VALIDATED CRASH SIMULATION OF THE MOST COMMON GUARDRAIL SYSTEM IN THE USA

by

Ala Tabiei

Director
CENTER OF EXCELLENCE IN DYNA3D ANALYSIS
Department of Aerospace Eng. & Eng. Mechanics
University of Cincinnati, Cincinnati, OH 45221-0070
www.ase.uc.edu/~atabiei
Tel. (513) 556-3367
Fax (513) 556-5038
E-mail address: atabiei@uceng.uc.edu

and

Jin Wu

Graduate Research Assistant
CENTER OF EXCELLENCE IN DYNA3D ANALYSIS
Department of Aerospace Eng. & Eng. Mechanics
University of Cincinnati, Cincinnati, OH 45221-0070
Tel. (513) 861-4360
E-mail address: wujj@email.uc.edu

Keywords: Crashworthiness simulation;
Guardrail vehicle impact;
Large-scale finite element simulation;
Roadside safety.

VALIDATED CRASH SIMULATION OF THE MOST COMMON GUARDRAIL SYSTEM IN THE USA

Ala Tabiei[1] and Jin Wu[2]

CENTER OF EXCELLENCE IN DYNA3D ANALYSIS
Department of Aerospace Eng. & Eng. Mechanics
University of Cincinnati, Cincinnati, OH 45221-0070
www.ase.uc.edu/~atabiei

ABSTRACT

The subject of this investigation is the development of an accurate simulation of a truck impacting a strong-post w-beam guardrail system, the most common system in the USA. Detailed methods for system simulation are proposed and three major issues, which involve the use of springs to simulate component crashworthiness behavior, are investigated. Rail to blockout bolt connection, soil-post-dynamic interaction, and effect of ends of guardrail are modeled and simulated. Soil-post interaction is modeled using both Lagrangian and Eulerian meshes and the results using the two methods are presented. Both qualitative and quantitative validation of the crash simulation is presented and discussed. The present paper provides a roadmap for simulation of highway safety structures.

INTRODUCTION

In recent years, roadway systems analysis and design has become one of the primary goals of the FHWA. This is because the number of vehicles on the roads and the roadside obstacles continues to increase. Most of the emphasis has been on conducting full-scale tests in order to gain insight into potential safety problems and to develop new and improved roadside hardware. The design of roadside hardware such as guardrails, roadway signs and light poles under vehicle impact are performed experimentally through an iterative process of design, build, test, redesign and retest. This cycle continues until the product meets its design criteria.

The vehicle fleet has evolved. Automobiles in use today cover a wider range of sizes and shapes than ever before and there is a need to use different materials for certain parts of roadside hardware. As a result, many of the factors used in the design of highway safety structures should now be reconsidered. It is economically impossible to perform full-scale field testing on a wide range of parameters. Impact simulation utilizing nonlinear FE analysis is thus rapidly becoming an effective tool in designing and evaluating these systems.

The main objective of the study is to define a finite element model that can accurately represent full-scale crash tests of the G4(1S) strong post guardrail as required by NCHRP Report 350 (Ross, 1993) In the course of this approach, finite element models will emerge that simulate the full-scale test data within an allowable margin of error. This approach will enable us to identify the crash sensitive components of the G4(1S) guardrail safety structure under investigation. Identification of the sensitive parameters can be used as feed back in an optimization process to design new and improved guardrail system that will eliminate truck rollover. Once we are successful in validating one or more finite element

[1] Director
[2] Graduate Research Assistant

models to represent full-scale crash tests, we have reached the point where the finite element simulation can be applied to new crash scenarios. Changing crash parameters, like critical angle of impact and vehicle speed, or the original design of the roadside safety structure will lead to an optimization process of the design of the roadside structure itself.

Three major issues are important when modeling the G4(1S) strong post guardrail for impact simulation. These issues are listed as follows:

- Rail to blockout bolt connection.
- Soil-post dynamic interaction.
- Effect of ends of guardrail.

These issues will be treated in detail in separate sections below. Several approaches are proposed for performing crash simulation of the system.

RESEARCH METHODOLOGY AND APPROACH

Finite Element Model

The finite element (FE) model of the G4(1S) strong post guardrail system is developed using the preprocessors HyperMesh and FEMB. The FE model of the C-2500 pickup truck is imported into the guardrail model to generate a full FE system model. Figure 1 shows the full FE model of the system. This full model is used to simulate the crashworthiness behavior of the guardrail system for evaluation of the NCHRP Report 350 for the 2000-kg pickup truck recommendations. Specific details and dimensions for the G4(1S) guardrail system are obtained from reference (Mak, 1995).

Simulation of Bolt Connection

The W-beam is connected to the blockout with one bolt through a slotted hole. In the experimental testing of the guardrail system it is observed that some bolt connections are subjected to very high forces that cause the bolts to shear through the W-beam and loss connection to the blockouts. This behavior is very important for accurate simulation of the impact event and drastically influences the redirection of the vehicle. Two different methods are available to simulate the bolt connection (Hendricks, 1997) and a third is proposed in this investigation (which is more accurate). The three methods of approximation are as follows:

Merging Nodes. The connection of the W-beam to the blockouts is modeled by merging the nodes of the two parts. However, this method does not accurately represent the behavior of the connections, especially if the bolts become highly stressed, thus causing the possibility of breakage or pull-out of the bolts during the simulation.

Using Tied Node Sets With Failure. The connection is modeled by using the “Tied Node Sets With Failure” option in LS-DYNA. The tied nodes will remain connected until an average failure strain is reached in the materials of connected parts. Obviously, this method does not allow any separation of the nodes until failure has occurred. In the actual bolt connection, however, due to the slotted hole and elongation of the bolt, some movement and separation prior to the failure will happen.

Using Nonlinear Springs. Compared with the above methods, using nonlinear springs is a better approach to mimic the bolt connection. In this approach, the nonlinear spring option is employed and the load curve for force-displacement of nonlinear springs is obtained through component simulation. A detailed model (4711 nodes and 4640 elements) of the bolted connection is developed using HyperMesh as shown in Figure 2. Both sides of the W-beam are assumed to be simply supported. The bolt is given a transverse displacement as a function of time. The surface-to-surface contact option is applied to calculate the bolt-beam force interaction. The RCFORC (resultant interface forces) option is invoked to collect the force data as a function of time and the displacements. The data is filtered with a frequency of 300 Hz. This way the load curve necessary for the nonlinear spring is obtained.

Since the blot is located in an arbitrary position relative to the hole, analysis is performed for two extreme cases. Figure 3 shows these two extreme cases. Results indicate that the location of the bolt has significant influence on the bolt-beam interaction. Prescribed transverse displacement with several rates is given to the end of the rail. Results indicate that the transverse rate of loading has little effect on the ultimate load carrying capacity of the bolt in the considered impact regime.

The nonlinear spring's load curve, which is an idealization of the bolt, should be obtained from the actual location of the bolt in the slot hole. However, since the location of the bolt in the slot hole is not known a priori, the two extreme cases are considered. Simulations are performed using both bolt locations; however, location of the bolt as depicted in Figure 3 (b) yields the best results. The value of the load in the load curve corresponding to the bolt pull-out goes to zero once the bolt is completely pulled out through the W-beam. Therefore, the post and W-beam can continue to separate without any further force transfer, which is what happens in actual bolt failure.

Simulation of Soil-Post Interaction

The simulation of the soil-post interaction, which obviously plays a vital role in the response of the guardrail during an impact event, is a complex and important issue. Since it is computationally expensive to include the soil FE model in the impact simulation, an alternative method is investigated (see Figure 4). The method involves the use of nonlinear springs. This method is employed in the investigation to simulate the soil's response during loading. The post in soil can be viewed as a beam with build-in end. This means that there are three force reactions and three moment reactions at the end of the beam. For the problem in hand, some reactions are ignored as they are assumed to be much smaller than others. The soil-post interaction consists mainly of three dominant reaction components as follows:

- Post-soil force interaction parallel to the W-beam guardrail (X-direction);
- Post-soil force interaction vertical to the W-beam guardrail (Y-direction);
- Post-soil torsional moment interaction about the axis of the post (about Z-direction).

In general, it can be assumed that the reactionary forces and moments consist of two distributed forces normal to the axis of the post and one distributed moment about the axis of the post. This assumption ignores any post pullout during an impact. These distributed reactions are due to the stiffness of the soil interacting with post deformation. Accordingly, the soil stiffness can be simulated using normal nonlinear axial springs and nonlinear torsional springs. The top left corner of Figure 4 shows a top view of a post with normal nonlinear axial springs K_1 and K_2 and nonlinear torsional springs K_3. These springs are attached to a master node and in turn the master node is attached to all nodes of the cross-section through rigid bodies. Consequently, forces in the springs are transferred properly to the entire beam cross-section.

The force-deflection curves (load curves) of these springs are obtained from component simulation. FE model (7864 nodes and 7032 elements) of the full-scale post imbedded in the soil is developed. Figure 5 depicts the FE model of the post-soil. Fifteen normal axial springs (5 for K_1 in the x-direction and 10 for K_2 in the y-direction) and six torsional springs (K_3) are employed for each post in the full system FE model. These numbers are chosen to represent the reaction distribution accurately. The load curves of these nonlinear springs are obtained through individual component simulation. For instance, to model the torsional rigidity of the post-soil a twisting angle as a function of time is applied at the upper portion of the post. The SECFORC option in LS-DYNA is invoked to obtain the cross-sectional moment (in the xy-plane) of the post at several locations in the soil-post model. The section moments at A, B, C, … etc. (see Figure 4) are obtained from the simulation. These section moments are used to extract load curves for the nonlinear torsional springs. The torsional springs are placed at locations A, B, C, … etc. in the full FE system model. The rotation data of these cross-sectional centers can be obtained from the NODOUT file. In the same fashion, lateral displacement is applied to the upper portion of the post to obtain the stiffnesses in the lateral directions. The SECFORC option is invoked, as for the case of torsional direction, to extract the load curves for the springs K_1 and K_2. Using the above described method the load curves (force vs. displacement or moment vs. rotation) are obtained. It is clear that this method dose not allow the interaction between the deformation of the soil in the three directions while obtaining the load curves. The stiffnesses are obtained in a de-coupled fashion. In this investigation, the material model for the soil, as proposed in reference (Schauer, 1997), is used to extract the load curves for the springs.

Crashworthiness simulation, in general, utilizes Lagrangian mesh and most of the explicit crash FE codes are Lagrangian. LS-DYNA recently has included Eulerian material models for impact simulation. In the soil-structure interaction it is expected that soil material will fail and significant material is pushed and shuffled around. It is known that Lagrangian meshes become unstable when sever distortion occurs. Therefore, a Lagrangian mesh for a soil-post interaction component simulation could render the extracted stiffnesses for the nonlinear springs inaccurate. For this purpose, the simulation of soil-post dynamic interaction behavior is carried out based on both Lagrangian mesh and Eulerian mesh.

Lagrangian Mesh. To simulate the post-soil interaction, several models were considered as follows:

- Post is assumed to be merged with soil. No contact definition between the post and the soil is necessary. This method yields a stiffer behavior and therefore, not recommended.
- Post is not merged with the soil. Automatic_single_surface contact is defined between the post and the soil. In this model the friction between the post and soil has great influence on the behavior.
- Post is not merged with the soil. Eroding contact is invoked to simulate soil failure. This method requires very dense mesh and yield incorrect results. The failed elements are removed which creates a gap between the soil and the post. This will cause the post to be pulled out with the application of negligible force in the axial direction of the post. This behavior is observed even when the friction coefficient exceeds one.

The model with automatic_single_surface contact is used to extract the stiffnesses of the nonlinear springs. The material model used is *Mat_Soil_and _Foam_Failure.

The mesh of the soil in the vicinity of the lower portion of the post utilizing Lagrangian mesh is severely distorted. This in general, would yield dubious results. To correct such severe mesh distortions, rezoning is necessary. However, rezoning is a complicated and cumbersome task. Therefore, in these situations, an Eulerian mesh can significantly simplify the analysis and simulation of such problems.

Eulerian Mesh. Mesh distortion is not an issue here because of the Eulerian formulation. The formulation allows material transfer and therefore, soil material can be pushed around with no mesh distortion. The material model used here is the same as in the Lagrangian mesh (*Mat_Soil_and_Foam_Failure) with the same values for the material constants.

In using the Eulerian formulation there is no need to define contact surfaces between the post (which is a Lagrangian mesh) and the soil (which is an Eulerian mesh). Interactions between the two materials occur through the viscous stresses. Since no contact surface with friction is defined the data for the cross sectional forces is much smoother than in the case of the Lagrangian mesh. Comparing the two mesh formulations, it is apparent that the Eulerian mesh yields much more stable behavior at high material deformation.

Simulation of End of Guardrail

The test setup for the G4(1S) system consisted of a 68.6 m guardrail section (Mak, 1995). The finite element model of the entire system is impractical and computationally inefficient and therefore, a simulated end effect must be included in the proposed FE model. Accurate simulation of the G4(1S) system is very much dependent on the accurate representation of the unmodeled portions. Since the W-beam redirects impacting vehicles primarily through beam tension, elastic springs are attached to the ends of the modeled W-beam to simulate its continuation in both directions. Initially, the behavior of the unmodeled portion of the W-beam is assumed to be in the elastic range during impact. The stiffness of the spring is derived from the following relationship:

$$K = \frac{EA}{L} \tag{1}$$

where E is the steel modulus of elasticity, A is the W-beam cross-section, and L is length of the unmodeled portion of the beam.

This approximation is investigated by developing a detailed finite element model of the unmodeled portion of the guardrail (L=25.7 m). The detailed model accounts for the effects of bolt connection and soil-post interaction. It is assumed that the effect of bolt sliding in the blockout-rail connections is insignificant. The SECFORC option is invoked in LS-DYNA to determine the cross-section forces. The simple linear spring relation was observed to be invalid for this crash situation and the cross-section forces obtained from the simulation of the detailed model are observed to be different than the ones obtained from the above equation. The section forces obtained from the detailed simulation are utilized in the full system model.

QUALITATIVE VALIDATION

A comparison of sequential photographs (overhead and frontal views) are depicted in Figures 6 through 9. Reference (Mak, 1995) provides the detailed information on the full-scale test results. The comparative figures indicate that the finite element simulation reasonably captures the basic sequence of events. Bolt pull-out and tire snagging phenomena are also observed in the finite element simulation. The vehicle ceases to contact the guardrail system at about 0.53 second. Simulation results predicted that the vehicle cease contact at about the same time. The rotation (yaw and roll) of the vehicle in the FE simulation rotates is the same as the test up to 0.18 second. However, these rotations cease to be the same after 0.18 second. It should be noted that the C2500 truck model was originally created and validated for frontal impact. The developers of the model were not primarily concerned with the detailed modeling of the vehicle suspension system. In addition, the model can not simulate tire deflation, which is observed in the test. Although these factors may not significantly effect the response of the vehicle, they have a considerable effect upon the response during a redirectional impact. The friction between the ground and the vehicle also will have a significant influence on the rotations. The ground friction is modeled in the simulation using a simple linear coulomb friction formulation. This formulation could be refined, using nonlinear friction law, to obtain more realistic rotations. Overall, however, the finite element simulation replicates the basic phenomenological behavior of the actual full-scale test.

QUANTITATIVE VALIDATION

While the qualitative validation of the developed FE model is conducted, the simulation must also be quantitatively validated. This can be accomplished by comparing the center of gravity acceleration of the vehicle obtained from the full-scale test and simulation. The NARD validation procedures are used in this paper.

NARD Validation Procedures

This validation procedure is based on the theory of signal processing and analysis, and consists of both time-domain and frequency-domain analyses. The present study uses only the time-domain validation portion. In the time-domain analysis, the following three measures are quantified:

Relative Moment Difference of Test and Simulation. The nth moment of test signal f(t) and its corresponding simulation output g(t) is defined as

$$M_n(f(t)) = \int_0^T t^n f(t)dt \text{ and } M_n(g(t)) = \int_0^T t^n g(t)dt \qquad (2)$$

Root Mean Square (RMS) Log Measure of Difference between Two Signals. The RMS log difference between two signals f(t) and g(t) is defined as

$$r_d = \left[\int_0^T \left[10\log\left(\frac{f^2(t)}{g^2(t)} \right) \right]^2 dt \right]^{0.5} \qquad (3)$$

The RMS log average of the two signals is defined by the following equation:

$$r_a = \left[0.5 \int_0^T \{[10\log(f^2(t))]^2 + [10\log(g^2(t))]^2\} dt \right]^{0.5} \qquad (4)$$

Correlation Measure between Two Signals. The energy measure of the correlation between two signals is given by the following equation:

$$R[f(t), g(t)] = \frac{\int_0^T f(t)g(t)dt}{\left[\left(\int_0^T f^2(t)dt \right) \left(\int_0^T g^2(t)dt \right) \right]^{0.5}} \qquad (5)$$

A high value of correlation (close to 1) indicates that the two signals are close to each other. The energy measure, however, is very sensitive to phase shift.

Comparison of Acceleration Data

Acceleration time histories for the simulated behavior and full-scale test are depicted in Figure 10 for an impact duration of 0.53 second. This impact duration is considered because the vehicle loses contact with the guardrail after 0.53 second. In the simulation, all data is collected using the nodal time history function in LS-TAURUS. Raw data, experimental and simulated, are filtered by the same frequency of 100 Hz. The validation results are shown in Table 1. All Relative Absolute Differences of moments are less than 0.20, which is considered an acceptable correlation value.

DISCUSSION AND CONCLUSION

A detailed roadmap is presented for modeling and simulation of the G4(1S) strong post guardrail system. This roadmap can be used for modeling and simulation of similar guardrail systems. The most important elements for crashworthiness simulation are identified and analyzed in detail. Detailed component simulation is a powerful tool for simplification of the full system model simulation. Some of the noteworthy observations are as follows:

- Approximating the stiffness of the unmodeled portions of the guardrail by a simple linear spring based on the reported equation is an acceptable simplification.
- Since position of the bolt in the slotted hole of the guardrail is random, two extreme cases are simulated and both must be used in the full model simulation to determine their effect on the total behavior.
- Both Lagrangian and Eulerian formulation is employed in the simulation of post-soil dynamic interaction. Theoretically these two methods should lead to the same results. However, there is some difference observed in the results, which is attributed to the mesh instability in the Lagrangian formulation. Eulerian mesh is more stable for soil simulation.
- All the above findings are incorporated in the full system model for crashworthiness simulation. Validation of the simulation is carried out both quantitatively and qualitatively.

The presented FE system model is validated. This model can be used for impact simulation of different vehicles as required by NCHRP report 350. In addition, this model can be used to improve the crashworthiness behavior of the G4(1S) guardrail system.

Table 1. Acceleration Validation

Relative Absolute Difference	
Zero Moment	0.126
1^{st} Moment	0.095
2^{nd} Moment	0.102
3^{rd} Moment	0.118
4^{th} Moment	0.132
5^{th} Moment	0.146
RMS Log Measures	
Log Difference r_d	10.1
Log Average r_a	9.35
r_d / r_a	1.08
Correlation Measure	
0.50	

ACKNOWLEDGMENTS

Funding for this investigation is provided by the FHWA under the Center of Excellence Collaborative agreement with Mr. Martin Hargrave as contract monitor. His encouragement and the discussion with Mr. Charlie McDevitt are greatly appreciated. Computing support was provided by the Ohio Supercomputer Center. Their support is gratefully acknowledged.

REFERENCES

1. Hendricks, Bart F., Martin, O. Sean and Wekezer, Jerzy W. (1997). "Impact Simulation of the 820C Vehicle with the G2 Guardrail." Publication No. FHWA-RD-96-212, Federal Highway Administration.
2. Mak, King K., Bligh, Roger P. and Menges, Wanda L. (1995). Crash Testing and Evaluation of Existing Guardrail Systems, Texas Transportation Institute, No. RF 471470.
3. Ross, Jr., H.E., Sicking, D.L., Zimmer, R.A. and Michie, J.D. (1993). NCHRP Report 350, Recommended Procedures for the Safety Performance Evaluation of Highway Features, Transportation Research Board, Washington, D.C.
4. Schauer, Dale, Tokarz, F., Kay, G., Lee, A., Logan, R., Coffie, E. and Ray, M. (1997). Preliminary Vehicle Impact Simulation Technology Advancement (Pre-VISTA), Publication No. FHWA -RD-96-059, Federal Highway Administration.
5. Tabiei, Ala and Wu, Jin (2000). "Roadmap for Crashworthiness Finite Element Simulation of Roadside Safety Structures." Finite Elements in Analysis and Design, Vol. 34, pp. 145-157.
6. FEMB User's Manual Version 26.5, Engineering Technology Associates, Inc., Madison Heights, MI, 1996.
7. HyperMesh Manual Version 2.0, Altair Engineering, Inc., Troy, MI, 1995.

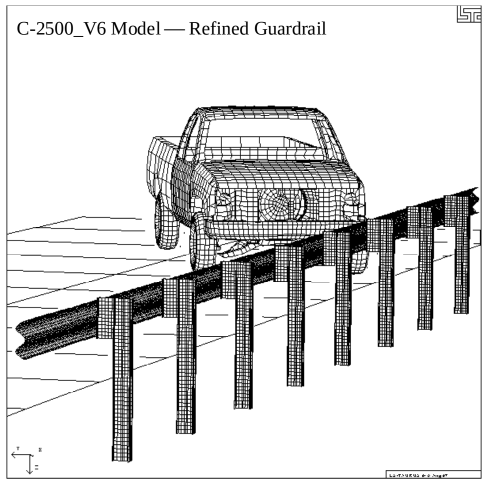


Figure 1. Vehicle and G4(1S) FE Model

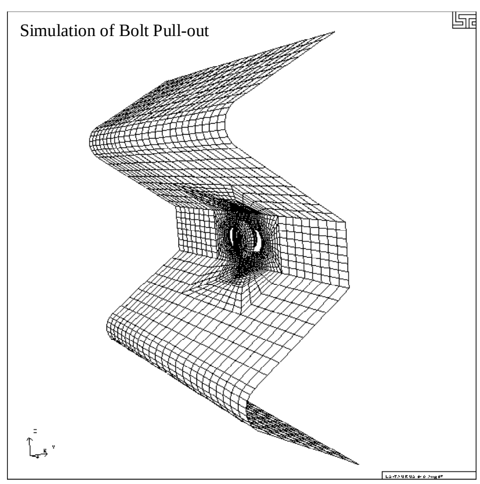
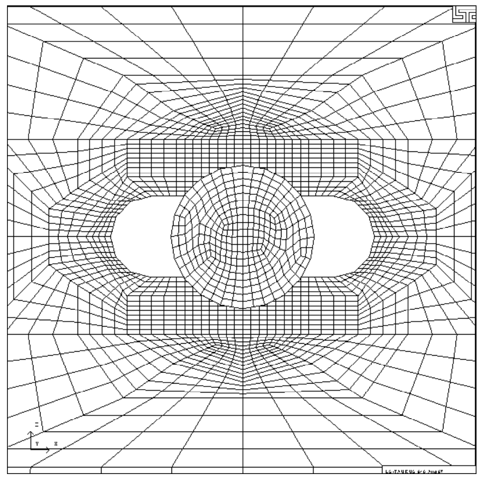
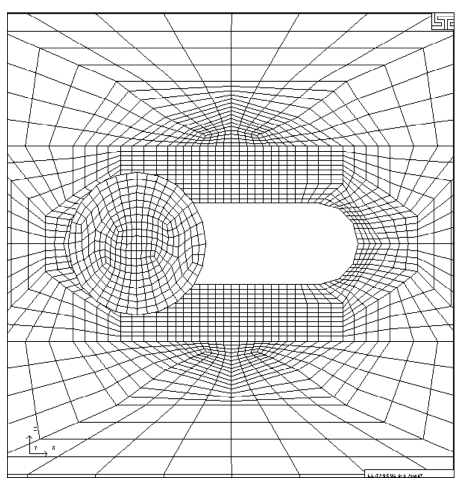


Figure 2. FE Model for Simulation of Bolt Pull-Out



(a). Bolt at the Center of the Hole



(b). Bolt offset from the Center of the Hole
Figure 3. Simulation of Bolt Pull-Out

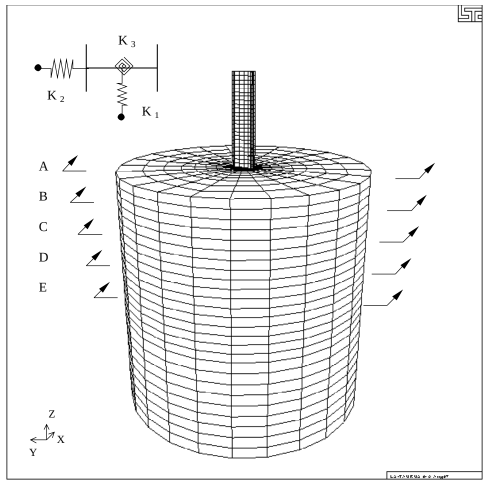


Figure 4. FE Model for Simulation of Dynamic Interaction Behavior
(Used for both Lagrangian Mesh and Eulerian Mesh)

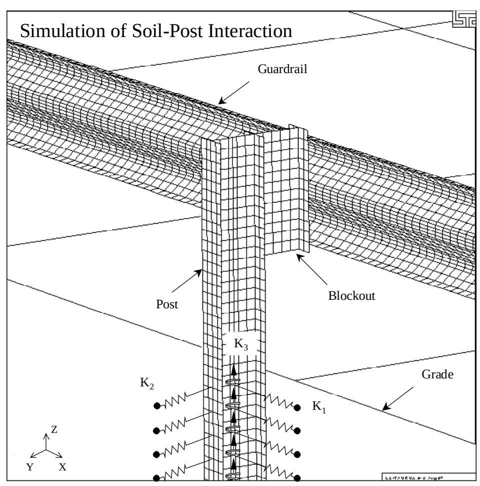
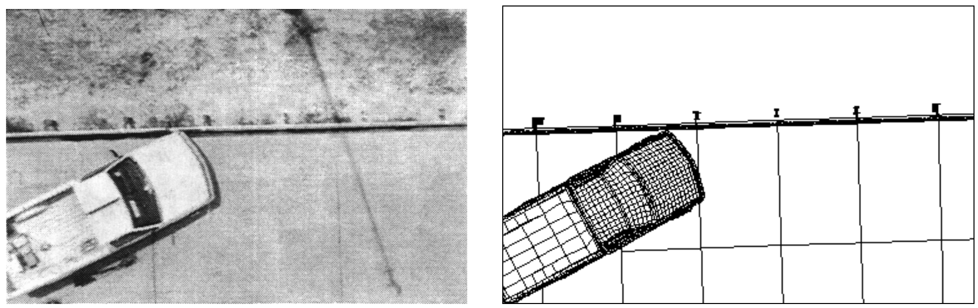
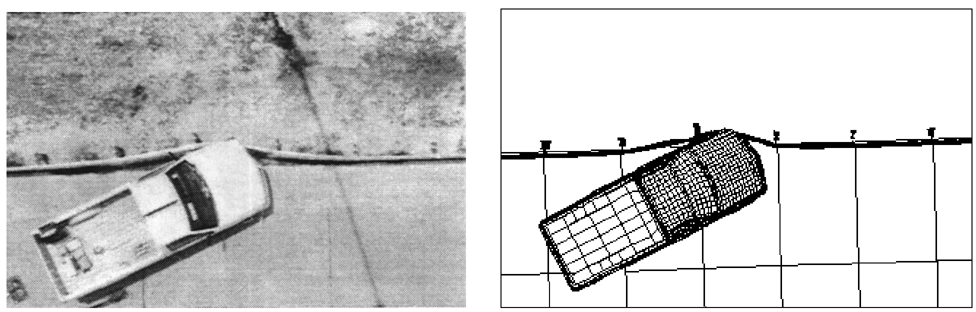
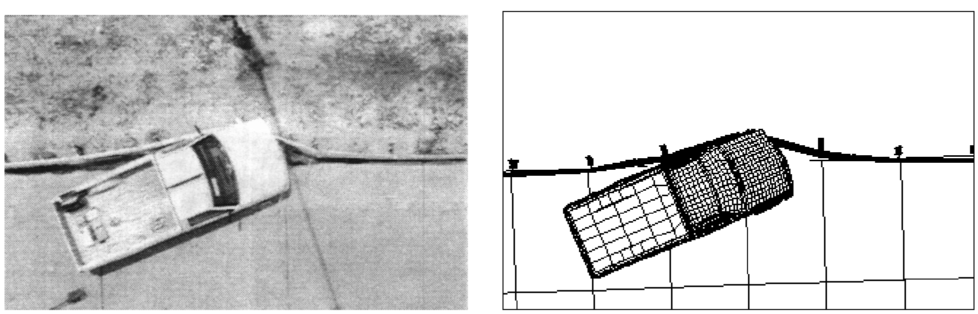


Figure 5. Simulation of Soil-Post Interaction


0.000 s


0.006 s


0.121 s

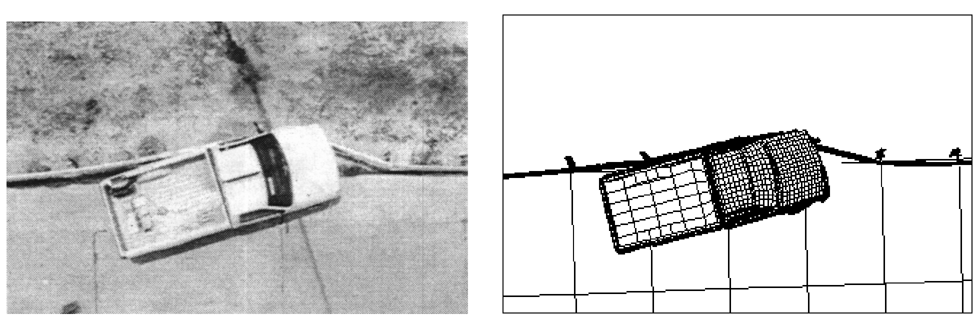
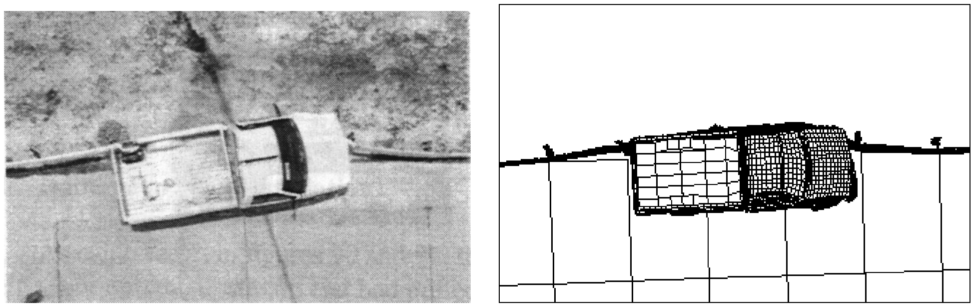
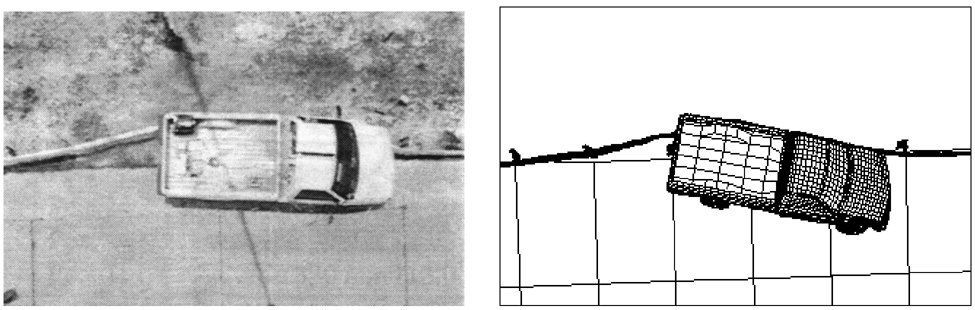
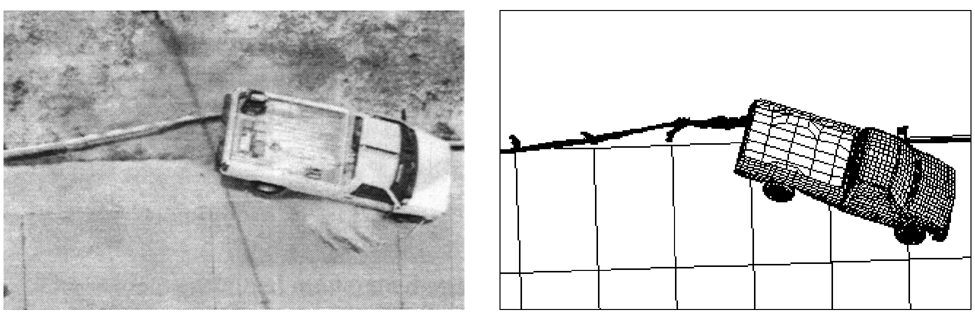

0.181 s

Figure 6. Comparison of Sequential Overhead Views in Test and Simulation


0.239 s


0.335 s


0.430 s

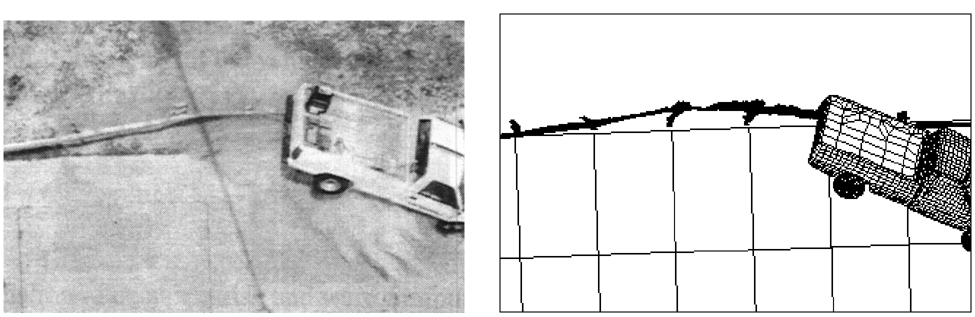

0.525 s

Figure 7. Comparison of Sequential Overhead Views in Test and Simulation (Continued)

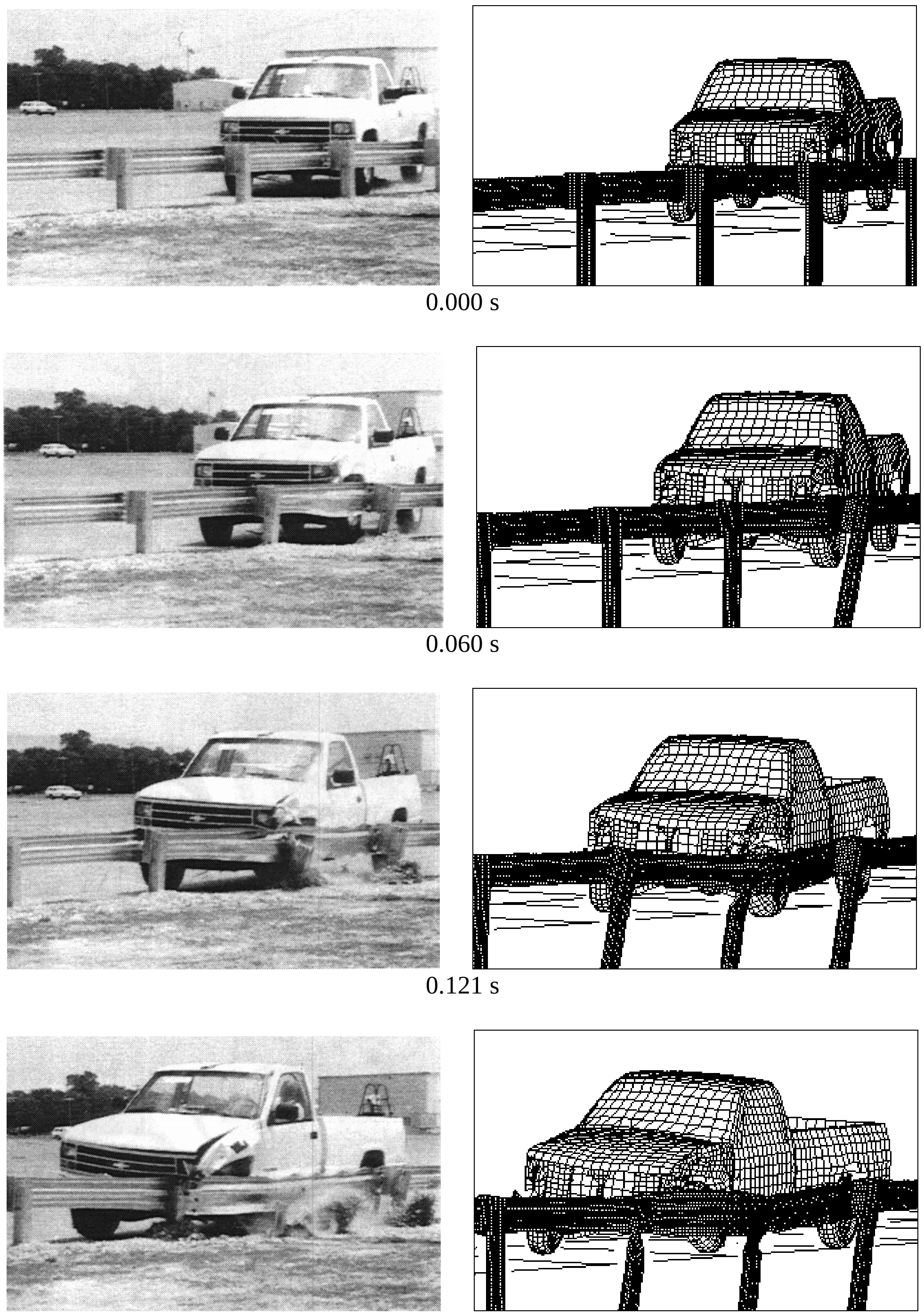
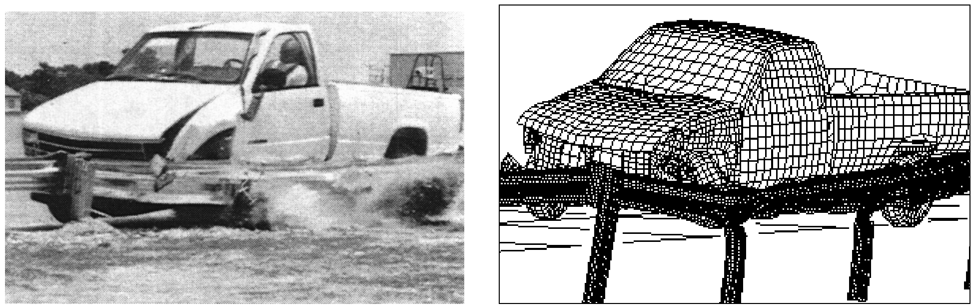
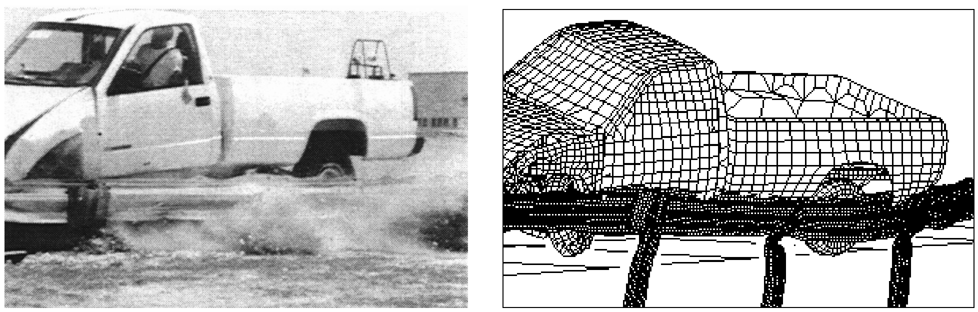


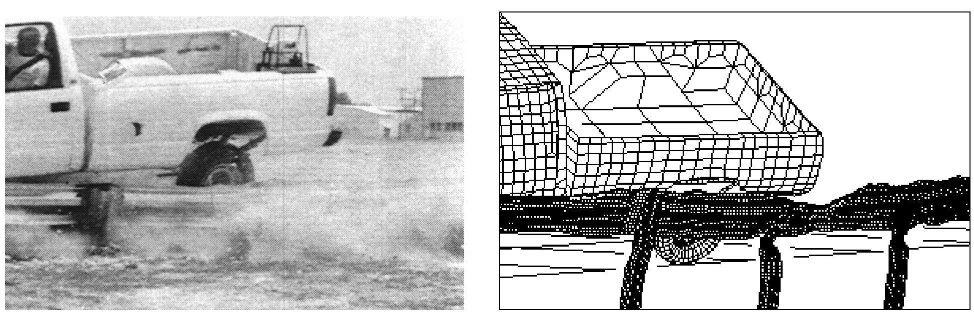
Figure 8. Comparison of Sequential Frontal Views in Test and Simulation



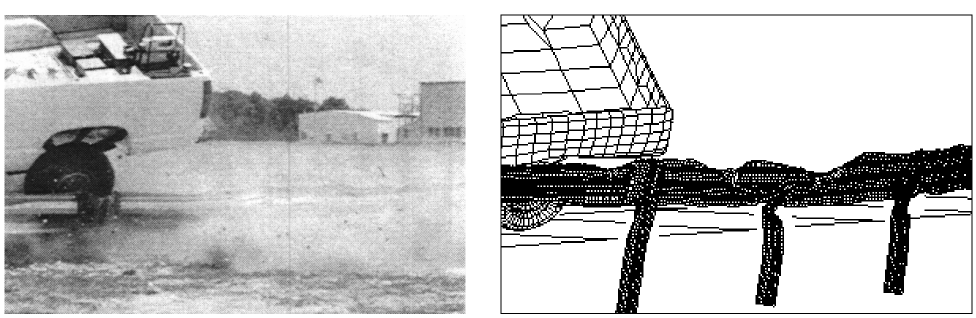
0.239 s



0.335 s



0.430 s



0.525 s

Figure 9. Comparison of Sequential Frontal Views in Test and Simulation (Continued)

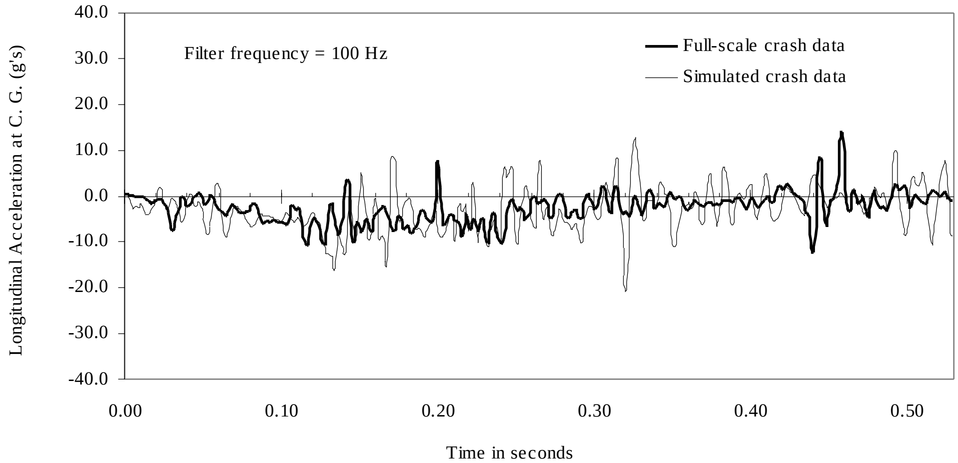


Figure 10. Longitudinal Acceleration at Center-of-Gravity