EVALUATION OF RAIL HEIGHT EFFECTS ON THE SAFETY PERFORMANCE OF W-BEAM BARRIERS

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ABSTRACT

The objective of this study is to investigate the effect of rail height on the safety performance of G4(1S) w-beam guardrail systems. The study involved three steps. In the first step, a detailed finite element model of the G4(1S) guardrail system was created. The model incorporated the details of the rail, connections, the post, the blockout, and the soil in which the post was embedded. To validate the model of the w-beam guardrail system, a model of the setup of this w-beam system in previous full-scale crash tests was created. Simulations were performed using this model and the results were compared to the full-scale crash test data. The results were similar indicating that the model was an accurate representation of the actual system. In the second step of the study, the validated model served as the basis for four additional models of the G4(1S) guardrail to reflect varying rail heights. In two of the four models, the rails were raised 40 and 75 mm (1.5 and 3 inches). In the other two models, the rails were lowered 40 and 75 mm. Simulations with these four new models were carried out and compared to the first simulation to evaluate the effect of rail height on safety performance. The simulation results indicated that the effectiveness of the barrier to

redirect a vehicle is compromised when the rail height is lower than recommended. The third step of the study consisted of performing full-scale crash tests with the guardrail at standard height and 60 mm (2.5 inches) lower. The data from the crash tests validated the simulation results.

KEYWORDS:

W-Beam Guardrail, Finite Element Analysis, Crash Testing, Highway Safety

INTRODUCTION

W-beam guardrails are the most common types of longitudinal roadside barriers used on the roadways in the United States. They have played an important role in improving the safety of highway systems when used to redirect vehicles away from roadside hazards such as bridge abutments, light poles, ditches, trees, mounds, or other fixed objects found on the roadside. Figure 1 shows the features of a typical w-beam guardrail barrier with steel posts and routed wood blockouts (typically referred to as the G4(1S) barrier). In this study, the safety performance of this barrier system is evaluated relative to the effect of variations in the rail height on its adequacy in redirecting the striking vehicle. Variations in rail height can occur as a result of installation shoddy, settlement, and/or successive overlays of the pavement. Rail height has become a more critical issue as larger vehicles such as sport utility vehicles (SUVs) and pick-up trucks have become a predominant element of the vehicle fleet.

In this analysis, the dynamic explicit finite element code LS-DYNA [1,2] is used to simulate the crash performance of a modified G4(1S) w-beam guardrail. A detailed finite element model of the guardrail was developed and simulations of a vehicle impacting the barrier with varied rail heights were performed. Upon completing the finite element analysis, two full-scale crash tests were performed at The Federal Highway Administration (FHWA) Federal Outdoor Impact Laboratory (FOIL) to validate the simulation results.

BACKGROUND

During the early 1960's a wide variety of guardrail systems were developed and installed on highways in the US. W-beam systems came into widespread use since standard steel sheet could be rolled into the W-shape to form a rigid beam that could "catch" the bumpers of typical vehicles. As guardrail systems evolved, variations in posts, rail connections, blockout, and other elements changed. Consequently, there are many variations of w-beam guardrail that have met crashworthiness standards and have been deployed on U.S. highways.

The Roadside Design Guide (RDG) designates the G4(1S) as a strong-post guardrail system. It incorporates a 12 guage steel w-beam rail, mounted on W150 x 14 (W6x9) steel posts spaced at 1.905m (6 ft 3 in) with a wood or steel blockout. The blockout was an element that was added to reduce the potential for an impacting vehicle to snag on the posts during impacts. While either steel or wood blockouts can be used, the barrier has only been certified to Test Level 2 (TL2) with steel blockouts, but has achieved TL 3 with routed wood blockouts. The barrier is noted to have a maximum dynamic deflection of about 1m (3 ft).

A series of full-scale crash tests have been conducted on w-beam guardrail systems at different testing agencies including the Texas Transportation Institute and the Midwest Roadside Safety Facility to examine the performance of the G4(1S) and G4(2W) guardrail systems in accordance with NCHRP Report 350 guidelines [3,4,5,6]. These guardrails were tested with different types of posts and blockouts. The full-scale crash tests (test with 2000P vehicle at 100 km/h impact speed and 25 degrees impact angle) showed that w-beam guardrails with steel blockouts do not meet Test Level 3 criteria of NCHRP Report 350. A similar full-scale crash test on a design with steel posts and wood blockouts at Test Level 3 did meet the NCHRP criteria. The data from one of the crash tests, which was conducted on a G4(1S) system, was used in this study to validate the model and analyze the influence of the w-beam guardrail height on its safety performance.

The effect of the rail height relative the vehicle is critical and became more critical in recent years for three reasons. The first relates to changes in the nature of vehicles (i.e. fleet) operating on U.S. highways. The use of larger vehicles such "Sport Utility Vehicles" (SUVs) and pick-up trucks has been on the rise in the US since the late 1980's and they now account from more than half of the vehicles in the fleet. These vehicles have higher bumpers and centers of gravity. These features make them more susceptible to overriding or rolling over standard barriers. Most w-beam barriers, were originally designed for standard-sized sedans, and thus could be less effective in redirecting these SUVs and pickup trucks. The second reason is related to road resurfacing practices. There has been increased use of resurfacing as a pavement management strategy, often without milling to lower the pavement before the addition of a new layer of material. The effect is a relative lowering of the height of the barrier. When agencies are faced with limited funds, they often do not make adjustments to the heights of barriers along resurfaced sections. The third reason relates to the basic installation tolerances currently considered acceptable for barrier height. The tolerances for the height are specified as ±75mm (±3in). The standard rail height, 550mm (21.5 in) from ground level to center of the rail, is specified but little testing has been undertaken to determine the degree of effect on safety performance for rail height variations within the tolerance limits.

COMPUTER MODEL DEVELOPMENT

The guardrail system used in this study is based on the modified G4(1S) design. The rails in this system are made up of standard 12-gauge w-beams with lengths of 3.807 m (12.5ft). The rails are supported using W150x12.6 (W6x9) steel posts. These posts are 1830 mm (72in) length and embedded 1100 mm (43.3in) into the ground. Routed wood blockouts are placed between the posts and the w-beam rails and have dimensions of 150 mm x 200 mm x 360 mm (6 in x 8 in x 14 in). The system level model of the G4(1S) guardrail system is modeled to have a total length of 53.3m (175 ft) and it is anchored at both ends using a standard Breakaway Cable Terminal (BCT). The system consists of 29 posts and 14 w-beam sections.

To create the finite element model of the w-beam guardrail system, several key features were carefully examined and appropriate modeling techniques were used to ensure that the model is an accurate representation of the actual system. First, explicit geometry of all components of the guardrail system were incorporated in the model (Figure 2). This included the w-beams, posts, blockouts, and bolts. This is important to ensure the correct mass, inertia, and stiffness of the different parts is reflected in the model. The soil was also explicitly modeled using solid elements. The shape of the post was incorporated in the soil mesh to simulate the post/soil interactions. The geometry of the bolts was found to affect system behavior so they were explicitly incorporated in the model.

The LS-DYNA finite element analysis program is used in this study [1,2]. It uses an explicit Lagrangian numerical method to solve three dimensional, dynamic, nonlinear, large displacement problems. While the software's initial focus was in military related studies, in the past 15 years, LS-DYNA has gained new ground in automotive analysis such as crashworthiness and occupant safety. More recently, the code has been successfully used in analyzing other various other structures including roadside hardware.

Modeling of Steel and Soil Components: Appropriate material and cross-sectional properties were assigned to all components of the guardrail system. Two main LS DYNA material types were used in the w-beam guardrail model. The metal components, such as the posts and w-beams, were represented as "piecewise_linear_plasticity" material in LS-DYNA. This material model has been extensively utilized to represent structural metals, such as steel and aluminum, and it has been fully validated and optimized. The material behavior is isotropic elasto-plastic with strain rate effects and failure. The properties used for these materials were extracted from the literature as well as data from coupon tests that were performed on similar steels. The "soil_and_foam" model in LS DYNA was used to representing the soil. The properties used for this model were back-calculated from previously conducted tests. These tests consisted of a Bogie vehicle impacting wood and steel posts that are embedded in similar soil to what have been used the full-scale crash test. Simulations with the same test setups were performed and the material properties were varied until acceptable comparisons were achieved between the tests and simulations.

Modeling of W-Beam, Post and Blockouts: A detailed finite element model of the steel post with wooden blockout is shown in Figure 3 and the finite element model of the w-beam is shown in Figure 4. For computational purposes, six rails located at the middle of the entire guardrail system were modeled using fine mesh while the remaining rails were modeled using coarser mesh. All post and rails were modeled using quadrilateral shell elements. The shell element used in this analysis is based on the Belytschko-Lin-Tsay shell formulation [7]. The material formulation used for the rail and post is the isotropic piecewise linear elastic-plastic model. Wooden blockouts were modeled using eight node reduced integration hexahedral solid elements. These elements capture the behavior of the model at much less cost because they consume much less computer time and memory.

Bolt Modeling: Eight small bolts were used to connect the w-beams together and a long bolt used to connect the rails to the wooden blockout and post as shown in Figures 5 and 6. For the small bolts, the material formulation selected for the bolts and nuts is the rigid material formulation. This assumption was made to reduce the computation time since small elements are needed to capture the geometry of the bolts. These elements would control the time step and lead to larger computation time. By assuming the rigid material model for the bolts, their element size is no longer critical since rigid elements do not control the time step. A spring is placed between the bolt head and the nut to represent the stiffness of the bolt. The properties of these springs are determined from the material properties, cross-sectional area, and length of the bolt. The long bolts have significant effect on the behavior of the G4(1S) system and have to be modeled in detail. To accurately and efficiently represent these bolts, special modeling technique was utilized. In this technique, the bolt is modeled with beam elements to capture its tensile, bending, and shear behavior. By using beam elements, the time step is not controlled by the cross-sectional geometry of the bolt. Hence, a larger simulation time step and smaller computation time is needed to reach a solution. Elasto-plastic material model with failure was assigned to the beam elements to simulate the nonlinear and failure behavior of the bolt. The geometry of the bolt is represented by shell elements with "null" material properties. The null shell elements have no effect on the stiffness of the bolts and their size does not affect the simulation time step. They are used to represent the bolt geometry for only contact purposes. Nodes from shell elements are tied to the beam element nodes to transfer the contact forces. This method was found to be very accurate and efficient and has been successfully used in several previous studies [8, 9, 10, 11].

<u>Soil and Soil/Post Interaction Modeling:</u> The soil was modeled as a cylindrical block 2.7m (9 ft) in diameter and 2.02m (6.5 ft) in length as shown in Figure 7. These dimensions were chosen such that the behavior of the soil and post/soil interaction is accurately captured with reasonable computation time. The outer boundaries of the soil model were constrained using the non-reflection boundary constraint option. This option is often used in modeling infinite domain and prevents the stress wave from reflecting at the fixed boundary. The soil block is modeled using eight node hexahedral solid elements. The shape of the post was incorporated into the soil mesh with appropriate flange and web thickness in order to avoid penetration between post and soil and to have full representation of the post/ soil interaction. Automatic single surface sliding interface is defined between the outer faces of the post and inner faces of the soil block to simulate the contact between the post and the soil and friction between the post and the soil was also included. The material constitutive model used for the soil is the "soil and crushable foam" model.

MODEL VALIDATION

Once the G4(1S) guardrail model was completed, it was combined with a vehicle model to simulate the setup for test 3-11 (i.e., 2000P, 100 km/hr (62 mph), 25 degrees test) as recommended in the NCHRP Report 350. Figure 8 depicts the model representation of G4(1S) guardrail system with the C2500 pickup truck (i.e., the typical 2000P vehicle used for testing roadside safety barriers). The vehicle weight is approximately 2000 kg (4400 lb). The vehicle orientation and initial speed were set in the model as recommended in Report 350, 25 degrees and 100 km/hr (62 mph). Details of the model size and setup are shown in Table 1.

A full-scale crash test, which was performed at the Texas Transportation Institute, was selected for model validation. The setup from this test was replicated in the G4(1S) and vehicle model. The model was then exercised to check it validity. Several simulations were performed to identify and correct deficiencies in the model. This process continued until reasonable correlations were obtained between the full-scale test and simulations. Figure 9 shows comparisons between the test and simulation. The roll and yaw angles comparisons are shown in Figure 10. Overall the simulations results compare well with the full-scale crash test.

The dynamic and permanent test article deflections reported in the TTI report has been compared to the simulation. The deflections are shown in Table 2. The dynamic deflection is higher in the simulation than in the test while the permanent deformation is slightly lower. This difference could be attributed to soil variation between one used in the model and the test. This difference did not affect the overall behavior of the vehicle which is the focus of this study. Rail permanent deformation from the test and simulations are shown in Figure 11.

The occupant impact velocity in the X and in the Y directions has been reported in the TTI report. These results are listed in Table 3 with the results of the simulation and the limits evaluated in the NCHRP Report 350. The results show good agreement between the test and simulation. Similarly, the occupant ridedown acceleration were compared to the full-scale crash and listed in Table 4.

RAIL HEIGHT EFFECT EVALUATION

Upon completing the validations, four additional simulations were run in which rail heights were varied. The rail heights in these simulations, measured from ground level to the center of the W-Beam rail were as follows: 475, 510, 550, 590, and 620 mm (18.5, 20, 21.5, 23, and 24.5 in). The middle height (550 mm) is the one from first simulation and full-scale crash test and was shown to meet all NCHRP Report 350 recommendations.

When analyzing the results and evaluating the performance of the guardrail system, the focus was on the potential of the vehicle to under-ride or override the w-beam guardrail and its capacity to remain upright during and after collision. These are typically the main critical criteria that guardrail systems have to meet. Occupant impact velocity and ridedown accelerations were less critical and were below the recommended limits.

All five models were identical except height of the rail. The results from the simulations are shown in Figures 12 to 15. The results showed that in the standard height case and the two increased height cases, the vehicle redirected and the barrier would likely meet all report 350 recommendations. For the two cases with reduced rail height, the vehicle over-rode the barrier and consequently did not meet on the report 350 criterion. The results indicate that reducing the height by as little as 40 mm (1.5 in) could hinder the ability of the barrier to redirect pickup trucks and large SUVs. Summary results from these simulations are listed in Table 5.

FULL-SCALE CRASH TESTS

To validate the simulation results, two full-scale crash tests were performed (Tests 04002 and 04003). Both tests were performed at The Federal Highway Administration (FHWA) Federal Outdoor Impact Laboratory (FOIL). The tests consisted of 2000P vehicle (Chevrolet C2500 pickup) impacting the w-beam guardrail at 100 km/hr impact speed and 25 degree impact angle. Both tests were identical except for the rail height. In the first test, the rail height relative to the vehicle was similar to the standard rail height simulation. In the second test, the rail was lowered by 60 mm (2.5 in). The effective rail heights for the two tests, from ground level to center of the rail, were 550 mm (21.5 in) for test 04002 and 490 mm (19 in) for test 04003. When measured from ground to the top of the rail, these heights would be equivalent to 700 mm (27.5 in) for test 04002 and 650 mm (25 in) for test 04003. The results from the first test are shown in Figure 16. The results from the second test are shown in Figure 17.

The results from the first test showed the barrier redirecting the pickup truck vehicle when the rail is set at the standard height. In the second test the vehicle overrode the barrier and rolled over upon impact with ground surface behind the barrier. These results confirmed the finite element simulation results. Summary results from the two full-scale crash tests are listed in Table 6.

CONCLUSIONS

Computer simulations were performed to evaluate the effect of guardrail height on the safety performance of G4(1S) barrier systems. First, a finite element model of the guardrail system was created and validated against full-scale crash tests performed by the Texas Transportation Institute. Next, the model of the G4(1S) guardrail system was modified to investigate five different rail heights: a standard height, two lower heights, and two higher heights. Simulations results showed that when the w-beam guardrail is lower than the standard height, there is a high risk of vehicle overriding the guardrail and/or rolling over. A higher guardrail position, on the other hand, would redirect the vehicle and meet all the NCHRP Report 350 criteria.

Two full-scale crash tests were conducted to validate the simulation results. The first test showed the barrier redirects the vehicle when the rail is set at the standard height. The second test showed that lowering the height by 60mm (2.5") caused the vehicle to override the barrier. This is in agreement with the simulation results.

The simulation results indicate that reducing the height by as little as 40 mm (1.5 in) could hinder the ability of the barrier to redirect pickup trucks and large SUVs. Considering the fact that bumper height could also vary among the test vehicles, reducing the tolerance on the rail height and setting the minimum height to be equal to the standard height, 550 mm (21.5 in) to center of the rail or 700 mm (27.5 in) to the top of the rail would lead to better barrier performance when impacted by pickup trucks and large SUVs.

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Table 1: FE Model Information

Parts	198
Nodes	106,268
Elements	108,133
Impact Speed	100 km/hr
Impact Angle	25 Degree
Simulation Time	0.5 s
LS-DYNA Version	LS960
Computer Platform	SGI Origin 2000
Vehicle Model	C2500R V9
Computation Time	48 hr

Table 2: Dynamic and Permanent Test Article Deflections (m).

	Crash test	Simulation
Dynamic deflection (m)	1	1.237
Permanent deflection (m)	0.7	0.637

Table 3: Occupant Impact Velocity from Full-Scale Crash Test and Simulation (m/s)

	Crash	Simulation	Preferred limit	Maximum limit
x-direction	-7.1	-5.27	9	12
y-direction	-4.4	-4.51	9	12

Table 4: Occupant Ridedown Acceleration from Full-Scale Test and Simulation.(g)

	Crash test	Simulatio	Preferred limit	Maximum
x-direction	-7.9	-7.44	15	20
y-direction	-8.4	-10.32	15	20

Table 5: Simulation Results Summary

	475 mm Rail Height	510 mm Rail Height	550 mm Rail Height	590 mm Rail Height	610 mm Rail Height
Occupant Impact Velocity (m/s)	-4.68	-6.12	-7.44	-8.28	-8.47
Occupant Ride Down Acceleration (g)	-3.98	-3.59	-5.27	-8.69	-13.92
Maximum Barrier Deformation (m)	.228	.511	0.637	.560	.455
Maximum Roll Angle (deg) – 0.5 sec duration	10.82	17.78	8.40	8.37	7.83
Maximum Yaw Angle (deg) – 0.5 sec duration	8.22	20.71	35.32	37.71	36.82

Table 6: Crash Test Results Summary

	Test 04002	Test 04003
Occupant Impact Velocity (m/s) – 1 sec Duration	-7.11	-7.52
Occupant Ride Down Acceleration (g) – 1 sec Duration	-9.16	-10.05
Maximum Roll Angle (deg) – 1 sec Duration	13.5	23.4
Maximum Yaw Angle (deg) – 1 sec Duration	40.1	42.8

Figure 1: Typical W-Beam Guard Rail System

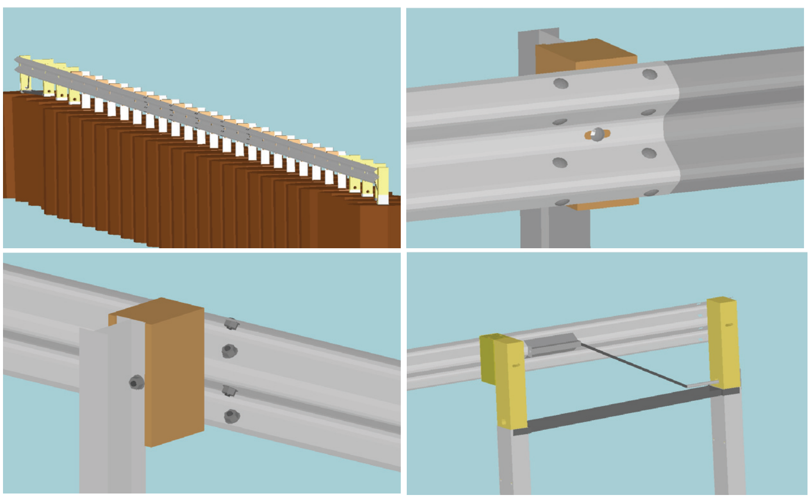

Figure 2: W-Beam Guard Rail Finite Element Model

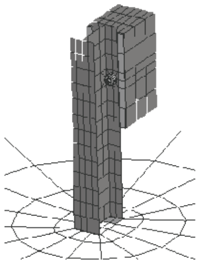

Figure 3: Finite Element Model of
Steel Post with Wooden Blockout

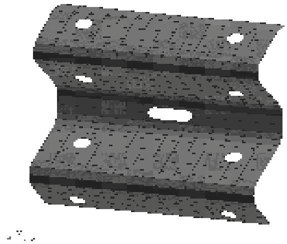

Figure 4: Finite Element Model
of W-beam Rail

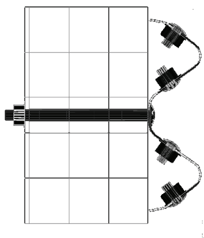

Figure 5: W-beam Connected
to Wooden Blockout

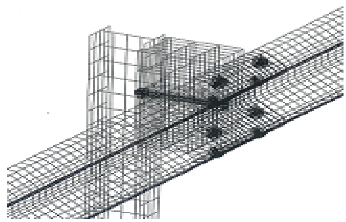

Figure 6: FE Model of w-beams
Connected to Post and Blockouts

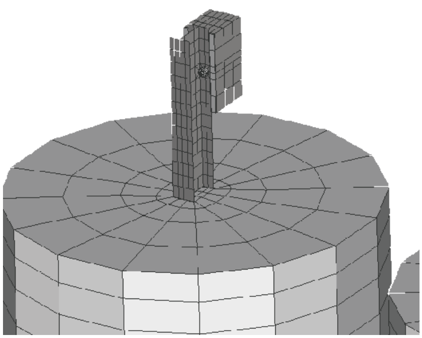

Figure 7: Soil Model with Post &
Guardrail Wooden Blockout

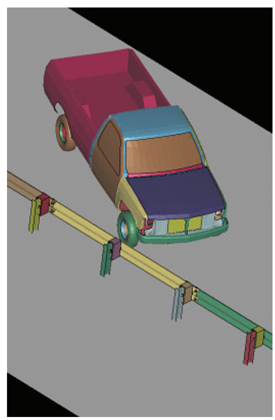

Figure 8: Complete G4(1S) System
Model with Vehicle

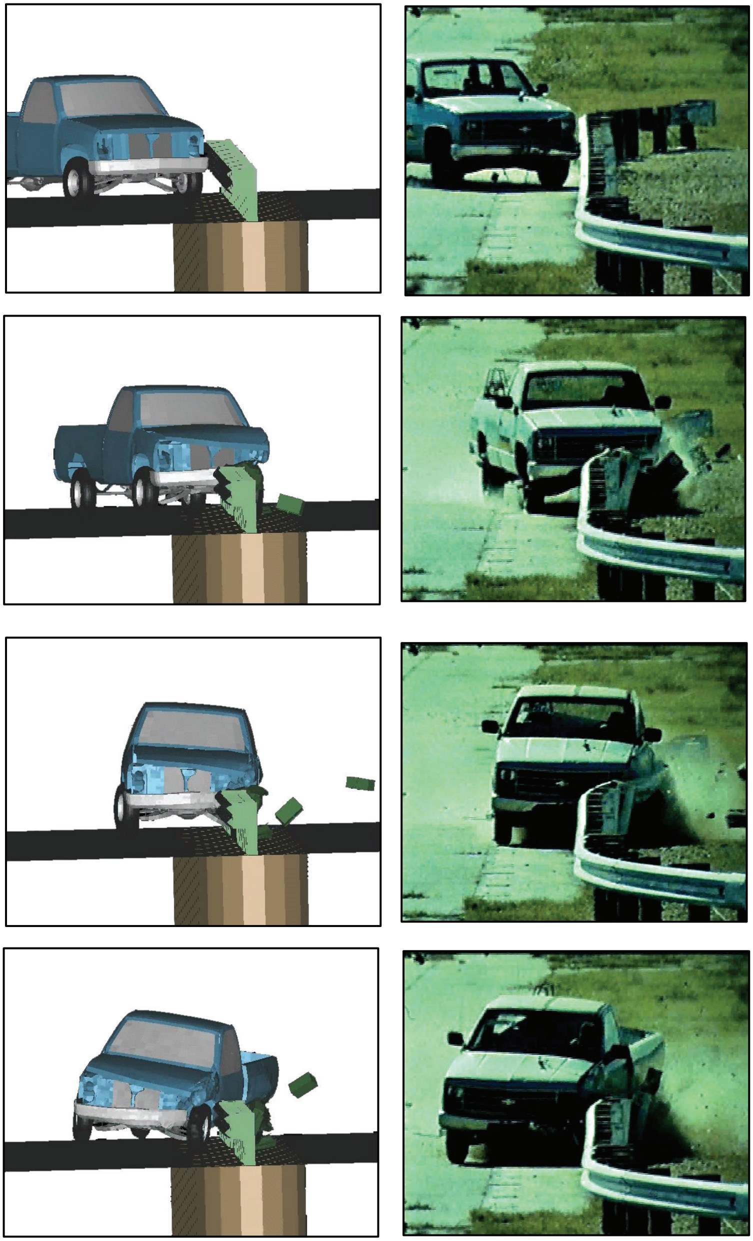

Figure 9: Full-Scale Crash Test/Simulation Comparisons

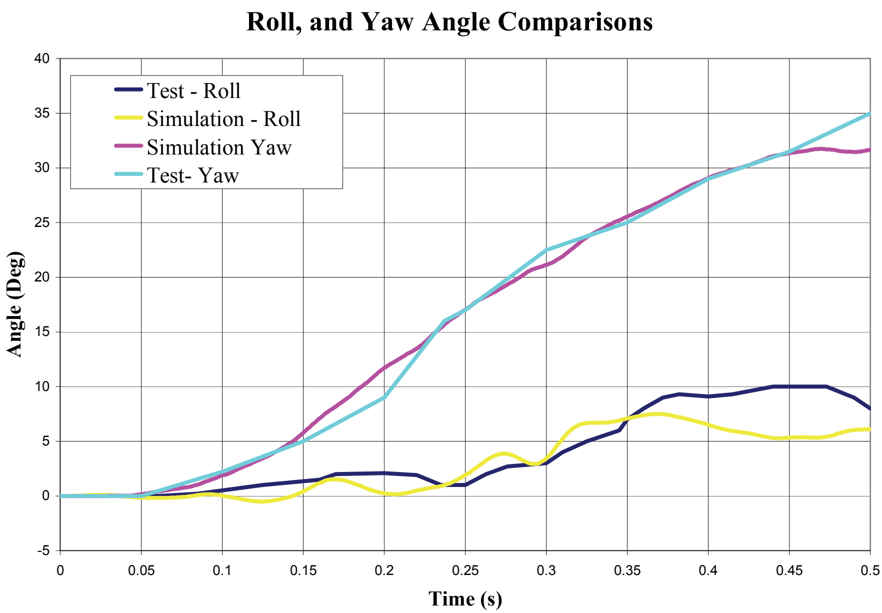

Figure 10: Roll and Pitch Full-Scale Crash Test/Simulation Comparisons

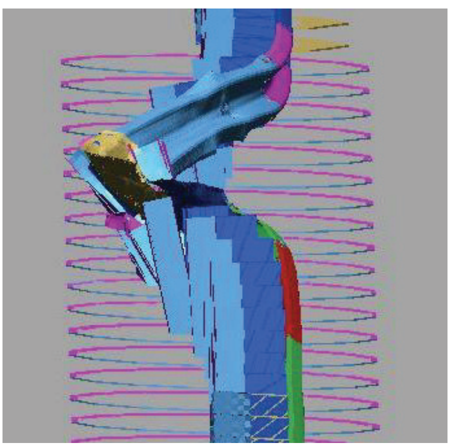

Figure 11: Dynamic and Permanent Test Article Deflections

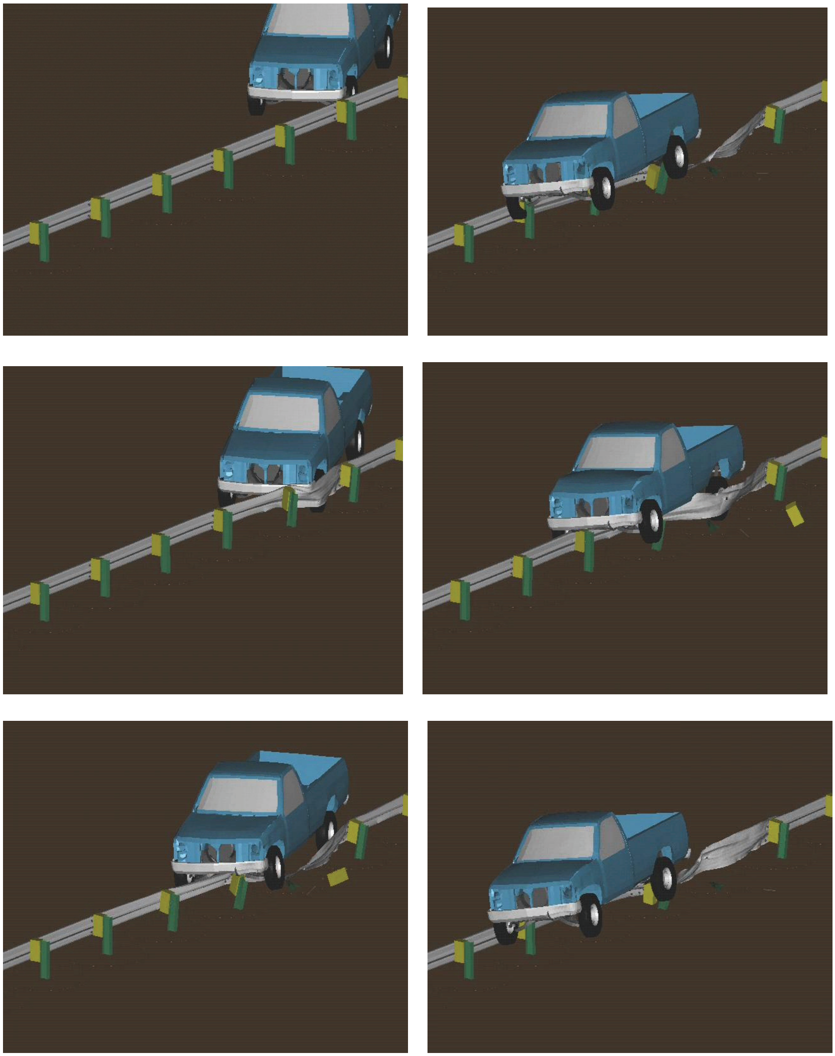

Figure 12: Simulation Results from the 475 mm Rail Height Case

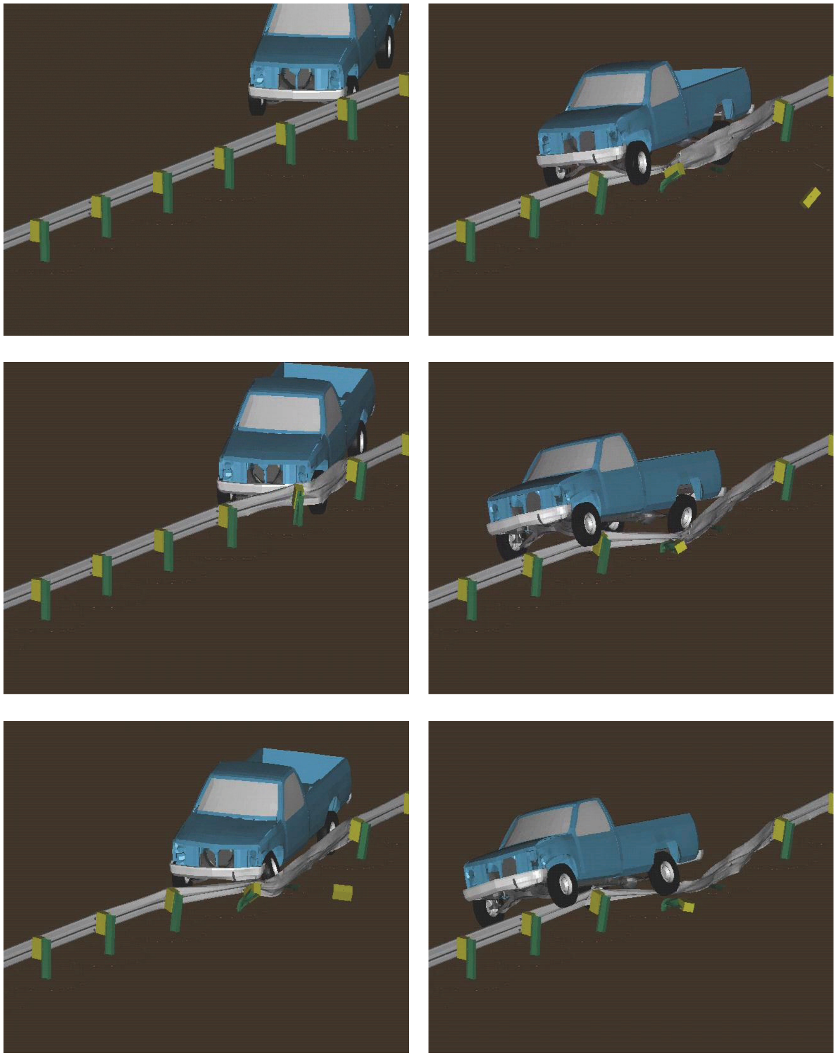

Figure 13: Simulation Results from the 510 mm Rail Height Case

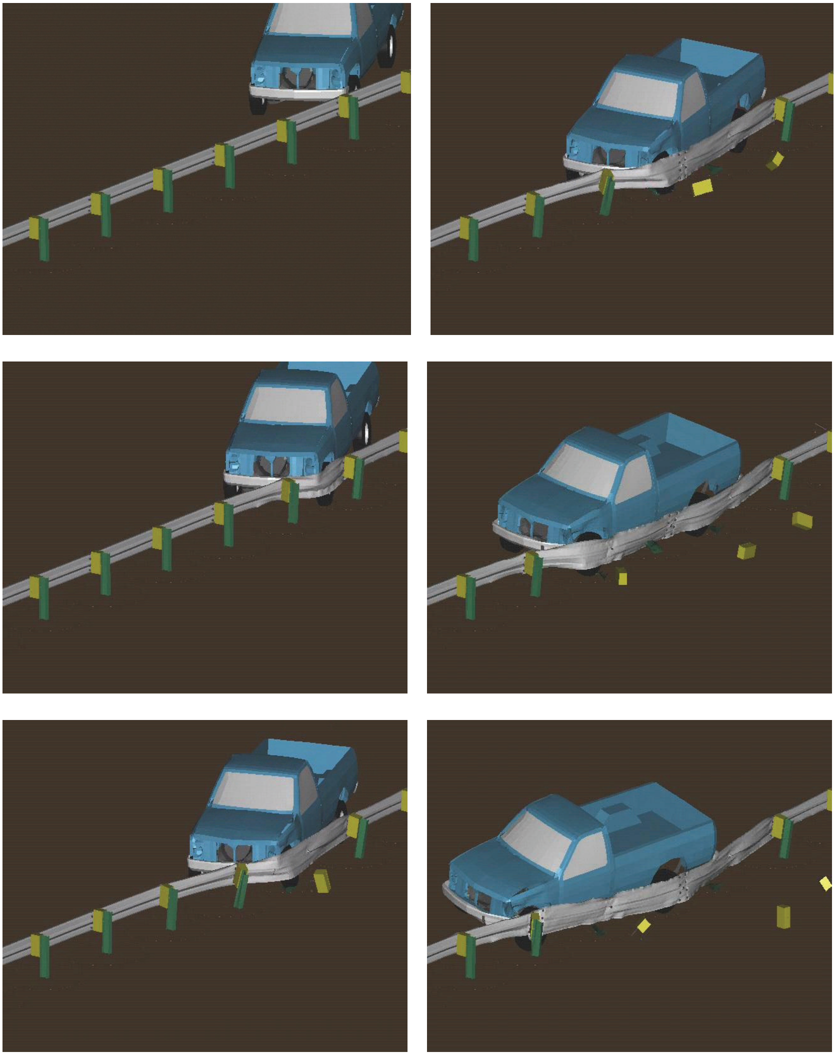

Figure 14: Simulation Results from the 550 mm Rail Height Case

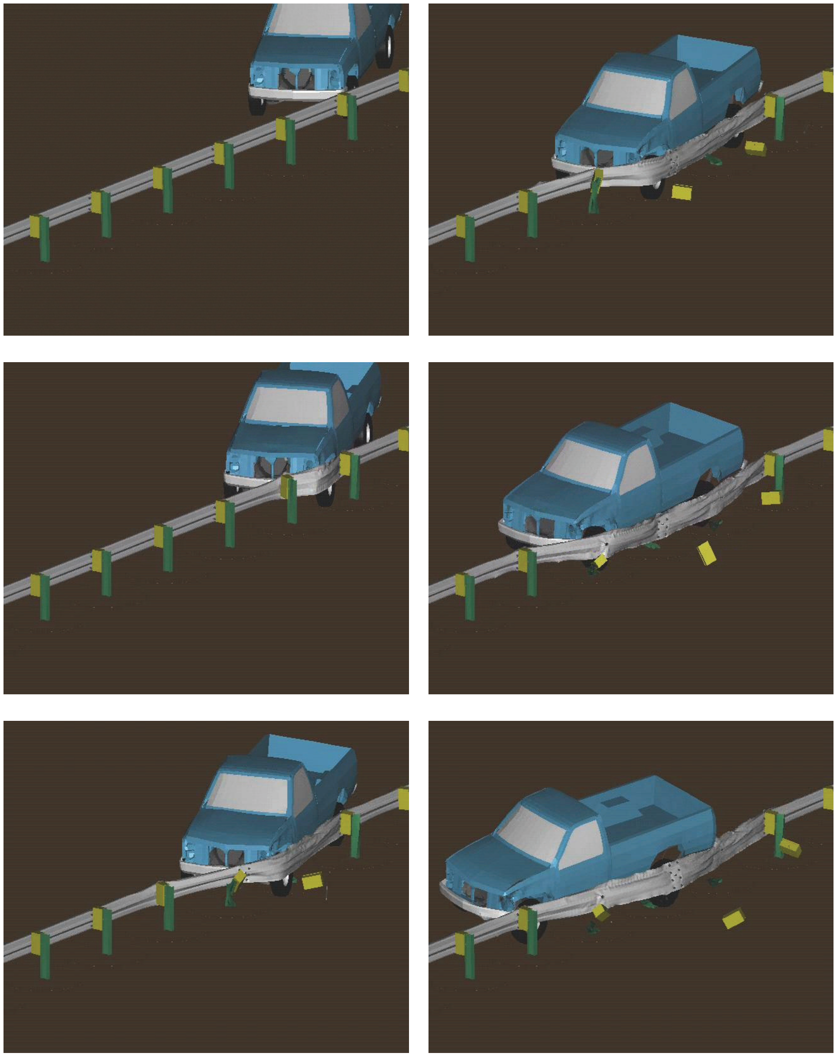

Figure 15: Simulation Results from the 590 mm Rail Height Case

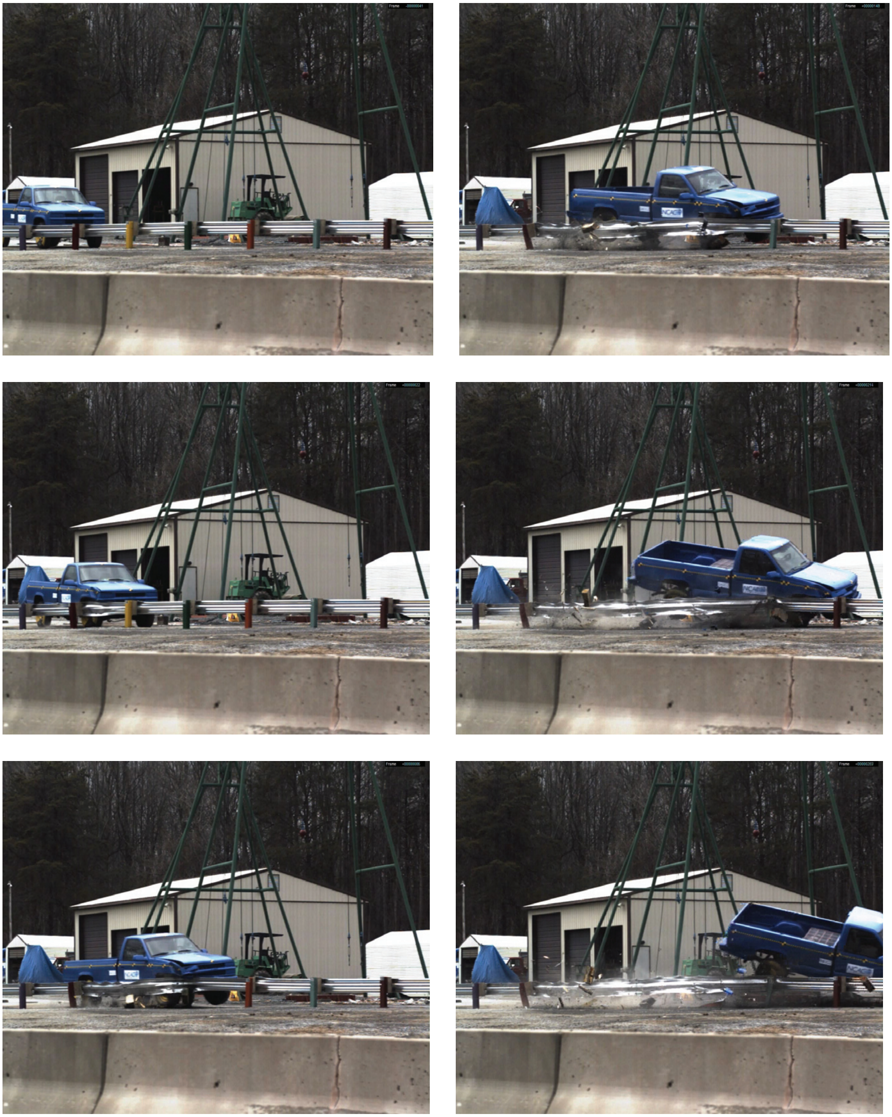

Figure 16: Full-Scale Test Results from Test 04002

Figure 17: Full-Scale Test Results from Test 04003