Development of a Slotted-Rail Breakaway Cable Terminal

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Development of the Slotted-Rail Breakaway Cable Terminal (SRBCT), a low-cost end treatment for W-beam guardrails, is presented in this paper. Longitudinal slots in guardrail segments are used to weaken the W-beam for head-on impacts, thereby allowing a nearly standard BCT design to meet nationally recognized safety standards. Static and dynamic laboratory testing of buckling characteristics of modified W-beam sections are presented. Full-scale crash tests of the SRBCT are described.

The Breakaway Cable Terminal (BCT) is a gating end treatment designed to allow controlled barrier penetration for vehicles impacting on its end. The gating action is provided by breakage of a wood post and dynamic buckling of a flared guardrail section. Longitudinal anchorage for the guardrail is provided by a cable attached to the leading wood post in such a way that, when the post breaks, the cable is released.

This system was originally designed to accommodate full-size automobiles and was shown to perform well for both head-on and side impacts (*1*). Based on these early successful crash tests, many states adopted the BCT as a standard guardrail terminal. Because the BCT relies on dynamic buckling of a flared section of W-beam, it is very sensitive to the way the barrier end is flared. Field surveys have indicated that many installations do not have proper flare rates (*2*) and that some BCTs are installed without a flared end. Further, recent crash tests have indicated that standard BCT designs will not perform satisfactorily when impacted by mini-size vehicles (*3*). Accident data studies have also indicated that the safety performance of the BCT has not been satisfactory.

Efforts to resolve the problems with the BCT have led to the development of the Eccentric Loader Breakaway Cable Terminal (ELBCT) (*4*). Although crash test results have indicated that this system should perform much better than standard BCT designs, the ELBCT is a more complex system and its cost will likely be relatively high. Further, the ELBCT still relies on the dynamic buckling of a W-beam guardrail and is, therefore, sensitive to the flare rate. Finally, standard BCTs cannot be easily retrofitted to ELBCT installations since the shapes of the flared barrier sections are somewhat different.

Over 100,000 BCT guardrail end treatments are estimated to have been installed across the country, and many states still use the BCT as a standard guardrail terminal. These systems do not meet current safety standards and will need to be replaced by a safer end treatment. This paper describes the development of a modified breakaway cable terminal, the Slotted-Rail Breakaway Cable Terminal (SRBCT), which meets current safety standards and can be used as a simple retrofit to current BCT systems. Additional details about the new end treatment can be found in Sicking et al. (*5*).

SLOTTED-RAIL CONCEPT

When a vehicle impacts the end of a BCT end treatment, it must first break a 6-in by 8-in wood post while buckling an unsupported 25-ft section of W-beam. With standard BCT designs, excessive deceleration forces have been shown to develop during this stage of impact. Thus, efforts to improve the performance of the BCT during head-on impacts have concentrated on reducing the impulse imparted to the vehicle during these early stages of impact.

Performance can be improved by reducing the section modulus of the beam. Since a W-beam redirects vehicles through membrane action rather than beam-bending strength, reducing its section modulus should have little effect on guardrail redirective capacity. Guardrail section modulus can be reduced by cutting longitudinal slots in the beam. The longitudinal slots divide the beam into several independent beams. An example of this weakening mechanism is shown in Figure 1. The three slots shown in this figure reduce the moment of inertia of the W-beam from 2.33 to approximately 0.02 in^4. Such a drastic decrease in section modulus greatly reduces the dynamic buckling strength of a section of W-beam and could eliminate the problems associated with head-on impacts with BCTs. Further, longitudinal slots do not significantly reduce the tensile strength of the standard W-beam. Three ½-in-wide slots reduce beam area from 1.99 to 1.83 in^2. This reduction in cross-sectional area is less than that found at the splice points where four ¾-in-diameter bolt holes reduce beam area to 1.61 in^2.

Advantages of the slotted rail concept include relatively low cost, ease of retrofitting existing installations, and a means of tuning W-beam buckling strength to any desired level. Due to these advantages, this concept was selected for further evaluation as a means of improving performance of BCT end treatments.

LABORATORY EVALUATION

Preliminary evaluation of the slotted-rail concept was conducted in three phases: static tests, pendulum tests, and full-scale dynamic tests. Static testing was conducted on numerous slot configurations to identify the minimum slot widths that allow independent movement of each beam section. These tests indicated that ½-in-wide slots were sufficient to prevent

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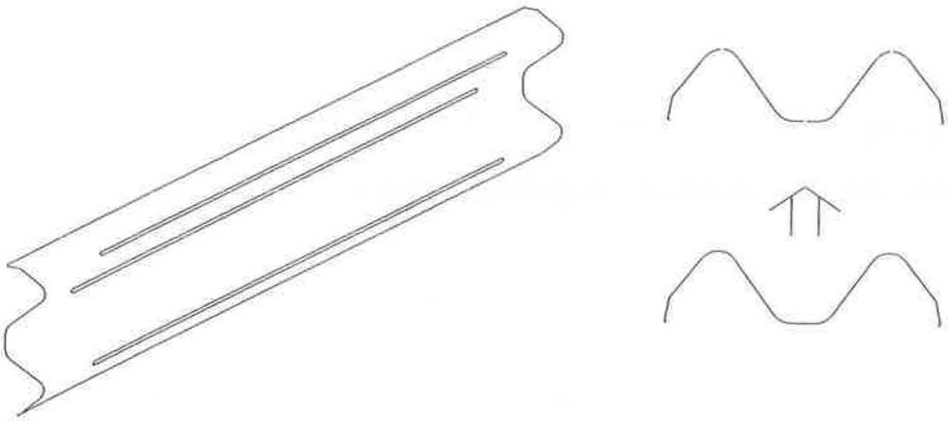

FIGURE 1 Reduction of W-beam's section modulus through longitudinal slots.

TABLE 1 STATIC SLOTTED-RAIL BUCKLING TESTS

Slot Length (in.)	Failure Load (lb)	Euler Buckling Load (lb)
36	23,700	18,000
48	8,200	10,000
60	4,900	6,400
24 and 30	19,500	26,000

FIGURE 2 Typical pendulum test configuration.

interference between beam sections, thereby allowing a controlled buckling failure. Subsequent static testing was conducted to identify static buckling strengths for various slot lengths. Based on preliminary static test results, it was concluded that a three-slot arrangement like that shown in Figure 1 would be necessary if the new BCT design were to be developed without a flared section. Thereafter, all testing involved this slot arrangement. Table 1 summarizes static test results.

Pendulum tests were then conducted to identify the low-speed dynamic-buckling strengths of various slot lengths. Test specimens were impacted by a 2,250-lb pendulum at 20 mph. A typical test setup is shown in Figure 2. Plots of energy dissipation versus deflection for each slot length are shown in Figures 3 and 4. Energy dissipation characteristics are similar for all slot lengths tested. Based on review of high-speed films and test results shown in these figures, it was concluded that the slotted-beam sections were not buckling in the fundamental mode and, as a result, differences in energy dissipation among the tested specimens could not be considered to be significant.

Full-scale dynamic tests were then conducted to determine the effects of impact speed on energy dissipation characteristics. Three full-scale crash tests were conducted on a 60-in slot design at impact speeds of 20, 30, and 40 mph. Figure 5 shows a typical test installation. The leading slotted section was unsupported in an effort to isolate forces generated during the buckling of the slotted-rail segment. Test results indicated that energy dissipated during buckling of slotted-rail segments was approximately proportional to the impact speed, as shown in Figure 6.

DEVELOPMENTAL TESTING

Preliminary test results indicated that the slotted-rail concept might be used to design a BCT-type end treatment that did not require a flared end. Such a system would require a significant length of slotted-rail segments to slowly decelerate vehicles impacting head-on. A full-scale test of a straight run of slotted guardrail segments was then conducted to determine the effects of longitudinal slots on the W-beam's redirective capacity. This test involved a full-size vehicle impacting a slotted section of rail at 50 mph and 25°. Upon impact, the test vehicle's bumper penetrated through a slot in the W-beam and extended the slot to a W-beam splice. As the slot was extended through the splice, it caused the modified W-beam segment to rupture, and the test vehicle penetrated behind the guardrail.

The solution to this problem is to prevent the vehicle from coming in direct contact with the slotted-rail sections. A cover plate was therefore developed that would shield the slots from impacting vehicles while allowing the slotted section to buckle during head-on impacts. The upstream end of the cover plate is bolted to the guardrail and the downstream end is clipped so it can slide during head-on impacts. The clips on the downstream end of the slotted segment are required to prevent the end of the cover plate from separating from the guardrail and snagging on vehicles impacting from the opposite direction. Figure 7 shows a schematic of the cover plate concept.

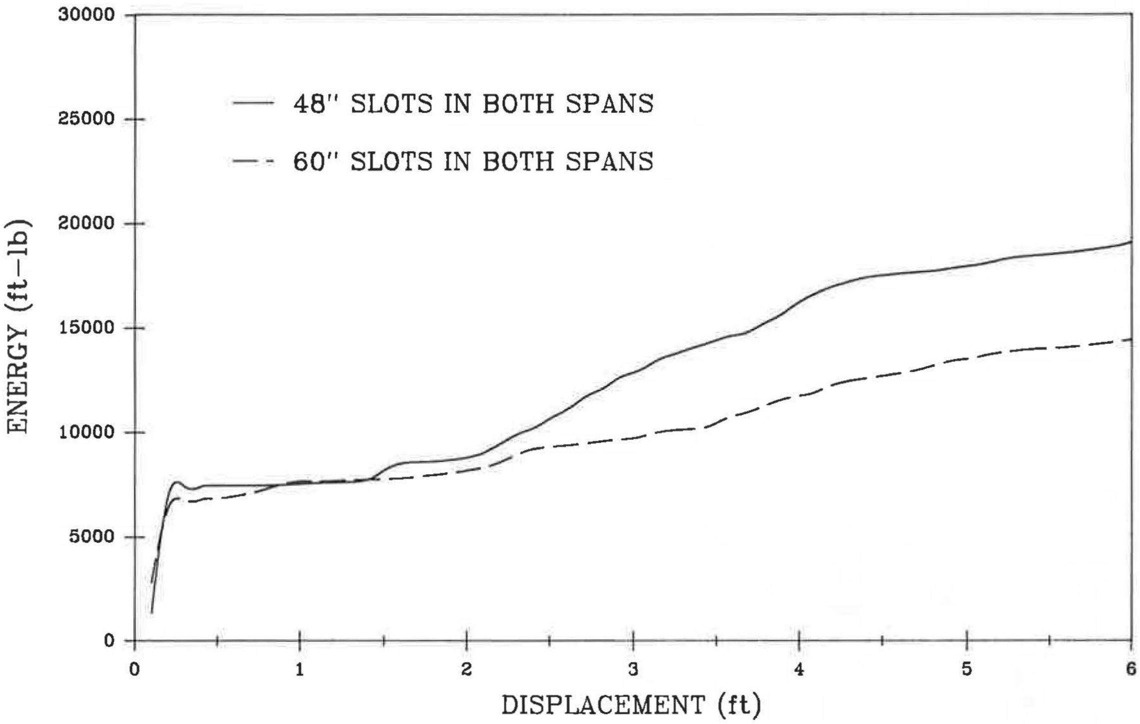

FIGURE 3 Pendulum test results: dynamic energy dissipation of slotted W-beam guardrail segments (48- and 60-in. slots).

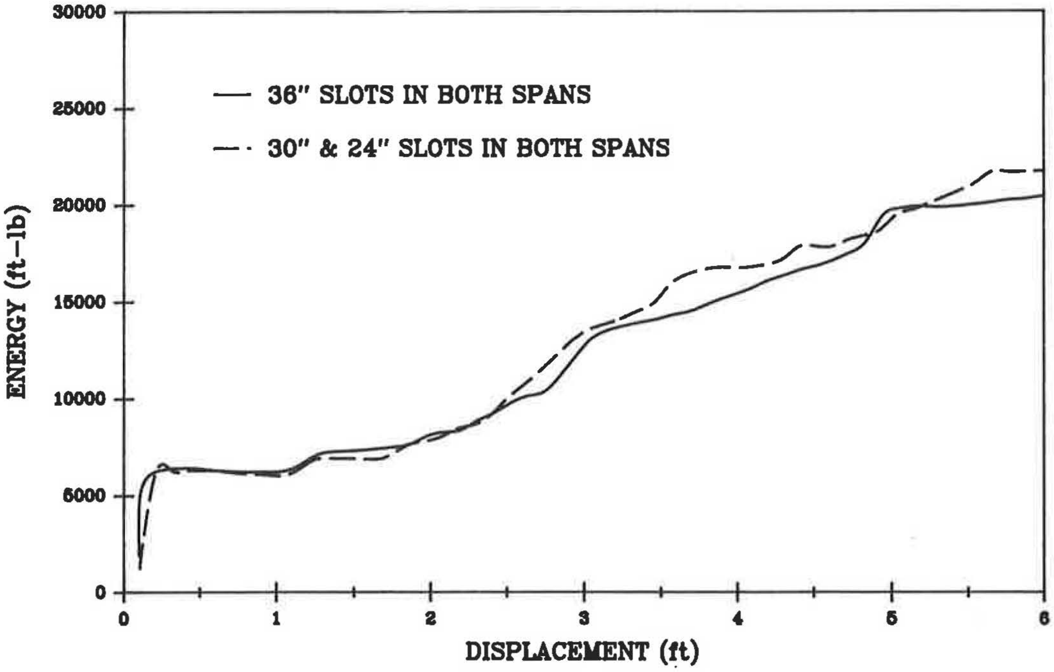

FIGURE 4 Pendulum test results: dynamic energy dissipation of slotted W-beam guardrail segments (36-in. and 30- and 24-in. slots).

Static and pendulum tests of cover-plated slotted segments were then undertaken to evaluate the effects of a cover plate on buckling characteristics. Static testing was conducted on both welded and bolted cover plates. Because these tests indicated little difference in performance between the two attachment mechanisms, the bolted design was selected as the most economical option. Static test results are summarized in Table 2. The scatter in these test results from the possibility of adjacent strips in the slotted region coming into sharp contact with each other during buckling. This phenomenon adds a degree of lateral bracing to the two strips in contact, thereby increasing buckling loads. Pendulum tests involved only 27-in slotted segments with bolted cover plates. Figure 8 shows that all pendulum test specimens exhibited a consistent buckling behavior. Static and pendulum tests indicated that cover plates increase energy dissipation and maximum buckling loads by approximately 30 percent.

A final developmental test was then conducted to investigate the head-on impact characteristics of a straight section of cover-plated slotted segments. This test involved a full-size sedan impacting the end of a 50-ft span of slotted guardrail segments at a speed of 60 mph. After the first slotted segment buckled, the unmodified section of guardrail rotated downward to form a ramp that projected the test vehicle over the top of the guardrail. Although no large decelerations were imparted to the vehicle and it showed little tendency to roll over, this test was deemed to be a failure since rollover could be expected under somewhat different impact conditions. As a result of these test findings, efforts to develop a straight guardrail terminal were abandoned.

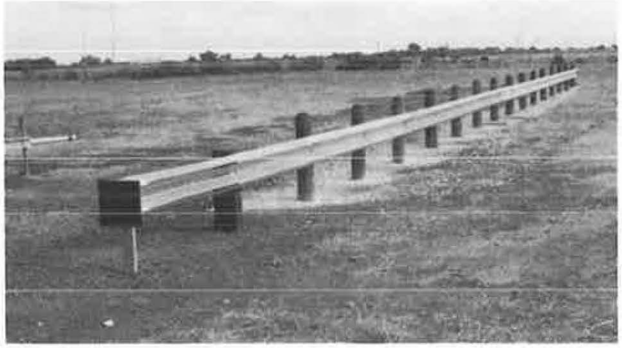

FIGURE 5 Typical preliminary crash test setup.

SLOTTED-RAIL BCT

Remaining design efforts concentrated on the development of a modification to standard BCT designs that would meet the nationally recognized safety criteria in *NCHRP Report 230* (*6*). The final SRBCT design incorporated a parabolic flare with a 4-ft offset as used in standard BCT designs. Modifications to the BCT design included incorporating 27-in-long slotted-rail segments within each of the first four guardrail spans and adding a ground-line cable to enhance breakage of posts 2, 3, and 4. The slotted-rail segments allow each guard-

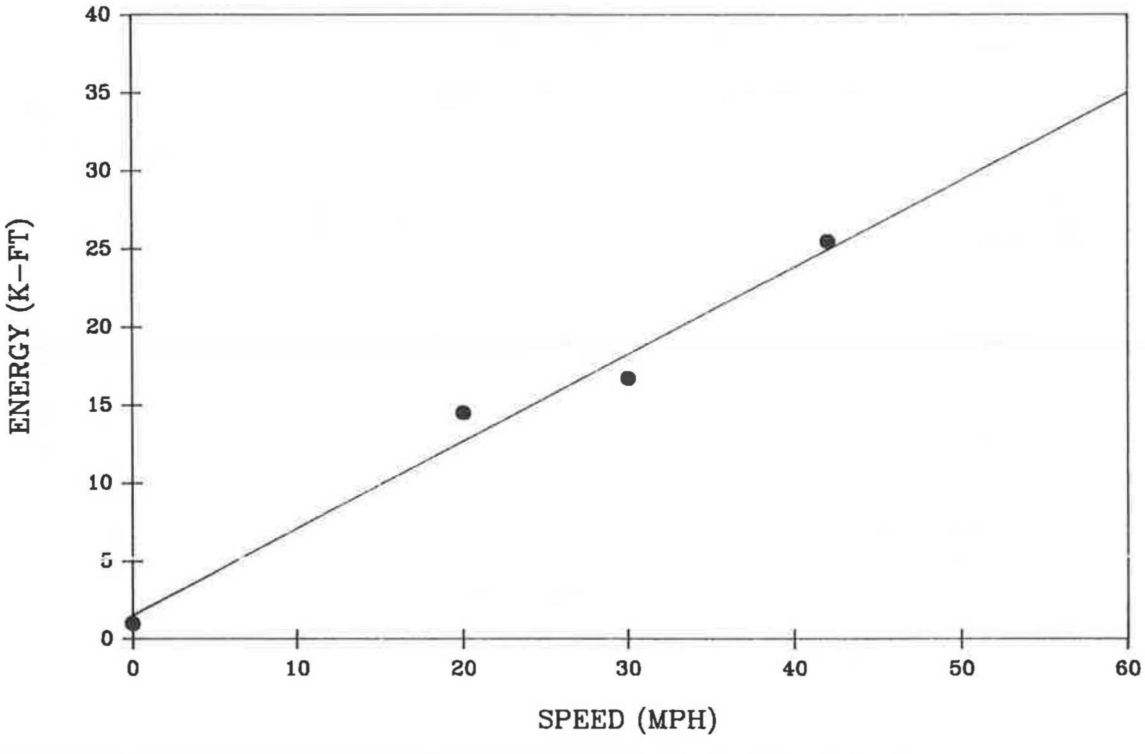

FIGURE 6 Relationship between energy dissipation and impact speed for 5-ft slotted sections.

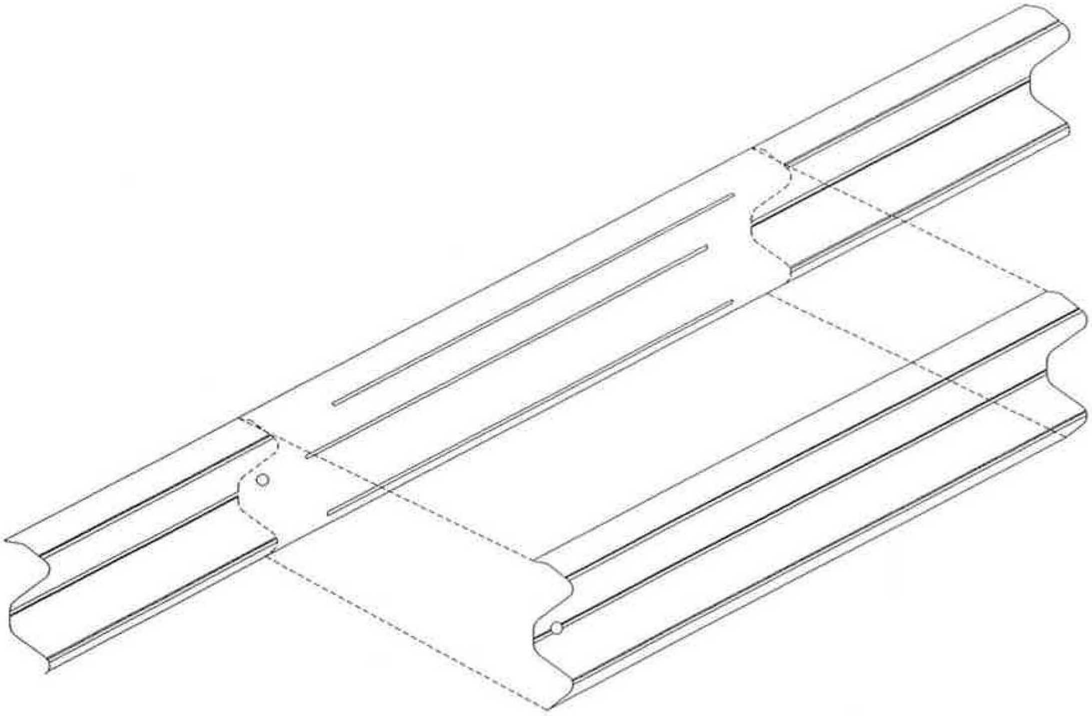

FIGURE 7 Cover plate concept.

TABLE 2 STATIC TESTS OF SLOTTED RAIL WITH COVER PLATES

Slot Length (in.)	Cover Plate Attachment	Buckling Load (lb)
36	Welded	32,000
30	Welded	24,000
30	Welded	25,000
27	Bolted	28,500
27	Bolted	35,500
27	Bolted	32,000
27	Bolted	28,500
27	Bolted	22,500
27	Bolted	24,600

rail span to buckle independently, thereby reducing head-on impact forces and allowing the guardrail to be bolted to every post. The ground-line cable, used to prevent longitudinal motion at the base of posts 2, 3, and 4, has been shown to reduce forces required to break wood posts (*5*). These three posts were also weakened with a 2.875-in-diameter hole drilled at the base. The addition of two posts between posts 3 and 4 and posts 4 and 5 in an effort to improve redirectional capacity of the system will be discussed later.

These changes from standard BCT designs are believed to be sufficient to meet *NCHRP Report 230* safety standards. The new end treatment incorporated a standard BCT end buffer and breakaway cable system. To conform to Texas's standard guardrail system, 7-in-diameter round wood posts were used in the prototype design. Dynamic testing has shown that a 6-in by 8-in wood post absorbs approximately the same amount of energy as 7-in round wood post. The SRBCT should, therefore, perform with the 6-in by 8-in rectangular wood posts normally used in BCT designs with little effect on head-on impact. Figure 9 shows the final SRBCT design.

COMPLIANCE TESTING

The safety performance of the new end treatment was investigated with four full-scale crash tests, as recommended by *NCHRP Report 230* (*6*).

Test SR-2

The terminal was first tested with a mini-size vehicle impacting the end treatment head-on at 60 mph. The vehicle was offset 15 in from the center of the first post towards the traffic side of the barrier. For this test, the installation had blockouts only on the first five posts. The vehicle penetrated through the end of the barrier at a relatively low speed after fracturing the first and second posts. The slotted-rail sections collapsed as expected. The longitudinal occupant-impact velocity was 35.1 ft/sec, and the longitudinal ridedown acceleration was 10.7 g. Although the longitudinal impact velocity was above the recommended limit of 30 ft/sec, it was well below the maximum allowable limit of 40 ft/sec (*6*). A few terminals, including VAT, ELBCT, and GET, actually meet recommended occupant-impact criteria for this test condition. However, many successful devices, including GREAT, SENTRE, and TREND, do not meet this requirement. Therefore, this test was considered successful. Note that the vehicle did not contact the third post, and its trajectory behind the guardrail

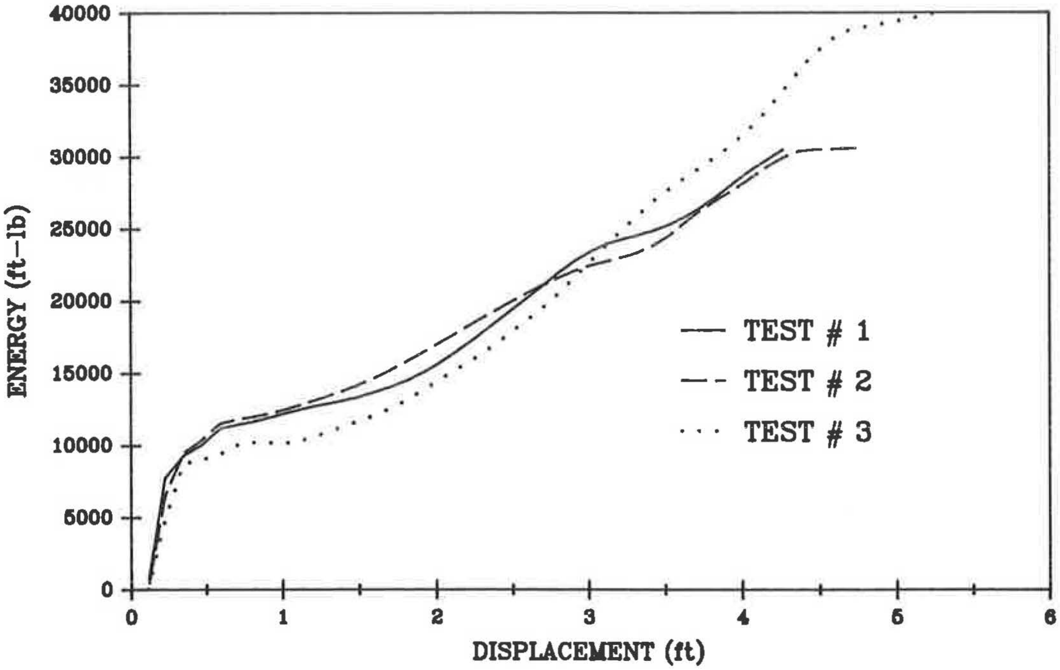

FIGURE 8 Pendulum test results of cover-plated specimens (27-in. slots).

carried it away from posts 4 and 5. Figure 10 shows the test vehicle and installation after test SR-2.

Test SR-3

This test examined the redirective capacity of the SRBCT. In it, a full-size vehicle impacted the terminal 12.5 ft from the end at 60 mph and 25°. The length of blocked-out rail was extended to include the first 43 ft of guardrail. Upon impact, the test vehicle began to redirect and was traveling parallel to the barrier when an unmodified guardrail section fractured at a splice. The vehicle yawed away from the barrier, and the driver's side was impaled on the exposed guardrail end. Figure 11 shows the test vehicle and system after test SR-3.

Test SR-4

As discussed above, two additional posts were added to the SRBCT between posts 3 and 4 and 4 and 5. These additional posts were not attached to the guardrail and were designed to provide additional lateral stiffness for redirectional purposes. The previous test was then repeated with much-improved performance. The test vehicle was smoothly redirected and all occupant-impact severity measures were within recommended limits. The maximum occupant impact velocity was 20.9 ft/sec, and the maximum occupant ridedown acceleration was 9.1 g. Although the velocity change (20.9 mph) during this test was somewhat higher than safety standard recommendations, the performance of this barrier was similar to that of most other guardrail systems, as shown in Table 3. The test was therefore considered a success. Figure 12 shows the test installation and test vehicle after test SR-4.

Test SR-5

This test evaluated terminal performance for mini-size vehicles impacting midway between the barrier end and the beginning of the length of need. The test vehicle impacted at the second post at 60 mph and 15°. The vehicle was smoothly redirected with no tendency for wheel snag. Although the lateral occupant-impact velocity (23.7 ft/sec) was above recommended limits, it was below the maximum allowable limit (*6*). Maximum occupant ridedown acceleration was 13.8 g. This test was considered a success. Figure 13 shows the test installation after test SR-5.

Test SR-6

The final test involved a full-size vehicle impacting the end of the terminal head-on at 60 mph. Upon impact, the first three posts were fractured and the vehicle penetrated the barrier in a controlled manner. The vehicle then traveled parallel to the barrier for approximately 100 ft before coming to rest. The longitudinal occupant-impact velocity was 17.4 ft/sec, and the maximum occupant ridedown acceleration was 5.8 g. All occupant risk values were within recommended limits (*6*), and the test was considered a success. The test vehicle and installation after test SR-6 are shown in Figure 14.

CONCLUSIONS AND RECOMMENDATIONS

The SRBCT has been tested and shown to meet *NCHRP Report 230* safety standards. The SRBCT does not rely on dynamic buckling of unsupported guardrails, and therefore its performance should not be affected by the shape of the

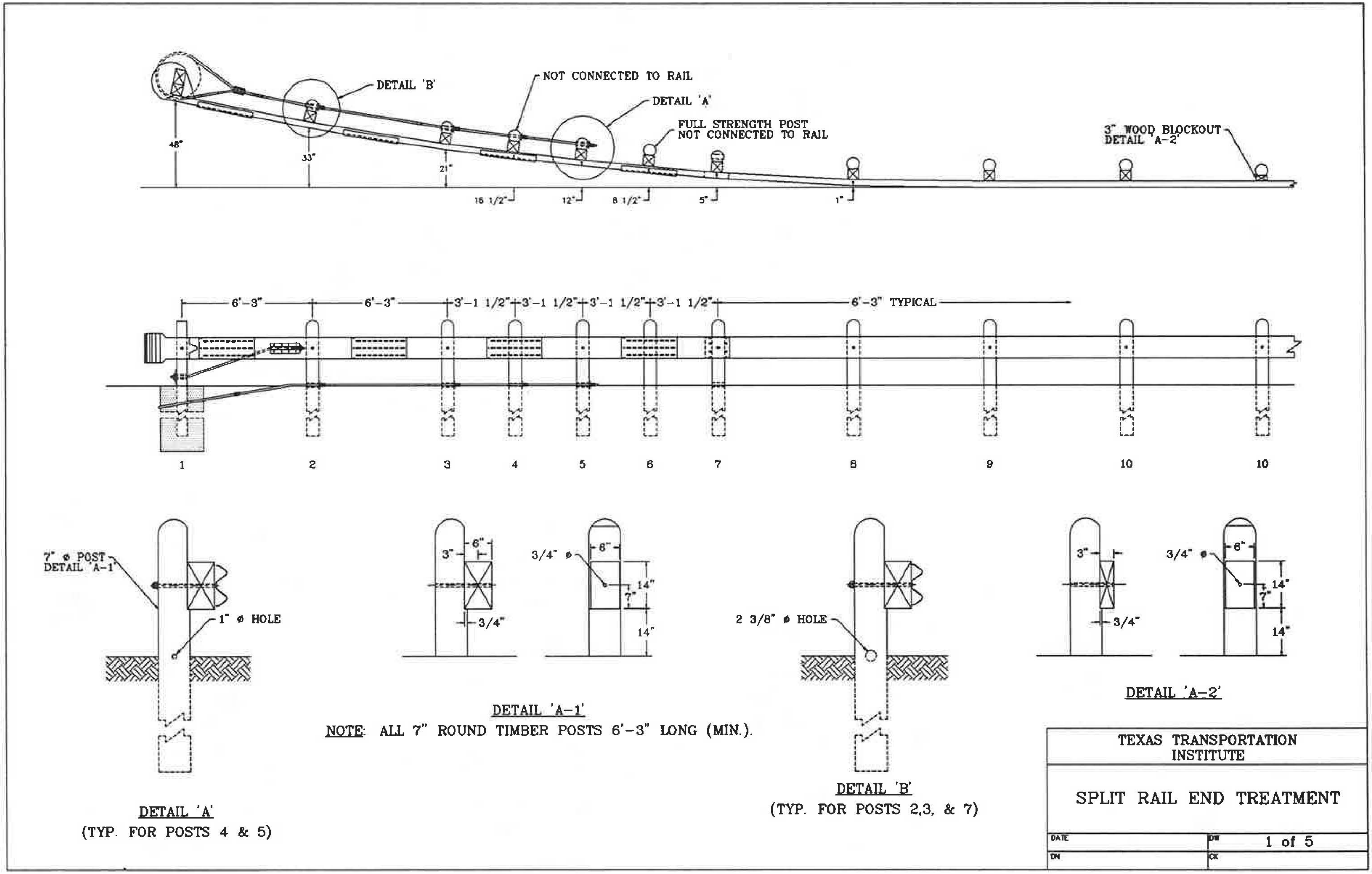

FIGURE 9 Final SRBCT design.

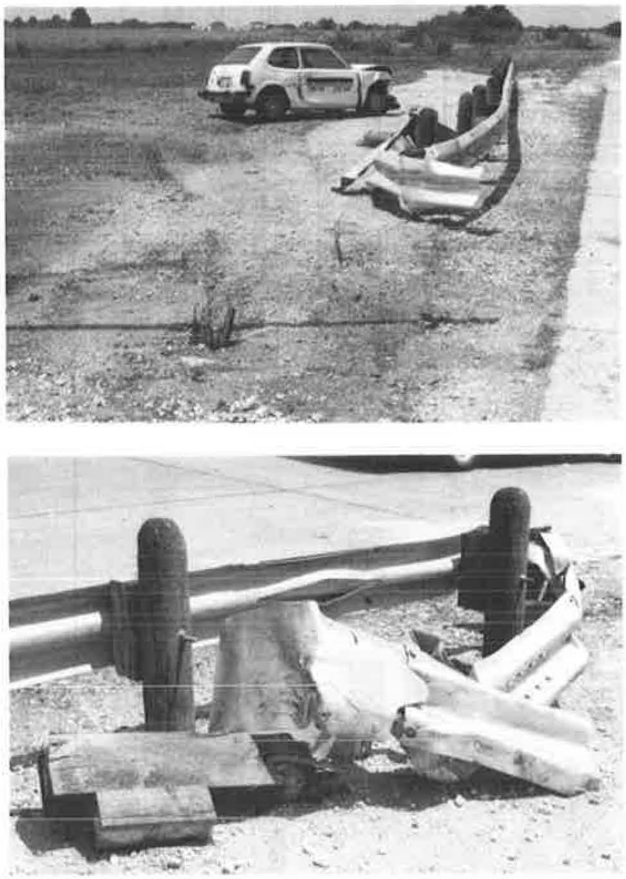

FIGURE 10 Test vehicle and installation after test SR-2.

FIGURE 11 Test vehicle and installation after test SR-3.

TABLE 3 VELOCITY CHANGES DURING LONGITUDINAL BARRIER IMPACTS

Vehicle Weight (lb)	Impact Velocity (mph)	Impact Angle (deg)	Service	Velocity Change (mph)
4,450	61.8	25.3	G4 (1S) on box culvert	24.6
4,500	58.2	25	G4 (1S) at turned down end	29.4
4,490	58.7	25	Guard fence at turned down end	22.6
4,490	58.5	23	Guard fence at turned down end	19.2
4,740	59.9	24	Rigid vertical wall	17.5
4,490	61.8	25.6	Rigid vertical wall	15.9

FIGURE 12 Test vehicle and installation after test SR-4.

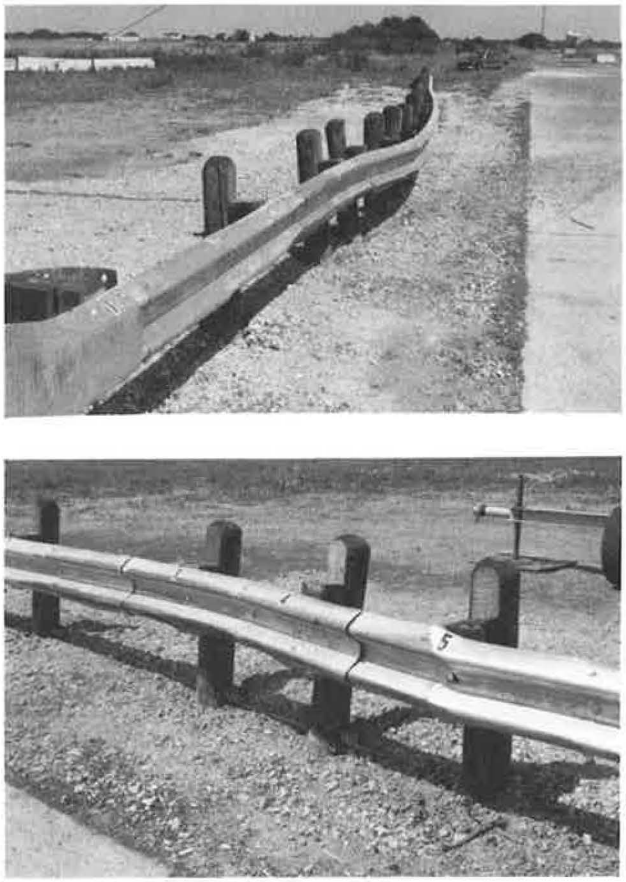

FIGURE 13 Test installation after test SR-5.

FIGURE 14 Test vehicle and installation after test SR-6.

flare. Furthermore, new mechanisms to enhance post breakaway should reduce any sensitivity to installation details. This end treatment should not be significantly more expensive than standard BCT designs. Major cost differences between the SRBCT and standard BCT designs are limited to the longitudinal slots and cover plates used on the first 25-ft segment of guardrail, the ground-line cable, and two additional posts. Therefore, whenever sufficient space is available for a 4-ft flared end treatment, this design should offer an inexpensive and safe alternative to the BCT. Finally, the design is quite similar to standard BCT designs, and retrofit of existing BCT installations should be inexpensive. Further testing of this device for retrofit situations is recommended.

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