crete barrier joints, because the joint was displaced several inches and the connector broken out by the large-sedan impact.

4. When the box beam was extended across the concrete barrier joint, the continuity connector and earth backfill provided adequate strength without the use of backup posts.

5. Use of carriage bolts instead of hex-head bolts to attach the box-beam rail to the concrete barrier reduced sheet-metal snagging.

6. The 4-ft clearance between the box-beam rail and the end of the concrete barrier is adequate.

For a full explanation of testing procedures, data analysis, and test results, the reader is referred to NYSDOT Research Report 117 (7).

ACKNOWLEDGMENTS

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The Connecticut Impact-Attenuation System

JOHN F. CARNEY III, CHARLES E. DOUGAN, and MARTIN W. HARGRAVE

ABSTRACT

The development of a new crash cushion is described. This impact-attenuation device is composed of steel tubular members formed from straight plate sections, which are bolted together to form a cluster. This device is unique in that it will trap an errant vehicle under most impact conditions. The vehicle will be redirected back out into the roadway only when the impact location is so close to the rear of the system that it is impossible to obtain acceptable energy-dissipation and deceleration-trapping responses because of the proximity of the site hazard. No other attenuation system in use today possesses this capability. In addition, the Connecticut impact-attenuation system exhibits the following characteristics: (a) it satisfies the impact performance standards outlined in Transportation Research Circular 191 and NCHRP Report 230, (b) it is inexpensive to fabricate, (c) the energy-dissipating tubes can be refurbished after impact and reused, (d) there is no flying debris associated with the crash event, and (e) it is constructed of readily available materials.

In May 1982 the Connecticut Department of Transportation (ConnDOT) initiated a research effort to develop a new highway crash cushion constructed of steel tubular members that would possess unique energy-dissipation characteristics. The system concept was an offshoot of the work performed in developing the Connecticut crash cushion (1,2), a truck-mounted attenuator that is currently being employed by ConnDOT field personnel and other state transportation agencies (3). The very favorable accident experience of the portable system (4,5) provided the incentive to apply the same engineering principles to the design and full-scale crash testing of the stationary crash cushion described in this paper.

Crash cushions are currently in widespread use in the United States to bring errant vehicles to a controlled stop when the impact is head on. Under side-impact conditions, systems using fender panels redirect the errant vehicle, even when the impact is near the front of the device. On the other hand, a sand-barrel crash cushion system provides almost no redirection and therefore possesses an inadequate energy-dissipation capacity when the vehicle is directed at the corner of the roadway hazard.

The California Department of Transportation (Caltrans) has recently completed 5 years of monitoring impact attenuators with video systems (6). Their report strongly recommended that further design work be done to make all crash cushions more energy absorbent when subjected to a side impact. The authors of this paper contend that an impact-attenuation device should trap the errant vehicle when it impacts the unit on the side unless the area of the impact on the device is so close to the back of the system that significant energy dissipation and acceptable deceleration responses are unobtainable because of the proximity of the hazard. Only in this situation should the impact-attenuation device redirect the vehicle back into the traffic flow. No energy-absorbing system currently employed possesses these characteristics, and it was the aim of this research project to develop such a system, employing steel tubes as the energy-dissipation components. Steel tubes possess the advantages of low cost, ready availability, and favorable energy-absorbing properties. Model tests conducted at Cambridge University in England (7) verified the analytical approach and ultimately led to two designs for a full-scale system. These two designs were subsequentially crash tested at the Calspan Advanced Technology Center in Buffalo, New York (8). The results of the seven crash tests performed by Calspan demonstrated the potential of the steel-tube attenuator design. The system was further refined during a series of nine crash tests conducted at the Texas Transportation Institute (TTI). These tests documented that this new device offered both redirection and entrapment capabilities, whereas commercially available attenuation systems provide either redirection or entrapment under side-impact conditions.

A technical description of the Connecticut impact-attenuation system (CIAS) is presented, the results of crash tests performed at TTI are documented, and the design changes that evolved during the testing program are outlined in chronological order.

DESCRIPTION OF THE SYSTEM

The CIAS, shown in Figure 1, is composed of 14 tubular members formed from straight (A-36) steel plate sections. These tubes are bolted together, rest on a concrete pad, and are attached to an appropriate backup structure. In order to cope with the redirectional crash test case involving an impact near the rear of the system, steel "tension" straps (ineffective under compressive loading) and "compression" pipes (ineffective in tension) are employed. This bracing system ensures that the crash cushion will respond in a stiff manner when subjected to an oblique impact near the rear of the unit, providing the necessary lateral force to redirect the errant vehicle. On the other hand, the braced tubes retain their unstiffened response when the attenuation system is crushed by impacts away from the back of the device.

The details of the analytical and experimental work that led to the design of the bracing system employed in the CIAS are reported elsewhere (9,10) and will not be repeated here. However, a few quasi-static results reported by Carney and Veillette (10) are reproduced to illustrate the dramatic effect that tension bracing has on the load-deflection response of a steel tube.

Figure 2 shows a tube with symmetrical double tension bracing with its loading rig. Small-scale tubes were tested (outside diameter, 4 in.; wall thickness, 0.087 in.; length, 2 in.) on an Instron 1321 testing machine interfaced with a Hewlett Packard 9825B data acquisition cartridge and plotter system. Before the testing, the tubes were annealed by being heated in an electric furnace for 20 min at 900°C and being allowed to cool slowly. High-tensile-strength steel wire (diameter 0.013 in.) was employed to provide the tension bracing. The wire lacing procedure was carefully done and typically consisted of 25 loops for each stiffener.

Figure 3 shows the theoretical and experimentally determined initial collapse loads obtained, in which P_θ and P_C are the initial collapse loads obtained for the braced and unbraced tubes, respectively. The correlation is considered to be quite good in view of the difficulties associated with accurate placement of the tension bracing. It is of interest to note that from the point of view of stiffness at the onset of collapse, double bracing at 30 degrees represents the optimum condition.

Dimensionless tube load-deflection curves for a wide range of bracing angles are presented in Figure 4 in which δ is the deflection of the tube, D is the outside tube diameter, and P is the applied load. The dramatic effect of the bracing angle on the stiffness and energy-dissipation capacity of the tube (area under P-δ curve) is readily apparent. It is of interest to note that when $\theta \geq 45$ degrees, the bracing does not act in tension during the deformation process and therefore has no effect on the response of the tube. The forces in the tension bracing for θ-values of 0 and 25 degrees are also presented in Figure 4.

It is emphasized that the tension bracing (steel straps) and compression bracing (1.5-in. ID pipe sections) have no effect on the response of the CIAS in head-on impacts. Under this loading, the tension bracing is loaded in compression and buckles. The compression bracing, being welded to the tube at one end only, carries no load during the collapse process because its free end separates from the tube wall when collapse occurs. The internal bracing system is only activated under side-impact conditions.

The effective performance of the CIAS under impact conditions is dependent on the appropriate interaction of the unit with its surroundings. The following peripheral system components are required:

1. A level concrete pad on which the steel tubes rest,
2. A structurally adequate backup structure,
3. Steel skids under the tubes to minimize friction during the collapse process, and

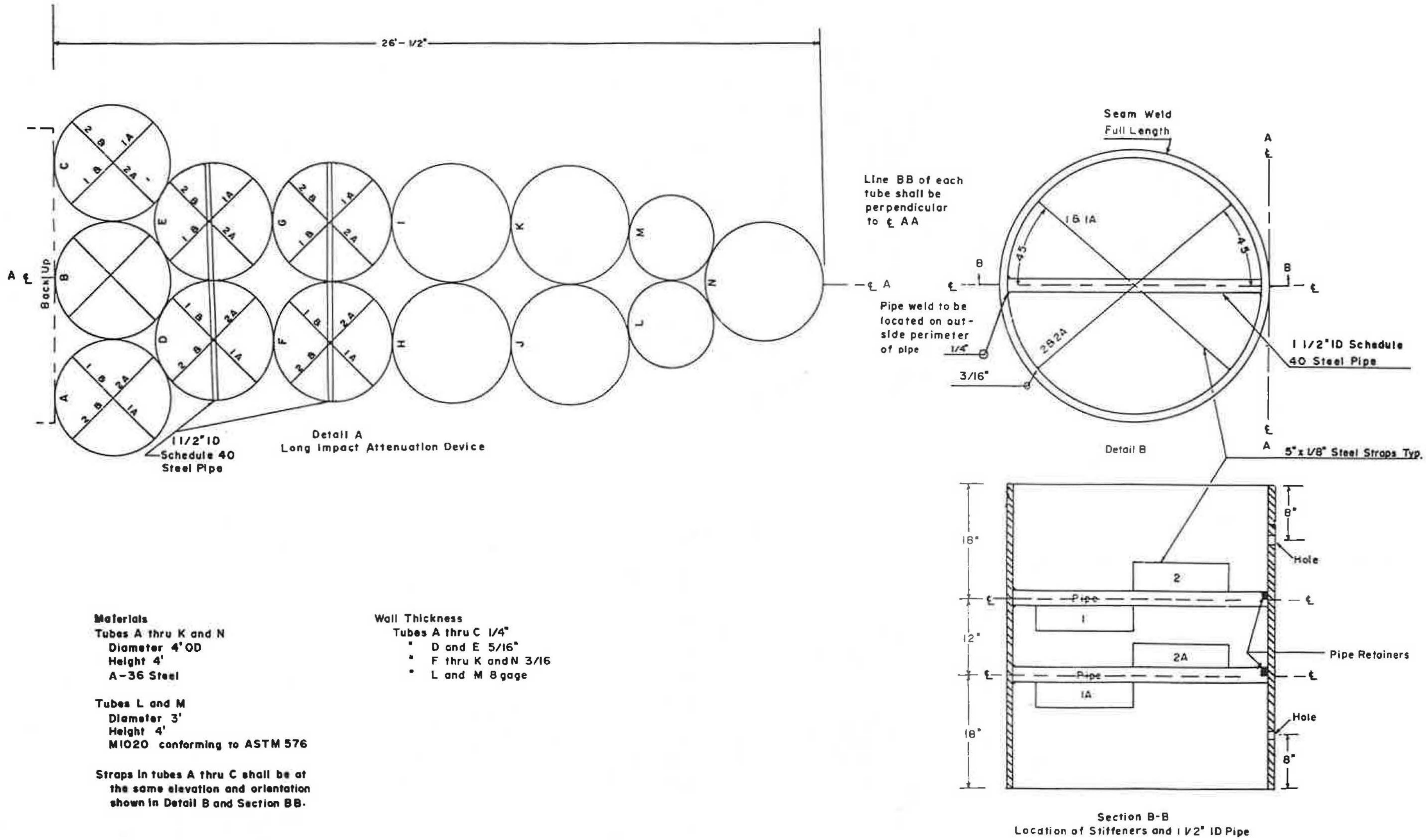

FIGURE 1 Shop fabrication details of CIAS.

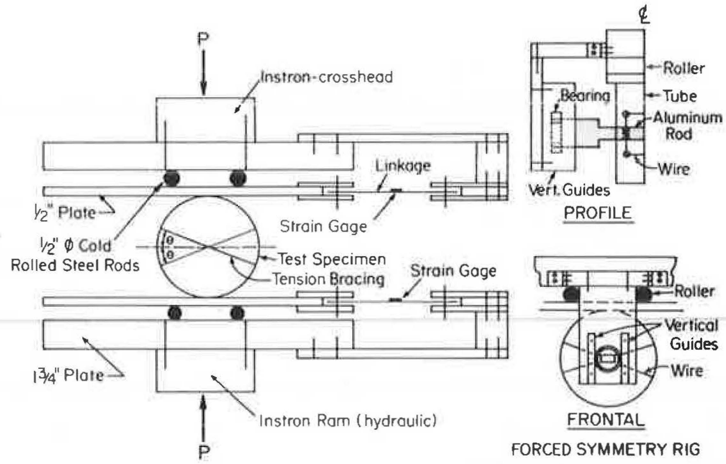

FIGURE 2 Braced tube and loading rig.

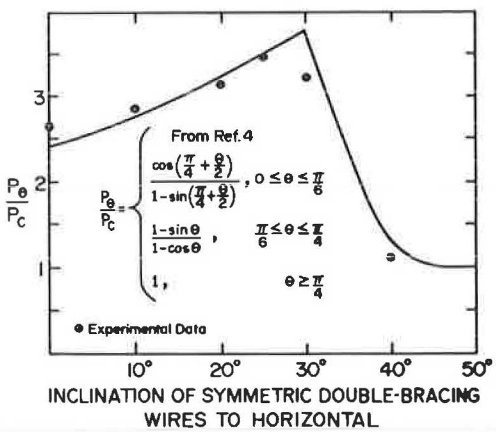

FIGURE 3 Variation in initial collapse loads with double bracing inclination.

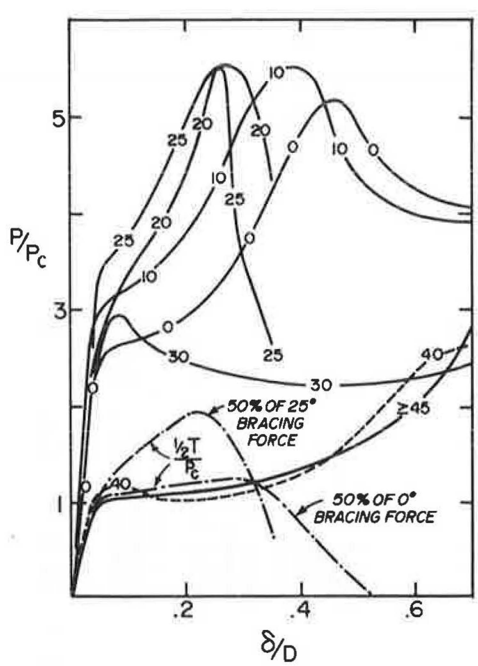

FIGURE 4 Load-deflection curves for double-braced tubes for various values of θ.

4. A vinyl-coated nylon nonlaminated cover to prevent the buildup of snow and ice in winter.

The complete design drawings for the CIAS may be obtained from Charles E. Dougan at ConnDOT.

The CIAS system is designed so that the tubes can be reused, even after an impact causing significant collapse of the system. Research has demonstrated that individual tubes can be reshaped and reused with an attendant saving in material cost. Thus, the CIAS has a potentially longer service life as compared with some of the conventional impact attenuators now in use. Test 9 described in the next section of the paper was conducted to show that the crash-test performance of the CIAS is unaffected when refurbished sections are used in the design. The data obtained verify that a CIAS constructed with refurbished cylindrical members meets all criteria set forth in NCHRP Report 230 and Transportation Research Circular (TRC) 191 (11,12).

CRASH-TEST PROGRAM

A total of nine full-scale crash tests were conducted at TTI. The crash tests were evaluated in accordance with the standards set forth in both TRC 191 and NCHRP Report 230. A summary of the nine crash tests is presented in Table 1. The complete individual crash-test reports and system design modifications made during the testing program have been described elsewhere (13).

It can be seen from Table 1 that design modifications took place during the first five crash tests. The major developments were as follows:

1. The height of the collapsing tubes was increased from 36 to 48 in. to eliminate vehicle ramping problems encountered in Tests 1 and 3.
2. The cover design was modified. Cellular plastic covers were replaced with a polyvinyl cover design. The polyvinyl cover remains attached to the crash cushion during the collapse and will prevent snow and ice from accumulating in the tube system in winter.
3. Steel skids were installed under the CIAS to reduce friction force buildup during the collapse process.
4. The tension stiffening system was modified, some tube thicknesses were changed, and an additional row of tubes was added to soften the impact response of the system.

TABLE 1 Summary of Crash-Tests Results

Test No.	Vehicle Weight (lb)	Impact Speed (mph)	Angle of Impact (degrees)	Point of Impact	Vehicle Stopping Distance (ft)	Occupant Impact Velocity[a] (ft/sec)		Vehicle Deceleration Data (g): Occupant Ridedown Peak[b] (10-msec Avg)		Vehicle Deceleration Data (g): Peak 50-msec Avg[c]		Vehicle Deceleration Data (g): Avg over Entire Event[c]	Vehicle Damage Classification[d] (TAD)	Comments
						Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Resultant			
1	4,500	59.9	0	Nose	NA	29.8	NA	13.7	NA	9.7	NA	NA	12FD2	Vehicle vaulted onto CIAS because of high center of gravity of vehicle and large friction forces developed at the rough concrete pad's surface; unit will rest on steel skids in future tests to reduce friction
2	1,800	59.8	0	Nose	13.4	34.9/39.2[e,f]	8.3	14.5	1.9	14.5	14.5	6.2	12FD3	Cellular plastic covers performed unsatisfactorily; new cover design used in subsequent tests
3	4,500	60.0	20	Along side	NA	28.2[e]	10.4	16.6	3.0	7.4	NA	NA	11FL4	Vehicle vaulted because of high center of gravity; tube heights increased from 36 to 48 in. to solve ramping problem
4	4,500	60.4	20	Along side	18.1	27.6[e]	11.5	20.6	1.5	13.3	13.5	6.5	11FD3	Stable impact response obtained; vehicle trapping achieved
5	4,500	61.7	0	Nose	19.5	29.7	NA	30.8	NA	12.7	12.9	6.3	12FD3	Polyvinyl cover design deemed satisfactory; no cover used in subsequent tests
6[g]	4,500	58.0	15	Corner of test hazard	NA	32.0	14.3[e]	9.6	11.6	9.5/6.6[h]	10.0	3.7/1.9[h]	11FL6	CIAS design now complete (see Figure 1) and used for Tests 6-9
7[g]	4,500	61.4	0	Nose	23.0	25.5[e]	4.5	12.6	0.9	10.4	10.4	5.2	12FD3	Excellent test results
8[g]	1,800	60.9	0	Nose	16.0	30.96/34.66[f]	NA	12.8	NA	11.6	11.6	5.7	12FD3	Excellent test results
9[g]	4,500	61.6	0	Nose	22.0	26.7	NA	12.8	NA	9.4	9.5	5.8	12FD2	Excellent test results; refurbished tubes employed

Note: NA = not applicable.

[a]NCHRP Report 230 recommends a longitudinal occupant impact velocity limit $[\Delta V_{Limit}]$ of 40 ft/sec/(acceptance factor). If the acceptance factor is set at 1.33, then $[(\Delta V)_{Design}]_{Long.}$ = 30 ft/sec. It recommends a lateral occupant impact velocity limit of 30 ft/sec (acceptance factor). If this acceptance factor is taken as 1.5, then $[(\Delta V)_{Design}]_{Lat.}$ = 20 ft/sec.

[b]NCHRP Report 230 recommends longitudinal and lateral occupant ridedown acceleration limits $[(a)_{Limit}]$ of 20 *g* /(acceptance factor) based on the highest 10-msec averages beginning with occupant impact. If the acceptance factor is set at 1.33 , then $(a)_{Design}$ = 15 *g* .

[c]For direct-on impacts, TRC 191 specifies a maximum average vehicle deceleration of 12 *g* as calculated from vehicle impact speed and passenger compartment stopping distance. When the test article functions by redirecting the vehicle, the maximum resultant 50-msec vehicle deceleration is specified to be 12 *g* when the impact angle is 15 degrees or less.

[d]Damage scale specified according to procedures developed by the Traffic Accident Data Project of the National Safety Council.

[e]Occurs first.

[f]The first impact velocity value is associated with the measured distance that the occupant would travel before impacting the compartment interior (1.25 ft). The second impact velocity value corresponds to an assumed occupant travel distance of 2 ft.

[g]Two longitudinal and two lateral accelerometers were employed. Occupant impact velocities and decelerations are average values.

[h]Lateral acceleration value.

The CIAS design was finalized following Test 5. No additional modifications were made during Tests 6 through 9, which are described as follows:

1. Test 6 (August 9, 1983)
   a. System tested: The impact attenuator tested was that shown in Figure 1.
   b. Test vehicle: A Plymouth Salon (1978) impacted the Connecticut attenuator at 58.0 mph and 15 degrees, directed at the rear corner of the system (Figure 5). The vehicle weighed 4,500 lb with 2,482 lb on the front axle and 2,018 lb on the rear axle.
   c. Test results: The crash cushion smoothly redirected the vehicle. Figures 6-8 show the CIAS and the vehicle after Test 6 (see Table 1 for measured decelerations). This test demonstrated that the tube-stiffening system provides the lateral resistance required to redirect a vehicle under these severe test conditions.

2. Test 7 (August 11, 1983)
   a. System tested: Same as that in Test 6 (see Figure 1).
   b. Test vehicle: A Plymouth Salon (1978) impacted the attenuator at 61.4 mph and 0 degrees. The vehicle weighed 4,500 lb with 2,460 lb on the front axle and 2,040 lb on the rear axle. Views of the test vehicle and the CIAS before the test are shown in Figures 9 and 10.

FIGURE 5 Vehicle alignment before Test 6.

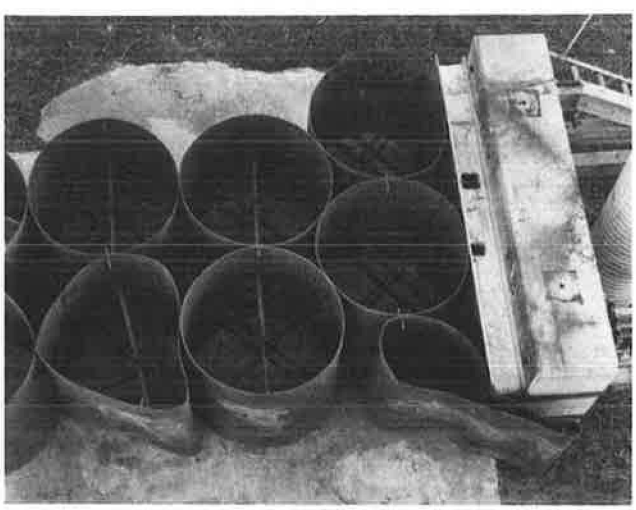

FIGURE 6 Top view of CIAS after Test 6.

   c. Test results: The vehicle collapsed the attenuator almost completely, as shown in Figure 11 (see Table 1 for measured decelerations). The front end of the car sustained an average crush of 13.5 in. (Figure 12). All occupant risk values in this test were well below the guidelines of both TRC 191 and NCHRP Report 230.

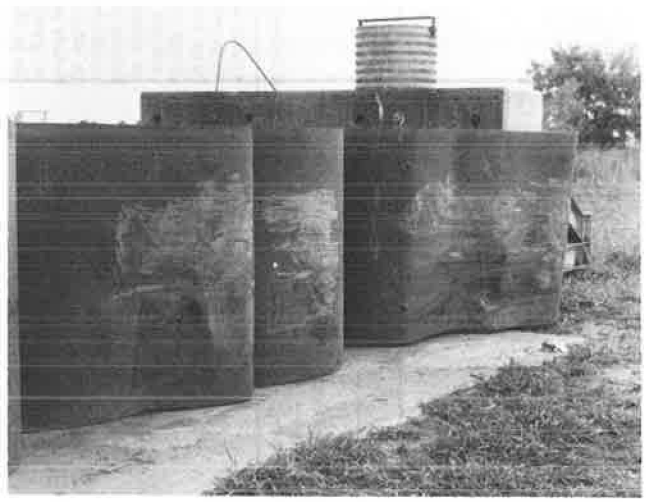

FIGURE 7 Side view of CIAS after Test 6.

FIGURE 8 Side view of CIAS showing test vehicle after Test 6.

FIGURE 9 Side view of CIAS before Test 7.

3. Test 8 (October 4, 1983)

a. System tested: Same as that in Tests 6 and 7 (see Figure 1).

b. Test vehicle: A Honda Civic (1977) impacted the attenuator at 60.9 mph and 0 degrees. The vehicle weighed 1,800 lb with 1,069 lb on the front axle and 731 lb on the rear axle (Figure 13).

c. Test results: The vehicle fully collapsed the first five rows of the attenuator, but the back two rows of the system were deformed only slightly (Figures 14 and 15). The front end of the vehicle sustained an average crush of 9 in. (Figure 16). Two occupant impact velocities are reported in Table 1 for this test. As in Test 2, they correspond to occupant travel distances of 1.25 and 2.0 ft.

FIGURE 10 Test vehicle before Test 7.

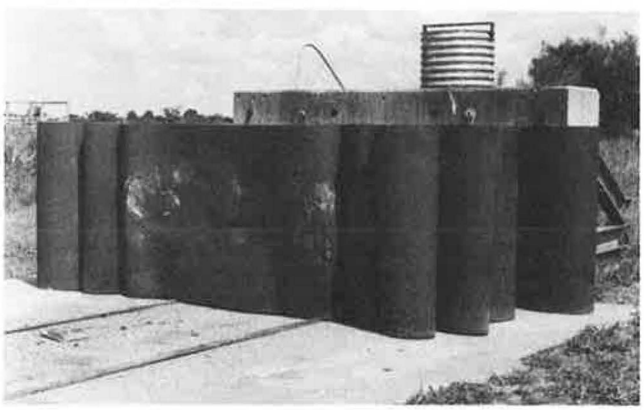

FIGURE 11 Front angular view of CIAS after Test 7.

FIGURE 12 Frontal damage sustained by vehicle in Test 7.

FIGURE 13 Test vehicle before Test 8.

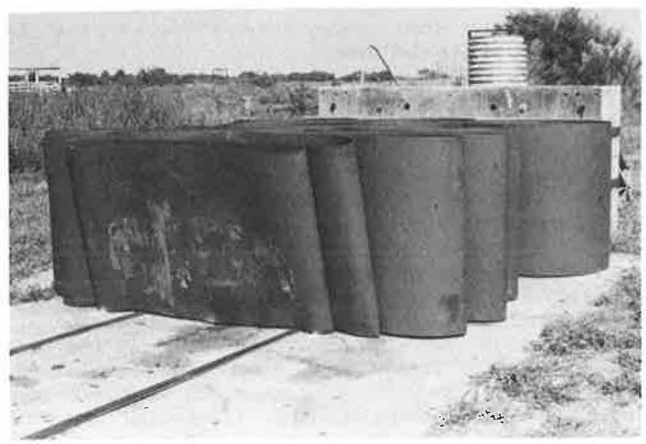

FIGURE 14 Side view of collapsed system, Test 8.

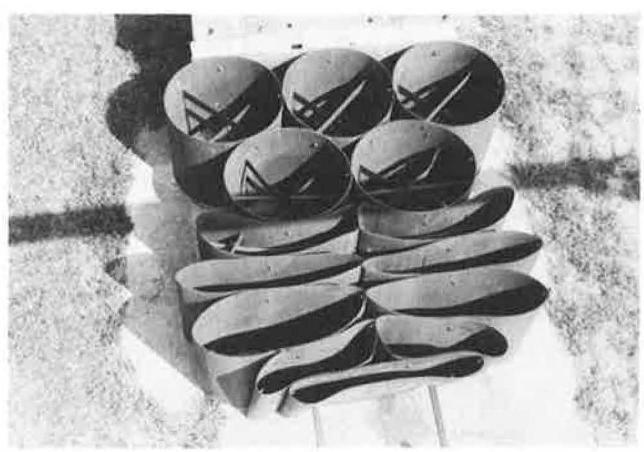

FIGURE 15 Top view of collapsed system, Test 8.

FIGURE 16 Damage sustained by vehicle, Test 8.

4. Test 9 (October 6, 1983)

a. System tested: Same as that in Tests 6-8 (see Figure 1).

b. Test vehicle: A Chrysler Newport (1979) impacted the attenuator at 61.6 mph and 0 degrees. The vehicle weighed 4,500 lb with 2,358 lb on the front axle and 2,142 lb on the rear axle.

c. Test results: This test is a repeat of Test 7 with refurbished CIAS materials. The unit was composed of 14 tubes used in previous crash tests to demonstrate that restored tubes would exhibit the same energy-dissipation behavior as virgin tubular sections.

Two major points were considered during the planning of the restoration process. First, the cost was to be held down without sacrificing quality. Second, the final process was to be one that could be practically performed on an attenuator in actual use after an impact.

The 4-ft-high tubes were available from four earlier crash tests: Tests 4, 5, 6, and 7. The prior location of each steel tube used in the restored unit and the action taken to correct the damage are summarized in Table 2. Six tubes had no previous damage: five of these (J, K, L, M, and N) were left undamaged from Test 6; the other (C) had not been used before. It contained thin 1/8-in. straps that were replaced with the correct pipes and straps. Three tubes (B, D, and E) were rerounded by placing hydraulic jacks inside them. Two tubes (F and G) were only slightly out of round. Neither contained bracing, but the addition of the needed pipes and straps made the tubes round again.

The remaining three tubes (A, H, and I) were rerolled by a commercial metal fabricator. Before the tubes could be rerolled, all protrusions such as seam welds and bracing had to be removed and ground smooth. Tube A had not been severely damaged. The

TABLE 2 Summary of Refurbished Tubes Used in Crash Test 9

Restored Unit Tube	Prior Location	Corrective Action
A	A, Test 6	Rerolled and steel added
B	B, Test 6	Rerounded with jacks
C	E, unused	Bracing replaced with correct type
D	D, Test 5	Rerounded with jacks
E	E, Test 6	Rerounded with jacks
F	H, Test 5	Rerounded with steel addition
G	I, Test 6	Rerounded with steel addition
H	J, Test 7	Rerolled
I	K, Test 7	Cut and reverse rolled
J	J, Test 5	Left undamaged
K	K, Test 6	Left undamaged
L	L, Test 5	Left undamaged
M	M, Test 5	Left undamaged
N	N, Test 5	Left undamaged

FIGURE 17 Tube A mounted in rolling mill.

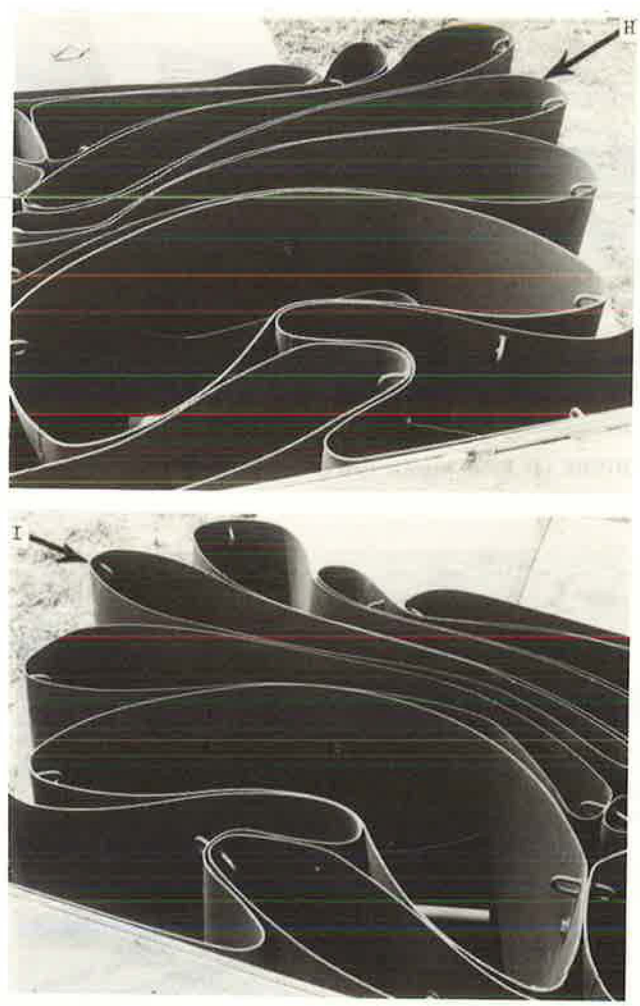

FIGURE 18 Tubes H and I after Test 7.

pipes and straps were removed and it was rerolled from the existing semiround shape. Figure 17 shows Tube A mounted in a rolling mill before it was rerolled. After 1.5 hr of rerolling, new pipes and straps were added to the tube.

Figure 18 shows Tubes H and I, which had been severely deformed, before each was removed from the previous attenuator. After 3 hr of rerolling, Tube H looked as it does in Figure 19. A different method of rerolling was tried for Tube I: it was cut along the seam with a torch. Figure 20 shows Tube I after cutting. It was then flattened, rolled on the reverse side, and rewelded. A total of 2.5 hr was spent cutting, rolling, and welding the tube.

It can be seen from Figures 21 and 22 and Table 1 that the system's response in Test 9 was essentially identical to that in Test 7. The only discernible difference to be reported concerns the relative stiffness of the front ends of the test vehicles employed in Tests 7 and 9. The Chrysler Newport was significantly stiffer than the Plymouth Salon used in Test 7, sustaining an average crush of only 8 in. This very successful test proves that collapsed tubes can be economically restored and used again in the CIAS without affecting system performance.

DISCUSSION

The final design of the CIAS evolved during the first phase of the testing program. No design changes were made subsequent to the fifth crash test. Tests 6-9 all exhibited excellent performance characteristics with respect to both NCHRP Report 230 and TRC 191.

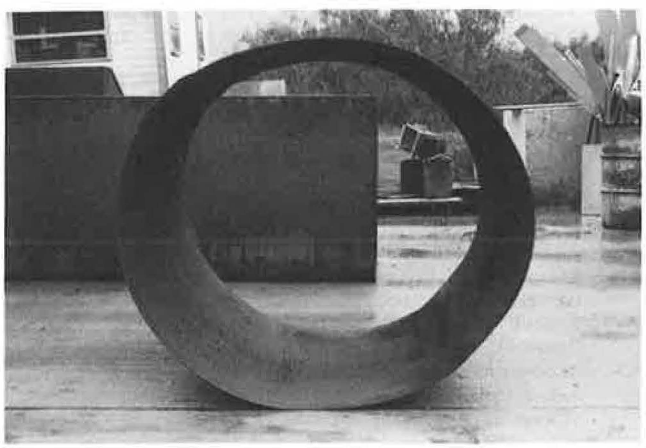

FIGURE 19 Tube H after rerolling.

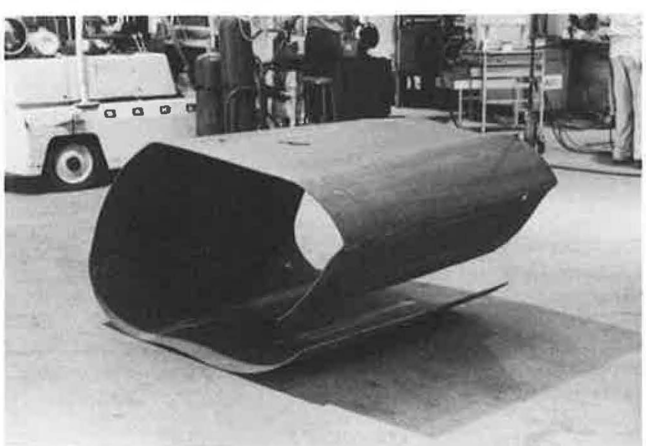

FIGURE 20 Tube I after cutting.

FIGURE 21 Before Test 9: test vehicle (top) and top view of CIAS (bottom).

The CIAS possesses unique trapping and redirectional characteristics. An extensive full-scale crash testing program (16 tests) (8) has verified the effectiveness of the system, which has a unit fabrication cost of $4,200. ConnDOT installed four such systems in the field in 1984. The locations were selected by the Office of Research and other affected units based on field experience. ConnDOT research personnel will monitor the performance of the CIAS, working closely with maintenance, design, traffic, and law enforcement personnel to obtain sufficient data to evaluate the effectiveness of the system. A 3-year performance evaluation is planned during which a frequent regular inspection routine will be set up. The inspectors will be equipped with cans of spray paint to cover scrape marks on the tubes caused by minor hits. With such a procedure, brush-type hits can be easily detected.

ConnDOT has produced a short narrated color film to document the construction of the units, highlight the crash-testing program, describe how the system is installed in the field, and summarize available performance data. Information regarding this film can be obtained from the second author of this paper.

SUMMARY AND CONCLUSIONS

The development of a new crash cushion is described in this paper. This impact-attenuation device is composed of steel tubular members formed from

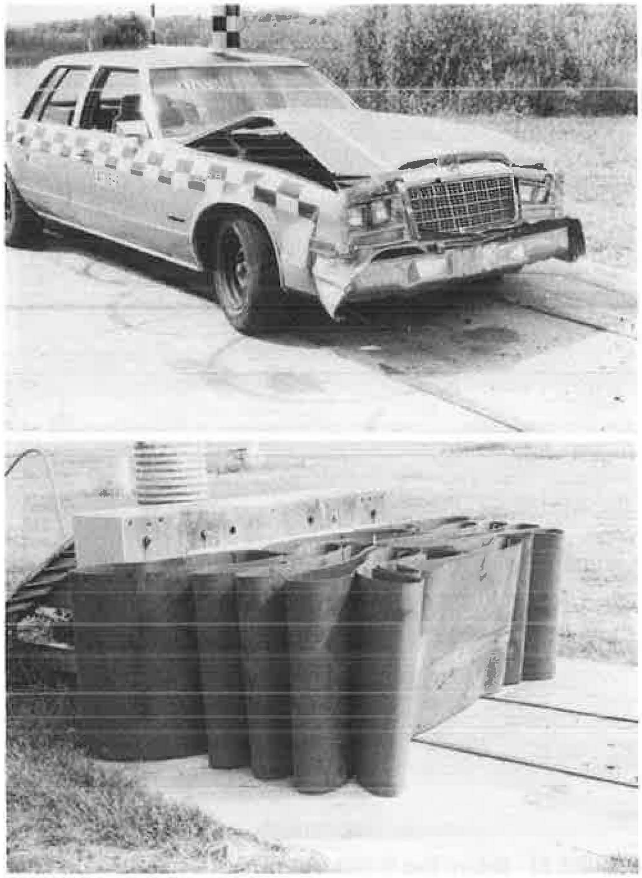

FIGURE 22 After Test 9: damage sustained by test vehicle (top) and side view of collapsed system (bottom).

straight plate sections, which are bolted together to form a cluster. This device is unique in that it will trap an errant vehicle under most impact conditions. The vehicle will be redirected back out into the roadway only when the impact location is so close to the rear of the system that it is impossible to obtain an acceptable energy-dissipation and deceleration-trapping response because of the proximity of the site hazard. No other attenuation system in use today possesses this capability.

In addition, the Connecticut impact-attenuation system exhibits the following characteristics:

1. It satisfies the impact performance standards outlined in TRC 191 and NCHRP Report 230;
2. It is inexpensive to fabricate;
3. It is inexpensive to repair after impact (Test 9 demonstrated that collapsed tubes can be restored to their original circular configurations and reused), and the energy-dissipating tubes can be refurbished and reused;
4. There is no flying debris associated with the crash event; and
5. It is constructed of readily available materials.

ACKNOWLEDGMENT

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