Structural Performance Levels for Portable Concrete Barriers

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ABSTRACT

There is a significant variation in the structural performance of different types of portable concrete barriers (PCBs) because of variations in connection strengths. Results of 20 full-scale crash tests on PCBs are examined and relationships between PCB connection strength and structural performance are established. On the basis of this information, five different service levels are proposed to classify PCB structural performance. These service levels are based on estimates of connection shear, torsion, and bending strength. This information can be used to estimate the structural performance of existing barriers or it can be used as a guide in barrier design.

During the past several years the use of the portable concrete barrier (PCB) as a longitudinal construction-zone barrier has become widespread. The construction-zone PCB consists of several precast PCB segments that are transported to the construction zone and connected end to end. The cross-sectional geometries of the PCB segments are patterned after the popular concrete median barrier safety shape. The concrete median barrier has proven to be an acceptable permanent barrier for many applications, and experience has shown that PCBs have performed well as construction barriers (1).

In general, the strength of PCB connections is much less than that of the PCB segments away from the connections. Therefore, the overall strength of the PCB is controlled by the strength properties of its connections. A survey of different types of connections in use reveals that there is a significant variation in their respective structural capacities. Hence, there is a significant variation in the potential structural performance of PCBs. Variations of PCB performance have been predicted by using computer simulations and have been observed in full-scale crash tests (1,2).

A straightforward procedure is presented to estimate the structural performance of PCBs on the basis of the strength properties of the connections. To do this, five different structural performance levels are defined based on the energy associated with the lateral component of velocity of the impacting vehicle. This energy is termed the impact severity (IS) in NCHRP Report 230 (3). Then existing full-scale PCB impact tests are examined and the IS for each test is calculated. In addition, the strength properties of the various connections represented in the crash tests are estimated by using simplified structural analyses. These results are then combined to make conservative estimates of the connection strength properties necessary to achieve each level of the structural performance scale. The issue of vehicle stability is not addressed.

PCB STRUCTURAL PERFORMANCE CRITERIA

Of primary concern in assessing the structural performance of PCBs is their relative capability to redirect impacting vehicles. Three service levels for classifying the strength of longitudinal barriers are recommended in NCHRP Report 230 (3). The authors used these three service levels in combination with two additional ones to develop the five PCB structural service levels presented in Table 1, which are based on the mass, velocity, and angle of impact of the most severe impact that the barrier is capable of withstanding.

IS is given as follows:

$$IS = 1/2\ (w/g)\ (V_i \sin \theta)^2 \qquad (1)$$

where

V_i = impact velocity,
w = weight of the impacting vehicle,
g = acceleration of gravity, and
θ = angle of impact (3).

The impact severity is a convenient measure of the relative severity of automobile impacts. In general, the impact severity may not always be an accurate indicator of the impact forces. However, for barriers of similar construction and stiffness, such as PCBs, it is a reasonable indicator of the relative magnitude of these forces. The minimum IS values corresponding to the five structural performance levels in the rating system are presented in Table 1.

TABLE 1 PCB Service Levels Compared with NCHRP 230 Service Levels

PCB Service Level	Corresponding NCHRP Level (3)	Collision Characteristics			IS (kip-ft)
		Weight (kips)	Speed (mph)	Angle (degrees)	
A	–	4.5 or 3.5	45 or 60	15	20.4
1	1	4.5	60	15	36.5
2A	2	4.5	60	25	97.3
2B	–	20	60	15	161.1
3	3	40	60	15	322.2

FULL-SCALE CRASH-TEST DATA

During the past 10 years, a total of 20 full-scale crash tests have been conducted on different PCBs.

TABLE 2 Summary of PCB Tests

Testing Agency	Test No.	Test Conditions Speed (mph)	Angle (degree)	Weight (kips)	Segment Length (ft)	Static Deflection (ft)	Data Point No.	Test Results and Comments
TTI	TX-1	60.9	17.8	4.5	15	0.9	1	Smooth redirection; negligible barrier damage
TTI	TX-2	55.9	26	4.51	15	1.3	2	Smooth redirection; negligible barrier damage
TTI	3825-7	59.2	25	4.5	12	1.8	3	Smooth redirection; slight barrier damage
TTI	3825-6	60.1	24	4.5	12	1.8	4	Vehicle redirected but rolled after recontact with pavement subsequent to primary collision; slight barrier damage
TTI	3825-5	60.7	25	4.5	12	1.6	5	Smooth redirection; slight barrier damage
TTI	3825-9	63.4	25	4.51	12	6.5	6	Smooth redirection; side plates failed; slight barrier damage
TTI	3825-8	57.7	15	20.0	15	1.8	7	Bus redirected but rolled 90 degrees onto side after collision; slight barrier damage
TTI	CMB-2	60.0	24	4.54	30	1.1	8	Smooth redirection; negligible barrier damage
Caltrans	291	65	7	4.86	12.5	0.5	9	Smooth redirection; slight barrier damage
Caltrans	292	68	23	4.86	12.5	1.9	10	Vehicle redirected but penetrated over top of barrier and slid sideways along top; segment fractured; major barrier damage
Caltrans	293	66	40	4.86	20	NA	11	Vehicle penetrated and rolled; segment tipped over; major barrier damage
Caltrans	294	39	25	4.7	20	0.5	12	Smooth redirection; steel vertical connection rods severely bent; significant barrier damage
SWRI	CMB-18	62	25	4.5	20	NA	13	Vehicle redirected; flexural failure in the segments; major barrier damage
SWRI	CMB-24	56	24	4.5	20	3.4	14	Vehicle redirected; joint failures; significant barrier damage
New York	NY-17	53	25	4.25	20	1.3	15	Smooth redirection; slight barrier damage
New York	NY-18	58	25	4.23	20	0.9	16	Vehicle redirected but rolled after recontact with pavement subsequent to primary collision; slight barrier damage
New York	NY-44	65	25	4.3	8	1.4	17	Vehicle redirected but subsequently rolled; slight barrier damage
New York	NY-45	66	15	2.18	8	0.3	18	Vehicle redirected but could have rolled; slight barrier damage
New York	NY-46	61	25	4.35	8	0.6	19	Vehicle redirected; slight barrier damage
New York	NY-47	61	15	2.18	20	0.3	20	Vehicle smoothly redirected; no significant barrier damage

Note: TTI = Texas Transportation Institute; Caltrans = California Department of Transportation; SWRI = Southwest Research Institute.

These tests were conducted by independent research organizations in California, Texas, and New York (2). General descriptions of the test conditions and results are presented in Table 2.

The structural performance of each PCB included in Table 2 is classified as either good or poor on the basis of NCHRP Report 230 criteria and the level of damage experienced by the barrier. The PCBs identified by data point numbers 6, 10, 13, and 14 were judged to exhibit poor structural performance. The remainder of the PCBs were judged to have exhibited good structural performance.

Previous evaluations of crash-test data have shown that the strength of PCBs is controlled to a large extent by the structural properties of the connections. The important structural properties of the connections are shear, bending, and torsional resistance (1,2). Further, it has been shown that acceptable estimates of these structural properties can be achieved by using the structural details of the connections and simplified structural analysis techniques (2).

There are seven different basic connection configurations represented in Table 2. General details of these seven connection configurations are presented in Figures 1-7. By using these details and specific connection details available from the respective testing agencies, estimates of the structural properties of the connections associated with each of the 20 crash tests were calculated (2). These data are presented in Table 3. Included in Table 3 are calculated values of IS and estimates of the connection slack in degrees. The connection slack is defined as the joint rotation before the connection exhibits significant flexural resistance. Excessive connection slack can result in excessive barrier deflection during an impact.

Figures 8, 9, and 10 are plots of connection strength versus impact severity. In some cases, the connection strength was greater than that required to resist the impact force. The performance of these PCBs is plotted as open triangles. In the other cases, the connection strength was less than that required to resist the impact forces. The performance of these PCBs is plotted as solid triangles. As would be expected, there is a boundary between the good performance data points and the poor performance data points for each strength property. This boundary corresponds to the minimum connection strength required to resist an impact of a given severity. The precise location of the boundary is not always well defined by the available test data.

In the absence of more definitive information, conservative locations for the boundaries between good and poor performance are determined by defining a lower-bound envelope on the good data points with two lines. These lines are located by using three control points for each structural property. The locations of these control points are based on the 20 data points discussed earlier, related information, and the goal of reaching conservative strength requirements. Logically, the magnitude of the shear, flexural, and torsional connection capacities required to resist a given level of impact must increase as the impact severity increases. The greater the impact severity, the more connection strength that is required. This trend is evident in the boundary lines indicated in Figures 8, 9, and 10 with dashed lines. The rationale behind location of the three control points for each structural property is discussed in the following.

For the lowest service level (A), the characteristics of the Virginia tongue and groove connection were used as control points. Details of the Virginia tongue and groove connection are similar to those of the partial tongue and groove with side plates (Figure 2), except that there are no side plates. The structural properties of this connection were calculated to be 32 kips for shear, 0 kip-ft for moment, and 7 kip-ft for torsion (2). These values were assigned to the service level A control points in each graph. This may appear arbitrary,

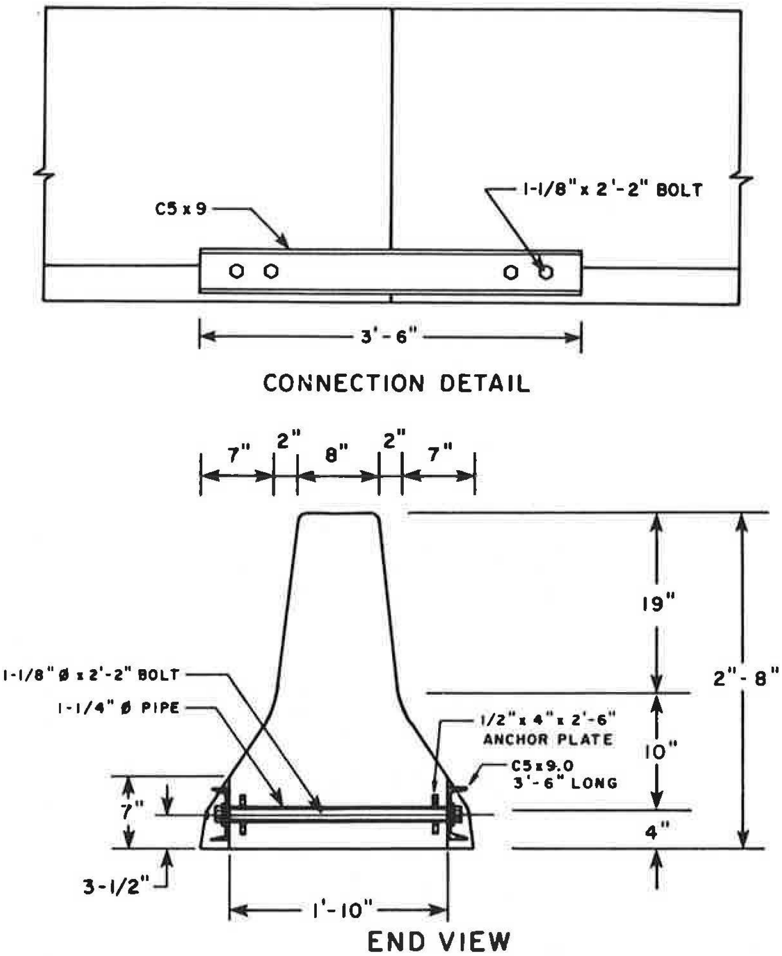

FIGURE 1 Side plate or side channels (channel splice).

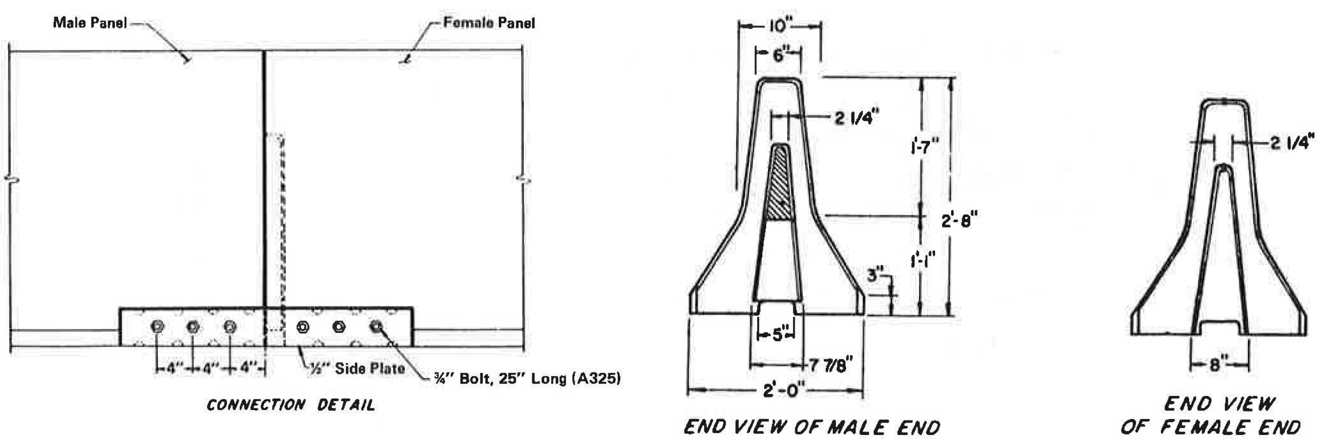

FIGURE 2 Partial tongue and groove and side plates.

because the Virginia tongue and groove connection has not been subjected to formal testing. However, it is the opinion of the authors that this barrier will meet at least service level A criteria based on favorable field performance reported in the literature (4).

In a related research project, Buth measured the maximum normal force between an impacting automobile and barrier for level 2A and 2B impacts (5). These data provide upper limits for the shear forces that must be resisted by connections at these impact levels. These measured upper-limit shear forces appear to be consistent with the shear strength data presented in Figure 10. Therefore, these two points are used in combination with the Virginia tongue and groove point to define the boundary line between good and poor shear strength performance. This boundary line is presented in Figure 10.

Examinations of data points 3, 4, 5, and 6 in Tables 2 and 3 show that a good connection performance at a level 2A test can be achieved with a nominal moment capacity of 50 kip-ft. These data

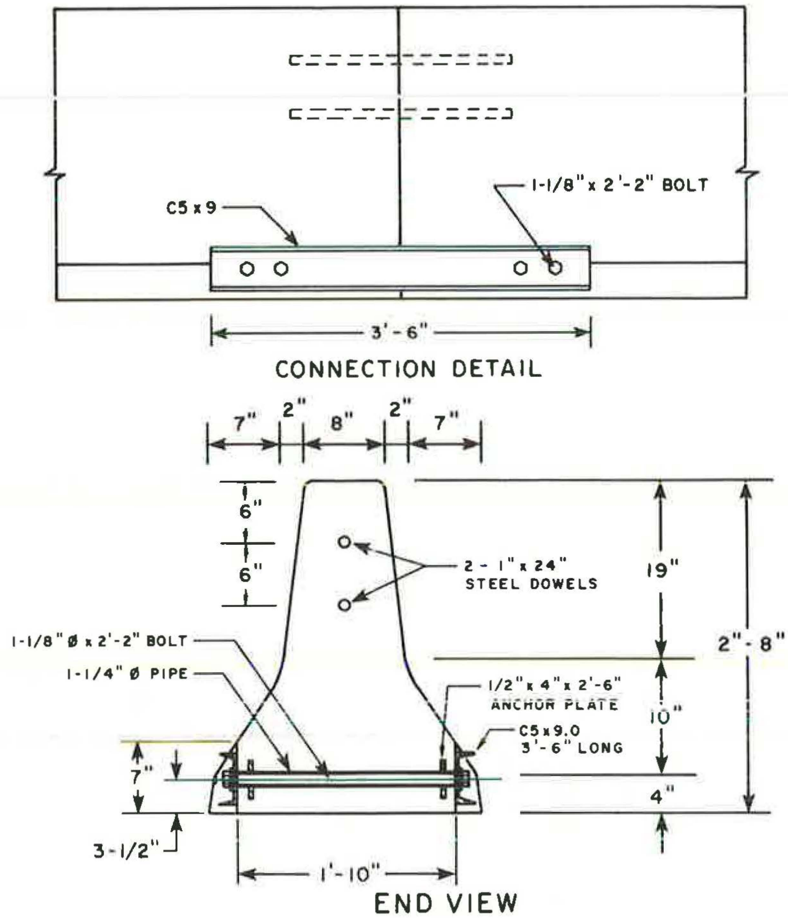

FIGURE 3 Side plate or side channels with steel dowel shear connection (channel splice).

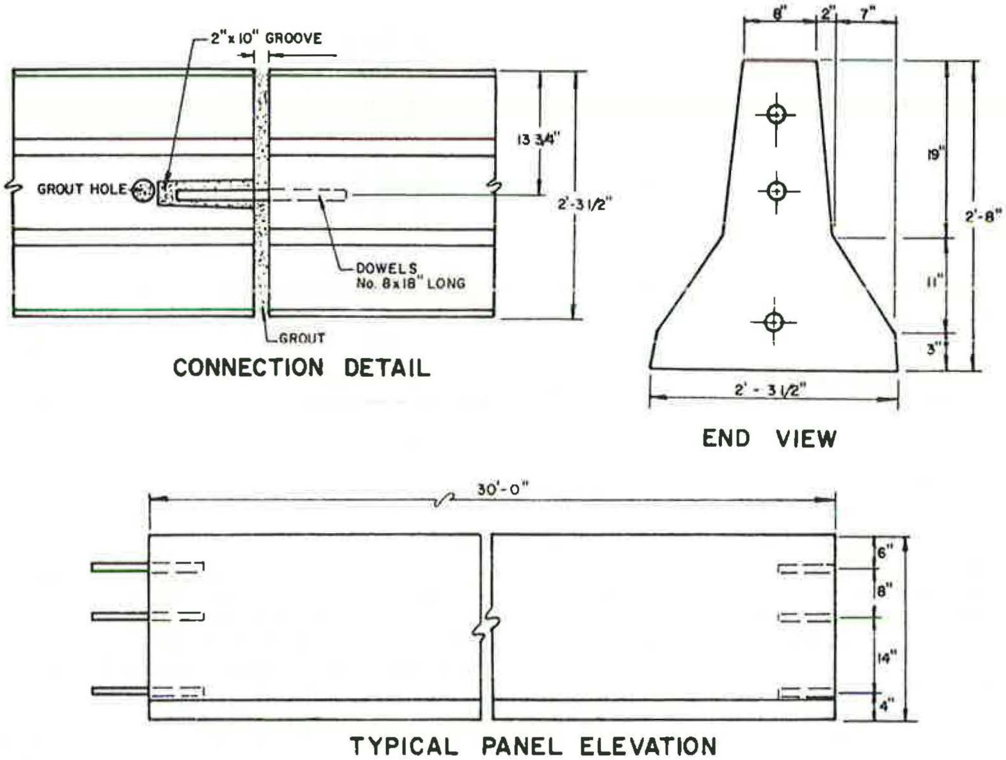

FIGURE 4 Grouted dowels (steel dowel joint).

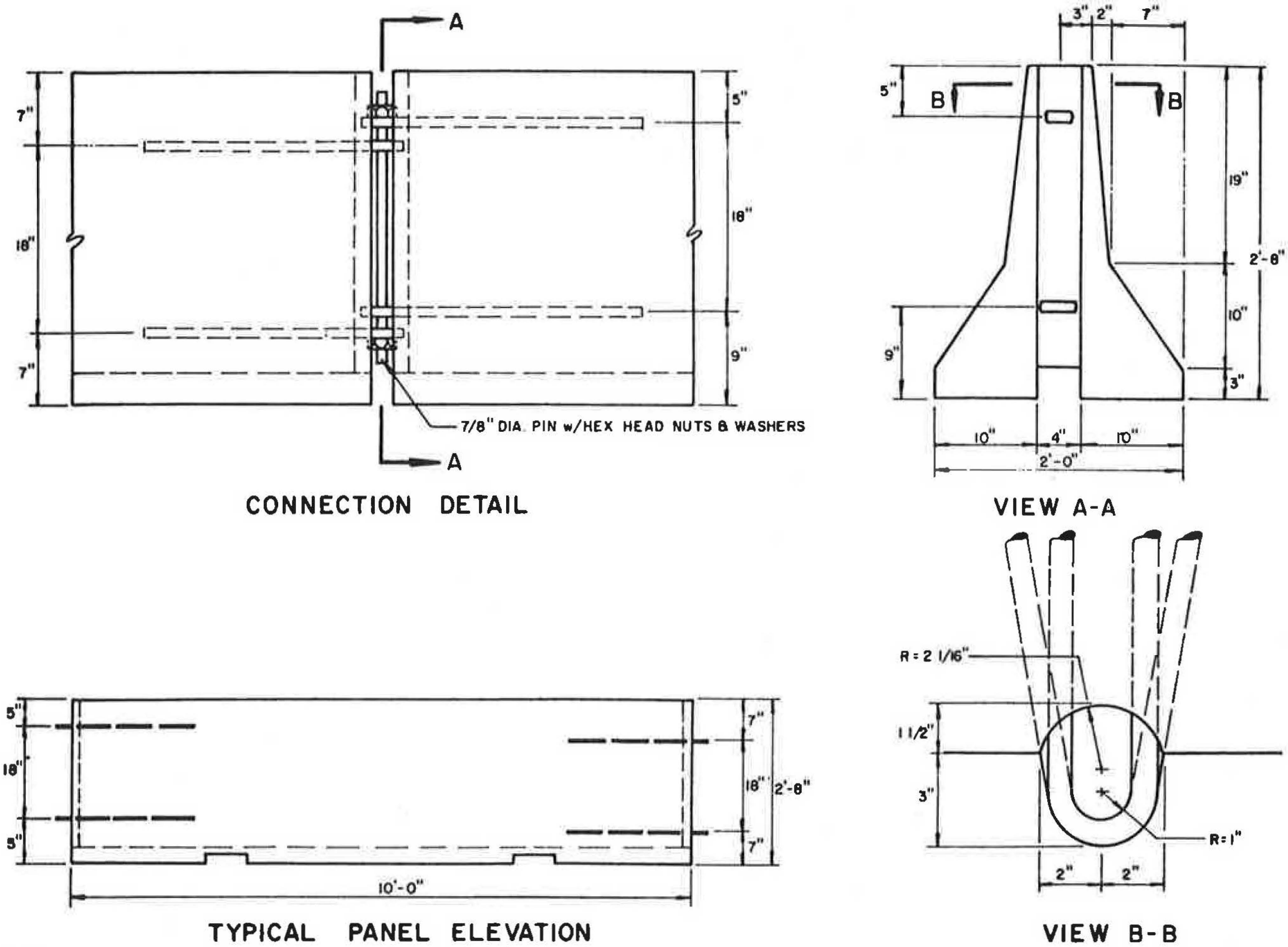

FIGURE 5 Vertical steel pin (pin and rebar).

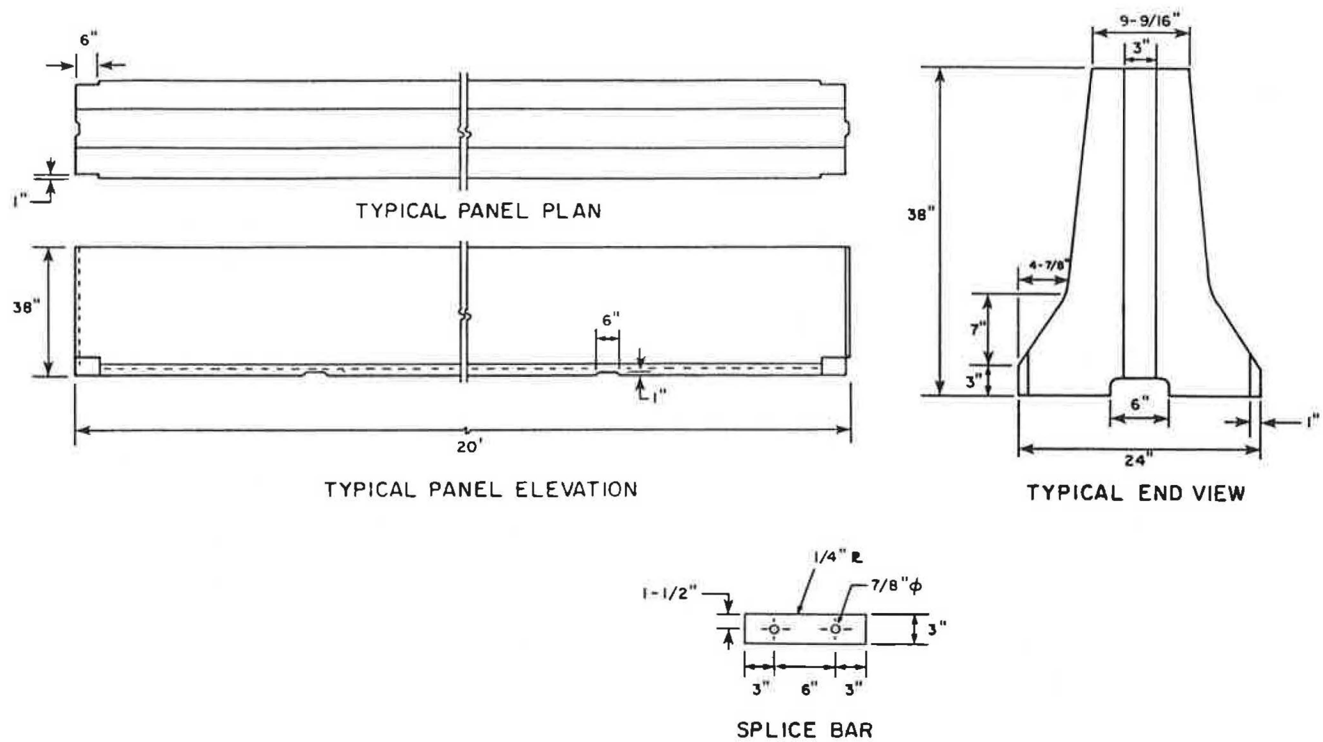

FIGURE 6 Tongue and groove and side plates.

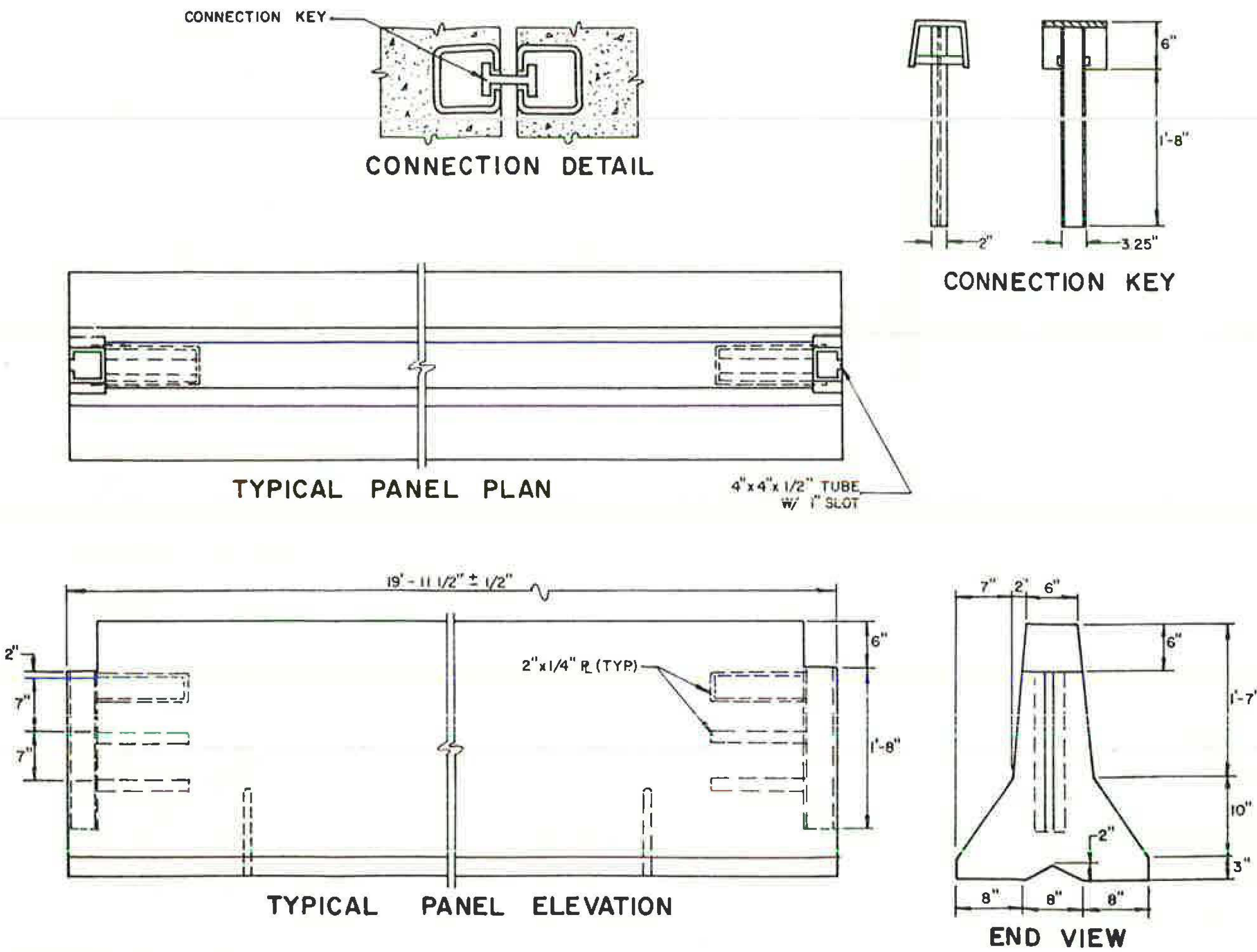

FIGURE 7 Vertical I-beam.

TABLE 3 Summary of PCB Connection Properties

Data Point No.	Connection Description	Connection Slack (degrees)	Connection Capacities Shear (kips)	Moment (kip-ft)	Torsion (kip-ft)	IS[a] (kip-ft)
1	Side plates (3 ft 6 in. x 5 in x 1/2 in., steel) (Figure 1)	5	90	117	53	52.1
2	Side channels (C5 x 9 x 3 ft 6 in., steel) (Figure 1)	3	90	117	53	90.5
3	Partial tongue and groove and side plates (3 ft 0 in. x 4 in. x 1/2 in. steel) (Figure 2)	3	76	103	67	94.1
4	Partial tongue and groove and side plates (3 ft 0 in. x 4 in. x 3/8 in. steel) (Figure 2)	3	57	77	52	89.8
5	Partial tongue and groove and side plates (3 ft 0 in. x 4 in. x 1/2 in. steel) (Figure 2)	3	38	52	37	98.9
6	Partial tongue and groove and side plates (3 ft 0 in x 4 in. x 1/8 in. steel) (Figure 2)	3	19	26	22	108.2
7	Side channels (C5 x 9 x 3 ft 6 in. steel) (Figure 3) plus three no. 8 x 18 in. steel rebar dowels	3	135	117	73	149.2
8	Three grouted dowels (no. 8 x 18 in.) (Figure 4)	0	60	50	37	90.3
9	Vertical steel pin (7/8 in. ø x 26 in.) (Figure 5)	9	46	31	35	10.2
10	Vertical steel pin (7/8 in. ø x 26 in.) (Figure 5)	9	46	31	35	114.6
11	Vertical steel pin (1 in. ø x 26 in.) (Figure 5)	8	55	40	42	292.2
12	Vertical steel pin (1 in. ø x 26 in.) (Figure 5)	8	55	40	42	42.6
13	Tongue and groove and side plates (12 in x 3 in. x 1/2 in. steel) (Figure 6)	3	27	9	16	103.2
14	Tongue and groove and side plates (12 in x 3 in. x 1/4 in. steel) (Figure 6)	3	27	9	16	77.8
15	Vertical I-beam (3 1/4 in. x 2 in.) (Figure 7)	10	208	61	87	71.2
16	Vertical I-beam (3 1/4 in. x 2 in.) (Figure 7)	0	208	61	87	86.3
17	Vertical I-beam (3 1/4 in. x 2 in.) (Figure 7)	10	208	61	87	108.4
18	Vertical I-beam (3 1/4 in. x 2 in.) (Figure 7)	10	208	61	87	21.2
19	Vertical I-beam (3 1/4 in. x 2 in.) (grouted joints) (Figure 7)	0	208	61	87	96.6
20	Vertical I-beam (3 1/4 in. x 2 in.) (Figure 7)	10	208	61	87	18.1

[a]The IS is calculated by using the data presented in Table 2 and Equation 1.

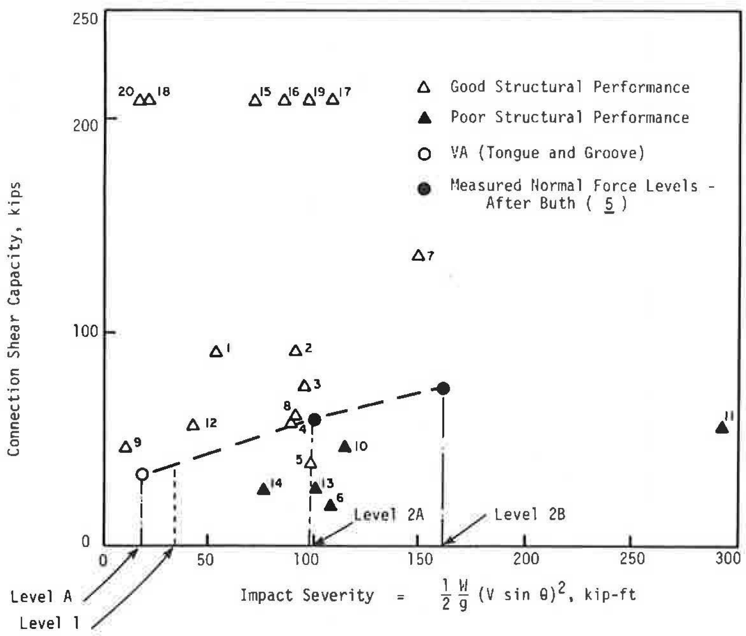

FIGURE 8 Shear capacity of connection versus impact severity.

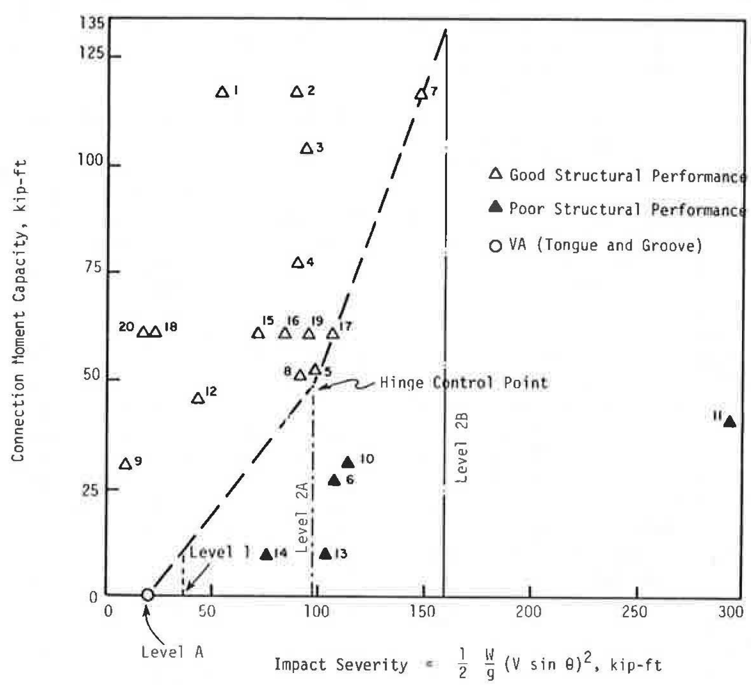

FIGURE 9 Moment capacity of connection versus impact severity.

points were used to establish a conservative control point as shown in Figure 9. Another control point for the moment capacity boundary line is established by using either point 17 or point 7. These control points are combined with the Virginia tongue and groove control point to establish boundary lines for moment capacity. By setting the boundary lines in this manner it appears that the required moment capacities for the service levels above 2A are probably quite conservative.

Further, examinations of data points 3, 4, 5, and 6 show that a nominal torsion capacity of 40 kip-ft is required to achieve a service level of 2A. This value was used as a control point. The second control point is established by data point 7. The use of data point 7 as the second control point may result in overdesigning barriers at the 2B impact energy level. The gap between points 7 and 11 through which the boundary line must pass is wide. The placement chosen here is likely to be highly conservative. The third control point is again established with the Virginia tongue and groove point. As with the flexural capacity, the torsional boundary line probably overestimates to some degree the required torsional strength for most connections.

PCB PERFORMANCE CRITERIA

The information presented in the previous section provides a relationship between the strength prop-

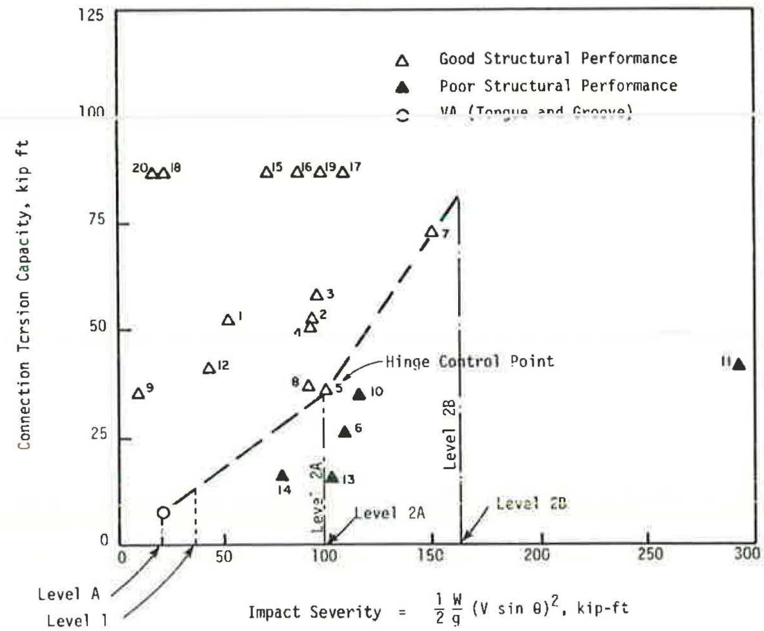

FIGURE 10 Torsion capacity of connection versus impact severity.

erties of PCB connections and the IS. This information allows the PCB structural service levels to be stated in terms of the estimated strength properties of the connections as shown in Table 4, which can be used to estimate the structural performance of existing PCBs. In addition, the information can be used as a design guideline for PCB connections. However, use of this information is not intended to supplant the need for full-scale testing.

In addition to strength considerations, adequate barrier performance often depends on the lateral deflection during impact. Experience suggests that a PCB may not perform adequately if the lateral deflections are greater than 2 ft (2). Further, the permissible lateral deflection based on available work-zone space varies significantly from site to site. The amount of lateral deflection that a particular PCB experiences has been shown to be primarily a function of three factors: the moment capacity of the connection, the amount of slack in the connection before development of the flexural resistance, and the length of the PCB segment (1,2). Guidance regarding the calculation of barrier deflection with variations of the three factors listed previously is available elsewhere (1,2).

Barrier connection strengths and barrier deflections are not the only factors that need to be considered in determining the safety performance of PCBs. For a full evaluation of safety, applicable sections of NCHRP Report 230 should be considered (3). Especially important is the criterion of rolling. Achieving structural connection adequacy and limiting deflection will not, in all cases, prevent vehicle rolling, as the testing to date illustrates.

TABLE 4 PCB Structural Service Levels

PCB Service Level	IS (kip-ft)	Minimum Shear Strength (kips)	Minimum Torsional Strength (kip-ft)	Minimum Flexural Strength (kip-ft)
A	20.4	30	10	0
1	36.5	40	15	10
2A	97.3	60	40	50
2B	161.1	75	80	130
3[a]	322.2	150	160	260

[a]The strength values for this interval are highly speculative. They were determined by multiplying the strength values for service level 2B by the ratio of the impact severities of service levels 3 and 2B.

COMPARISONS OF DIFFERENT CONNECTION DETAILS

Most PCB connections in use today can be placed into one of 10 different generic categories, arbitrarily designated C1 through C10. Specific details of these categories were presented by Ivey and Buth (2). In Table 5 the strength characteristics of the 10 different connection categories are presented, which were determined by using a uniform set of material strength properties (2). These relative strengths do not necessarily represent the strength of any particular design. Each connection could be made stronger or weaker by using different materials. The purpose of this exercise is to compare generic types of connections, not specific connection designs.

It may be seen that connections C1, C2, and C3 are rated as service level A because they lack significant moment capacities. Connections C4 and C5 are rated as service level 1, and connections C6, C7, C8, and C9 are rated as service level 2A. Connection C10 is qualified as service level 2B. Examination of Table 5 suggests that the classification is dominated by the moment capacity requirement for levels 1 and higher.

Connection C10 is the only connection analyzed that appears to meet service level 2B. This does not mean that it is the only design that can meet 2B. Connections C6 through C9 could all be designed to meet the 130-kip-ft moment capacity. Likewise, specific connections could be designed to be weaker than indicated in Table 5. Before a particular connection is advocated for a given level of service, a specific analysis of that connection should be made. In addition, other safety-related issues, such as vehicle roll stability, should be addressed. This is particularly true for the higher service levels.

CONCLUSIONS

PCBs have become increasingly popular as longitudinal construction-zone barriers in the past few years.

TABLE 5 Strength Characteristics of Connection Types

Connection Designation	Connection Name	Strength Characteristics[a] Shear (kips)	Moment (kip-ft)	Torsion (kip-ft)	Estimated Service Level
C1	Tongue and groove	32	0	7	A
C2	Steel dowel	60	0	37	A
C3	Grid slot	60	0	30	A
C4	Top T-lock	190	11	56	1
C5	Lapped joint	47	22	24	1
C6	Pin and rebar	85	57	60	2A
C7	Vertical I-beam	210	61	87	2A
C8	Bottom T-lock	590	66	370	2A
C9	Channel splice	67	80	36	2A
C10	Welsbach	160	139	94	2B

[a]These strength characteristics were calculated by using average material strength *(2)*. In many cases these levels are not the same as those for specific designs used in some states.

Examinations of in-service experiences and results of full-scale crash tests show that the strength of PCBs is primarily a function of the PCB connection strength. Further, an examination of the wide variety of different types of PCBs in use around the country reveals a wide variation in PCB connection strength properties, which ultimately leads to a wide variation in PCB performance. Five different service levels are presented in this paper to quantify the structural performance of PCBs on the basis of shear, torsion, and bending strength of the connections. By using these service levels, the expected structural performance of 10 different types of generic connections in common use was classified.

The information contained in this paper can be used to estimate the structural performance of existing barriers or it can be used as a guide in the design of PCB connections. The service levels do not address the stability of the impacting vehicle.

ACKNOWLEDGMENTS

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