DEVELOPMENT OF A NEW COLLAPSING-RING BRIDGE RAIL SYSTEM

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An energy-absorbing bridge rail system that uses the plastic deformation of steel rings as the primary impact energy absorber has been developed through full-scale crash testing and the use of the BARRIER VII computer program. The system design not only is capable of withstanding impacts by large vehicles such as buses and trucks but also does not impart high accelerations to impacting smaller vehicles. Ten full-scale crash tests were performed with vehicles ranging from 2,000 to 40,000 lb (907 to 18 144 kg). Redirection of high-speed [55 mph (89 km/h)], 40,000-lb (18 144-kg) vehicles (articulated and nonarticulated) impacting at a 19-deg angle was demonstrated. No significant elastic rebound of the rails and energy-absorbing rings was evident during the test. Vehicle damage was limited to mostly sheet metal damage of the impacting front quadrant and side panels with limited suspension damage at the same quadrant. Bridge rail damage ranged from slight for the subcompact vehicle impact to extreme for heavy vehicle impacts. Tests were documented by strain gauge, vehicle accelerometer, and high-speed movie data as well as permanent deformation measurements.

•A NEED exists for a bridge rail design that not only is capable of withstanding impacts by large vehicles such as buses and trucks but that also does not impart high accelerations to impacting smaller vehicles. Accordingly, this paper presents information on the development of a concept known as the collapsing-ring bridge rail system (CRBRS), which appears to be capable of fulfilling that need. Although this system represents an advance in state of the art in bridge rail design, it is constructed with conventional materials and barrier elements that are currently used in highway construction.

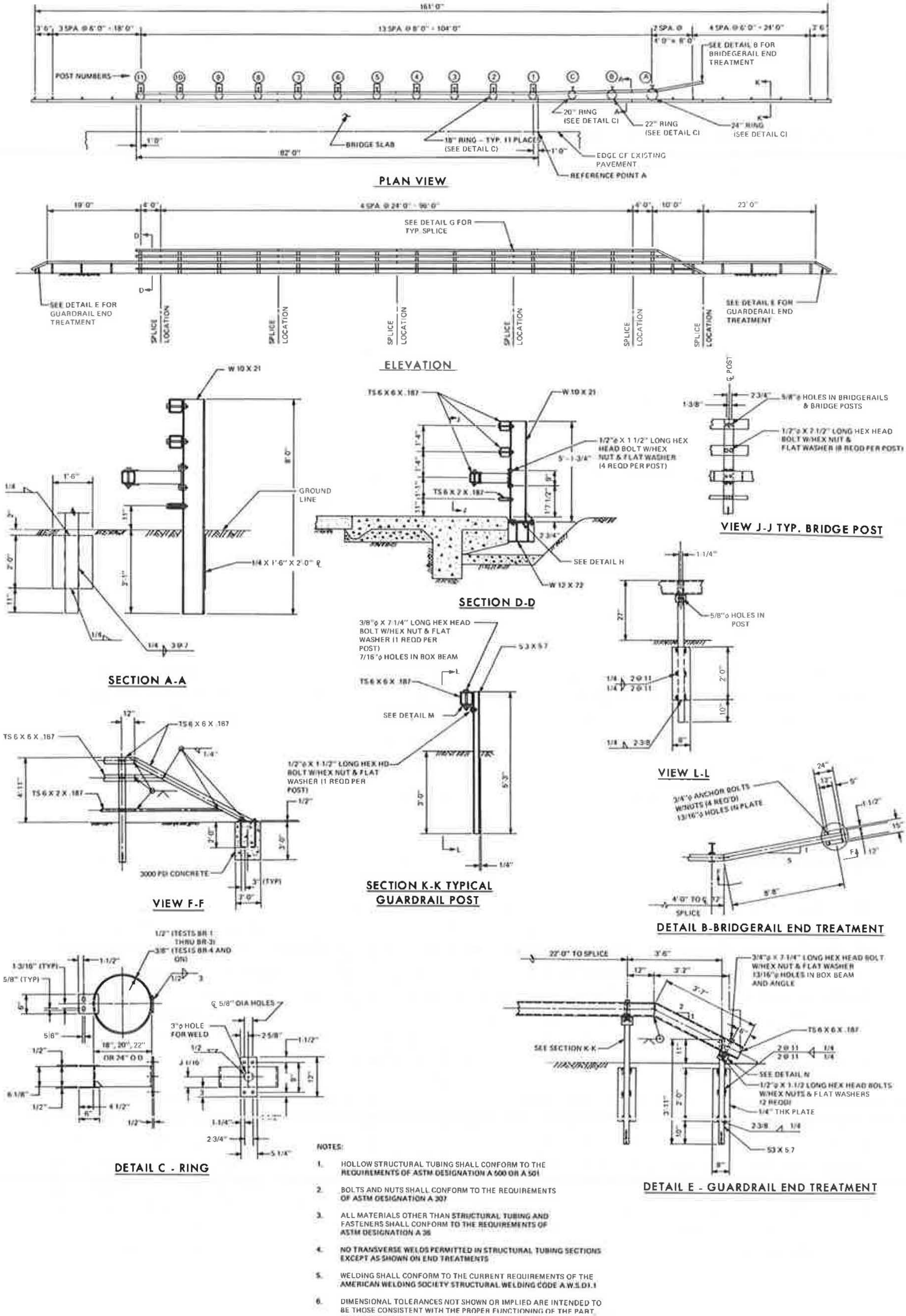
BACKGROUND

The idea of using steel rings as a primary energy-absorbing device for the bridge rail system described was conceived by the staff of the Offices of Research and Development of the Federal Highway Administration. It was recognized that vehicle impact energy could be dissipated in thick-walled rings by their partial or complete collapse. Initial analysis and testing of the rings were performed by Perrone (1) to determine the required ring geometry and material characteristics. After these initial studies, the bridge rail system that incorporated the collapsing-ring concept as shown in Figure 1 was designed by FHWA, and a vehicle crash test program was initiated.

The following performance goals were established for the design of this new system:

1. Reduction in impact severity, as compared with that in conventional nondeflecting bridge rail designs, for vehicles weighing from 2,000 to 4,000 lb (907 to 1814 kg) when impacting the system at 60 mph (97 km/h) and 25 deg. This is achieved through the use of the plastic deformation of the collapsing ring. The complete collapse of at least one ring without excessive vehicle contact with the elements of the outer railing system was desired for 4,000-lb (1814-kg) vehicle, 60-mph (97-km/h), 25-deg impacts.
2. Redirection of vehicles in impacts as severe as a 25,000-lb (11 340-kg) school bus

Figure 1. Collapsing-ring bridge rail system.



NOTES:

1. HOLLOW STRUCTURAL TUBING SHALL CONFORM TO THE REQUIREMENTS OF ASTM DESIGNATION A 500 OR A 501
2. BOLTS AND NUTS SHALL CONFORM TO THE REQUIREMENTS OF ASTM DESIGNATION A 307
3. ALL MATERIALS OTHER THAN STRUCTURAL TUBING AND FASTENERS SHALL CONFORM TO THE REQUIREMENTS OF ASTM DESIGNATION A 36
4. NO TRANSVERSE WELDS PERMITTED IN STRUCTURAL TUBING SECTIONS EXCEPT AS SHOWN ON END TREATMENTS
5. WELDING SHALL CONFORM TO THE CURRENT REQUIREMENTS OF THE AMERICAN WELDING SOCIETY STRUCTURAL WELDING CODE A.W.S.D1.1
6. DIMENSIONAL TOLERANCES NOT SHOWN OR IMPLIED ARE INTENDED TO BE THOSE CONSISTENT WITH THE PROPER FUNCTIONING OF THE PART INCLUDING ITS APPEARANCE AND ACCEPTED MANUFACTURING PRACTICES

Figure 1. Continued.

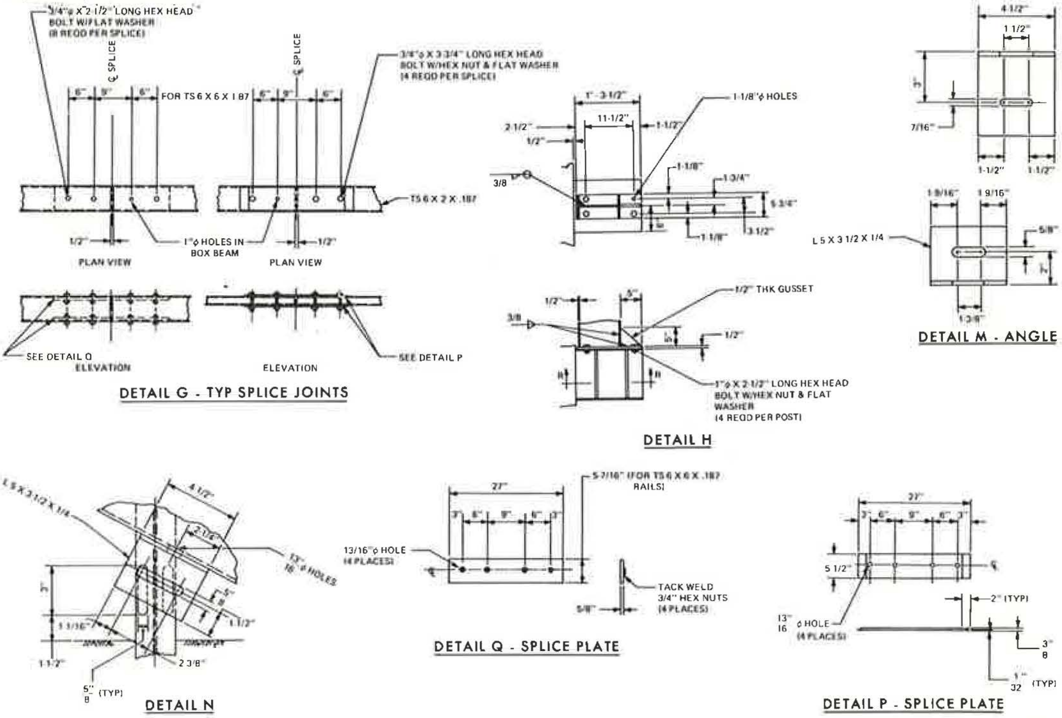


Table 1. Vehicle crash results.

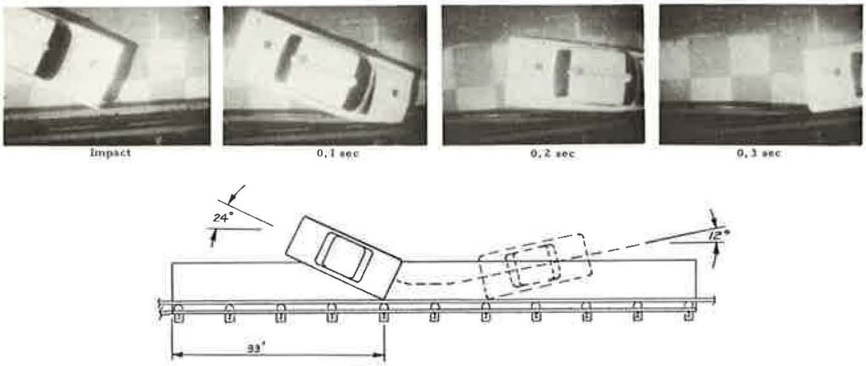
Test No.	Vehicle Weight (lb)	Impact Speed (mph)	Impact Angle (deg)	Vehicle Exit Conditions Angle (deg) Measured	Vehicle Exit Conditions Angle (deg) Predicted	Vehicle Exit Conditions Speed (mph) Measured	Vehicle Exit Conditions Speed (mph) Predicted	Maximum Avg Vehicle Acceleration[a] Longitudinal (y) Measured	Maximum Avg Vehicle Acceleration[a] Longitudinal (y) Predicted	Maximum Avg Vehicle Acceleration[a] Lateral (x) Measured	Maximum Avg Vehicle Acceleration[a] Lateral (x) Predicted	Maximum Permanent Ring Deflection (in.) Measured	Maximum Permanent Ring Deflection (in.) Predicted
BR-1	19,000	34.4	7.5	0.6		27		-0.86		0.40		0.5	
BR-2	19,000	56.0	7.3	2	3.2	56	53	-1.26	-0.89	2.67	3.29	3.4	1.02
BR-3	3,960	60.0	24.7	12	19.6	43	42	-6.05	-6.32	8.46	18.17	7.06	13.27
BR-4	4,097	60.0	25.9	5.6	19.9	36	42	-6.81	-6.35	6.56	18.19		13.31
BR-5	3,910	56.1	23.9	12	18.7	42	38	-5.61	-5.72	6.58	18.50	13.75	11.76
BR-6	2,090	55.7	23.5	13	45	41	39	-6.15	-4.55	12.24	16.91	4.0	5.44
BR-7	4,230	56.7	29.1	10	32	41	34	-5.57	-5.53	8.18	21.78	18.0	17.33
BR-8	19,000	60.9	13.9	2	1	54	52	-2.09	-2.00	3.90	7.03	16.38	10.42[b]
BR-9	40,000	54.3	19.1	13	6.6	42	53	-1.42	-0.43	2.63	1.24	54.0	34.0[b]
BR-10	40,000	55.1	19.0	11	6.6	44	53	-3.55	-0.43	8.86	1.24	23.25	28.0[b]

Note: 1 lb = 0.45 kg. 1 mph = 1.6 km/h.

[a] Maximum acceleration over 50-msec duration obtained from high-speed movie film.

[b] Rail deflections.

Figure 2. Results of full-scale crash test BR-5.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impacting the railing at 60 mph (97 km/h) and 20 deg. In such impacts, behavior of the outer railing system elements as a conventional nondeflecting bridge was desired.

3. Approach rail-bridge rail transition design to be capable of handling 60-mph (97-km/h) collisions with 4,000-lb (1814-kg) vehicles in impacts of 60 mph (97 km/h) and 25 deg.

As the program progressed, it appeared that the capability of the system to handle heavy vehicle impacts might significantly exceed initial design goals if dynamic displacement of the backup posts could occur with some form of limit on the leaning of the system during impact. This would require a somewhat predictable failure mode of the post at the baseplate connection, such as a tension failure of the anchor bolts. Computer runs made with the BARRIER VII program (2) indicated that collisions as severe as a 40,000-lb (18 144-kg) intercity bus or a 40,000-lb (18 144-kg) tractor-trailer rig at 60 mph (97 km/h) and 15 deg might be handled in such a manner. Accordingly 60-mph (97-km/h), 15-deg tests with these vehicles were added to the program.

TEST PROGRAM

Ten full-scale crash tests with vehicles ranging from 2,100 to 40,000 lb (952 to 18 144 kg) were conducted to examine the dynamic performance of the system in terms of the stated performance goals. Only one design change was made to the system during this test program. An initial ring thickness of ½ in. (12.7 mm), used in tests BR-1 to BR-3, was finalized to a thickness of ⅜ in. (9.5 mm) and then was evaluated by tests BR-4 to BR-10, which included standard-sized and small vehicles impacting at large angles, and large vehicles impacting at moderate angles. In addition, one test evaluated dynamic performance of the approach guardrail-bridge rail transition. Test procedures and data reduction methods are discussed elsewhere (3).

COMPUTER SIMULATION

The BARRIER VII (2) computer program was developed to predict the behavior of an automobile striking a protective barrier. The barrier is idealized as a structural framework of arbitrary configuration, and the automobile as a body surrounded by a cushion of springs. Large displacements and inelastic behavior, including hysteresis effects on unloading, are considered in the barrier structure. The automobile slides along the barrier, and the effects of normal forces, friction forces, and wheel drag forces are considered in determining its motions. The program and its capabilities are described in detail in another report (2).

In the modeling of the CRBRS, only two of the structural members available in the BARRIER VII program were used. These were the beam and the post. Post elements were used to model all posts in the system, and various beam elements were used to model the rail sections and the collapsing ring. The collapsing rings were modeled by a combination of two simple beam elements in parallel.

The BARRIER VII program was used to predict the collision outcome for each test in the test series. Vehicle trajectories and accelerations and barrier responses were predicted with varying degrees of accuracy. From the BARRIER VII program, in conjunction with the photographic and accelerometer data gathered during full-scale testing, the forces and moments on and displacements of key system elements were evaluated over the duration of the collision process.

TEST RESULTS

Results of the test series are given in Table 1. Theoretical predictions of the vehicle and barrier behavior computed by the BARRIER VII program are compared to experimentally derived values for the 10 tests. Comparisons are made for vehicle exit angle, exit speed, and maximum average accelerations and for maximum permanent barrier ring deflection.

In test BR-1, a test abort was unsuccessfully attempted resulting in a 34-mph (55-km/h) impact compared to a 60-mph (97-km/h) target speed. Test BR-2 was therefore designed to meet the target conditions of BR-1. From test BR-3, it was determined that the rings were too stiff (i.e., the design goal of complete collapse of one ring under the test conditions was not met), and a design change was initiated. Test BR-4 was scheduled to provide data on system performance using the new ³⁄₈-in.-thick (9.5-mm) rings (which were used for all subsequent tests). During test BR-4, a failure of the front rail at a butt-welded joint, which was neither authorized by the design drawings nor observed before the test, occurred. Test BR-5 was a repeat of test BR-4. Tests BR-6 through BR-10 were conducted as given in Table 1. Further details on these tests are given elsewhere (3), and a description of the more significant tests in this series follows. Data for vehicles and the collapsing-ring bridge rail for tests BR-5 through BR-10 are given in Table 2. The data for rails, rings, and pavement condition, which were the same for each of these tests, are as follows (1 in. = 25.4 mm and 1 ft = 0.3 m):

Item	Measurement
Bridge rail, in.	TS 6 × 6 × 0.1875
Post, ft	W 10 × 21 × 5.15
Bridge post spacing, ft	8
Installation length, ft	82
Steel rings	
Thickness, in.	0.375
Outside diameter, in.	18.0
Length, in.	6.12
Pavement condition	Dry

Test BR-2

The vehicle in test BR-2 was a 1962 Ward school bus weighing 12,050 lb (5480 kg) when empty and 19,000 lb (8618 kg) when ballasted with three sections of 20-in. (508-mm) internal-diameter steel tubing rigidly attached to the vehicle structure. The bus impacted the front rail at post 2 (posts on the simulated bridge deck are numbered consecutively beginning upstream as shown in Figure 1) with a speed of 56 mph (90 km/h) and an impact angle of 7.3 deg. The bus was redirected almost parallel to the rail; it rolled 13.8 deg toward the rail and then 10 deg away from the rail. Maximum 50-msec average accelerations were 1.3 *g* (longitudinal) and 2.60 *g* (lateral); maximum permanent ring deflection was 3.4 in. (86.4 mm) at post 2.

Test BR-5

The 3,910-lb (1773-kg) 1964 Chevrolet Impala sedan impacted the front rail at post 5 with a speed of 56 mph (90 km/h) and an impact angle of 24 deg and was smoothly redirected as shown in Figure 2. Figure 3 shows the condition of the vehicle and the rail barrier after the impact. The design goal of complete collapse of one ring without excessive vehicle contact with other elements of the system with the given impact conditions was met with the ³⁄₈-in.-thick (9.5-mm) rings. The comparison of predicted and experimental results is shown in Figure 4.

Test BR-6

The 2,090-lb (948-kg) 1972 VW subcompact sedan impacted the front rail between posts

Figure 3. Condition of vehicle and collapsing-ring bridge rail after impact in test BR-5.

Figure 4. Results of BARRIER VII simulation versus those of actual test BR-5.

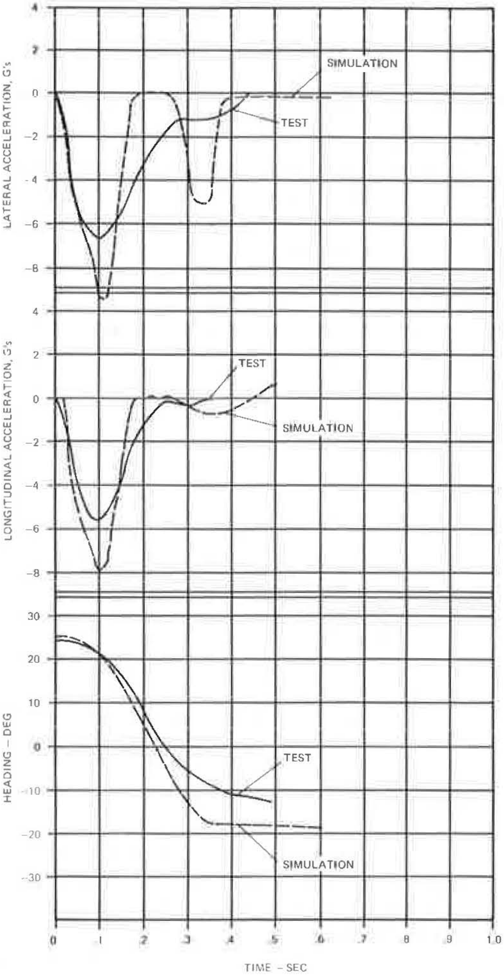
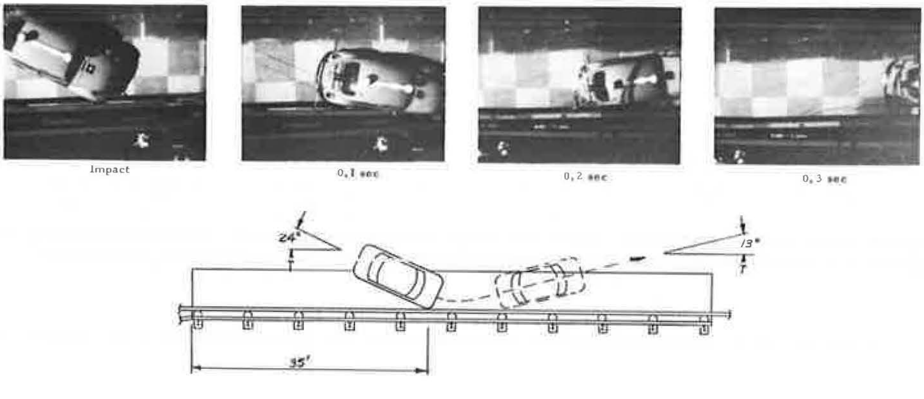


Figure 5. Results of full-scale crash test BR-6.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5 and 6 with a speed of 56 mph (90 km/h) and an impact angle of 24 deg and was smoothly redirected as shown in Figure 5. Vehicle and barrier damage is shown in Figure 6, and the comparison of predicted and experimental results is shown in Figure 7.

Test BR-7

The 4,230-lb (1018-kg) sedan impacted the approach guardrail-bridge rail transition with a speed of 57 mph (92 km/h) and an impact angle of 29 deg. As shown in Figure 8, the vehicle impacted the guardrail, completely collapsed the first ring (resulting in backup rail translation of the soil), mounted posts A, B, and C at the end of the bridge rail, and was then smoothly redirected. Maximum permanent deflection of this post was 22.9 in. Vehicle and barrier damage is shown in Figure 9.

Test BR-8

The 19,000-lb (8618-kg) school bus impacted the front rail at post 8 with a speed of 61 mph (98 km/h) and an impact angle of 14 deg. As shown in Figure 10, the bus rolled toward the rail to a maximum roll angle of 15 deg, and the rear of the bus impacted the two upper rails before being redirected. For the first time in the test series, two bridge posts sustained damage: Posts 7 and 8 sustained baseplate bending, and the two bolts nearest the bridge deck in post 8 failed in tension. Vehicle and installation damage are shown in Figure 11. The comparison of experimental and theoretical vehicle dynamics is shown in Figure 12.

Test BR-9

The scenicruiser intercity bus ballasted to 40,000 lb (18 144 kg) with 10,200 lb (4627 kg) of sand bags in the baggage compartment impacted the front rail at post 2 with a speed of 54 mph (87 km/h) and an impact angle of 19 deg. As shown in Figure 13 and Figure 14, the bus completely collapsed rings in the impact zone, rolled toward the rail, and the rear of the bus impacted the three-rail system. The redirected bus reached a maximum roll angle of 20 deg (toward the rail) before returning to an upright position. The significance of the vehicle's c.g. being lowered by the ballast and of the ballast spilling free of the vehicle is not clearly defined. In the extreme case, had the vehicle been redirected in a manner that raised the c.g., a rollover might have occurred.

The bottom rail (rub rail) failed completely. Considerable post damage was sustained: Posts 2 through 5 failed in bending and torsion with all four baseplate bolts fractured; posts 1, 6, and 7 sustained baseplate bending, and the two bolts nearest the bridge deck failed in tension. In addition, all three soil-mounted posts upstream of the bridge deck were displaced laterally with a maximum permanent displacement of approximately 26 in. (660 mm). The comparison of experimental and theoretical vehicle dynamics is shown in Fgiure 15.

Test BR-10

The 40,000-lb (18 144-kg) tractor-trailer truck impacted the front rail at post 4 with a speed of 55 mph (89 km/h) and an impact angle of 20 deg. As shown in Figure 16, the truck tractor impacted the front rail and initiated a roll toward the barrier as it was redirected. The roll continued as the trailer impacted the two upper rails and ended when both the tractor and the trailer rolled on their right sides. The tractor had nearly recovered to a 0-deg roll attitude before trailer momentum initiated the final roll sequence of the complete rig. Little damage was sustained by the tractor cab because of the roll. Bridge posts 2 through 5 sustained baseplate bending, and the two bolts nearest the bridge deck failed in tension. This damage is shown in Figure 17.

Figure 6. Condition of vehicle and collapsing-ring bridge rail after impact in test BR-6.

Figure 7. Results of BARRIER VII simulation versus those of actual test BR-6.

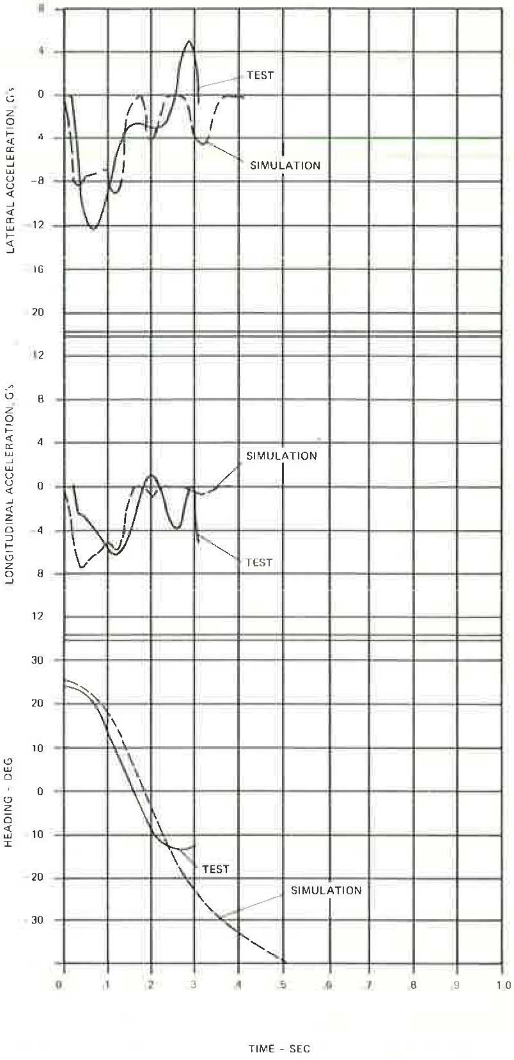

Figure 8. Results of full-scale crash test BR-7.

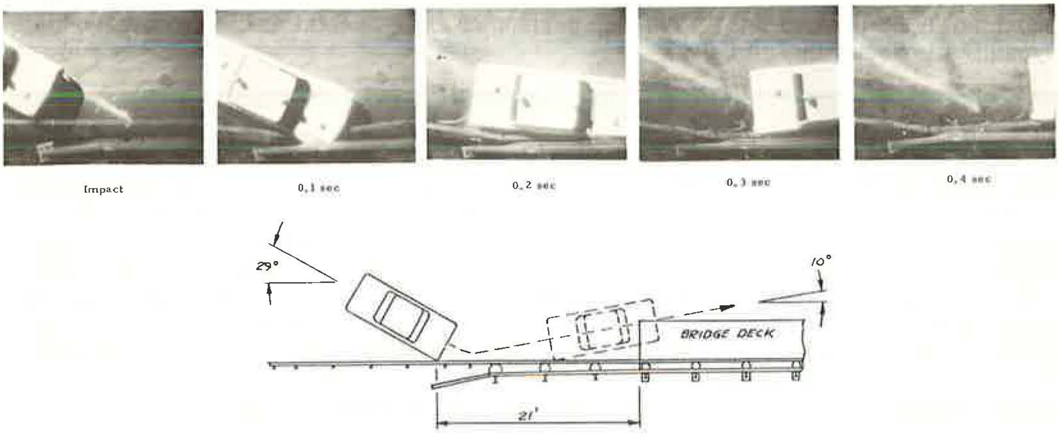
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Figure 9. Condition of vehicle and collapsing-ring bridge rail after impact in test BR-7.

Table 2. Data for vehicles and barriers for impact tests.

Test	Maximum Permanent Ring Deflection (in.)			Vehicle Weight[a] (lb)	Impact		Exit Angle (deg)	Vehicle Acceleration[b] (g)		Vehicle Rebound Distance (ft)
	Front Rail	Midrail	Top Rail		Speed (mph)	Angle (deg)		Lateral	Longitudinal	
BR-5	13.75			3,910	56.1	23.9	12.0	6.58	-5.61	20
BR-6	4.0			2,090	55.7	23.5	13.0	12.24	-6.15	10
BR-7	18.0			4,230	56.7	29.1	10.0	8.18	-5.57	12
BR-8	16.4	1.8	2.4	19,000	60.9	13.9	2.0	3.90	-2.09	25
BR-9	24	38	42.5	40,000	54.3	19.1	13.2	2.63	-1.42	30
BR-10	23.3	30.8	35.8	40,000	55.1	19.0	11.0	8.86	-3.55	25

Note: 1 in. = 25.4 mm. 1 lb = 0.45 kg. 1 ft = 0.3 m.

[a] With instrumentation. [b] For the top rail, 50-msec average.

Figure 10. Results of full-scale crash test BR-8.

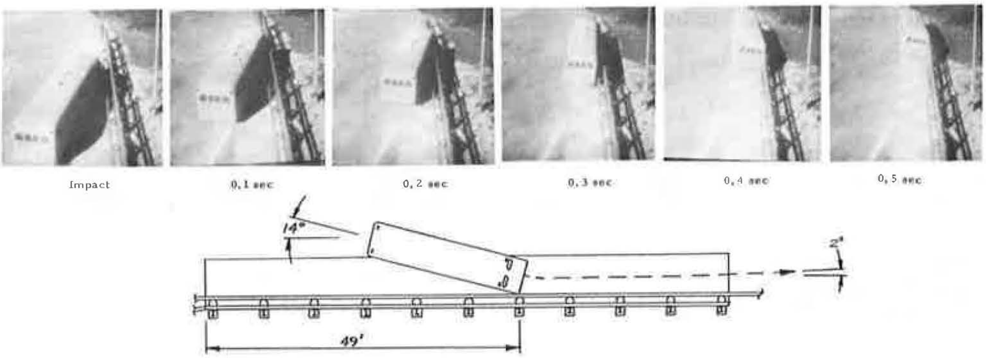


Figure 11. Condition of vehicle and collapsing-ring bridge rail after impact in test BR-8.

Figure 12. Results of BARRIER VII simulation versus those of actual test BR-8.

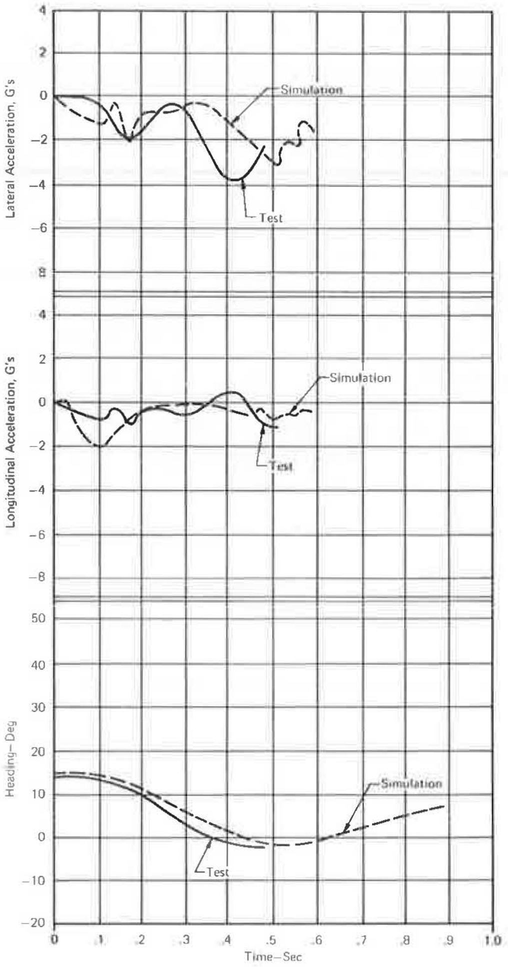


Figure 13. Results of full-scale crash test BR-9.

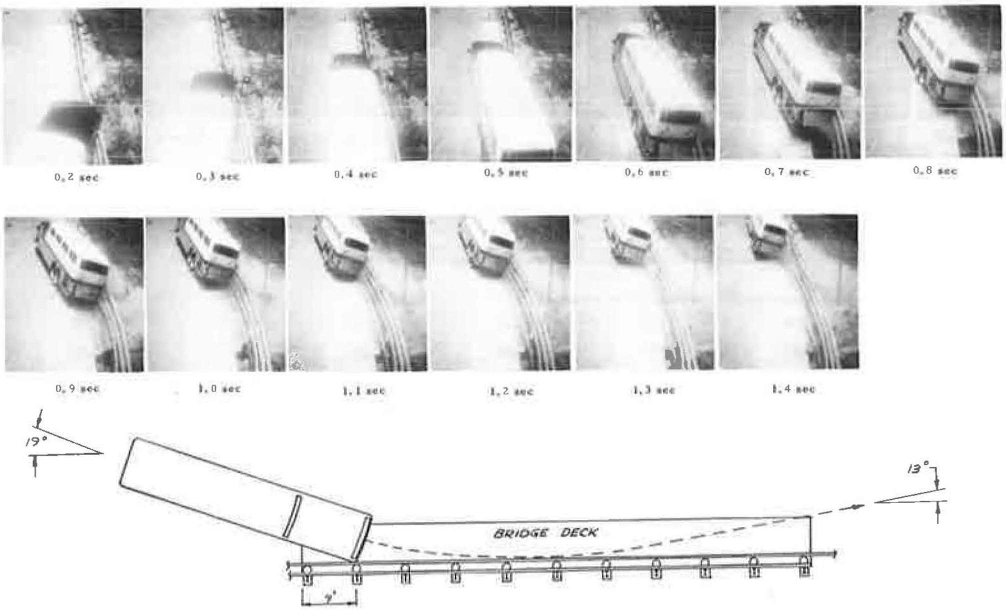


Figure 14. Condition of vehicle and collapsing-ring bridge rail after impact in test BR-9.

Figure 15. Results of BARRIER VII simulation versus those of actual test BR-9.

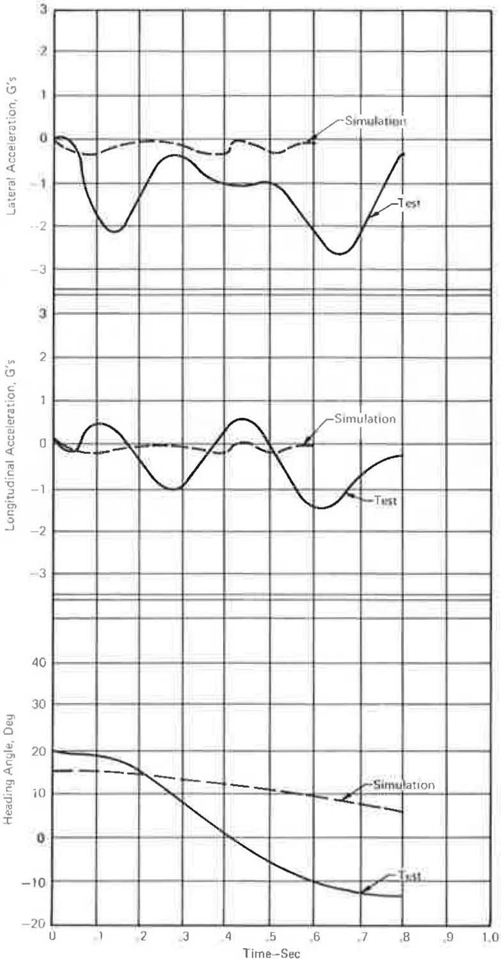


Figure 16. Results of full-scale crash test BR-10.

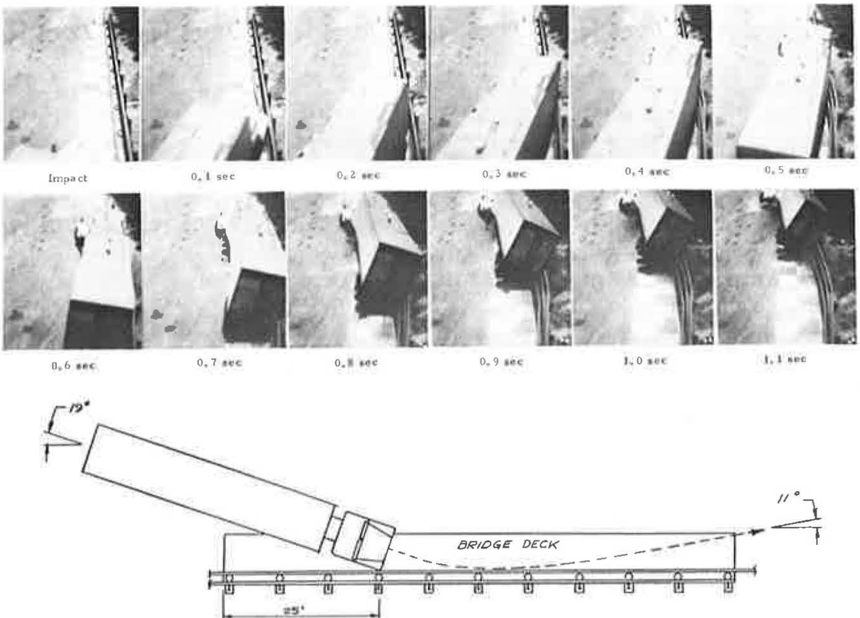
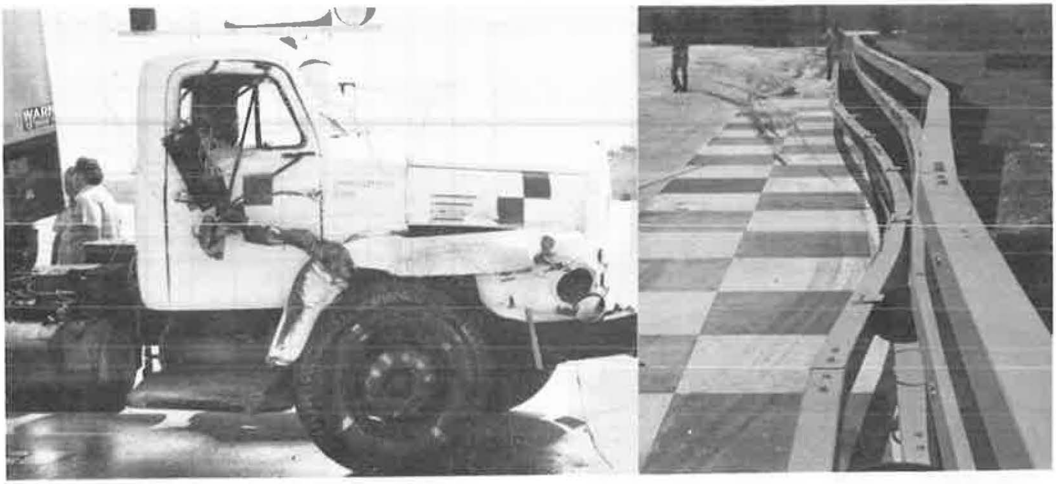


Figure 17. Condition of vehicle and collapsing-ring bridge rail after impact in test BR-10.



DISCUSSION OF RESULTS

Tests conducted in this program demonstrated that the following design goals were met with the use of $^{3}/_{8}$-in.-thick (9.5-mm) rings:

1. Reduction in impact severity, as compared with that in conventional nondeflecting bridge rail designs, was shown in test BR-5, in which 13.8 in. (350.5 mm) of permanent deformation occurred in one collapsing ring that was impacted by a 3,900-lb (1770-kg) vehicle at 56 mph (90 km/h) and 24 deg and in test BR-6, in which 4.0 in. (101 mm) of permanent deformation occurred in one collapsing ring that was impacted by a 2,090-lb (948-kg) VW at 56 mph (90-km/h) and 24 deg. The vehicle was driven away from the impact zone after test BR-6.
2. A 19,000-lb (8618-kg) school bus was successfully redirected by the bridge rail system in a 61-mph (98-km/h) impact at 14 deg (test BR-8), and a 2.4-in. (61-mm) maximum permanent deflection occurred in the outer railing elements. This shows that, in the outer backup railing, elements behaved much as conventional nondeflecting designs under impacts near the upper limit of their ultimate resistance. In test BR-8, the maximum dynamic load impacting the barrier was in the order of 75,000 lb (34 119 kg), and few conventional railings are designed to withstand forces of this magnitude.
3. Successful redirection of a 40,000-lb (18 144-kg) scenicruiser bus impacting the system at 54 mph (87 km/h) and 19 deg was demonstrated in test BR-9, and a maximum permanent deflection of 42.5 in. (1079.5 mm) of the top rail of the outer rail elements occurred.
4. A 40,000-lb (18 144-kg) tractor-trailer rig was retained and redirected in a 55-mph (89-km/h), 20-deg impact (test BR-10); however, the vehicle rolled on its side. Maximum permanent post displacement was 35.8 in. (909.7 mm) at the height of the top rail and 23.3 in. (591.8 mm) at the height of the collapsing ring. System design changes aimed at reducing leaning of the posts in such impacts may help reduce such roll-over events.
5. Satisfactory redirection was obtained when the approach rail transition was impacted with a 4,200-lb (1905-kg) vehicle at 57 mph (92 km/h) and 20 deg. This resulted in a maximum permanent ring deflection of 18 in. (457 mm) (test BR-7).

No significant elastic rebound of the rails and the energy-absorbing rings was evident during the tests. For a large number of moderate impacts expected in actual service, it is anticipated that the system could be restored by a maintenance crew using a hydraulic jack. Rings with less than 4-in. (101-mm) permanent deformation were succesfully restored and reused in this program. In cases where significant ring deformation and rail deformation occur, replacement of these elements will be required.

REFERENCES

1. N. Perrone. Thick-Walled Rings for Energy-Absorbing Bridge Rail Systems. Rept. FHWA-RD-73-49, Dec. 1972.
2. G. H. Powell. BARRIER VII—A Computer Program for Evaluation of Automobile Barrier Systems. Rept. FHWA-RD-73-, March 1973.
3. J. D. Michie, M. E. Bronstad, C. E. Kimball, J. A. Wentworth, and J. G. Viner. Development of a Collapsing Ring Bridge Railing System. Federal Highway Administration.