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TL-5 Development of 42 and 51-inch Tall Single-faced, F-shape Concrete Barriers

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TL-5 DEVELOPMENT OF 42- AND 51-IN. TALL, SINGLE-FACED, F-SHAPE CONCRETE BARRIERS

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Technical Report Documentation Page

1. Report No. TRP-03-149-04	2.	3. Recipient's Accession No.

4. Title and Subtitle	5. Report Date
TL-5 Development of 42- and 51-In. Tall, Single-Faced, F-Shape Concrete Barriers	April 30, 2004
	6.

7. Author(s)	8. Performing Organization Report No.
Faller, R.K., Sicking, D.L., Larsen, J., Rohde, J.R., Bielenberg, R.W., and Polivka, K.A.,	TRP-03-149-04

9. Performing Organization Name and Address	10. Project/Task/Work Unit No.
Midwest Roadside Safety Facility (MwRSF) University of Nebraska-Lincoln 527 Nebraska Hall Lincoln, Nebraska 68588-0529	
	11. Contract © or Grant (G) No. SPR-3(017)

12. Sponsoring Organization Name and Address	13. Type of Report and Period Covered
Midwest States' Regional Pooled Fund Program Nebraska Department of Roads 1500 Nebraska Highway 2 Lincoln, Nebraska 68502	Final Report 2001-2004
	14. Sponsoring Agency Code RPFP-02-04

15. Supplementary Notes

Prepared in cooperation with U.S. Department of Transportation, Federal Highway Administration

16. Abstract (Limit: 200 words)

A review of tractor-trailer impacts into rigid barrier systems was conducted in order to study the dynamic lateral vehicular loads imparted into common barrier systems. For a selected number of crash tests, researchers performed two linear regression analyses on the estimated lateral peak load versus impact severity. This analytical investigation resulted in a peak lateral design load ranging between 681 to 689 N (153 to 155 kips) and 1,081 to 1,103 N (243 to 248 kips) for the AASHTO PL-3 and NCHRP 350 TL-5 impact conditions, respectively.

Researchers then determined the redirective capacities of four existing barrier designs using the standard yield-line analytical procedures. It was determined that the standard yield-line analytical procedures likely underestimate the redirective capacity of solid, reinforced concrete parapets, since other factors likely contribute to the redirective capacity of reinforced and non-reinforced concrete barrier systems. Since a "modified" yield-line analysis procedure is currently unavailable, the standard yield-line analysis procedure was used but in combination with a scaled-down design impact load. The new barrier systems were developed using a peak design impact load ranging between 939 N (211 kips) to 996 N (224 kips) or based on an average design impact load of approximately 965 N (217 kips).

Two single-faced, F-Shape concrete barrier systems were designed to meet the TL-5 impact safety standards using the existing yield-line analysis procedures and for 1,067-mm (42-in.) and the 1,295-mm (51-in.) top-mounting heights. Attachment options were provided for anchoring the barriers to generic reinforced concrete slabs and a median foundation. The barrier and foundation systems were based on a conservative design approach where full-scale vehicle crash testing would not be required. Three research projects were recommended that would advance the state-of-the art for concrete barrier designs and provide new, more economical and innovative barrier and anchorage support systems

17. Document Analysis/Descriptors	18. Availability Statement
Highway Safety, Analysis, Design, Roadside Appurtenance, Longitudinal Barrier, Concrete Barrier, Median Barrier, and Bridge Rail	No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	55	

DISCLAIMER STATEMENT

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views nor policies of the State Highway Departments participating in the Midwest States' Regional Pooled Fund Research Program nor the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGMENTS

Minnesota Department of Transportation

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Mohammad Dehdashti, P.E., Design Standards Engineer
Ron Cassellius, Former Research Program Coordinator
Andrew Halverson, P.E., Former Assistant Design Standards Engineer
Bruce Westby, P.E., Assistant Design Standards Engineer
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Daniel Smith, P.E., Research and Development Engineer

Montana Department of Transportation

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1 INTRODUCTION

1.1 Problem Statement

Median barriers are commonly used to separate divided highways and opposing vehicle traffic lanes. Although many median barriers are very similar to the longitudinal barriers found along the roadside, some designs differ in that each side of the barrier can safely accommodate vehicle-to-barrier impacts. For freeway conditions with a larger percentage of heavy vehicle traffic, taller median barrier designs may also be warranted. In many of these situations, 1,067-mm (42-in.) tall rigid concrete median barriers have been used to prevent larger trucks from crossing over the median and penetrating into opposing traffic lanes. In the past, these barrier systems have included both un-reinforced and reinforced versions of a symmetric, New Jersey shape concrete median barrier installed with a thin asphaltic concrete layer adjacent to the base (*1-3*). Consequently, situations may arise that require the use of single-faced barriers within the median and along unidirectional lanes of traffic in order to protect motorists from drop-offs, steep slopes, or other hazards. Single-faced barriers may also be preferred within medians that are too wide to use the double-faced barrier designs and too narrow to meet the clear zone requirements. Besides the capability to capture and redirect heavy trucks, increasing barrier height from 1,067 mm (42 in.) to approximately 1,270-mm (50 in.) or more has been considered in order to provide additional glare screen protection.

In general, single-faced barriers are believed to be less expensive to construct, more aesthetically pleasing, and better suited to separate traffic lanes from pedestrian and bicycle facilities than the double-faced barriers. However, there are concerns that these taller, single-faced barrier designs may not have the necessary steel reinforcement nor foundation anchorage required for redirecting the heavier, tractor-trailer vehicles. More specifically, it is uncertain whether these

single-faced barriers will meet the Test Level 5 (TL-5) safety performance criteria provided in the National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* (*4*).

Recently, the Wisconsin Department of Transportation (Ws DOT) began to update their standard concrete barrier details to incorporate a change from the New Jersey shape to the F-shape. During that process, it also seemed appropriate to investigate other desired features, including a change from the more standard 813-mm (32-in.) high barriers to the taller versions in order to provide glare screen protection as well as the ability to contain and redirect heavy tractor-trailer vehicles.

1.2 Research Objective

The objective of this research project was to design two different single-faced concrete barrier systems to meet the TL-5 criteria of NCHRP Report No. 350. The two F-shape concrete barrier configurations were to include both 1,067-mm (42-in.) and 1,295-mm (51-in.) tall designs. The final designs were to address: (1) the prevention of concrete blowouts using an appropriate amount of steel reinforcement; (2) the prevention of vehicle penetrations through or vaulting over the top of the barriers; and (3) the determination of adequate foundation and anchorage support to prevent lateral displacement and tipping of the barrier systems, especially under situations with no backside fill or other support material.

1.3 Research Plan

This study involved the design and development of two single-faced, F-shape concrete barriers for median applications. Past research efforts have shown that 1,067-mm (42-in.) tall concrete barriers have successfully redirected heavy, tractor-trailer vehicles. In addition to these

studies, other heavy vehicle crash testing projects have been performed on different bridge railing and barrier configurations as well as on an instrumented tall concrete wall. The lateral dynamic impact loads imparted to these various barrier configurations have been determined using the onboard vehicle accelerometers, and if available, using the load cells placed on the instrumented wall panels. An analysis of these test results led to an estimate for an impact load for use in this research study. This impact load was then used to design two single-faced, F-shape concrete barriers for median and bridge railing applications. A yield-line analysis and strength design procedure (*5-6*) provided the means for determining the redirective capacities of the candidate barrier configurations. Once the final barrier designs were selected, appropriate foundation and anchorage details were determined for each configuration.

2 LITERATURE REVIEW AND BARRIER INVESTIGATION

For this study, a literature review was performed in order to acquire information on the testing of barrier systems capable of redirecting heavy, tractor-trailer vehicles. The information garnered from this review was used to provide insight into the actual design lateral impact load as well as the minimum barrier configuration (i.e., reinforcement, size, thickness, structural capacity, anchorage, etc.) deemed necessary to redirect heavy vehicles. For this study, results from previous crash tests conducted into rigid barrier systems were deemed more appropriate for consideration and further evaluation, thus resulting in the selection of eleven tractor-trailer vehicle crash tests with gross vehicle weights ranging approximately between 22,680 kg (50,000 lbs) and 36,287 kg (80,000 lbs). These eleven tests were conducted on rigid bridge railings and median barriers in the 1980's through the 1990's in the Unite States (U.S.) (*1-2*,*7-14*). All of these referenced crash tests were performed by the Texas Transportation Institute (TTI) of Texas A&M University.

Tables 1 and 2 contain a summary of the test information and parameters for the tractor-trailer barrier impacts identified above. Table 3 contains a summary of the test conditions and results for the tractor-trailer barrier impacts identified previously. Finally, Table 4 provides available barrier displacements and calculated barrier capacities for selected barrier configurations chosen from these crash tests.

As previously mentioned, a barrier's redirective capacity, R_W, can be determined using the yield-line analysis and strength design procedure presented in References (*5*) and (*6*). For this procedure, a barrier's redirective capacity is largely based on the moment capacity of the wall, M_W, the cantilever capacity between the parapet and the foundation, M_C, the capacity of additional beams located near the top of the parapet, M_B, and the height of the parapet, H. In addition, R_W is

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Table 1. Summary of Test Information and Parameters for Selected Heavy, Tractor-Trailer Vehicle Crash Tests.

Test No.	Test Date	Test Agency	Reference No.	Vehicle		Barrier Description	Barrier Height (in.)
				Trailer Type	Cab Type		
7046-3	4/7/87	TTI	7	Van	Cab-Over	Vertical Instrumented Tall Wall	90
7046-4	5/8/87	TTI	7	Tanker	Conventional	Vertical Instrumented Tall Wall	90
7046-9	5/27/88	TTI	7	Van	Conventional	Vertical Instrumented Tall Wall	90
7069-13	7/11/88	TTI	11-12	Van	Conventional	Vertical Concrete Bridge Railing	42
7069-10	3/3/88	TTI	11-12	Van	Conventional	F-Shape Concrete Bridge Railing	42
4798-13	5/26/83	TTI	2	Van	Cab-Over	Reinforced Concrete Median Barrier w/ Asphalt	42
7162-1	8/9/90	TTI	1	Van	Conventional	Ontario Un-Reinforced Concrete Median Barrier w/ Asphalt	42
1	NA	TTI	8-9	Tanker	Conventional	Texas T5 Modified Concrete Bridge Railing w/ Extended NJ Shape	90
2416-1	9/18/84	TTI	10	Van	Conventional	Texas T5 HT Modified Concrete Bridge Railing w/ Texas C4 Metal Rail w/ 32-In. NJ Shape	50
6	NA	TTI	13	Van	Conventional	Texas C202 Modified Open Concrete Bridge Rail w/ Metal Rail	54
405511-2	12/12/95	TTI	14	Van	Conventional	Vertical Concrete Bridge Railing	42

NA - Not available   TTI - Texas Transportation Institute
1 in. = 25.4 mm

Table 2. Summary of Test Information and Parameters for Selected Heavy, Tractor-Trailer Vehicle Crash Tests (Continued).

Test No.	Reference No.	Test Inertial Weight (lbs)	Individual Weights			Vehicle Dimensions			
			Tractor Front Axle (lbs)	Tractor Rear Tandem Axle (lbs)	Trailer Rear Tandem Axle (lbs)	Tractor Wheelbase (in.)	Trailer Wheelbase (in.)	Overall Tractor-Trailer Length (in.)	Trailer Length (in.)
7046-3	7	80,080	11,680	34,140	34,260	164.5	362.75	612.75	480
7046-4	7	79,900	11,840	33,570	34,490	236	350	665	439.5+
7046-9	7	50,000	8,540	19,790	21,670	169	430.5	703.5	538
7069-13	11-12	50,050	7,920	22,250	19,880	169	438	698	540
7069-10	11-12	50,000	9,400	21,760	18,840	182	434	710	538
4798-13	2	80,180	12,150	34,010	34,020	147.5	368.5	602.5	480
7162-1	1	80,000	11,580	34,350	34,070	171	429.6	688.8	536.4
1	8-9	80,120	12,070	34,050	34,000	201	346	650	439+
2416-1	10	80,080	12,020	34,170	33,890	199.5	377.75	685.25	480
6	13	79,770	11,490	33,760	34,520	162	351	647	480
405511-2	14	79,366	11,210	34,249	33,907	186	413	699	NA

NA - Not available
1 kg = 2.204623 lbs
1 in. = 25.4 mm

Table 3. Summary of Test Conditions and Results for Selected Heavy, Tractor-Trailer Vehicle Crash Tests.

Test No.	Reference No.	Impact Speed (mph)	Impact Angle (degrees)	Impact Severity (kip-ft)		Peak 0.050-Sec Average Decelerations (G's)			
				Entire Truck	Tractor Rear Tandems	Lateral (Rear Tractor Tandem Axle)	Longitudinal (Rear Tractor Tandem Axle)	Lateral (Other Location)	Longitudinal (Other Location)
7046-3	7	55.0	15.3	563.9	240.4	9.7	-3.2	NA	NA
7046-4	7	54.8	16.0	609.4	256.0	12.3	2.1	NA	NA
7046-9	7	50.4	14.6	269.8	106.8	6.8 (Tractor C.G.)	-2.4 (Tractor C.G.)	NA	NA
7069-13	11-12	51.4	16.2	344.1	153.0	Est. 5.0	NA	3.7	-3.3
7069-10	11-12	52.2	14.0	266.6	116.0	Est. 7.5	NA	4.7	-2.2
4798-13	2	52.1	16.5	586.9	248.9	-9.3	-6.5	-9.3	-6.5
7162-1	1	49.6	15.1	446.5	191.7	-7.9	-1.2	-9.7	2
1	8-9	51.4	15	474.0	201.4	5.54	-1.77	6.92	NA
2416-1	10	48.4	14.5	393.1	167.8	5.5	-2.4	NA	NA
6	13	49.1	15	430.6	182.3	5.94	1.68	NA	NA
405511-2	14	49.8	14.5	412.5	178.0	Est. 8	NA	Est. 8	NA

NA - Not available
1 km/hr = 0.6213712 mph   1 Joule = 0.7375621 ft-lbs
1 lb = 0.2248089 N
1 in. = 25.4 mm

Table 4. Summary of Barrier Displacements and Barrier Capacities for Selected Heavy, Tractor-Trailer Vehicle Crash Tests.

Test No.	Reference No.	Barrier Displacement (in.)	Yield-Line Redirective Barrier Capacity, R_W (kips)	
			TTI	MwRSF
7046-3	7	NA	NA	NA
7046-4	7	NA	NA	NA
7046-9	7	NA	NA	NA
7069-13	11-12	NA	198	210
7069-10	11-12	NA	127	129
4798-13	2	NA	NA	Est. $\geq$ 793[1]
7162-1	1	NA	NA	Est. $\geq$ 158[2]
1	8-9	4.0 (Dynamic)	NA	NA
2416-1	10	10.8 (Dynamic)	NA	NA
6	13	12 (P.S.)	NA	NA
405511-2	14	NA	198	210

NA - Not available   P.S. - Permanent Set

[1] - Vertical steel reinforcement was not used to anchor the parapet to the foundation nor to provide the cantilevered moment capacity of the wall, M_C. An estimate for the torsional capacity of the reinforced wall provided a basis for M_C for use within the yield-line analysis procedure for concrete parapets. An estimate for the barrier's redirective capacity, R_W, is shown above.

[2] - Vertical steel reinforcement was not used to anchor the parapet to the foundation nor to provide the cantilevered moment capacity of the wall, M_C. An estimate for the torsional capacity of the un-reinforced wall provided a basis for M_C for use within the yield-line analysis procedure for concrete parapets. An estimate for the barrier's redirective capacity, R_W, is shown above.

1 lb = 0.2248089 N
1 in. = 25.4 mm

significantly influenced by the location of the impact region on the parapet. For example, an impact within an interior region of the parapet provides increased redirective capacity over that occurring near the end of or at an expansion joint within a similarly reinforced parapet. As shown in Table 4, R_W values for the F-shape and vertical concrete bridge railings have been determined by both TTI and the Midwest Roadside Safety Facility (MwRSF). For the F-shape bridge railing, TTI and MwRSF determined R_W to be 565 and 574 N (127 and 129 kips), respectively. For the vertical bridge railing, TTI and MwRSF determined R_W to be 881 and 934 N (198 and 210 kips), respectively. Therefore, it can be stated that the predicted barrier capacities correlated reasonably well when determined by independent research organizations.

In addition to these two single-faced parapets, two other concrete parapets were analyzed by MwRSF researchers - the un-reinforced and reinforced versions of the symmetric, New Jersey shape concrete median barrier. These two parapets were determined to be of special interest since they are included in AASHTO's *Roadside Design Guide* (*3*) and typically are used in median applications where protection for heavy trucks is desired. For both of these designs, no vertical steel reinforcement was utilized to anchor the barrier systems to their foundations. However, a 76-mm (3-in.) asphaltic concrete pad was placed near each barrier's base and on both sides in order to provide resistance to lateral movement.

During both crash tests, the full-size New Jersey barriers redirected the impacting tractor-trailer vehicles without significant consequence. For both configurations, the barriers appeared to have remained attached to the foundation surface without rotation upward nor backward. Since no physical attachment was provided between each barrier and its foundation, there must have been other mechanisms which contributed to the barrier's effective cantilevered moment capacity, and

ultimately to the barrier's overall redirective capacity. Other possible mechanisms for resisting barrier uplift and rotation may have included: (1) the barrier's torsional capacity; (2) the downward vehicular load applied to the barrier resulting from a trailer box leaning on the top of the parapet; (3) the barrier's dead weight based on an unknown effective length and limited by the barrier's bending capacity about the transverse barrier axis; (4) the translational and rotational inertial forces generated as a result of the significant barrier mass and resistance to movement; and (5) the frictional forces generated between the asphaltic concrete overlay and the toe of the concrete barrier's traffic-side face while based on some effective length.

Although several mechanisms may actually contribute to the cantilevered moment capacity, MwRSF researchers believed that the barrier's torsional capacity may have the largest influence on this M_C parameter out of the five items listed above. An attempt was then made to quantify the torsional capacities for both the un-reinforced and reinforced versions of the 1,067-mm (42-in.) high symmetric, New-Jersey shape concrete median barrier using the elementary procedures identified in reinforced concrete design texts published by Wang and Salmon (*15*) and MacGregor (*16*). For the un-reinforced Ontario tall wall, the minimum nominal torsional capacity was believed to be greater than or equal to 43.3 kN-m (489 kip-in). For the reinforced New Jersey parapet, the minimum nominal torsional capacity was believed to be greater than or equal to 163.3 kN-m (1,845 kip-in). Torsional capacities were then adjusted using a reduction factor of $\phi = 0.85$. Using the analytical procedures described above, the redirective capacities for the un-reinforced Ontario tall wall and reinforced New Jersey barrier were estimated to be greater than or equal to 703 N (158 kips) and 3,527 N (793 kips), respectively.

Based on these results, several points could be made. First, the 1,067-mm (42-in.) tall, reinforced New Jersey shape concrete median barrier provides significant reserve capacity above that needed to redirect TL-5 tractor-trailer vehicles. Therefore, it is believed that this barrier should be further optimized using a reduction of the longitudinal and vertical steel reinforcement.

Second, the redirective capacity of the non-reinforced, Ontario tall wall was significantly lower than that provided by the other 1,067-mm (42-in.) tall concrete parapets evaluated according to the actual TL-5 impact conditions. Following a review of the test results, it should be noted that some of the vehicle ballast broke loose and fell out of the side of the trailer box during the impact event. It was also observed that the trailer's rear tandem axle assembly broke away from the trailer box prior to the impact between the barrier and the trailer's tandem axle. Therefore, the potential exists that the un-reinforced concrete median barrier may not have experienced the full impact load nor the double load pulse that would have been observed had the ballast remained in place and the rear tandem remained attached to the trailer. However, the non-reinforced Ontario tall wall was found to meet the heavy vehicle impact safety standards.

Although TL-5 heavy vehicle impacts into un-reinforced concrete median barriers may result in increased barrier damage, barrier performance is still judged acceptable when the vehicle is contained and redirected on the traffic-side face of the barrier system.

3 DESIGN IMPACT LOAD

3.1 Instrumented Wall Testing with Heavy Vehicles

In 1989, researchers at the TTI completed a study to determine the magnitude and duration of the dynamic lateral loads occurring when heavy vehicles impact rigid concrete barriers (7). In an effort to measure these loads, a 2,286-mm (90-in.) tall rigid concrete wall was constructed and instrumented with load cells. Methodologies were also presented for calculating the impact force from the onboard vehicle accelerometer data. For each test, a comparison was then made between the measured dynamic wall loads and that determined from the vehicle accelerometers. A total of ten full-scale vehicle crash tests were performed, consisting of a full-size sedan, pickup trucks, Chevrolet Suburbans, a single-unit truck, an inter-city bus, tractor van-trailers, and a tractor tank-trailer.

Three full-scale vehicle crash tests were performed with tractor-trailer vehicles ranging in weight from approximately 22,680 kg (50,000 lbs) to 36,287 kg (80,000 lbs), as summarized in Table 5. For the 36,287-kg (80,000-lb) vehicle tests, the peak impact forces were measured to be 979 N (220 kips) and 1,815 N (408 kips) for the van- and tanker-style trailers, respectively. During these same tests, the peak impact forces imparted to the wall by the tractor's rear tandem axles were found to be 783 N (176 kips) and 943 N (212 kips) for the van- and tanker-style trailers, respectively. For the 22,680-kg (50,000-lb) vehicle test, a peak impact force of 667 N (150 kips) was imparted to the wall, occurring as a result of the impact by the tractor's rear tandem axles.

Based on the 36,287-kg (80,000-lb) truck test results, a lateral impact force between 783 N (176 kips) and 943 N (212 kips) would seem appropriate for designing 1,067-mm (42-in.) high rigid parapets; since, the rail design would be governed by the load imparted by the tractor's rear tandem

Table 5. Tractor-Trailer Vehicle Crash Tests and Results for Instrumented Wall.

| Test No. | Trailer Type | Vehicle Weight (lbs) | Impact Condition | | Impact Severity (kip-ft) | Maximum Impact Force[1] (kips) | Height of Maximum Resultant Force (in.) | Maximum Impact Force of Rear Tractor Tandem Axles[1] (kips) | Height of Resultant Force of Rear Tractor Tandem Axles (in.) |
			Speed (mph)	Angle (deg)					
7046-3	Van	80,080	55.0	15.3	563.9	220	70.0	176	44.0
7046-4	Tank	79,900	54.8	16.0	609.4	408	56.0	212	40.5
7046-9	Van	50,000	50.4	14.6	269.8	150	35.0	150	35.0

[1] - Maximum 0.050-sec average force as determined from the instrumented wall loads cells.

1 kg = 2.204623 lbs

1 in. = 25.4 mm

1 km/hr = 0.6213712 mph

1 lb = 0.2248089 N

1 Joule = 0.7375621 ft-lbs

axles versus the peak load measured higher up the instrumented "tall" wall. Additionally, if one considered the results from the 22,680-kg (50,000-lb) truck test, a higher lateral impact load may need to be considered than that discussed previously. In past research, it has been reported that the lateral impact force is approximately proportional to the impact severity for a given test. For convenience, the target impact severities for the 22,680-kg (50,000-lb) and 36,287-kg (80,000-lb) truck test conditions have been provided in Table 6. Therefore, if an adjustment were made to the lateral load based on an increase in impact severity for the TL-5 test condition, then the lateral impact force would be increased by nearly 63 percent or to a force level of 1,085 N (244 kips).

3.2 Load Estimation Using Linear Regression

Following a review of the instrumented wall results for both the 22,680-kg (50,000-lb) and 36,287-kg (80,000-lb) tractor-trailer crash tests, it was determined that a more rational method for estimating the design impact load was required. Therefore, MwRSF researchers performed a linear regression on the estimated lateral peak load versus impact severity for a selected number of tractor-trailer tests. This linear regression analysis was conducted for both the total impact severity of the tractor trailer as well as for the impact severity of the tractor's rear tandem axles. For this analysis, the lateral peak loads were calculated using the 50-msec average lateral accelerations multiplied by the corresponding weights (i.e., total vehicle weight or weight on tandems). The six tractor-trailer crash tests used for this investigation were TTI test nos. 7069-10, 4798-13, 7162-1, 2416-1, 6, and 405511-2, as shown in Tables 1 through 4.

For the linear regression analysis of the impact load and severity data, the general curve was determined to be of the general form:

$$y = m \cdot x + b \tag{1}$$

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Table 6. Target Impact Conditions for Tractor-Trailer Vehicle Tests According to NCHRP Report No. 350 (_4_) and AASHTO (_17_).

Test No.	Test Guidelines	Trailer Type	Test Designation	Vehicle Weight kg (lbs)	Impact Condition		Impact Severity kJ (kip-ft)	Suggested IS Tolerance kJ (kip-ft)
					Speed kph (mph)	Angle (deg)		
5-12	NCHRP (_4_)	Van	36000V	36,000 (79,366)	80.0 (49.71)	15.0	595.4 (439.2)	-72.3 to +76.9 (-53.3 to +56.7)
6-12	NCHRP (_4_)	Tank	36000T	36,000 (79,366)	80.0 (49.71)	15.0	595.4 (439.2)	-72.3 to +76.9 (-53.3 to +56.7)
PL-3	AASHTO (_17_)	Van	50 Kips	22,680 (50,000)	80.47 (50.0)	15.0	379.5 (279.9)	NA

1 kg = 2.204623 lbs
1 in. = 25.4 mm
1 km/hr = 0.6213712 mph
1 lb = 0.2248089 N
1 Joule = 0.7375621 ft-lbs

where y - barrier impact load, kips,
        x - calculated impact severity, kip-ft,
        m - slope of the line, and
        b - vertical ordinate for the line at x=0 and set equal to 0.

For this case, the slope coefficient, m, was determined using the following expression:

$$m = \sum x_i \cdot y_i / \sum x_i^2 \qquad (2)$$

where i = 1 to n (n = 6 for this analysis).

From the analysis based on using the total vehicle impact severity, the following linear relationship

was determined:

$$Y = (0.5543) \cdot X_{TV} \qquad (3)$$

where Y - design impact load, kips, and
        X_{TV} - total vehicle impact severity, kip-ft.

This relationship is shown graphically in Figure 1.

From the analysis based on using the impact severity for the tractor's rear tandem axle, the following

relationship was determined:

$$Y = (1.2988) \cdot X_{RT} \qquad (4)$$

where Y - design impact load, kips, and
        X_{RT} - impact severity for tractor's rear tandem axle, kip-ft.

This relationship is shown graphically in Figure 2.

Using Equation (3), the design impact load was estimated for two tractor-trailer vehicle test

cases, as provided in Table 7a. For the TL-5 impact condition of NCHRP Report No. 350, a design

impact load was calculated to be 1,081 N (243 kips). For the PL-3 impact condition found in

AASHTO's *Guide Specifications for Bridge Railings* (*17*), a design impact load of 689 N (155 kips)

was determined.
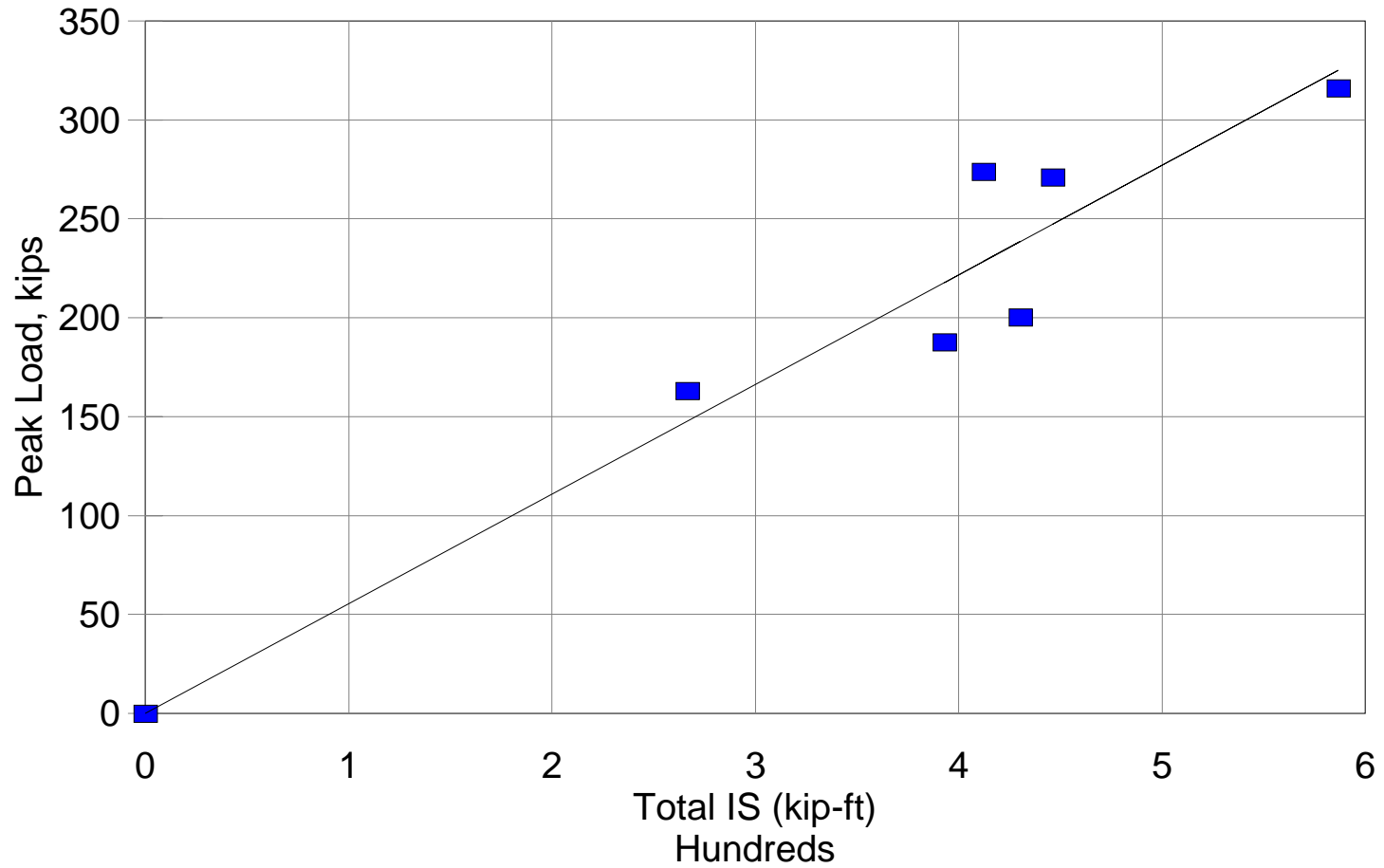
Figure 1. Peak Load and Total Impact Severity (Tractor-Trailer Impacts) [1lb=0.2248089 N and 1 Joule=0.7375621 ft-lbs]
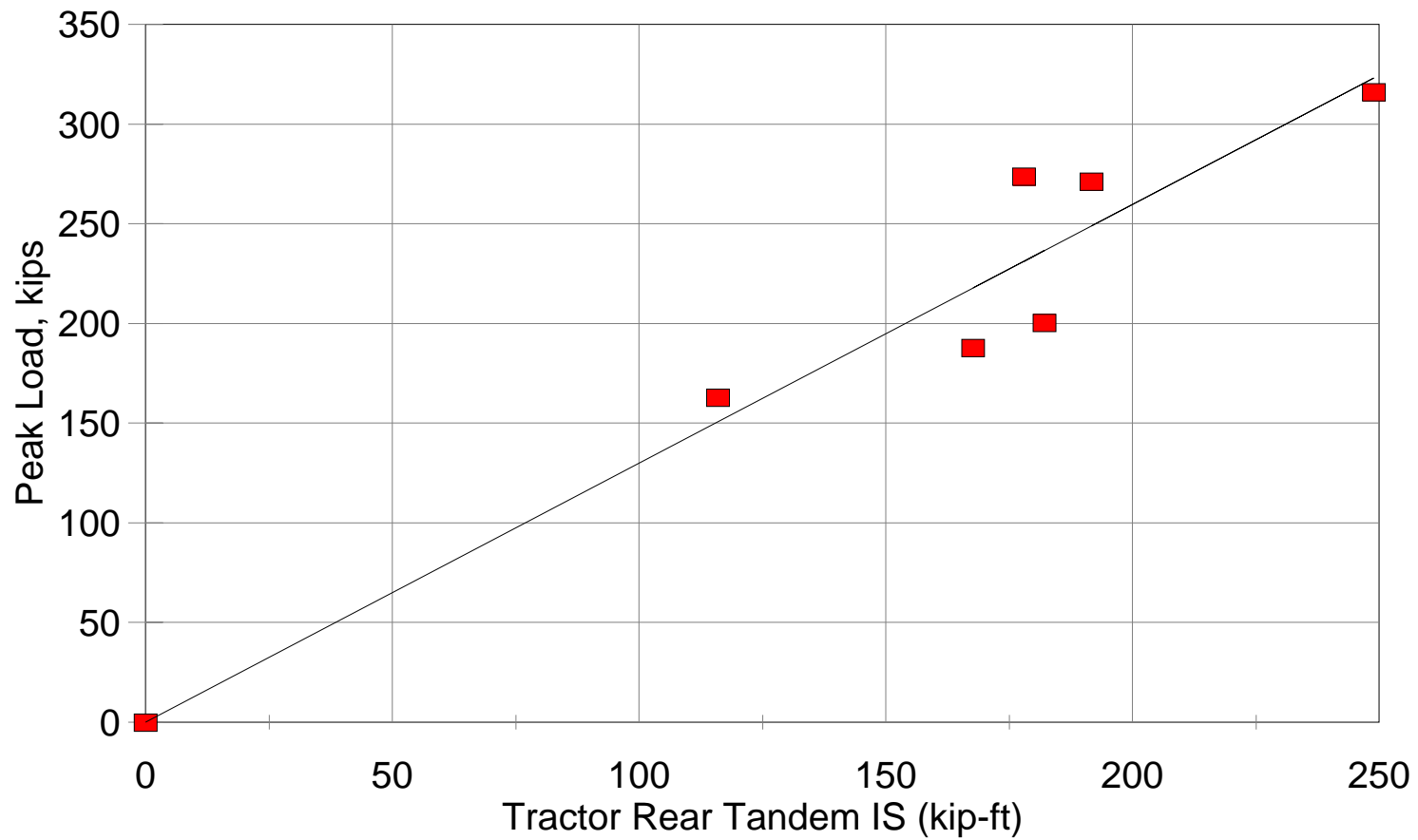
Figure 2. Peak Load and Impact Severity for Tractor's Rear Tandems [1lb=0.2248089 N and 1 Joule=0.7375621 ft-lbs]

In order to use Equation (4) to estimate the design impact load, it was first necessary to determine the weight carried by the tractor's rear tandem axles. For the eleven trucks identified in Tables 1 through 4, the average weight on the tractor's rear tandem axle for the 22,680-kg (50,000-lb) and 36,287-kg (80,000-lb) trucks were 9,640 kg (21,252 lbs) and 15,488 kg (34,145 lbs), respectively. Once the weights had been estimated, the corresponding impact severities were calculated using the appropriate impact speed and angle of the test conditions. As shown in Table 7b, the estimate for the design impact load was then determined using Equation (4) for the TL-5 and PL-3 tractor-trailer impact conditions. For the TL-5 impact condition of NCHRP Report No. 350, a design impact load was calculated to be 1,103 N (248 kips). For the PL-3 impact condition found in AASHTO's *Guide Specifications for Bridge Railings*, a design impact load of 681 N (153 kips) was determined.

3.3 Final Peak Design Load Range

In summary, the analytical investigation has resulted in a peak design load ranging between 681 to 689 N (153 to 155 kips) and 1,081 to 1,103 N (243 to 248 kips) for the AASHTO PL-3 and NCHRP 350 TL-5 impact conditions, respectively.

Table 7a. Design Impact Load Based on Total Vehicle Impact Severity (Target Impact Conditions).

Test No.	Test Guidelines	Test Designation	Vehicle Weight (lbs)	Total Vehicle Impact Severity (kip-ft)	Design Impact Load (kips)
5-12	NCHRP (4)	36000V	79,366	439.2	243
PL-3	AASHTO (17)	50 Kips	50,000	279.9	155

1 kg = 2.204623 lbs
1 in. = 25.4 mm
1 lb = 0.2248089 N
1 Joule = 0.7375621 ft-lbs

Table 7b. Design Impact Load Based on Impact Severity of Tractor's Rear Tandem Axle (Target Impact Conditions).

Test No.	Test Guidelines	Test Designation	Vehicle Weight (lbs)	Total Vehicle Impact Severity (kip-ft)	Tractor Rear Tandem Axle Weight[1] (lbs)	Tractor Rear Tandem Impact Severity (kip-ft)	Design Impact Load (kips)
5-12	NCHRP (4)	36000V	79,366	439.2	34,145	191.2	248
PL-3	AASHTO (17)	50 Kips	50,000	279.9	21,252	117.6	153

[1] - Average weight based on prior tractor-trailer truck tests conducted by TTI.

1 kg = 2.204623 lbs
1 in. = 25.4 mm
1 lb = 0.2248089 N
1 Joule = 0.7375621 ft-lbs

4 DESIGN METHODOLOGY

4.1 Barrier Capacity Considerations

Once peak lateral loads were determined, it was then necessary to compare that load to the predicted capacities of existing railing configurations. Four barrier systems were selected for further examination: (1) the 1,067-mm (42-in.) tall F-Shape, half-section bridge railing system [test no. 7069-10] (*11-12*), as shown in Figures 3 and 4; (2) the 1,067-mm (42-in.) tall, vertical concrete bridge railing system [test no. 405511-2] (*14*), as shown in Figures 5 and 6; (3) the 1,067-mm (42-in.) tall, non-reinforced New Jersey Shape concrete median barrier, or "Ontario tall wall," [test no. 7162-1] (*1*), as shown in Figure 7; and (4) the 1,067-mm (42-in.) tall, reinforced New Jersey shape concrete median barrier [test no. 4798-13] (*2*), as shown in Figure 8.

4.1.1 F-Shape, Half-Section Bridge Railing (PL-3 Impact Condition)

As shown in Table 4, the F-Shape, half-section bridge railing system was estimated to have a redirective barrier capacity, R_w, ranging between 565 N (127 kips) and 574 N (129 kips) according to the yield-line analysis procedures provided in References (*5*) and (*6*). For test no. 7069-10, the actual impact severities for the entire vehicle and tractor's rear tandems were 361.5 kJ (266.6 kip-ft) and 157.3 kJ (116.0 kip-ft), respectively. These impact severities would have resulted in peak design loads, according to Equations 3 and 4, equal to 658 N (148 kips) and 672 N (151 kips), respectively.

During the crash test, the tractor-trailer vehicle was successfully redirected by the bridge railing system and without damage to the parapet. However, using the yield-line analysis procedure, greater damage to the barrier system would have been expected under this impact condition since the predicted peak load was approximately 17 percent greater than the rated redirective capacity. This result may indicate that the yield-line analysis procedure underestimates the redirective barrier capacity of a solid, reinforced concrete parapet.

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276 MPa (40 ksi) REINFORCING STEEL
(414 MPa (60 ksi) acceptable)
25 MPa (3600 psi) CONCRETE

438 mm

124 mm

228 mm

4 #22 (#7)
LONGIT. BARS

305 mm

38 mm

38 mm

1.07 m

4 #25 (#8)
LONGIT. BARS

#15 (#5) @ 121 mm C-C

3 #13 (#4) LONGIT. BARS
(TOP)

178 mm

51 mm

76 mm

38 mm

#15 (#5) @ 203 mm C-C
#15 (#5) @ 203 mm C-C

76 mm

254 mm

32 mm

3 #15 (#5) LONGIT. BARS (BOTTOM)
#13 (#4) @ 241 mm C-C

25 mm

TEST INSTALLATION OVERHANG = 991 mm
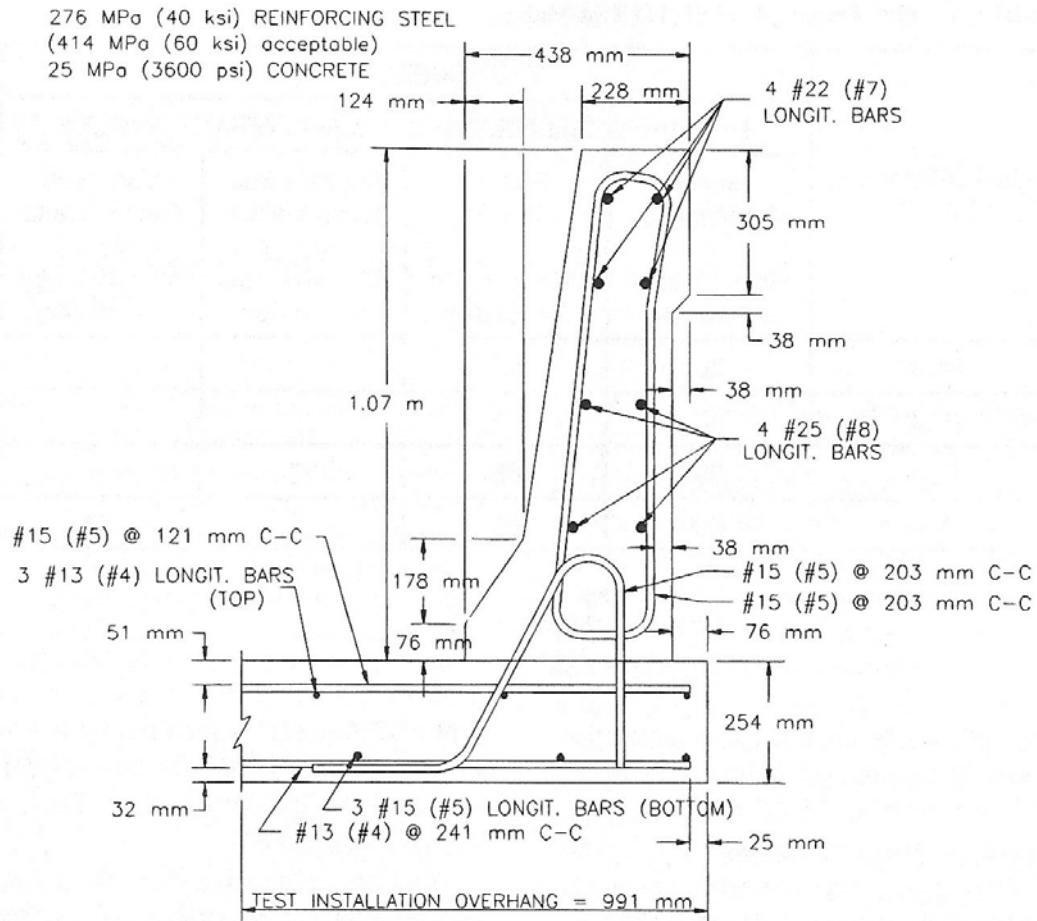
1mm = 0.039 in
1 m = 3.28 ft

Figure 3. F-Shape, Half-Section Bridge Railing (PL-3 Impact Condition) [Reference No. 11]

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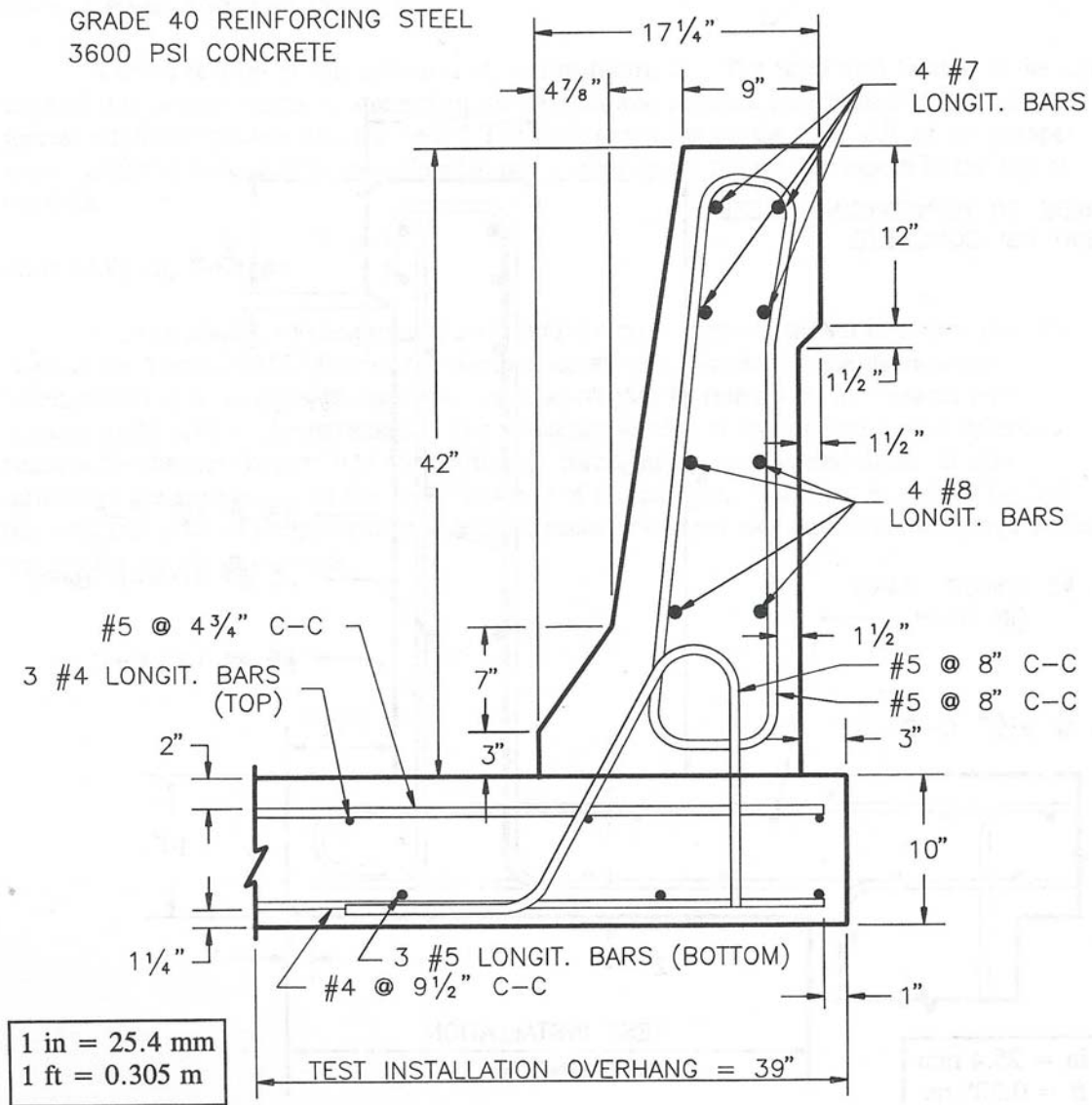
Figure 4. F-Shape, Half-Section Bridge Railing (PL-3 Impact Condition) [Reference No. 12]

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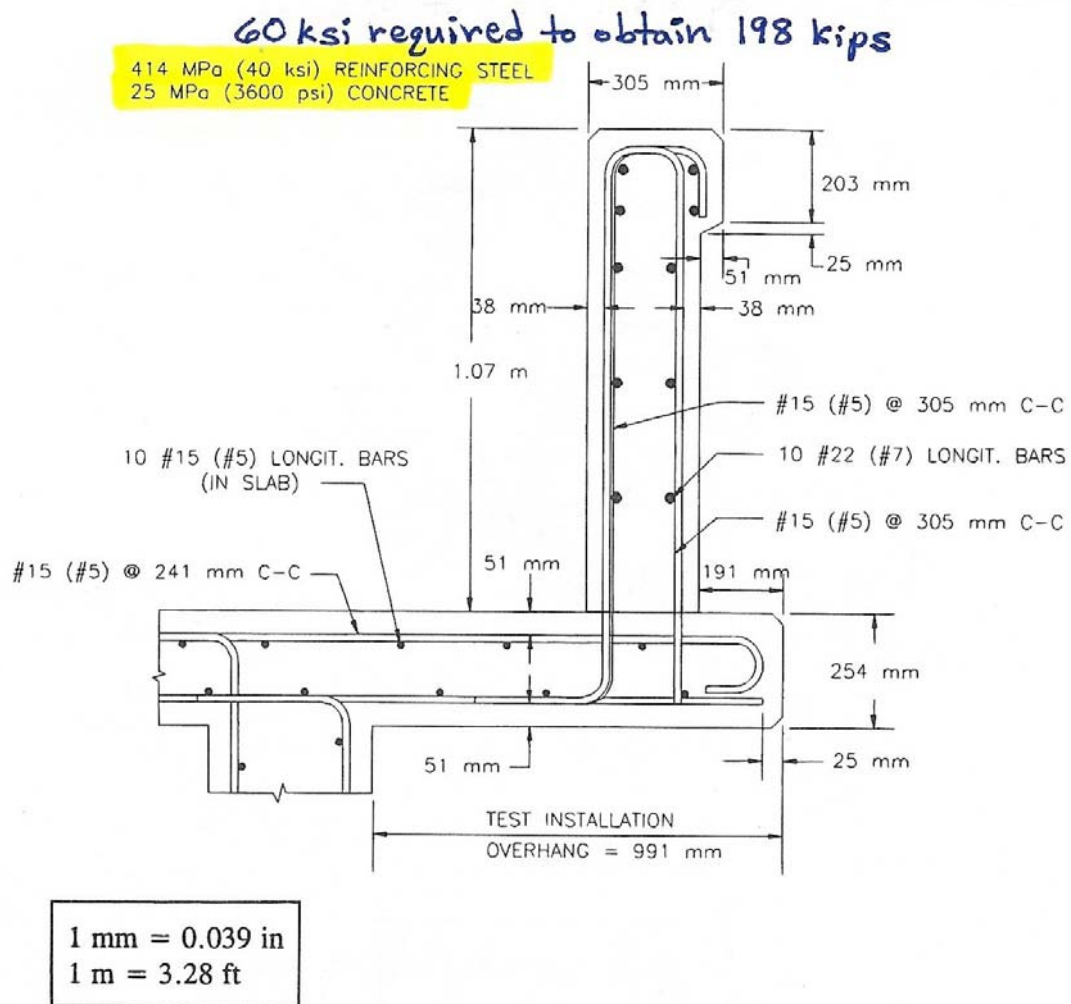
Figure 5. Vertical Bridge Railing (TL-5 Impact Condition) [Reference No. 11]
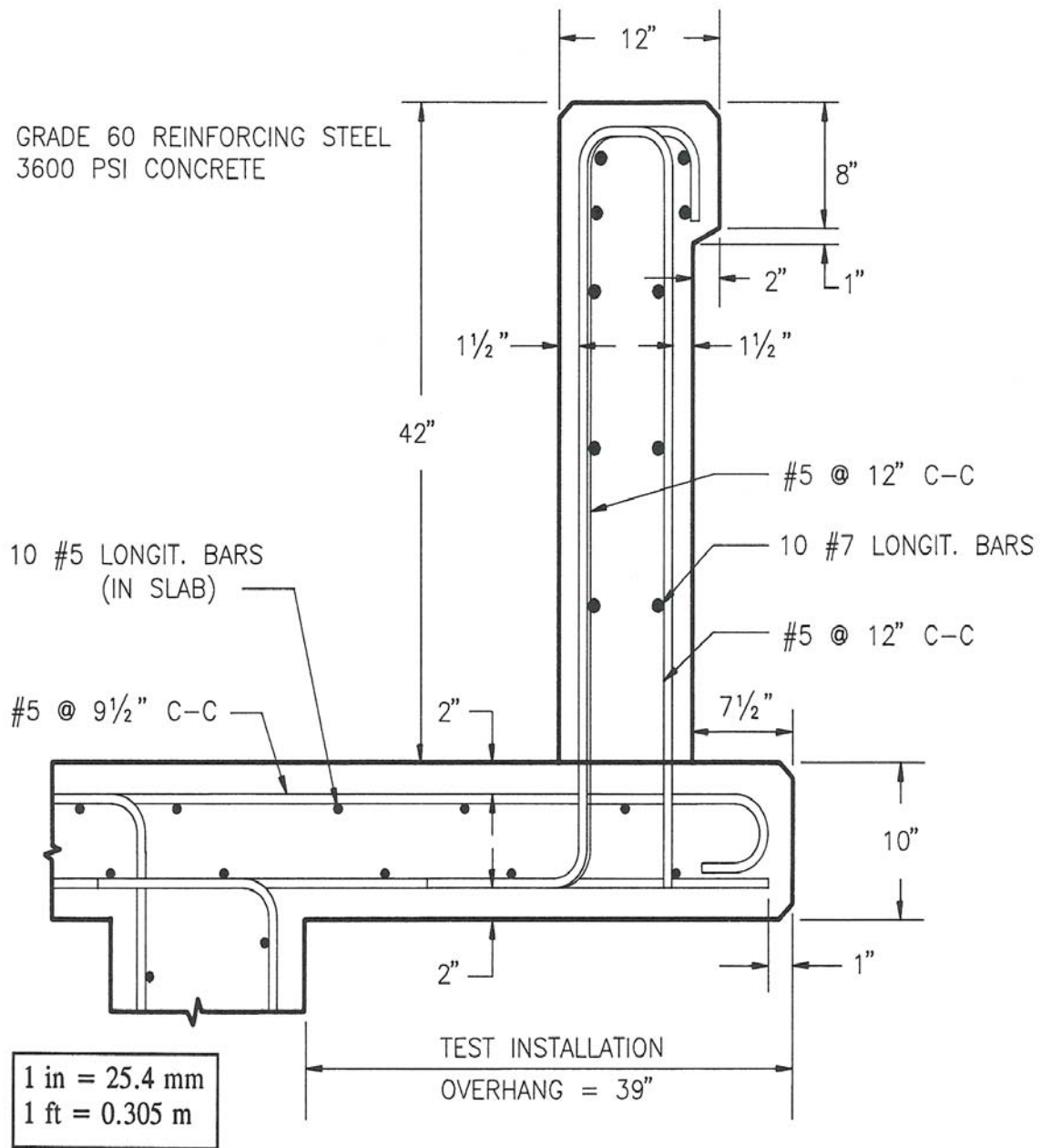
Figure 6. Vertical Bridge Railing (TL-5 Impact Condition) [Reference No. 12]
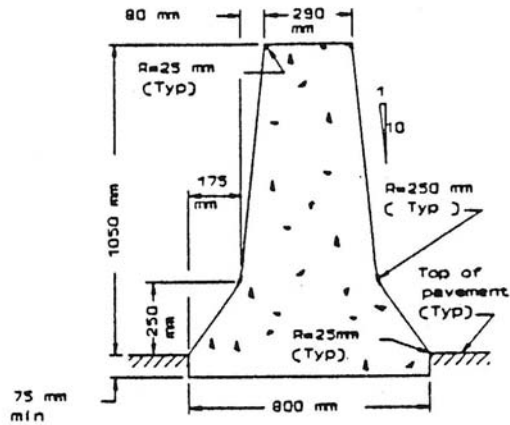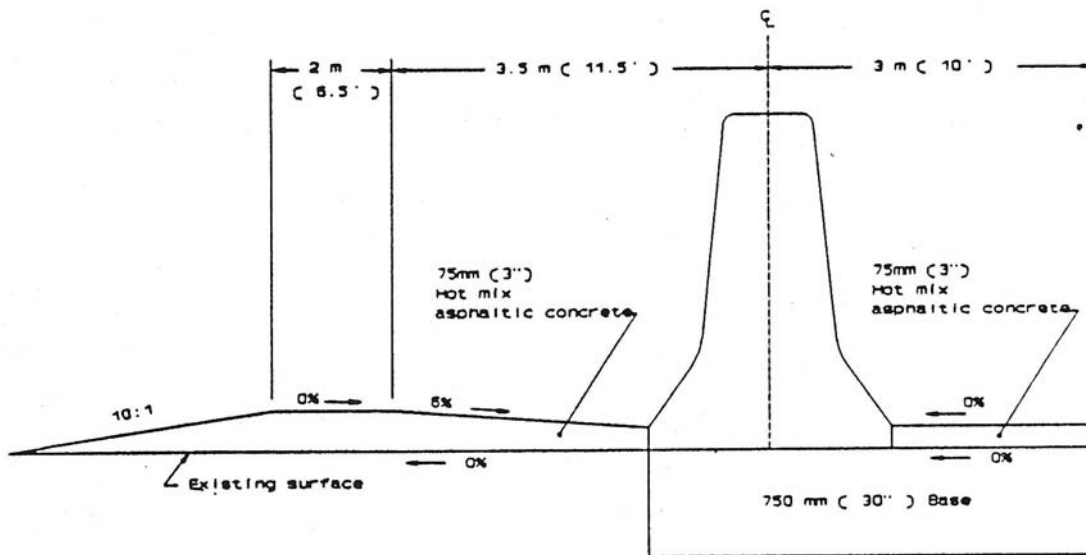
Figure 7. Ontario Tall Wall (TL-5 Impact Condition) [Reference No. 1]
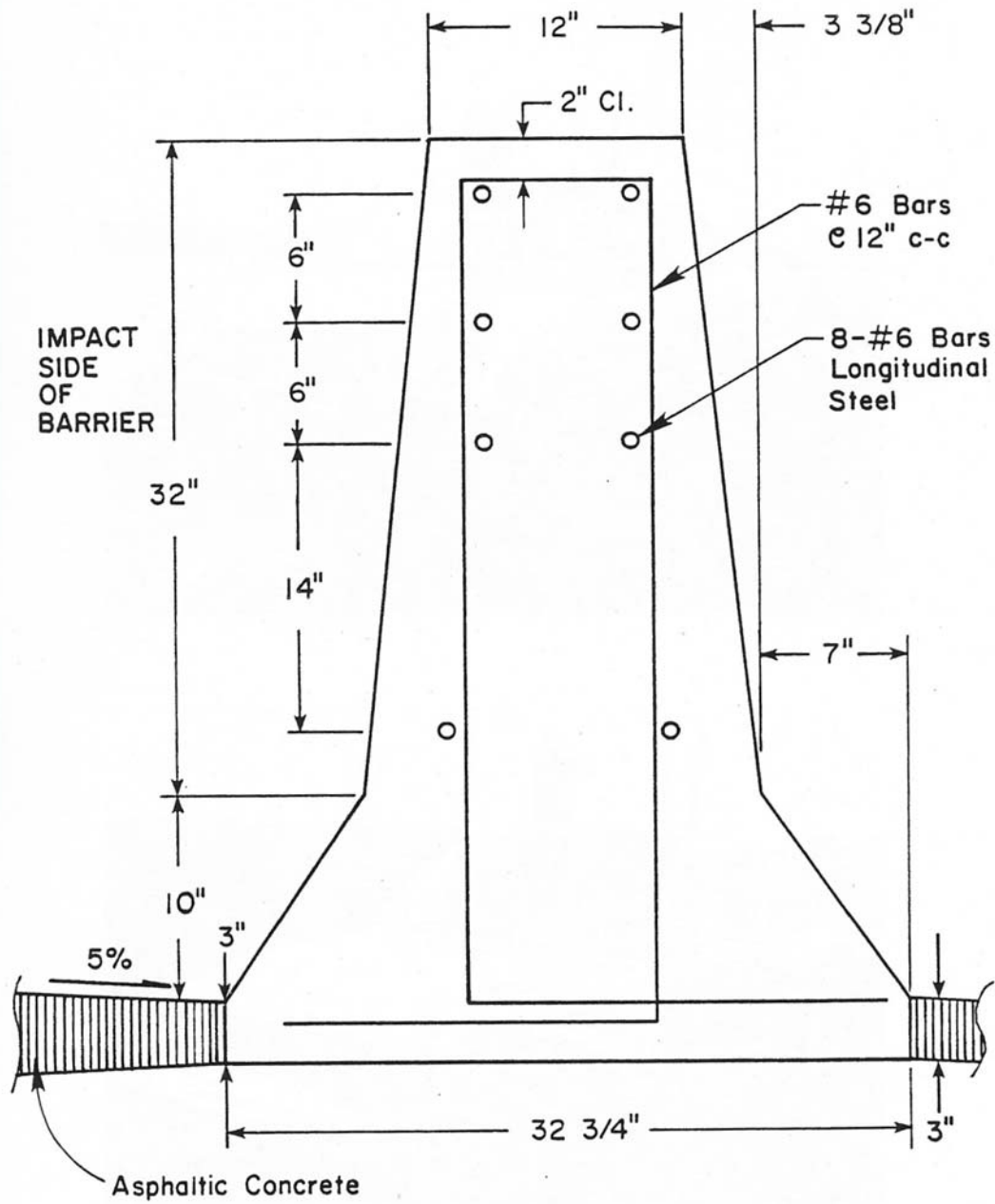
Figure 8. Reinforced, New Jersey Median Barrier (TL-5 Impact Condition) [Reference No. 2]

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4.1.2 Vertical Bridge Railing (TL-5 Impact Condition)

As shown in Table 4, the vertical concrete bridge railing system was estimated to have a redirective barrier capacity, R_W, ranging between 881 N (198 kips) and 934 N (210 kips) according to the yield-line analysis procedures provided in References (*5*) and (*6*). For test no. 405511-2, the actual impact severities for the entire vehicle and tractor's rear tandems were 559.3 kJ (412.5 kip-ft) and 241.3 kJ (178.0 kip-ft), respectively. These impact severities would have resulted in peak design loads, according to Equations 3 and 4, equal to 1,019 N (229 kips) and 1,028 N (231 kips), respectively.

During the crash test, the tractor-trailer vehicle was successfully redirected by the bridge railing system and without damage to the parapet. From the yield-line analysis procedure, once again, greater damage to the barrier system would have been expected since the predicted peak load was approximately 13 percent greater than the rated redirective capacity. Again, this result may indicate that the yield-line analysis procedure underestimates the redirective barrier capacity of a solid, reinforced concrete parapet.

4.1.3 Non-Reinforced, New Jersey Shape Concrete Median Barrier (TL-5 Impact Condition)

In Section 2, it was discussed that the non-reinforced, New Jersey Shape concrete median barrier successfully redirected a heavy, tractor-trailer vehicle. During the impact event, however, some vehicle ballast became dislodged and fell outside of the trailer, and the trailer's rear tandem axle assembly broke away from the trailer. For test no. 7162-1, the actual impact severities for the entire vehicle and tractor's rear tandems were 605.4 kJ (446.5 kip-ft) and 259.9 kJ (191.7 kip-ft), respectively. These impact severities would have resulted in peak design loads, according to Equations 3 and 4, equal to 1,099 N (247 kips) and 1,108 N (249 kips), respectively. With the

shifting ballast and significant trailer damage, one would reason that these estimated peak loads would not likely have been imparted to the barrier system. However, a review of the peak 0.050-sec average lateral decelerations showed that a significant lateral load was likely imparted to the barrier by the tractor's rear tandems.

Before crash testing, five shrinkage cracks were noted in the barrier. During the test, the barrier appeared to have remained attached to the foundation without rotation upward nor backward. Following the test, one of the original five cracks increased in width from 4.8 mm (3/16 in.) to 6.35 mm (1/4 in.), and a new crack, measuring 1.6 mm (1/16 in.) wide, formed upstream of impact.

Due to the interest in this barrier, MwRSF researchers attempted to estimate the barrier's redirective capacity using alternative strengths in lieu of the cantilevered moment capacity. Thus, as previously discussed in Section 2, researchers substituted the barrier's torsional capacity into the yield-line analysis expression in order to approximate a minimum redirective capacity. Using a conservative value for torsional strength, combined with a moment capacity of the wall set equal to zero, a conservative estimate for the barrier's redirective capacity was found to be at least 703 N (158 kips). It should be noted that this barrier capacity is much less than the 1,103-N (248-kip) estimated load imparted to this parapet. Therefore, it is believed that other factors may have contributed to the barrier's capacity. First, the torsional capacity may have been greater than the conservative value used in the analysis. Second, frictional forces generated between the asphalt overlay and the barrier's toe may have provided additional cantilevered capacity and resistance to overturning. Third, other factors identified in Section 2 may also have contributed to an increased barrier capacity. In addition, the translational and rotational inertial effects may have further aided in the vehicle's containment and redirection.

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Finally, this analysis may very well have revealed why the yield-line analytical procedure possibly underestimates a solid, concrete barrier's redirective capacity.

4.1.4 Reinforced, New Jersey Shape Concrete Median Barrier (TL-5 Impact Condition)

In Section 2, it was also discussed that the reinforced, New Jersey Shape concrete median barrier successfully redirected a heavy, tractor-trailer vehicle. For test no. 4798-13, the actual impact severities for the entire vehicle and tractor's rear tandems were 795.7 kJ (586.9 kip-ft) and 337.5 kJ (248.9 kip-ft), respectively. These impact severities would have resulted in peak design loads, according to Equations 3 and 4, equal to 1,446 N (325 kips) and 1,437 N (323 kips), respectively. Using the peak 0.050-sec average lateral deceleration of 9.3 G's multiplied by the weight on the tractor's rear tandem axle of 15,427 kg (34,010 lbs), a peak lateral load imparted to the reinforced barrier was approximated to be 1,406 N (316 kips). This result correlates very well with the results obtained from Equations 3 and 4.

During the test, the barrier appeared to have remained attached to the foundation without rotation upward nor backward. Due to the interest in this barrier, MwRSF researchers attempted to estimate the barrier's redirective capacity using alternative strengths in lieu of the cantilevered moment capacity. Thus, as previously discussed in Section 2, researchers substituted the barrier's torsional capacity into the yield-line analysis expression in order to approximate a minimum redirective capacity. Using a conservative value for torsional strength, combined with a calculated moment capacity of the wall, a conservative estimate for the barrier's redirective capacity was found to be at least 3,527 N (793 kips). This barrier capacity is much greater than the peak design load ranging between 1,081 N (243 kips) and 1,103 N (248 kips) for the TL-5 impact conditions. However, it should be noted that this estimated barrier capacity would not be possible without the

consideration of the torsional strength of the reinforced concrete parapet in the yield-line analytical procedure.

Once again, this analysis may very well have revealed why the yield-line analytical procedure underestimates a solid, concrete barrier's redirective capacity.

4.2 Two Design Philosophies

Based on the impact load investigation and the evaluation of existing barrier configurations previously presented, MwRSF researchers evaluated the two basic philosophies for designing the 813-mm (42-in.) and 1,295-mm (51-in.) tall, F-shape, half-section concrete barriers to meet the TL-5 safety performance criteria. The first design philosophy consisted of using the new TL-5 design impact load, which ranged between 1,081 N (243 kips) and 1,103 N (248 kips), in combination with a "modified" yield-line analysis procedure. The "modified" yield-line analysis procedure would likely incorporate the torsional capacity of the solid, concrete parapet. Since limited analysis has been conducted in order to investigate this hypothesis, it does not seem appropriate to employ this "modified" analytical procedure at this time.

The second design philosophy utilized the existing yield-line analytical procedure but in combination with a scaled-down design impact load. This scaled-down design impact load considered two major factors: (1) the redirective capacity of the successfully crash tested vertical wall, as determined by both TTI and MwRSF, and (2) the difference between the actual impact severity of test no. 405511-2 and the target impact severity for the TL-5 impact condition. As shown in Table 4, the redirective barrier capacity for the vertical wall was determined to be 881 N (198 kips) and 934 N (210 kips), as determined by TTI and MwRSF, respectively, thus resulting in an average capacity of 907 N (204 kips). The target impact severity for the TL-5 impact condition was

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595.5 kJ (439.2 kip-ft) or approximately 6.5 percent greater than the impact severity for the actual

crash test. Therefore, it was deemed appropriate to increase the required barrier capacity by 6.5

percent to the design impact load ranging between 939 N (211 kips) and 996 N (224 kips) or to an

average design impact load value of approximately 965 N (217 kips).

5 NEW BARRIER AND FOUNDATION CONFIGURATIONS

5.1 Barrier Options

The objective of this research project was to develop two different single-faced, F-Shape concrete barrier systems to meet the TL-5 safety performance criteria. The two F-Shape concrete barrier configurations were to include both 1,067-mm (42-in.) and 1,295-mm (51-in.) tall designs. These designs considered: (1) the appropriate amount of steel reinforcement necessary to prevent concrete blowouts; (2) the prevention of vehicle penetrations through or vaulting over the top of the barriers; and (3) the determination of adequate foundation and anchorage support to prevent lateral displacement and rotation of the barrier systems.

Using the existing yield-line analysis procedures, several barrier configurations were investigated within each height category in order to determine each barrier's redirective capacity. For this project, a total of 216 different F-Shape configurations were analyzed. This analysis included varying several parameters which influence overall barrier capacity, including the minimum 28-day concrete compressive strength, barrier width, size of longitudinal and vertical steel reinforcing bars, quantity of longitudinal steel reinforcement per face, and spacing of vertical steel reinforcement. All analyses, as part of this design effort, were conducted using Grade 60 steel reinforcement. In addition, the design effort assumed that the barrier's cantilevered bending capacity at the base would be matched with an equivalent or greater capacity in the foundation, thus satisfying the yield-line analysis assumptions.

For the 1,067-mm (42-in.) tall barriers, a total of 108 different configurations were analyzed. Details of the parameters investigated as well as the results of this analysis are provided in Appendix A. MwRSF researchers selected five preferred barrier configurations that provided redirective

capacities within the range of 939 N (211 kips) to 996 N (224 kips), as shown in Figure 9. These five preferred configurations were all based on a minimum 28-day concrete compressive strength of 31.03 MPa (4,500 psi). Although only five preferred barrier configurations were recommended out of the 108 configurations, other alternatives which provide acceptable redirective capacities would also be acceptable. It should be noted that the barrier systems shown in Figure 9 do not include details for the reinforcing steel required to anchor the parapets to a foundation system.

For the 1,295-mm (51-in.) tall barriers, a total of 108 different configurations were analyzed. Details of the parameters investigated as well as the results of this analysis are provided in Appendix B. MwRSF researchers selected three preferred barrier configurations that provided redirective capacities within the range of 939 N (211 kips) to 996 N (224 kips), as shown in Figure 10. These three preferred configurations were all based on a minimum 28-day concrete compressive strength of 31.03 MPa (4,500 psi). Although only three preferred barrier configurations were recommended out of the 108 configurations, other alternatives which provide acceptable redirective capacities would once again be acceptable. It should be noted that the barrier systems shown in Figure 10 do not include details for the reinforcing steel required to anchor the parapets to a foundation system.

5.2 Foundation Options

As part of the project requirements, details were provided for anchoring the single-faced, F-Shape concrete barrier systems to both bridge decks and median foundations. For bridge deck applications, two different bridge deck configurations have been provided. These configurations were based on previously acceptable attachment details that were subjected to TL-5 crash tests on reinforced concrete parapets. An example of an acceptable bridge deck configuration is provided in Figure 11. The first bridge deck design, measuring 254-mm (10-in.) thick, was utilized during two

Option No. 1
(Rw = 213 kips)

18¼"
10"
12"
1½"
1½"
42"
4⅞"
8 – #8
LONGITUDINAL BARS
7"
3"
#5 STIRRUPS
@ 8" O.C.

Option No. 2
(Rw = 211 kips)

19¼"
11"
12"
1½"
1½"
42"
4⅞"
8 – #7
LONGITUDINAL BARS
7"
3"
#5 STIRRUPS
@ 8" O.C.

Option No. 3
(Rw = 215 kips)

19¼"
11"
12"
1½"
1½"
42"
4⅞"
10 – #8
LONGITUDINAL BARS
7"
3"
#5 STIRRUPS
@ 10" O.C.

Option No. 4
(Rw = 218 kips)

20¼"
12"
12"
1½"
1½"
42"
4⅞"
10 – #7
LONGITUDINAL BARS
7"
3"
#5 STIRRUPS
@ 10" O.C.

Option No. 5
(Rw = 215 kips)

20¼"
12"
12"
1½"
1½"
42"
4⅞"
10 – #8
LONGITUDINAL BARS
7"
3"
#5 STIRRUPS
@ 12" O.C.

Notes: (1) Barrier capacity based on the development of the barrier's cantilevered bending capacity at the base and with the assumption that an equivalent size and spacing of steel bars, to that used for the vertical reinforcement, is included.
(2) Typical foundation and steel reinforcement details are included in subsequent details.
(3) Use Grade 60 reinforcing steel bars.
(4) Use a minimum 28-day concrete compressive strength of 4500 psi.
(5) Use 1½" clear cover.
(6) No. 5 stirrups shown with general looped configuration. Alternative configurations are permissible and to be determined by the individual State Departments of Transportation.
(7) 1 in. = 25.4 mm

Figure 9. Cross-Sectional Details and Steel Reinforcement for 1,067-mm (42-in.) Tall, Concrete Barrier
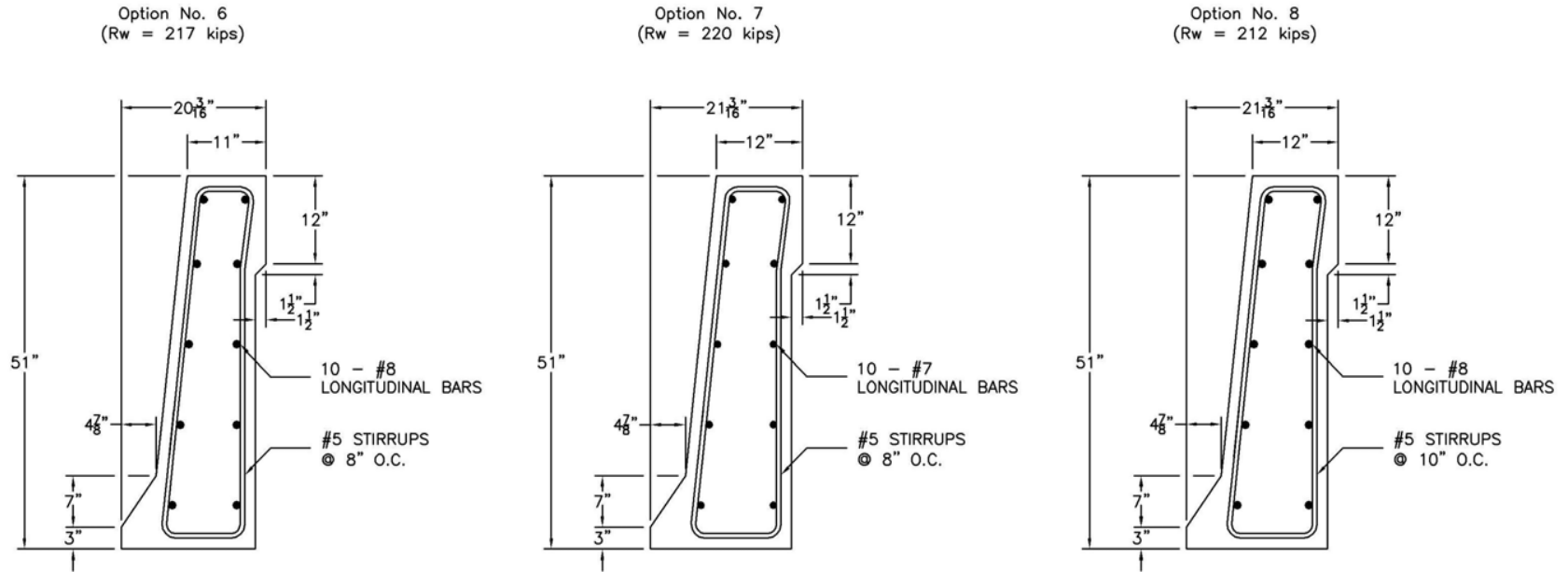
Option No. 6
(Rw = 217 kips)

Option No. 7
(Rw = 220 kips)

Option No. 8
(Rw = 212 kips)

20 3/16"
11"
12"
1 1/2"
1 1/2"
51"
4 7/8"
7"
3"

10 − #8
LONGITUDINAL BARS

#5 STIRRUPS
@ 8" O.C.

21 3/16"
12"
12"
1 1/2"
1 1/2"
51"
4 7/8"
7"
3"

10 − #7
LONGITUDINAL BARS

#5 STIRRUPS
@ 8" O.C.

21 3/16"
12"
12"
1 1/2"
1 1/2"
51"
4 7/8"
7"
3"

10 − #8
LONGITUDINAL BARS

#5 STIRRUPS
@ 10" O.C.

Notes: (1) Barrier capacity based on the development of the barrier's cantilevered bending capacity at the base and with the
assumption that an equivalent size and spacing of steel bars, to that used for the vertical reinforcement, is included.
(2) Typical foundation and steel reinforcement details are included in subsequent details.
(3) Use Grade 60 reinforcing steel bars.
(4) Use a minimum 28-day concrete compressive strength of 4500 psi.
(5) Use 1 1/2" clear cover.
(6) No. 5 stirrups shown with general looped configuration. Alternative configurations are permissible and to be determined by
the individual State Departments of Transportation.
(7) 1 in. = 25.4 mm

Figure 10. Cross-Sectional Details and Steel Reinforcement for 1,295-mm (51-in.) Tall, Concrete Barrier
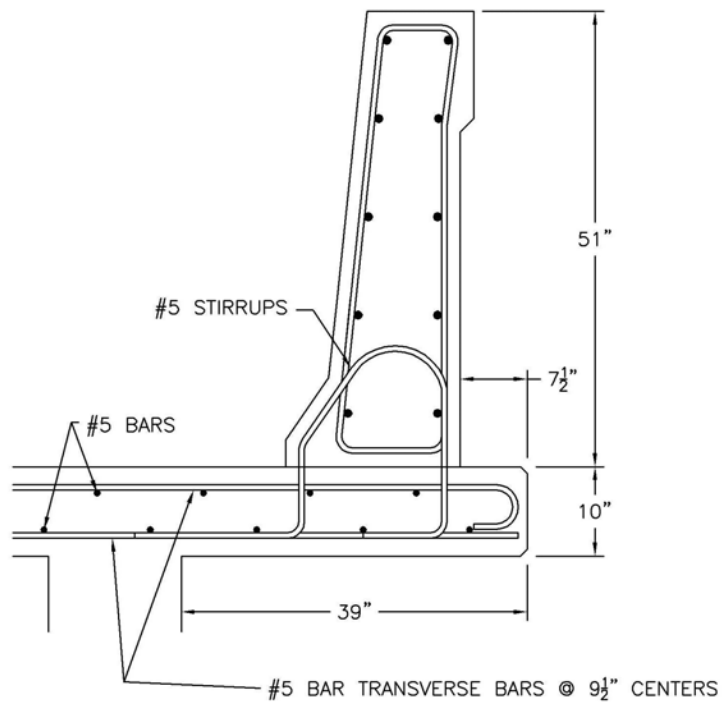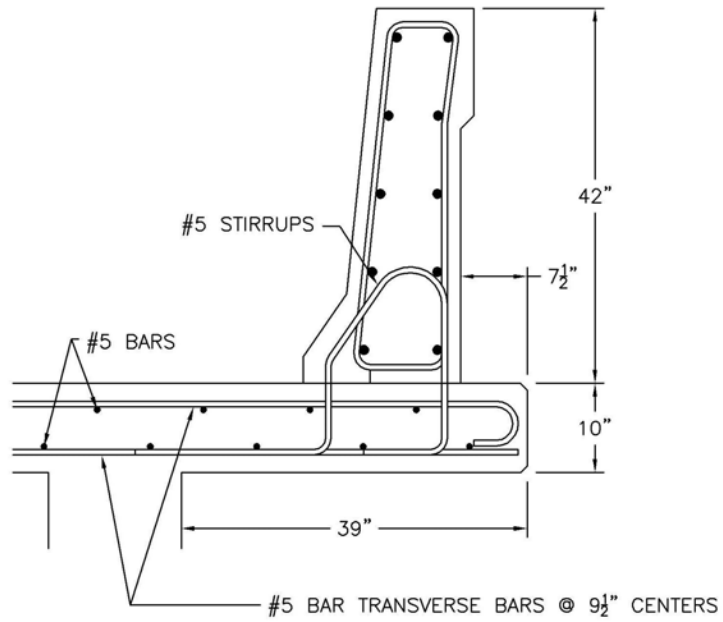
36

#5 STIRRUPS

#5 BARS

42"

7½"

10"

39"

#5 BAR TRANSVERSE BARS @ 9½" CENTERS

#5 STIRRUPS

#5 BARS

51"

7½"

10"

39"

#5 BAR TRANSVERSE BARS @ 9½" CENTERS

Notes: (1) No. 5 stirrups, used to attach the barrier to the deck, follow same spacing of barrier loop stirrups.
(2) Use Grade 60 reinforcing steel bars.
(3) Use a minimum 28-day concrete compressive strength of 4500 psi.
(4) 1 in. = 25.4 mm

Figure 11. Barrier Attachment Using a 254-mm (10-in.) Thick, Reinforced Concrete Bridge Deck

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successful crash tests (*11-12*,*14*) conducted on a 1,067-mm (42-in.) tall vertical concrete parapet bridge railing according to the PL-3 and TL-5 impact safety standards. The second example of an acceptable bridge deck configuration is provided in Figure 12. This bridge deck design, measuring 203-mm (8-in.) thick, was utilized during a successful crash test (*18*) conducted on a 1,067-mm (42-in.) tall, aesthetic open concrete bridge railing according to the TL-5 impact safety standards.

For median applications, only one general foundation support configuration was provided. This foundation detail consisted of a 610-mm (24-in.) square, reinforced concrete footing used to anchor acceptable TL-5 concrete parapets, as shown in Figure 13. For this median configuration, the foundation detail was used to develop the cantilevered moment capacity of the concrete parapet as well as to prevent lateral displacement and tipping of the barrier. The design of the square footing was largely based on the three major considerations; (1) the width necessary to support the base of the wall combined with a reasonable depth; (2) the appropriate overall concrete cross-sectional area and steel reinforcement necessary to provide adequate torsional capacity; and (3) the required shrinkage and temperature steel reinforcement in the longitudinal, lateral, and vertical directions of the concrete footing.

Finally, the steel reinforcement contained within the square foundation, as shown in Figure 13, should more than adequately provide the torsional capacity necessary for developing the parapet's cantilevered moment capacity. Actually, the same foundation design, but utilizing vertical No. 4 stirrups or hoop bars spaced on 1,219-mm (48-in.) centers versus the 508-mm (20-in.) spacing, would also have provided adequate torsional capacity. However, further analysis of the shrinkage and temperature steel requirements resulted in a reduced spacing using No. 6 hoop bars, mostly governed by the steel requirements in the transverse or lateral direction across the foundation.
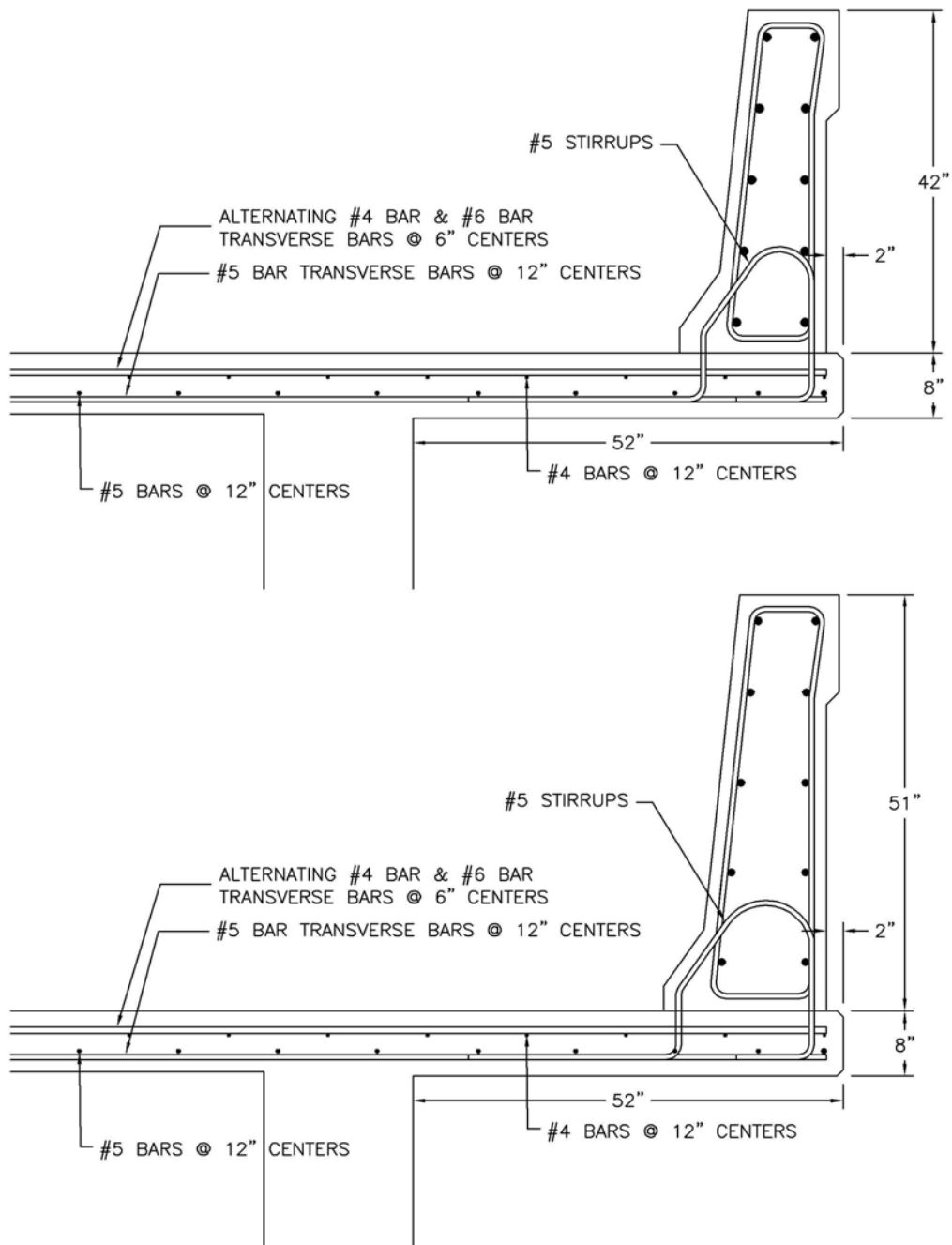
#5 STIRRUPS

ALTERNATING #4 BAR & #6 BAR
TRANSVERSE BARS @ 6" CENTERS

#5 BAR TRANSVERSE BARS @ 12" CENTERS

42"

2"

8"

52"

#4 BARS @ 12" CENTERS

#5 BARS @ 12" CENTERS

#5 STIRRUPS

ALTERNATING #4 BAR & #6 BAR
TRANSVERSE BARS @ 6" CENTERS

#5 BAR TRANSVERSE BARS @ 12" CENTERS

51"

2"

8"

52"

#4 BARS @ 12" CENTERS

#5 BARS @ 12" CENTERS

Notes: (1) No. 5 stirrups, used to attach the barrier to the deck, follow same
            spacing of barrier loop stirrups.
        (2) Use Grade 60 reinforcing steel bars.
        (3) Use a minimum 28-day concrete compressive strength of 4500 psi.
        (4) 1 in. = 25.4 mm

Figure 12. Barrier Attachment Using a 203-mm (8-in.) Thick, Reinforced Concrete Bridge Deck
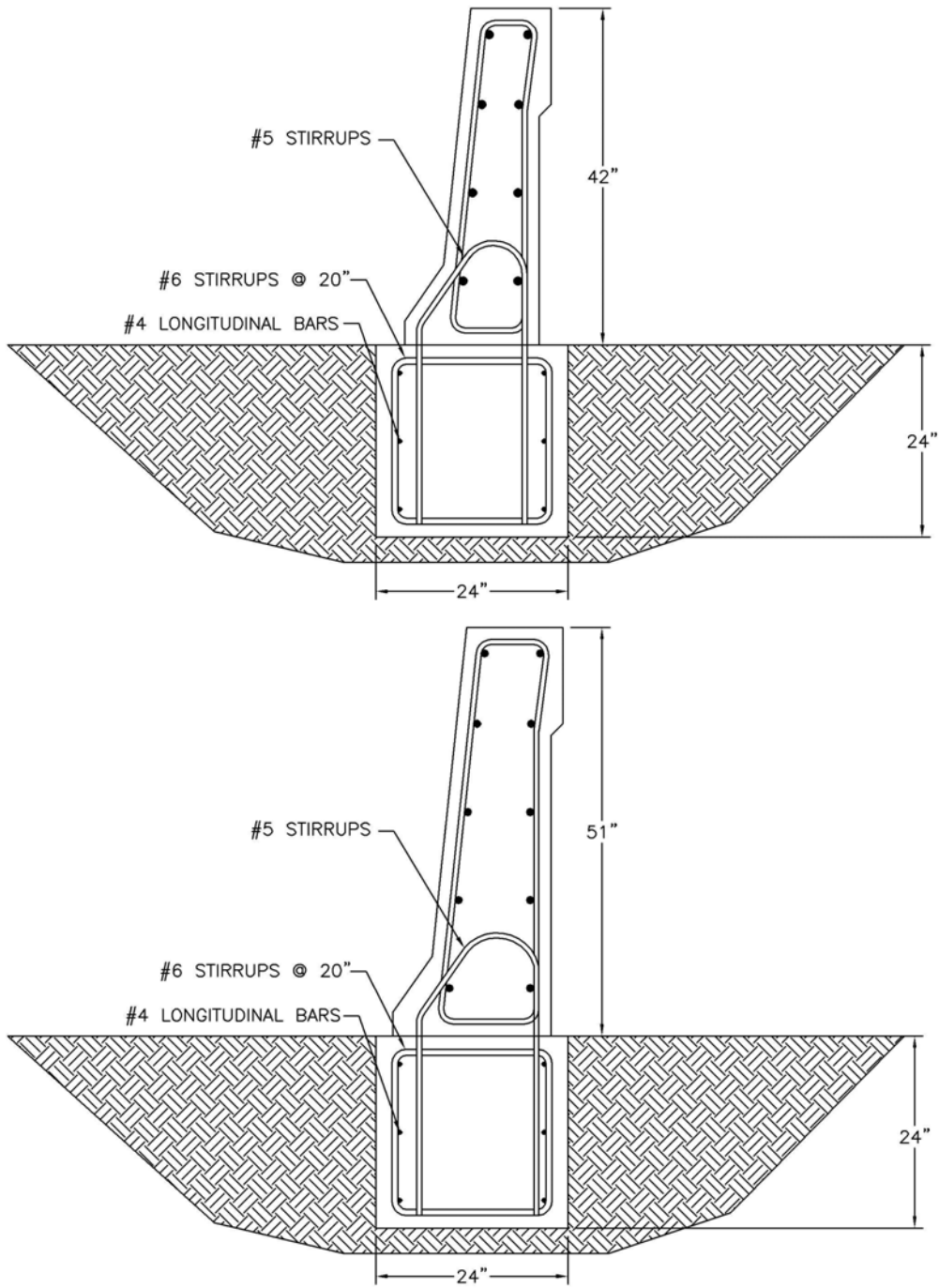
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Notes: (1) No. 5 stirrups, used to attach the barrier to the deck, follow same
spacing of barrier loop stirrups.
(2) Use Grade 60 reinforcing steel bars.
(3) Use a minimum 28-day concrete compressive strength of 4500 psi.
(4) 1 in. = 25.4 mm

Figure 13. Barrier Attachment Using a 610-mm (24-in.) Square, Reinforced Concrete Footing

6 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A literature review was conducted on tractor-trailer impacts into rigid barrier systems in order to study and better understand the dynamic lateral vehicular loads imparted into common barrier systems. The impact conditions and results were also obtained from those crash tests in order to develop relationships between impact severity and lateral loading to the barrier system. For a selected number of barrier tests, MwRSF researchers performed two different linear regression analyses on the estimated lateral peak load versus impact severity. The first analysis used the total impact severity for the tractor trailer, while the second analysis used the impact severity for the tractor's rear tandem axles. For each case, a linear relationship was developed between either the total vehicle's impact severity or that of the tractor's tandems and the lateral design impact load. In summary, this analytical investigation resulted in a peak lateral design load ranging between 681 to 689 N (153 to 155 kips) and 1,081 to 1,103 N (243 to 248 kips) for the AASHTO PL-3 and NCHRP 350 TL-5 impact conditions, respectively.

Subsequently, MwRSF researchers determined the redirective capacities of four existing barrier configurations using the standard yield-line analytical procedures. From these analyses, it was determined that the standard yield-line analytical procedures likely underestimate the redirective capacities of solid, reinforced concrete parapets. MwRSF researchers also believe that other factors, those currently not included in the yield-line procedures, likely contribute to the redirective capacity of a reinforced or non-reinforced concrete barrier system. Consequently, barrier systems that have been shown to meet the TL-5 impact safety standards during crash tests have calculated redirective capacities much lower than peak lateral design load. Since a "modified" yield-line analysis procedure is neither available nor calibrated, it was deemed appropriate to use the standard yield-line

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analysis procedure but in combination with a scaled-down design impact load. Therefore, the new barrier systems were developed using a peak design impact load ranging between 939 N (211 kips) and 996 N (224 kips) or to an average design impact load value of approximately 965 N (217 kips).

Two different single-faced, F-Shape concrete barrier systems were designed to meet the TL-5 safety performance criteria using the existing yield-line analytical procedures. The F-Shape configurations included designs for both the 1,067-mm (42-in.) and the 1,295-mm (51-in.) top-mounting heights. For the 1,067-mm (42-in.) height, five preferred configurations were provided using top barrier widths of 254 mm (10 in.), 279 mm (11 in.), and 305 mm (12 in.), while three preferred configurations were recommended for the 1,295-mm (51-in.) height using top barrier widths of 279 mm (11 in.) and 305 mm (12 in.). The size, quantity, and spacing of longitudinal and vertical steel reinforcing bars were selected in order to prevent concrete blowouts as well as to prevent vehicle penetrations through or vaulting over the top of the barriers.

Attachment options were also provided for anchoring the barrier systems to generic reinforced concrete slabs and foundations. Two reinforced, concrete bridge deck configurations - one 254-mm (10-in.) thick and one 203-mm (8-in.) thick - were provided with details for the longitudinal and transverse steel reinforcement. One additional foundation detail was provided using a square, reinforced concrete footing placed within soil and used to support the half-section barrier system. These three foundation and support systems were recommended based on a conservative design approach where full-scale vehicle crash testing would not be required. It should be noted that other designs may also meet the TL-5 impact safety standards and those which are less costly and easier to construct. However, these configurations would require a more aggressive design approach and would require full-scale vehicle crash testing in order to certify their acceptable safety

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performance.

Following the completion of this research study, it was apparent that there exists a significant need for future research in several areas. These new research projects are deemed necessary in order to advance the state-of-the-art for concrete barrier designs as well as to provide new, more economical and innovative barrier and anchorage support systems for the State Highway Departments. Recommended projects for future consideration include:

(1) Research is needed to develop new, TL-5 concrete median barrier and anchorage support systems that incorporate an optimized longitudinal and vertical steel reinforcement configuration while considering all barrier shapes. The steel reinforcement requirements should be based on (a) the quantity and spacing of steel bars necessary for resisting vehicular impact loads, and (b) the minimum required shrinkage and temperature steel as well as all other geographically-based environmental considerations (i.e., excessive freeze-thaw cycles). Several barrier cross-sections are to be considered, including the vertical, constant slope, and F-Shape geometries in both half or full section, as well as any other aesthetics details and stepped upper barrier surfaces that improve occupant safety.

(2) Guidelines should also be determined for anchoring the new barrier systems to rigid foundations or setting barriers within asphalt pads. This research should include the development, crash testing, and evaluation of several new, low-cost foundation anchoring systems according to the TL-5 impact safety standards and for use with median barrier systems discussed previously in Research Need No. 1.

(3) A research study is also needed that will provide researchers and designers with a better understanding of how a barrier's torsional capacity (both for reinforced and non-reinforced

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sections), inertial forces, and asphalt restraint against the front toe of the barrier, contribute to a barrier's overall redirective capacity. This effort should also be combined with experimental static and dynamic testing as well as finite element modeling in order to determine the ultimate strength of rigid parapets that were designed according to the standard yield-line analysis procedures. The results obtained from this analysis should be included for consideration in a "modified" yield-line analysis procedure for solid, and even open, concrete parapets.

(4) The proposed research projects identified in item nos. (1) through (3) above should also be considered at the TL-4 impact conditions for barrier heights ranging between 813 to 1,067 mm (32 to 42 in.).

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8 APPENDICES

APPENDIX A

Design Parameters and Analysis Results for 1,067-mm (42-in.) Height

Table A-1. Summary of Analysis Results for 42-in. Height and 10-in. Top Width

Table A-2. Summary of Analysis Results for 42-in. Height and 11-in. Top Width

Table A-3. Summary of Analysis Results for 42-in. Height and 12-in. Top Width

Table A-1. Summary of Analysis Results for 42-in. Height and 10-in. Top Width

Height (in.)	Top Barrier Width (in.)	Longitudinal Bar Size	Quantity per face	F'c (ksi)	Fy (ksi)	Vertical Bar Size	Spacing O.C. (in.)	Mw (k-in.)	Mc (k-in.)	Mb (k-in.)	φMw (k-ft/ft)	φMc (k-ft/ft)	φMb (k-ft)	Lc (ft)	Rw (kips)
42	10	7	4	3.6	60	5	8	1247.2	262.6	0	26.7	19.7	0.0	16.2	**182**
42	10	7	4	3.6	60	5	10	1247.2	218.5	0	26.7	16.4	0.0	17.3	**162**
42	10	7	4	3.6	60	5	12	1247.2	188.7	0	26.7	14.2	0.0	18.2	**147**
42	10	7	4	4	60	5	8	1281.3	267.4	0	27.5	20.1	0.0	16.3	**186**
42	10	7	4	4	60	5	10	1281.3	223	0	27.5	16.7	0.0	17.3	**165**
42	10	7	4	4	60	5	12	1281.3	192.9	0	27.5	14.5	0.0	18.2	**151**
42	10	7	4	4.5	60	5	8	1322.4	273.2	0	28.3	20.5	0.0	16.3	**191**
42	10	7	4	4.5	60	5	10	1322.4	228.3	0	28.3	17.1	0.0	17.3	**170**
42	10	7	4	4.5	60	5	12	1322.4	197.9	0	28.3	14.8	0.0	18.3	**155**
42	10	7	5	3.6	60	5	8	1478	262.6	0	31.7	19.7	0.0	17.2	**193**
42	10	7	5	3.6	60	5	10	1478	218.5	0	31.7	16.4	0.0	18.3	**172**
42	10	7	5	3.6	60	5	12	1478	188.7	0	31.7	14.2	0.0	19.3	**156**
42	10	7	5	4	60	5	8	1514.8	267.4	0	32.5	20.1	0.0	17.2	**197**
42	10	7	5	4	60	5	10	1514.8	223	0	32.5	16.7	0.0	18.4	**175**
42	10	7	5	4	60	5	12	1514.8	192.9	0	32.5	14.5	0.0	19.4	**160**
42	10	7	5	4.5	60	5	8	1559	273.2	0	33.4	20.5	0.0	17.3	**202**
42	10	7	5	4.5	60	5	10	1559	228.3	0	33.4	17.1	0.0	18.4	**180**
42	10	7	5	4.5	60	5	12	1559	197.9	0	33.4	14.8	0.0	19.4	**164**
42	10	8	4	3.6	60	5	8	1723.3	262.6	0	36.9	19.7	0.0	18.1	**204**
42	10	8	4	3.6	60	5	10	1723.3	218.5	0	36.9	16.4	0.0	19.4	**182**
42	10	8	4	3.6	60	5	12	1723.3	188.7	0	36.9	14.2	0.0	20.5	**166**
42	10	8	4	4	60	5	8	1762.3	267.4	0	37.8	20.1	0.0	18.2	**208**
42	10	8	4	4	60	5	10	1762.3	223	0	37.8	16.7	0.0	19.4	**185**
42	10	8	4	4	60	5	12	1762.3	192.9	0	37.8	14.5	0.0	20.5	**169**
42	10	8	4	4.5	60	5	8	1809.2	273.2	0	38.8	20.5	0.0	18.2	**213** No. 1
42	10	8	4	4.5	60	5	10	1809.2	228.3	0	38.8	17.1	0.0	19.4	**190**
42	10	8	4	4.5	60	5	12	1809.2	197.9	0	38.8	14.8	0.0	20.5	**174**
42	10	8	5	3.6	60	5	8	2061.7	262.6	0	44.2	19.7	0.0	19.4	**218**
42	10	8	5	3.6	60	5	10	2061.7	218.5	0	44.2	16.4	0.0	20.7	**194**
42	10	8	5	3.6	60	5	12	2061.7	188.7	0	44.2	14.2	0.0	21.9	**177**
42	10	8	5	4	60	5	8	2103.6	267.4	0	45.1	20.1	0.0	19.4	**222**
42	10	8	5	4	60	5	10	2103.6	223	0	45.1	16.7	0.0	20.7	**198**
42	10	8	5	4	60	5	12	2103.6	192.9	0	45.1	14.5	0.0	21.9	**181**
42	10	8	5	4.5	60	5	8	2154.2	273.2	0	46.2	20.5	0.0	19.4	**227**
42	10	8	5	4.5	60	5	10	2154.2	228.3	0	46.2	17.1	0.0	20.7	**203**
42	10	8	5	4.5	60	5	12	2154.2	197.9	0	46.2	14.8	0.0	21.9	**186**

Table A-2. Summary of Analysis Results for 42-in. Height and 11-in. Top Width

Height (in.)	Top Barrier Width (in.)	Longitudinal Bar Size	Quantity per face	F'c (ksi)	Fy (ksi)	Vertical Bar Size	Spacing O.C. (in.)	Mw (k-in.)	Mc (k-in.)	Mb (k-in.)	φMw (k-ft/ft)	φMc (k-ft/ft)	φMb (k-ft)	Lc (ft)	Rw (kips)	
42	11	7	4	3.6	60	5	8	1391.2	290.5	0	29.8	21.8	0.0	16.3	202	
42	11	7	4	3.6	60	5	10	1391.2	240.9	0	29.8	18.1	0.0	17.3	179	
42	11	7	4	3.6	60	5	12	1391.2	207.3	0	29.8	15.5	0.0	18.3	162	
42	11	7	4	4	60	5	8	1425.3	295.3	0	30.5	22.1	0.0	16.3	206	
42	11	7	4	4	60	5	10	1425.3	245.4	0	30.5	18.4	0.0	17.4	183	
42	11	7	4	4	60	5	12	1425.3	211.5	0	30.5	15.9	0.0	18.3	166	
42	11	7	4	4.5	60	5	8	1466.4	301.1	0	31.4	22.6	0.0	16.3	211	No. 2
42	11	7	4	4.5	60	5	10	1466.4	250.7	0	31.4	18.8	0.0	17.4	187	
42	11	7	4	4.5	60	5	12	1466.4	216.5	0	31.4	16.2	0.0	18.3	170	
42	11	7	5	3.6	60	5	8	1658	290.5	0	35.5	21.8	0.0	17.3	215	
42	11	7	5	3.6	60	5	10	1658	240.9	0	35.5	18.1	0.0	18.4	190	
42	11	7	5	3.6	60	5	12	1658	207.3	0	35.5	15.5	0.0	19.5	173	
42	11	7	5	4	60	5	8	1694.8	295.3	0	36.3	22.1	0.0	17.3	219	
42	11	7	5	4	60	5	10	1694.8	245.4	0	36.3	18.4	0.0	18.5	194	
42	11	7	5	4	60	5	12	1694.8	211.5	0	36.3	15.9	0.0	19.5	177	
42	11	7	5	4.5	60	5	8	1739	301.1	0	37.3	22.6	0.0	17.3	224	
42	11	7	5	4.5	60	5	10	1739	250.7	0	37.3	18.8	0.0	18.5	199	
42	11	7	5	4.5	60	5	12	1739	216.5	0	37.3	16.2	0.0	19.5	181	
42	11	8	4	3.6	60	5	8	1723.3	290.5	0	36.9	21.8	0.0	17.5	218	
42	11	8	4	3.6	60	5	10	1723.3	240.9	0	36.9	18.1	0.0	18.7	193	
42	11	8	4	3.6	60	5	12	1723.3	207.3	0	36.9	15.5	0.0	19.8	176	
42	11	8	4	4	60	5	8	1762.3	295.3	0	37.8	22.1	0.0	17.5	222	
42	11	8	4	4	60	5	10	1762.3	245.4	0	37.8	18.4	0.0	18.7	197	
42	11	8	4	4	60	5	12	1762.3	211.5	0	37.8	15.9	0.0	19.8	179	
42	11	8	4	4.5	60	5	8	1809.2	301.1	0	38.8	22.6	0.0	17.6	227	
42	11	8	4	4.5	60	5	10	1809.2	250.7	0	38.8	18.8	0.0	18.8	202	
42	11	8	4	4.5	60	5	12	1809.2	216.5	0	38.8	16.2	0.0	19.8	184	
42	11	8	5	3.6	60	5	8	2061.7	290.5	0	44.2	21.8	0.0	18.7	232	
42	11	8	5	3.6	60	5	10	2061.7	240.9	0	44.2	18.1	0.0	20.0	206	
42	11	8	5	3.6	60	5	12	2061.7	207.3	0	44.2	15.5	0.0	21.2	188	
42	11	8	5	4	60	5	8	2103.6	295.3	0	45.1	22.1	0.0	18.7	236	
42	11	8	5	4	60	5	10	2103.6	245.4	0	45.1	18.4	0.0	20.0	210	
42	11	8	5	4	60	5	12	2103.6	211.5	0	45.1	15.9	0.0	21.2	192	
42	11	8	5	4.5	60	5	8	2154.2	301.1	0	46.2	22.6	0.0	18.7	241	
42	11	8	5	4.5	60	5	10	2154.2	250.7	0	46.2	18.8	0.0	20.0	215	No. 3
42	11	8	5	4.5	60	5	12	2154.2	216.5	0	46.2	16.2	0.0	21.2	196	

Table A-3. Summary of Analysis Results for 42-in. Height and 12-in. Top Width

Height (in.)	Top Barrier Width (in.)	Longitudinal Bar Size	Quantity per face	F'c (ksi)	Fy (ksi)	Vertical Bar Size	Spacing O.C. (in.)	Mw (k-in.)	Mc (k-in.)	Mb (k-in.)	φMw (k-ft/ft)	φMc (k-ft/ft)	φMb (k-ft)	Lc (ft)	Rw (kips)	
42	12	7	4	3.6	60	5	8	1535.5	318.4	0	32.9	23.9	0.0	16.3	222	
42	12	7	4	3.6	60	5	10	1535.5	263.2	0	32.9	19.7	0.0	17.4	196	
42	12	7	4	3.6	60	5	12	1535.5	225.9	0	32.9	16.9	0.0	18.4	178	
42	12	7	4	4	60	5	8	1569.6	323.2	0	33.6	24.2	0.0	16.3	226	
42	12	7	4	4	60	5	10	1569.6	267.7	0	33.6	20.1	0.0	17.4	200	
42	12	7	4	4	60	5	12	1569.6	230.1	0	33.6	17.3	0.0	18.4	181	
42	12	7	4	4.5	60	5	8	1610.7	329	0	34.5	24.7	0.0	16.4	231	
42	12	7	4	4.5	60	5	10	1610.7	273	0	34.5	20.5	0.0	17.5	204	
42	12	7	4	4.5	60	5	12	1610.7	235.1	0	34.5	17.6	0.0	18.4	186	
42	12	7	5	3.6	60	5	8	1838.4	318.4	0	39.4	23.9	0.0	17.3	236	
42	12	7	5	3.6	60	5	10	1838.4	263.2	0	39.4	19.7	0.0	18.5	209	
42	12	7	5	3.6	60	5	12	1838.4	225.9	0	39.4	16.9	0.0	19.6	190	
42	12	7	5	4	60	5	8	1875.1	323.2	0	40.2	24.2	0.0	17.4	240	
42	12	7	5	4	60	5	10	1875.1	267.7	0	40.2	20.1	0.0	18.6	213	
42	12	7	5	4	60	5	12	1875.1	230.1	0	40.2	17.3	0.0	19.6	194	
42	12	7	5	4.5	60	5	8	1919.4	329	0	41.1	24.7	0.0	17.4	245	
42	12	7	5	4.5	60	5	10	1919.4	273	0	41.1	20.5	0.0	18.6	218	No. 4
42	12	7	5	4.5	60	5	12	1919.4	235.1	0	41.1	17.6	0.0	19.6	198	
42	12	8	4	3.6	60	5	8	1913.9	318.4	0	41.0	23.9	0.0	17.6	240	
42	12	8	4	3.6	60	5	10	1913.9	263.2	0	41.0	19.7	0.0	18.8	212	
42	12	8	4	3.6	60	5	12	1913.9	225.9	0	41.0	16.9	0.0	19.9	193	
42	12	8	4	4	60	5	8	1952.8	323.2	0	41.8	24.2	0.0	17.6	244	
42	12	8	4	4	60	5	10	1952.8	267.7	0	41.8	20.1	0.0	18.8	216	
42	12	8	4	4	60	5	12	1952.8	230.1	0	41.8	17.3	0.0	19.9	196	
42	12	8	4	4.5	60	5	8	1999.7	329	0	42.9	24.7	0.0	17.6	249	
42	12	8	4	4.5	60	5	10	1999.7	273	0	42.9	20.5	0.0	18.9	221	
42	12	8	4	4.5	60	5	12	1999.7	235.1	0	42.9	17.6	0.0	19.9	201	
42	12	8	5	3.6	60	5	8	2299.8	318.4	0	49.3	23.9	0.0	18.8	256	
42	12	8	5	3.6	60	5	10	2299.8	263.2	0	49.3	19.7	0.0	20.1	227	
42	12	8	5	3.6	60	5	12	2299.8	225.9	0	49.3	16.9	0.0	21.4	207	
42	12	8	5	4	60	5	8	2341.8	323.2	0	50.2	24.2	0.0	18.8	260	
42	12	8	5	4	60	5	10	2341.8	267.7	0	50.2	20.1	0.0	20.2	231	
42	12	8	5	4	60	5	12	2341.8	230.1	0	50.2	17.3	0.0	21.3	211	
42	12	8	5	4.5	60	5	8	2392.4	329	0	51.3	24.7	0.0	18.8	265	
42	12	8	5	4.5	60	5	10	2392.4	273	0	51.3	20.5	0.0	20.2	236	
42	12	8	5	4.5	60	5	12	2392.4	235.1	0	51.3	17.6	0.0	21.3	215	No. 5

APPENDIX B

Design Parameters and Analysis Results for 1,295-mm (51-in.) Height

Table B-1. Summary of Analysis Results for 51-in. Height and 10-in. Top Width

Table B-2. Summary of Analysis Results for 51-in. Height and 11-in. Top Width

Table B-3. Summary of Analysis Results for 51-in. Height and 12-in. Top Width

Table B-1. Summary of Analysis Results for 51-in. Height and 10-in. Top Width

Height (in.)	Top Barrier Width (in.)	Longitudinal Bar Size	Quantity per face	F'c (ksi)	Fy (ksi)	Vertical Bar Size	Spacing O.C. (in.)	Mw (k-in.)	Mc (k-in.)	Mb (k-in.)	φMw (k-ft/ft)	φMc (k-ft/ft)	φMb (k-ft)	Lc (ft)	Rw (kips)
51	10	7	4	3.6	60	5	8	1312	262.6	0	23.2	19.7	0.0	17.6	**163**
51	10	7	4	3.6	60	5	10	1312	218.5	0	23.2	16.4	0.0	18.8	**145**
51	10	7	4	3.6	60	5	12	1312	188.7	0	23.2	14.2	0.0	19.9	**132**
51	10	7	4	4	60	5	8	1350.7	267.4	0	23.8	20.1	0.0	17.7	**167**
51	10	7	4	4	60	5	10	1350.7	223	0	23.8	16.7	0.0	18.9	**149**
51	10	7	4	4	60	5	12	1350.7	192.9	0	23.8	14.5	0.0	19.9	**136**
51	10	7	4	4.5	60	5	8	1397.3	273.2	0	24.7	20.5	0.0	17.8	**171**
51	10	7	4	4.5	60	5	10	1397.3	228.3	0	24.7	17.1	0.0	19.0	**153**
51	10	7	4	4.5	60	5	12	1397.3	197.9	0	24.7	14.8	0.0	20.0	**140**
51	10	7	5	3.6	60	5	8	1547.8	262.6	0	27.3	19.7	0.0	18.7	**173**
51	10	7	5	3.6	60	5	10	1547.8	218.5	0	27.3	16.4	0.0	20.0	**154**
51	10	7	5	3.6	60	5	12	1547.8	188.7	0	27.3	14.2	0.0	21.2	**141**
51	10	7	5	4	60	5	8	1589.7	267.4	0	28.1	20.1	0.0	18.8	**177**
51	10	7	5	4	60	5	10	1589.7	223	0	28.1	16.7	0.0	20.1	**158**
51	10	7	5	4	60	5	12	1589.7	192.9	0	28.1	14.5	0.0	21.2	**144**
51	10	7	5	4.5	60	5	8	1640	273.2	0	28.9	20.5	0.0	18.8	**182**
51	10	7	5	4.5	60	5	10	1640	228.3	0	28.9	17.1	0.0	20.1	**162**
51	10	7	5	4.5	60	5	12	1640	197.9	0	28.9	14.8	0.0	21.3	**148**
51	10	8	4	3.6	60	5	8	1607.7	262.6	0	28.4	19.7	0.0	19.0	**176**
51	10	8	4	3.6	60	5	10	1607.7	218.5	0	28.4	16.4	0.0	20.3	**157**
51	10	8	4	3.6	60	5	12	1607.7	188.7	0	28.4	14.2	0.0	21.5	**143**
51	10	8	4	4	60	5	8	1652	267.4	0	29.2	20.1	0.0	19.0	**180**
51	10	8	4	4	60	5	10	1652	223	0	29.2	16.7	0.0	20.4	**160**
51	10	8	4	4	60	5	12	1652	192.9	0	29.2	14.5	0.0	21.5	**147**
51	10	8	4	4.5	60	5	8	1705.3	273.2	0	30.1	20.5	0.0	19.1	**184**
51	10	8	4	4.5	60	5	10	1705.3	228.3	0	30.1	17.1	0.0	20.4	**165**
51	10	8	4	4.5	60	5	12	1705.3	197.9	0	30.1	14.8	0.0	21.6	**151**
51	10	8	5	3.6	60	5	8	1904.4	262.6	0	33.6	19.7	0.0	20.2	**187**
51	10	8	5	3.6	60	5	10	1904.4	218.5	0	33.6	16.4	0.0	21.7	**167**
51	10	8	5	3.6	60	5	12	1904.4	188.7	0	33.6	14.2	0.0	23.0	**153**
51	10	8	5	4	60	5	8	1952.1	267.4	0	34.4	20.1	0.0	20.3	**191**
51	10	8	5	4	60	5	10	1952.1	223	0	34.4	16.7	0.0	21.7	**171**
51	10	8	5	4	60	5	12	1952.1	192.9	0	34.4	14.5	0.0	23.0	**156**
51	10	8	5	4.5	60	5	8	2009.6	273.2	0	35.5	20.5	0.0	20.3	**196**
51	10	8	5	4.5	60	5	10	2009.6	228.3	0	35.5	17.1	0.0	21.8	**175**
51	10	8	5	4.5	60	5	12	2009.6	197.9	0	35.5	14.8	0.0	23.0	**161**

Table B-2. Summary of Analysis Results for 51-in. Height and 11-in. Top Width

Height (in.)	Top Barrier Width (in.)	Longitudinal Bar Size	Quantity per face	F'c (ksi)	Fy (ksi)	Vertical Bar Size	Spacing O.C. (in.)	Mw (k-in.)	Mc (k-in.)	Mb (k-in.)	φMw (k-ft/ft)	φMc (k-ft/ft)	φMb (k-ft)	Lc (ft)	Rw (kips)
51	11	7	4	3.6	60	5	8	1456	290.5	0	25.7	21.8	0.0	17.7	181
51	11	7	4	3.6	60	5	10	1456	240.9	0	25.7	18.1	0.0	18.9	161
51	11	7	4	3.6	60	5	12	1456	207.3	0	25.7	15.5	0.0	20.0	146
51	11	7	4	4	60	5	8	1494.7	295.3	0	26.4	22.1	0.0	17.7	185
51	11	7	4	4	60	5	10	1494.7	245.4	0	26.4	18.4	0.0	18.9	164
51	11	7	4	4	60	5	12	1494.7	211.5	0	26.4	15.9	0.0	20.0	149
51	11	7	4	4.5	60	5	8	1541.3	301.1	0	27.2	22.6	0.0	17.8	189
51	11	7	4	4.5	60	5	10	1541.3	250.7	0	27.2	18.8	0.0	19.0	168
51	11	7	4	4.5	60	5	12	1541.3	216.5	0	27.2	16.2	0.0	20.1	153
51	11	7	5	3.6	60	5	8	1727.8	290.5	0	30.5	21.8	0.0	18.8	192
51	11	7	5	3.6	60	5	10	1727.8	240.9	0	30.5	18.1	0.0	20.1	171
51	11	7	5	3.6	60	5	12	1727.8	207.3	0	30.5	15.5	0.0	21.3	156
51	11	7	5	4	60	5	8	1769.7	295.3	0	31.2	22.1	0.0	18.8	196
51	11	7	5	4	60	5	10	1769.7	245.4	0	31.2	18.4	0.0	20.2	175
51	11	7	5	4	60	5	12	1769.7	211.5	0	31.2	15.9	0.0	21.3	159
51	11	7	5	4.5	60	5	8	1820	301.1	0	32.1	22.6	0.0	18.9	201
51	11	7	5	4.5	60	5	10	1820	250.7	0	32.1	18.8	0.0	20.2	179
51	11	7	5	4.5	60	5	12	1820	216.5	0	32.1	16.2	0.0	21.4	163
51	11	8	4	3.6	60	5	8	1797.3	290.5	0	31.7	21.8	0.0	19.0	195
51	11	8	4	3.6	60	5	10	1797.3	240.9	0	31.7	18.1	0.0	20.4	174
51	11	8	4	3.6	60	5	12	1797.3	207.3	0	31.7	15.5	0.0	21.6	158
51	11	8	4	4	60	5	8	1841.6	295.3	0	32.5	22.1	0.0	19.1	199
51	11	8	4	4	60	5	10	1841.6	245.4	0	32.5	18.4	0.0	20.5	177
51	11	8	4	4	60	5	12	1841.6	211.5	0	32.5	15.9	0.0	21.7	162
51	11	8	4	4.5	60	5	8	1894.9	301.1	0	33.4	22.6	0.0	19.2	204
51	11	8	4	4.5	60	5	10	1894.9	250.7	0	33.4	18.8	0.0	20.5	182
51	11	8	4	4.5	60	5	12	1894.9	216.5	0	33.4	16.2	0.0	21.7	166
51	11	8	5	3.6	60	5	8	2141.4	290.5	0	37.8	21.8	0.0	20.3	208
51	11	8	5	3.6	60	5	10	2141.4	240.9	0	37.8	18.1	0.0	21.8	186
51	11	8	5	3.6	60	5	12	2141.4	207.3	0	37.8	15.5	0.0	23.2	169
51	11	8	5	4	60	5	8	2189.1	295.3	0	38.6	22.1	0.0	20.4	212
51	11	8	5	4	60	5	10	2189.1	245.4	0	38.6	18.4	0.0	21.9	189
51	11	8	5	4	60	5	12	2189.1	211.5	0	38.6	15.9	0.0	23.2	173
51	11	8	5	4.5	60	5	8	2246.6	301.1	0	39.6	22.6	0.0	20.4	217	No. 6
51	11	8	5	4.5	60	5	10	2246.6	250.7	0	39.6	18.8	0.0	21.9	194
51	11	8	5	4.5	60	5	12	2246.6	216.5	0	39.6	16.2	0.0	23.2	177

Table B-3. Summary of Analysis Results for 51-in. Height and 12-in. Top Width

Height (in.)	Top Barrier Width (in.)	Longitudinal Bar Size	Quantity per face	F'c (ksi)	Fy (ksi)	Vertical Bar Size	Spacing O.C. (in.)	Mw (k-in.)	Mc (k-in.)	Mb (k-in.)	φMw (k-ft/ft)	φMc (k-ft/ft)	φMb (k-ft)	Lc (ft)	Rw (kips)	
51	12	7	4	3.6	60	5	8	1600.3	318.4	0	28.2	23.9	0.0	17.7	199	
51	12	7	4	3.6	60	5	10	1600.3	263.2	0	28.2	19.7	0.0	18.9	176	
51	12	7	4	3.6	60	5	12	1600.3	225.9	0	28.2	16.9	0.0	20.0	160	
51	12	7	4	4	60	5	8	1639	323.2	0	28.9	24.2	0.0	17.7	202	
51	12	7	4	4	60	5	10	1639	267.7	0	28.9	20.1	0.0	19.0	179	
51	12	7	4	4	60	5	12	1639	230.1	0	28.9	17.3	0.0	20.1	163	
51	12	7	4	4.5	60	5	8	1685.6	329	0	29.7	24.7	0.0	17.8	207	
51	12	7	4	4.5	60	5	10	1685.6	273	0	29.7	20.5	0.0	19.0	183	
51	12	7	4	4.5	60	5	12	1685.6	235.1	0	29.7	17.6	0.0	20.1	167	
51	12	7	5	3.6	60	5	8	1908.2	318.4	0	33.7	23.9	0.0	18.8	212	
51	12	7	5	3.6	60	5	10	1908.2	263.2	0	33.7	19.7	0.0	20.2	188	
51	12	7	5	3.6	60	5	12	1908.2	225.9	0	33.7	16.9	0.0	21.4	171	
51	12	7	5	4	60	5	8	1940	323.2	0	34.2	24.2	0.0	18.8	215	
51	12	7	5	4	60	5	10	1940	267.7	0	34.2	20.1	0.0	20.2	191	
51	12	7	5	4	60	5	12	1940	230.1	0	34.2	17.3	0.0	21.4	174	
51	12	7	5	4.5	60	5	8	2000.3	329	0	35.3	24.7	0.0	18.9	220	No. 7
51	12	7	5	4.5	60	5	10	2000.3	273	0	35.3	20.5	0.0	20.3	195	
51	12	7	5	4.5	60	5	12	2000.3	235.1	0	35.3	17.6	0.0	21.5	178	
51	12	8	4	3.6	60	5	8	1987.8	318.4	0	35.1	23.9	0.0	19.1	215	
51	12	8	4	3.6	60	5	10	1987.8	263.2	0	35.1	19.7	0.0	20.5	191	
51	12	8	4	3.6	60	5	12	1987.8	225.9	0	35.1	16.9	0.0	21.8	173	
51	12	8	4	4	60	5	8	2032.1	323.2	0	35.9	24.2	0.0	19.2	219	
51	12	8	4	4	60	5	10	2032.1	267.7	0	35.9	20.1	0.0	20.6	194	
51	12	8	4	4	60	5	12	2032.1	230.1	0	35.9	17.3	0.0	21.8	177	
51	12	8	4	4.5	60	5	8	2085.4	329	0	36.8	24.7	0.0	19.2	223	
51	12	8	4	4.5	60	5	10	2085.4	273	0	36.8	20.5	0.0	20.6	199	
51	12	8	4	4.5	60	5	12	2085.4	235.1	0	36.8	17.6	0.0	21.8	181	
51	12	8	5	3.6	60	5	8	2379.6	318.4	0	42.0	23.9	0.0	20.4	230	
51	12	8	5	3.6	60	5	10	2379.6	263.2	0	42.0	19.7	0.0	22.0	204	
51	12	8	5	3.6	60	5	12	2379.6	225.9	0	42.0	16.9	0.0	23.3	186	
51	12	8	5	4	60	5	8	2427.3	323.2	0	42.8	24.2	0.0	20.5	234	
51	12	8	5	4	60	5	10	2427.3	267.7	0	42.8	20.1	0.0	22.0	208	
51	12	8	5	4	60	5	12	2427.3	230.1	0	42.8	17.3	0.0	23.4	190	
51	12	8	5	4.5	60	5	8	2484.8	329	0	43.8	24.7	0.0	20.5	238	
51	12	8	5	4.5	60	5	10	2484.8	273	0	43.8	20.5	0.0	22.0	212	No. 8
51	12	8	5	4.5	60	5	12	2484.8	235.1	0	43.8	17.6	0.0	23.4	194	