PENDULUM TESTS USING RIGID AND CRUSHABLE BUMPERS

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The test program discussed in this paper consisted of 19 tests of a breakaway sign support using a 2,000-lb (907-kg) pendulum mass impacting the support at 20 mph (32 km/h). Use of both rigid and crushable bumpers permitted examination of these techniques compared with current momentum-change criterion. In addition, the effects of bolt-tightening torque on the slip-base release loads were investigated. Hi-Lok frangible nuts, which control tightening torque, were also evaluated for the design torque condition. Only in the crushable bumper tests were dramatically different results obtained for the various nut-tightening torques when momentum change was used as the criterion. Momentum change with the hard bumper was 65 ± 15 lbf-sec (289 ± 67 N-s) for all base-nut torque levels. Momentum change with the crushable bumper ranged from 88 lbf-sec (391 N-s) for design torque condition to 398 lbf-sec (1770 N-s) for the overtorqued condition. Repeatability of slip-base loads was generally good when both a calibrated torque wrench and the Hi-Lok torque control nuts were used. It was concluded that momentum-change criterion is insufficient in evaluating results of pendulum tests using a rigid bumper. Use of a bumper with vehicle crush characteristics appears to provide a superior experimental evaluation.

•DEVELOPMENT of breakaway sign and luminaire supports during the 1960s has contributed greatly to the safety of the roadside. In a Federal Highway Administration circular memorandum (1), an acceptance criterion was set for luminaire supports. This criterion was a vehicle momentum change of 1,100 lbf-sec (4893 N-s) or less based on full-scale crash tests. A later FHWA report (2) permitted dynamic laboratory tests (a ballistic pendulum of other equivalent means) to be used instead of the more expensive and generally less repeatable vehicle impact test. This laboratory test criterion specified a change in pendulum momentum of 400 lbf-sec (1779 N-s) or less.

Chisholm and Viner (3) in a recent FHWA report discussed the relationship between the two criteria. It is apparent from their work that correlation of pendulum tests and vehicle impact tests varies considerably. Factors that may be the cause of poor data correlation include different types of base supports (e.g., frangible, shoe, and slip), fracture or initiation force level, strain rate sensitivity of materials, vehicle crush properties, and insufficiency of momentum-change criterion. For an illustration, breakaway base supports A and B are evaluated by pendulum tests, and the idealized results are shown in Figure 1a; although the resistance forces are different, the momentum changes (i.e.,, area of force-time plot) are equal. These same base supports are then evaluated in vehicle crash tests (Figure 1b). For A, the vehicle crushes until resistance force is sufficient to initiate base-support fracture F_A at time T_{A_1} from time T_{A_1} to T_{A_2}; no further vehicle crushing occurs, and momentun change is caused by breaking and displacing the support. Characteristics for the B test are similar to those for the A test except addition of vehicle crushing is necessary to achieve the higher base-support initiation force F_B. The point to be made is that there is significant difference between the momentum change (or linear impulse) for the two plots of Figure 1b, even though pendulum tests based on momentum change alone (Figure 1a) may suggest equivalent base-support performance.

Figure 1. Comparison of vehicle and pendulum tests.

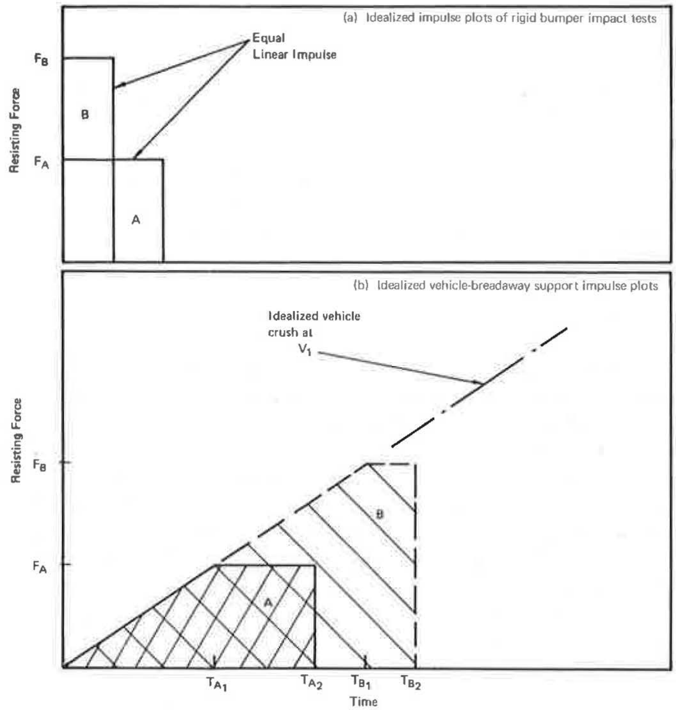


Figure 2. Sign support details.

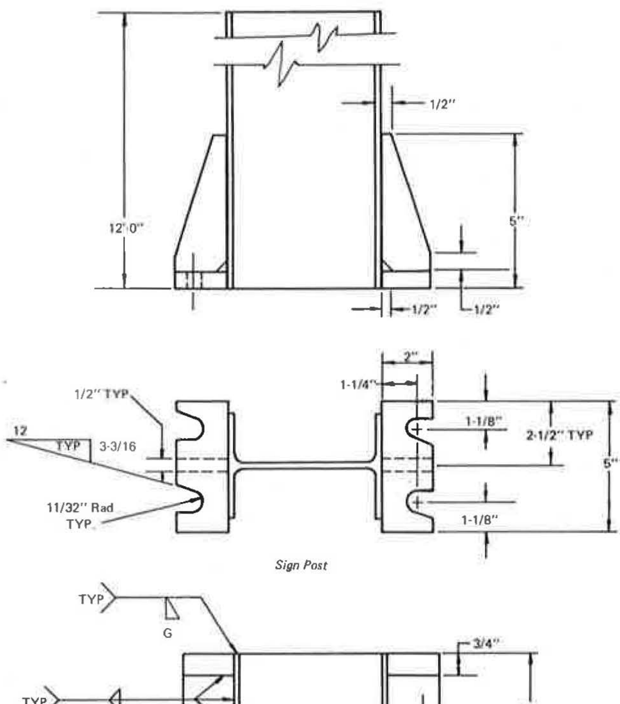
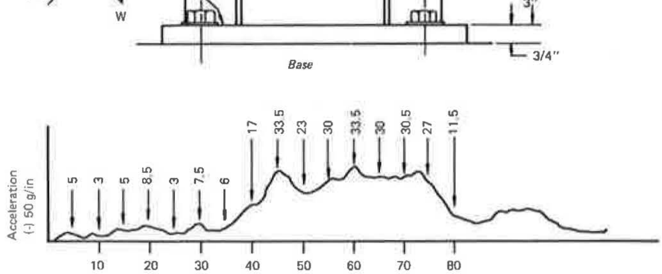


Figure 3. Acceleration versus time.



Ref: Ford Motor Company

In view of the limitation of rigid bumper pendulum tests, a decision was made to investigate the use of a crushable bumper in pendulum tests to better simulate actual interaction of the vehicle and the breakaway support. This paper discusses and compares results of pendulum experiments using both rigid and crushable pendulum bumpers on a common breakaway sign support. In addition, effects of bolt torque control on slip-base loads and momentum change were studied.

TEST PROGRAM

Nineteen tests were conducted by using a 2,000-lb (907-kg) pendulum mass equipped with both hard and crushable bumpers. The deformable bumpers were designed to simulate vehicle crush and were constructed in stages using aluminum honeycomb as the energy-absorbing element.

A typical sign support specified by many states was selected as the impacted test article. A light section [W 6 in. by 8.5 lb/ft (W 15.2 cm by 12.3 kg/m)] was selected to minimize inertial effects on the data. Dimensions of the slip base are shown in Figure 2; the design nut-tightening torque for this slip-base support using ⅝-in.-diameter (15.9-mm) ASTM A325 bolts is 450 lbf-in. (51 N · m).

Since a purpose of this program was to study the relative performance of pendulum bumpers, a complete sign assembly was not used. To compensate for resistance of the fuse plate (i.e., the upper breakaway hinge) in a sign support assembly, the height of the support was increased from the usual 7 to 12 ft (2.1 to 3.7 m).

CRUSHABLE BUMPER DESIGN

Several design requirements were established for the crushable bumper. A decision was made to design the bumper using time-acceleration data from an impact of a 1971 Ford Pinto (subcompact) automobile into a rigid pole at the vehicle centerline. Although the time-acceleration data were from tests conducted at 30 mph (48 km/h), it was felt that the bumper would yield good results at 20 mph (32 km/h). In addition, the bumper was to be inexpensive and lend itself to rapid fabrication. (Near the end of the program, the bumper was further simplified, and this resulted in cost savings.)

Aluminum honeycomb material was selected for the bumper assembly because the material is readily available, the crushing strength is predictable, the material cost is relatively low, the density is quite low (so that a change in bumper configuration would have a negligible effect on the pendulum weight), and the honeycomb material can be supplied in a wide range of crushing strengths.

Selection of the proper honeycomb densities required determination of impact force versus vehicle displacement for the full-scale automobile. Accordingly, the acceleration-time curve for the 1971 Pinto was integrated, and an average acceleration was determined for each 5-msec interval and used in developing a simplified force-time curve. (Only the first 80-msec of the curve were used, since it was felt that the slip-base sign would fail within that time span.) Based on these force-time data, a force-displacement curve was calculated and was the basis of the dimensional and density design of the bumper. Steps used in formulating the force-displacement property are shown in Figures 3, 4, 5, and 6. Figures 3, 4, and 5 apply to a 1971 Pinto impacting a rigid pole at 30 mph (48 km/h) at the vehicle centerline. Figure 7 shows the bumper configurations. The final bumper design is shown in Figure 7b.

Column instability occurred with the initial crushable bumper configuration in those tests with high base-nut torques. To provide lateral support to the bumper column, guide channels were added to the bumper design as shown in Figure 7d. It should be noted that this design allowed a much more rapid and economical test procedure.

Figure 4. Dynamic force versus time.

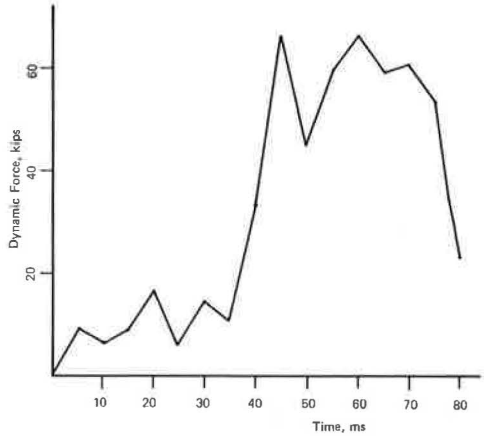


Figure 5. Dynamic force versus vehicle displacement.

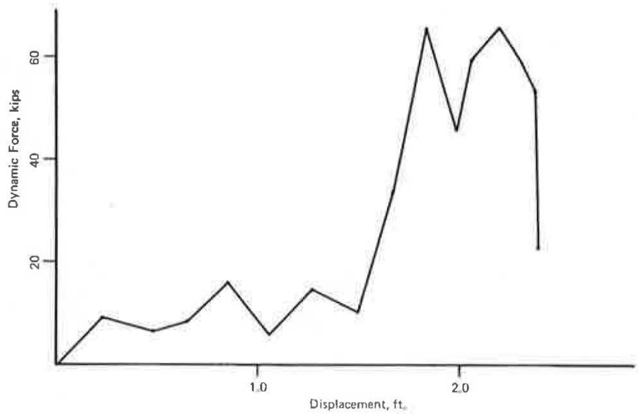
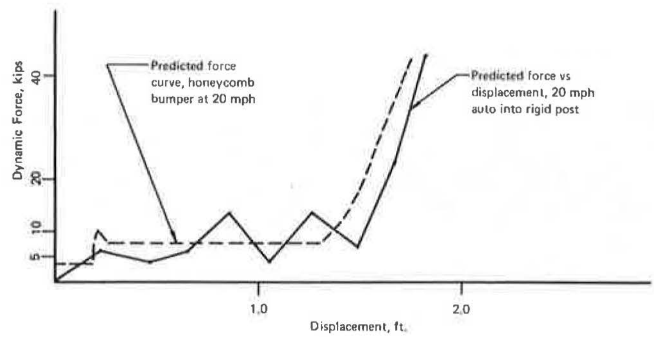


Figure 6. Predicted force response of honeycomb bumper.



TEST PROCEDURE

The sign base was installed on a rigid foundation as shown in Figure 8. The sign support was attached to the base for each test using four ⅝-in.-diameter (15.9-mm) galvanized ASTM A325 bolts. Heavy hex nuts (ASTM A325) used for the 0, 900, and 1,350-lbf-in. (0, 102, and 153-N·m) torque tests were installed with a calibrated torque wrench by using the installation method specified on typical state plans. The CHL14-10 Hi-Lok nut used for the 450-lbf-in. (50.8-N·m) torque tests is designed to provide the bolt preload of a heavy hex nut installed at that torque. During installation, the

Figure 7. Bumper configurations.

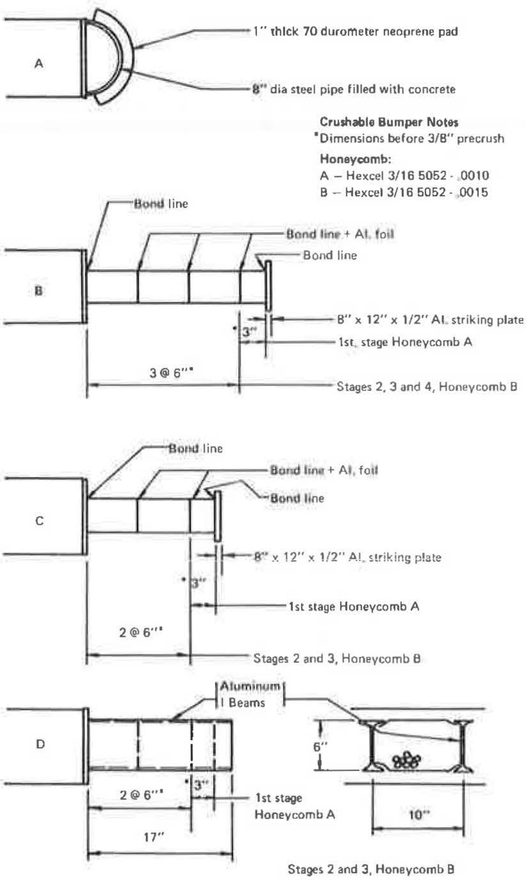


Figure 8. Test installation.

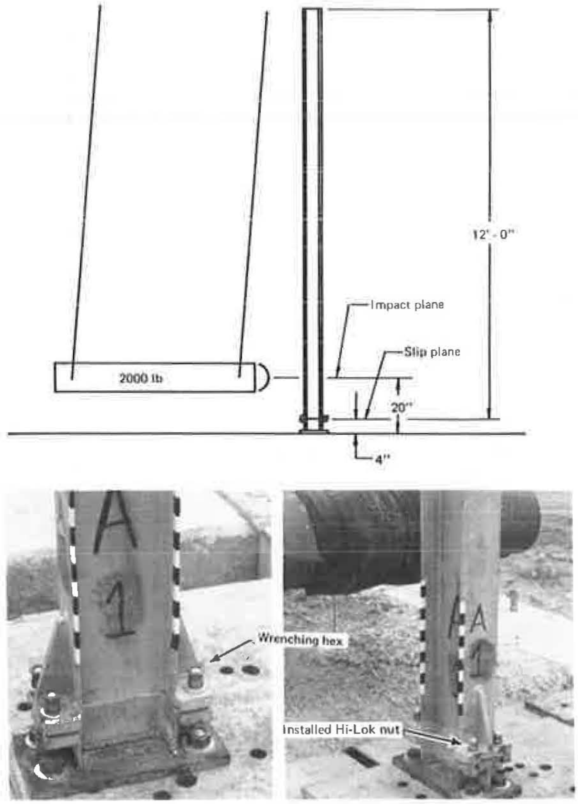
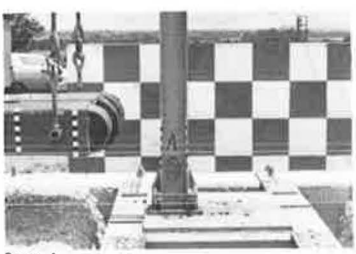
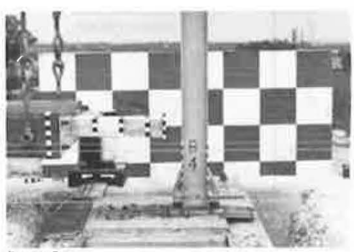


Figure 9. Test program bumpers.


Bumper A


Bumper B


Bumper C


Bumper D

unique wrenching hex automatically shears off at the nut's torque-off groove when a predetermined design torque is reached.

Four different bumper configurations were used as shown in Figures 7 and 9. Buckling of the deformable bumpers B and C led to a redesign, configuration D, which performed as desired.

The 2,000-lb (907-kg) pendulum mass was hoisted to the appropriate drop height for a 20-mph (32-km/h) impact and was released. Impact data were obtained from a high-speed camera and accelerometers mounted on the pendulum mass. Data recorded by high-speed tape recorders were replayed and recorded (unfiltered) on oscillograph charts. A summary of the data acquisition systems is given in Table 1.

TEST RESULTS

Results of the tests are given in Table 2; an example of a data trace for test B-4(2) is shown in Figure 10. When the hard bumper was used, the peak force generally increased as nut torque increased, although linear-impulse (change-in-momentum) values were within a range of 65 ± 15 lbf-sec (289 ± 67 N-s).

The crushable bumper tests used three bumper configurations. Buckling of the bumpers occurred in tests B-5, B-6, B-7, B-8, and B-9. Bumpers in tests B-1(2), B-2, B-3, and B-4(2) performed as designed. Figure 11 shows the bumpers after testing. The successful performance (no buckling) of the C configuration bumper in tests B-2 and B-3 can be attributed to the low resistance afforded by the sign support installed with the Hi-Lok nuts. In tests with the same bumper design but with higher installation torques (tests B-5 and B-7), instability of the bumpers occurred because of the higher loads.

Comparison of results in tests B-2 and B-3 with the C bumper indicates good repeatability when the Hi-Lok nuts were used. Test B-1(2) with the improved bumper yielded similar force and impulse values. The hard bumper-Hi-Lok nut tests A-1 and A-2 demonstrated excellent repeatability for peak force and impulse values. Other torque test values were more erratic, although the two 900-lbf-in. (102-N·m) torque test results were in close agreement.

Figures 12 and 13 contain sequential photographs of the test series.

CONCLUSIONS

1. A crushable bumper has been designed and evaluated for use in evaluating breakaway or yielding highway structures. The bumper approximates the front end crush properties of a subcompact car (i.e., 1971 Ford Pinto) striking a rigid pole at 20 to 30 mph (32 to 48 km/h). The design is simple, economical, and easy to use. Use of the crushable bumper should improve the effectiveness of pendulum tests in predicting safe roadside structures.

2. Momentum change criterion alone is insufficient in evaluating results of pendulum tests using a rigid bumper. Base-support initiation force, which is less predictable, may be a necessary qualification to the change-of-momentum criterion. The crushable bumper appears to be a preferable alternate.

3. In a comparison of impulse values from the hard bumper tests with those from crushable bumper tests, the difference in impulse values for a range of base torques is demonstrated only with the crushable bumper tests.

4. Repeatability of the slip-base test results was generally good for a specified torque. Installation of the sign support using Hi-Lok torque control nuts provides control over the slip-initiation load comparable to that obtained with a careful installation of conventional units using a calibrated torque wrench and can be inspected visually.

Table 1. Electronic data acquisition system.

Component	Function	Equipment	Description
Transducer	Converts a physical phenomenon to an electric signal	Accelerometer	Kistler 815A7, ±250g; frequency response -5 percent at 1 Hz and ±5 percent at 6000 Hz
Tape recorder	Provides permanent, high-quality magnetic tape record of test data	CEC VR-3300 magnetic tape recorder-reproducer	14-channel FM recorder Tape speeds: 1⅞ to 60 in./sec Extended bandwidth: DC to 20 kc Center frequency: 108 kc Signal/noise: 55 dB minimum Input sensitivity: 0.5 to 10.0v rms Linearity: 0.5 percent of full scale
Oscillograph	Provides analog traces of raw and filtered data	CEC 5-124A oscillograph	8-channel oscillograph with independent galvonometer and galvonometer circuits; typical galvonometers used are CDC 7-326 (within ±5 percent flat frequency response from 0 to 3000 Hz) and CDC 7-361 (0 to 5000 Hz)
Preamplifier	Scales and amplifies transducer signal	Southwest Research Institute design	Completes transducer circuit and amplifies signal by factor of 5 for tape recording

Note: 1 in. = 2.54 cm.

Table 2. Summary of test data.

Specimen No.	Bumper Configuration[a]	Slip-Base Nut	Slip-Base Nut Torque (lbf-in.)	Peak Acceleration (g)	Peak Force (kips)	Impact Duration (sec)	Linear Impulse (lbf-sec)
A-1	Hard A	Hi-Lok	450	11.8	23.7	0.008	63
A-2	Hard A	Hi-Lok	450	11.5	23.0	0.006	60
A-3	Hard A	Heavy hex	1,350	15.0	30.0	0.006	57
A-4	Hard A	Heavy hex	1,350	13.4	26.9	0.007	75
A-5	Hard A	Heavy hex	900	12.6	25.1	0.006	63
A-6	Hard A	Heavy hex	900	12.7	25.5	0.007	69
A-7	Hard A	Heavy hex	0	9.8	19.5	0.007	50
A-8	Hard A	Heavy hex	0	11.8	23.6	0.007	57
B-1(2)	Crushable D	Hi-Lok	450	4.8	9.6	0.017	88
B-2	Crushable C	Hi-Lok	450	3.4	6.8	0.019	79
B-3	Crushable C	Hi-Lok	450	3.6	7.1	0.018	71
B-4(2)	Crushable D	Heavy hex	900	9.8	19.6	0.043	322
B-5	Crushable C[b]	Heavy hex	900	7.7	15.5	0.071	398
B-6	Crushable B[b]	Heavy hex	900	9.4	18.9	0.065	280
B-7	Crushable C[b]	Heavy hex	1,350	13.7	27.3	0.050	287
B-8	Crushable B[b]	Heavy hex	1,350	13.0	26.0	0.065	331
B-9	Crushable B[b]	Heavy hex	1,350	12.5	25.0	0.065	291

Note: 1 lbf-in. = 0.113 N-m. 1 lbf = 4.4 N.

[a]See Figures 7 and 9. [b]Bumpers buckled.

Figure 10. Data trace for test B-4(2).

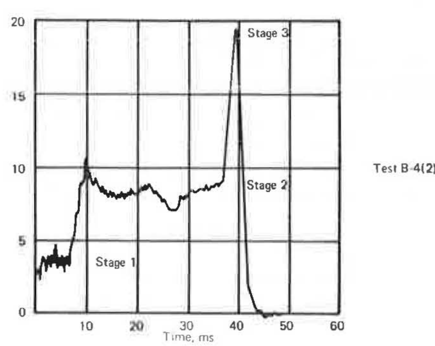
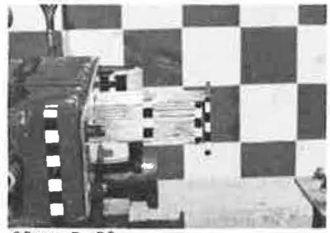
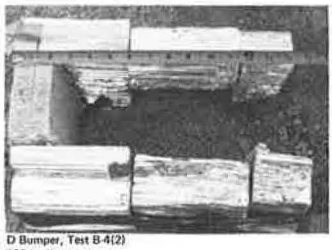


Figure 11. Bumpers after testing.

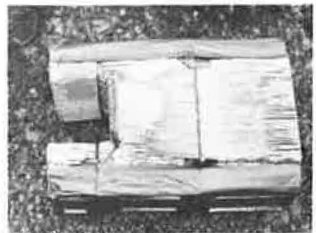
B Bumper (buckled)



C Bumper, Test B-2

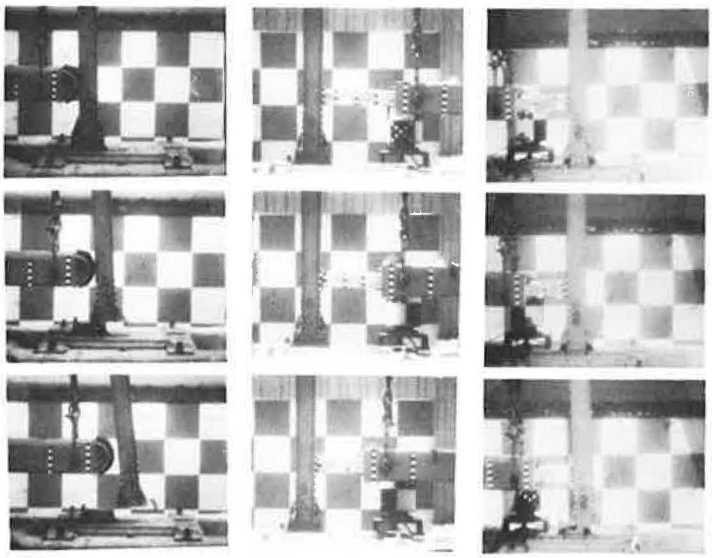


D Bumper, Test B-4(2)
900 in.-lbs torque



D Bumper, Test B-1(2)
Hi Lok Test

Figure 12. Sequential results of tests on bumpers A, B, and C.



Impact

+0.01 sec

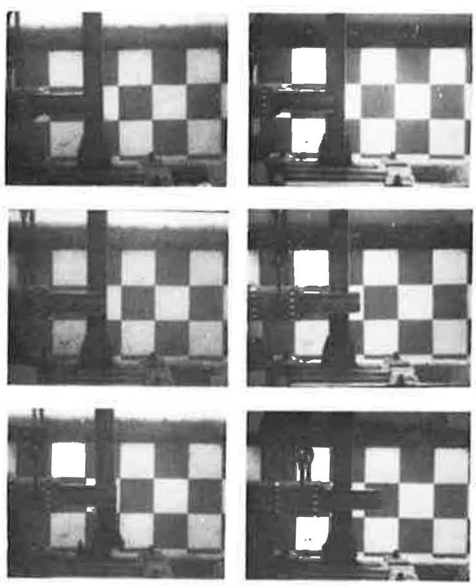
+0.02 sec

Hard Bumper A

4-Stage Bumper B

3-Stage Bumper C

Figure 13. Sequential results of tests on bumper D.



Impact

+0.01 sec

+0.02 sec

B-1(2)

B-4(2)

REFERENCES

1. Application of Highway Safety Measures, Breakaway Luminaire Supports. Federal Highway Administration, Circular Memorandum, June 5, 1968.
2. Application of Highway Safety Measures, Breakaway Luminaire Supports, Office of Traffic Operations, Federal Highway Administration, Notice TO-20, Nov. 16, 1970.
3. D. B. Chisholm and J G. Viner. Dynamic Testing of Luminaire Supports. Office of Research and Development, Federal Highway Administration, Final Rept., July 1973.