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Anchoring and Stiffening Techniques for Portable Concrete Barriers

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ANCHORING AND STIFFENING TECHNIQUES FOR PORTABLE CONCRETE BARRIERS

by

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ANCHORING AND STIFFENING TECHNIQUES FOR PORTABLE CONCRETE BARRIERS

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Portable concrete barrier (PCB) systems are utilized on federal and state highways in circumstances such as placing adjacent to vertical drop-offs and in construction zones. PCB systems are most commonly used in a free-standing configuration, which are known to have relatively large deflections when impacted. Large deflections are undesirable when dealing with limited space. In order to allow PCBs to be used in space restricted locations, seven PCB anchoring and stiffening techniques were tested and evaluated as per *Manual for Assessing Safety Hardware* (MASH) testing standards. Results will allow the New Jersey Department of Transportation to update guidance for their use and installation of PCBs.

Techniques that restrict deflections included the use of anchorage and stiffeners on the PCBs. Pin and bolt anchor rods were used to anchor PCBs to road surfaces, and box beam rails and non-shrink grout wedges were used as stiffeners. Box beam rails were mounted on the back side of the system and non-shrink grout wedges were placed between barrier sections.

Full-scale crash tests indicated that anchoring of PCBs limits barrier deflection when impacted. Box beam stiffening of free-standing systems reduced dynamic barrier deflections from 40.7 in. to 33.0 in. The bolt anchored version of the PCB system had 4.9 in. of dynamic deflection, by far the least amount; additionally the vehicle was more stable than the pin anchorage systems.

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS iii

TABLE OF CONTENTS iv

LIST OF FIGURES vi

LIST OF TABLES vii

CHAPTER 1. INTRODUCTION 1
- 1.1 Research Statement 1
- 1.2 Background 3

CHAPTER 2. LITERATURE REVIEW 5
- 2.1 New Jersey Shaped PCBs 6
  - 2.1.1 Free-standing and Unanchored System for New York State's PCBs 6
  - 2.1.2 Box-Beam Stiffening of NYSDOT PCBs 7
  - 2.1.3 New York State's PCBs in Pin Anchored Configurations 9
- 2.2 F-Shape PCBs in Free-Standing Configurations 11
  - 2.2.1 Development of MwRSF F-Shape PCB 11
  - 2.2.2 Modified Virginia DOT F-Shape PCBs 12
  - 2.2.3 F-Shape PCB Evaluation under Update to NCHRP Report 350 13
- 2.3 Anchorage of F-Shape PCBs 14
  - 2.3.1 Tie-Down System for F-Shape PCBs 14
  - 2.3.2 Tie-Down System for Redesigned F-Shape PCBs 15
  - 2.3.3 Tie-Down System for F-Shape PCBs on Asphalt Road Surfaces.... 16
  - 2.3.4 PCB System for Off-Road Applications 17

CHAPTER 3. SYSTEM DETAILS 19
- 3.1 Pin Anchorage 21
- 3.2 Bolt Anchorage 22
- 3.3 Box-Beam Rail as Stiffener 23
- 3.4 Non-Shrink Grout 24

CHAPTER 4. EVALUATION CRITERIA 25

CHAPTER 5. NEW JERSEY PCB TESTS 28
- 5.1 Test No. NJPCB-1 28
  - 5.1.1 Test Description and Vehicle Behavior 29
  - 5.1.2 Barrier Deflections 29
  - 5.1.3 Barrier Damage 30
  - 5.1.4 Vehicle Damage 30
- 5.2 Test No. NJPCB-2 31
  - 5.2.1 Test Description and Vehicle Behavior 32
  - 5.2.2 Barrier Deflections 32
  - 5.2.3 Barrier Damage 33
  - 5.2.4 Vehicle Damage 33
- 5.3 Test No. NJPCB-3 34

        - 5.3.1 Test Description and Vehicle Behavior 35
        - 5.3.2 Barrier Deflections 35
        - 5.3.3 Barrier Damage 36
        - 5.3.4 Vehicle Damage 36
    - 5.4 Test No. NJPCB-4 37
        - 5.4.1 Test Description and Vehicle Behavior 38
        - 5.4.2 Barrier Deflections 38
        - 5.4.3 Barrier Damage 39
        - 5.4.4 Vehicle Damage 39
    - 5.5 Test No. NJPCB-5 40
        - 5.5.1 Test Description and Vehicle Behavior 41
        - 5.5.2 Barrier Deflections 41
        - 5.5.3 Barrier Damage 42
        - 5.5.4 Vehicle Damage 42
    - 5.6 Test No. NJPCB-6 43
        - 5.6.1 Test Description and Vehicle Behavior 44
        - 5.6.2 Barrier Deflections 44
        - 5.6.3 Barrier Damage 45
        - 5.6.4 Vehicle Behavior 45
    - 5.7 Test No. NJPCB-7 46
        - 5.7.1 Test Description and Vehicle Behavior 47
        - 5.7.2 Barrier Deflections 47
        - 5.7.3 Barrier Damage 48
        - 5.7.4 Vehicle Behavior 48

- CHAPTER 6. DISCUSSION AND ANALYSIS 49
    - 6.1 Free-standing Systems 51
    - 6.2 Pin Anchorage Systems 51
    - 6.3 Bolt Anchorage System 52

- CHAPTER 7. CONCLUSION AND FUTURE WORK 53

- CHAPTER 8. REFERENCES 58

LIST OF FIGURES

Figure 1. New Jersey Barrier (left) and F-Shape Barrier (right) profiles 4
Figure 2. PCBs with Box-Beam Stiffener...8
Figure 3. Initial Prototype of F-Shaped PCB segment 11
Figure 4. Updated design of F-Shaped PCB 12
Figure 5. Steel Tie-Down Strap 15
Figure 6. Tie-Down System for Redesigned F-Shaped PCBs 16
Figure 7. Tie-Down System for Asphalt Surface...17
Figure 8. PCB ski design 18
Figure 9. Barrier System 19
Figure 10. Connection between barriers 20
Figure 11. Pin Anchors on Barriers 21
Figure 12. Bolt Anchors on Barriers...22
Figure 13. Box Beam Stiffeners..23
Figure 14. Non-Shrink Grout between barriers 24
Figure 15. Impact Condition and Location 26
Figure 16. Results Summary of full-scale crash test – NJPCB-1 28
Figure 17. Sequential View of Vehicle Behavior – NJPCB-1................................29
Figure 18. Barrier Deflection (Impact location, during impact, and Post Impact) ...29
Figure 19. Barrier Damage – Barrier 4 (Top) and Barrier 5 (Bottom) 30
Figure 20. Results Summary of full-scale crash test – NJPCB-2 31
Figure 21. Sequential View of Vehicle Behavior – NJPCB-2................................32
Figure 22. Barrier Deflection (Impact location, during impact, and Post Impact) ...32
Figure 23. Barrier Damage – Barrier 4 (Top) and Barrier 5 (Bottom) 33
Figure 24. Results Summary of full-scale crash test – NJPCB-3 34
Figure 25. Sequential View of Vehicle Behavior – NJPCB-3................................35
Figure 26. Barrier Deflection (Impact location, during impact, and Post Impact) ...35
Figure 27. Barrier Damage – Barrier no. 4 (Top) and Barrier no. 5 (Bottom) 36
Figure 28. Results Summary of full-scale crash test – NJPCB-4 37
Figure 29. Sequential View of Vehicle Behavior – NJPCB-4................................38
Figure 30. Barrier Deflection (Impact location, during impact, and Post Impact) ...38
Figure 31. Barrier Damage – Barrier no. 4 (Top) and Barrier no. 5 (Bottom) 39
Figure 32. Results Summary of full-scale crash test – NJPCB-5 40
Figure 33. Sequential View of Vehicle Behavior – NJPCB-5................................41
Figure 34. Barrier Deflection (Impact location, during impact, and Post Impact) ...41
Figure 35. Barrier Damage – Barrier 4 (Top) and Barrier 5 (Bottom) 42
Figure 36. Results Summary of full-scale crash test – NJPCB-6 43
Figure 37. Sequential View of Vehicle Behavior – NJPCB-6................................44
Figure 38. Barrier Deflection (Impact location, during impact, and Post Impact) ...44
Figure 39. Barrier Damage – Barrier 4 (Top) and Barrier 5 (Bottom) 45
Figure 40. Results Summary of full-scale crash test – NJPCB-7 46
Figure 41. Sequential View of Vehicle Behavior – NJPCB-7................................47
Figure 42. Barrier Deflection (Impact location, during impact, and Post Impact) ...47
Figure 43. Barrier Damage – Barrier 4 (Top) and Barrier 5 (Bottom) 48
Figure 44. Dynamic Deflection and Permanent Set Deflection – NJPCB-2 52

LIST OF TABLES

Table 1. NJDOT *Roadway Design Manual* – PCB guidance 1
Table 2. NJDOT PCBs in various configurations..2
Table 3. System Performance of New Jersey Shaped PCBs 5
Table 4. System Performance of F-Shaped PCBs in accordance with NCHRP 350 3-11...6
Table 5. MASH 2016 TL-3 Crash Test Conditions for Longitudinal Barriers.........25
Table 6. Full-Scale Crash Tests Results – Barrier Deflections and Impact Severities..50
Table 7. Full-Scale Crash Tests Results – Vehicle Behavior 50
Table 8. PCB guidance – Change in Allowable Movements...................................54
Table 9. PCB guidance – Change in Joint Treatments with dynamic deflections....55
Table 10. PCB guidance – Change in Joint Treatments with Permanent set deflections 56

CHAPTER 1. INTRODUCTION

1.1 Research Statement

Portable concrete barrier systems (PCBs), also known as temporary concrete barriers systems (TCBs) are used for several functions, including: preventing motorists from intruding into the work space within work zones; providing positive protection for construction and maintenance workers; separating two-way or opposing traffic; shielding vehicles from roadside and median hazards; and separating pedestrians and bicyclists from vehicle traffic.

The New Jersey Department of Transportation (NJDOT) currently uses a New Jersey shape PCB design with I-beam connection key in their work zones and construction areas. The New Jersey *Roadway Design Manual* [1] provides guidance on allowable barrier deflections for various classes of PCB joint and anchoring treatments for impact conditions such as a 4,400-lb pickup truck with impact angle of 25 degrees at 62 mph (listed in Table 1).

Table 1. NJDOT *Roadway Design Manual* – PCB guidance

Joint Class	Use	Joint Treatment
A	Allowable movement over 16 to 42 inches	Connection Key only
B	Allowable movement over 11 to 16 inches	Connection Key and grout in every joint
C	Maximum allowable movement of 11 inches	Connection Key and grout in every joint and pin every other unit. In units to be anchored, pins should be required in every recess.
D	No allowable movement (i.e. bridge parapet)	Connection Key and grout in every joint and bolt every anchor pocket hole in every unit.

The joint treatment guidance and allowable deflection limits are based on test data from previous testing standards and need to be updated with current testing standards specified in *Manual for Assessing Safety Hardware* (MASH) [2]. Testing of other PCB systems has indicated that dynamic barrier deflections can increase significantly when compared to deflections based on older crash test data.

To reduce dynamic deflections and maximize barrier crashworthiness, the anchoring and stiffening techniques used in New Jersey shaped PCBs were evaluated with full-scale crash testing. The results would allow the NJDOT to develop and update guidance for the installation and use of PCBs.

Only crash tests at Test Level 3 (TL3) that would maximize lateral deflections and vehicle instability were considered. Thus, the MASH small car was omitted from the research due to its low mass relative to the 2270P pickup truck (5,000 lb) test vehicle. Each test utilized a separate configuration of either bolts or pins anchoring some or all of the barriers to a concrete tarmac, as listed in Table 2. The configurations were then crash tested and evaluated in accordance with MASH TL-3 test 3-11.

Table 2. NJDOT PCBs in various configurations

Test No.	**Type of Anchors**	**System Configuration**	**Joint Class**
NJPCB-1	Pin	Barriers 1, 3, 5, 7, 9, and 10 pin anchored to concrete tarmac	C
NJPCB-2	Bolt	All ten barrier segments bolt anchored to concrete tarmac	D
NJPCB-3	Pin	Free-standing system with barriers 1 and 10 pin anchored to concrete tarmac	A
NJPCB-4	Pin	Free-standing system with barriers 1 and 10 pin anchored to concrete tarmac	B
NJPCB-5	Pin	Box-Beam Stiffened to all nine joints between barrier segments, and barriers 1 and 10 pin anchored to concrete tarmac	B (modified)
NJPCB-6	Pin	Barriers 1 and 10 pinned on both sides, and barriers 2 through 9 pin anchored on back side to concrete tarmac	C (modified)
NJPCB-7	Pin	Barriers 1 and 10 pinned on both sides, and barriers 2 through 9 pin anchored on traffic side to concrete tarmac	C (modified)

Note that the joint class treatments mentioned in Table 2 also contains modified joint classes based on anchoring techniques. The updated PCB guidance will be based on the maximum system deflection for Test Level 3, and to get maximum deflections small car full-scale crash tests were not considered, as they produce low system deflections.

1.2 Background

Whenever a traffic control plan is developed that utilizes PCB system, it is important to define acceptable barrier deflection criteria. The acceptable deflection criteria can be expected to vary, depending on the application. The deflection criteria should be selected to reduce the propensity of the barrier being displaced too far. The best example of such a situation is when the barrier is used on the edge of a bridge deck. A conventional PCB can be pulled off of the bridge by a single segment that is pushed off of the deck, endangering workers and traffic below the bridge. Therefore, deflections that could lead to such behavior should be avoided. Under this situation it is generally accepted that barriers should be designed to contain almost all impacts without allowing the center of gravity of any barrier segment to extend beyond the edge of the bridge. PCBs are more frequently used in applications where lateral deflections are less catastrophic, but still must be controlled.

There are many PCB designs in use, varying widely in terms of steel reinforcement, joint connection, and segment length. The most common barriers used on federal and state roadways are the New Jersey shape and F-shape barriers (see Figure 1). The F-shape barriers were developed in the 1970s, while the New Jersey shape was developed in the 1950s. Width at the top of a New Jersey shaped barrier is narrower than F-shaped barriers, while specific dimensions (length, height, and width), connection joints, reinforcements, materials and other features differ from state to state. The focus of this study is primarily on New Jersey shape PCBs.

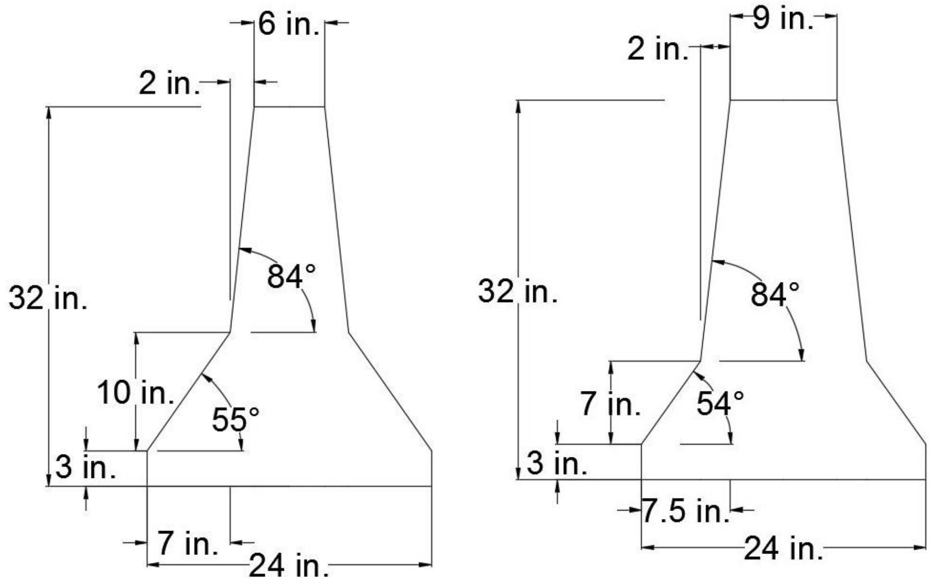


Figure 1. New Jersey Barrier (left) and F-Shape Barrier (right) profiles

Several anchoring and stiffening techniques have been incorporated into selected PCB systems to reduce barrier deflections and allow their use in restricted work zones with confined space behind the barrier system. Some of these systems have included the use of stiffening beams placed on the back side of the barriers and across the joints, the placement of vertical pins or rods through either the front toe or both toes of the barrier and into the pavement or bridge deck surface, as well as the use of an anchorage system that connects the joint hardware to the deck surface.

CHAPTER 2. LITERATURE REVIEW

A literature search was conducted in order to review (1) previous PCB systems barrier deflections, and (2) barrier anchoring and stiffening techniques. A brief summary of relevant research studies is provided herein and include test descriptions, test conditions, dynamic deflections and maximum lateral permanent sets. Performance summaries of a few New Jersey shaped and F-Shaped PCB systems are listed in Tables 3 and 4. Data reported in SI units in their respective reports were converted to English units herein.

Table 3. System Performance of New Jersey Shaped PCBs

Test No.	Dynamic Deflection (in.)	Permanent Set Deflection (in.)	System Configuration
473220-7	184.7	Penetrated	Free-standing configuration with connection keys
473220-14	50	50	Free-standing configuration with connection keys
NYTCB-1	27.6	26	Box-Beam stiffener used between barrier nos. 4 through 7, and connection keys
NYTCB-2	40.3	39½	Free-standing configuration with connection keys
NYTCB-3	30.9	26	Box-Beam stiffener used between barrier nos. 2 through 9, and connection keys
NYTCB-4	64.8	53½	Barrier nos. 1, 3, 5, 7, and 9 pinned on back side, and connection keys
NYTCB-5	20.5	9	All barrier segments pinned on backside, and connection keys

Note: (i) Test Nos. 473220-7 and 473220-14 were conducted by TTI, and the remaining tests were conducted by Midwest Roadside Safety Facility (MwRSF)

(ii) Test Nos. 473220-7 and 473220-14 were conducted in accordance with NCHRP 350 3-11, and the remaining tests were according to MASH.

(iii) All tests were conducted on Concrete Tarmac

Table 4. System Performance of F-Shaped PCBs in accordance with NCHRP 350 3-11

Test No.	Dynamic Deflection (in.)	Permanent Set Deflection (in.)	System Configuration
ITMP-1	-	39	Pin and Loop connection
ITMP-2	45.3	44⅞	Pin and Loop connection
402041-1	72	67¼	Pin and Loop connection
2214TB-1	56.7	56¾	Free-Standing
2214TB-2	79.7	73	Free-Standing
ITD-1	37.8	33½	Tie-down
KTB-1	11.3	3½	Tie-down
FTB-1	21.8	11⅛	Pinned on traffic side, and asphalt as support surface

Note: (i) Test No. 402041-1 was conducted by TTI, all others were conducted by MwRSF

(ii) Test Nos. 2214TB-1 and 2214TB-2 were conducted in accordance with Update to NCHRP 350 3-11, which is now known as MASH.

(iii) Test No. FTB-1 was conducted on asphalt, all others were conducted on Concrete Tarmac

2.1 New Jersey Shaped PCBs

2.1.1 Free-standing and Unanchored System for New York State's PCBs

In 1999, a free-standing version of the NYSDOT PCBs with unpinned ends was tested by the Texas Transportation Institute (TTI) [3]. The full-scale crash test consisted of ten 20-ft long, New Jersey shape PCB segments with a total system length of 200 ft. The PCB system utilized an I-beam key barrier-to-barrier connection. In test no. 473220-7, a 4,575-lb pickup truck impacted the system at a speed of 60.9 mph and at an angle of 26.3 degrees. During impact, three of the barrier joints failed, causing the barrier at the point of impact to overturn. Subsequently, the vehicle overrode the barrier and rolled over. The test was determined to be unacceptable according to the NCHRP Report 350 test criteria. The joint failure was due to substandard welding in the connection joints.

In 2001, TTI tested a redesigned New Jersey shaped PCB (termed as NYDOT PCB) in free-standing configuration [4]. The full-scale crash test consisted of ten 20-ft long, New Jersey shape PCB segments with a total system length of 200 ft. The PCB system utilized an I-beam key barrier-to-barrier connection. In test no. 473220-14, a 4,577-lb pickup truck impacted at a speed of 62.6 mph and at an angle of 25.6 degrees. During the impact, the vehicle was redirected smoothly, and the test was determined to be acceptable according to the NCHRP Report 350 requirements. The barrier system experienced 50 in. of maximum lateral dynamic deflection and 50 in. of permanent set. During the test, the upstream end was pulled $5^{13}/_{16}$ in. longitudinally downstream, while the downstream end displaced $^{3}/_{16}$ in. longitudinally upstream. The noted lateral barrier deflections would be correlated to the unpinned section ends. Concerns over the relatively large barrier deflection caused NYSDOT to contract with MwRSF to conduct barrier stiffening research.

2.1.2 Box-Beam Stiffening of NYSDOT PCBs

In 2008, MwRSF investigated NYSDOT PCBs in three different configurations [5]. The research study included three full-scale vehicle crash tests with 2270P pickup trucks conducted in accordance with the TL-3 evaluation criteria published in MASH. In all three tests, the first and last barrier sections were anchored to the concrete tarmac.

The PCB system was stiffened using box beams bolted across barrier joints on the backside of the system in order to limit system deflections, as shown in Figure 2. Anchoring of PCB systems with pins or bolted-through connections had been previously tested, but this process is time consuming and may result in damage to the bridge. NYSDOT personnel developed a concept of using box-beam stiffener that would minimize barrier deflections while preventing bridge deck damage.

Figure 2. PCBs with Box-Beam Stiffener

The first test installation consisted of ten 20-ft long, New Jersey shape PCB segments for a total system length of 200 ft. The PCB system was free-standing with both end segments pin anchored to the tarmac with nine 1-in. diameter × 15½-in. long, A36 steel rods – five anchors on the traffic side and four anchors on the back side. Each anchor rod was driven into a hole drilled in the concrete to an embedment depth of 5 in. The PCB system utilized an I-beam key barrier-to-barrier connection. The three joints between barrier nos. 4 and 7 were stiffened with box beams. Each box beam stiffener consisted of a 6-in. × 6-in. × $^{3}/_{16}$-in. ASTM A500 Grade C box beam, which was 12 ft long. The box beams were connected to the barriers with ¾-in. diameter × 17-in. long, Grade 5 continuously threaded rod. During test no. NYTCB-1, a 5,016-lb pickup truck impacted the system at a speed of 61.8 mph and at an angle of 24.6 degrees. The vehicle was redirected smoothly, and the test was determined to be acceptable according to MASH requirements. The barrier system experienced maximum lateral dynamic deflection of 27.6 in. and permanent set deflection of 26 in.

The second test, test no. NYTCB-2, consisted of an unstiffened version of the NYSDOT PCBs with pin anchored ends. In this test, a 5,024-lb pickup truck impacted the system at a speed of 61.2 mph and at an angle of 25.8 degrees. The vehicle redirected smoothly and the test was determined to be acceptable according to MASH requirements. The barrier system experienced 40.3 in. of maximum lateral dynamic deflection and 39½ in. of permanent set deflection.

The third full-scale crash test utilized a system that was identical to test no. NYTCB-1, except with a more robust box-beam stiffener. Test no. NYTCB-3 consisted of stiffening six joints between barrier nos. 2 and 8 with 6-in. × 8-in. × ¼-in. box beam sections. In addition, this system was installed with the back side of the barrier sections placed 12 in. away from a simulated bridge deck edge. In this test, a 5,001-lb pickup truck impacted the system at a speed of 63.5 mph and at an angle of 24.4 degrees. The vehicle was redirected smoothly, and the test was determined to be acceptable according to MASH requirements. This system experienced 30.9 in. of dynamic deflection and 26 in. of permanent set deflection.

2.1.3 New York State's PCBs in Pin Anchored Configurations

In 2009 and 2010, two different versions of NYSDOT's TCB system were evaluated [6-7]. The research study included two full-scale vehicle crash tests with 2270P pickup trucks conducted in accordance to the TL-3 evaluation criteria published in MASH. For PCBs located adjacent to vertical drop-offs, NYSDOT found it desirable to utilize vertical pins through the back-side toe of the PCBs in order to reduce barrier deflections as well as to reduce the need for workers to be positioned on the traffic-side face of the system when installing anchors.

Test no. NYTCB-4 was a pinned version of the NYSDOT PCB system [6]. The system consisted of ten 20-ft long, New Jersey shaped PCBs with a total system length of 200 ft, with barriers 1, 3, 5, 7, and 9 pinned on the back side to the concrete tarmac with steel rods placed through the pin anchor recesses of the barrier sections and set into drilled holes in the concrete tarmac. A 5,172-lb pickup truck impacted the system at a speed of 62.3 mph and at an angle of 24.3 degrees. During impact, the joint between barrier nos. 4 and 5 completely separated at approximately the same time that the vehicle exited the barrier system. The barrier system experienced 64.8 in. of maximum lateral dynamic deflection and 53½ in. of permanent set deflection. This significant increase of dynamic deflection was the result of the separation of the joint. However, the vehicle was contained and smoothly redirected. Although complete joint separation occurred and is generally undesirable, the test was determined to be acceptable according to MASH requirements.

For test NYTCB-5 every PCB segment was pin anchored on the back side to the concrete surface. The test installation consisted of ten 20-ft long, New Jersey shape PCB segments with a total system length of 200 ft. The PCB system utilized an I-beam key barrier-to-barrier connection, and the system was placed 12 in. laterally from the edge of a simulated bridge deck. A 5,124-lb pickup truck impacted the system at a speed of 64.3 mph and at an angle of 26.2 degrees. The vehicle was redirected smoothly, and the test was determined to be acceptable according to MASH requirements. The maximum lateral dynamic barrier deflection was 20.5 in. and the permanent set of the barrier system was 9 in.

2.2 F-Shape PCBs in Free-Standing Configurations

2.2.1 Development of MwRSF F-Shape PCB

In 1996, an F-Shape PCB was developed and tested by the MwRSF for the Midwest States Regional Pooled Fund program [9]. Before this, PCB configurations varied significantly from state to state. Therefore, a need existed to develop, test, and evaluate one standardized PCB design which met TL-3 impact safety standards set forth in NCHRP Report 350. The redesigned F-Shaped PCB is shown in Figure 3.

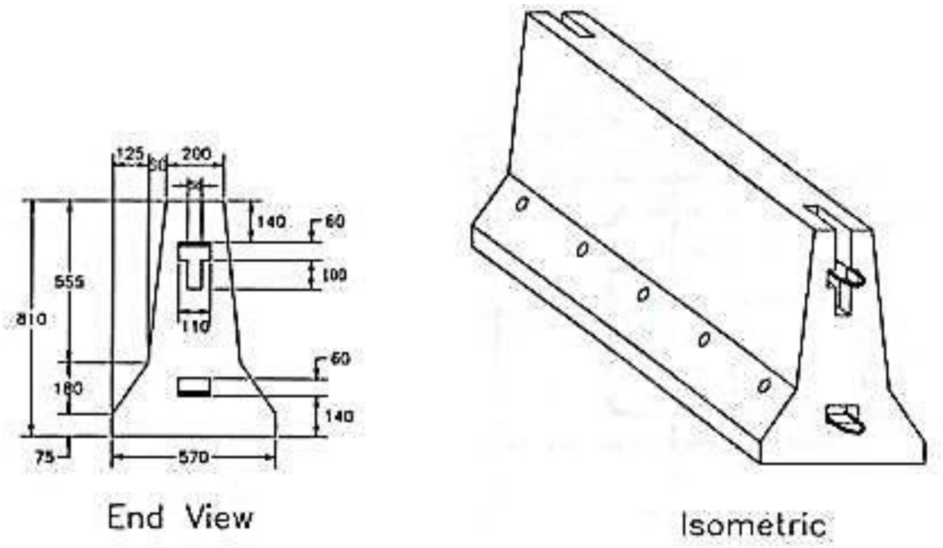


Figure 3. Initial Prototype of F-Shaped PCB segment

This system consisted of sixteen 12 ft – 5½ in. long, F-Shape PCB segments for a total system length of 203 ft – 3¾ in. The PCB system was free-standing on a concrete surface and utilized a pin and loop barrier-to-barrier connection. In test no. ITMP-1, a 4,409-lb pickup truck impacted the PCB system at a speed of 64.1 mph and at an angle of 27.6 degrees. Upon impact, the vehicle climbed and overrode the system, and the test was deemed unsuccessful as per NCHRP Report 350.

Upon inspection of the damaged barrier system, it was discovered that considerable damage occurred at the barrier joints. It was determined that this damage was likely caused by the weakened recessed areas located at the top end of each barrier segment. The recessed areas were incorporated for future use in implementing a rigid joint for permanent barrier installations. In order to reduce joint rotations and prevent barrier uplift, it was necessary to strengthen the barrier ends by eliminating the recessed areas. Hence, the F-shape barriers were redesigned, as shown in Figure 4.

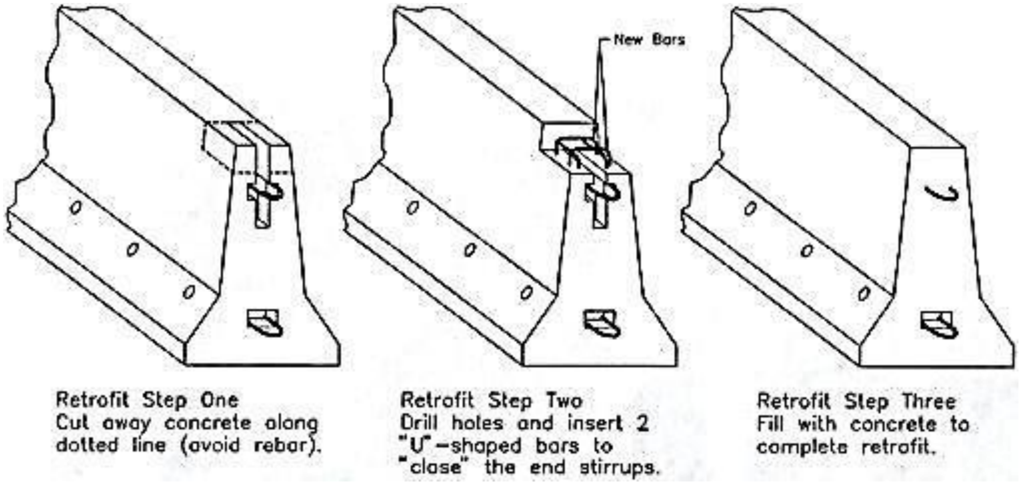


Figure 4. Updated design of F-Shaped PCB

The redesigned system consisted of twenty one 12 ft – 5½ in. long, F-shape PCB segments for a total system length of 267 ft – 5½ in. The PCB system was free-standing on a concrete surface and utilized a pin and loop barrier-to-barrier connection. In test no. ITMP-2, a 4,420-lb pickup truck impacted the PCB system at a speed of 62.3 mph and at an angle of 27.1 degrees. The system contained and redirected the vehicle with maximum lateral dynamic and permanent set deflections of 45.3 in. and 44⅞ in., respectively, and was determined to be successful according to TL-3 of NCHRP Report 350.

2.2.2 Modified Virginia DOT F-Shape PCBs

In 1998, a modified Virginia Department of Transportation (VDOT) PCB was tested and evaluated by TTI according to specifications of NCHRP Report 350 test level 3 (TL-3) [10]. The test no. 402041-1 consisted of five 20 ft – $^{5}/_{32}$ in long, modified VDOT

PCB segments for a total system length of 100 ft – $^{15}/_{16}$ in. The PCB system was free-standing on a concrete surface and utilized a pin and loop barrier-to-barrier connection. In test no. 402041-1, a 4,480-lb pickup truck impacted the PCB system at a speed 62.5 mph and at an angle of 24.6 degrees. The system contained and redirected the vehicle with maximum lateral dynamic and permanent set deflections of 72 in. and 67¼ in., respectively, and was determined to be successful according to TL-3 of NCHRP Report 350.

2.2.3 F-Shape PCB Evaluation under Update to NCHRP Report 350

With constant changes and upgrades to vehicles, standards for tests and evaluations of roadside safety hardware must also change. Thus, NCHRP Report 350 was updated to include heavier vehicles with higher centers of gravity. In 2006, MwRSF researchers conducted another crash test under the impact conditions outlined in the update to NCHRP Report 350 (now known as MASH) on the F-shaped PCB system that had been previously tested [11].

The system consisted of sixteen 12 ft – 6 in. long, F-shape PCB segments for a total system length of 204 ft – 6 in. The PCB system was free-standing on a concrete surface and utilized a pin and loop barrier-to-barrier connection. In test no. 2214TB-1, a 5,000-lb pickup truck impacted the system at a speed of 61.8 mph and at an angle of 25.7 degrees. The system contained and redirected the vehicle with maximum lateral dynamic and permanent set deflections of 56.7 in. and 56¾ in. respectively. The test vehicle utilized for 2214TB-1 was a ¾-ton 2-door pickup truck, rather, subsequent investigation revealed that an alternative vehicle was preferred in the update to NCHRP Report 350. Hence, test no. 2214TB-2 was conducted with the recommended vehicle.

The system consisted of sixteen 12 ft – 6 in. long, F-shape PCB segments for a total system length of 204 ft – 6 in. The PCB system was free-standing on a concrete surface and utilized a pin and loop barrier-to-barrier connection. During test no. 2214TB-2, a 5,000-lb pickup truck impacted the system at a speed of 61.9 mph and at an angle of 25.4 degrees. The system contained and redirected the vehicle with maximum lateral dynamic and permanent set deflections of 79.7 in. and 73 in., respectively, and was found to be successful according to the TL-3 safety criteria published in the update to NCHRP Report 350.

2.3 Anchorage of F-Shape PCBs

2.3.1 Tie-Down System for F-Shape PCBs

In 2002, a tie-down system for PCBs was developed and tested by MwRSF [12]. Free-standing PCB systems near vertical drop-offs are at risk of being displaced off of the bridge deck when impacted by an errant vehicle. In order to decrease this risk, MwRSF developed a steel tie-down strap that could be placed on the connection pin at the PCB joints and anchored to the bridge deck using drop-in anchors. The design consisted of a 3-in. wide × ¼-in. thick × 36-in. long piece of ASTM A36 steel bent into a trapezoidal shape. The straps were attached to the bridge deck using two ¾-in. diameter drop-in anchors and ¾-in. diameter × 2¼-in. long ISO Class 8.8 bolts, as shown in Figure 5.

Figure 5. Steel Tie-Down Strap

The test installation consisted of sixteen 12 ft – 6 in. long, F-shape PCB segments placed 12 in. away from a bridge deck edge. In test no. ITD-1, a 4,435-lb pickup truck impacted the system at a speed of 60.6 mph and at an angle of 24.3 degrees. The PCB system contained and redirected the vehicle with maximum lateral dynamic and permanent set barrier deflections of 37.8 in. and 33½ in., respectively. In test no. ITD-1, only one PCB segment was displaced completely off the bridge deck with two PCB segments partially displaced off the bridge deck. Thus, the results from test no. ITD-1 were successful according to TL-3 of NCHRP Report 350.

2.3.2 Tie-Down System for Redesigned F-Shape PCBs

In 2003, MwRSF developed a tie-down system for redesigned F-shape PCBs that incorporated a bolt-through detail [13]. The redesigned F-shape PCBs incorporated a three loop connection that provided double shear at two locations on each pin. The bolt-through, tie-down system consisted of three 1⅛-in. diameter ASTM A307 anchor bolts with heavy hex nuts and 3-in. × 3-in. × ½-in. thick washers spaced evenly across the traffic side of each PCB segment, as shown in Figure 6. Each anchor bolt was epoxied into the concrete with an embedment depth of 12 in.

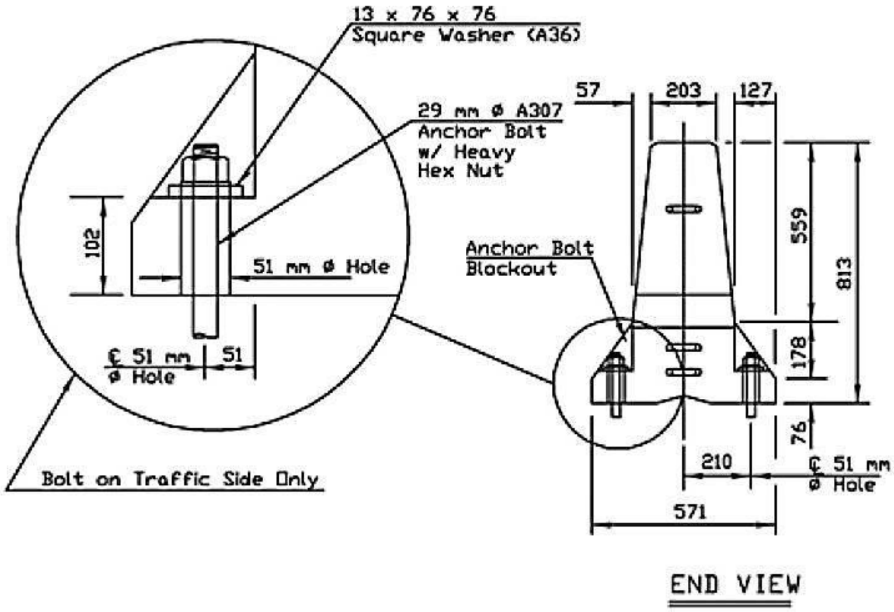


Figure 6. Tie-Down System for Redesigned F-Shaped PCBs

The test installation consisted of sixteen 12 ft – 6 in. long, redesigned F-shape PCB segments were placed adjacent to a bridge deck edge with a total system length of 204 ft. In test no. KTB-1, a 4,448-lb pickup truck impacted the system at a speed of 62.0 mph and at an angle of 25.3 degrees. The system contained and redirected the vehicle with maximum lateral dynamic and permanent set deflections of 11.3 in. and 3½ in., respectively, and was considered successful according to TL-3 of NCHRP Report 350.

2.3.3 Tie-Down System for F-Shape PCBs on Asphalt Road Surfaces

In 2006, MwRSF developed a tie-down system for PCBs on an asphalt road surface [14]. Previously developed tie-down systems had been only tested on concrete surfaces. The tie-down system consisted of F-shape PCB segments placed on a 2-in. thick asphalt pad with three 1½-in. diameter × 36-in. long, A36 steel pins installed through the holes on the traffic-side toe of the PCB segments, as shown in Figure 7.

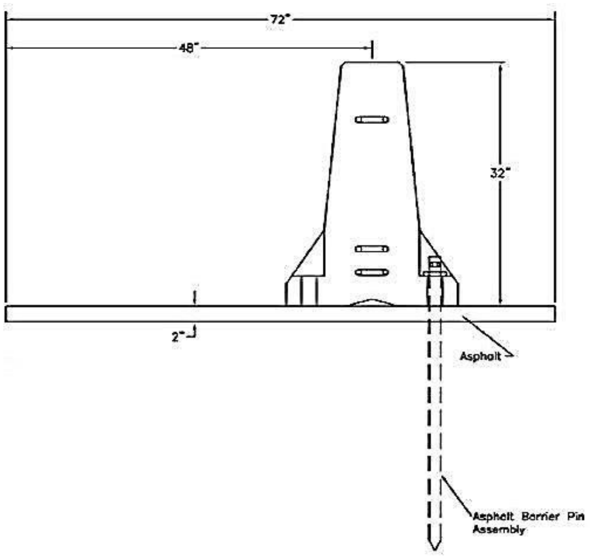


Figure 7. Tie-Down System for Asphalt Surface

The test installation consisted of sixteen 12 ft – 6 in. long, F-shape PCB segments placed 6 in. from a 3-ft wide × 3-ft deep trench. The tie-down pins were installed on the middle ten PCB segments. During test no. FTB-1, a 4,434-lb pickup truck impacted the system at a speed of 61.3 mph and at an angle of 25.4 degrees. The tie-down PCB system contained and redirected the vehicle with maximum lateral dynamic and permanent set barrier deflections of 21.8 in. and 11⅛ in., respectively. A portion of the soil and asphalt fractured and separated away from the road surface beneath the PCB system due to loading of the tie-down pins. This separation did not adversely affect the performance of the system, and was deemed successful according to TL-3 of NCHRP Report 350.

2.3.4 PCB System for Off-Road Applications

In 1996, MwRSF developed a PCB system for placement on a soil foundation [15]. PCB systems are typically placed on concrete or bituminous surfaces, but it is often impractical and costly to follow this practice. Therefore, it was determined that development of a PCB system capable of placement on soil foundations or native fill with slopes 10H:1V or flatter would be economical. In order to mitigate the potential of barrier tipping, a ski system was developed. The design called for two ski systems to be attached to each PCB segment. The maximum overturning moment of a PCB during a crash test was estimated to be 3.3 kip-ft and each ski system was designed to resist half of this moment. A 2-ft × 2-ft square piece of ¾-in. thick plywood was placed under the ski to prevent it from gouging into the soil. The ski was attached to the plywood with ¼-in. long wood screw, as shown in Figure 8.

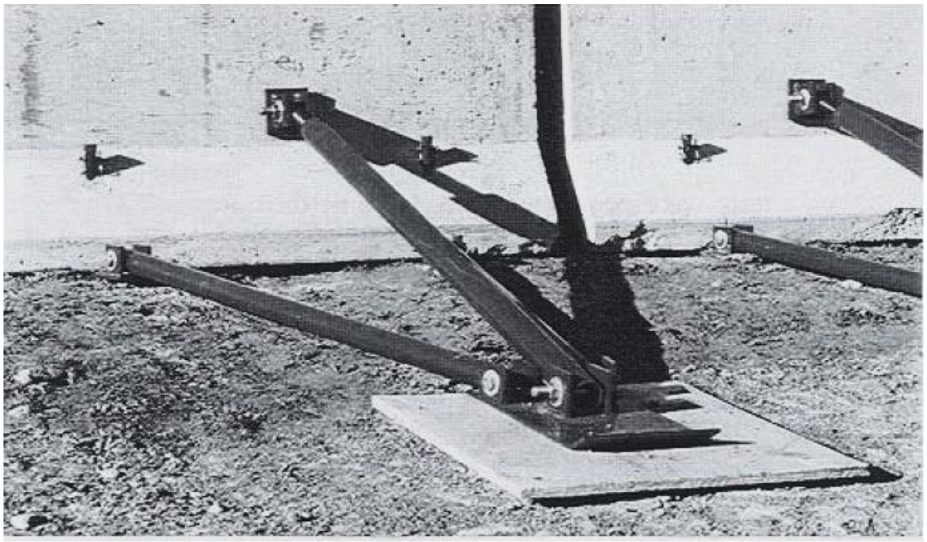


Figure 8. PCB ski design

The test installation consisted of seventeen 12 ft – 6 in. long, F-shape PCB segments for a total system length of 203 ft – 5½ in. In test no. KTS-1, a 4,405-lb pickup truck impacted the PCB system at a speed of 61.9 mph and at an angle of 26.9 degrees. The system contained and redirected the vehicle with a permanent set deflection of $45^{11}/_{16}$ in. and was considered successful according to TL-3 of NCHRP Report 350.

CHAPTER 3. SYSTEM DETAILS

A 32-in. tall New Jersey shape PCB was chosen for this research study, which is representative of the typical PCB used by NJDOT to create work zones and construction areas (see Figure 9). Each PCB segment measured 20 ft long and utilized an I-beam connection key for the barrier-to-barrier connection, as shown in Figure 10. This research study was focused on the evaluation of NJDOT PCBs, as mentioned in NJDOT’s *Roadway Design Manual* [1]. Brief system details are provided herein, more details is in respective test reports [20-26].

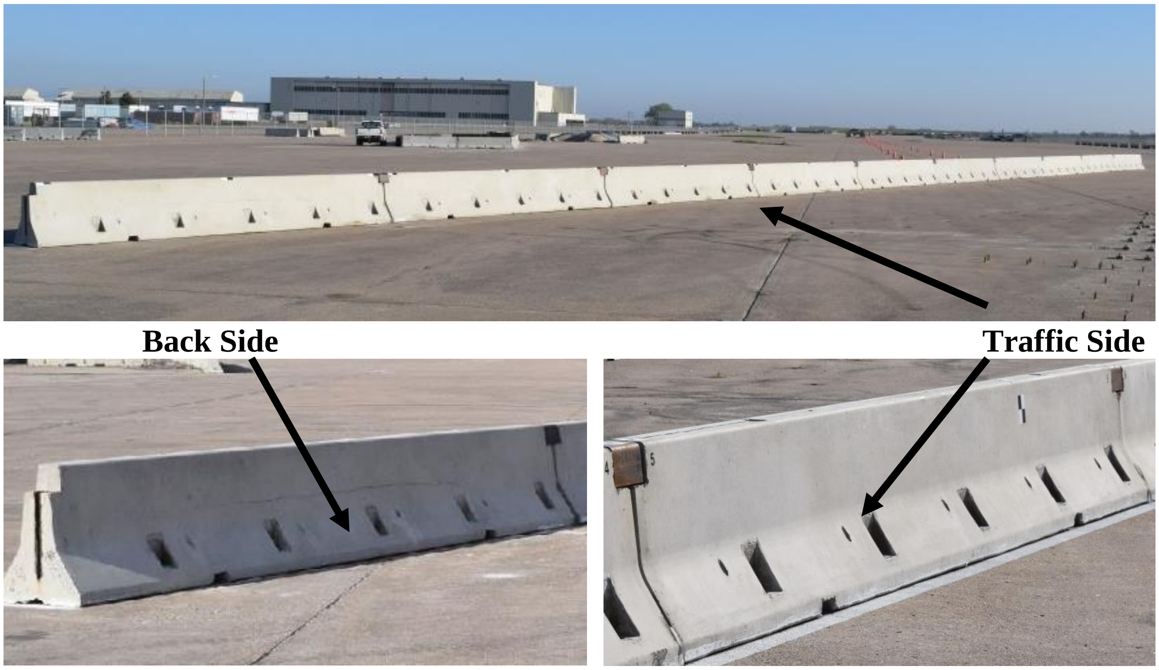


Figure 9. Barrier System

Figure 10. Connection between barriers

Each test installation consisted of ten 20-ft long NJDOT PCBs. The concrete used for the barrier sections consisted of a concrete mix with a minimum 28-day compressive strength of 3,700 psi. A minimum concrete cover of 1½ in. was used along all rebar in the barrier. All of the steel reinforcement in the barrier was ASTM A615 Grade 60 rebar and consisted of four No. 6 longitudinal bars, eight No. 4 bars for the vertical stirrups, four No. 6 lateral bars, and nine No. 4 bars for the pin anchor hole reinforcement loops. No steel reinforcement was used for the bolt anchor pockets.

The connection key assembly consisted of ½-in. thick ASTM A36 steel plates welded together to form the key shape. A connection socket was configured at each end of the PCB, consisting of three ASTM A36 steel plates welded on the sides of ASTM A500 Grade B or C steel tube. The connection key was inserted into the steel tubes of two adjoining PCBs to form the connection.

Two anchoring techniques and two stiffening techniques are studied. Anchoring techniques include use of pins and bolts. Stiffening techniques include use of box beam rails and non-shrink grout wedges placed between barrier sections.

3.1 Pin Anchorage

Each barrier section of NJDOT PCBs consists of five pin anchor recesses on traffic side (also called front side) and four pin anchor recesses on the back side, as shown in Figure 11. Pin anchors are of 1-in. diameter by 15-in. long, ASTM A36 steel pins, and are inserted into 1¼-in. diameter holes in the road surface. During installation, the barrier segments were connected and then pulled in a direction parallel to longitudinal axis, removing slack in the joints. Next, 1¼-in. diameter holes were drilled on road surface using pin anchor recesses as guides. Finally, the steel pins were embedded to a depth of 5 in.

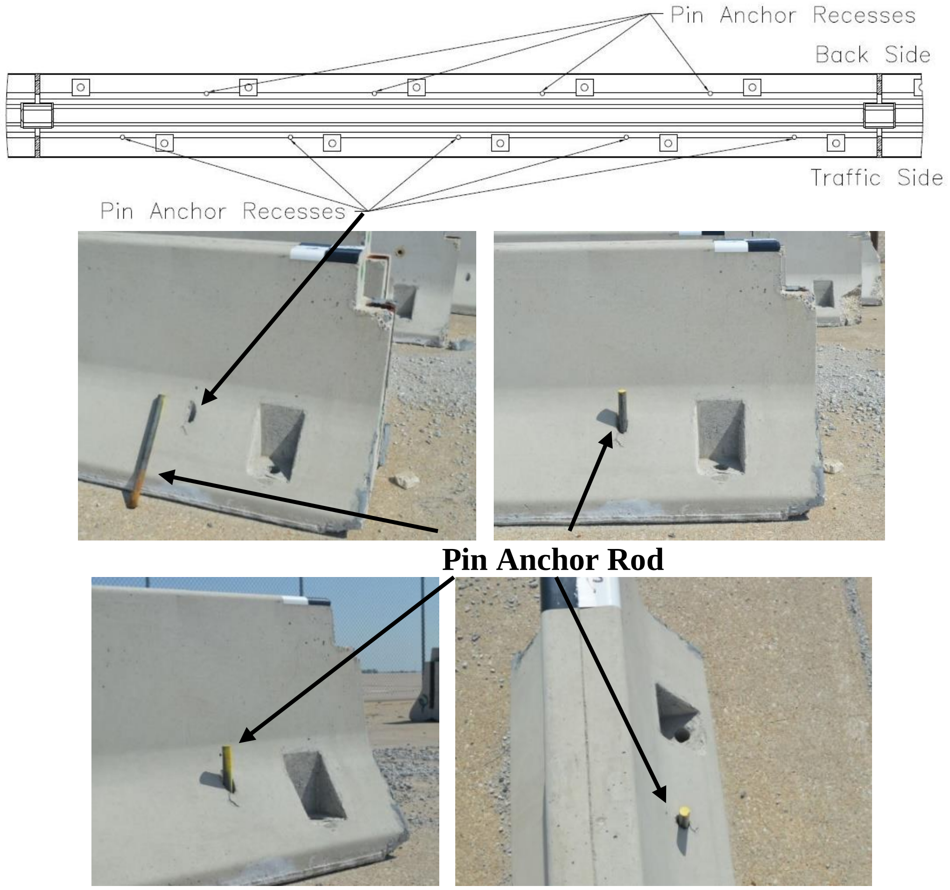


Figure 11. Pin Anchors on Barriers

3.2 Bolt Anchorage

Each barrier section consists of five bolt anchor recesses (pockets) on the traffic side and five bolt anchor pockets on the back side, as shown in Figure 12. Bolt anchors are made of 1-in. diameter ASTM F1554 Grade 36 threaded rods epoxied into 1⅛-in. diameter holes on road surface. During installation, the barrier segments were connected and then pulled in a direction parallel to the longitudinal axis, removing slack in the joints. Next, 1⅛-in. diameter holes were drilled on road surface using bolt anchor recesses as guides. Then, the anchor rods were embedded to a depth of 7 in. The bond strength of the epoxy used to anchor rods to road surface was 1,461 psi [21]. Bolts were nutted and had washers beneath the nuts.

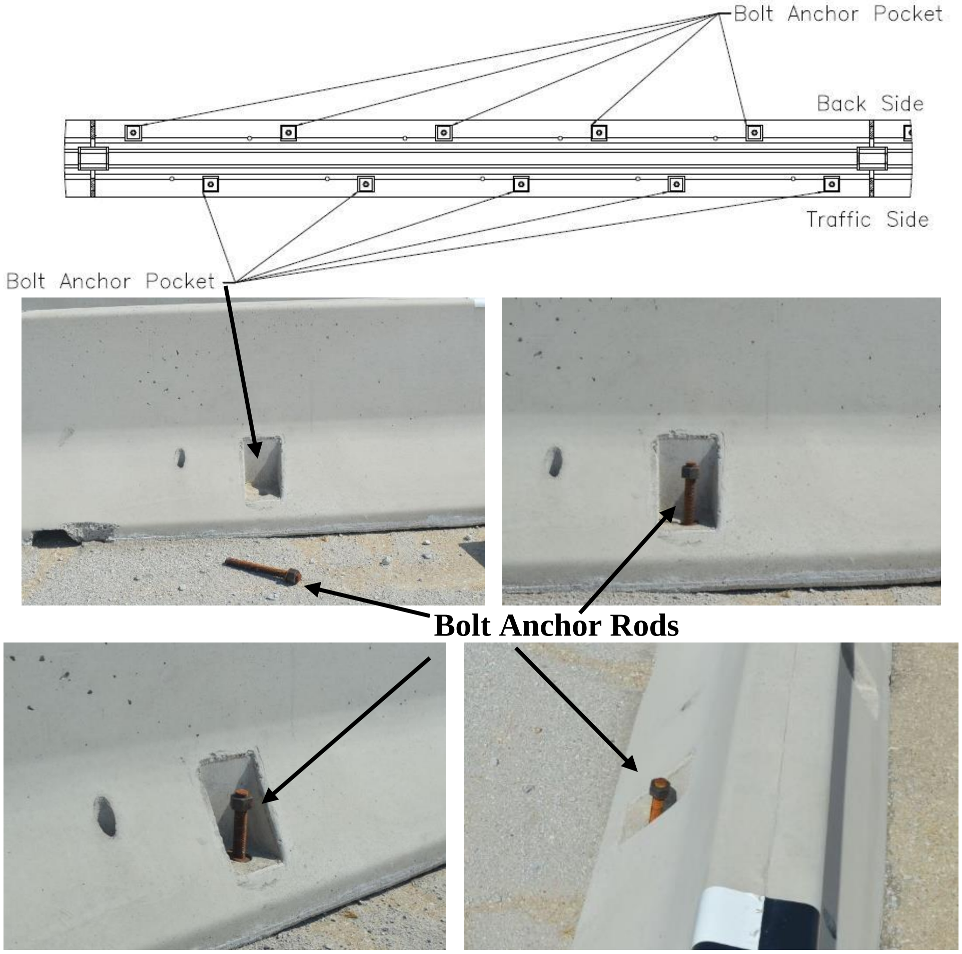


Figure 12. Bolt Anchors on Barriers

3.3 Box-Beam Rail as Stiffener

Box beam rail stiffeners were mounted on the back face of the system at each joint, as shown in Figure 13 [24]. Box beam stiffeners are believed to be capable of reducing lateral deflections and preventing separation of the barriers when deflected and suspended over the edge of a bridge deck [5]. This is due to the high tensile capacity of the steel, which allows the barrier and the box beam to act as a composite bending member, with the concrete in compression on the traffic face of the barrier and the steel in tension. Each box beam stiffener consisted of a 6-in. × 6-in. × $^{3}/_{16}$-in. ASTM A500 Grade C box beam. The box beam rails were mounted on barriers with ¾ in. diameter by 17 in. long ASTM A307 Grade A bolts. Box Beam rails mounting details are in test report.

Figure 13. Box Beam Stiffeners

3.4 Non-Shrink Grout

Non-shrink grout is a construction material with a high compressive strength commonly used to fill voids in areas of high concentrated loads. Grout was used to limit the rotation within the connection between barriers. Grout wedges between barriers allow the entire barrier system to act as a continuous element, so that the load disperses throughout all barrier segments rather than being concentrated on those in the impact zone. Non-shrink grout wedges were placed at the toe between adjacent barriers, as shown in Figure 14. Non-shrink grout wedges consisted of a grout mix with a minimum 1-day compressive strength of 1,000 psi.

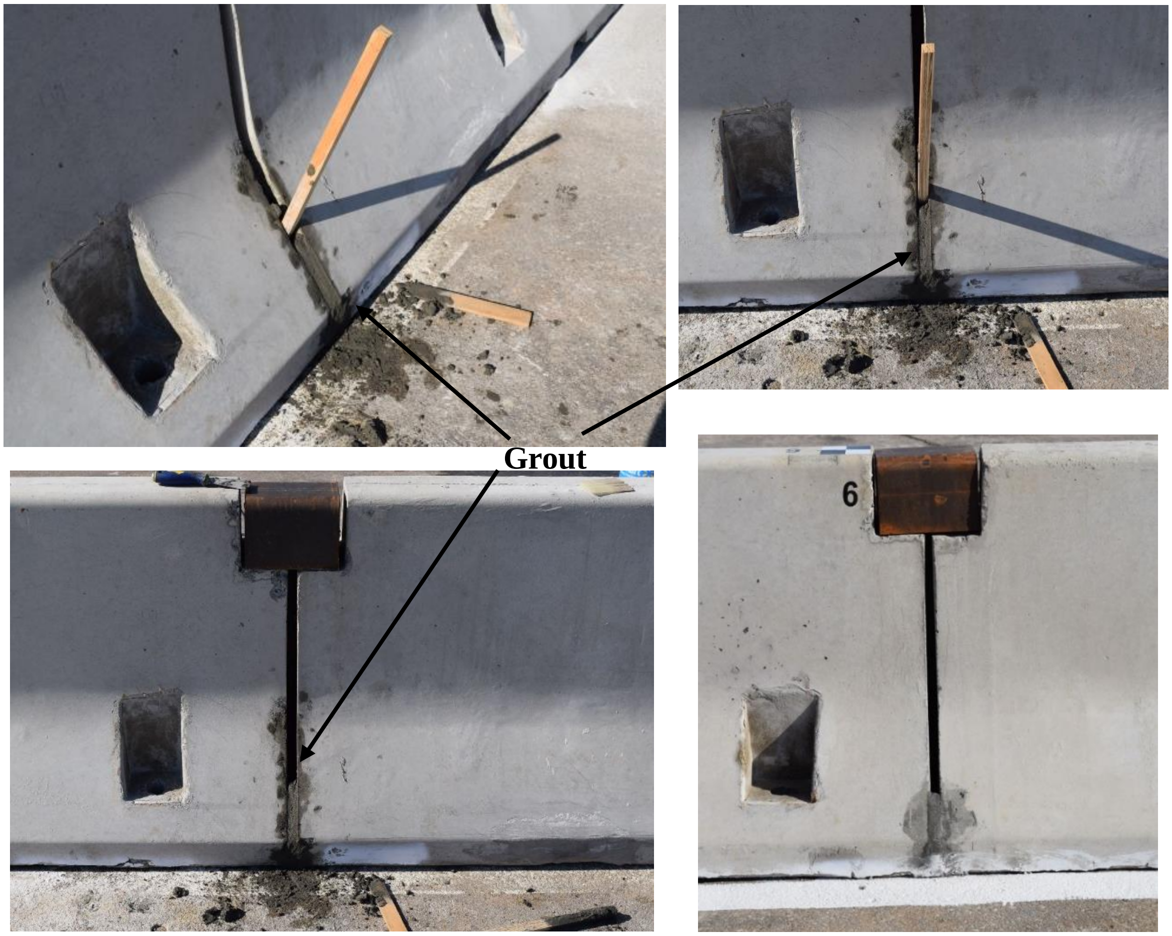


Figure 14. Non-Shrink Grout between barriers

CHAPTER 4. EVALUATION CRITERIA

The different anchorage and stiffening techniques were evaluated using full-scale crash testing, specifically using Test Level 3 (TL-3) criteria of the *Manual for Assessing Safety Hardware, Second Edition* (MASH 2016) [2]. According to TL-3 of MASH 2016, longitudinal barrier systems (such as PCBs) must be subjected to two full-scale vehicle crash tests, as summarized in Table 5.

Table 5. MASH 2016 TL-3 Crash Test Conditions for Longitudinal Barriers

Test Article	Test Designation No.	Test Vehicle	Vehicle Weight (lb)	Impact Conditions	
				Speed (mph)	Angle (degrees)
Longitudinal Barrier	3-10	1100C	2,425	62	25
	3-11	2270P	5,000	62	25

Of the two tests, only test no. 3-11 (hereafter referred as 3-11) fell within the scope of the research, as the low mass of the 1100C small car test vehicle used in test no. 3-10 makes it unlikely to cause large barrier deflections or damage. Reports FHWA-RD-77-4 and FHWA/RD-86/153 catalogue the successful testing of the small car according to test 3-10 under NCHRP 350 [16-17], and report TRP-03-177-06 demonstrated that the small car could pass MASH 2009 [18]. The successful tests demonstrate that the car is unlikely to cause significant damage to the barrier as outlined in the objective. Further, research has shown that New Jersey shape PCBs experience only slight barrier deflections when impacted by small cars [19]. Finally, MASH safety performance criteria for small cars were not changed in the revisions between 2009 and 2016, which reduces the need for further evaluation under test 3-10.

The combination of the successful tests and the low deflections means that the 1100C test vehicle may be reasonably excluded from investigation. In contrast, a 2270P vehicle has the highest center of gravity (c.g.) and the highest mass of the TL-3 vehicles. As a high c.g. makes a vehicle more prone to high roll and pitch movement in this type of impact, the 2270P vehicle is thus at the greatest risk of vehicle instability within the TL-3 group. Similarly, its high mass relative to the other test vehicles produces greater forces during impact and increases the likelihood of large deflections and severe damage to the barrier. Thus, the pickup truck test 3-11, was deemed to be the most critical to evaluate performance of the different PCB anchorage configurations.

Critical Impact Point Location

In test 3-11, the test vehicle is impacted into the test article at a critical impact point (CIP), a location on the test article expected to maximize the risk of the test failing to pass MASH safety evaluation criteria. This could mean maximizing the risk of vehicle rollover or instability, penetration behind the test article by the vehicle, exceeding occupant risk value tolerances, or some combination thereof. The CIP is determined by using Table 2.7 of MASH 2016 [2]. Determined initial vehicle impact location is a point 4 ft – $3^{3}/_{16}$ in. upstream from the centerline of the joint between barriers 4 and 5, as shown in Figure 15.

Figure 15. Impact Condition and Location

Under MASH 2016, tests were required to meet a minimum impact severity, and required not to exceed Occupant Risk values and Euler Angular movements. Impact severity is the amount of kinetic energy acting perpendicular to the longitudinal axis of barrier systems as found in equation 4.1.

$$I.S. = \frac{1}{2} M * (V * \sin[\theta])^2 \tag{4.1}$$

Where

$I.S. = \text{Impact Severity, kip} - \text{ft}$
$M = \text{Vehicle mass, kips}$
$V = \text{Vehicle impact velocity, ft/s)}$
$\theta = \text{Angle of impact, radians}$

Occupant Risk values are in terms of longitudinal and lateral Occupant Impact Velocities (OIVs) and Occupant Ridedown Accelerations (ORAs), which are velocities and accelerations experienced by occupants in the occupant compartment during impact. Euler Angular movements are Roll, Pitch and Yaw experienced by the vehicle during the impact.

CHAPTER 5. NEW JERSEY PCB TESTS

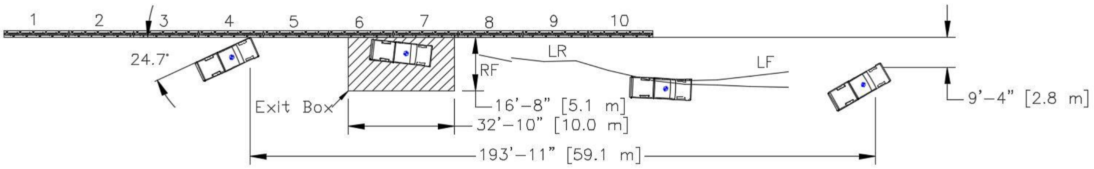
5.1 Test No. NJPCB-1

Test no. NJPCB-1 (herein after referred to as NJPCB-1) was conducted with barriers 1, 3, 5, 7, 9, and 10 pinned to concrete tarmac with non-shrink grout wedges, a class C joint. Summary of the Results are provided in Figure 16, details of NJPCB-1 are in test report [20]. NJPCB-1 was determined to be successful according to MASH requirements.

Vehicle Kinematics

t = 0 msec *t = 104 msec* *t = 210 msec* *t = 1688 msec*

Schematic View



Impact Conditions and Results

- Test Number NJPCB-1
- Test Article .... New Jersey PCB
- Total Length .... 200 ft
- Key Component – Anchor Pins
  - Pin Size .... 1-in. diameter unthreaded rod
  - Pin Length .... 15 in.
  - Embedment Depth .... 5 in.
  - Pinned Barriers .... 1, 3, 5, 7, 9, and 10
- Vehicle Model .... 2010 Dodge Ram 1500 pickup truck
  - Test Inertial .... 5,013 lb
- Impact Conditions
  - Speed .... 62.6 mph
  - Angle .... 24.7 degrees
  - Impact Location .... 49$^{1}/_{16}$ in. upstream from joint 4-5
- Exit Conditions
  - Speed .... 50.7 mph
  - Angle .... 9.2 degrees
- Vehicle Stability .... Satisfactory
- Test Article Damage .... Moderate
- Vehicle Damage .... Moderate
- Maximum Test Article Deflections
  - Permanent Set .... 6¼ in.
  - Dynamic .... 13.5 in.
- Occupant Risk Values

Occupant Risk		Value	MASH Limit
OIV (ft/s)	Longitudinal	-14.27	± 40
	Lateral	19.33	± 40
ORA (g's)	Longitudinal	-9.97	± 20.49
	Lateral	7.17	± 20.49
Maximum Angular Displacement (degrees)	Roll	-39.9	± 75
	Pitch	-12.8	± 75

Figure 16. Results Summary of full-scale crash test – NJPCB-1

5.1.1 Test Description and Vehicle Behavior

A 5,013-lb pickup truck impacted the system at a speed of 62.6 mph and at an angle of 24.7 degrees, resulting in an impact severity of 114.9 kip-ft. Vehicle experienced roll of -39.9 degrees and pitch of -12.8 degrees. Longitudinal and Lateral Occupant Ridedown Acceleration (ORA) were -9.97 g's and 7.17 g's respectively, and Longitudinal and Lateral Occupant Impact Velocity (OIV) were -14.27 ft/s and 19.33 ft/s respectively. All occupant risk values were found to be within limits, and the occupant compartment deformations were also deemed acceptable as per MASH recommended values. Sequential views of the vehicle kinematics during the test from a downstream perspective are shown in Figure 17.

t = 0 msec *t = 116 msec* *t = 752 msec* *t = 996 msec*

Figure 17. Sequential View of Vehicle Behavior – NJPCB-1

5.1.2 Barrier Deflections

The barrier system experienced a maximum lateral dynamic deflection of 13.5 in. and a permanent set deflection of 6¼ in., as shown in Figure 18.

Figure 18. Barrier Deflection (Impact location, during impact, and Post Impact)

5.1.3 Barrier Damage

Scuff marks, cracks, and spalling near the barrier toe occurred on barriers 3, 4, 5 and 6. Barriers 3 and 6 had minor cracks and spalling, which would make them reusable with minor repairs. Severe damage occurred to barriers 4 and 5 rendering them non-reusable (see Figure 19). Barrier 4 had major spalling on ends at the barrier toe and below connection key, damage near connection key meant the steel reinforcement is no longer intact, and was deemed non-reusable. Barrier 5 experienced a fracture extending through its entire height and exposing its steel reinforcement near the top.

Figure 19. Barrier Damage – Barrier 4 (Top) and Barrier 5 (Bottom)

5.1.4 Vehicle Damage

Majority of the vehicle damage was concentrated on the impact left-front corner and left side. Denting, scraping, and gouging were observed on the entire left side of the vehicle. The windshield had cracks, and left-front window was shattered due to deployment of airbags and occupant head impacting the window. The occupant compartment experienced minor deformations, all within MASH allowable limits.

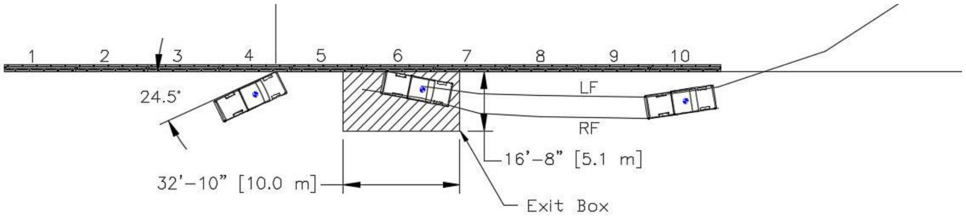
5.2 Test No. NJPCB-2

NJPCB-2 was conducted with Barriers 1 through 10 bolted to concrete tarmac, and non-shrink grout wedges between barriers, a class D joint. Summary of the results are provided in Figure 20, details of NJPCB-2 are in test report [21]. NJPCB-2 was determined to be successful according to MASH requirements.

Vehicle Kinematics

t = 0 msec *t = 74 msec* *t = 570 msec* *t = 1468 msec*

Schematic View



Impact Conditions and Results

- Test Number NJPCB-2
- Test Article ....New Jersey PCB
- Total Length .... 200 ft
- Key Component – Bolt Anchors
  - Bolt Size ....1-in. diameter threaded rod
  - Bolt Length...14 in.
  - Embedment Depth ....7 in.
  - Bolted Barriers .... 1 through 10
  - Epoxy Minimum Bond Strength..................1,461 psi [21]
- Vehicle Model ....2011 Dodge Ram 1500 Quadcab
  - Test Inertial...4,992 lb
- Impact Conditions
  - Speed ....62.6 mph
  - Angle ....24.5 degrees
  - Impact Location...........45$^{13}/_{16}$ in. upstream from joint 4-5
- Exit Conditions
  - Speed ....51.3 mph
  - Angle ....9.9 degrees
- Vehicle Stability ....Satisfactory
- Test Article Damage...Moderate
- Vehicle Damage ....Moderate
- Maximum Test Article Deflections
  - Permanent Set...- ½ in.
  - Dynamic ....4.9 in.
- Occupant Risk Values

Occupant Risk		**Value**	**MASH Limit**
OIV (ft/s)	Longitudinal	-16.66	± 40
	Lateral	24.06	± 40
ORA (g’s)	Longitudinal	-10.05	± 20.49
	Lateral	9.99	± 20.49
Maximum Angular Displacement (degrees)	Roll	20.7	± 75
	Pitch	-12.0	± 75

Figure 20. Results Summary of full-scale crash test – NJPCB-2

5.2.1 Test Description and Vehicle Behavior

A 4,992-lb pickup truck impacted the system at a speed of 62.6 mph and at an angle of 24.5 degrees, resulting in an impact severity of 112.6 kip-ft. Vehicle experienced roll of 20.7 degrees and pitch of -12.0 degrees. Longitudinal and Lateral Occupant Ridedown Acceleration (ORA) were -10.05 g's and 9.99 g's respectively, and Longitudinal and Lateral Occupant Impact Velocity (OIV) were -16.66 ft/s and 24.06 ft/s respectively. Upon investigation of the results, all occupant risk values were found to be within limits, and the occupant compartment deformations were also deemed acceptable as per MASH recommended values. Sequential views of the vehicle kinematics during the test from a downstream perspective are shown in Figure 21.

t = 0 msec *t = 52 msec* *t = 734 msec* *t = 1468 msec*

Figure 21. Sequential View of Vehicle Behavior – NJPCB-2

5.2.2 Barrier Deflections

The barrier system experienced a maximum lateral dynamic deflection of 5 in. and a permanent set deflection of -½ in., as shown in Figure 22.

Figure 22. Barrier Deflection (Impact location, during impact, and Post Impact)

5.2.3 Barrier Damage

Scuff marks, cracks, and spalling near the barrier toe occurred on barriers 3, 4, 5 and 6. Barriers 3 and 6 had minor cracks and spalling, which would make them reusable with minor repairs. Severe damage occurred to barriers 4 and 5 rendering them as non-reusable (see Figure 23). Barriers 4 and 5 experienced fracture extending through their entire height and toward joint connection between them, which exposed steel reinforcement near the top on both barriers.

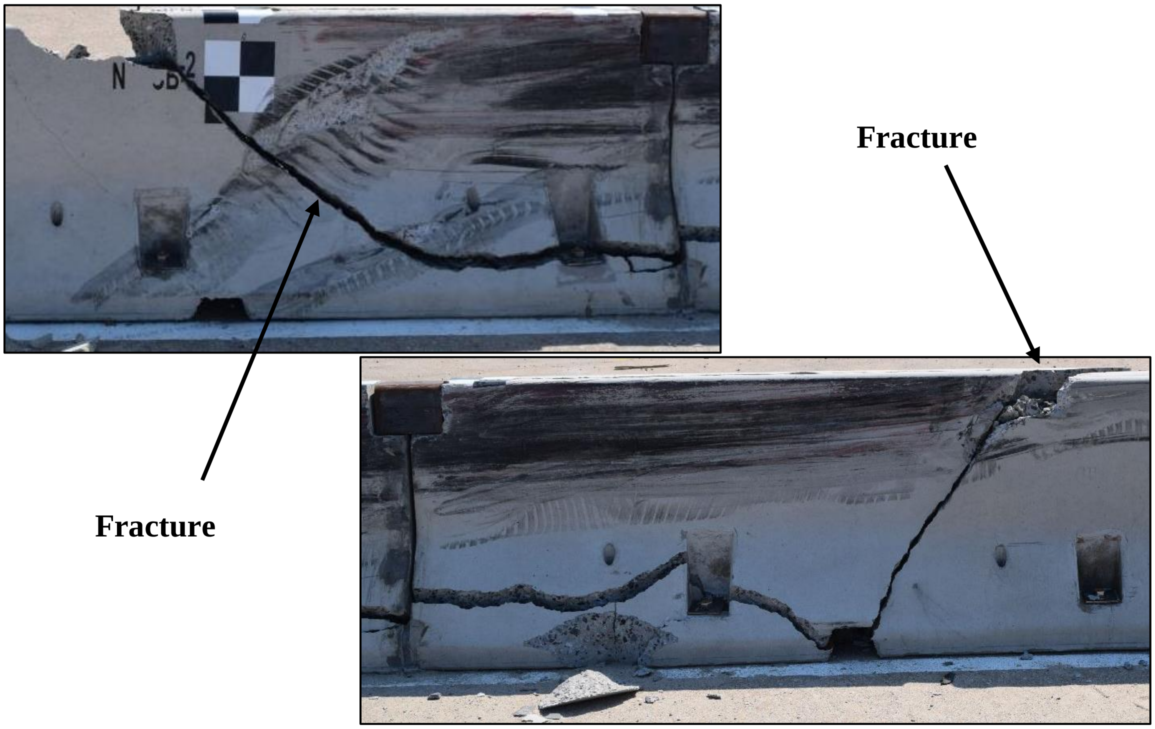


Figure 23. Barrier Damage – Barrier 4 (Top) and Barrier 5 (Bottom)

5.2.4 Vehicle Damage

Majority of the vehicle damage was concentrated on the impact left-front corner and left side. Denting, scraping, and gouging were observed on the entire left side of the vehicle. The windshield had cracks. The occupant compartment experienced minor deformations, all within MASH allowable limits.

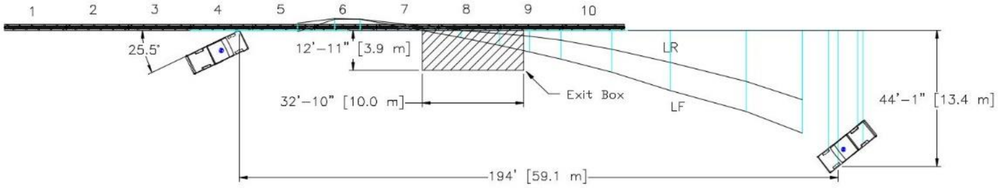
5.3 Test No. NJPCB-3

NJPCB-3 was conducted with Barriers 1 and 10 pin anchored to concrete tarmac, a class A joint. Summary of the results are provided in Figure 24, details of NJPCB-3 are in test report [22]. NJPCB-3 was determined to be successful according to MASH requirements.

Vehicle Kinematics

t = 0 msec *t = 62 msec* *t = 232 msec* *t = 796 msec*

Schematic View



Impact Conditions and Results

- Test Number NJPCB-3
- Test Article .... New Jersey PCB
- Total Length .... 200 ft
- Key Component – Anchor Pins
  Pin Size........ 1-in. diameter unthreaded rod
  Pin Length .... 15 in.
  Embedment Depth .... 5 in.
  Pinned Barriers .... 1 and 10
- Vehicle Model .... 2010 Dodge Ram 1500 pickup truck
  Test Inertial........ 4,999 lb
- Impact Conditions
  Speed .... 62.3 mph
  Angle .... 25.8 degrees
  Impact Location........ $46^{3}/_{16}$ in. upstream from joint 4-5
- Exit Conditions
  Speed .... 51.7 mph
  Angle .... 11.9 degrees
- Vehicle Stability .... Satisfactory
- Test Article Damage .... Moderate
- Vehicle Damage........ Moderate
- Maximum Test Article Deflections
  Permanent Set .... 36⅝ in.
  Dynamic........ 38.1 in.
- Occupant Risk Values

Occupant Risk		Value	MASH Limit
OIV (ft/s)	Longitudinal	-13.52	± 40
	Lateral	18.01	± 40
ORA (g's)	Longitudinal	-5.23	± 20.49
	Lateral	9.61	± 20.49
Maximum Angular Displacement (degrees)	Roll	-17.2	± 75
	Pitch	-9.0	± 75

Figure 24. Results Summary of full-scale crash test – NJPCB-3

5.3.1 Test Description and Vehicle Behavior

A 4,999-lb pickup truck impacted the system at a speed of 62.3 mph and at an angle of 25.8 degrees, resulting in an impact severity of 121.9 kip-ft. Vehicle experienced roll of -17.2 degrees and pitch of -9.0 degrees. Longitudinal and Lateral Occupant Ridedown Acceleration (ORA) were -5.23 g's and 9.61 g's respectively, and Longitudinal and Lateral Occupant Impact Velocity (OIV) were -13.52 ft/s and 18.01 ft/s respectively. Upon investigation of the results, all occupant risk values were found to be within limits, and the occupant compartment deformations were also deemed acceptable as per MASH recommended values. Sequential views of the vehicle kinematics during the test from a downstream perspective are shown in Figure 25.


t = 0 msec *t = 122 msec* *t = 602 msec* *t = 1232 msec*

Figure 25. Sequential View of Vehicle Behavior – NJPCB-3

5.3.2 Barrier Deflections

The barrier system experienced a maximum lateral dynamic deflection of 38.1 in. and a permanent set deflection of 36⅝ in., as shown in Figure 26.

Figure 26. Barrier Deflection (Impact location, during impact, and Post Impact)

5.3.3 Barrier Damage

Scuff marks, cracks, and spalling near the barrier toe occurred on barriers 3, 4, 5, 6, 7 and 8. Barriers 3, 7, and 8 had minor cracks and spalling, which would make them reusable with minor repairs. Severe damage occurred to barriers 4 and 5 rendering them as non-reusable (see Figure 27). Barriers 4 and 5 experienced vertical cracks that extended on front, top and back faces, major spalling near pin and bolt anchor recesses and below connection key, which makes them ineffective to reuse. Barrier 6 experienced vertical cracking and spalling near the connection key, which meant the steel reinforcement was no longer intact, and the barrier was deemed non-reusable.

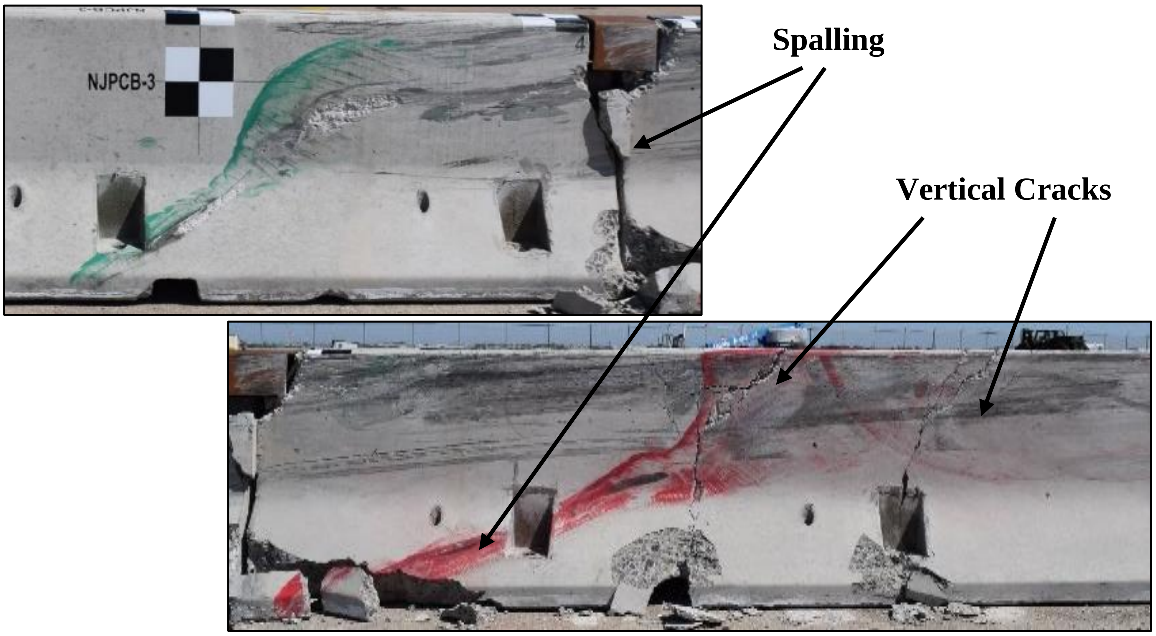


Figure 27. Barrier Damage – Barrier no. 4 (Top) and Barrier no. 5 (Bottom)

5.3.4 Vehicle Damage

The majority of the damage was concentrated on the left-front corner and left side of the vehicle where the impact occurred. Denting, scraping, and gouging were observed on the entire left side of the vehicle. The windshield had cracks. Occupant compartment experienced minor deformations, all within MASH allowable limits.

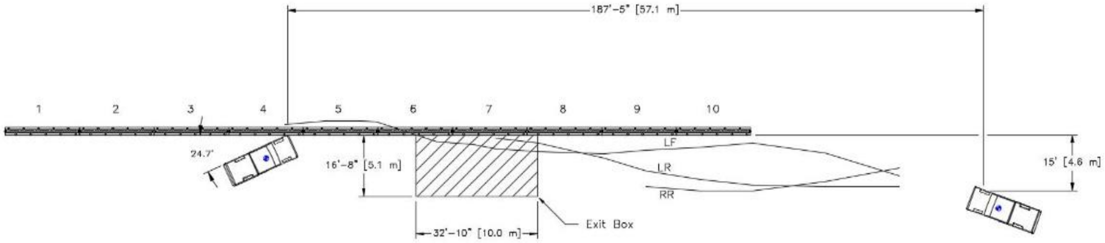
5.4 Test No. NJPCB-4

NJPCB-4 was conducted with Barriers 1 and 10 pin anchored to concrete tarmac, and with non-shrink grout wedges, a class B joint. Summary of the results are provided in Figure 28, details of NJPCB-4 are in test report [23]. NJPCB-4 was determined to be successful according to MASH requirements.

Vehicle Kinematics

t = 0 msec *t = 40 msec* *t = 226 msec* *t = 634 msec*

Schematic View



Impact Conditions and Results

- Test Number ... NJPCB-4
- Test Article ... New Jersey PCB
- Total Length ... 200 ft
- Key Component – Anchor Pins
  - Pin Size ... 1-in. diameter unthreaded rod
  - Pin Length ... 15 in.
  - Embedment Depth ... 5 in.
  - Pinned Barriers ... 1 and 10
- Vehicle Model ... 2011 Dodge Ram 1500 pickup truck
  - Test Inertial ... 5,000 lb
- Impact Conditions
  - Speed ... 62.8 mph
  - Angle ... 24.5 degrees
  - Impact Location ... 45½ in. upstream from joint 4-5
- Exit Conditions
  - Speed ... 54.2 mph
  - Angle ... 8.4 degrees
- Vehicle Stability ... Satisfactory
- Test Article Damage ... Moderate
- Vehicle Damage ... Moderate
- Maximum Test Article Deflections
  - Permanent Set ... 38 in.
  - Dynamic ... 40.7 in.
- Occupant Risk Values

Occupant Risk		Value	MASH Limit
OIV (ft/s)	Longitudinal	-12.1	± 40
	Lateral	18.7	± 40
ORA (g's)	Longitudinal	-4.0	± 20.49
	Lateral	12.1	± 20.49
Maximum Angular Displacement (degrees)	Roll	-16.2	± 75
	Pitch	-14.2	± 75

Figure 28. Results Summary of full-scale crash test – NJPCB-4

5.4.1 Test Description and Vehicle Behavior

A 5,000-lb pickup truck impacted the system at a speed of 62.8 mph and at an angle of 24.5 degrees, resulting in an impact severity of 114.1 kip-ft. Vehicle experienced roll of -16.2 degrees and pitch of -14.2 degrees. Longitudinal and Lateral Occupant Ridedown Acceleration (ORA) were -4.0 g's and 12.1 g's respectively, and Longitudinal and Lateral Occupant Impact Velocity (OIV) were -12.1 ft/s and 18.7 ft/s respectively. Upon investigation of the results, all occupant risk values were found to be within limits, and the occupant compartment deformations were also deemed acceptable as per MASH recommended values. Sequential views of the vehicle kinematics during the test from a downstream perspective are shown in Figure 29.

t = 0 msec *t = 84 msec* *t = 648 msec* *t = 2636 msec*

Figure 29. Sequential View of Vehicle Behavior – NJPCB-4

5.4.2 Barrier Deflections

The barrier system experienced a maximum lateral dynamic deflection of 40.7 in. and a permanent set deflection of 38 in., as shown in Figure 30.

Figure 30. Barrier Deflection (Impact location, during impact, and Post Impact)

5.4.3 Barrier Damage

Cracks, and spalling occurred on barriers 2, 3, 4, 5, 6, 7 and 8. Barriers 2, 3, 7, and 8 had minor cracks and spalling, which would make them reusable with minor repairs. Severe damage occurred to barriers 4 and 5 rendering them as non-reusable (see Figure 31). Barriers 4 and 5 experienced vertical cracks that extended on front, top and back faces, major spalling near pin and bolt anchor recesses and below connection key, which makes them ineffective to reuse. Barrier 6 had vertical cracks and spalling near connection key, which meant the steel reinforcement was no longer intact, and the barrier was deemed non-reusable.

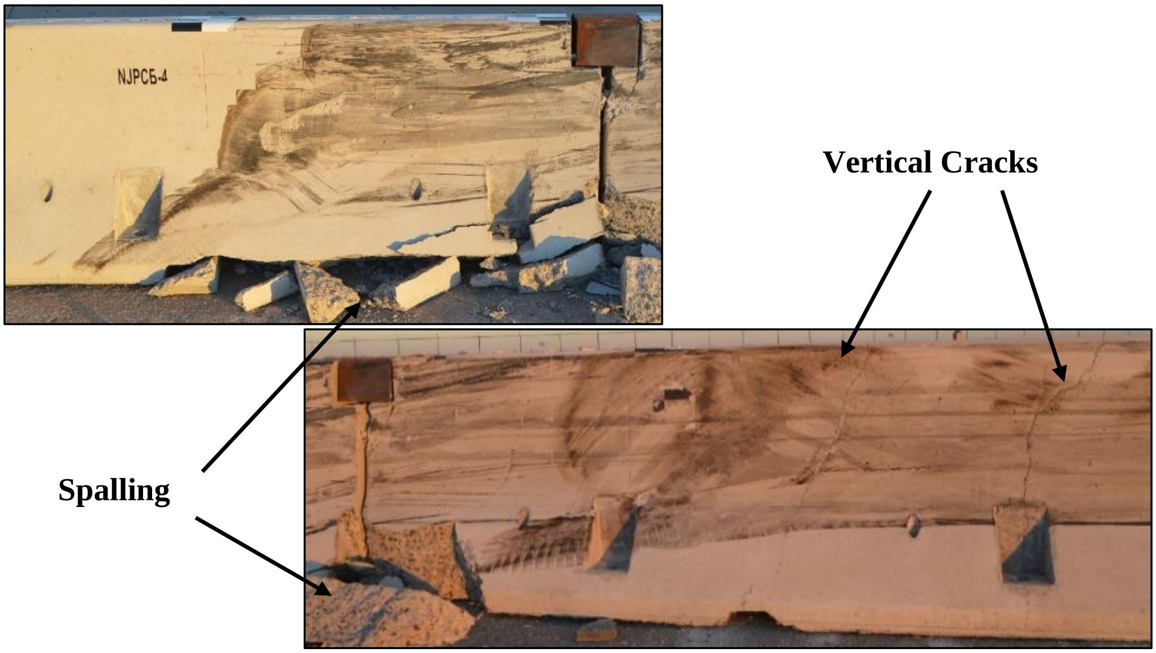


Figure 31. Barrier Damage – Barrier no. 4 (Top) and Barrier no. 5 (Bottom)

5.4.4 Vehicle Damage

The majority of the damage was concentrated on the left-front corner and left side of the vehicle where the impact occurred. Denting, scraping, and gouging were observed on the entire left side of the vehicle. The windshield had cracks. Occupant compartment experienced minor deformations, all within MASH allowable limits.

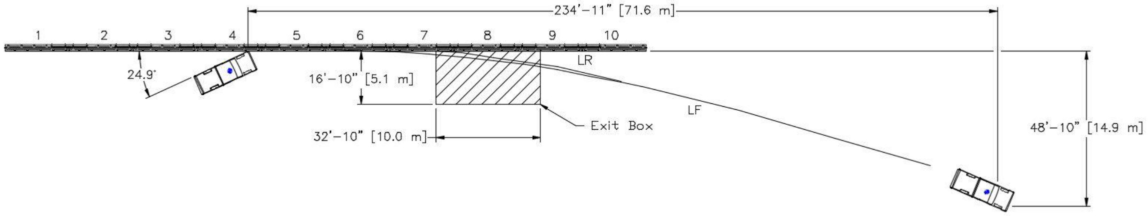
5.5 Test No. NJPCB-5

NJPCB-5 was conducted with Barriers 1 and 10 pin anchored to concrete tarmac, and box beam rails mounted on back side of barriers at each joint, a class B joint (modified Joint Class B). Summary of the results are provided in Figure 32, details of NJPCB-5 are in test report [24]. NJPCB-5 was determined to be successful according to MASH requirements.

Vehicle Kinematics

t = 0 msec *t = 56 msec* *t = 218 msec* *t = 642 msec*

Schematic View



Impact Conditions and Results

• Test Number	NJPCB-5
• Test Article	New Jersey PCB
• Total Length	200 ft
• Key Component – Anchor Pins and Box Beam Rails	
Pin Size	1-in. diameter unthreaded rod
Pin Length	15 in.
Embedment Depth	5 in.
Pinned Barriers	1 and 10
Box Beam Rail Size	6 in. × 6 in. × $^3/_{16}$ in.
Box Beam Rail Length	12 ft
• Vehicle Model	2009 Dodge Ram 1500 pickup truck
Test Inertial	5,001 lb
• Impact Conditions	
Speed	62.7 mph
Angle	24.9 degrees
Impact Location	49⅜ in. upstream from joint 4-5
• Exit Conditions	
Speed	47.7 mph
Angle	4.9 degrees

• Vehicle Stability	Satisfactory
• Test Article Damage	Moderate
• Vehicle Damage	Moderate
• Maximum Test Article Deflections	
Permanent Set	32½ in.
Dynamic	33.0 in.
• Occupant Risk Values	

Occupant Risk		Value	MASH Limit
OIV (ft/s)	Longitudinal	-13.6	± 40
	Lateral	21.6	± 40
ORA (g's)	Longitudinal	-7.65	± 20.49
	Lateral	9.62	± 20.49
Maximum Angular Displacement (degrees)	Roll	-7.9	± 75
	Pitch	-12.5	± 75

Figure 32. Results Summary of full-scale crash test – NJPCB-5

5.5.1 Test Description and Vehicle Behavior

A 5,001-lb pickup truck impacted the system at a speed of 62.7 mph and at an angle of 24.9 degrees, resulting in an impact severity of 116.3 kip-ft. Vehicle experienced roll of -7.9 degrees and pitch of -12.5 degrees. Longitudinal and Lateral Occupant Ridedown Acceleration (ORA) were -7.65 g's and 9.62 g's respectively, and Longitudinal and Lateral Occupant Impact Velocity (OIV) were -13.6 ft/s and 21.6 ft/s respectively. Upon investigation of the results, all occupant risk values were found to be within limits, and the occupant compartment deformations were also deemed acceptable as per MASH recommended values. Sequential views of the vehicle kinematics during the test from a downstream perspective are shown in Figure 33.

t = 0 msec *t = 238 msec* *t = 642 msec* *t = 1518 msec*

Figure 33. Sequential View of Vehicle Behavior – NJPCB-5

5.5.2 Barrier Deflections

The barrier system experienced a maximum lateral dynamic deflection of 33.0 in. and a permanent set deflection of 32½ in., as shown in Figure 34.

Figure 34. Barrier Deflection (Impact location, during impact, and Post Impact)

5.5.3 Barrier Damage

Scuff marks, cracks, and spalling near the barrier toe occurred on barriers 2, 3, 4, 5, 6, 7 and 8. Barriers 2, 3, 7, and 8 had minor cracks and spalling, which would make them reusable with minor repairs. Severe damage occurred to barriers 4 and 5 rendering them as non-reusable (see Figure 35). Barriers 4 and 5 experienced vertical cracks that extended on front, top and back faces, major spalling near pin and bolt anchor recesses and below connection key. Barrier 6 had vertical cracks and spalling near connection key, which meant the steel reinforcement was no longer intact, and the barrier was deemed non-reusable.

Figure 35. Barrier Damage – Barrier 4 (Top) and Barrier 5 (Bottom)

5.5.4 Vehicle Damage

The majority of the damage was concentrated on the left-front corner and left side of the vehicle where the impact occurred. Denting, scraping, and gouging were observed on the entire left side of the vehicle. The windshield had cracks. Occupant compartment experienced minor deformations, all within MASH allowable limits.

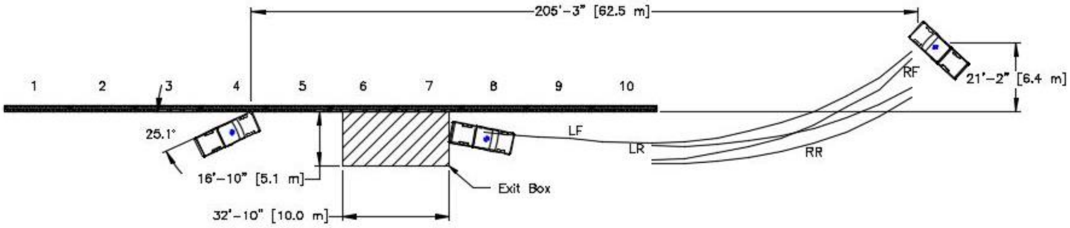
5.6 Test No. NJPCB-6

NJPCB-6 was conducted with barriers 1 and 10 pinned on traffic side and back side, and barrier 2 through 9 pinned on back side to concrete tarmac with non-shrink grout wedges, a class C joint (modified Joint Class C). Summary of the Results are provided in Figure 36, details of NJPCB-6 are in test report [25]. NJPCB-6 was determined to be successful according to MASH requirements.

Vehicle Kinematics

t = 0 msec *t = 160 msec* *t = 398 msec* *t = 752 msec*

Schematic View



Impact Conditions and Results

- Test Number NJPCB-6
- Test Article .... New Jersey PCB
- Total Length .... 200 ft
- Key Component – Anchor Pins
  Pin Size .... 1-in. diameter unthreaded rod
  Pin Length .... 15 in.
  Embedment Depth .... 5 in.
  Pinned Barriers – Traffic and Back Side .... 1 and 10
  Pinned Barriers – Back Side .... 2 – 9
- Vehicle Model .... 2009 Dodge Ram 1500 pickup truck
  Test Inertial .... 5,000 lb
- Impact Conditions
  Speed .... 62.9 mph
  Angle .... 25.1 degrees
  Impact Location .... $45^{11}/_{16}$ in. upstream from joint 4-5
- Exit Conditions
  Speed .... 52.5 mph
  Angle .... 8.0 degrees
- Vehicle Stability .... Satisfactory

- Test Article Damage .... Moderate
- Vehicle Damage .... Moderate
- Maximum Test Article Deflections
  Permanent Set .... 3¾ in.
  Dynamic .... 15.2 in.
- Occupant Risk Values

Occupant Risk		Value	MASH Limit
OIV (ft/s)	Longitudinal	-17.30	± 40
	Lateral	20.67	± 40
ORA (g's)	Longitudinal	-9.73	± 20.49
	Lateral	8.43	± 20.49
Maximum Angular Displacement (degrees)	Roll	28.9	± 75
	Pitch	-12.2	± 75

Figure 36. Results Summary of full-scale crash test – NJPCB-6

5.6.1 Test Description and Vehicle Behavior

A 5,000-lb pickup truck impacted the system at a speed of 62.9 mph and at an angle of 25.1 degrees, resulting in an impact severity of 119.2 kip-ft. Vehicle experienced roll of -28.9 degrees and pitch of -12.2 degrees. Longitudinal and Lateral Occupant Ridedown Acceleration (ORA) were -9.73 g's and 8.43 g's respectively, and Longitudinal and Lateral Occupant Impact Velocity (OIV) were -17.30 ft/s and 20.67 ft/s respectively. Upon investigation of the results, all occupant risk values were found to be within limits, and the occupant compartment deformations were also deemed acceptable as per MASH recommended values. Sequential views of the vehicle kinematics during the test from a downstream perspective are shown in Figure 37.

t = 0 msec *t = 194 msec* *t = 398 msec* *t = 720 msec*

Figure 37. Sequential View of Vehicle Behavior – NJPCB-6

5.6.2 Barrier Deflections

The barrier system experienced a maximum lateral dynamic deflection of 15.2 in. and a permanent set deflection of 3¾ in., as shown in Figure 38.

Figure 38. Barrier Deflection (Impact location, during impact, and Post Impact)

5.6.3 Barrier Damage

Scuff marks, cracks, and spalling near the barrier toe occurred on barriers 2, 3, 4, 5, 6, and 7. Barriers 2, 3, and 7 had minor cracks and spalling, which would make them reusable with minor repairs. Severe damage occurred to barriers 4 and 5 rendering them as non-reusable (see Figure 39). Barriers 4 and 5 experienced fracture extending through their entire height and toward joint connection between them, which exposed steel reinforcement near the top on both barriers. Barrier 6 had vertical cracks and spalling near pin anchors on its back face and near connection key, which meant the steel reinforcement was no longer intact, and the barrier was deemed non-reusable.

Figure 39. Barrier Damage – Barrier 4 (Top) and Barrier 5 (Bottom)

5.6.4 Vehicle Behavior

The majority of the damage was concentrated on the left-front corner and left side of the vehicle where the impact occurred. Denting, scraping, and gouging were observed on the entire left side of the vehicle. The windshield had cracks. Occupant compartment experienced minor deformations, all within MASH allowable limits.

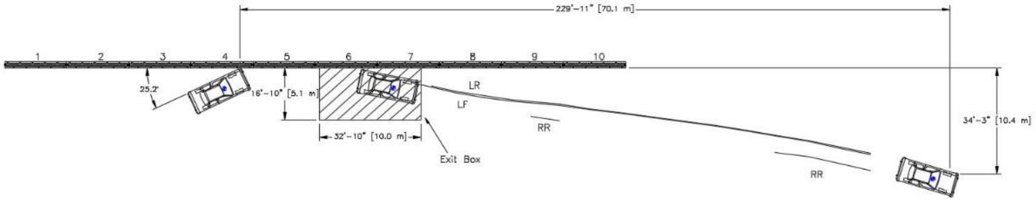
5.7 Test No. NJPCB-7

NJPCB-7 was conducted with barriers 1 and 10 pinned on traffic side and back side, and barrier 2 through 9 pinned on traffic side to concrete tarmac with non-shrink grout wedges, a class C joint (modified Joint Class C). Summary of the Results are provided in Figure 40, details of NJPCB-7 are in test report [26]. NJPCB-7 was determined to be successful according to MASH requirements.

Vehicle Kinematics

t = 0 msec *t = 144 msec* *t = 290 msec* *t = 722 msec*

Schematic View



Impact Conditions and Results

- Test Number NJPCB-7
- Test Article .... New Jersey PCB
- Total Length .... 200 ft
- Key Component – Anchor Pins
  - Pin Size .... 1-in. diameter unthreaded rod
  - Pin Length .... 15 in.
  - Embedment Depth .... 5 in.
  - Pinned Barriers – Traffic and Back Side .... 1 and 10
  - Pinned Barriers – Traffic Side .... 2 – 9
- Vehicle Model .... 2010 Dodge Ram 1500 pickup truck
  - Test Inertial .... 5,000 lb
- Impact Conditions
  - Speed .... 62.8 mph
  - Angle .... 25.2 degrees
  - Impact Location .... $46^{5}/_{16}$ in. upstream from joint 4-5
- Exit Conditions
  - Speed .... 54.8 mph
  - Angle .... 7.1 degrees
- Vehicle Stability .... Satisfactory
- Test Article Damage .... Moderate
- Vehicle Damage .... Moderate
- Maximum Test Article Deflections
  - Permanent Set .... 6¼ in.
  - Dynamic .... 11.4 in.
- Occupant Risk Values

Occupant Risk		Value	MASH Limit
OIV (ft/s)	Longitudinal	-14.09	± 40
	Lateral	21.56	± 40
ORA (g's)	Longitudinal	-3.65	± 20.49
	Lateral	7.98	± 20.49
Maximum Angular Displacement (degrees)	Roll	-29.2	± 75
	Pitch	-18.6	± 75

Figure 40. Results Summary of full-scale crash test – NJPCB-7

5.7.1 Test Description and Vehicle Behavior

A 5,000-lb pickup truck impacted the system at a speed of 62.8 mph and at an angle of 25.2 degrees, resulting in an impact severity of 119.1 kip-ft. Vehicle experienced roll of -29.19 degrees and pitch of -18.62 degrees. Longitudinal and Lateral Occupant Ridedown Acceleration (ORA) were -3.65 g's and 7.98 g's respectively, and Longitudinal and Lateral Occupant Impact Velocity (OIV) were -14.09 ft/s and 21.56 ft/s respectively. Upon investigation of the results, all occupant risk values were found to be within limits, and the occupant compartment deformations were also deemed acceptable as per MASH recommended values. Sequential views of the vehicle kinematics during the test from a downstream perspective are shown in Figure 41.

t = 0 msec *t = 140 msec* *t = 290 msec* *t = 658 msec*

Figure 41. Sequential View of Vehicle Behavior – NJPCB-7

5.7.2 Barrier Deflections

The barrier system experienced a maximum lateral dynamic deflection of 11.4 in. and a permanent set deflection of 6¼ in., as shown in Figure 42.

Figure 42. Barrier Deflection (Impact location, during impact, and Post Impact)

5.7.3 Barrier Damage

Scuff marks, cracks, and spalling near the barrier toe occurred on barriers 3, 4, 5, and 6. Barrier 3 had minor cracks and spalling, which would make them reusable with minor repairs. Severe damage occurred to barriers 4 and 5 rendering them as non-reusable (see Figure 43). Barriers 4 and 5 experienced fracture extending through their entire height and toward joint connection between them, which exposed steel reinforcement near the top on both barriers. Barrier 6 had vertical cracks and spalling near pin anchors on its back face and near connection key, which meant the steel reinforcement was no longer intact, and the barrier was deemed non-reusable.

Figure 43. Barrier Damage – Barrier 4 (Top) and Barrier 5 (Bottom)

5.7.4 Vehicle Behavior

The majority of the damage was concentrated on the left-front corner and left side of the vehicle where the impact occurred. Denting, scraping, and gouging were observed on the entire left side of the vehicle. The windshield had cracks. Occupant compartment experienced minor deformations, all within MASH allowable limits.

CHAPTER 6. DISCUSSION AND ANALYSIS

Anchoring and stiffening techniques for NJDOT PCBs were evaluated for reducing barrier deflections. Seven full-scale crash test techniques consisted of one joint class A, two joint class B, three joint class C and one joint class D configurations. In addition, all safety performance evaluations were performed using the criteria found in MASH. The systems were constructed with ten 20-ft long, PCB segments utilizing a connection key between the barrier sections with the first and last sections anchored to the tarmac and subjected to full-scale crash testing.

NYTCB-2, a free-standing PCB system was considered as a baseline test to compare results of NJPCB systems. NYTCB-2 utilized New Jersey shaped NYSDOT PCBs, which are nearly identical to NJPCBs except for additional bolt anchor pockets on NJPCBs. NYTCB-2 consisted of the same system configuration as of NJPCB-3, except slack was removed from all joints in NJPCB systems.

Seven full-scale crash tests were performed with approximately the same impact severity (I.S.), ranging from 112.6 to 121.9 kip-ft considering the combined effect of the vehicle mass, impact speed, and impact angle. A summary of test results is listed in Tables 6 and 7. Table 6 includes the number of anchor pins or bolts used in a system, dynamic deflection, permanent set, and impact severity. Table 7 includes maximum vehicle roll and pitch, maximum longitudinal and lateral OIVs, and maximum longitudinal and lateral ORAs.

The tested embodiments discussed are separated into three primary groups for comparison: 1) free-standing barriers without anchorage (NJPCB-3, NJPCB-4 and NJPCB-5), 2) barriers using pin anchorage (NJPCB-1, NJPCB-6 and NJPCB-7), and 3) barriers using bolted anchorage (NJPCB-2).

Table 6. Full-Scale Crash Tests Results – Barrier Deflections and Impact Severities

Test No.	Joint Class	Anchored Barriers	No. of Anchor Pins/Bolts	Dynamic Deflection (in.)	Permanent Set (in.)	Impact Severity (kip-ft)
Baseline						
NYTCB-2	A	1 and 10	18	40.3	39½	119.2
Free-Standing Systems						
NJPCB-3	A	1 and 10	18	38.1	36⅝	121.9
NJPCB-4	B	1 and 10	18	40.7	38	114.1
NJPCB-5	B	1 and 10	18	33.0	32½	116.3
Pin Anchorage Systems						
NJPCB-1	C	1, 3, 5, 7, 9 and 10	54	13.5	6¼	114.9
NJPCB-6	C	1 and 10 (Both) 2-9 (Back)	50	15.2	3¾	119.2
NJPCB-7	C	1 and 10 (Both) 2-9 (Front)	58	11.4	6¼	119.1
Bolt Anchorage System						
NJPCB-2	D	1-10	100	4.9	-½ (Forward)	112.6

Table 7. Full-Scale Crash Tests Results – Vehicle Behavior

Test No.	Roll (deg.)	Pitch (deg.)	OIV (ft/s)		ORA (g's)	
			Longitudinal	Lateral	Longitudinal	Lateral
Baseline						
NYTCB-2	-12.4	-10.6	-15.88	20.74	-5.44	8.09
Free-Standing Systems						
NJPCB-3	-17.2	-9.0	-13.52	18.01	-5.23	9.61
NJPCB-4	-16.2	-14.2	-12.1	18.7	-4.0	12.1
NJPCB-5	-7.9	-12.5	-13.6	21.6	-7.65	9.62
Pin Anchorage Systems						
NJPCB-1	-39.9	-12.8	-14.27	19.33	-9.97	7.17
NJPCB-6	28.9	-12.2	-17.30	20.67	-9.73	8.43
NJPCB-7	-29.2	-18.6	-14.09	21.56	-3.65	7.98
Bolt Anchorage System						
NJPCB-2	20.7	-12.0	-16.66	24.06	-10.05	9.99

The PCB system contained and redirected the impact vehicle for all seven tests. In terms of impacting angle, contact with system, and redirection, general vehicle behavior was similarly experienced for all seven systems, but occupant risk values and vehicle Euler Angular movements varied.

6.1 Free-standing Systems

NJPCB-3 and NJPCB-4 had very similar overall results, both of which are similar to the baseline, NYTCB-2. Although NJPCB-4 had grout between the barriers and its I.S. was 6.4% less than NJPCB-3, it still had slightly larger deflection than NJPCB-3.

The box beam stiffening for NJPCB-5 significantly reduced barrier deflections relative to NJPCB-3, NJPCB-4 and the baseline (approximately 17%). The box-beam stiffeners also stabilized the truck in terms of roll, with approximately a 50% reduction, and this is without notably affecting the OIVs and ORAs.

6.2 Pin Anchorage Systems

Pin anchoring of barriers in NJPCB-1, NJCPB-6 and NJPCB-7 significantly reduced the barrier deflections relative to free-standing systems and the baseline, but vehicle instability was higher. Alternate pin anchoring for NJPCB-1 experienced four times higher vehicle instability in terms of roll, while pitch, ORAs and OIVs did not differ much.

NJPCB-6 and NJPCB-7 had similar vehicle stability and I.S., but traffic side pin anchoring in NJPCB-7 experienced lower barrier deflections compared to back side pin anchoring, approximately 15% reduction. Relatively high vehicle roll was observed in NJPCB-1 compared to NJPCB-6 and NJPCB-7, which may be due to the majority of vehicle contact being with barrier 5, which was pin anchored on both sides.

6.3 Bolt Anchorage System

The bolt anchoring system in NJPCB-2 deflected the least among all seven tests. Upon examination of I.S. values and barrier deflections, it was evident that the bolt anchored system was effective in reducing barrier deflections. Dynamic barrier deflection for NJPCB-2 was 4.9 in., which included tipping of the barrier along the top surface, as shown in Figure 44.

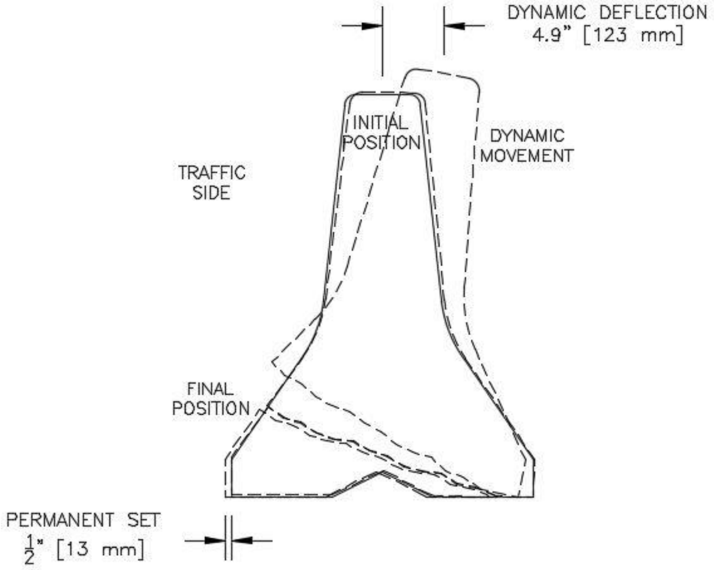


Figure 44. Dynamic Deflection and Permanent Set Deflection – NJPCB-2

Bolt anchored system also stabilized the truck in terms of roll, with approximately a 40% reduction when compared to pin anchorage systems. Pitch, ORAs and OIVs were comparable to other tests, even though NJPCB-2 had all barriers anchored. This may be because there were no steel reinforcements for bolt anchor pockets, while pin anchor recesses have steel reinforcements.

CHAPTER 7. CONCLUSION AND FUTURE WORK

Anchoring and stiffening techniques for PCBs were evaluated according to MASH using full-scale crash tests. Anchoring techniques included use of pins and bolts, and stiffening techniques included use of box beam rails and non-shrink grout wedges placed at toes between barriers. These techniques were intended to limit barrier deflections, and to implement and update NJDOT's PCB installation guidance.

Seven full-scale crash tests were conducted with 2270P vehicle, and were determined to be successful per criteria set forth in MASH. These seven full-scale crash tests were grouped in three categories:

(a) Joint classes A and B consisted of a similar type of anchoring technique, but featured different stiffening techniques. Among tests with joint classes A and B, NJPCB-5 used grout and box beam stiffeners, which resulted in the lowest barrier deflections and low occupant risk values.

(b) Joint class C consisted of alternate barrier anchorage, barrier anchorage on the back side and barrier anchorage on the traffic side. These anchorages made the PCB system stiffer when compared to joint classes A and B. The comparison of dynamic deflections, barrier damages and occupant risk values indicated that the traffic side pin anchored system was stiffer and resulted in the lowest dynamic deflection among joint class C.

(c) Joint class D consisted of bolt anchors epoxied to concrete tarmac, with the least system deflection observed among all joint classes, and occupant risk values considerably lower when compared to pin anchorage systems. Vehicle stability was satisfactory, and system damage was limited to barriers 4 and 5.

Table 8 contains usage limits according to dynamic deflections observed during the tests, and the changes are based on allowable movements. It is not specified in the NJDOT's *Roadway Design Manual* whether the data listed in Table 1 were considered as dynamic deflection or permanent set deflection. Hence, both deflection limits are listed. Limits used in Table 8 include data from tests mentioned in the literature review.

Table 8. PCB guidance – Change in Allowable Movements

Joint Class	**Allowable Movement**		**Joint Treatment**
	Dynamic Deflection	**Permanent Set Deflection**	
A	Up to 41 in.	Up to 40 in.	Connection Key
B	Up to 41 in.	Up to 41 in.	Connection Key and grout in every joint
C	Up to 16 in.	Up to 7 in.	Connection Key and grout in every joint. Alternate anchored units, all units anchored on traffic side, or all units anchored on back side
D	Up to 5 in.	No allowable movement	Connection Key and grout in every joint and bolt every anchor pocket hole in every unit.

Instead of changing allowable movements in PCB usage guidance, changes can be made in specification of Joint Classes. Joint Treatments are organized into the classes based on the dynamic deflections found during testing. Types of Joint Treatments that fall under different Joint Classes are listed in Table 9. The updated PCB guidance is based on seven full-scale crash tests on NJDOT New Jersey shape PCBs. All tested systems had ten 20-ft long PCBs and used connection keys, and all systems successfully passed MASH Safety Evaluation Criteria. All four joint classes use connection keys for barrier to barrier connections, and end barriers anchored to road surface on both sides. Joint classes B and C include grouted toes. As yet, no joint treatment was able to prevent dynamic deflection and thus none should be listed under Joint Class D.

Table 9. PCB guidance – Change in Joint Treatments with dynamic deflections

Joint Class	**Use**	**Test No.**	**Joint Treatment**
A	Allowable movement over 16 to 42 inches	NJPCB-3	Free-standing system with barriers 1 and 10 pin anchored to concrete tarmac
		NJPCB-4	Free-standing system with barriers 1 and 10 pin anchored to concrete tarmac
		NJPCB-5	Box-Beam Stiffened to all nine joints between barrier segments, and barriers 1 and 10 pin anchored to concrete tarmac
B	Allowable movement over 11 to 16 inches	NJPCB-1	Barriers 1, 3, 5, 7, 9, and 10 pin anchored to concrete tarmac
		NJPCB-6	Barriers 1 and 10 pinned on both sides, and barriers 2 through 9 pin anchored on back side to concrete tarmac
		NJPCB-7	Barriers 1 and 10 pinned on both sides, and barriers 2 through 9 pin anchored on traffic side to concrete tarmac
C	Maximum allowable movement of 11 inches	NJPCB-2	All ten barrier segments bolt anchored to concrete tarmac
D	No allowable movement	N/A	No test met this criteria

Joint Treatments are organized into the classes based on the permanent set deflections found during testing. Types of Joint Treatments that fall under different Joint Classes are listed in Table 10. No observed test were found to have permanent set deflections within the range from 11 to 16 in., hence no test fall in to Joint Class B. Tests with pin anchorage techniques had permanent set deflections ranged within 11 in., so pin anchorage tests are in Joint Class C. Permanent set deflection observed in NJPCB-2 was considered negligible as the barrier deflected ½ in. forward.

Table 10. PCB guidance – Change in Joint Treatments with Permanent set deflections

Joint Class	**Use**	**Test No.**	**Joint Treatment**
A	Allowable movement over 16 to 42 inches	NJPCB-3	Free-standing system with barriers 1 and 10 pin anchored to concrete tarmac
		NJPCB-4	Free-standing system with barriers 1 and 10 pin anchored to concrete tarmac
		NJPCB-5	Box-Beam Stiffened to all nine joints between barrier segments, and barriers 1 and 10 pin anchored to concrete tarmac
B	Allowable movement over 11 to 16 inches	N/A	No test met this criteria
C	Maximum allowable movement of 11 inches	NJPCB-1	Barriers 1, 3, 5, 7, 9, and 10 pin anchored to concrete tarmac
		NJPCB-6	Barriers 1 and 10 pinned on both sides, and barriers 2 through 9 pin anchored on back side to concrete tarmac
		NJPCB-7	Barriers 1 and 10 pinned on both sides, and barriers 2 through 9 pin anchored on traffic side to concrete tarmac
D	No allowable movement	NJPCB-2	All ten barrier segments bolt anchored to concrete tarmac

Future Work

Further work could improve on the vehicle instabilities caused by the barrier impacts and evaluate anchorage techniques with other anchor embodiments, surfaces, and system lengths. A non-exhaustive list of suggestions for future research is included below:

(a) Conduct additional crash tests on hot mix asphalt (HMA) surfaces to evaluate whether the prior anchorage tests are still acceptable, and characterize the system behavior on HMA

(b) Conduct crash testing using shorter overall system lengths to evaluate the minimum effective length of the system with different anchorage and stiffening techniques

(c) Utilize steel reinforcement in the barrier toe to provide additional fracture resistance to Class D joint barriers with bolt anchorage

(d) Increase barrier strength via including more rebar and higher compressive strength concrete mix

(e) Conduct a crash test with all barriers pinned for vehicle and system behavior comparison against bolted barriers

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