concrete segments were still intact tack and functional, but the segments in the impact areas were starting to show signs of accumulated distress due to the impact and abrasion from the ten vehicle crashes that had now been absorbed and resisted by the same barrier without any concrete segments, steel hinge pins, or welded steel plate hinges, being replaced.

The horizontal longitudinal crack in the lower neck of the downstream half of module 26 still had not enlarged. However, some corner spalling had now developed at the base of segments 26, through 28. Skid pads had broken loose from the bottom of segments 28 and 31. There was a 1-ft-long diagonal crack in the bottom of the cap at the upstream end of module 47. Concrete spalling had developed around the upper hinge inset at the downstream ends of segments 49 and 50. Also, the downstream corner of the cap of module 54 was still broken. Therefore, it was decided to remove and replace the most severely damaged and structurally distressed concrete segments before the next crash test, which was scheduled to be a heavy vehicle impacting the barrier at 25 degrees. Modules 26, 47, 49, and 54 were replaced.

The left front corner of the vehicle was severely crushed. The left half of the front bumper was severely twisted and bent. The doors on the left side of the vehicle were scraped and the left front tire was flat. Nevertheless, the occupant compartment was entirely undamaged and there were no protrusions of the steering wheel in the compartment.

11. Test 031986-1

The connector used in test 031986-1 was the hinge plate (1). Barrier segment length was 3.1 ft, and the total system length was 200 ft. In this test, a 4850-lb vehicle impacted the barrier at an actual speed of 50 mi/h and at an actual angle of 25 degrees. The vehicle was nearly redirected and about parallel to the line of the barrier when the hinges failed at hinge 28 and the barrier completely separated at that point. The vehicle glanced off already partially displaced module 34 and finally came to a stop against the barrier with the vehicle's front end opposite hinge 35. Thus, even though the barrier had failed structurally, the failure was delayed long enough to contain and redirect the vehicle and bring it to a stop against the impact side of the virtually undisturbed downstream portion of the barrier. However, the two loose ends of the barrier at the break were thrown out about 17 ft behind the barrier. A 22-ft wide opening was formed between the two broken ends. Tire scuff and rub marks on the face of the barrier showed that the front of the vehicle was past hinge 33 when hinge 28 failed. The marks also showed that the maximum vertical rise of the left front tire was about 9 in before the barrier failed. The right front and rear tires maintained contact with the pavement at all times. The vehicle never rolled excessively.

Inspection disclosed that the failed hinge 28 occurred in the welded hinge components attached to the upstream end of module 27. Failure was due to undersized fillet welds attaching the hinge plates to their back plates. Inadvertently, a set of prototype hinge weldments were used that had been discarded because earlier developmental tests had disclosed their inadequacy and larger fillit weldswere used thereafter. Surprisingly, these undersized welds withstood the preceding ten less critical tests. This barrier was laterally displaced between hinges 12 and 40. Longitudinal movement occurred between hinges 13 and 41. The unanchored ends of the barrier did not move in any direction. A considerable amount of concrete spalling occurred at the corners of the base on the back side of segments on each side of the break due to excessive hinge deflection after the barrier failed. Some spalling also occurred on the upstream ends of segments 26 and 27 around the upper hinge inset. Concrete segments 57 and 58 were cracked in the lower neck area at the upstream end, but these cracks undoubtedly had occurred in an earlier test. The steel hinge pins at hinges 28, through 30 were slightly bent. A moderately crushed left front of the vehicle was the only significant damage.

12. Test 032586-1

The connector used in test 032586-1 was the hinge plate (1). Barrier segment length was 3.1 ft, and the total system length was 200 ft. In this test, a 4020-lb vehicle impacted the barrier at an actual speed of 44 mi/h and at an actual angle of 15 degrees. The vehicle was smoothly redirected.

The only roll of the vehicle was its lean away from the barrier as the left front and rear tires climbed the sloping face of the barrier, and its lesser counter-roll that occurred after all wheels returned to the pavement. Tire scuff and rub marks indicated that the maximum vertical rise of the left tires was about 18 in. The roll angle induced in the vehicle was the largest in any of the tests to date but was still not great enough to cause rollover. The right front tire was in contact with the pavement throughout the collision, and the right rear tire lost contact only lost contact when its rear end rebounded from the barrier. There was no visual evidence that any of the barrier segments tilted during the impact.

There was no movement in any direction at the unanchored ends of the barrier. Nor was there any physical damage or signs of distress in any of the concrete segments, steel hinge pins, or welded steel hinge plates. The left front end of the vehicle was moderately crushed and there were some scratches on the left side of body.

13. Test 032886-1

The connector used in test 032886-1 was the hinge plate (1). Barrier segment length was 20 ft, and the total system length was 200 ft. In this test, a 5100-lb vehicle impacted the barrier at an actual speed of 57 mi/h and at an actual angle of 25 degrees. The vehicle was smoothly redirected. The vehicle leaned away from the barrier as its left front and rear tires mounted the sloping face of the barrier. Tire scuff and rub marks indicated that the maximum vertical rise of the left front tire was about 18 in. There was some reverse roll and both rear tires lost contact with the pavement when the rear of the vehicle rebounded from the barrier. However, the vehicle at no time came close to rolling over. There was no visual evidence that any of the concrete segments tilted during the collision.

The unanchored upstream end of the barrier moved 4 5/16 in longitudinally. The unanchored downstream end of the barrier did not move, but longitudinal movement in the hinges extended downstream to hinge 47. Concrete spalling occurred at the lower base corners of the segments at hinges 25 through 32. The skid pads were knocked loose from segments 32 through 34. The steel hinge pins were slightly bent at hinges 26, 27, 28, and 33. At hinges 29, 30, and 32 the pins were moderately bent and at hinge 31 the pin was badly bent. There was no sign of distress in the welded steel plate hinges or in their attachment to the 7/8-in-diameter steel through rods.

The left front of the vehicle was severely crushed and its left front wheel suspension system was damaged. The left front tire also was flat, and there were some scratches and grooves on the left side of the body. The occupant compartment however, was intact and undamaged and there were no protrusions of steering wheel in the compartment.

E. California Department of Transportation

1. Test 291

The connector used in test 291 was the pin and rebar (3b) with a 7/8 in diameter unanchored pin. Barrier segment length was 12 ft. In this test, a 4860-lb vehicle impacted the barrier at an actual speed of 64 mi/h and an actual angle of 7 degrees.

The vehicle was smoothly redirected although the left side tires rode near the top of the barrier during redirection. The maximum permanent deflection of the barrier system was 0.52 ft. Barrier damage consisted of cosmetic scarring and slight spalling.

2. Test 292

The connector used in test 292 was the pin and rebar (3b) with a 7/8 in diameter unanchored pin. Barrier segment was 12 ft. In this test, a 4860-lb vehicle impacted the barrier at an actual speed of 68 mi/h and an actual angle of 23 degree.

The vehicle was launched airborne partially into the work zone, and came down on top of the barrier system before completely landing on the ground. Deflection of the barrier was not applicable since the vehicle was airborne well into the work zone. Barrier damage consisted of the impacted segment being cracked in half and one of its pins coming out of the loops.

3. Test 293

The connector used in test 293 was the pin and rebar (3c) with a 1-in-diameter unanchored pin. Barrier segment length was 20 ft. In this test, a 4860-lb vehicle impacted the barrier at an actual speed of 66 mi/h and an actual angle of 40 degrees.

The vehicle was launched airborne partially into the work zone, landed on the ground then rolled over once, coming to rest on its wheels. Deflection of the barrier was not applicable since the vehicle was airborne well into the work zone. Barrier damage consisted of the impacted segment overturning and the pins of this segment being bent out of the loops as the segment overturned.

4. Test 294

The connector used in test 294 was the pin and rebar (3c) with a 1-in-diameter-unanchored pin. Barrier segment length was 20 ft. In this test a 4509 lb vehicle impacted the barrier at an actual speed of 39 mi/h and an actual angle of 25 degrees.

The vehicle was redirected, although it was airborne for 16 ft and came close to rolling over. The maximum permanent deflection of the barrier system was 0.46 ft. Barrier damage consisted of slight spalling, although some of the pins were severely bent.

Appendix C

State Interviews

1. Colorado Department of Highways

Connector Type: Pin and rebar
Type of Visit: Office
Date of Visit: January 21, 1987
Personnel Interviewed: Standards and specifications engineer

Colorado's pin and rebar connector has the 7/8 inch diameter by 28 inches long pin and the #5 bar for loops. Colorado has used this connector for the last 10 years and the same design is used for temporary and permanent installations. The hook and bar connector that was previously stated as being used in Colorado was used in 1974 but later abandoned because of its poor structural strength.

Colorado personnel believe that the pin and loop connector's biggest advantage is when barrier is being moved or replaced. The pin and loop connector does make it easy for damaged segments to be removed or replaced, or if an area needs to be opened in the barrier run. A slight change in the horizontal grooves on the end of the barrier would further facilitate removal of a barrier section from an inner location in a barrier run.

The pin does not have a nut on the bottom. Colorado makes the pin longer so it does not pull out of the bottom loop. Although Colorado personnel are aware of California research that shows that the pin pulls out of the bottom loops on impact, they do not think they have a problem with their design because their pin projects approximately 7 in through the bottom loop.

Colorado's design has a 1/2 in batter (1:12) on each segment end, measured from the segment center to each outside edge. This batter helps in placing the barrier on curves. They believe that the barrier can be placed on 100-ft-radius curves. This also gives some slack for putting the pin in the barrier. The segment length they use is 10 ft.

The bottom corners of Colorado's barrier do get damaged occasionally. They remove these segments and patch the corners in their maintenance yard. They believe the damage is caused most often by impacts from heavy vehicles, and not by the normal impacts from cars.

For end treatments on their barriers Colorado uses the 12 ft ramped end segments when barrier is outside the 30-ft clear zone. When barrier is inside the 30 ft clear zone, they use an impact attenuator.

Colorado does not have an anchoring detail for its temporary barriers. They place and move segments around using a small crane mounted on a flatbed truck. Their connectors are not grouted when being used in temporary fashion in the field. They also have a taper on the corner of the barriers to avoid snagging by snowplows. When placing barriers in the field, they do not pull the connectors tight.

Since it has gone to the pin and rebar connector, Colorado has had excellent experience with its portable concrete barrier.

2. District of Columbia Department of Public Works

Connector Type: Tongue and groove, plate insert, pin and rebar
Type of Visit: Office and one field site
Date of Visit: May 7, 1987
Personnel Interviewed: Design and construction departments (no field personnel interviewed)

The District of Columbia recently changed its specification for portable concrete barrier connector to the pin and rebar type. None of this type of connector, however, is currently in the field. The field site visited showed that the tongue and groove and plate insert connectors were still being used. Many of the barriers at the site visited, which was a city street, were not connected.

The engineers in the District of Columbia believe there could be some problems in breaking the loop rebars during handling. They believe the pin and rebar connector would be efficient for curves and angles. They have experienced some difficulty with the plate insert connector for curves and angles.

The District of Columbia has no written procedures specifying a surface treatment when barriers are placed. They think the 1 1/4 in pin is probably over-designed. They do not know how they would get a nut on the bottom of the pin as shown in the plans.

Since they are using the tongue and groove and plate insert connectors currently, they believe the prices to furnish barrier will go up substantially when they specify the new pin and rebar type connector. From bids on the first jobs that included the new connector, the prices will go up $10 to $15 per linear foot for furnishing the pin and rebar connector. They already have a large supply of tongue and groove connectors in the area, as well as some of the plate insert connectors. These connectors are used in the surrounding States of Maryland and Virginia.

The current plans state that approved alternates can be used, and they feel that probably the plate insert would be an approved alternate.

The construction engineer believes that many times the tongue on the tongue and groove connector is broken off from handling and any impacts that might have occurred on the barrier.

They are not aware of any anchoring that is used with the barrier segments.

3. Illinois Department of Transportation

Connector Type: Pin and wire rope
Type of Visit: Office and two field sites
Date of Visit: February 10, 1987
Personnel Interviewed: Standards and specifications engineer

Illinois uses pin and wire rope connector that was developed in 1978 based on a review of the FHWA report "Concrete Median Barrier Research," No. FHWA-RD-77-4. (13) In addition, Illinois reviewed standards from 25 other States. The FHWA report recommended a pin and loop connector. Illinois decided to use wire rope rather than rebar for the loops because the wire rope was expected to be more reusable.

The first connectors used in Illinois were on the Edens Expressway in Chicago. In these connectors the #4 rebar rather than the wire rope was used for the loops.

Illinois specifies that three styrofoam pads be placed underneath the barrier segments. These styrofoam pads lock the barrier in place, thereby cancelling the rolling effect that occurs when gravel lies between the barrier and the pavement underneath. For each segment Illinois specifies three 24-in-by-24-in styrofoam pads. These pads are placed underneath the barrier but not across the connection. They are not used for leveling; they simply are used for increasing the friction between the barrier and the pavement underneath.

For additional support the Illinois connector specification calls for a vertical #5 rebar. It keeps the wire rope loops from being pulled out of the end of the barrier. If the loops have been fabricated so that they go through the barrier, then this additional bar may be omitted.

Illinois generally uses 10 ft segments for barrier, although 12 ft and 20 ft segments have been used. All of the State's portable concrete barriers are precast. Illinois has no cast-in-place barriers.

An engineer in Chicago who works for the Illinois DOT was contacted concerning impacts on the barrier. In Chicago impacts to the barrier have moved the barrier by up to 2 ft, but have not penetrated the barrier. The engineer who was contacted called portable concrete barriers "the greatest thing we've done for construction safety."

Illinois has three different anchoring methods. On bridge decks with less than 2 ft of space behind the barrier, they use an anchoring system consisting of angles. The plate of the angle is bolted to the concrete and then the barrier is placed against the angle. The second method is a pin that goes into the barrier itself and down into asphalt pavement. The third method calls for a 1-in-asphalt base to be placed behind the barrier. Illinois has used the pinned barrier for permanent installations. It has used all these anchoring methods for the last 7 or 8 years with good success.

The connector detail plan for Illinois does not specify a gap, but the loops are set so that when the connection is made there is about a 1 1/2 in gap between the segments. Illinois specifies not more than 1 in of offset between the barrier segments to prevent any snagging of vehicles.

One of the problems of application in Illinois arises on two-lane bridges. In these narrow situations, contractors often leave connectors out of some segments of the barrier in order to furnish access to the work area. Illinois has developed a detail using barrels and attenuators that will furnish some contractor access to their sites, but still feels they have a problem keeping these barriers connected.

Across bridge decks, Illinois uses a 3-in-by-12-in tube. A connection detail ties this tube barrier into the PCB. In this detail, a W-beam coming from the end of the tube is blocked out from the barrier to prevent snagging and then is bolted into the side of the barrier.

Sometimes, smaller rebars are substituted for the usual 7/8 in pin. The design engineer who was interviewed had heard of substitutions as small as #4 rebars where additional space was needed.

Barriers are often replaced in the field after impacts or when they are damaged by handling. When these replacements are necessary, it is not difficult with the pin connectors to replace a segment in the middle of a barrier run.

Illinois does not have specific criteria relating to maintenance of the barrier. It would replace barrier if chunks are missing or realign barrier if there is an offset of more than 1 in from segment to segment.

Illinois barriers are reinforced with rebar and also wire mesh. Part of the reason for this type of reinforcement is that it prevents large chunks of concrete from becoming flying missiles if the barrier is impacted by a heavy vehicle.

Illinois has used its connector detail since 1978 without major modifications. From field experience, personnel believe that their barrier and the connector are withstanding vehicle impacts, even in the Chicago area, and have no plans at this time for further modifications to their PCB connector.

4. Iowa Department of Transportation

Connector Type: Pin and wire rope
Type of Visit: Office
Date of Visit: January 22, 1987
Personnel Interviewed: Construction Section

No site visits were made in Iowa because of lack of work zones during the winter season.

Iowa has used the pin and wire rope connector for portable concrete barrier for about 7 years. Before 1978, it used timber barricades and various other types of barrier, but only the pin and wire rope connector has been used for portable concrete barrier.

Iowa specifies a gap width between its PCB of 3 in, plus or minus 1/2 in. They believe they need this width for the fabrication of the portable barriers. They believe in this compromise of the gap width between having a tighter segment and the workability or constructability of the barriers.

For placing barriers in curves, Iowa standards allow for corners to be clipped somewhat for placement in especially tight curves. Since these corners must be cast already clipped for placement in curves, there is not a lot of use of them in the field.

Iowa personnel do not believe there is a problem in the field of a lack of connectors in their portable concrete barriers. They encourage inspectors to make sure that the segments are connected at all times. The only time they do not have this connection is when opening up a gap to allow contractor access into a work area. Normally these areas are on two-lane roads around bridge construction where the barrier takes up room and is run across the shoulder causing the contractors difficulty in getting their equipment in and out of the work area.

Neither are there problems with the pin connectors in moving for access or to replace a damaged segment in the middle of a barrier run.

Iowa normally uses standard 10-ft segment but they are allowing up to 20-ft segment believing these may be used more in the future. Normally their PCB is the standard New Jersey size and cross-section. In order to reduce glare for opposing traffic, they are building some permanent barrier that is up to 42 in high. Also, they have gone to wider tops (up to 9 in.)

Iowa uses an anchoring strap. This strap, anchored into the surface below, runs to just above the bottom set of loops in the connector and connects with the loops in the pin into the barrier to prevent overturning. They rely on the anchoring system at a bridge structure where they are using one lane at a time and when they have little deflection distance (less than 2 ft behind the barrier).

Iowa has problems with leveling segments when it runs the barrier out across an earth shoulder. Sometimes they have to hollow out some of the shoulder to make the segment level. There is a small amount of play for differences in vertical alignment, but they would normally level the barrier on a shoulder.

Most of the impacts that Iowa sees on its barrier system deflect the barrier only a few inches, and then the barrier can be realigned using skid loaders. They have limited experience in having to replace a segment due to an accident. They believe that most of their impacts are at a angle much flatter than 15 or 25 degrees.

Iowa has a specification for connecting PCB to a steel barrier rail that is used on bridges. The barrier cross-section is made vertical and then tapered into the normal safety shape. PCB is used on the approach and the steel rail is used across the bridge.

Overall, Iowa personnel are very satisfied and confident with their pin and wire rope connectors. They believe the gap of 3 in plus or minus 1/2 in is the best compromise for ease of fabrication and workability in the field, and believe the barriers are performing well.

5. Kansas Department of Transportation

Connector Type: Tongue and groove with dowels; with side plates
Type of Visit: Resident office and one field site
Date of Visit: May 28, 1987
Personnel Interviewed: Resident construction engineer

Kansas uses the tongue and groove connector with the single dowel bar, a 1-in-diameter bar 2 ft 2 in long. As an alternate connector, they use the tongue and groove with side plates when a segment has to be replaced and the dowels cannot be put back in the barrier run. Barrier segments are 10 ft long.

Kansas contractors use a hydraulic system to lift barrier segments, using two rubber pads around the upper portion of the barrier.

A major construction project was visited. There had been many impacts on the barrier system in this project. The configuration of the barrier was two or three parallel runs forming an S curve through the project. In viewing barrier in the field, there was evidence of many impacts, some near the top of the barrier. The resident engineer believes small cars overturn with the barrier because of their narrow wheel width. He believes also that gas tanks are subject to rupture when cars go up on the barriers.

At the resident engineer's office, 11 accident reports were obtained that involved vehicle contacts with the barrier. A summary of these accidents is given in table 10. It is quite evident from looking at the accidents that barriers are being pushed out of line and overturned. One vehicle hit the barrier segment, overturned the segment, and entered the opposing lane of travel. A diagram of this accident (No.11) is shown in figure 44. Also, in accident No. 1, two vehicles hit the barrier and pushed segments of the barrier into opposing lanes, causing two cars in the opposing direction to become involved in the accident. The diagram of this accident is shown as figure 45.

While at the site, the barrier near the start of the taper was inspected. Twenty-five connections were observed. Of these 25 connectors, 5 did not have a gap, so whether the dowel bar had been installed could not be determined; 19 had been installed with the dowel bar as specified; and 1 had not had the dowel installed. The one connection where the dowel bar had not been installed was a segment that appeared to have been replaced after the barrier run had been installed.

Table 10. Kansas visit accident summary

No.	Date	Time of Day	Vehicle Type	Circumstances
1.	9/30/86	9:00am	1. Ford Pickup 2. Mercury Comet 3. Audi 4. Honda	Southbound vehicles 1 and 2 slid into barrier while attempting to stop for traffic. Barrier was pushed into path of northbound vehicles 3 and 4.
2.	11/19/86	11:05pm	1. Ford Mustang	Northbound vehicle 1 hit barrier on right at approximately 55 mi/h while avoiding uninvolved vehicle. Vehicle then crossed roadway, struck barrier on left, then recrossed roadway and struck right barrier run again.
3.	2/1/87	3:50am	1. Chevy Truck (4WD)	Northbound vehicle 1 struck center barrier, vehicle stradled barrier and traveled 200 ft, then vehicle came off of barrier and traveled another 50 ft.
4.	2/7/87	4:03pm	1. Buick Sedan 2. Chevy El Camino 3. Chevy S10 PU 4. Cadillac	Northbound vehicle 1 skidded in S curve hit barrier and flew over into southbound lanes striking vehicles 2, 3, and 4.
5.	2/7/87	7:05pm	1. Honda	Southbound vehicle 1 was forced into barrier, became airborne and overturned.
6.	2/13/87	7:54am	1. White Semi-Trailer	Truck overturned in curve and struck barrier.
7.	2/15/87	1:00am	1. Chevy S10 PU	Northbound Pickup struck barrier at 55 mi/h, then crossed both lanes and struck opposite barrier.
8.	2/20/87	11:10pm	1. Chevy Camaro 2. Chevy Celebrity	Northbound vehicle 1 struck barrier at 55-60, burst into flames and struck vehicle 2.

Table 10. Kansas visit accident summary (concluded)

No.	Date	Time of Day	Vehicle Type	Circumstances
9.	2/24/87	3:55am	1. Mack Truck (empty trash truck)	Northbound vehicle 1 struck barrier, destroying two sections.
10.	3/6/87	11:45pm	1. Dodge Aspen	Southbound vehicle 1 struck left barrier, spun out and then struck right barrier.
11.	3/14/87	6:40pm	1. Buick Rivera 2. Isuzu Pickup 3. Toyota Corolla	Southbound vehicle 1 hit center barrier, overturning 1 segment. Vehicle 1 then went over barrier into northbound lanes. Debris from barrier and vehicle 1 struck northbound vehicles 2 and 3.

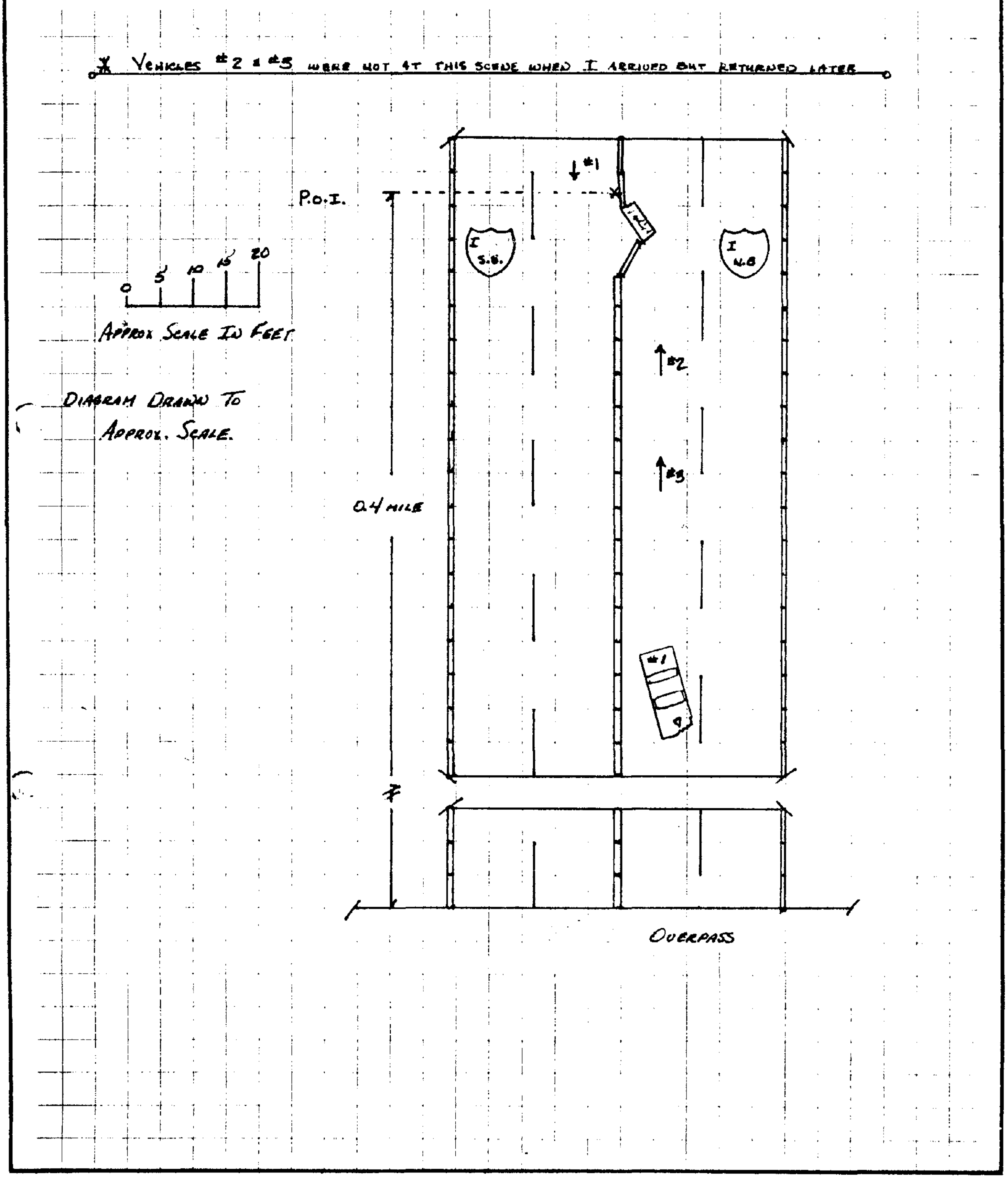
PAGE 4

DIAGRAM WHAT HAPPENED

Draw scene as observed. Refer to vehicles, drivers, and pedestrians by numbers assigned in this report

SHOW (1) Outline of street and access points and identify specifically by number
(2) Paths of units prior to and after impact, skidmarks, and point of impact (POI)
(3) Location of signs, traffic controls, and reference points
(4) Location of other property hit/damaged (trees, signs, etc.)
(5) Special features at location (bridge, overpass, culvert, etc.)
(6) Location of temporary highway conditions
(7) All measurements to locate the accident relative to a specific, fixed, uniquely identifiable and locatable point

Indicate NORTH by Arrow


* VEHICLES #2 & #5 WERE NOT AT THIS SCENE WHEN I ARRIVED BUT RETURNED LATER

APPROX SCALE IN FEET

DIAGRAM DRAWN TO APPROX. SCALE.

Figure 44. Accident 11 diagram (police drawing)

PAGE 7

DIAGRAM WHAT HAPPENED

Draw scene as observed. Refer to vehicles, drivers, and pedestrians by numbers assigned in this report.

SHOW (1) Outline of street and access points and identify specifically by number
(2) Paths of units prior to and after impact, skidmarks, and point of impact (POI)
(3) Location of signs, traffic controls, and reference points
(4) Location of other property hit/damaged (trees, signs, etc.)
(5) Special features at location (bridge, overpass, culvert, etc.)
(F ion of temporary highway conditions
surements to locate the accident relative to a specific, fixed, uniquely identifiable and locatable point

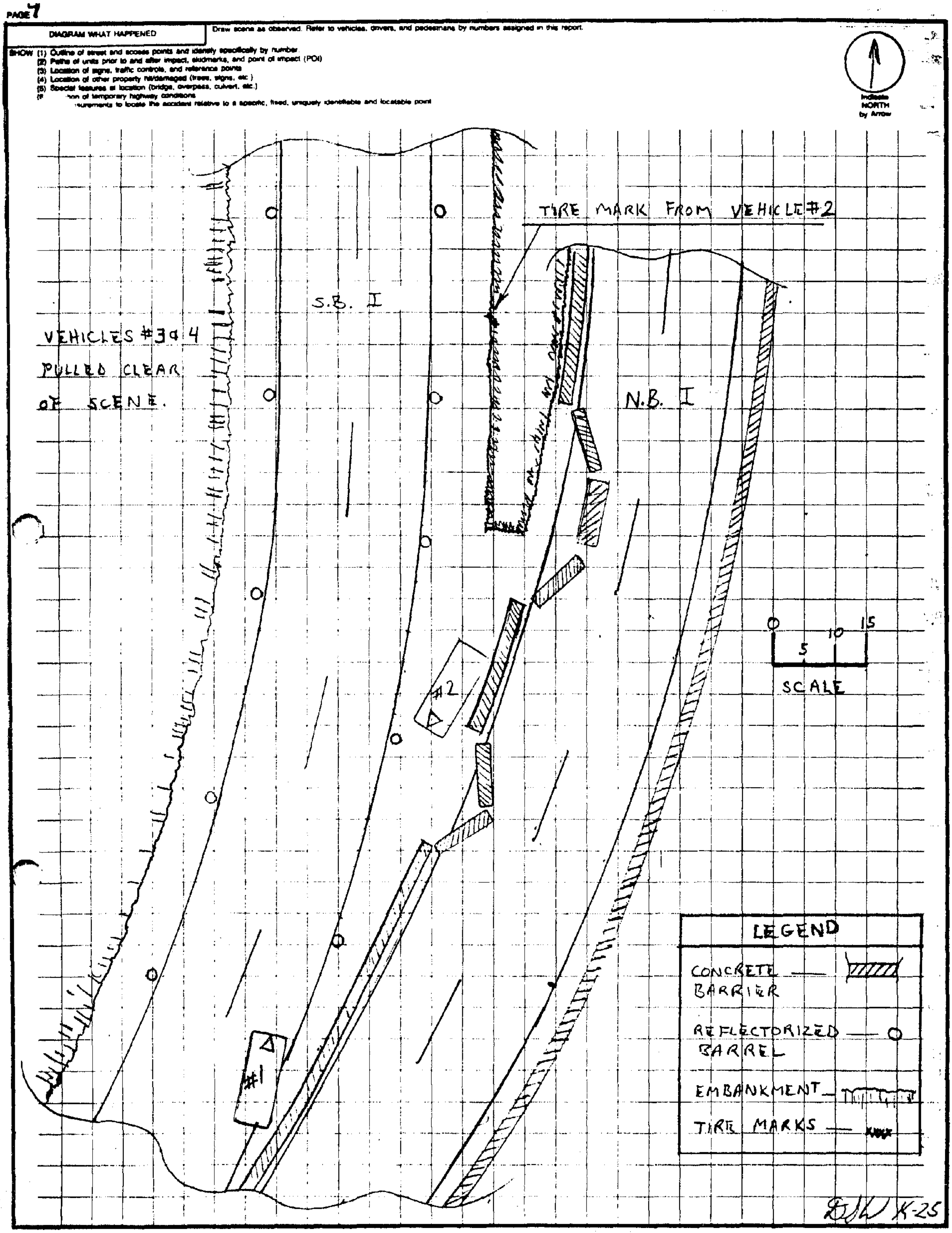


Figure 45. Accident 1 diagram (police drawing)

Kansas does specify a 1/4-in-to-1/2-in-gap between the barrier segment, but the resident engineer stated that it is difficult placing the barriers to control the gap that closely. The resident engineer also stated that they normally have inspectors on the site when the barriers are being placed to be sure that all the dowel bars are installed. The resident engineer also stated that dowel bars installed are normally the 1-in dowel bar with the washer in the middle, but also that other rebars are used if it is not possible to find the regular dowel bar.

A review of the accident reports in Kansas shows that there are some problems when vehicles strike the barriers connected with the dowel bar. Particularly, it seems that in the S curve there are some high-angle impacts where cars are overturning the barrier segments and then going over the barrier into opposing lanes. The single dowel probably has little torsion strength to resist overturning moment once a car is up and on the barrier. Other accident reports show that the barriers redirected and contained trucks in some accidents involving the barrier.

There are no plans to change or modify the connector at this time.

6. Maine Department of Transportation

Connector Type: Pin and rebar
Type of Visit: Office
Date of Visit: January 16, 1987
Personnel Interviewed: Construction, design, and bridge maintenance sections

Maine uses a pin and rebar connector with #5 rebar for loops and the 7/8 in pin. One problem Maine has had in the application of its PCB connector is installation of the 7/8 in pin. The design for the connector as shown on Maine's standard plan leaves very little gap between segments, making it difficult to install the 7/8 in pin in the field. Personnel in Maine admit that few of the pins actually used are #7 or 7/8 in. Much more common is use of #5 rebar and in some cases even #4 rebar for the pin.

The barrier segments are tapered 1/4 in on both sides. Even with this taper, the segments are very difficult to install in curves, and estimates are that the barrier cannot be set on a 300-ft-radius curve.

Maine has had some minor hits on its barriers. At times, cars have hit the ramped end segment and have ramped. Normally, with car impacts,the barrier system gives about a 6 in deflection. In Maine,segments have not been replaced in the field after accidents. Impact angles are usually low, and personnel have not seen impacts on unconnected barrier systems.

In Maine,the segments are normally placed with a hoist on a truck bed. For this reason, Maine personnel think that sections longer than 10-ft would be a problem to handle and haul. The booms used on the truck would have difficulty lifting longer and heavier segments and in being able to place them in traffic.

For modifications, Maine personnel think they need to change the depth of the drainage slots in the barrier.

Because of problems with snow plowing and with being covered, side delineators are rarely used. Delineators are used instead on the top of the barriers.

The pin has a bend in the end of about 2 in. This pin is at variance with what is shown on Maine's plan. A nut is tack welded onto the top of the 7/8 in pin. Bars used in the field are normally #5 to #4 rebars. These bars are usually bent when the barrier system is impacted.

Maine has many circumstances where connectors within existing systems are needed or where two runs of barrier join together. In the field, the application is seen where a W beam with fishtail is put across the gap between the two barrier segments. The structural integrity of this kind of connector is not known.

Overall, Maine personnel believe that they have no problems with the design of their barrier system. However, as used in the field and for their type of roads, which have many curves and tight geometry, the use and application of the barrier are problems because of the substitution of smaller pins for the 7/8 in pin called for in design plans.

7. Michigan Department of Transportation

Connector Type: Pin and eyebolt and dowel
Type of Visit: Office
Date of Visit: February 11, 1987
Personnel Interviewed: Barrier advisory committee

Michigan was visited during a regular meeting of the department's barrier advisory committee. Although no field sites were visited, considerable correspondence and memoranda were received that covered some field inspections of barrier connectors.

In Michigan the pin and eyebolt is the specified connector. Michigan also has used a cast in-place barrier that is, after the first use, cut apart and used subsequently as a doweled connector using two 22 in #8 steel bars.

Much of Michigan's barrier has a 10 in top. The reason for using this wider cross-section is to furnish an overturning moment of inertia similar to that afforded by the GM-shaped barrier which Michigan had used previously. Personnel in Michigan believe this size barrier top also gives barrier additional strength to resist impact by heavy trucks.

Michigan has been reviewing its connector design/in order to come up with an improved design that will solve some of the problems associated with both the pin and eye bolt and dowel connectors.

About 50 percent of the barrier in Michigan is being slip-formed or cast in-place. After the first use it is sawed up in pieces and becomes precast without a method of connection. The dowel bars are then retrofitted to the sawed-up barrier segments.

Michigan is finding that usually when eye bolt loops are broken off in the field, the spacing of the replaced loops has been changed. If a segment is replaced or moved for contractors' access, the dowel bars are sometimes omitted. When they have to replace a segment sometimes the dowel connector can be converted to an eye bolt connector.

The only surface treatment Michigan specifies is placing building paper underneath barrier that is being cast in-place.

In order to compute the strength of their barrier system, Michigan reviewed barrier research carried out at the Texas Transportation Institute. No calculations for the weight of the system and the surface friction were given in this research. Because of its heavier barrier segments and wider cross-section, Michigan believes these factors were critical to computing the overall strength of their barriers. They also have acquired information from Minnesota relating to how Minnesota changed from a eye bolt system to a pin and wire rope system.

Michigan has not looked at cost in considering connector systems. Contractors can furnish any acceptable barriers. Normally, if contractors have old barriers these are usually pin and eye bolt, and this is what is used. If the contractor has to furnish new barrier, then it is usually cast in-place, and for later applications the dowel connectors are used.

Michigan uses anchoring when there is less than 4 ft from the traveled edge to a drop-off or other excavation. They are considering alternate methods of anchoring at this time.

Although Michigan believes they have a potential connector problem, they believe their present system is not resulting in catastrophic accidents. Sometimes trucks do go through their barrier, but they have not gathered any accident data that show a real problem with either of their connectors.

Michigan is considering doing some crash testing to look at alternate connectors. The crash tests that they envision would probably start off with a wider cross-section barrier without any connector, and then move to a test of the dowel connector, to a test of their eye bolt connector, and finally to a test of pin and wire rope or pin and continuous wire rope connector.

Michigan believes such crash tests may resolve its problems with existing connectors, and may give it some grounds to require use of additional connectors. They believe that before any change could be made they would have to consider how the older barriers could be retrofitted, as well as the fabrication of new barriers.

Also obtained in the Michigan interview were a number of memoranda prepared since 1980 by the department's barrier advisory committee. These memoranda discussed design changes for new stock, existing stock, slip form design, and precast design. They are also looking at grouting in some wire rope and eye bolts and at conducting simple pull-out tests in their materials lab. Following is a verbatim report from a field inspection team that had observed the two types of barrier connectors in the field in Michigan.(14)

Pin-and-eyebolt connection were used on 7 projects. A total of 284 joint connections were inspected on six of these projects, and compared to the design shown on Standard Plan II-52D.

Forty-three (15%) of the connections were recorded as substandard to the design, as follows: pin missing (5), one or more eyebolts missing (31), pin not through all four eyebolts (7). An additional 35 - 50 connections (9 - 18%) were noted as substandard for the following reasons: eyebolt projecting too far from barrier face (3 in - 6 in projection, as compared to 1 1/2 in on the standard); excessive vertical separation between paired eyebolts (4 in to 10 in, as compared to 2 in on the standard); connecting pin cleared top eyebolt by one in or less (6 in implied by standard); 1/2 in diameter reinforcing steel used for connecting pin (3/4 in diameter required by standard).

Many of the joint deficiencies noted above are due, in our opinion, to the ease in which these eyebolts break off in shear. Although these barrier units are originally precast with eyebolts correctly positioned, the team observed many older-looking barrier segments with odd-placed eyebolts. These eyebolts were obvious retrofits, as the stubs of the original eyebolts remained - at the optimum location - in the barrier face.

At the three project sites having dowel-connected PCB, a total of 105 joint connections were inspected. According to the approved design, the team should have observed 210 1-in connecting steel bars. In fact, they observed 150 bars of 1-in diameter, 8 bars of 3/4-in diameter, 26 bars of 1/2-in diameter, and 26 joints with a bar missing. Fortunately, the one project which accounted for 80 percent of the total barrier footage was correctly doweled. The 26 joints having 1/2-in connecting bars and the 26 joints having no connecting bars were, in fact, the same 26 joints, which occurred all on one project.

Observation of these substandard connections brought out an important point concerning horizontal dowels: where the wrong connector (or none) has been used, there is no easy way to correct the situation. The connection could involve repositioning the total barrier line from the defective joint to one end of the line. Although we are experiencing very little in the way of accidents, we could expect similar repositioning problems after an accident.

The gap between barrier segments in a dowelled barrier line affects the ease of repositioning an individual segment, because theoretically only enough barrier segments need be moved to develop a 22-in gap. Therefore, a contractor might be expected to place as wide a gap as the project engineer will permit. However, joint strength is dependent on keeping the gap small.

Gap size was observed and recorded on two projects. On the 1-mile project, maximum gap observed was 2 1/2 in, with most gaps at 1 in or less. On a much smaller project (190 ft), maximum gaps of 5 in were observed with many gaps near 2 in. On this project, it was noted that the dowel holes in adjoining barrier faces did not always align with each other. The contractor's solution was to use bendable 1/2-in bars with larger gap spacing between segments. At these joints the team could not tell how much penetration was obtained by the steel bars into either barrier segment.

Continuous slipformed barrier (first use) was viewed on one project (2 miles). The barrier has been slipformed in place with three continuous steel bars. Immediately after concrete placement, the green concrete was chipped away with claw hammers at 10-ft intervals, creating a vertical separation approximately 3 in wide in the concrete. The gapping operation worked around the continuous steel bars, however, so that these bars remained uncut during the PCB use on the project.

When viewed by the motorist at highway speeds, this barrier line presented a neat, clean appearance. At lower speeds, however, it was obvious that the gapping operation (above) produced PCB sections with jagged faces, some of which were not entirely vertical. This could produce connection problems when these 10-ft segments are prepared for re-use on another project.

8. Minnesota Department of Transportation

Connector Type: Pin and wire rope
Type of Visit: Office
Date of Visit: March 13, 1987
Personnel Interviewed: Standards Engineer (St. Paul office)

Minnesota performed two studies (April 1979 and May 1980) in which its barrier systems were evaluated as a result of accidents. A conclusion of the 1979 study was that the eyebolts (in concrete inserts) used for the loop in their pin and loop connectors were the weakest point of the system and they needed an improved anchoring method. The barrier performed well except where heavy trucks impacted it. The State recommended that Minnesota go to the wire rope loops in place of the eyebolts. Minnesota also recommended that in areas of narrow clearance (for example, bridgedecks) in which there is little room to allow the barrier to move at impact, the barrier should be anchored to concrete decks or pavements. Where lateral displacement was not a problem, it was recommended that no anchoring was needed. Based on a recommendation of the 1979 study, Minnesota started using the wire cable connector.

At the time of the 1980 study, Minnesota had two types of barriers: a revised one with the eye bolts, and the type III, with the newer wire rope loops. The second study concluded that both types of barriers performed acceptably in the field, although there were large displacements from large truck accidents. As a result of these large displacements, Minnesota developed a technical memorandum which specified when to use 8323A and type III barriers. The type III barriers were to be used along bridge construction sites or along deep drop-offs. Minnesota also developed specifications for anchoring the type III barriers when used in such instances. The type older barrier had no means to be anchored to pavement surface. Minnesota also found that although type III barrier with wire loops were not penetrated by large vehicles, the barrier had large deflections. Portable concrete barrier was still the most effective temporary barrier. The recommendation was to continue using 8323A and type III barriers and to develop guidelines for acceptable damage.

9. Missouri Highway and Transportation Department

Connector Type: Tongue and groove with continuous cable
Type of Visit: Office and two field sites
Date of Visit: February 9, 1987 (office)
May 27, 1987 (field sites)
Personnel Interviewed: Planning and construction sections

Besides the tongue and groove connector with continuous cable, Missouri also uses a connector that has anchoring pins. The diameter of the cable threaded through the barrier is 1/2 in. The same design barriers are used for permanent and temporary installations. The cable that runs through the barrier segments is secured at the ends with a wedged anchor. Cable is not tied to the ground or to any permanent fixture on the roadway.

Missouri personnel believe the cable system is easy to install and gives the strength needed for a temporary barrier system. With this type of connector they do not have to worry about exact spacing or about damage to pins, such as would be the case with a pin and loop connector.

In replacing a barrier, they have to take the cable out and then re-tension it. In some cases, if there is a long run of cable to be removed, the cable can be cut and spliced later.

This system was originally designed in connection with fabricators in Missouri and has not been changed since it was developed. All temporary barrier is now precast.

Barrier segments are 10-ft long in Missouri. They considered 20-ft segments but decided their maintenance workers and small contractors would have trouble in handling longer sections. They also felt that 20-ft barrier would be a problem in curves, such as where they have temporary bypass roadways.

Missouri specifies a 1/4-in gap between the segments faces in their barriers. They feel that the tongue and groove connector with cable allows enough play for curves and angles and that it is not considered a problem in their State.

The construction section personnel are aware of some impacts where barrier was moved but not destroyed. The barrier usually moved less than one ft. On one of the field site visits a segment that had been struck at about a 45 degree angle was viewed. The speed of the vehicle that had struck the barrier was not known. For this high-angle hit, the deflection was 3 ft to 5 ft. The car was re-directed, but some chunks of concrete had been knocked out of the barrier around the end of the segment.

The operation of moving barrier also was viewed in the field. In a moving operation, Missouri uses one truck and a boom operator. Three persons are used on the ground to move the barrier segments. A clamp is used for lifting barrier segments.

Field personnel believe it is not difficult to realign barrier after it has been struck. If necessary they can cut the cable and restring it. Overall, Missouri personnel in both the office and the field are satisfied with their tongue and groove connector with continuous cable and believe they are getting good performance from their connector in the field.

10. Ohio Department of Transportation

Connector Type: Pin and rebar, tongue and groove
Type of Visit: Office and one field site
Date of Visit: February 12, 1987
Personnel Interviewed: Construction, maintenance, design and location, and research and development sections (no field personnel interviewed)

Ohio prefers the pin and rebar connector but the tongue and groove connector is permitted as an alternate except on bridge decks. The tongue and groove connector, which was used first, is a proprietary design from a company in Virginia. When local people started fabricating barriers, they used the pin and loop design. Now, in Ohio, the pin and loop predominates.

The minimum length specified for Ohio barrier segments is 10 ft, but the lengths found in the field range from 10 ft to 15 ft. Ohio specifies that a 10-ft or 12-ft section be used on horizontal curves having a radius sharper than 400 ft.

During installation the pin and rebar connectors are pulled tight, leaving about a 1 3/4-in gap between segments. During installation of the tongue and groove connectors, no gap is left between the segments.

Ohio personnel in looking at their design, reviewed California crash tests that showed that unanchored pins pull up and disengage on impact. Ohio personnel believe California now uses a bolted pin to keep the pins from pulling out. Personnel in Ohio believe that if there is a nut on the bottom of the pin it should be called a "bolt and loop" connector.

For high-impact conditions, Ohio has designed a modification that stiffens and strengthens the pin and rebar connector. This modification is shown in figure 46. The modification calls for an angle to be added to the connection on the non-traffic side and either grout or a steel or hardwood shim on the traffic side to pick up connector slack. Also, for these high-impact conditions where there is a minimal deflection distance available, Ohio personnel believe the connection should be bolted.

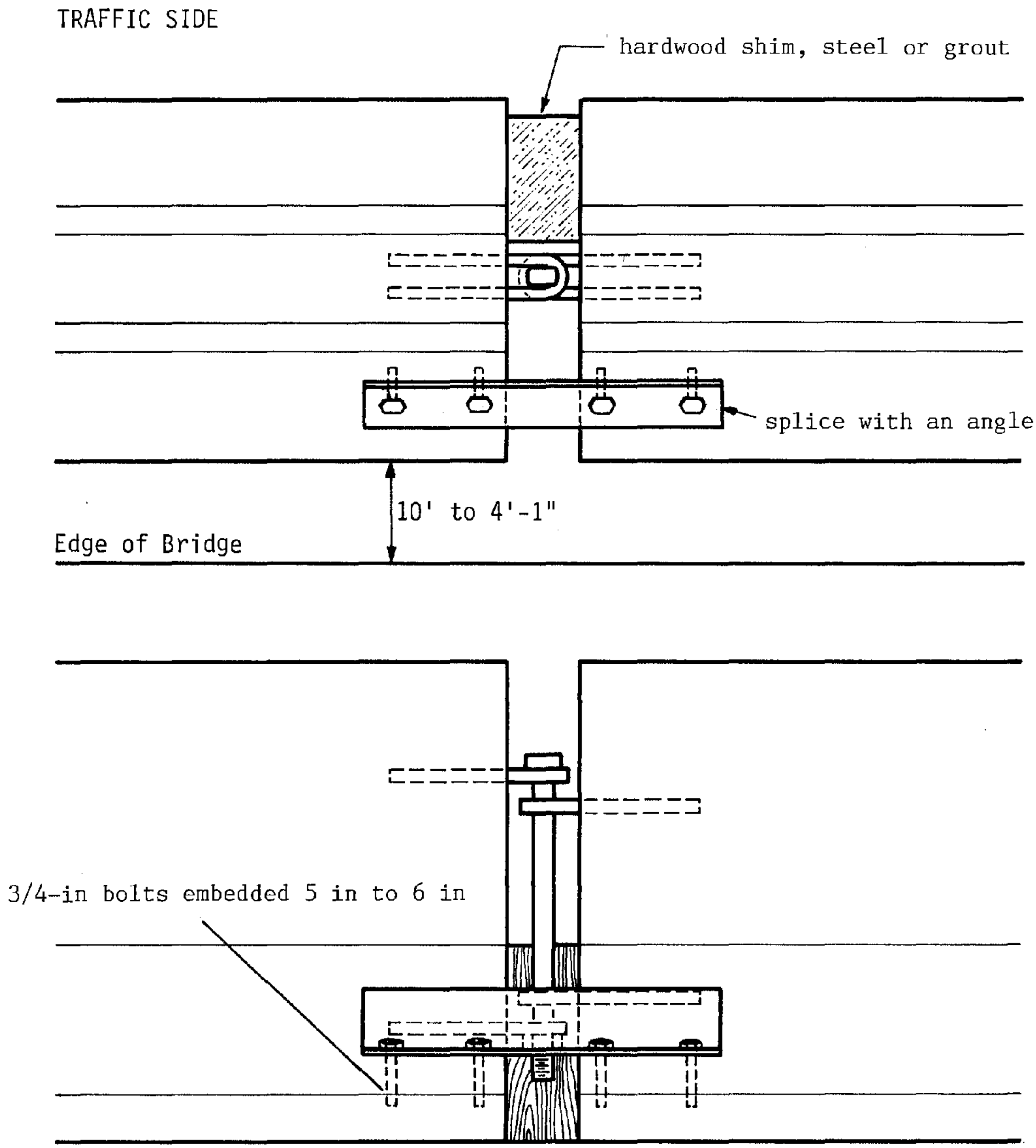


Figure 46. Ohio joint stiffener

Ohio personnel believe there is a need to crash test anchored segments and also segments with stiffened and strengthened connectors. Many think that any time barrier is put on a bridge near an unprotected edge the connectors should be stiffened and strengthened; and further that it is important to bolt the barrier and stiffen the joints as much as possible.

Ohio believes that, overall, the pin and rebar connectors are performing well. Because of their concern about bridges, Ohio has designed and is still working on a modification for stiffening and strengthening their connector on barrier that is placed on bridges.

The field site visited employed the tongue and groove connector.

11. Texas State Department of Highways and Public Transportation
(Houston District Office)

Connector Types: Triple dowel, lapped joint channel splice, top-T
Type of Visit: Office and three field sites
Date of Visit: December 30-31, 1986
Personnel Interviewed: Construction and Design Section (Houston District Office)

Texas has used more connector types than any other State. In the Houston district, they have used grid slot, lapped joint, triple dowel, tongue and groove, top-T, dowel and V, and the channel splice at various times. Of all these connectors the channel splice connector is believed to perform best. In fact, they sometimes use the channel splice connector in permanent barrier systems.

The sites visited employed the grid slot and channel splice connectors. Texas is going to the channel splice as much as possible on new jobs. The grid slot is easy to place, but they think that for Houston expressways this type of connector does not perform adequately. For the grid slot a grid of #6 and #4 rebars is dropped into a slot in the ends of adjacent barriers, and the slot is then filled with grout. The grout, however, usually shrinks up and cracks and then pops out when the barrier is hit. At one site, a semi-trailer truck struck barrier connected with the grid slot. Two segments of barrier were overturned and rolled down a side slope onto a frontage road.

The design of the channel splice has been changed to recess the channel so it does not protrude beyond the barrier face. With the older design there was a snag point with the channel beyond the barrier face. Inspectors saw evidence of tires and treads and motorists complained. Texas also has widened its drainage slots to 2 ft by 3 in to keep the drainage slots from being blocked.

Use of 30-ft segments of barrier is popular. Ten-foot segments have also been used but the engineers interviewed believe the shorter sections are too light except in special circumstances.

Even with 30-ft segments the connector is important because the engineers think the connector gets hits when the segments are placed at sharp angles. The barrier segments are displaced even with the channel splice and 30-ft sections. One impact incident that had destroyed a barrier segment appeared to have been hit at almost 90 degrees.

Texas has a standard for transition segments. It ties guardrail into the barrier end as a safety end treatment. The full barrier shape was causing a snag point because the lower part of the barrier was outside the face of the W-beam guardrail. Texas is developing a barrier segment that has a vertical face where the guardrail attaches. They also are "blocking out" the W-beam to prevent snagging at the transition. The engineers interviewed believe the ramped end section was useless and should be discarded.

In using barrier, Texas sometimes has both directions of traffic separated by a barrier and another barrier on the right side of the road. Sometimes the traffic may be in a 20 to 30-ft cross section. They also may close ramps and continue these barriers for 2 to 3 miles. They reported an accident involving a fuel truck on a slope where its spilled fuel had begun running under vehicles that were stopped behind the truck. Because it is very difficult to get emergency vehicles into such areas, the personnel interviewed would like to find a way to provide a gate or movable barrier segment within a barrier run to allow access for emergency vehicles, contractors, etc. They have used gates in some areas but are not happy with the design. They now are required by FHWA to maintain a shoulder in these areas.

Using the channel splice with 30-ft segments is sometimes difficult in horizontal curves. Their plans have a note that the channel may be heated at the midpoint and pre-bent for curves. There is also about a 1-in cushion between the barrier segments that allows for some angling. In the field, barriers at angles usually appeared to have a channel on only one side. Also, if there is too much difficulty a metal guardrail is used in the back to make the connection. They also use the metal guardrail alternative to allow for use of obsolete barriers such as those with the lapped joint and bolt connector.

As far as maintenance is concerned, the 30-ft sections are easier to maintain because they do not move or they move less in a normal hit. However, if they are moved they are harder to realign.

Overall, the personnel interviewed in Texas were very happy with the channel splice connector. It works better than all the other connector systems they have tried. A lot of labor is required to make the connections using bolts, and removing the connectors often requires cutting the nuts off the bolts. However, with the channel splice, field personnel have considerable confidence in the barrier and feel they need a strong system on Houston urban expressways. The channel splice for them has an additional advantage because, in using that connector, the space between barrier segments is controlled. With other connectors, barriers were sometimes spread out to make up more distance to some fixed point.

12. Virginia Department of Highways and Transportation

Connector Type: Tongue and groove, plate insert
Type of Visit: Office and four field sites
Date of Visits: May 5, 1987
Personnel Interviewed: Design Maintenance and Construction personnel

Virginia uses the tongue and groove connector and the plate insert connector as an alternate. Virginia specifies a maximum of 1 in between barrier segments. This width is based on an evaluation by the Virginia Highway and Transportation Research Council. They do not grout between their joints.

In Virginia, 12-ft segments usually are used, but on curves 8-ft or 10-ft segments may be used. In the middle of a barrier run, female-female segments can be lifted out if replacement of segments is necessary. Engineers in Virginia believe that segments are replaced only after impacts by trucks.

Virginia had a request for use of the pin and loop connector as used in North Carolina, but rejected this request because of the width of the joint opening in the North Carolina barrier. Virginia was afraid that this joint opening would become a snag point for vehicles impacting the barrier.

For lifting and placing barrier, Virginia uses a sling that goes in drainage slots under the barrier. Their plans show a thin, 1/16-in-steel-tongue protector that goes on the male part of the barrier. This protector was not seen, however, on any of the barrier at the sites visited.

Virginia believes its barrier performs well in accidents as documented by reports from the Virginia Highway and Transportation Research Council. Virginia did receive a request to develop small animal escape routes through its barrier to prevent the animals from being trapped on the roadway.

Virginia also uses some plate insert connector. In visiting a site in Northern Virginia, the tongue and groove and plate insert barriers were intermixed. In this case, when the connector would not work as it was designed, the connector between the two different barrier segments was made with about a 4-ft length of W-beam bolted to both segments. Virginia uses the GREAT system for end treatment.

Those interviewed in the turnpike authority stated that when semi-trailer trucks impact the barriers, the trucks usually go through the barriers and totally destroy segments. In some of these accidents, chunks of concrete have even been knocked into opposing lanes. Also, a maintenance worker was struck with a flying piece of concrete during one of these barrier accidents.

The turnpike maintenance engineer believes barrier segments do need reinforcement as well as a change in the position of the steady-burn light that is placed on top. The present position of this light coincides with the lifting sling placement and therefore, at times, the light has to be taken off for each installation of the barrier.

Engineers in Virginia believe contractors have large stockpiles of the current barrier, and that to replace all of this barrier would be very costly.

Overall officials in Virginia think their tongue and groove connectors are performing well except for truck impacts. There is some thought that their barrier segments should be reinforced for collisions with heavier vehicles.

Virginia does have a standard plan for reinforcing barrier segments that are used as exterior barrier on bridge parapets. This standard also calls for the barrier to be anchored to the surface.

13. Wisconsin Department of Transportation

Connector Type: Pin and wire rope with rebar
Type of Visit: Office
Date of Visit: February 2, 1987
Personnel Interviewed: Standards engineer, engineer in construction department (cost information)

In Wisconsin's pin and loop wire rope connector, the pin is a 1 1/4-in diameter-steel bar. The loop is formed from a wire rope that runs the entire length of the barrier segment. Prior to this design, Wisconsin formed 3-in-diameter loops from a #4 reinforcing steel bar. When the reinforcing steel was being bent, many times it would fracture. Another problem encountered while using reinforcing steel for loops was that the large diameter loops did not allow the barriers segment to mate sufficiently close to each other. A 3-in gap between the barriers was possible even when they were pushed up against each other. This gap allowed for up to 1 1/2 - to 2-in of misalignment between the adjacent units, which could lead to snagging problems when impacted by vehicles.

Wisconsin had previously used #6 reinforcing steel for the pin, but upon learning from accidents in Minnesota that these #6 pins bent easily, they converted to the 1 1/4-in-diameter-steel pin. Wisconsin had also used the 5/8-in-diameter-wire rope, but after an analysis they went back to the 1/2-in-diameter-wire rope, which Illinois and Minnesota use. This allowed Wisconsin to have a standard barrier that could be used throughout the three-State region. The 1/2-in-diameter-wire rope was analyzed by the bridge department, who determined that the 1/2-in-diameter-wire rope provided adequate strength.

Wisconsin uses 10-ft-barrier segments with #4 reinforcing steel throughout. The wire rope that forms the loop is connected to the #4 rebars with wire sizing. The cable is embedded 3 ft into the concrete, which provides enough bond resistance to keep from being pulled out, even with only the sizing on it. The Minnesota design discussed also in this appendix, shows a cable running the entire length of the barrier segment and that loops back on the ends, and is also a Wisconsin option. Wisconsin uses reinforcing steel because they believe that the rigid bar makes fabricating a concrete barrier easier.

In horizontal curves the barriers can be used in curvatures up to 5 degrees. In vertical curves the barriers are a problem near shoulders or ditches where there is a break in the vertical alignment. Generally, there are no problems in horizontal curves. The barrier is used for temporary use only. On bridges, a channel is mounted to the bridge deck and the barriers are placed on top of the channel to anchor them and to keep them from sliding horizontally.

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