Crash Tests of Box-Beam Upgradings for Discontinuous-Panel Bridge Railing

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A 6- by 6- by 3/16-in box-beam guiderail upgrading for discontinuous-panel bridge railings was tested to develop a system for safe redirection of 4500-lb cars impacting at 60 mph and 25°. After several design changes and seven crash tests, the system consists of a single box beam blocked out from the existing railing on the bridge and a double box-beam approach guiderail that has the upper rail blocked out from the S3x5.7 posts. This system will provide a safe, economical, and relatively easy-to-maintain upgrading for discontinuous-panel bridge rails.

Through the early 1960s, New York State's standard bridge rail consisted of short panels (up to about 20 ft long) that did not have connections between adjacent panels. These railings, designed to meet American Association of State Highway Officials (AASHO) specifications (1), included three or four thin-wall steel-tube rails supported by three posts connected to the bridge deck by heavy anchor plates and bolts. However, impact tests conducted in the mid-1960s (2) resulted in high decelerations and dangerous vehicle reactions. When subjected to a severe impact, a railing panel could deflect, which allowed the vehicle to snag on the end of the adjacent panel. The highest 50-ms average deceleration recorded was 22 g. As a result of that research, discontinuous-panel bridge railings were eliminated from state design standards for future installations.

Although these railings have not been erected for more than 13 years, many remain in service throughout the state. The Structures Design and Construction Division of the New York State Department of Transportation is now upgrading structures where these rails were installed. Because complete statewide replacement of these railing systems is not economically feasible, other less-costly solutions were needed. Efforts thus were directed toward modifications to improve the existing railings.

One suggested design to upgrade performance was to attach a continuous 6- by 6- by 3/16-in box-beam guiderail to the existing bridge rail and splice it to the approach guiderail at either end of the bridge. Blocked out from the face of the bridge rail, the box beam is intended to limit deflections of the existing rail by distributing the load over more than one panel and to equalize deflections across the joints, thus preventing vehicles from snagging on the ends of panels. Such a system would make use of existing approach box-beam guiderail without any special transitions or anchorages. It would require a minimum of new hardware, which is a substantial benefit from the standpoint of both initial cost and maintenance inventory requirements. More important, a successful upgrading system would save the cost of replacing much of the discontinuous-panel bridge rail now in service in New York State.

METHODOLOGY AND DESCRIPTION OF BARRIERS

This study consisted of seven full-scale crash tests to determine the performance of box-beam guiderail upgradings for discontinuous-panel bridge rail. [More information about these tests is presented elsewhere (3).] Testing details were taken from National Cooperative Highway Research Program (NCHRP) Report 153 (4) and its successor, Transportation Research Board (TRB) Research Circular 191 (5). All seven tests were standard strength tests and used target impact conditions of 4500-lb vehicles at 60 mph and 25°. Because of test site limitations, the inclusion of 15° tests with 2250-lb vehicles would have required construction of a second simulated bridge deck at considerable additional cost and long delays in the test program. Based on the excellent results achieved in the large-vehicle tests, it was decided that the delay and cost of performing the 15°, 2250-lb tests were not justified. Two additional factors supported that decision. First, about 75 installations of this upgrading system have been completed, and no unsatisfactory collisions by small vehicles have been recorded. Second, the final configurations of the railing system provided a 12-in blockout from the bridge-rail posts and a dual rail in the transition to eliminate any potential for snagging or wheel entrapments of small vehicles. Sufficient clearance from the posts and an absence of vertical projections or rail faces that may be climbed by the front wheel have both been shown to be important to prevent wheel snag and high roll potential (6,7).

The box-beam upgrading consists of a 6- by 6- by 3/16-in box-beam guiderail mounted in front of the existing railing at a height of 27 in above the pavement. Tubular steel blockouts (6x8x0.25 in), which vary in depth from 6.75 to 11 in, were used at each bridge-rail post. A 3-ft-deep, 3-ft-wide concrete footing was used to anchor the bridge rail for these tests, which protruded above grade 10 in for the first test and 6 in for the others, to simulate a curb and safety walk.

Because field experience with discontinuous bridge rail had shown the anchor bolt and deck details on actual bridges to be adequate for severe impacts, it was not necessary to duplicate an actual deck for these tests. Instead, an asphalt pavement was placed adjacent to the curb to simulate the deck. A firmly anchored timber curb, which was the same height as the concrete curb, was used to simulate the granite curb normally used on bridge approaches. The approach guiderail was a 6- by 6- by 3/16-in box beam mounted 30 in high on S3x5.7 posts driven into compacted granular fill on 6-ft centers. The last 18-ft section of the box beam upstream of the bridge was tapered down to 27 in in height to meet the upgrading elevation.

The first design, shown in Figure 1, was impacted on the bridge. Upstream of the bridge the 6-ft post spacing was closed to 3 ft (8 spaces) and 2 ft (4 spaces), and the last S3x5.7 post was 4 ft from the first bridge-rail post. On the bridge the box beam was connected to each 5x5x0.75x8-in-long support angle with one 3/4- by 8-in long bolt. A support angle was welded to each 11-in-high blockout, which was then bolted to the bridge-rail post by using four 3/4- by 7-in long bolts. Two 4x8x0.625-in backup plates were used at each post. The approach guiderail was a standard box beam that had standard post-to-rail connections: 3/8- by 7-in long A325 bolts. Post-to-rail connections were provided every 6 ft, starting 6 ft from the bridge, and the remaining posts in the transition were unconnected back-up posts.

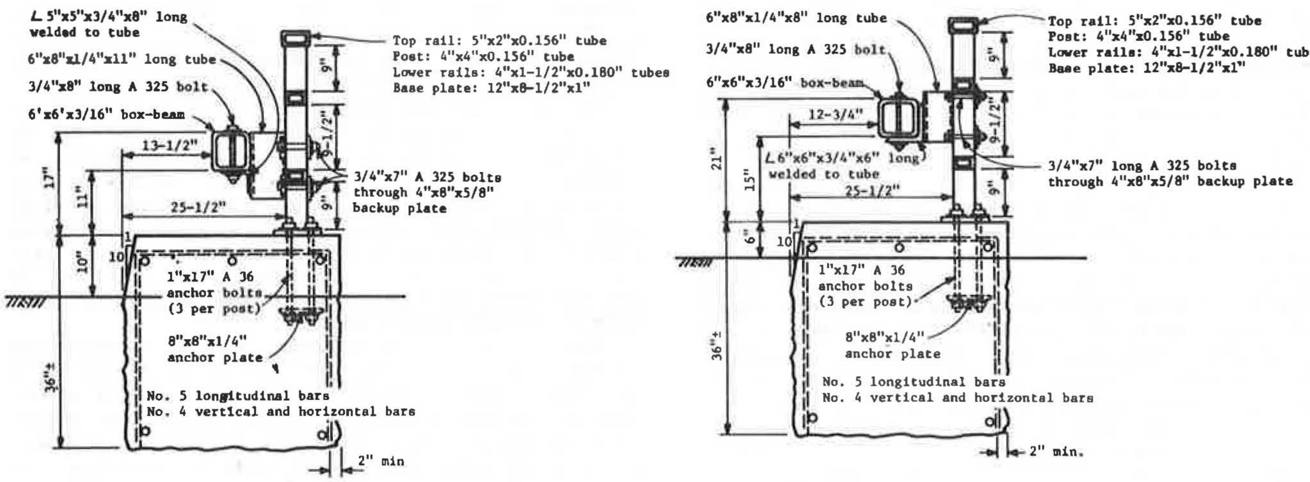
A second design with a modified blockout and support-angle configuration is also shown in Figure 1. It was tested three times--twice with impact on the bridge and once with impact on the approach rail. The first two of these tests were standard strength tests, and a low impact speed on the first required retest. The third test, which impacted 10 ft upstream of the first bridge-rail post, was a standard strength test of the transition.

Following unsatisfactory performance in the transition test, the design was revised as shown in Figure 1. Five W6x8.5 posts with 8-in-wide, 6-in-high blockouts were set on 3-ft centers upstream of the bridge. The 6- by 6- by 3/16-in box-beam guiderail was bolted to the blockouts by using two 3/4- by 7-in long A325 carriage bolts. The blockouts were connected to the W6x8.5 posts by using two 3/4- by 1-1/2-in long A325 bolts. Because of a snag that occurred in the first transition test, the support angle was removed from the first bridge-rail blockout and replaced by two 3/4- by 7-in-long A307 carriage bolts and a 0.75-in spacer plate. All of the remaining blockouts on the bridge rail remained unchanged from the previous tests.

After the successful performance of this design with impact at the center of the W6x8.5 post configuration, the system was impacted upstream of the first W6x8.5 post to determine the redirective characteristics of the secondary transition from light to heavy posts. Because that transition performed poorly, a third and final transition design was prepared for the final test. That design, shown in Figure 2, includes a second 6- by 6- by 3/16-in box beam installed below the primary rail. The latter is blocked out from the bridge posts and the S3x5.7 approach posts for the entire length of the second rail. The second rail is connected to the posts by using standard guiderail connections, and the primary rail is fastened to the 6x8x0.25-in blockouts by using one 3/4- by 7-in-long A307 carriage bolt. The blockouts are connected to the posts by using one 5/16- by 1-1/2-in-long A307 bolt. Upstream of the beginning of the lower rail, the primary rail is mounted by using the standard guiderail connection.

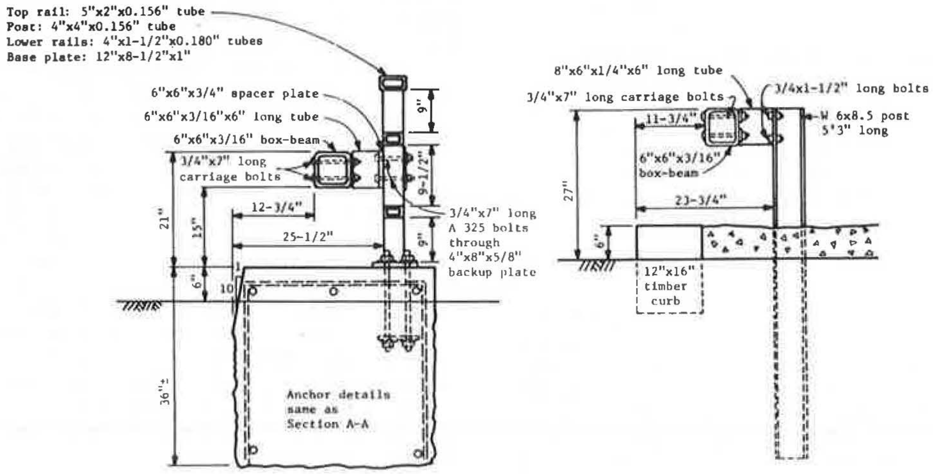
Seven full-scale crash tests of the box-beam upgrading system are summarized in Table 1. For all seven tests, target impact conditions were 4500 lb,

Figure 1. Details of bridge-rail upgrading and guiderail evaluated in tests 19-21B.


First Design (Test 19)

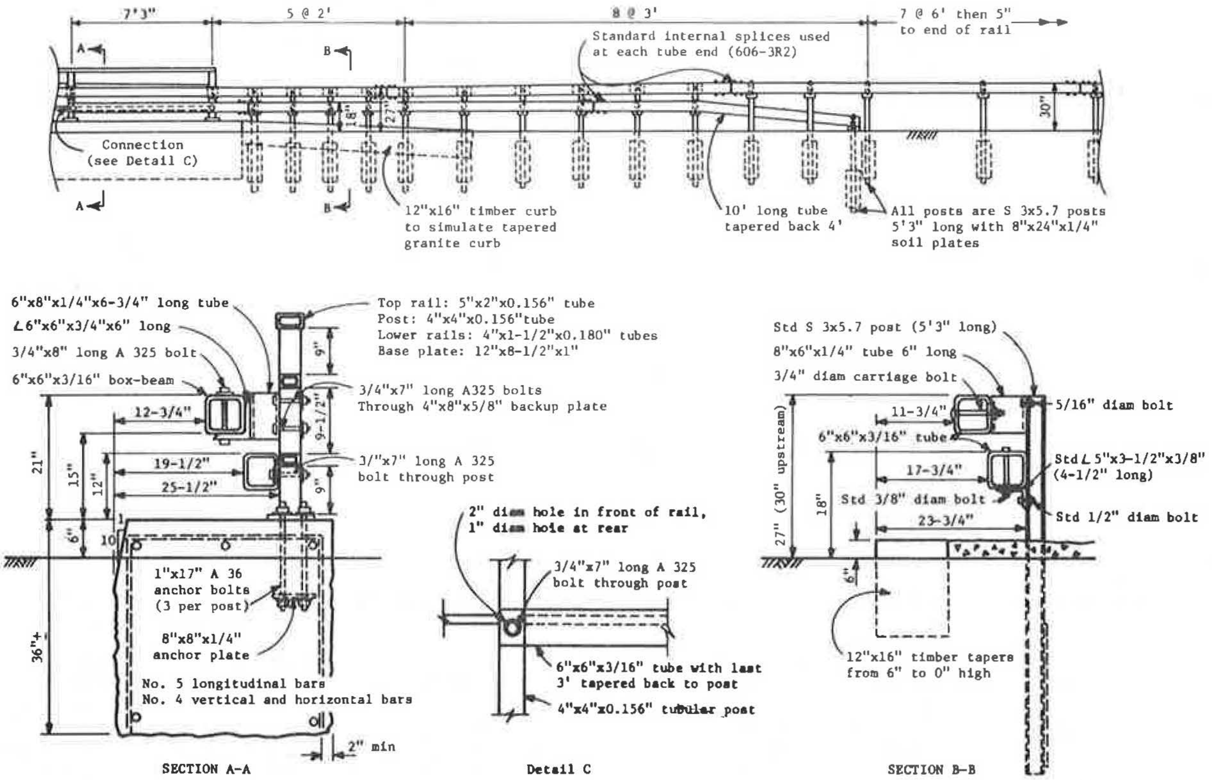
Second Design (Tests 20, 20A, 21)

Third Design (Tests 21A, 21B)


(First Bridge Post)

(Approach)

Figure 2. Final design (test 28).



60 mph, and 25°, although actual impact conditions varied somewhat.

IMPACTS ON BRIDGE

For the first test (test 19), a 4010-lb sedan impacted the upgrading at 48.7 mph and 25°, 5 ft downstream from the first bridge-rail post. Impact occurred on the right front wheel and fender. The car was in contact with the 10-in-high curb for 22 ft and the rail assembly for 7 ft and had a maximum dynamic barrier deflection of 0.1 ft. The car traveled about 125 ft along an exit trajectory of 11° before stopping. The highest 50-ms longitudinal deceleration was 2.4 g, but the lateral deceleration was lost due to equipment malfunction.

Vehicle damage was limited to the front bumper, fender, hood, right-side front door, and the right front tire and wheel. There was no permanent rail deflection and no structural damage to either the curb or the rail. Only minor scrapes and paint marks were observed on the rail. Vehicle redirection was accomplished primarily by impact of the wheel and front frame assembly on the curb. Inspection of the crashed car showed that sheet-metal damage, which occurred during contact with the rail, was superficial and none was driven back into the structural members.

Several design changes were made before the next test. As described previously, the blockout and support-angle configurations and sizes were changed, and the 10-in curb height was reduced to 6 in. The latter is more representative of existing installations (where resurfacing has resulted in a similar height reduction) and provides a more severe test of the railing because less of the impact is absorbed by the lowered curb.

For the second test (test 20), a 4540-lb station wagon impacted the upgrading at 48.7 mph and 27°, 2 ft downstream of the first bridge-rail post. Impact was on the right front fender and wheel. The car was in contact with the 6-in curb for 30 ft and with the rail for 18 ft. Maximum dynamic deflection was 1.1 ft. On impact, the car was redirected smoothly and did not begin to roll or pitch until it was exiting the rail. After leaving the curb, the car traveled about 100 ft along a 12° exit trajectory before stopping. The highest 50-ms decelerations were 7.0 g longitudinal and 4.2 g lateral. Vehicle damage included a bent bumper, grill, right-side sheet metal, sprung hood, broken radiator, and flattened right-side tires. Two sections of the box beam were bent and the first bridge-rail section was deflected back 0.4 ft at the top because all three posts separated from their base plates at the welds. The blockouts on the first and third bridge-rail posts were bent and slightly deformed, and the one on the second post was twisted and partly crushed. Maximum permanent deflection was 0.5 ft.

Because impact speed in test 20 was significantly below 60 mph, it was repeated. For test 20A, a 4420-lb sedan impacted the upgrading at 56.8 mph and 25°, 5 ft downstream of the first bridge-rail post. Impact was on the right front bumper, fender, and wheel. The car was in contact with the curb for 20 ft and the rail for 12 ft. Maximum dynamic barrier deflection was 0.5 ft. After leaving the barrier, the vehicle traveled along a 12° exit trajectory for about 125 ft. The highest 50-ms decelerations were 8.7 g longitudinal and 3.8 g lateral.

Vehicle damage was similar to that incurred in the two previous tests: bent bumper, grill, and right-side sheet metal; flattened right-side tires; and a sprung hood. Two box-beam sections were damaged and the first three bridge-rail posts were deflected back 2.5 in because the 1-in-thick base

Table 1. Results of full-scale crash tests.

Item	Test 19: Single Rail on 11-in Blockouts	Test 20: Single Rail on 6.75-in Blockouts	Test 20A: Single Rail on 6.75-in Blockouts	Test 21: Single Rail on S3x5.7 Posts	Test 21A: Single Rail on W6x8.5 Posts	Test 21B: Single Rail on W6x8.5 and S3x5.7 Posts	Test 28: Double Rail on S3x5.7 Posts
Point of impact	5 ft onto bridge	2 ft onto bridge	5 ft onto bridge	10 ft before bridge	10 ft before bridge	10 ft before first W6x8.5	10 ft before bridge
Vehicle weight (lb)	4010	4540	4420	4500	4540	4500	4700
Vehicle speed (mph)	48.7	48.7	56.8	60.9	58.8	55.0	56.8
Impact angle (°)	25	27	27	25	25	25	25
Exit angle (°)	11	12	12	12	6	3	10
Maximum roll (°)	-9	-10	-5	-14	-5	-18	+2
Maximum pitch (°)	+11	+5	+3	+10	0	+8	+3
Maximum yaw (°)	+10	0	-6	-10	-6	-45	0
Contact distance[a] (ft)	22/7	30/18	20/12	29/22	29/24	13[b]	20/20
Contact time (ms)	389	304	214	476	340	170	260
Deflection (ft)							
Dynamic	0.1	1.1	0.5	2.0	0.5	2.0	1.5
Permanent	0.0	0.5	0.3	1.3	0.4	1.3	0.8
Deceleration (*g*)							
50-ms avg							
Longitudinal	2.4	7.0	8.7	NA	NA	7.0	6.0
Lateral	NA	4.2	3.8	NA	NA	5.6	9.0
Maximum peak							
Longitudinal	10.0	21.0	21.0	NA	NA	26.0	10.0
Lateral	NA	7.8	7.4	NA	NA	16.9	14.1
Avg continuous							
Longitudinal	0.4	3.0	3.8	NA	NA	5.0	2.5
Lateral	NA	1.3	0.9	NA	NA	2.0	3.9
Vehicle	1974 Matador sedan	1973 Plymouth wagon	1970 Dodge sedan	1968 Buick sedan	1968 Dodge sedan	1970 Mercury sedan	1969 Cadillac sedan
Damage							
TAD	RFQ-4	RFQ-4	RFQ-6	RFQ-7	RFQ-4	RFQ-6	RFQ-5
SAE	01RYEW6	01RDEW9	01RDEW9	01RDEW9	01RDEW9	01RDAW9	01RYAW6
Results and comments	11-in blockouts and 10-in curb; good redirection, speed too low	Same as test 19 with modified blockouts and lower curb; good redirection, speed too low	Same as test 20 at higher speed; good redirection, good decelerations	Transition test on light-post approach rail; vehicle snagged on first rail post	Transition test on heavy-post approach rail; good redirection even through transition	Transition test on heavy- and light-post approach rail; vehicle snagged on first two W6x8.5 posts	Transition test on light-post approach rail; good redirection, good deceleration

Note: NA = not available, TAD = Traffic Accident Data Project, and SAE = Society of Automotive Engineers.

[a] First distance is on curb, second on rail.

[b] No curb, rail only.

plates were bowed upward. The first four blockouts were bent from 0.25 to 0.75 in and the maximum permanent barrier deflection at the face of the box beam was 0.3 ft.

Based on this test, it appears that the box-beam upgrading has adequate strength to withstand standard strength test impacts (4500 lb, 60 mph, and 25°) on the bridge rail.

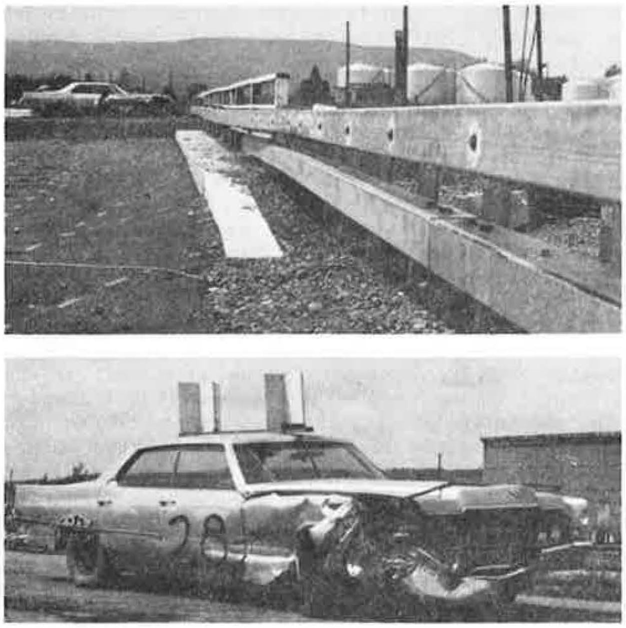
TRANSITION TESTS

The guiderail approach transition was tested next. In the first of these tests (test 21), a 4500-lb car impacted at 60.9 mph and 25°, 10 ft upstream of the first bridge-rail post. Impact was on the right front fender, bumper, and wheel. The car was in contact with the curb for 29 ft and the rail for 22 ft. The maximum dynamic deflection for both the guiderail and the upgrading was 2.0 ft at the first bridge-rail post. Vehicle redirection was smooth until 5 ft after impact when the 3/4-in vertical bolt at the first blockout broke, which allowed the box beam to rise as the car rolled -14°. As the front of the vehicle left the upgrading, the right rear wheel caught the first bridge-rail post and 0.75-in support angle and spun out to the left. Maximum permanent rail deflection was 1.3 ft at the first bridge-rail post. After losing contact with the barrier, the car traveled along a 12° trajectory about 100 ft more, spinning sharply to the right because of severe damage to the right front suspension and sheet metal. Decelerations were not available because of equipment malfunction, but this loss of data is not significant here because the snag and poor redirection after leaving the rail make this design unacceptable.

The vehicle suffered extensive sheet-metal and structural damage to the entire front end and right side. The right rear wheel was torn from the frame, and the hood tore loose and broke the windshield but did not penetrate into the passenger compartment. Approach-rail damage included two bent box-beam sections, six S3x5.7 posts bent over from 4 in to nearly flat to the ground, and three posts pushed through the soil 2-4 in. The first bridge-rail section was bent and twisted, and the first two bridge-rail posts failed at the base-plate welds after the plates bowed. The first blockout was crushed and the support angles on the second and third were bent. The maximum permanent deflection of the box-beam guiderail was 1.3 ft about 5 ft upstream of the bridge rail. The maximum permanent deflection, measured to the top of the bridge rail at the first post, was 0.9 ft.

Because of the snagging and subsequent poor redirection experienced in test 21, the approach guiderail system was stiffened, as described previously, by adding heavy posts just upstream of the bridge. For test 21A, a 4540-lb sedan impacted the approach rail at 58.8 mph and 25°, 10 ft upstream of the first bridge-rail post. Impact was on the right front fender and wheel. The car was in contact with the curb for 29 ft and the rail for 24 ft. Maximum dynamic deflection was 0.5 ft on the guiderail, 6 ft upstream of the first bridge-rail post. Vehicle redirection was very smooth and vehicle reactions during impact were very slight. After losing contact with the rail, the car continued another 100 ft

Figure 3. Barrier and vehicle damage resulting from test 28.



along a 6° exit trajectory. Deceleration data were again lost due to equipment malfunction, but the observed vehicle reactions indicate that this was a gentle redirection.

Vehicle damage was moderate and typical. It included bent bumper and grill, a crumpled right front fender, right-side sheet-metal damage, and a flattened right front tire. Damage to the upgrading was also moderate. One section of the 6x6-in box beam was bent, and all five W6x8.5 posts were pushed through the soil from 3 to 6 in, but none were bent. The first three bridge-rail posts were deflected from 0.50 to 3.50 in, and the modified blockout on the first bridge-rail post was crushed 0.25 ft. The maximum permanent deflections were 0.4 ft on the guiderail (about 6 ft upstream of the first bridge-rail post) and 0.3 ft at the top of the bridge rail at the first post.

Based on the previous tests, it appears that both the upgrading and stiffened approach rail have adequate strength to withstand standard impacts and smoothly redirect impacting vehicles with acceptable decelerations. Inclusion of the W6x8.5 posts in the transition design, however, introduces a secondary transition upstream of the bridge where the post type changes from S3x5.7. This transition area was tested next.

For test 21B, impact was to occur upstream of the first W6x8.5 post. It was therefore necessary to locate the rail in front of the existing bridge-rail footing and simulate a bridge rail by stiffening the box beam downstream of the approach rail. The test was performed with neither bridge rail nor footing because those areas were outside the impact zone.

A 4500-lb sedan impacted the guiderail at 55.0 mph and 25°, 10 ft upstream of the first W6x8.5 post, i.e., 24 ft upstream of what should have been the first bridge-rail post. Impact occurred on the right front fender and front bumper. The car was in contact with the rail for 13 ft and had a maximum dynamic deflection of 2.0 ft. Vehicle redirection was quick but smooth for the first 10 ft, but on contacting the first W6x8.5 post, the right front suspension and wheel snagged and the rear of the car spun sharply to the left. On initial impact, the 6x6-in box beam began to slice into the sheet metal of the right front fender and, by the time the car reached the heavy post, the fender was twisted and hooked over the top of the box beam.

Because of this intrusion of the rail into the car, the 6-in blockout on the heavy post was not wide enough to prevent snagging. A second snag, which was less severe than the first, occurred at the second W6x8.5 post, and the vehicle was wrenched free of the box beam. The car slid free of the rail as it yawed to the right. It recontacted the rail and came to rest 48 ft after leaving the rail.

The maximum 50-ms average decelerations were 7.0 g longitudinal and 5.6 g lateral, but deceleration spikes of 26.0 g longitudinal and 16.9 g lateral were observed as the car impacted the W6x8.5 posts. Vehicle damage was severe and extensive. The hood, front end, and right-side sheet metal were crumpled; the engine compartment was deeply penetrated; and the frame was bent. Also, the right front suspension was broken and twisted and the right-side tires flattened. On the barrier, three sections of rail were badly bent--two bent both back and up, six S3x5.7 posts were bent and/or twisted at ground level, and two W6x8.5 posts were bent over and their blockouts crushed. The maximum permanent deflection was 1.3 ft, 5 ft downstream from the impact.

After analysis of the results of the previous six tests, the entire approach-rail segment of the upgrading was redesigned by the Structures Design and Construction Division. This new design added a second 6- by 6- by 3/16-in box-beam rail in the transition to strengthen the rail upstream of the bridge and to prevent contact with the S3x5.7 guiderail posts and the first bridge posts. By doubling the rail strength, it was possible to eliminate the stronger W6x8.5 posts.

For the final test (test 28), the double-rail system was impacted by a 4700-lb car at 56.8 mph and 25°, 10 ft upstream of the first bridge-rail post. Impact occurred on the right front fender and right edge of the front bumper, and the car remained in contact with the rail for 20 ft and had a maximum dynamic deflection of 1.5 ft. The vehicle redirected quickly and smoothly, the transition onto the bridge was without any adverse reaction, and the car exited along a 10° trajectory. Maximum roll was only +2°, maximum pitch was +3°, and there was no yaw until after loss of contact when the right front suspension damage caused the car to turn to the right as it came to a stop some 125 ft after impact. The maximum 50-ms average decelerations were 6.0 g longitudinal and 9.0 g lateral.

Vehicle damage was moderate; the bumper, grill, and right front fender and suspension were crushed and bent and there were dents in the right-side doors and right rear fender. The right front suspension was broken and the tire flattened; the vehicle could not have been driven from the scene. Barrier damage was limited to eight displaced posts (only one was bent 0.25 in) and two bent rail sections at the upper rail splice in the vicinity of impact (one blockout was crushed 2 in and one base plate was bowed 0.50 in), both on the first bridge-rail post. The maximum permanent deflection was 0.8 ft about 7 ft downstream of the impact point. Vehicle and barrier damage resulting from this test is shown in Figure 3.

DISCUSSION AND FINDINGS

The seven tests performed in this study were standard strength tests for longitudinal barriers with target impact conditions of 4500 lb, 60 mph, and 25°. Impact speeds in the first two tests on the bridge were low (49 mph in each test) but, in the third test, the higher speed (57 mph), the very smooth vehicle redirection, and the very moderate rail damage confirm that this upgrading satisfies the standard strength test criteria. Vehicle trajectory hazards were minimal in all three tests and had exit angles between 11° and 12°. Vehicle decelerations (50-ms average) were all below the values specified for 15° impacts.

The first guiderail and bridge-rail transition that used S3x5.7 posts and one box-beam rail performed poorly and had two specific problems. First, the lateral strength of the approach guiderail was significantly less than that of the bridge rail, which resulted in partial pocketing as the vehicle approached the first bridge-rail post. Second, the weak post-to-rail connection on the guiderail, which is designed to fail on impact, permitted the rail to raise more than 2 ft when the vehicle pocketed and decelerated abruptly upstream of the bridge. This led to a failure of the rail connection at the first bridge-rail post by exposing that blockout, which then snagged the vehicle's rear wheel.

To eliminate these problems, the transition was redesigned for the next test. To increase the lateral strength of the guiderail, W6x8.5 posts were added upstream from the bridge. To prevent wheel contact on these heavier posts, 6-in-deep blockouts were added. Two 3/4-in carriage bolts were used to connect the rail to the first bridge post and each of the W6x8.5 posts. The standard strength test on this transition resulted in very good performance and confirmed the adequacy of this design. However, by adding the heavy posts in the transition area, a secondary transition was introduced at the change in post sizes. Post spacing for the first five S3x5.7 posts was reduced to 2 ft in an attempt to equalize the lateral strengths as closely as possible on both sides of this transition point. However, test 21B demonstrated that this design was not adequate. On initial impact, the box-beam rail cut sharply into the vehicle sheet metal, probably aggravated by the added stiffness achieved in the transition zone by adding the extra posts. This penetration of the rail element into the side of the car permitted the front suspension and wheel to intrude behind the rail face. This presented no problem in the area of the S3x5.7 posts, which yielded on impact with the bumper. However, when the vehicle reached the heavy posts, the combined effects of barrier deflection plus intrusion of the rail into the car resulted in a solid impact of the suspension, wheel, and frame assembly on the first two heavy posts, and a violent snag and spin-out occurred.

To eliminate this undesirable performance, the transition was completely redesigned for the final test. The W6x8.5 posts were eliminated, and S3x5.7 posts were used throughout. A second 6- by 6- by 3/16-in box-beam rail was added in the transition zone to increase lateral strength of the guiderail. By doubling the rail face width from 6 to 12 in, penetration of the rail into the car would be reduced, and contact with both the guiderail posts and the first bridge-rail post would be eliminated. Both ends of the lower rail were safely terminated, i.e., flush with a bridge post on the downstream end and tapered behind the posts and down to the ground on the upstream end.

The success of the final design was demonstrated in tests 20A and 28. The vehicle decelerations experienced were comparable with those reported for other tests of very stiff bridge-railing systems and were near or below acceptable decelerations for 15° impacts (5). Vehicle redirection was good, roll angles were low (-5° and +2°), and potential pocketing and snagging points were eliminated by the balanced stiffness of the transitions from one to two tubes and from two tubes to the bridge rail. Vehicle damage was moderate, considering the severity of the impacts, and compared favorably with damage reported in tests of other bridge-rail upgrading systems (6). Although no tests were run with 2250-lb vehicles at 15°, this system appears to be capable of providing smooth redirection for those impacts. The two large-vehicle tests discussed earlier resulted in smooth redirection and low roll angles, and the final design includes no potential snag points or areas to trap a small-vehicle wheel. In addition, about 75 similar upgradings are now in service throughout the state and there have been no known adverse reactions with small vehicles. Both snagging and high roll angles have been problems in tests with small-vehicle impacts at 15° conducted elsewhere (6,7). However, these problems can be attributed to two conditions that were eliminated in this design: (a) insufficient clearance to the posts and a narrow rail face that permitted wheel-post contact and (b) a high curb that could be easily climbed by the front wheel and result in high roll angles. Based on these tests, the following conclusions appear warranted:

1. Performance of the discontinuous-panel bridge rail was raised to current standards by the addition of a single 6- by 6- by 3/16-in box-beam upgrading,
2. Stiffening the approach guiderail with W6x8.5 posts eliminated pocketing at the end of the bridge but created a snag point at the transition from S3x5.7,
3. The double-rail transition design provided smooth vehicle redirection through the transition onto the upgraded bridge rail, and
4. The final upgrading design appears capable of safely redirecting 4500-lb vehicles impacting at 60 mph and 25° at any point on the bridge or approach rails.

ACKNOWLEDGMENT

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REFERENCES

1. Standard Specifications for Highway Bridges, 7th ed. AASHO, Washington, DC, 1957, pp. 195-198.
2. M.D. Graham and others. New Highway Barriers: The Practical Application of Theoretical Design. HRB, Highway Research Record 174, 1967, pp. 88-183.
3. J.E. Bryden and K.C. Hahn. Crash Tests of Box-Beam Upgradings for Discontinuous-Panel Bridge Railings. Engineering Research and Development Bureau, New York State Department of Transportation, Albany, Res. Rept. 92, Sept. 1981.
4. M.E. Bronstad and J.D. Michie. Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances. NCHRP, Rept. 153, 1974.
5. Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances. TRB, Transportation Research Circular 191, Feb. 1978.
6. J.D. Michie and M.E. Bronstad. Upgrading Safety Performance in Retrofitting Traffic Railing Systems. Southwest Research Institute, Rept. FHWA-RD-77-40, Sept. 1978.
7. Monthly Progress Report on Development of Safer Bridge Railing Design. Highway Research Institute, Texas Transportation Institute, Texas A&M Univ., College Station, Dec. 1980-Jan. 1981.