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IMPROVEMENTS TO THE WEAK-POST W-BEAM GUARDRAIL

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ABSTRACT

The weak-post w-beam guardrail has been widely used in a number of northeastern states for many decades. Weak-post guardrails are characterized by larger dynamic deflections in a collision and are considered more forgiving than other, stiffer barriers. When located with adequate clear space behind the barrier most states have experienced good performance with these barriers over the past several decades. Unfortunately, recent crash tests of the standard weak-post w-beam guardrail involving the 2000-kg pickup truck resulted in a series of unacceptable test results including over-riding and penetrating the guardrail. Design modifications to the weak-post w-beam guardrail were explored using finite element simulations and full-scale crash tests. An improved version of the weak-post w-beam guardrail system was developed and tested and found to satisfy the requirements of NCHRP Report 350 for Test Level 3.

KEYWORD

Roadside safety, weak-post w-beam guardrails, Report 350, crash testing, simulation.

INTRODUCTION

The weak-post w-beam guardrail has been a popular guardrail system in States like Connecticut, New York and Pennsylvania and, to a lesser extent, in Virginia and North Carolina.*(1)* The system was first used in New York in 1965 after research conducted in the early 1960s indicated high deceleration problems with an older generation of strong-post systems that resulted from wheel snagging and pocketing.*(2)* New York developed the weak-post w-beam guardrail, cable guardrail, and box-beam guardrail systems at this time. A two-year in-service evaluation conducted by NY DOT from November 1967 through October 1969 found that weak-post guardrail crashes were significantly less severe than strong-post w-beam crashes.*(3)* Overall 212 weak-post w-beam guardrail crashes and 1,045 strong-post W-beam crashes were analyzed. Weak-post W-beam crashes were categorized as 1.9 percent fatal, 10.8 percent "hospital," and 87.3 percent "other," compared with 3.3 percent fatal, 15.8 percent "hospital," and 80.9 percent "other" for strong-post w-beam guardrails. Penn DOT has also found crashes involving weak-post W-beam barriers to be less severe than those involving strong-post W-beam barriers.

The Weak-Post W-Beam Guardrail

The weak-post W-beam guardrail is composed of W-beam rails supported on weak S75x8.5 steel posts with rectangular soil plates. The system performs much like the cable guardrail in that the posts hold up the rail at the proper height until the guardrail is struck by an errant vehicle. When struck by the vehicle, the weak posts break or bend away from the rail. The posts are spaced at 3810 mm, and the rail is connected to the posts using 8-mm diameter bolts with 44-mm square washers under the head. The bolts are designed to fail in an impact allowing the rail to separate easily from the post. The rail separation from the post is an important feature of the design since this action allows the rail to remain in contact with vehicle instead of being pulled to the ground by the post. Once the rail is separated from the post, the W-beam section redirects the vehicle, acting like a cable that is anchored at the ends.

The height of the rail has changed at various times over the history of the weak-post w-beam guardrail system. Initially in 1965, NY DOT installed the barriers with a top-of-rail height of 685mm for roadside barriers and 740mm for median barriers.*(4)* In 1969 the top-of rail height for weak-post w-beam guardrails was increased to

840mm after a small number of vehicle vaulting cases were observed.*(4)* Through field investigations in the late 1970s, NY DOT found many of their barriers installed at heights substantially below the then current 840mm standard either because of early installations when the standard was lower, construction variations, post settlements, or pavement overlays. In 1983 NY DOT conducted a study of current vehicle profiles and decided that lowering the top-of-rail height to 760mm provided a good compromise to minimize the chances of vaulting or under-ride.*(4)* Today, standards for top-of-rail height for weak-post W-beam are 770 mm for roadside barriers in Pennsylvania and New York and median barriers in Pennsylvania and 840 mm for roadside barriers in Connecticut and median barriers in Connecticut and New York.

Crash Tests

The weak-post W-beam guardrail has been crash tested successfully using a variety of crash test procedures over the past thirty years. The system has satisfied the recommendations of NCHRP Report 230 resulting in crash tests with dynamic lateral deflections of about 2200-mm in the large-car Report 230 test (Test 10).*(5) (6)* More recent crash tests using full-size pickup trucks and vans have been less successful. A test of a large van documented in NCHRP Report 289 first suggested that there might be performance problems with "nonstandard" test vehicles when the van rolled over in a 100-km/hr collision.*(7)* A Report 350 test level three crash test at 100 km/hr with the 2000-kg pickup truck resulted in the pickup truck riding over the barrier.*(1)* Ray and McGinnis have summarized the full-scale testing on this barrier system prior to the year 1995 in NCHRP Synthesis 244.*(1)*

Crash tests using the 2000P pickup truck test vehicle have proven to be difficult for the weak-post w-beam guardrail system. The system has not had trouble passing the NCHRP 350 3-10 test with the 820C test vehicle. Even with the 2000P pickup truck the weak-post w-beam has passed NCHRP 350 level 2 requirements at 70 km/h and in a test conducted at Pennsylvania Transportation Institute (PTI) in July 1998 it performed very well at an impact speed of 87 km/h.*(8)* In a December 1998 PTI crash test at 103 km/h and 26 degrees impact angle, however, the 2000P pickup truck penetrated the barrier when the guardrail tore at a splice location.*(8)*

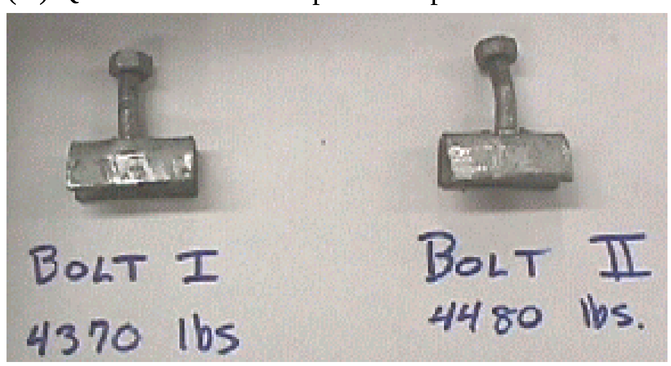
The safety evaluation of a barrier according to NCHRP Report 350 is performed on the basis of three factors: structural adequacy, occupant risk and vehicle trajectory.*(9)* In all crash tests in which the vehicle has been contained by the barrier, the parameters for occupant risk and vehicle trajectory have all been well within acceptable limits. It is the structural adequacy requirement in the 2000-kg pickup truck test that has challenged the weak-post w-beam guardrail system most. All crash tests with the 2000P pickup impacting at 100 km/h or higher at a nominal 25º impact angle have resulted in either a rupture of the rail or an overriding of the rail.

The goal of this research was to redesign the weak-post w-beam guardrail such that it meets the NCHRP Report 350 requirements for test level three. Solving three specific design problems were essential for obtaining acceptable crash test performance:

- Post-rail connection performance,
- Guardrail rupture, and
- Guardrail mounting height.

This goal was pursued using a variety of techniques including structural design, laboratory experiments, finite element analyses and full-scale crash tests. More detailed information about the finite element analyses and the full-scale crash tests can be found in a series of other documents.*(10)(11)(12)(13)(14)*

(A) Quasi-static test setup for rail-post connection.



(B) Typical failure of standard connection detail.

(C) Typical failure of improved connection detail

Figure 1. Laboratory tests of connection components.

DESIGN PROBLEMS

Connection Performance

The performance of the guardrail-post connection in weak-post guardrail systems is a fundamental aspect of the way these types of guardrails are supposed to behave. The w-beam rails of weak-post systems should detach easily and reliably from the posts prior to the vehicle striking the post. If the connection is too strong, the rail can be carried to the ground allowing the vehicle to vault over the rail. Since vaulting over the rail had been observed in several weak-post guardrail crash tests, understanding the performance of the rail-to-post connection details was considered to be important.*(15)* It was observed in a crash test at PTI that the release of the rail from the post occurred by pulling the bolt and washer through the slot in the w-beam, however, this occurrence was not documented in the PTI test report. *(8)*

The standard connection for the weak-post w-beam guardrail consists of one 7.94 mm A307A bolt which connects two thickness of guardrail to the flange of an S75x8.5 post. One 44-mm square 12 gauge washer is positioned under the head of the bolt since the guardrail slot is 16 mm wide. A nut is attached to the bolt on the flange-side of the post completing the connection. This standard connection was assembled and subjected to a series of quasi-static pull-tests in the 400,000 lbs load tester shown in the top portion of figure 1.

First, a series of tensile tests was performed on 7.94 mm A307A bolts obtained from Penn DOT maintenance garage inventories. As shown in table 2, the bolts failed at loads above 20 kN, the nominal failure strength for this size and grade of bolt, in all but one of six tensile tests. Notwithstanding the one substandard value, the axial tension tests of the bolts indicated that the bolts met the appropriate materials specifications.

The loading experienced by a bolt in a guardrail connection is likely to be much more complicated than the conditions replicated by a simple axial tension test. In order to explore the performance of the bolted connection in more realistic conditions, a load testing fixture was built as shown in the top portion of Figure 1. The fixture allowed the load to be applied to the connection through the guardrail and flange in the same manner as occurs in an actual collision event. The guardrail was attached to one side of the loading frame and the web of the post was attached to the other. The connection was positioned at several angles to replicate the bending and twisting that occurs in a typical collision. The fixture simulated two loading conditions: bending about a 30 degree angle about the longitudinal direction of the guardrail and bending about a 30 degree angle about the guardrail axis in combination with a 15 degree twist in the axial direction of the post. In addition to these orientations, the bolts were sometimes positioned in the center of the slot and sometimes at the edge of the slot. This combination of loading conditions provided a realistic method of examining the connection performance while still being relatively easy to replicate in the laboratory.

Table 1 shows the results of this test series. When the standard connection was tested, several different failure modes were observed. Sometimes the square washer would deform into a U shape and pulled through the guardrail slot as shown in the middle portion of Figure 1. In other cases the nut would be stripped off the bolt in a series of jerks as shown in the left portion of Figure 2. Neither failure mode was considered to be a desirable or repeatable means of releasing the guardrail from the post. As shown in Table 1, the failure loads when the washer was pulled through the slot or the nut was stripped off the bolt were generally similar to the failure load of an axially loaded bolt. The time and displacement required to fail the connection, however, was much longer for both these failure modes than fracturing the bolt as shown in Figure 2. Stripping the nut off the bolt or pulling the washer through the guardrail slot takes time which could cause the guardrail to be pulled to the ground. As shown

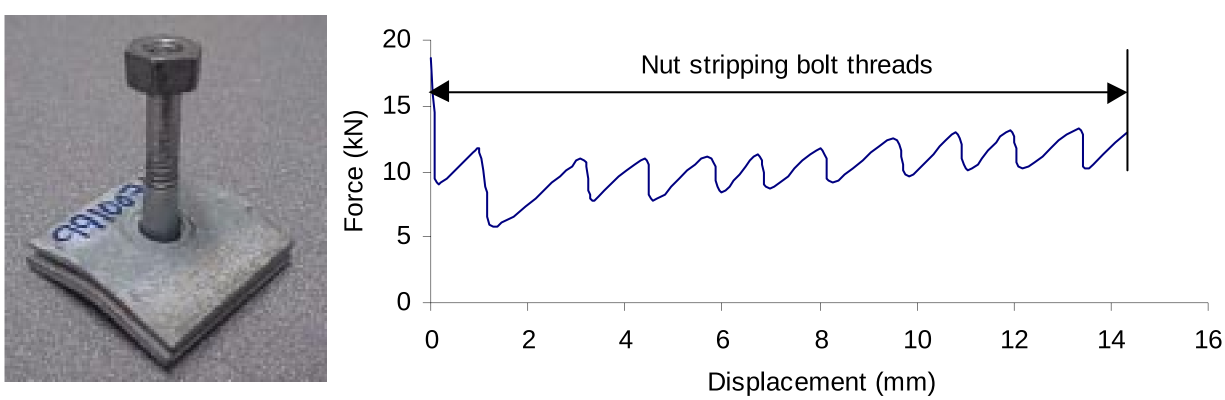


Figure 2. Failure mode (left) and force-displacement (right) for connections that fail by stripping the threads of the bolt.

Table 1. Laboratory results for connection strength experiments.

Test No.	Test Type	Orientation	Ultimate Strength (kN)	Failure Mode
Standard 7.94-mm diameter A307A bolt				
99092001	Bolt Strength	Axial	27.3	Fractured through the threads
99092002	Bolt Strength	Axial	27.0	Fractured through the threads
99092003	Bolt Strength	Axial	26.1	Fractured through the threads
99092004	Bolt Strength	Axial	22.4	Fractured through the threads
99092005	Bolt Strength	Axial	15.4	Fractured through the threads
99092006	Bolt Strength	Axial	19.9	Fractured through the threads
Standard connection with 7.94-mm A307A bolt, one nut and one 40-mm square washer				
99072001	Connection	30º/0º edge	19.4	Washer pulled through slot
99072002	Connection	30º/0º edge	19.9	Washer pulled through slot
99072003	Connection	30º/0º center	27.0	Washer pulled through slot
99072004	Connection	30º/15º edge	22.5	Nut stripped off threads
99072005	Connection	30º/15º edge	17.7	Nut stripped off threads
99072004	Connection	30º/15º edge	18.5	Washer pulled through slot
Improved connection with 6.35 A307A bolt, two nuts and two 40-mm square washers				
99100702	Connection	30º/0º center	17.1	Bolt fractured
99100703	Connection	30º/0º center	17.8	Bolt fractured
99100704	Connection	30º/0º edge	18.0	Bolt fractured
99101101	Connection	30º/15º center	13.4	Bolt fractured
99101102	Connection	30º/15º center	16.3	Bolt fractured
99101102	Connection	30º/15º center	13.0	Bolt fractured

in the right portion of Figure 2, the nut had to be pulled through 14 mm of bolt thread prior to releasing the guardrail from the post. A more brittle fracture mode where the failure occurs quickly is desirable in order to eliminate the possibility of the guardrail being pulled to the ground.

An improved connection featuring two 44-mm square washers and two nuts and a smaller bolt was then tested and the results are shown in Table 1. The double square washers prevent the washers from pulling through the slot and the double nuts prevent the nuts from stripping the bolt threads. This isolates the failure in the bolt. As shown in Table 1, the failure mode is very repeatable for this connection and all six tests resulted in the same type of failure.

Guardrail Rupture

Guardrail rupture must be avoided to prevent the vehicle from penetrating the barrier. The two common reasons for guardrail ruptures are: (1) complex loadings at splice connections and (2) bending around sharp edges.

A splice failure occurred in a test of a 2000-kg pickup truck striking the guardrail at 100 km/hr and 25 degrees.*(8)* Splice failures were examined extensively in a related project and that research is documented elsewhere.*(10) (16)* The splice in the standard weak-post w-beam guardrail is located at each post. This location is prone to complex bending and twisting loadings that sometimes result in splice failures. One way to avoid this problem is to move the splice to the mid-span.

A full-scale crash test was performed according to NCHRP Report 350 test 3-11 conditions using the improved connection described in the previous section and with the splices relocated to the mid-span.

As shown in Figure 3, the test resulted in an unexpected guardrail rupture. A nick formed on the rail at the second post downstream of the impact point. The nick can be seen in the upper photograph in Figure 3. The nick passed across the front of the vehicle (see the middle photograph of Figure 3) and, when it passed the bumper and reached the tension side of the guardrail, the guardrail material ruptured completely as shown in the bottom portion of Figure 3.

Figure 3. Test of a weak-post w-beam guardrail with splice at the mid-span and an improved connection showing the rupture of the guardrail.*(3)*

Prior to performing this test, a finite element simulation of the new design was performed. The simulation, unlike the full-scale test, did not reveal any performance problems. When the simulation was examined more closely, however, the same type of nick in the rail could be clearly observed as shown in Figure 4. The finite element simulation did not predict the rupture because the failure condition for the guardrail material was not set in the material model. Wright and Ray suggested values for the properties of guardrail steel, including the effective plastic strain at failure, that can be used in modeling collision using LS-DYNA. *(17)* Unfortunately, the effective plastic strain at failure is sensitive to the mesh density used in the model so, unless there is experimental evidence to confirm the specific value of the effective plastic strain at failure for a particular mesh, it is usually prudent to leave the failure condition out. Unfortunately, when this is done it is not possible to observe the failure. When the failure condition was added, the guardrail tore in exactly the same manner as observed in the full-scale crash test.

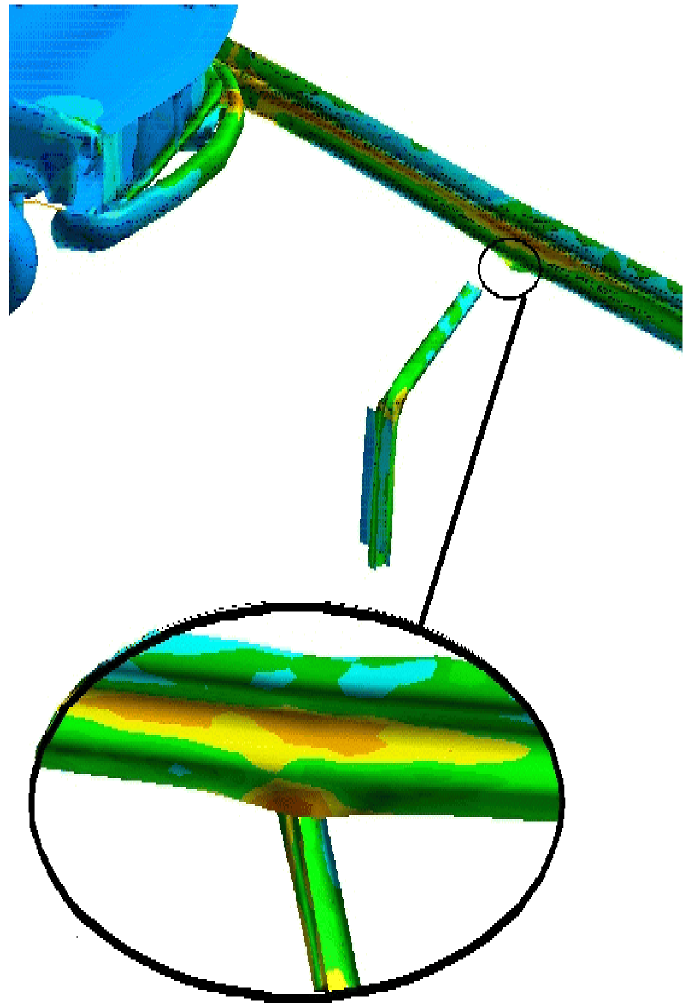


Figure 4. Finite element simulation of a weak-post w-beam guardrail with splice at the mid-span and an improved connection showing the potential for nicking the guardrail.

Examining the stress and strain distributions in the finite element simulations showed that the bottom edge of the guardrail experiences high stress and strain concentration as the rail slides up the sharp edge of the steel flange after the connection has released the post. These large strains cause a nick to form which can transform into a small tear. Once the tear has been initiated, it may continue progressively rupturing the guardrail. One solution to

Table 2. Stress and strain reductions due to the guardrail backup plates.

Maximum Value	Guardrail Without Backup Plate	Guardrail With Backup Plate	Guardrail Reduction (%)	Backup Plate
Effective Stress (MPa)	588	512	13	554
Effective Plastic Strain	0.37	0.23	38	0.28

this problem that has been used for strong steel-post guardrail is to use a w-beam backup plate as a sacrificial element to shield the guardrail. Finite element simulations were performed both with and without backup plates and the stresses and strains at the critical location were examined. The results of these simulations, shown in Table 2, indicate that the addition of backup plates reduces by 38 percent the effective plastic strain experienced by the guardrail. W-beam backup plates were added to the modified weak-post w-beam guardrail design to protect the guardrail from tearing on the sharp edge of the post. Another solution would be to use a different post cross-section with more rounded edges.

Guardrail Mounting Height

The weak-post w-beam guardrail system, like most other common guardrail systems, was originally designed in the early 1960's when the vehicle population dominated by large passenger sedans. Consequently, most guardrail systems have functioned well in impacts with passenger cars. Over the last decade, however, the vehicle mix has shifted dramatically such that the smallest vehicles have masses less than 1000 kg and the large passenger car has virtually disappeared to be replaced by an assortment of vans, minivans, sport utility vehicles and pickup trucks. Guardrail height that was appropriate when the vehicle mix was dominated by large passenger cars may no longer be appropriate for today's wide range of vehicles.

A full-scale crash test was performed on a modified weak-post w-beam guardrail.*(12)* The guardrail was mounted at the Penn DOT standard height of 770 mm but with the improved connection, mid-span splices and backup plates. Initially, the 100 km/hr 25 degree impact resulted in acceptable performance as illustrated in Figure 5. As the vehicle was being redirected, however, the front impact-side tire re-contacted the w-beam rail. The rotation of the tire and the low position of the rail with respect to the tire allowed the guardrail to be rotated under the tire. The vehicle then easily rode over the barrier.

Similar behavior was noted in finite element simulations as shown on the left side of Figure 5. The finite element simulations were used to vary a number of design parameters to avoid the vehicle override problem observed in the test. The design change that most reduced the likelihood of the vehicle overriding the barrier was to increase the rail height by 50 mm. A finite element simulation of the new system with a rail height of 820 mm was performed and is shown in the left portion of figure 6. The finite element simulation indicated that the vehicle would be smoothly redirected if the guardrail height were 820 mm.

The modified weak-post w-beam guardrail system with the higher 820-mm mounting height was subjected to a full-scale crash test according to NCHRP Report 350 test 3-11 conditions (i.e., a 2000-kg pickup truck striking the barrier at 100 km/hr and 25 degrees).*(13)* The results of this test are shown in comparison with the finite element simulation in Figure 6. The vehicle was smoothly redirected after impact and appeared to meet all the relevant evaluation criteria of NCHRP Report 350 as shown in Table 3. In addition, the finite element simulation predicted these results with reasonable accuracy prior to the performance of the test.

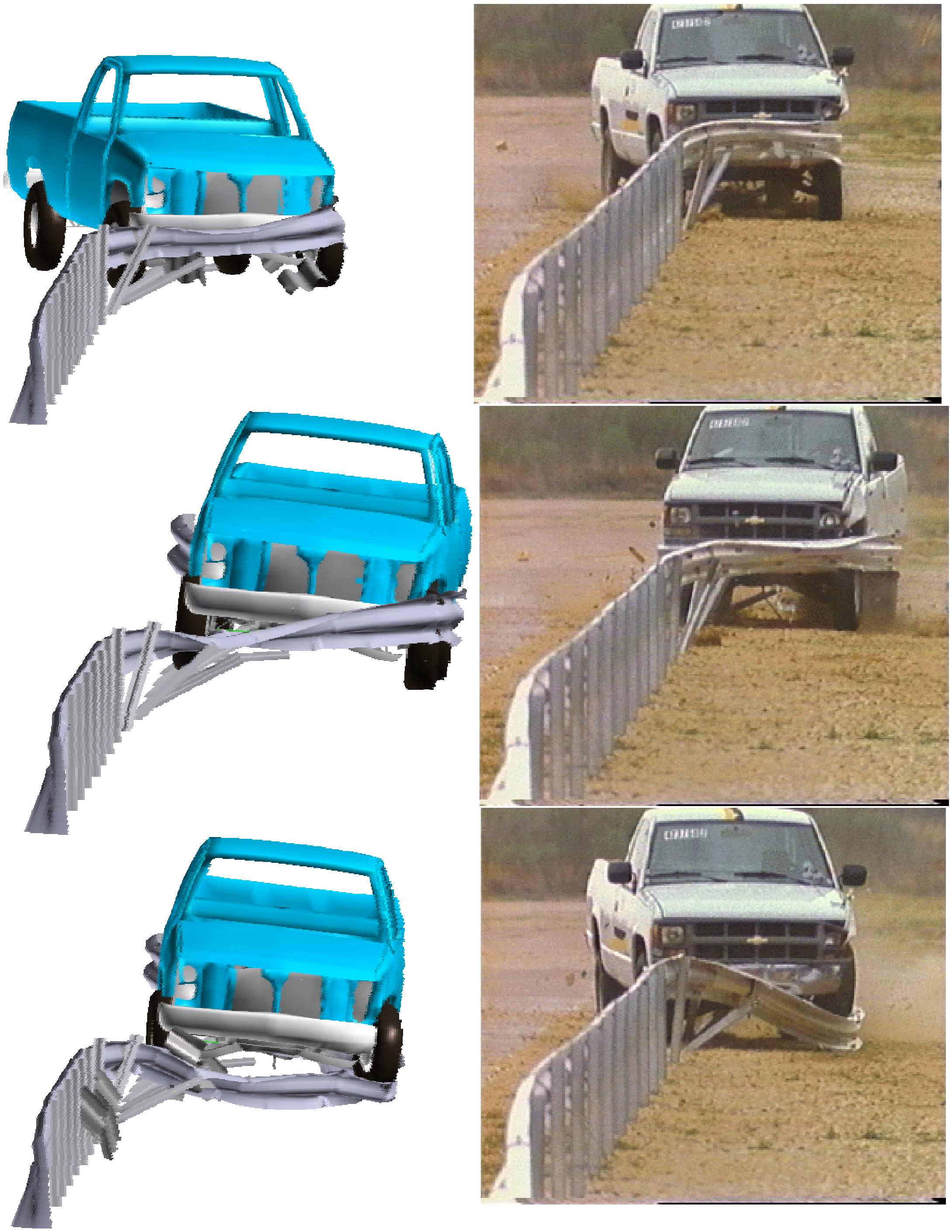


Figure 5. Finite element simulation and full-scale test of a 2000-kg pickup truck (1994 Chevrolet 2500) striking a modified weak-post w-beam with an improved connection, splices in the midspan and w-beam backup plates.

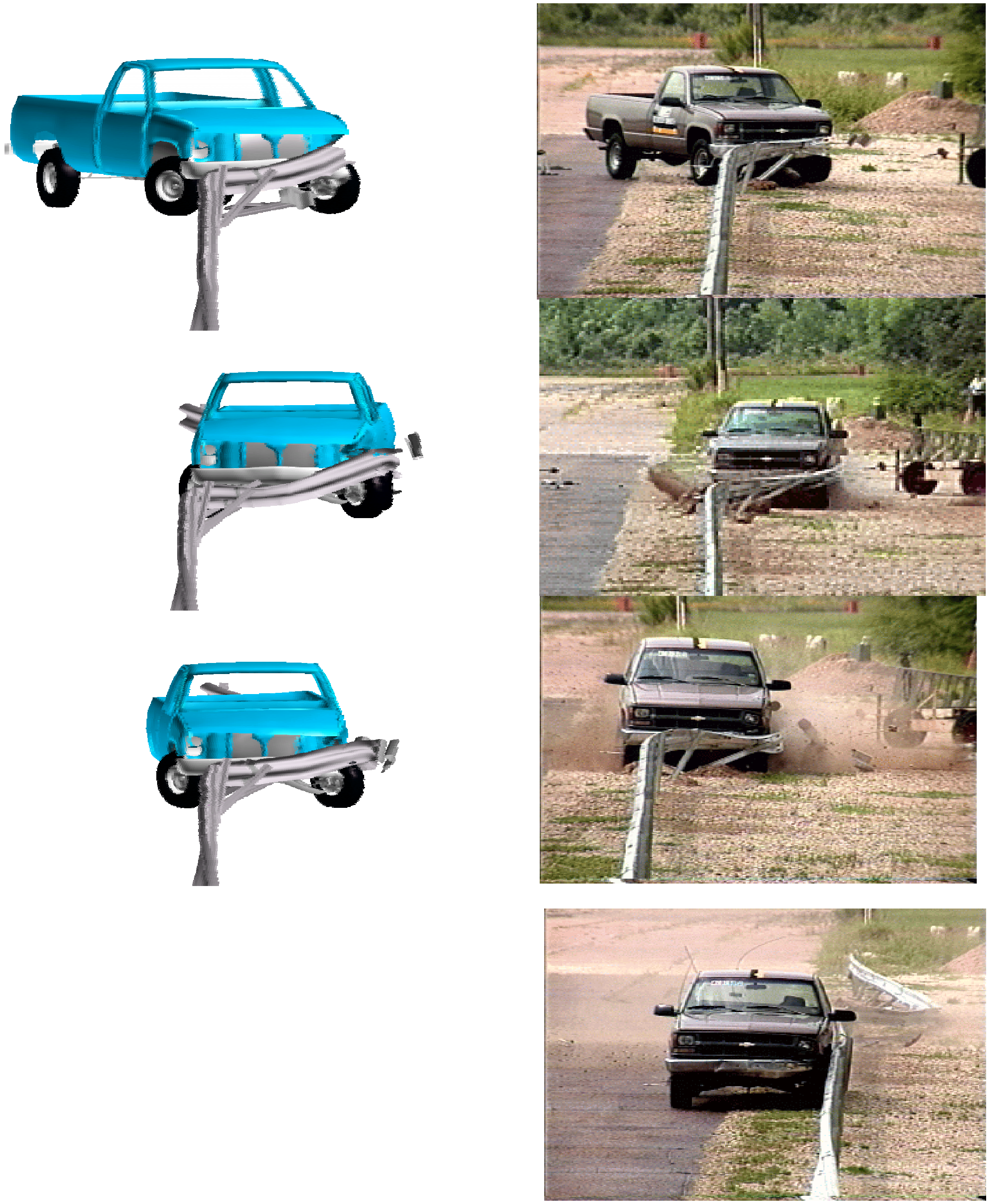


Figure 6. Finite element simulation and crash test of a 2000-kg pickup truck (1995 Chevrolet C2500) striking a modified weak-post w-beam guardrail with an improved connection, w-beam backup plates, splices at the mid-span and 820-mm rail height -- final design.

While the results of the pickup truck test appeared to satisfy the requirements of NCHRP Report 350, there was concern that raising the guardrail height might adversely affect the performance of the system for small cars. A finite element simulation of the test 3-10 conditions (i.e., an 820-kg passenger car striking the barrier at 100 km/hr and 20 degrees) was performed and is summarized in Figure 7. The generic 820-kg small car finite element model developed by Cofie and Ray was used in this simulation.*(18)* Even though the bumper of the small car is below the bottom of the guardrail, the simulations indicated that the vehicle would be smoothly redirected. The weak-posts of the guardrail system were easily bent over by the bumper of the vehicle and the guardrail redirected the vehicle by interacting with the body panels of the vehicle.

Table 3. NCHRP Report 350 evaluation criteria for finite element simulations and full-scale tests.

	Test 3-10		Test 3-11	
	Simulation	Test	Simulation	Test
Structural Adequacy				
A. Vehicle was contained and redirected	Yes	Yes	Yes	Yes
Maximum dynamic deflection (m)	1.10	1.03	2.00	1.65
Occupant Risk				
D. No hazardous detached elements	No	No¶	No	No¶
F. Vehicle must remain upright and stable	Yes	Yes	Yes	Yes
H. Occupant impact velocity				
Longitudinal < 9 m/s	5.8	3.3	NR	NR
Lateral < 9 m/s	4.4	4.5	NR	NR
I. Occupant ridedown acceleration				
Longitudinal <15 g's	12.4	6.0	NR	NR
Lateral < 15 g's	10.0	5.0	NR	NR
Vehicle Trajectory				
K. Preferred not to intrude into traveled lanes				
Distance in front of barrier (m)	UNK	7.6	UNK	0.0
L. Longitudinal occupant kinematics				
Velocity < 12 m/s	NR	NR	3.6	3.9
Acceleration < 20 g's	NR	NR	8.1	5.9
M. Exit angle < 60% of impact angle	2.9°	1°	1°	2°

UNK = Unknown because the simulation was not continued long enough to make the evaluation.
NR = Not a required evaluation criterion for this test.
¶ There were detached posts but these were judged not to be a hazard to either the vehicle compartment or following traffic.

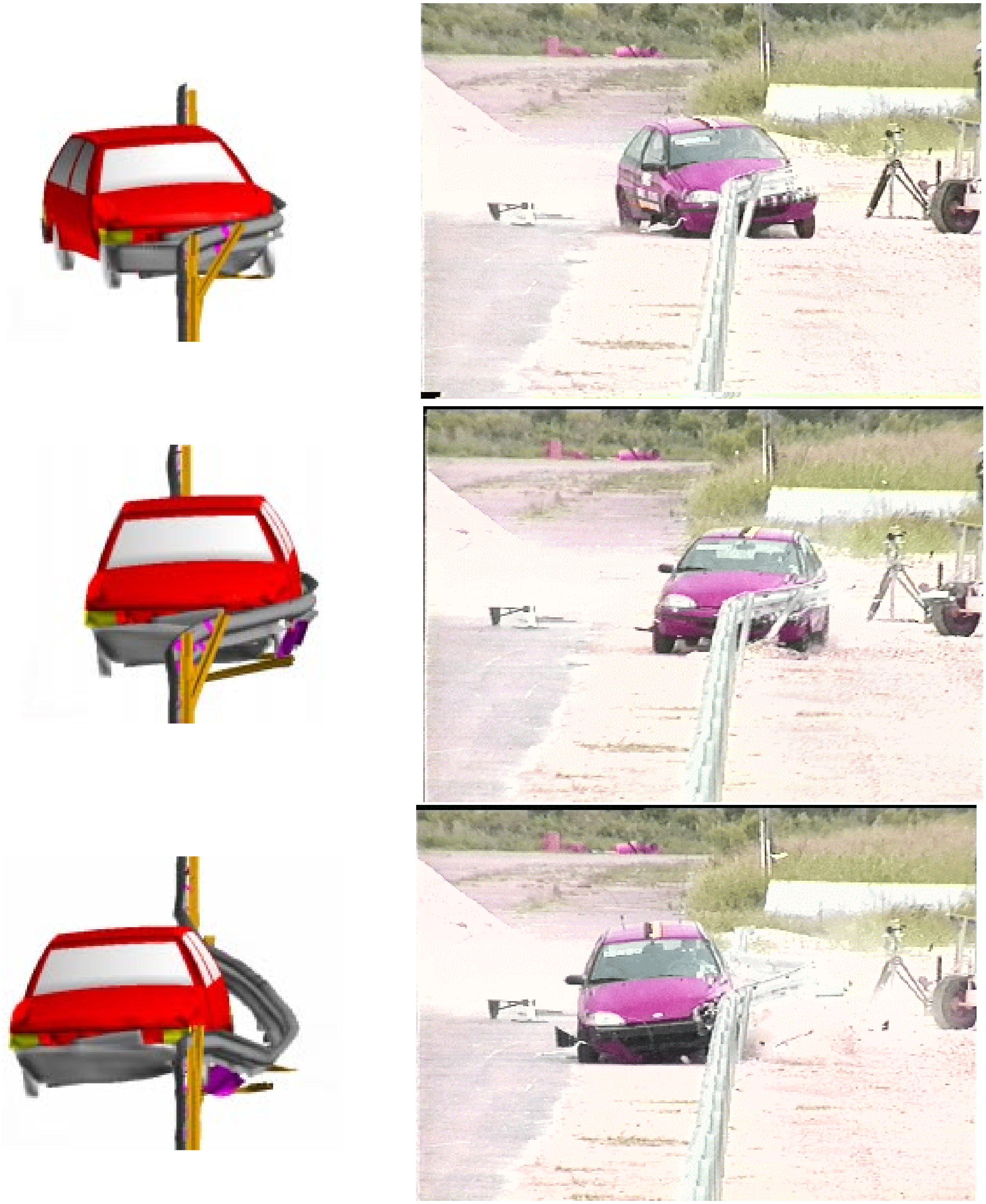


Figure 7. Finite element simulation and full-scale crash test of a 820-kg small car striking a modified weak-post w-beam guardrail system with an improved connection, w-beam backup plates, splices at mid-span and 820-mm rail height -- final design.

A full-scale crash test was performed to confirm the results of the finite element simulation. The results are summarized in the right portion of figure 7.*(13)* The test vehicle, a 1997 Geo Metro, was smoothly redirected in the manner predicted by the finite element simulations. While a post ruptured the gas tank as the vehicle drove over the post, the test appeared to pass all the relevant Report 350 evaluation criteria as shown in Table 3.

FINAL DESIGN

The two full-scale crash tests described above indicate that the final modifications to the weak-post w-beam guardrail resulted in a system that satisfies the requirements of NCHRP Report 350 for test level three. The final modified system, shown in figure 8, consists of the following components:

- 12 gauge w-beam guardrail mounted 820-mm above the ground with splices at mid-span,
- S75x8.5 weak steel posts with soil plates spaced at 1308 mm and attached to the rail at non-splice locations
- W-beam backup places at each post,
- A post-rail connection consisting of one 7.94 A307A bolt with two 40-mm square washers and two nuts and
- A rail support bolt.

(A) Midspan splices, rail height and backup plates. (B) Improved connection. (C) Rail support bolt.

Figure 8.Final design details of the improved weak-post w-beam guardrail.

CONCLUSIONS

Relatively small changes in several important design details resulted in significantly improved crash test performance of the weak-post w-beam guardrail. The post-rail connection was redesigned so the connection fails consistently and at the appropriate time. Guardrail splices were relocated to the mid-span (i.e., non-post locations) to minimize the chance for guardrail rupture. Standard w-beam backup plates were added at post locations to provide a sacrificial element to protect the guardrail as it slides up the sharp edge of the post in a collision. Finally, the guardrail height was raised 50 mm to a height of 820 mm to prevent the wheel of the 2000-kg pickup truck from riding over the rail element. This increase in rail height dramatically improved the performance of the system when struck by a pickup truck while not degrading the performance for small car impacts. The resulting system appears to satisfy the recommendations of NCHRP Report 350 for test level three.

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REFERENCES

1. RAY, M. H. and R. G. McGinnis, “Guardrail and Median Barrier Crashworthiness,” Synthesis No. 244, National Cooperative Highway Research Program, Washington, D.C. (1997).

2. GRAHAM, M. D., W. C. Burnett, J. L. Gibson and R. H. Freer, “New Highway Barriers: The Practical Application of Theoretical Design,” Highway Research Record 174, Highway Research Board, Washington, D.C. (1967).

3. VANZWEEDEN, J and J. E. Bryden, “In-Service Performance of Highway Barriers”, Research Report 51, Engineering Research and Development Bureau, New York State Department of Transportation (1977).

4. BRYDEN, J. E., “Development of Proposed Height Standards and Tolerance for Light-Post Traffic Barriers,” Research Report 111, Engineering Research and Development Bureau, New York State Department of Transportation (1984).

5. MICHIE, J. D., L. R. Calcote and M. E. Bronstad, “Guardrail Performance and Design,” NCHRP Report 115, Highway Research Board, Washington, D.C. (1971).

6. MICHIE, J. D., “Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenance,” National Cooperative Highway Research Program Report 230, Transportation Research Board, Washington, D.C. (1981).

7. BRONSTAD, M. E., J. D. Michie, and J. D. Mayer, Jr., “Performance of Longitudinal Traffic Barriers,” NCHRP Report 289, National Cooperative Highway Research Program, Washington, D.C. (1987).

8. KILARSKI, W. P., M. El-Gindy, B. D. St. John and B. Peacheux, “Type 2 Weak Post Guardrail Testing,” Pennsylvania Transportation Institute, Pennsylvania State University, State College, PA (1999).

9. ROSS, H. E., Jr., D. L. Sicking, R. A. Zimmer and J. D. Michie, “Recommended Procedures for the Safety Performance Evaluation of Highway Features,” NCHRP Report 350, Transportation Research Board, Washington, D.C. (1993).

10. ENGSTRAND, K. E., Improvements to the Weak-Post W-Beam Guardrail, Master’s of Science Thesis, Worcester Polytechnic Institute, Worcester, MA (2000).

11. BUTH, E. C., W. L. Menges and S. K. Schoeneman, “NCHRP Report 350 Test 3-11 on the Modified PennDOT Type 2 Guide Rail,” Texas Transportation Institute, Texas A&M University, College Station, TX (2000).

12. BUTH, E. C., W. L. Menges and S. K. Schoeneman, “NCHRP Report 350 Test 3-11 on the Modified PennDOT Type 2 Guide Rail --- Test 2,” Texas Transportation Institute, Texas A&M University, College Station, TX (2000).

13. BUTH, E. C., W. L. Menges and S. K. Schoeneman, “NCHRP Report 350 Test 3-11 on the Modified PennDOT Type 3 Guide Rail --- Test 3,” Texas Transportation Institute, Texas A&M University, College Station, TX (2000).

14. BUTH, E. C., W. L. Menges and S. K. Schoeneman, “NCHRP Report 350 Test 3-10 on the Modified PennDOT Type 2 Guide Rail --- Test 4,” Texas Transportation Institute, Texas A&M University, College Station, TX (2000).

15. Mak, K., D.L. Alberson, “Test Report No. 7147-21 (Draft Report),” Texas Transportation Institute, Texas A&M University System, 1993.

16. ENGSTRAND, K. E., M. H. Ray and C. A. Plaxico, “Performance of W-Beam Splices,” Transportation Research Record (in press), Transportation Research Board, Washington, D.C. (2001).

17. WRIGHT, A. E. and M. H. Ray, “Characterizing Guardrail Steel for LS-DYNA3D Simulations,” Transportation Research Record 1647, Transportation Research Board, Washington, D.C. (1996).

18. COFIE, E., “Finite Element Model of a Small Automobile Impacting a Rigid Pole,” Report No. FHWA-RD-94-151, Federal Highway Administration, Washington, D.C. (1994).