Optimum Design of Pin and Loop Portable Concrete Barrier Connectors

JAMES LOUMIET, JERRY L. GRAHAM, AND JAMES MIGLETZ

Portable concrete barriers provide positive protection for highway work zones. Since the connection is often structurally the weakest part of the barrier system, connector design is a critical variable in barrier performance. A survey was conducted to determine which connectors are used by the states. The pin and loop connector is the most widely used, and for this reason, was singled out for analysis. This paper contains a static analysis of a pin and loop connector. The analysis, along with past crash test experience, is used to determine optimum pin and loop connector design. A table is included that lists the strengths of pin and loop connectors used by the states.

Portable concrete barriers are used to provide positive protection for highway work zones and to separate work activity from traffic moving through the work zone. Originally, timber barricades were used to perform this function, but research by the Virginia Highway and Transportation Research Council in the 1970s found that 45.3 percent of the vehicles that came into contact with timber barricades penetrated the work zone (*1*). As a result, the timber barricade was eventually replaced by the more effective concrete barrier.

Several varieties of concrete barriers have been designed and used in the field. The most commonly used barrier is the New Jersey barrier. It is 32 inches high and has a 24-inch base width and a 6-inch top width. It also has a 55-degree batter-curb face and an upper portion that is at 84 degrees from the horizontal. The barrier is designed to both protect workers and equipment behind the work zone and to safely redirect vehicles impacting the barrier.

Originally, concrete barriers were used as permanent installations in medians to separate traffic. In some phases of highway construction, barriers were also used in work zone traffic control. While most of the concrete barrier was cast in place, some precast barriers were also used. Precast barriers led to the development of a barrier that could be moved from one location to another and could be placed in position temporarily.

Initially the segments of the portable concrete barrier (PCB) were simply butted end-to-end. It soon became evident, however, that the segments needed to be connected to be effective. While the use of PCB, especially the New Jersey barrier, spread rapidly in the 1970s, various agencies developed a wide variety of methods for connecting the barrier segments. As stated in one report, "Although 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"(*2*).

Graham-Migletz Enterprises, Inc., P.O. Box 348, Independence, Mo. 64050.

PRESENT USE OF PORTABLE CONCRETE BARRIER CONNECTORS

In a 1985 telephone survey, the Federal Highway Administration (FHWA) polled states through regional offices to determine what types of connectors were being used in each state. The authors sent the results of this survey to the principal construction engineer of each state highway agency, including Puerto Rico and the District of Columbia. A letter was also sent asking each engineer to verify the type of connector used in his or her state, and to send copies of the state's standard plan(s) on portable concrete barriers.

Forty-eight of the 52 agencies polled responded to the survey and confirmed the type of PCB connector used. Some states specified a number of connectors, having some as primary and others as alternates. Some states specified a number of acceptable connectors with no preference. Table 1 shows the complete survey results (*3*).

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. Forty-six agencies use some variation of the pin and loop connector. The pin and loop category is further divided into four subdivisions: pin and rebar (27 agencies), pin and wire rope (14 agencies), pin and eyebolt (2 agencies), and pin and plate (1 agency). Two agencies did not specify the type of pin and loop connector used.

Need for Design Analysis of PCB Connectors

For the PCB system to protect work zones and redirect vehicles, it must be capable of withstanding the kinetic energy exerted by an impacting vehicle. Since the connection is often structurally the weakest part of the barrier system, the connection design is often a critical variable in barrier performance for a given impact. The connector must not only absorb some of the impact energy, but must also be able to limit the movement and rotation of barrier segments. Past research has shown that barriers with stronger and stiffer connections will laterally deflect less than barriers with weaker and looser connections. Crash testing has shown that barrier connectors with higher torsional strength and stiffness help prevent barrier torsional rotation, and hence overturn, and prevent vehicle ramping for a vehicle impacting a barrier (*3*). Crash testing has also shown that loop arrangement on pin and loop connectors is a critical variable in barrier performance. Figure 1 shows the two most common types of loop arrangements—

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	Straight Tongue & Groove		
	with Steel Dowels	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	Welsbach	20 ft	Yes
	with Side Plate			
New Mexico	Pin & Rebar		12 ft 6 in	Yes
	Straight Tongue & Groove		10 ft	
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 min.	Yes
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		
		Triple Dowel	30 ft ± 4 in	
Utah	Pin & Plate	Pin & Wire Rope	10 ft, 12 ft,	Yes
			12 ft 6 in, 20 ft	
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	Yes
			10 ft	

TABLE 1 *continued*

State	Primary Connector	Alternate Connector	Barrier Segment Length	Confirmed By Engineer
Wisconsin	Pin & Rebar with Wire Rope		10 ft	Yes
Wyoming	Pin & Rebar		10 ft	Yes
	Pin & Wire Rope			
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		

inserted and staggered. Since limited lateral deflection and limited torsional rotation are arguably the most important feature of a PCB, it is preferable to use barriers with stronger, stiffer connectors.

Pin and loop connectors were singled out for analysis because of their widespread use. As stated earlier, analysis of these connectors is important since connector design directly influences barrier performance for a given impact. Also, there is much contradiction among previous reports for some connector static strengths. For example, one study (*4*) gives the tensile capacity of the Idaho pin and rebar as 61 kips, whereas another study (*5*) gives this same capacity as 23 kips. It was impossible to tell why these discrepancies occurred since only one report (*4*) showed the computations that yielded their capacities.

Forces Involved

Figure 2 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 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 capacities analyzed are the ultimate tensile capacity (*P*), the ultimate moment capacity (*M*), the ultimate shear capacity (*V*), and the ultimate torsion capacity (*T*). In general, barrier connectors will usually be subjected to moment or torsion dynamic loading because of impact. For this reason, moment and torsion capacities are the most important gauge of connector strength. Tensile capacity is important because it directly determines the moment capacity. Shear capacity is important because barrier deflection has been shown to be sensitive to this capacity. In general, a pin and loop connector under tensile loading conditions will fail because of any of the following reasons:

1. Pin fails because of transverse loading. If the pin is not anchored on both top and bottom, then failure will occur at incipient yielding of the pin, because 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

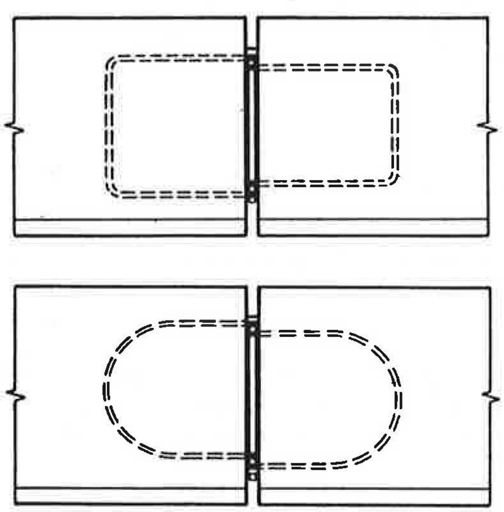

FIGURE 1 Pin and loop connectors: inserted loop arrangement (California), *top;* staggered loop arrangement (Arkansas), *bottom.*

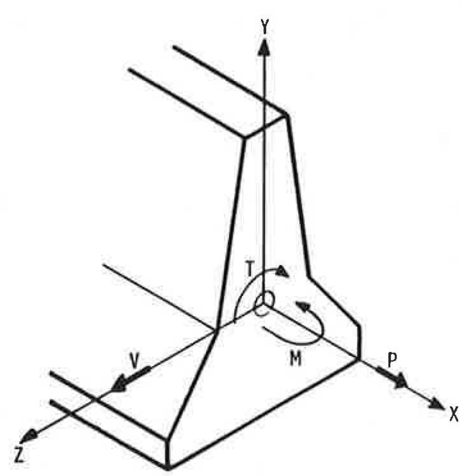

FIGURE 2 Coordinate system for portable concrete barrier.

certainly in danger of doing so. If the pin is anchored, however, then pin failure is because of rupture.

2. Loops fail in tension.
3. Loops pull out of barrier (only if top and bottom loops are not physically connected).
4. Concrete shears because of force on loops.

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

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.

A pin and loop connector under shear loading conditions will fail for any of the following reasons:

1. Pin fails because of transverse loading.
2. Loops fail in tension.
3. Concrete shears laterally because of forces on loops (this occurs for rebar loops only).
4. For wire rope, concrete shears longitudinally because of forces on loops, since forces on wire rope always resolve 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.

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 because of 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.

Analytical Determination of Connector Strengths

An analysis of the pin and wire rope connector used by the Arkansas State Highway Department is given in this section. The following assumptions were used for the analysis:

1. Connector strengths are analyzed using the mechanical properties of the actual materials in the connector. Mechanical properties are assumed only when actual properties are unknown.
2. Concrete is an integral part of the connector system, and is therefore taken into account in the failure analysis.
3. The ultimate shear strength (vc) of concrete is governed by the equation

$$v_c = 2\sqrt{f'_c} \quad (1)$$

where f'_c is the compressive strength of the concrete.

4. Barriers are pulled tight at the connectors for pin and loop connectors.
5. Anchored pins are evaluated for catastrophic failure. Unanchored pins are evaluated for incipient yielding.
6. Forces on anchor nuts that are induced by transverse loading on the pin are assumed to be of insufficient magnitude to cause failure in the threaded portion of the pin.
7. All structural steels are considered ductile.
8. All structural hardware is the same material unless otherwise specified.
9. The masses of the various components of the connector are disregarded.

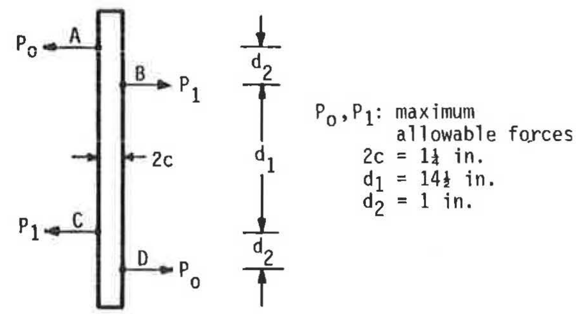

FIGURE 3 Free body diagram (FBD) of pin of Arkansas connector (tensile).

The Arkansas pin and wire rope is shown in Figure 3. It has a pin diameter of 1.25 inches and a wire rope diameter of five-eighths of an inch.

Tensile Capacity

The possible modes of failure of this connector in tension are: (a) pin fails in transverse loading, (b) loops fail in tension, or (c) concrete shears because of forces on loops.

Tensile Capacity of Connector for Pin Failure The pin is under the loading condition shown in Figure 3. Letting

$$F = P_1 + P_0 \quad (2)$$

and summing forces in the X direction yields:

$$\sum F_x = P_1 + P_0 - P_1 - P_0 = 0 \quad (3)$$

Now summing moments about D yields:

$$\sum M_D = 0 = d_2P_1 - (d_2 + d_1)\,P_1 + (d_1 + 2d_2)\,P_0 \quad (4)$$

$$P_1 = [(d_1 + 2d_2)/d_1]\,P_0 = 1.138\,P_0 \quad (5)$$

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_0/A and the maximum moment is $d_2 \times P_0$.

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_0:

$$P_0\,(\sigma_f)(A) = (60\text{ ksi})\,\frac{\pi}{4}\,(1.25)^2$$
$$P_0 = 73.6\text{ kips} \quad (6)$$

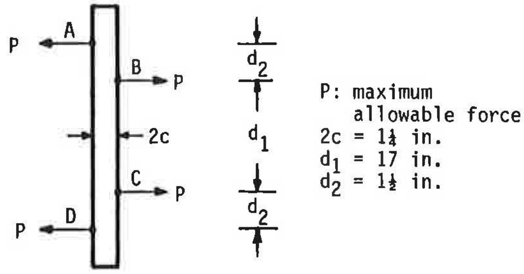

FIGURE 4 FBD of pin of California connector (tensile).

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

$$F = P_0 + P_1 = 73.6 \text{ kips} + (1.138)(73.6 \text{ kips})$$

$$F = 157.8 \text{ kips}$$

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

For an unanchored pin as used by the California Department of Transportation, the pin is under the loading condition shown in Figure 4. 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:

$$\sigma_x = \frac{Mc}{I} = \frac{4d_2P}{\pi c^3} = \frac{4(1.5)P}{\pi(0.625)^3} = 7.823\ P \qquad (7)$$

$$\tau_{xz} = \frac{P}{A} = \frac{P}{c^2} = \frac{P}{\pi(0.625)^2} = 0.815\ P \qquad (8)$$

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

$$\sigma_1 = \frac{\sigma_x}{2} + \left[\left(\frac{\sigma_x}{2}\right)^2 + (\tau_{xz})^2\right]^{1/2} = 7.908\ P \qquad (9)$$

$$\sigma_2 = 0 \qquad (10)$$

$$\sigma_3 = \frac{\sigma_x}{2} - \left[\left(\frac{\sigma_x}{2}\right)^2 + (\tau_{xz})^2\right]^{1/2} = -0.085\ P \qquad (11)$$

The Von Mises (Distortion Energy) Theory (*6*) will be used to evaluate for the strength of the pin, because this theory best agrees with experimental results. This theory states that failure will 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:

$$(7.908\ P)^2 + (0.085\ P)^2 + (9.993\ P)^2 = 2\sigma_f^2 \qquad (12)$$

Because the pin is not anchored on both ends, it is evaluated for incipient yielding.

Therefore, for σ_f = 36,000 psi, P = 4.5 kips. Letting $F = 2\ P$:

$$F = (2)\ (4.5 \text{ kips})$$

$$F = 9.0 \text{ kips}$$

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

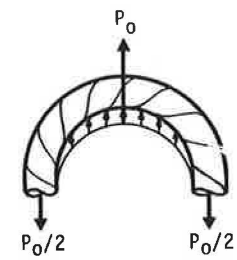

FIGURE 5 FBD of loop of Arkansas connector (tensile).

Tensile Capacity of Connector for Loop Failure For loop failure to occur, these 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 5.

Arkansas specifies a five-eighths of an inch diameter wire rope with a minimum breaking strength of 17.9 tons (35,800 lb).

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

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

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

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

Tensile Capacity of Connector for Concrete Shear The concrete is in the loading condition shown in Figure 6. 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,

$$v_c = 2\sqrt{2{,}500} = 100 \text{ psi}$$

For A_c = 466.35 inches, 2 A_c = 932.7 inches
Solving for F:

$$F = (100 \text{ psi})(932.7 \text{ inches})$$

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

Therefore, the concrete is the failure mechanism for the connector under static loading conditions.

The tensile capacity of the Arkansas pin and wire rope connector is 93.3 kips and is determined by the capacity of the concrete in shear.

Moment Capacity

The moment capacity, M, of the Arkansas pin and wire rope connector is the distance, r, between the pin center and the

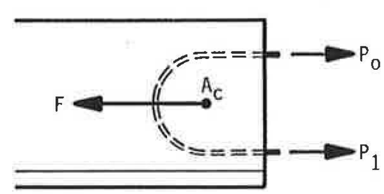

FIGURE 6 FBD of concrete of Arkansas connector (tensile).

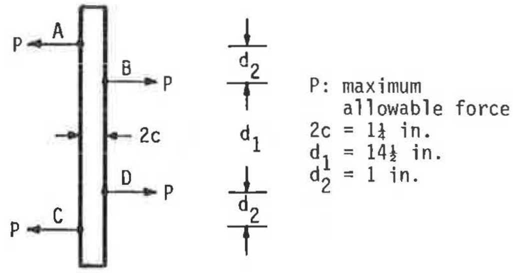

FIGURE 7 FBD of pin of Arkansas connector (torsion).

extreme fibers of the barrier crossed into the tension capacity of the connector. Therefore,

$$M = r \times F$$

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

$$M = 93.3 \text{ kip-ft} \qquad (13)$$

The moment capacity of the connector is 93.3 kip-ft.

Shear Capacity

The possible modes of failure of this connector in shear are: (a) pin fails in transverse loading, (b) loops fail in tension or (c) concrete shears because of forces on loops. Since these modes of failure are the same as those for tensile capacity, the shear capacity is equal to the tensile capacity. The shear capacity of the Arkansas pin and wire rope connector is 93.3 kips.

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 7. Equilibrium of moments and forces dictates that $F = 2\,P$.

TABLE 2 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

Solving for P yields:

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

Now solving for F:

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

$$F = 147.2 \text{ kips}$$

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

$$T = r_2 \times V \qquad (14)$$

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

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

$$T = 121.3 \text{ kip-ft}$$

The torsion capacity, T, of this connector is 121.3 kip-feet

Summary of Analytical Determination of Connector Strengths

The results of the complete static analysis are shown in Table 2, which contains the structural capacities of the pin and rebar, pin and wire rope, and pin and eyebolt connectors. The structural capacities for these connectors were calculated using GME in-house software modeled after the analysis just performed.

The most interesting result of the analysis of pin and loop connectors is the large difference in the capacities of connectors with anchored pins and 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 range from 77 kips to 106 kips. This discrepancy is because the mode of failure is assumed to change from yielding to rupture when going from unanchored to anchored pins. Admittedly, these results should be viewed with some caution, since these failure modes may not be the actual failure modes of barriers under impact conditions. For example, Caltrans crash tests 291-294 showed that impacted barrier segments tend to rotate on the bottom edge opposite the impact side, rather than around the segments' longitudinal axis. Because of this, loops on inserted loop connectors interlock when a segment begins rotating, which helps to prevent segment rotation. This makes the connector much stronger in torsion than static analysis shows it to be, and much stronger in torsion than a staggered loop connector and this illustrates the importance of crash testing in determining connector acceptability. This analysis also illustrates the large difference in structural integrity between the unanchored pin connector and the structurally superior anchored pin connectors. Yet to date, only six states specify anchoring for their pins.

Invariably, the pin is the critical component of unanchored pin connectors because the pin needs only to be pulled and bent out of the loops to destroy the integrity of the connection. One factor that compounds this problem is the distance between the two top loops or the two bottom loops of the connector. The greater this distance 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 in strength calculations. For example, doubling the pin diameter will increase the strength of a pin by a factor of 4.

On the other hand, the structural capacity of the various components of anchored pin connectors is in the same general range, between 77 kips to 160 kips. This is because the anchored pin must now be ruptured to destroy the integrity of the connection. While unanchored pin moment capacities range from 2 kips to 13.4 kips, anchored pin moment capacities range from 76.6 kips to 106 kips.

The analysis also revealed that not all connector designs are based on standardized design practices as specified by authoritative organizations. For example, one state connector did 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 and cited by Wang and Salmon (*7*).

As stated earlier, only one report, TTI's *Barriers in Construction Zones* (*4*), actually showed the computations that 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 or different connector specifications than GME did for analysis. For example, TTI used 60 ksi for failure strength in some calculations, whereas GME used 36 ksi for several calculations. Other differences included different analytical techniques and round-off errors.

RECOMMENDATIONS

The following are recommendations based on the state of portable concrete barrier technology.

1. Inserted loops are preferable to staggered loops in pin and loop connector design because of the inserted loops resistance to torsional overturn of individual barrier segments.
2. Pins in pin and loop connectors should be anchored at both ends of the barrier segment. Only nut and washer anchoring will prevent pins from being bent out of the loop when the pin is loaded.
3. Because of its greater strength, wire rope is generally preferable to steel reinforcing bars for forming loops in pin and loop connectors.
4. States should use PCB connectors only if they have been structurally analyzed and successfully crash tested.
5. Connectors should be designed to match the strength of all components of the connector.

REFERENCES

1. F. N. Lisle and B. T. Hargroves. Evaluation of Performance of Portable Precast Traffic Barriers. In *Transportation Research*

Record 769, TRB, National Research Council, Washington, D.C., 1980, pp. 30–37.
2. J. M. Morales. *Technical Advisory for Concepts of Temporary Barriers in Work Zones*. FHWA, U.S. Department of Transportation, May 1985.
3. J. L. Graham, J. R. Loumiet, and J. Migletz. *Portable Concrete Barrier Connectors*. Final Report, FHWA, U.S. Department of Transportation, Aug. 1987.
4. D. L. Ivey et al. *Barriers in Construction Zones*. Volume 3: Appendices B, C, D, E, and F, Texas Transportation Institute, Texas A&M University, College Station, April 1985, pp. 163 – 199.
5. D. L. Ivey et al. Portable Concrete Median Barriers: Structural Design and Dynamic Performance. In *Transportation Research Record 769*, TRB National Research Council, Washington, D.C., 1980, pp. 20–30.
6. J. A. Collins. *Failure of Materials in Mechanical Design, Analysis, Prediction, Prevention*. Wiley-Interscience. 1981, pp. 137–141, 149.
7. C. K. Wang and C. G. Salmon. *Reinforced Concrete Design*. 4th ed. Harper & Row, New York, 1985, pp. 209, 215–219.