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Transition of Temporary Concrete Barrier

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Abstract

The objective of this research was to design a transition from temporary concrete barriers to a permanent concrete barrier for median applications. The researchers at Midwest Roadside Safety Facility utilized a combination of free-standing and tied-down Kansas temporary concrete barriers and a dual-nested thrie beam for the transition to the single-slope permanent barrier as well as a transition cap. Two full-scale vehicle crash tests were performed on the system. Evaluation of the approach transition required testing at two Critical Impact Point (CIP) locations. The first tests was performed using a half-ton pickup truck that impacted the temporary barriers 1,432 mm upstream from the permanent barrier, at a speed and angle of 100.7 km/h and 24.7 degrees, respectively. The second crash test was also performed using a half-ton truck that impacted the temporary barriers 16.6 m upstream from the permanent barrier, at a speed and angle of 100.1 km/h and 26.2 degrees, respectively. Both tests were conducted and reported in accordance with requirements specified in the Manual for Assessing Safety Hardware (MASH) and were determined to be acceptable according to the Test Level 3 (TL-3) evaluation criteria.

Keywords: roadside safety, temporary concrete barrier, F-shape, transition, TL-3, crash testing, compliance testing

1. Introduction

Temporary concrete barrier (TCB) is one of the most common types of roadside hardware found on U.S. highways. TCB systems redirect errant vehicles through a combination of various forces and mechanisms, including inertial resistance developed by the acceleration of several barrier segments, lateral friction loads, and the tensile loads developed from the mass and friction of the barrier segments upstream and downstream of the impacted region. Although TCB technologies have advanced in recent years with the development of methods for limiting deflection, there exists a need for safely transitioning between a free-standing TCB system and other roadside hardware.

In practice, TCBs must be connected and transitioned to many types of barriers, as shown in Figure 1. Sometimes the TCBs are connected to similarly shaped permanent concrete barriers, whereas at other times they must be connected to vertical concrete barriers, tubular steel bridge railings, *W*-beam guardrail, *thrie*-beam guardrail, and open concrete bridge railings. Unfortunately, there has been only limited effort devoted to resolving transition issues. Thus, a need existed to identify the critical approach transition that is desired by state departments of transportation.

Identifying the temporary barrier transition designs that are needed and their usage characteristics is necessary to develop transition designs for resolving these problems. However, addressing all of the possible transition situations would be costly. Thus, because only a small number of transitions will actually be developed, identifying the most prominent need is required. This would ultimately lead to the development of a transition between TCB systems and other types of longitudinal barrier system. The new design should provide a significant improvement in safety of the motoring public.

The objective of this research study is to identify the most prominent transition scenario between TCB and other types of barriers and develop a TCB transition for the highest priority situation. The transition design was to be developed for use with the Kansas *F*-shape TCB (Polivka et al., 2003, 2006a) that is currently used by several states participating in the Midwest Pooled Fund Program. This effort was performed in accordance with the Test Level 3 (TL-3) guidelines found in the *Manual for Assessing Safety Hardware (MASH)*; American Association of State Highway and Transportation Officials [AASHTO], 2009).

The research objective was achieved through the completion of several tasks. First, a survey of the Midwest States Regional Pooled Fund members was conducted to identify the most prominent transition need with respect to TCBs. Next, the researchers designed a TCB transition for the most prominent need. After the transition design was developed, a computer simulation modeling was undertaken to analyze and determine the Critical Impact

Fig. 1. Temporary concrete barrier transition types.

Points (CIPs) for the transition. Two full-scale vehicle crash tests were performed on the transition system. The crash tests utilized half-ton pickup trucks, each weighing approximately 2,270 kg. The targeted impact conditions for the tests were an impact speed of 100.0 km/h and an impact angle of 25 degrees. Next, the test results were analyzed, evaluated, and documented. Finally, conclusions and recommendations were made that pertain to the safety performance of the design for a TCB transition.

2. Background

To date, there has been very little research in the design of safe transitions between freestanding TCBs and other roadside barriers. The majority of temporary barrier systems were tested and approved based on the performance of the free-standing barrier design, whereas the performance of the system when attached to different barrier systems was left largely undefined. Some research has been done on transition designs for proprietary temporary barrier designs such as the Vulcan barrier developed by Energy Absorption Systems, Inc. in the United States and the Delta Bloc and VarioGuard systems developed in Europe. These transition designs consist of transitions from the proprietary temporary barrier segments to various barrier types including *W*-beam, thrie beam, rigid concrete parapets, and crash cushions. However, these transitions are all designed for use with proprietary barriers systems that utilize specialized shapes, materials, and connections. These proprietary design elements are not consistent with or representative of the nonproprietary temporary barrier designs that are currently used by the majority of state departments of transportation in the United States. In addition, there is limited public information available on the design and testing of these proprietary transition designs other than information posted on the manufacturer's web site.

In 2005, the Midwest Roadside Safety Facility (MwRSF) designed and evaluated a transition from a free-standing TCB to a rigid concrete barrier (Bielenberg et al., 2007, Bielenberg et al., 2006). This design was developed for roadside applications and was not intended for use in median installations. The test installation consisted of five rigidly constrained barriers on the downstream end, four transition barriers, and 13 free-standing barriers on the upstream end. The rigid barrier end was simulated by bolting down the final five *F*-shape barriers with 29-mm diameter B7 threaded rods epoxied into the concrete at an embedment depth of 304 mm. The transition in stiffness between the free-standing TCB and the rigid barrier was developed over four TCB segments by using an asphalt pin tie-down system with varied spacing on the traffic-side face of the barrier segments. The first barrier in the transition (also the one adjacent to the free-standing barriers) had a single pin at the downstream end on the traffic side face of the barrier. The second barrier had pins installed at the two outermost hole locations on the traffic side face of the barrier. The final two barriers had all three pins installed on the traffic side. The free-standing barrier and the bolted-down barrier were joined by a pin and loop connection at the joint. To reduce the potential for vehicle snag at the rigid barrier joint, a nested thrie beam was also bolted across both sides of the barrier at the joint between the pinned barrier and the rigid barrier system. In Test no. FTB-2, a 2,030-kg pickup truck impacted the system 1,219 mm upstream of the joint between barrier

nos. 14 and 15, which are the first two pinned barriers in the transition at a speed of 102.7 km/h and at an angle of 26.1 degrees. During the impact, the vehicle was safely redirected, and the test was determined to be acceptable according to the TL-3 safety performance criteria of test designation 3-21 found in NCHRP Report No. 350 (Ross et al., 1993).

3. Test Criteria

Approach transitions, such as TCB transitions, must satisfy impact safety standards to be accepted by the Federal Highway Administration (FHWA) for use on National Highway Systems (NHS) construction projects or as a replacement for existing designs not meeting current safety standards. According to TL-3 of *MASH*, longitudinal barriers must be subjected to two full-scale vehicle crash tests. The two full-scale crash tests are as follows:

1. Test Designation 3-20, consisting of a 1,100-kg small car impacting the barrier system at a nominal speed and angle of 100.0 km/h and 25 degrees.
2. Test Designation 3-21, consisting of a 2,270-kg pickup truck impacting the barrier system at a nominal speed and angle of 100 km/h and 25 degrees.

Previous research has demonstrated that the passenger car test was unnecessary for the transition (AASHTO, 1989; Bronstad et al., 1976; Buth et al., 1990; Fortuniewicz et al., 1982; Polivka et al., 2006b), and test designation no. 3-21 was deemed sufficient to evaluate the approach transition. Two CIPs must be evaluated for the approach transition. The first CIP is located adjacent to the point where the transition attaches to the permanent barrier and is used to evaluate snag and pocketing near the hazard. The second CIP is located near the upstream end of the transition and is used to evaluate the stiffness transition, which can cause pocketing and vehicle instability.

4. TCB Transition Design

4.1. Evaluation of Critical TCB Transition Need

At the onset of this project, the Midwest States Regional Pooled Fund states were surveyed. The states were given eight types of commonly used TCB transitions and invited to add their own as desired. For each transition, the states were asked to (1) identify the usefulness of the transition, (2) identify the approximate percentage of all temporary barrier transitions that each type composes, and (3) rank the transition types in order of importance.

After compiling the state responses, the various transition needs were organized into a limited number of design categories. Priorities for the project were assigned based on (1) the importance of the transition to the states participating in the Midwest States Pooled Fund Program, (2) the number of different systems that can be addressed simultaneously, and (3) the potential for the development of a successful design. According to the responses, the most useful transitions were those connecting TCBs to safety shape and vertical permanent concrete barriers. The highest percentage of all of the transitions currently in use were those connecting TCBs to permanent concrete safety-shape barriers and tubular steel bridge railings. In rank of importance, transitions to permanent concrete safety shape barriers were again at the top, followed by transitions to *W*-beam guardrail.

As the most popular in all three categories, the transition between TCBs and permanent concrete safety-shape barriers was chosen for development of a transition solution. Realizing that such a transition may be applicable to more than one type of permanent concrete barrier, the researchers expanded the scope of the design to include vertical concrete parapets, safety-shape parapets, and single-slope barriers, but intending to only test the most critical. Because an NCHRP Report No. 350 compliant design for the transition between TCB and permanent safety-shaped barriers for roadside applications was recently developed (Bielenberg et al., 2007, Bielenberg et al., 2006), a median application was selected for this study. An end-to-end barrier transition was selected as opposed to an offset-overlap barrier transition, because it was deemed the more common and more useful type of transition. Therefore, it was decided to design an end-to-end transition between free-standing TCBs and permanent concrete barrier for median applications.

The preliminary transition design was based on the previously developed, roadside approach transition between a free-standing TCB and a rigid *F*-shape barrier. Thus, the design utilized varying numbers of steel pins driven through holes in the toe of the barrier to provide for the stiffness transition and three beam sections to connect the final temporary barrier section to the permanent barrier. Because the new transition was intended for use in medians, the steel pins would be required on both sides of the barriers rather than solely on the traffic-side face. In addition, some form of transition piece would be required to prevent vehicle snag on the permanent barrier due to the difference in the barrier heights.

4.2. Determination of Critical Rigid Barrier Geometry

The next phase of the research was to determine the type of permanent concrete barrier that would be the most critical in a transition. To make this determination, the shapes of various permanent median barrier designs were compared to the shape of the narrow and wide versions of the 813-mm tall *F*-shape temporary barrier. The following comparisons were completed:

1. 813-mm *F*-shape temporary barrier to 813 mm and 1,067-mm *F*-shape and New Jersey (NJ)-shape median barriers;
2. 813-mm *F*-shape temporary barrier to 813-mm and 1,067-mm Texas (TX) and California (CA) single-slope median barriers;
3. 813-mm *F*-shape temporary barrier to 813-mm and 1,067-mm vertical median barriers;
4. Wide, 813-mm *F*-shape temporary barrier to 813-mm and 1,067-mm *F*-shape and NJ-shape median barriers;
5. Wide, 813-mm *F*-shape temporary barrier to 813-mm and 1,067-mm TX and CA single-slope median barriers; and
6. Wide, 813-mm *F*-shape temporary barrier to 813-mm and 1,067-mm vertical median barriers.

From the comparison of the various shapes, it was determined that the 1,067-mm tall CA single-slope median barrier provided the worst-case situation. The taller shapes were found to pose higher snag potentials due to the difference in barrier height. Figure 2 shows a comparison of the tall versions of the *F*-shape, vertical shape and single slope barriers with the *F*-shape TCB cross-section. Comparison of the *F*-shape temporary barrier geometry with the single-slope barrier showed that there was a high potential for vehicle snag on the sides of the permanent barrier as well as on the 254-mm height difference of the barriers. It was determined that shifting the temporary barrier toward the traffic-flow side of the single slope so that the slope breakpoint at the top of the toe of the temporary barrier lines up with the traffic-side face of the permanent single slope would help alleviate some of the snag potential on the single-slope barrier. This asymmetrical placement

Note: (1) The 32" temporary *F*-shape barrier is shown as the front/upstream barrier.

Fig. 2. *F*-shape Temporary concrete barrier alignment with median barrier.

Fig. 3. Temporary concrete barrier transition Critical Impact Point-2000P 100 km/h at 25 degree impact location-test TCBT-2.

would only present a safety concern if the temporary barrier were used to separate traffic flowing in the same direction, such as in a gore area. However, it was believed that this situation would be better treated with a barrier end treatment.

4.3. Determination of CIP

Two CIPs needed to be evaluated for the approach transition. LS-DYNA (Hallquist, 1997) was used to determine the CIP for the second full-scale crash test on the TCB transition, test TCBT-2. For this CIP, barrier deflections are expected potentially causing pocketing in the system resulting in potentially

Fig. 4. Temporary concrete barrier transition Critical Impact Point - 2000P 100 km/h at 25 degree - 150 ms - Test No. TCBT-2.

unstable vehicle behavior or vehicle override of the system. A detailed model of the TCB was built and impacted at various locations along the barrier to determine the likely CIP. Selected results of the simulations are shown in Figure 3 through Figure 7. Four different cases are presented. Additional impact points beyond those noted herein were simulated to determine the CIP through a process of applying the results of each simulated impact point to bracket and narrow down the choice of the CIP to the critical location. The impact points shown below were selected to illustrate the general process used to select the CIP.

Fig. 5. Temporary concrete barrier transition Critical Impact Point - 2000P
100 km/h at 25 degree - 300 ms - Test No. TCBT-2.

Case A – impact just upstream of barrier 3

Case B – impact 12 barrier length upstream from Case A

Case C – impact 1 barrier length upstream from Case A (just upstream of barrier 4)

Case D – impact 112 barrier lengths upstream from Case A.

Determination of the CIP considered evaluation of the stability of the impacting vehicle as well as examination of vehicle behavior including barrier motions such as displacement, roll and yaw. Top view sequential images

Fig. 6. Temporary concrete barrier transition Critical Impact Point - 200p 100 km/h at 25 degree - Test No. TCBT-2.

for the four cases are shown in Figure 3 (initial impact), Figure 4 (at 150 ms), and Figure 5 (at 300 ms). Downstream views are shown in Figure 6 (at 300 ms and 500 ms). Barrier displacement, barrier roll, and barrier yaw are shown in Figure 7 through Figure 12.

Case A exhibited relatively limited barrier motion; although the vehicle exhibited the most pitch, that motion did not cause any significant indication of the vehicle becoming unstable; and thus Case A was ruled out

Fig. 7. Critical Impact Point determination plots - Test No. TCBT-2.

Fig. 8. Critical Impact Point determination plots - Test No. TCBT-2.

Fig. 9. Critical Impact Point determination plots - Test No. TCBT-2.

Fig. 10. Critical Impact Point determination plots - Test No. TCBT-2.

Fig. 11. Critical Impact Point determination plots - Test No. TCBT-2.

Fig. 12. Critical Impact Point determination plots - Test No. TCBT-2.

for the CIP. Impacts downstream of Case A were expected to produce even lower barrier motions due to the increased constraint on the barriers in the transition. Case D appeared to have the smoothest redirection of the vehicle and was thus ruled out for the CIP. Cases B and C demonstrated somewhat similar behavior, but researchers concluded that Case C had higher barrier motions overall and slightly more vehicle roll than Case B. Thus, Case C was chosen as the CIP for test no. TCBT-2.

It should be noted that the CIP for the downstream CIP adjacent to a permanent barrier was chosen as 1.3 m upstream of the permanent barrier. This value is based on guidance for CIP values for rigid barriers and temporary concrete barriers provided in Table 2.6 in *MASH*. It represents the distance upstream of a post or joint in a rigid barrier that has increased potential for vehicle snag. Due to the high stiffness of the anchored temporary concrete barrier sections adjacent to the permanent barrier, it was believed that this CIP location would be sufficient to determine the potential for snag on the rigid median barrier.

4.4. TCB Approach Transition to 42-Inch High Single-Slope Barrier Design Details

The 50.9-m long test installation for the transition from temporary concrete barriers to a permanent concrete median barrier is shown in Figure 13. The test installation consisted of a rigid parapet, four transition barriers, eight free-standing barriers on the upstream end, and a transition cap. The transition and free-standing barriers were installed on a 76-mm thick asphalt pad.

The transition utilized a varied spacing of the asphalt pin tie-down system to create a transition in stiffness over a series of four barrier segments. The asphalt pins used in the design were 38-mm diameter $\times$ 978-mm long ASTM A36 steel pins with 76-mm $\times$ 76-mm $\times$ 13-mm ASTM A36 steel cap plates with a 38.1-mm diameter hole in the center. The steel cap was welded on to the pin on the top and bottom surfaces of the plate at a position of 914 mm from the bottom of the pin to the top of the plate. These pins were installed in the holes on the front and back face of the four barriers in the transition section of the installation. The first barrier in the transition (the one adjacent to the free-standing barrier) had a single pin at the downstream end on the front and back sides. The second barrier had pins installed at the two outermost hole locations on the front and back faces. The final two barriers had all three pins installed on the front and back faces.

To reduce the potential vehicle snag at the joint between the pinned barriers and the rigid parapet, a transition cap and nested thrie beam sections were added. The nested 12-gauge thrie beam sections were bolted across

Fig. 13. Temporary concrete barrier approach transition to 42-in. high single-slope barrier.

both sides of the barrier at the joint between the pinned barrier and the rigid parapet. It should be noted that 10-gauge thrie beam can be substituted for the nested 12-gauge in actual installations if desired. The substitution of 10-gauge thrie beam in lieu of nesting is allowable based on the previous design and crash testing of approach guardrail transitions that utilized 10-gauge thrie beam (Faller et al., 2000, 2001). The thrie beam was bolted to the barriers using five 19-mm diameter $\times$ 152-mm long, Power Fasteners Wedge-Bolt Anchors at each end of the beam. In addition, the middle of the thrie section was attached to the pinned barrier with two 19-mm diameter Grade 5 bolts and 19-mm diameter RedHead Multi-Set II Drop-in Anchors. A wooden spacer block was used to offset the thrie beam from the concrete barrier on the back side of the installation. The 12-gauge ASTM A36 steel transition cap was 154 mm and 206 mm wide at the top and bottom, respectively, with a height of 254 mm. Four 12-gauge ASTM A36 gussets were stitch welded on three sides inside the cap.

The TCB system utilized the Kansas *F*-shape TCB barrier that consists of a 3,810-mm long barrier segment with a pin and loop type connection comprised of two sets of three rebar loops on each barrier interconnection. Full details of the Kansas *F*-shape TCB can be found in previous reports detailing its design and testing (Polivka et al., 2003, 2006a).

The barriers used a pin-and-loop type connection comprising two sets of three rebar loops on each barrier interconnection. Each loop assembly was configured with three ASTM A706 Grade 60 No. 6 bars that were bent into a loop shape. The vertical pin used in the connection consisted of a 32-mm diameter $\times$ 711-mm long round bar comprising ASTM A36 steel. The pin was held in place using one 64-mm $\times$ 102-mm $\times$ 13-mm ASTM A36 steel plate with a 35-mm diameter hole centered on it. The plate was welded 64 mm below the top of the pin. A gap of 92 mm between the ends of two consecutive barriers was formed from the result of pulling the connection taut.

The single-slope permanent concrete barrier was 545 mm and 203 mm wide at the base and top, respectively, with an overall height of 1,067 mm from the ground to the top of the barrier. The single-slope concrete barrier had an overall length of 4,064 mm.

5. Full-Scale Crash Testing

5.1. Test No. TCBT-1

Test no. TCBT-1 was performed to evaluate the transition adjacent to the permanent median barrier. A summary of the test results and the sequential photographs are shown in Figure 14. The 2,347-kg pickup truck, with a dummy placed in the right-front seat, impacted the TCB to permanent barrier transition, at a speed of 100.6 km/h and at an angle of 24.7 degrees.

Fig. 14. Summary of test results and sequential photographs, Test No. TCBT-1.

Initial vehicle impact was to occur 1,311 mm upstream from the upstream end of the permanent barrier. Actual vehicle impact occurred 1,432 mm upstream from the upstream end of the permanent barrier. As the vehicle impacted the system and began to redirect, the right-front fender engaged the slope of the steel transition cap on the final temporary barrier segment and was prevented from snagging on the single slope barrier. By 0.034 sec, the right-front corner of the vehicle reached the permanent concrete barrier, but snagging of the vehicle was mitigated by the reduced deflection of the temporary barrier segment and the thrie beam section. The vehicle continued to redirect and yaw counter clockwise and became parallel with the barrier system at 0.188 sec with a resultant velocity of 80.1 km/h. The vehicle continued to redirect with minimal pitch and roll motions until exiting the barrier system at 0.318 sec with a trajectory angle of 4.2 degrees and a resultant velocity of 78.2 km/h. The final position of the vehicle was determined to be 63.7 m downstream of impact and 9.9 m laterally behind the traffic-side face of the system.

Vehicle damage was moderate, and damage was concentrated on the right-front corner of the vehicle. The right-front corner, hood, and bumper were deformed inward. Major sheet metal deformations were found above the right-side wheel well and along the lower portion of the right-side doors. The right-front wheel was detached from the vehicle. Barrier damage consisted of scrapes and contact marks on the TCB, permanent barrier, and the thrie beam section, cracking of temporary barrier sections, and deformed thrie beam. The maximum lateral permanent set barrier deflection was 6.4 mm at the downstream end of barrier no. 1. The maximum lateral dynamic barrier deflection was 66 mm on the middle of the non-impact-side of the thrie beam, as determined from high-speed digital video analysis. Posttest damage photographs are shown in Figure 15.

Fig. 15. Posttest damage, Test No. TCBT-1.

Test no. TCBT-1 was determined to be acceptable according to the TL-3 safety performance criteria found in *MASH* using test designation no. 3-21.

5.2. Test No. TCBT-2

Test no. TCBT-2 was performed to evaluate the upstream end of the approach transition. A summary of the test results and the sequential photographs are shown in Figure 16. The 2,341-kg pickup truck, with the dummy placed in the right-front seat, impacted the TCB to permanent concrete barrier transition at a speed of 100.1 km/h and at an angle of 26.2 degrees. Initial vehicle impact was to occur 1,022 mm upstream from the downstream end of barrier no. 5. Actual vehicle impact occurred 1,048 mm upstream from the downstream end of barrier no. 5. After impact with the barrier system, the front-right corner of the vehicle crushed inward and the vehicle began to redirect. By 0.070 sec, the impact of the vehicle with barrier no. 4 caused a large crack to form near the midspan of barrier no. 4 that fractured the barrier into two pieces connected by the portions of the reinforcing steel. The vehicle continued to redirect with the front of the vehicle pitching upward as the right-front corner of the vehicle climbed the sloped face of the deflected temporary barrier segments. By 0.206 sec, the vehicle had become parallel to the system with a resultant velocity of 80.6 km/h. At 0.260 sec, the rear of the vehicle impacted the upstream half of barrier no. 4. Impact with the fractured barrier segment caused the right-rear wheel of the vehicle to snag the fractured barrier and pitch the rear of the vehicle upward rapidly. The vehicle exited the barrier at 0.346 sec at a trajectory angle of 14.0 degrees and a resultant velocity of 69.2 km/h. The vehicle came to rest 56.1 m downstream from impact and 20.4 m laterally away from the traffic-side face of the barrier. It should be noted that though *MASH* safety requirements do not require exit box criteria for evaluation of roadside safety hardware, it is recommended that it be reported. Thus, it was noted in this test that the vehicle trajectory as it exited the system in test no. TCBT-2 exceeded the exit box criteria, as shown in Figure 16.

Vehicle damage was moderate, and the damage was concentrated on the right side of the vehicle. The right-front corner including the front bumper and the right-front fender were deformed inward. The right-front wheel assembly disengaged from the upper and lower control arms. Sheet metal deformation and contact marks were noted along the entire right side of the vehicle. The right-rear wheel disengaged from the vehicle. System damage consisted of scrapes, contact marks, and concrete spalling on TCB and asphalt pin deflections, cracking of temporary barrier sections, and a fractured temporary barrier. As noted above, barrier no. 4 was cracked and fractured near the midspan of the barrier, and some of the longitudinal rebar was fractured. Deformation of several concrete temporary barrier loop joints and connection pins were noted in the impact region. The maximum lateral

Fig. 16. Summary of test results and sequential photographs, Test No. TCBT-2.

permanent set barrier deflection was 864 mm at the downstream end of barrier no. 5, as measured in the field. The maximum lateral dynamic barrier deflection was 864 mm at the upstream end of barrier no. 5, as determined from high-speed digital video analysis. Posttest damage photographs are shown in Figure 17.

Test no. TCBT-2 was determined to be acceptable according to the TL-3 safety performance criteria found in *MASH* using test designation no. 3-21.

6. Summary, Conclusions, and Recommendations

The barrier system developed during the TCB research described herein was an approach transition between free-standing TCBs and permanent concrete median barriers. An analysis of common median barrier geometries

Fig. 17. Posttest damage, Test No. TCBT-2.

identified the critical median barrier design for the approach transition as the 1,067-mm tall CA single-slope median barrier due to its height as compared to the *F*-shape TCB. Evaluation of the approach transition required testing at two CIP locations. The first was a CIP to evaluate vehicle interaction with the permanent barrier, and the second was a CIP to evaluate the stiffness transition near the upstream end of the system. Full-scale crash testing at both CIP locations demonstrated that the impacting vehicle was safely and smoothly redirected, and the testing of the approach transition was judged acceptable according to the TL-3 safety criteria set forth in *MASH*. This new design provides a means of safely transitioning from free-standing TCBs to permanent median barriers.

The approach transition described herein was designed for use with the Kansas *F*-shape TCB system. Therefore, it should not be used with other TCB systems or joint designs without further study. To adapt the design for use with other temporary barrier designs, the design factors noted previously

for the termination and anchorage system would need to be considered, such as barrier connections, segment lengths, reinforcement, and geometry.

The approach transition design between free-standing and a permanent concrete median barrier detailed in this report should be applied when designers are attaching free-standing TCB in the median to permanent concrete barriers or tie-down temporary barrier systems that provide a high degree of constraint on lateral deflection. This requires that the approach transition be applied when free-standing *F*-shape temporary barriers are connected to permanent concrete barrier, the bolt-through tie-down system for concrete roadways, or the asphalt pin tie-down system. When the approach transition is used in conjunction with the bolt-through tie-down system or the asphalt pin tie-down system, the three beam guardrail on the downstream end of the transition is not necessary due to the similar stiffness and deflection levels of the tie-down barriers and the transition. Use of the three beam sections is required when the system is attached to rigid barriers to reduce the potential for vehicle snag.

It should also be noted that the approach transition design used pins on both sides of the barrier due to the system's application in the median. However, the researchers cannot recommend using anchorage on both sides of the temporary barrier segment to create a median installation of TCB with limited deflection without further testing. There are concerns that placing anchorage on the back side of the barrier can induce increased vertical rotation of the barrier segments that could increase the potential for vehicles to climb the sloped barrier face and become unstable.

The approach transition design was tested with the 42-in. tall, CA single-slope median barrier because this barrier was identified as the most critical barrier design for the transition. However, there are other permanent concrete median barriers that can be attached to the approach transition as long as the following guidelines are applied.

1. If the permanent median barrier is 813-mm high, the sloped, steel transition cap is not required for the transition. For barriers with heights greater than 813-mm high, the steel transition cap is required. The cap design can be adjusted for different height and shape barriers as long as the adjusted cap provides equivalent slope, permanent barrier coverage, barrier overlap, structural capacity, and anchorage as compared to the original design.
2. Alignment of the temporary barrier system with the permanent barrier may also change when the transition is applied to different permanent barrier geometries, as shown in Figure 2. When attaching to a single-slope barrier profile, the slope break point between the toe of the barrier and the main face of the barrier should be aligned flush with the oncoming traffic side of the single-slope

barrier. For safety shape barriers, the toe of the temporary barrier should be aligned flush with the toe of the oncoming traffic side of the median barrier. Vertical median barriers require that the toe of the temporary barrier segments on the reverse direction traffic side be aligned with the base of the permanent barrier on the reverse-direction traffic side. These alignments will prevent vehicle snag for oncoming traffic on the permanent median barrier while preventing snag on the toe of the barrier for reverse direction impacts.

3. The three beam sections that span the gap between the end of the temporary barrier and the permanent median barrier should be used in all instances.

Finally, the researchers also believe that the bolt-through tie-down system developed previously could be safely applied to transitions on concrete surfaces using the configuration developed herein. The asphalt pin and bolt-through tie-down systems are believed to possess similar lateral restraint and thus can be interchanged in the transition design as needed.

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