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TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Transportation Research Record
1–11
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DOI: 10.1177/0361198118758676
journals.sagepub.com/home/trr
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Development of a Standardized Buttress for Approach Guardrail Transitions

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Abstract

Approach guardrail transitions (AGTs) incorporate increased post and rail sizes, reduced post spacings, and specialized buttress end geometries to smoothly transition from deformable W-beam guardrail to rigid barriers. This transition in barrier stiffness makes AGTs sensitive systems that require specific combinations of these components to function properly. Changing components, or even the removal of a curb below the rail, can negatively affect the safety performance of an otherwise crashworthy system. However, recent full-scale crash testing has indicated that a properly designed buttress at the downstream end of an AGT may be utilized with multiple AGT systems. Thus, the objective of this project was to develop a standardized buttress to reduce vehicle snag and be compatible with a wide variety of previously developed Thrie beam AGT systems, either with or without a curb. The standardized buttress was designed with a dual taper on its front upstream edge. A longer lower taper was designed to mitigate tire snag below the rail, while a shorter upper taper was designed to prevent vehicle snag and limit the unsupported span length of the rail. This buttress design was evaluated in combination with a critically weak AGT without a curb, which represented the worst-case scenario. The standardized buttress was successfully crash tested to MASH TL-3. Guidance was provided for both the attachment of the buttress to various Thrie beam AGTs as well as how to transition the shape of the buttress to adjacent bridge rails or rigid parapets downstream of the AGT.

Approach guardrail transitions (AGTs) are utilized to attach deformable W-beam guardrail to various rigid barriers, including bridge rails and reinforced concrete parapets. To smoothly transition between the different barrier stiffnesses and prevent vehicle snag, AGTs typically incorporate thicker and/or larger guardrail segments (i.e., Thrie beam), increased post sizes, and decreased post spacings. In addition, the upstream end of the rigid barrier to which the AGT is attached is often modified with various tapers and flares to minimize the risk of vehicle snag. Curbs have also been placed below the guardrail and adjacent to the rigid barrier to further reduce the likelihood of tire snag. AGTs consist of a specific combination of these components and roadside features to make them crashworthy.

Over the last couple of decades, multiple AGTs have been developed to satisfy the safety performance criteria of either the Manual for Assessing Safety Hardware (MASH) or NCHRP Report 350 (*1,2*). However, full-scale crash testing has illustrated the sensitive nature of guardrail stiffness transitions. Changing only a single component or feature of an AGT can significantly alter its safety performance. For example, the addition/removal of a curb, altering the geometry of the rigid parapet, or altering the embedment length of the transition posts, can be the difference between a failure and a successfully crash tested AGT (*3–11*). Owing to the sensitivity of stiffness transitions, AGT components and features (e.g., curb usage and rigid barrier geometry) are not interchangeable between systems.

The majority of failures observed during crash testing have been the result of excessive vehicle contact with the rigid parapet, especially for AGTs that did not utilize a curb beneath the guardrail. These tests indicated that the geometry of the rigid parapet was more critical than previously believed. Thus, the development of a concrete buttress end geometry was desired to minimize the risk of vehicle snag and to be crashworthy in combination with various Thrie beam AGTs.

Research Objective

The objective of this research project was to develop and evaluate a standardized buttress geometry for use with Thrie beam AGTs. The transition buttress needed to be compatible with all of the previously developed Thrie beam AGT systems that were successfully crash tested to the Test Level 3 (TL-3) performance criteria of either MASH or NCHRP

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Report 350. In addition, the buttress needed to safely transition from stiffened Thrie beam to a variety of concrete parapet and bridge rail shapes. Finally, AGTs incorporating the standardized buttress needed to be crashworthy in both curbed and non-curbed installation configurations.

Standardized Buttress Design

Development of the standardized transition buttress began with a review of previous full-scale crash testing on AGTs connected to concrete parapets. Since a limited number of AGTs had been evaluated to MASH standards, the review included both MASH and NCHRP Report 350 tested systems. Thirty-nine crash tests, which were conducted on 20 different transition systems, were reviewed in order to identify tendencies between the crashworthy systems and those that failed to meet the safety criteria (*12*). Knowledge gathered from this review was utilized to guide the design of the standardized buttress.

During the literature review, it was noted that nearly all AGTs were designed with the Thrie beam end connector mounted vertically on the concrete parapet. If the parapet had a sloped face (e.g., New Jersey, F-shape, or single slope barriers), a wedge-shaped connection plate was typically utilized between the Thrie beam end connector and the parapet, which allowed the rail to remain in a vertical orientation. Only two tests were conducted on Thrie beam AGTs with the rail twisted to match the sloped face of the parapet, and both of those NCHRP Report 350 tests resulted in vehicle rollovers (*5,13*). Thus, it was desired to keep the rail element vertical throughout the AGT. To keep the AGT design simple and avoid the added components and costs associated with requiring a connection plate, the standardized buttress was designed with a vertical front face geometry. The vertical shape could then be transitioned into different parapet shapes downstream of the rail end connector.

Multiple AGTs have been designed with a rub rail placed below the rail to mitigate tire snag. However, five out of the seven tests conducted on AGTs incorporating rub rails were failures, of which four were vehicle rollovers (*14–19*). These results indicate that tire interactions with rub rails may lead to vehicle instabilities during redirection. Therefore, a rub rail was not incorporated into the design of the standardized buttress.

Without a rub rail, the front upstream corner of the buttress needed to be tapered back to reduce snag on the buttress. Previous crash testing has shown that tapering the front corner 4 to 5 in. backward was sufficient to prevent snag and often resulted in crashworthy designs (*11,20,21*). Therefore, the lateral extent of the taper on the front corner of the standardized buttress was desired to be at least 4 inches.

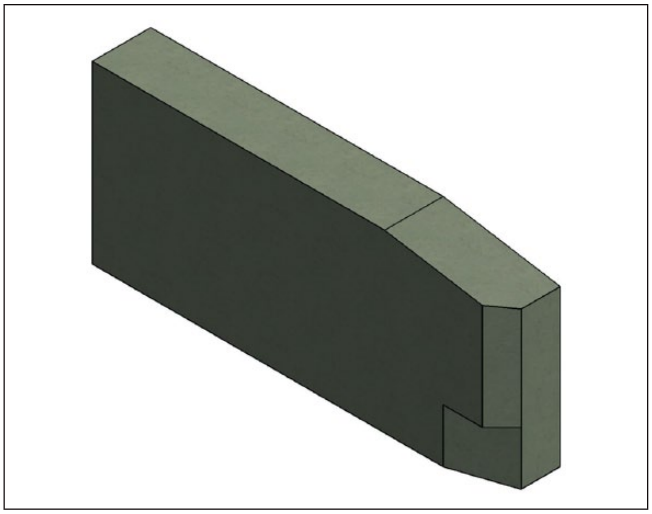


Figure 1. General shape of the standardized AGT buttress incorporating a dual tapered front edge.

The slope of the taper, and the associated longitudinal extent of the taper, affects the performance of the standardized buttress in opposing ways. A shallow slope over a long distance was desired to reduce vehicle and tire snag on the buttress. However, increasing the longitudinal length of the taper also increases the unsupported length of the Thrie beam between the buttress and the adjacent transition post. Increasing the unsupported length of the rail would result in a reduction in stiffness, an increase in deflection, and increased potential for vehicle snag. Thus, a steeper taper over a shorter longitudinal distance was desired to maintain rail stiffness and prevent excessive deflections.

To balance these two effects, a dual taper design was selected, as shown in Figure 1. The lower portion of the buttress below the Thrie beam utilized a shallow taper to minimize tire snag, while the upper portion of the buttress behind the rail utilized a steep taper to limit the unsupported span length of the rail but still reduce vehicle snag. Previous MASH crash testing has demonstrated that a slope rate of 3:1 can prevent tire snag during vehicle impacts into AGTs (*22*). Thus, the lower taper on the buttress had a 3:1 slope, which resulted in a 12-in. long by 4-in. deep taper. The lower taper extended to the bottom of the Thrie beam, or a height of 11 inches. The upper taper had a 1:1 slope, resulting in a 4-in. by 4-in. taper behind the rail.

To prevent vehicle snag on the buttress above the Thrie beam, the upstream face of the standardized buttress was set at 32 in. tall, which was 1 in. above the top of the Thrie beam. However, many concrete barriers and bridge rails are installed with a 36 in. height to satisfy MASH TL-4. Thus, to match the height of adjacent TL-4 bridge rails, the height of the standardized buttress was transitioned from 32 in. up to 36 in. utilizing a 6:1 vertical slope beginning at the upstream end of the buttress.

The standardized buttress was designed with a 7-ft length to limit the total length of the AGT system while still providing enough barrier length to resist impact loads. To be compatible with adjacent TL-4 bridge rails and concrete parapets, the capacity of the buttress was designed to withstand a TL-4 impact load of 80 kips. The final configuration was 12 in. wide and was reinforced with 16 no. 4 rebar stirrups. In addition, six no. 4 longitudinal rebar were placed along each of the front and back faces of the buttress. The top edges of the buttress were chamfered 1 in.

Selection of Critical Transition Configuration

The standardized buttress needed to be compatible with a wide variety of Thrie beam AGT systems, both with and without a curb. Therefore, the buttress had to be connected to a critical AGT creating a worst-case scenario in order to properly evaluate the system. A review of existing AGTs successfully tested to TL-3 of MASH or NCHRP Report 350 was conducted to find the weakest Thrie beam AGT design (i.e., the most flexible system). This critically weak AGT would pose the greatest risk of vehicle snag on the rigid buttress. The system with the highest dynamic deflection was an AGT originally developed for the Iowa Department of Transportation (DOT). This transition utilized the smallest transition posts and the shortest embedment depths of the reviewed systems. Thus, the Iowa AGT was identified as the weakest of the reviewed transition systems.

Further, the Iowa AGT was successfully tested to both MASH and NCHRP Report 350 TL-3 criteria when used in combination with a curb (3,*4*,6). However, similar AGTs evaluated without a curb failed to satisfy either testing standard. These crash test results not only reinforce the notion that this system is the most susceptible to vehicle snagging, but also indicates that testing without a curb is more critical by allowing the vehicle tires to extend under the rail and snag on the buttress. Therefore, the AGT originally developed for the Iowa DOT, but without a curb, was selected as the critical AGT configuration for the evaluation of the standardized buttress.

To prevent altering the stiffness of the selected AGT, the rail segments and posts needed to be positioned properly relative to the buttress. The original design had an 11-in. offset between the upstream face of the buttress and the centerline of the first transition post. A 1-in. chamfer was present on the corners of the buttress creating a 12-in. span length in which the rail was unsupported in the lateral direction. Since the new standardized buttress incorporated a 4-in. × 4-in. chamfer on the front corner behind the rail, the centerline of the first transition post was placed 8 in. upstream of the buttress to maintain the 12-in. unsupported span length. These dimensions are shown in Figure 2.

Finally, the upstream end of the original AGT design, which was untested and connected to 27-in. tall guardrail, was altered to incorporate the MASH TL-3 crashworthy, Midwest Guardrail System (MGS) stiffness transition (*23,24*). Both the original Iowa AGT and the critical configuration utilized to test the standardized buttress are shown in Figure 3.

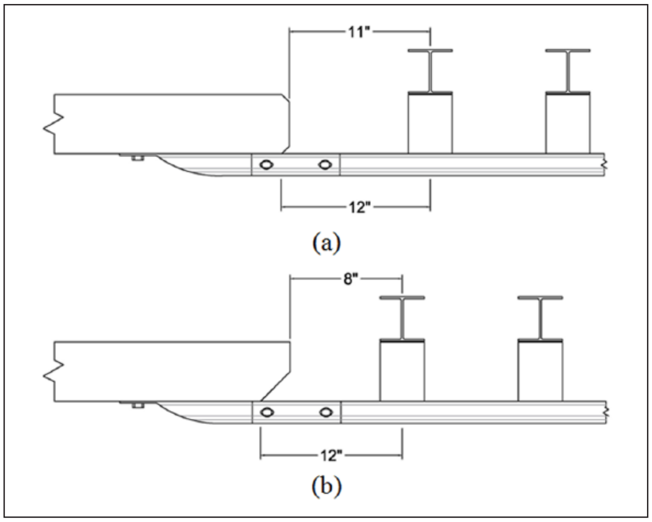


Figure 2. Buttress to transition offset: (*a*) original as-tested AGT and (*b*) AGT in combination with the standardized buttress.

Full-Scale Test AGTB-1

A full-scale crash test was conducted on the proposed standardized buttress in combination with a critical Thrie beam AGT according to MASH 3–21 criteria. The 2270P pickup truck impacted the AGT approximately 80½ in. upstream from the buttress to maximize the potential for vehicle snag on the upstream end of the buttress. The pickup was contained and redirected with moderate vehicle roll and pitch displacements of 27.3 degrees and 10.6 degrees, respectively. The maximum dynamic deflection of the Thrie beam guardrail and the support posts adjacent to the buttress was 6.0 inches. The left-front tire disengaged from the pickup as it contacted the buttress below the rail. The tire was pushed backward into the wheel well and toe pan area of the floor, causing a maximum occupant compartment deformation of 4¼ in., which was within the 9 in. MASH limit. A summary of the test results, including sequential photographs, is shown in Figure 4.

Occupant impact velocities (OIVs) and occupant ride-down accelerations (ORAs) were calculated from the on-board acceleration data. While the OIVs fell within MASH acceptable ranges, the longitudinal ORA value was −30.0 g, which exceeded the 20.49 g MASH limit. The longitudinal ORA was surprising, as longitudinal ORAs of this magnitude had not been previously observed in oblique angle crash tests, and there was no indication from the test video that vehicle decelerations were excessive. While there was some vehicle and tire snag on the tapered portions of the buttress, it did not appear to be significant

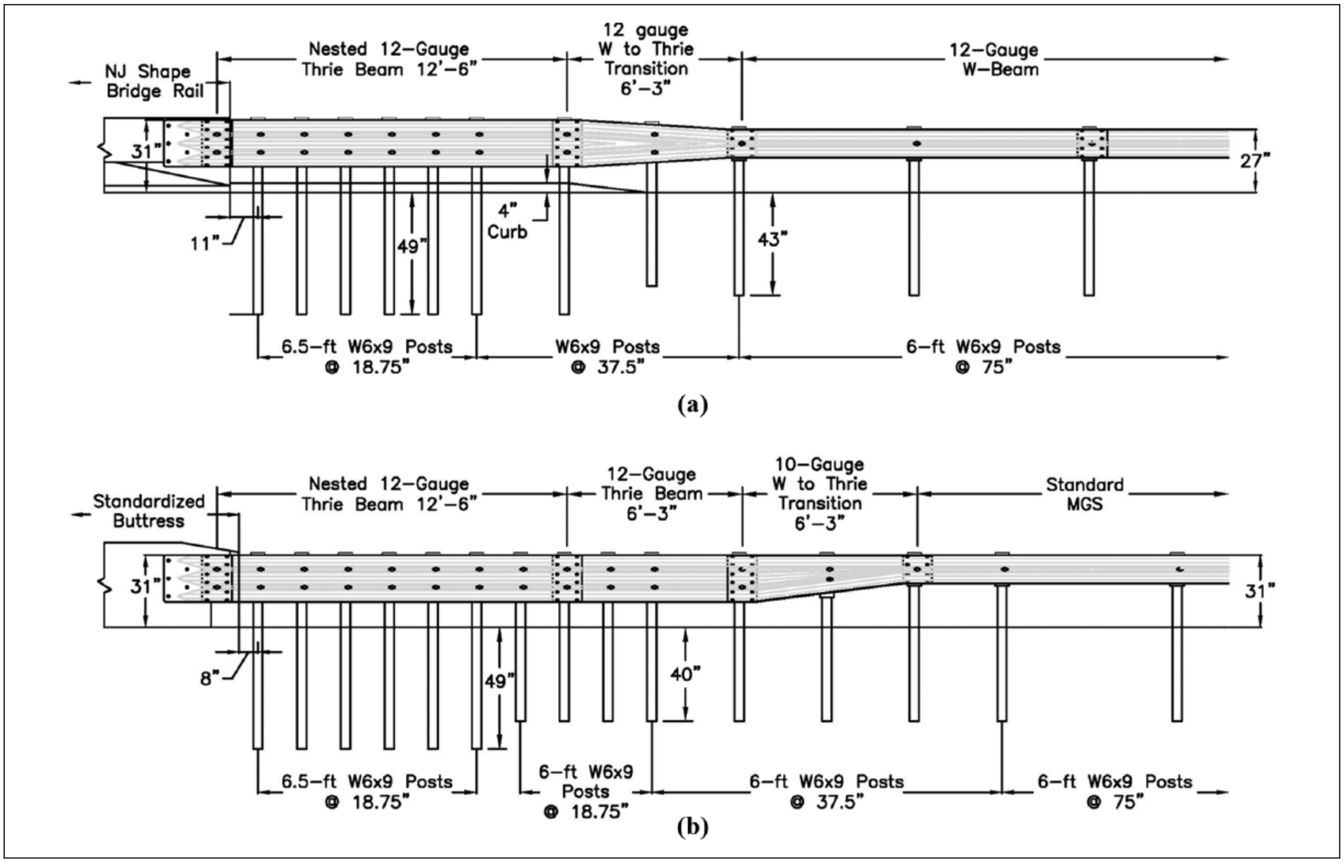


Figure 3. Selected AGT design: (*a*) original as-tested configuration and (*b*) critical configuration for evaluating the standardized buttress.

enough to cause accelerations of this magnitude. Review of the crash-tested vehicle revealed significant deformations to the floorpan and shifting of the seat frame. Unfortunately, the on-board data recorders were positioned on a mounting bracket which was attached to the seat frame. Thus, if the seat frame displaced during the test, the measured accelerations would apply only to the local acceleration of the seat frame and would not be representative of the vehicle as a whole. On-board video cameras showed significant and sudden movement of the seats beginning approximately 100 ms into the impact event, which occurred at the same time as the large deceleration spike in the data. In addition, there was an 18 g positive longitudinal acceleration spike following the −30 g spike, as shown in Figure 4, which corresponded to a 4.5 mph increase in vehicle velocity. Since the vehicle did not increase its velocity during redirection, this was further evidence that the acceleration data was compromised by the shifting seat frame. Thus, the accelerometer data was believed to be in error.

Although this large deceleration spike and resulting longitudinal ORA seemed unrealistic and was likely magnified by movement of the accelerometers relative to the vehicle, the actual ORA values for test AGTB-1 could not be obtained. Therefore, the test was determined to be a failure according to MASH evaluation criteria because of excessive longitudinal ORA. Complete details of the crash test can be found in Rosenbaugh et al. (*12*).

Buttress Redesign

After the failure experienced during test no. AGTB-1, the buttress was redesigned to reduce the amount of vehicle and tire snag. The dual taper design and reinforcement pattern of the buttress was maintained, but small changes were made to the tapers on the front edge of the buttress. To reduce the severity of tire snag below the rail, the slope of the lower taper was reduced from a 3:1 slope to a 4:1 slope. In addition, the lateral offset of the lower taper was increased by ½ in. to 4½ inches. The height of the lower taper increased to 14 in. to reduce the vehicle snag on the lower portion of the upper taper. The 14-in. height also corresponded to the height to the bottom of the transition blockout. Thus, the lower taper measured 4.5 in. deep × 18 in. long × 14 in. high.

High-speed video from test AGTB-1 showed that the pickup truck bumper and front corner were not at risk of impacting the front face of the buttress. However, a reduction to the slope of the taper may reduce snag on the taper itself. Thus, a small reduction in the lateral extent of the upper taper

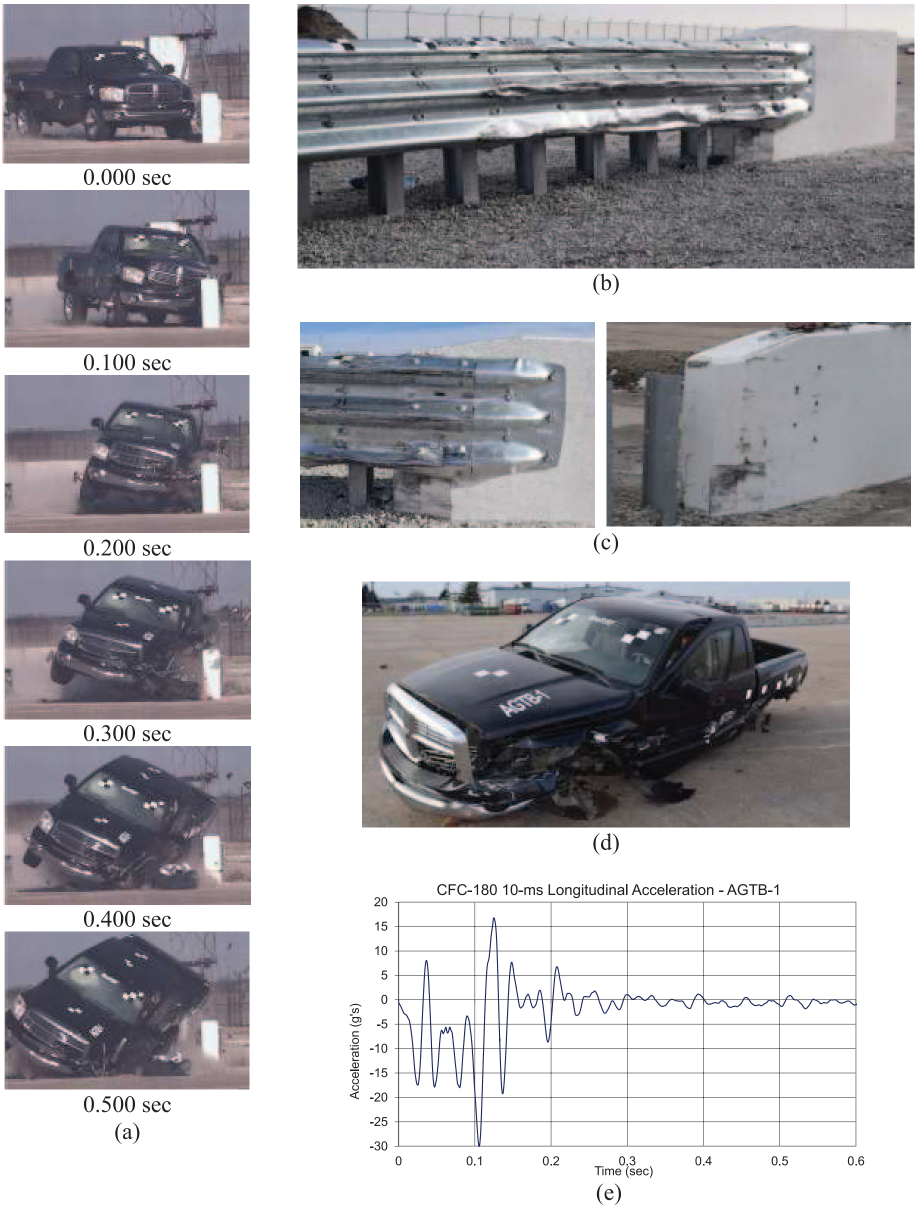


Figure 4. Test results from test AGTB-1: (*a*) sequential photos, (*b*) system damage, (*c*) AGT and buttress damage, (*d*) vehicle damage, and (*e*) longitudinal acceleration.

resulted in a 3 in. deep × 4 in. long chamfer. The final design for the standardized buttress is shown in Figure 5.

Full-Scale Crash Test AGTB-2

A second MASH 3–21 full-scale crash test was conducted on the redesigned standardized end buttress in combination with the critical AGT. The transition design and post-to-buttress offset distance remained the same from test AGTB-1, and only the geometry changes to the buttress were different. Photographs of the test installation for test AGTB-2 are shown in Figure 6.

The 2270P pickup truck impacted the AGT at 62.4 mph and a 25.4-degree impact angle approximately 86 in. upstream of the buttress to maximize the potential for vehicle snag on the buttress. The pickup was contained, redirected, and remained relatively stable throughout the impact event. The maximum deflection of the Thrie beam guardrail and the support posts adjacent to the buttress was 5.3 inches. The right-front tire extended under the rail and snagged on the lower taper of the buttress, which caused it to push backward into the wheel well and toe pan. However, occupant compartment deformations were all within the MASH limits. A

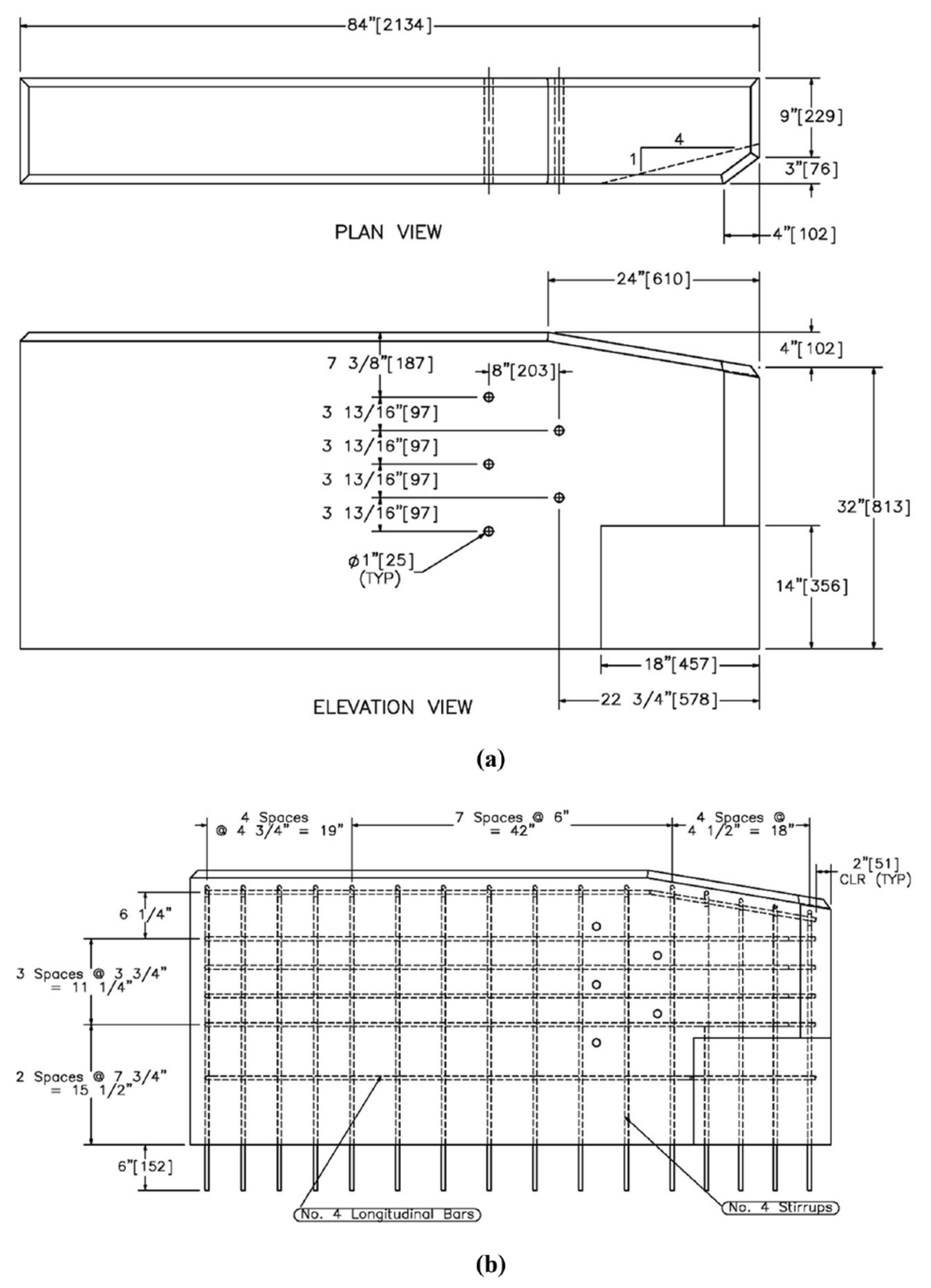


Figure 5. Final standardized buttress design with (*a*) exterior geometry and (*b*) reinforcing layout.

summary of the test results, including sequential photographs, is shown in Figure 7.

During the test, the windshield had shattered and deformed a maximum of 4⅛ inches. However, high-speed video showed the windshield was damaged as a result of airbag deployment, not from interaction with the barrier. Airbags have been shown to shatter, and even tear, windshields in previous oblique angle impacts (*25*). Similar to the previous

(a)

(b)

(c)

(d)

Figure 6. Test installation photographs: (*a*) layout, (*b*) buttress connection, (*c*) buttress overhead, and (*d*) adjacent posts.

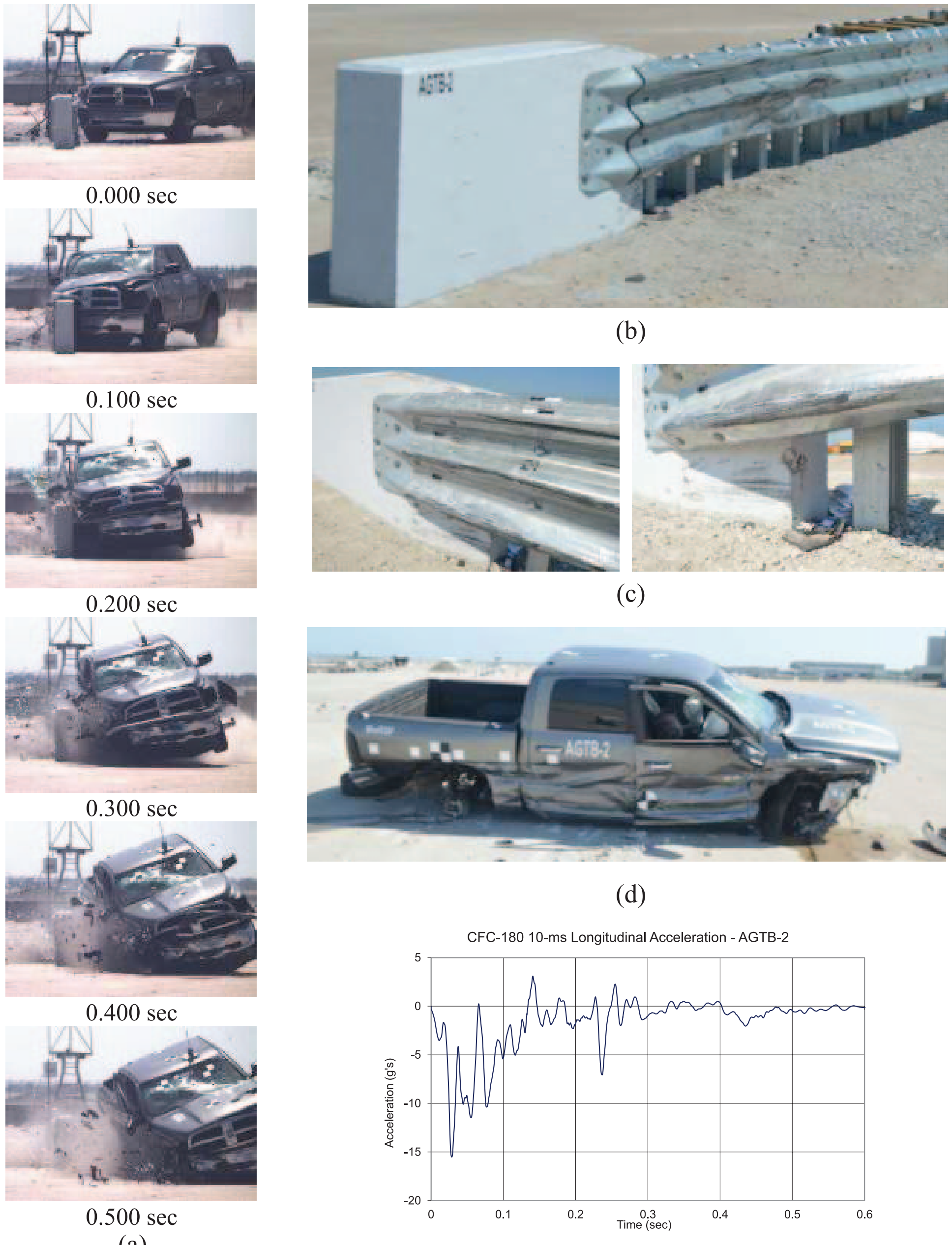
tests, the windshield was not considered in the evaluation of test no. AGTB-2 because the windshield damage was not caused by interaction with the barrier system.

Lateral and longitudinal OIVs and ORA were calculated from the on-board accelerometers, and all values satisfied the MASH limits. The longitudinal ORA value was −7.1 g, showing a significantly reduced value than compared with test AGTB-1. Therefore, the standardized concrete buttress satisfied the evaluation criteria of MASH test 3–21. Complete details of the crash test can be found in Rosenbaugh et al. (*12*).

A comparison of the test results from both full-scale tests is shown in Table 1. In general, the OIV and ORA values recorded for AGTB-2 were lower than those observed during AGTB-1. Although the ORAs during test AGTB-1 may have occurred after the seat frame began shifting, the OIVs would have been calculated prior to the seat frame shifting. In addition, both the vehicle roll and pitch angular displacements were reduced during AGTB-2. Thus, the redesigned buttress may have resulted in reduced snag and increased stability.

Conclusions, Recommendations, and Implementation Guidance

A standardized concrete buttress was developed and successfully crash tested to MASH test 3–21 safety performance criteria. MASH test 3–20 with the small car was not considered critical since the lighter weight vehicle would result in reduced rail deflections and a reduced risk of snag on the buttress. A MASH 3–20 test was conducted on a different



(a)

(b)

(c)

(d)

(e)

Figure 7. Test results from test AGTB-2: (*a*) sequential photos, (*b*) system damage, (*c*) AGT and buttress damage, (*d*) vehicle damage, and (e) longitudinal acceleration.

transition system incorporating a similar version of the standardized buttress (*26*). This AGT utilized a top rail height of 34 in., or 3 in. higher than standard transitions. Thus, there was an increased risk of the small car extending under the rail and snagging on the buttress. The 34 in. tall transition was attached to the buttress design developed here, except the buttress height and the height of the taper transition point were each increased 3 in. The full-scale crash test results on this increased height AGT satisfied MASH 3–20 evaluation criteria. Since the standard 31-in. lower rail height would reduce the risk of small car snag, the test on a 34 in. tall AGT reinforced the idea that the small car test was not critical. Therefore, the standardized transition buttress was considered to be a MASH crashworthy device.

The standardized buttress was developed to be compatible with a wide variety of Thrie beam AGT systems, both with and without a curb. As part of its evaluation, it was crash tested in combination with a critically weak approach

Table 1. Test Results from Tests AGTB-1 and AGTB-2 (*12*)

Test criteria	Test AGTB-1	Test AGTB-2	MASH limit
Impact speed	61.9 mph	62.4 mph	na
Impact angle	24.4°	25.4°	na
Maximum dynamic deflection	6.0 in.	5.3 in.	na
Maximum vehicle roll	27.3°	21.2°	75°
Maximum vehicle pitch	10.6°	6.3°	75°
OIV:			
Lateral	27.7 ft/s	24.6 ft/s	≤40 ft/s
Longitudinal	22.7 ft/s	20.3 ft/s	≤40 ft/s
ORA:			
Lateral	−10.0 g's	−10.4 g's	≤20.49 g's
Longitudinal	−30.0 g's	−7.1 g's	≤20.49 g's
Occupant compartment crush:			
Wheel well & toe pan	4¼ in.	6⅜ in.	≤9 in.
Floor pan	3⅜ in.	4 in.	≤12 in.
Side front panel	3¾ in.	6¾ in.	≤12 in.
Side door (below seat)	3 in.	2 in.	≤12 in.
Side door (above seat)	3⅞ in.	4¼ in.	≤9 in.

Note: na = not applicable.

guardrail transition without a curb. This worst-case scenario posed the greatest risk for snag on the upstream end of the buttress. Since the buttress proved crashworthy in this critical configuration, the standardized buttress should remain crashworthy when utilized with other AGTs as the stiffer systems would only reduce vehicle snag. Therefore, the standardized buttress can be used in combination with any Thrie beam AGT system that has previously been successfully tested to either NCHRP Report 350 or MASH criteria. These AGTs may be either ¼-post or ½-post spacings (i.e., 18¾-in. and 37½-in. post spacings). Further, since the standardized buttress was tested without a curb, and curbs tend to reduce tire snag, the standardized buttress can be utilized with these AGTs in either a curbed or non-curbed installation.

For the successful attachment of various AGTs to the standardized transition buttress, the same post, blockout, and rail components from the original as-tested AGT design should be utilized within the transition region. Thus, the post size, post embedment depth, post spacing, blockouts, rail thickness, rail height, and rail segment lengths should not be altered when the standardized buttress is utilized within other AGT designs. However, the offset between the buttress and the first transition post may vary. The unsupported span length of the rail, which is measured from the location where the rail is no longer laterally supported by the buttress to the centerline of the adjacent post, should remain the same as the original as-tested AGT so that the stiffness of the transition is not affected. Examples of this distance are shown in Figure 8. Because the unsupported span length varies with the flares, tapers, and post spacings utilized among various AGT designs, the offset distance from the standardized buttress to the first transition post will vary. Subsequently, the location of the Thrie beam terminal connector attachment bolts will also vary.

Until recently, most AGTs were only evaluated and crash tested near the connection between the rail and the rigid parapet. However, more recent testing has highlighted the critical nature of the upstream stiffness transition between W-beam guardrail and the stiffened Thrie beam AGT. New AGT installations should utilize a crashworthy upstream stiffness transition even if they were not originally developed with one. For installations transitioning from MGS to the standardized buttress, it is recommended to utilize the MGS stiffness transition on the upstream end of the AGT, as was done here with the Iowa AGT. Details on how to incorporate the MGS stiffness transition into a Thrie beam AGT can be found in previous reports and papers (8,9,*23,24,27*).

The standardized transition buttress was developed with a vertical face to optimize vehicle stability during impacts. However, the adjacent bridge rail or concrete parapet may not have the same geometry. Thus, the downstream end of the buttress must contain a shape transition aligned with the adjacent bridge rail or concrete parapet. Shape transitions should be gradual to prevent vehicle instabilities. Based on previous simulation efforts, transitions to the face geometry of a rigid barrier incorporating lateral slopes steeper than 10:1 may cause stability issues (*28*). Thus, it is recommended to utilize a maximum 10:1 lateral slope to transition the shape of the standardized buttress, and shape transitions may begin 6 in. downstream of the Thrie beam terminal connector, or 8 in. downstream of the attachment bolts. For drastic shape changes, the length of the buttress may need to be extended beyond its 7 ft minimum length.

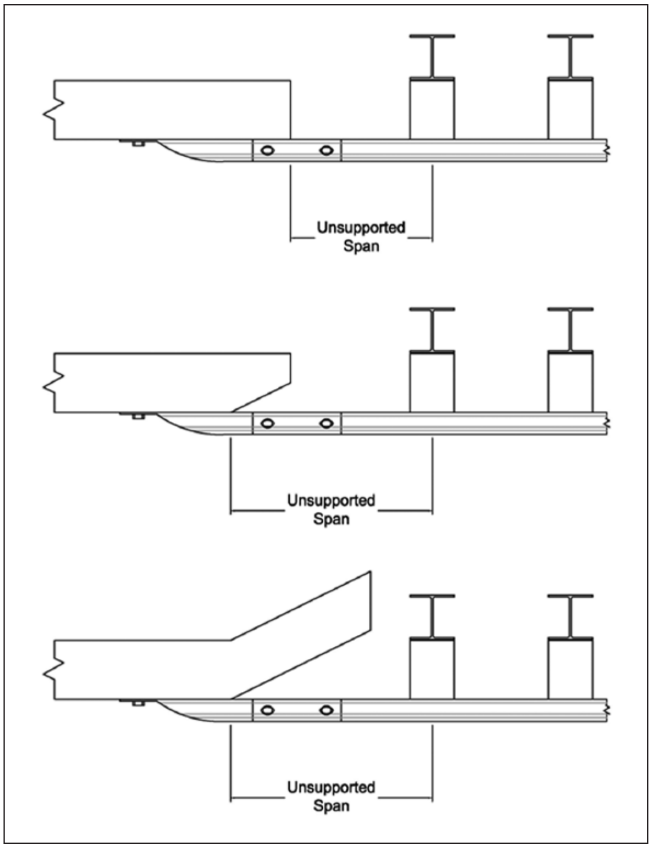


Figure 8. Examples of unsupported span lengths for various AGT configurations.

Height transitions may be necessary for attachment to taller bridge rails and concrete parapets. The upstream end of the buttress was successfully tested with a vertical taper of 4 in. over a 24-in. length. This vertical slope on the upstream end may be continued upward with the same 6:1 slope until the desired height is reached. Note, this is a steeper slope than the previous 8:1 vertical slope guidance stemming from previous testing (*29*). Finally, if the adjacent bridge rail or parapet is only 32 in. tall, the entire buttress can be installed with a constant 32 in. top height. Further implementation guidance can be found in Rosenbaugh et al. (*12*).

Acknowledgments

The authors wish to acknowledge several sources that made a contribution to this project: (1) the State DOTs comprising the Midwest States Pooled Fund for sponsoring and guiding the research project and (2) MwRSF personnel for constructing the test installations and conducting the crash tests.

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The Standing Committee on Roadside Safety Design peer-reviewed this paper (18-05386).