Development of an LS-DYNA Occupant Model for use in Crash Analyses of Roadside Safety Features

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This paper presents the development and validation of an LS-DYNA finite element occupant model suitable for use in crash analyses of roadside safety features. The addition of an occupant model in crash simulations can provide a link between vehicle accelerations and occupant injury. Injury measures for the vehicle occupants can provide additional evaluation criteria for the effectiveness of roadside safety features. The use of an occupant model in roadside hardware crash analyses will also improve the fidelity of the crash analysis by correctly modeling the inertial effects of the occupants and their interaction with the vehicle motions.

The approach used here is to construct much of the occupant model from rigid bodies connected by joints. The geometry and weight of each body segment were obtained from specifications of anthropomorphic test devices (ATDs) commonly used in crash testing. Additional flexible components of the occupant model, such as the neck and spine, were modeled using deformable elements with geometry and properties chosen to match those of the ATDs. Using the correct combination of deformable and rigid components results in an occupant model that is computationally efficient and capable of simulating occupant kinematics in a collision.

INTRODUCTION

There has been an ongoing research program sponsored by the Federal Highway Administration (FHWA) to develop modeling tools and advance the use of finite element crash analyses for design of roadside safety features *(1,2)*. To assist in this effort, FHWA has developed a series of vehicle models that can be used in crash analyses. These vehicle models developed for crash analyses with roadside hardware typically have less than 100,000 elements and allow for the longer simulation durations typically required for the analysis of roadside hardware. These models have been used by researchers in the analysis and development of a range of roadside safety features such as guardrails and breakaway luminaire supports *(e.g. 3,4)*.

Finite element analyses of roadside hardware crashworthiness have different requirements than analyses performed for vehicle crashworthiness. The primary objectives are to determine the response of a roadside safety feature to impact and the resulting vehicle motions, as opposed to the detailed crush response of the vehicle. Since the post collision motions of the vehicle are important to the analysis, the duration of the collision event can be many times longer than a vehicle-to-vehicle collision or frontal impact into a fixed barrier. The major role of many roadside longitudinal barriers during an impact is to redirect the vehicle smoothly back in the direction of travel and to discourage vehicle motions that would result in a vehicle rollover or uncontrollable redirection into the traffic flow. An additional goal of roadside safety features is to produce a load distribution on the vehicle that does not result in vehicle deformations in the occupant compartment.

Most crash analyses of roadside safety features have been performed without modeling of the occupants. The effectiveness of these safety features have been primarily evaluated based on the crash kinematics and deformations of the vehicle and roadside hardware. Direct measures of the crash response of occupants have not been used to evaluate the effectiveness of a roadside safety feature. Instead, secondary risk measures for occupants are evaluated such as occupant compartment intrusion and vehicle ride down acceleration. Using this analysis approach, an estimate of the severity of occupant secondary impacts with the vehicle interior can be obtained. However, this approach can not accurately assess the interaction of the occupants with the vehicle interior and crash safety features such as restraints, crash padding, and airbags.

Recently, there has been interest in the development and application of an occupant model in roadside crash analysis to improve the link between vehicle accelerations and occupant response and injury. Including occupant models in crash simulations would be helpful in both correctly modeling the inertial effects of the occupants in the collision and providing additional information about the potential for injury of the occupants. This document describes the development of a finite element occupant model that can be used in crash analyses of roadside safety features. The occupant model uses a combination of simple rigid body kinematics modeling and detailed modeling of anthropomorphic test device (ATD) components. The occupant model development takes advantage of the previous development of ATDs and ATD components as human surrogates.

Several finite element models of occupants or ATDs have been developed with varying degrees of biofidelity. For example, models of the Part 572 Subpart B Side Impact Dummy (e.g., the SID) have been developed and applied for analysis of various crashworthiness problems. These include both proprietary models developed by automobile manufacturers *(5,6)* and models developed under sponsorship of the U.S. Department of transportation *(7,8)*. These detailed finite element models of ATDs include descriptions of the mechanical components that make up the ATD structure such as the ribs, spine box, rubber neck and lower spine, internal rib damper, foam padding, abdominal insert, and outer rubber jacket. An additional level of occupant modeling with potentially the highest level of biofidelity is to model the correct anatomic structures of the human. An example of this approach is the Total Human Model for Safety (THUMS) described in Reference 9. Several additional anatomic human models exist for various body components. An example is the finite element model of the human anatomic pelvis and leg developed under a NHTSA sponsored program *(10)*. This type of model could be applied to study lower extremity injuries in vehicle frontal collisions. All of these detailed models can be useful to analyze and help develop improved tools for occupant protection systems. However, these models can be very complex and computationally demanding. A more computationally efficient model is needed for use in crash analyses of roadside safety features.

OCCUPANT MODEL DEVELOPMENT

Simulations of vehicle collisions with roadside safety features can have large computational requirements. As a result, an occupant model for this application should not significantly increase the computational requirements or control the minimum time step. Therefore, the model must be computationally efficient and easy to incorporate into existing vehicle models. The occupant model adapted in this effort is based on a DYNA3D model originally developed for analysis of occupants in a train collision *(11,12)*. The resulting occupant model is shown in Figure 1. The modeling approach adapted in this effort was to construct the majority of the occupant model from rigid bodies connected by joints. A sketch of an example rotational joint configuration for the ankle is shown in Figure 2. Rigid body joint blocks in the lower leg and foot are used to define the joint constraint. Nonlinear springs and dampers were included in the joint definitions to control the range of motions and appropriate rotational resistance. The nonlinear spring characteristics are determined based on the initial angle of the joint. Other joints in the extremities of the occupant model are defined using the same methodology. As defined, the joint modeling does not allow for failure or assessment of injury measures at the joints. This modeling of the occupant arms and legs is similar in approach to the rigid body kinematics models such as the Articulated Total Body (ATB) model or MADYMO.

The current version of the occupant model is created to model the response of seated occupants only. This is similar to the configuration of typical ATDs used in crash testing. The geometry of the pelvis, hips, and upper legs does not allow a sufficient range of motion for the occupant to reach an upright standing position. In the occupant model, a spherical joint is defined at the connection of the upper leg/femur rigid component and the hip/pelvis rigid component. A section of deformable soft tissue or foam material in the upper portion of the thigh connecting the pelvis and upper leg allows for flexibility of the hip joint while limiting the range of motion. This modeling approach was based on a similar geometry used in the construction of ATDs.

This new occupant model differs from the rigid body kinematics models in the modeling approach for the abdomen, lower spine, head, and neck. The head and neck behavior is obtained by including a deformable model of a rubber anthropomorphic test device (ATD) neck. Similarly, deformable ATD lower spine and abdominal insert components are included in the model to control the motions of the thorax. Using this limited set of deformable ATD components with the rigid components for the bulk of the occupant resulted in a model that is computationally efficient and capable of reproducing ATD or occupant kinematics with sufficient fidelity.

The Dummy model contains approximately 3100 deformable hexahedral brick elements and the remainder of the occupant model is lumped into 15 rigid body definitions. The deformable components are composed of relatively soft materials and result in a stable time step for the occupant model of approximately 8 microseconds. This time step is sufficiently large that it would not be a limiting factor in roadside hardware crash simulations. A comparable detailed finite element model of an ATD *(e.g. 7, 8)* has on the order of 20,000 deformable elements and a time step size of approximately one microsecond produced by internal steel components such as the rib bars. As a result, the detailed ATD modeling approach requires more than an order of magnitude more computational time than the occupant model developed in this study.

The current version of the occupant model was developed using the TrueGrid preprocessor code (*13*). Many of the model features are parameterized to facilitate positioning of the occupant into a specific seating configuration or scaling the model to adjust occupant size. The model is constructed entirely using the available features within LS-DYNA *(14)* and no additional software or code development is required for the use of the model. Therefore, this model is compatible with typical roadside crash analysis methods and can be easily implemented in the LS-DYNA vehicle models.

The geometry and weight of each body segment were obtained from specifications of ATD components. In particular, the various body component inertial properties were created to match those of the 50% male Hybrid III dummy. Additional models were created for the 5% female and 95% male dummies by scaling of the occupant model. However, efforts to calibrate and validate the occupant model have primarily been performed for the 50% male.

An example application of the occupant model is the design of a commuter train seat incorporating lap and shoulder belts, as shown in Figure 3. This is an application where a relatively simple occupant model is sufficient. The primary objective was to create a seat design that was capable of supporting the maximum expected loads in a collision. The requirement of the occupant model is to provide a reasonable estimate of the occupant inertial loads when subjected to a collision acceleration pulse. The simulation shown in Figure 3 is for three restrained 95% male occupants in the forward seat and three unrestrained 95% occupants in the rear seat. This combination produces the largest possible occupant loading on the seat frame from the six large male occupants.

In addition to developing a seat frame capable of supporting the collision loads, variations in the seat padding were evaluated to minimize head injuries. Therefore, the occupant model needed to be able to simulate the crash responses that can be compared to injury criteria. This would be true in many crash analysis applications. As a result, the fidelity of the head and neck components is important for the utility of the occupant model. Modeling the deformable ATD neck components provides a simple method of reproducing appropriate head and neck behaviors in the occupant model.

OCCUPANT MODEL VALIDATION

Validation of the occupant model is important for it to be applied in crashworthiness research. The approach used to validate the model is to compare it to experiments performed on ATDs or ATD components. The most important capability to be validated is the ability of the model to reproduce the ATD kinematics under a variety of collision loads. In addition, it is desirable to validate the head and neck components of the model due to the importance of head and neck injuries for many crash applications.

Two different testing configurations have been used to validate the occupant model. The first uses a pendulum calibration test configuration to validate the head and neck components. The second uses a rigid-seat sled test to validate the model kinematics for a frontal loading of a restrained dummy. These validation efforts are described below.

Head and Neck Model Calibration

The behavior of the head and neck system is very important for assessing occupant response and injury potential in collisions. Therefore, a series of finite element calculations were performed to simulate the neck bending calibration test used to check the kinematic performance of the neck in anthropomorphic test devices (ATDs). The neck bending calibration test and ATD neck performance guidelines were obtained from Reference 15. The test consists of mounting the neck and headform on a pendulum and dropping it from a height to obtain an impact velocity between 21.5 to 25.5 feet per second (fps). The pendulum is then decelerated at approximately 20 g with a duration of approximately 30 ms. The resultant rotation of the head and neck chordal displacement are then measured and checked against the acceptable performance corridors. Additional information on neck performance criteria and testing of mechanical, cadaver and volunteer subject necks is available in References 16 through 19.

In preliminary calculations, both the Blatz-Ko rubber and viscoelastic constitutive models were evaluated for the rubber neck section. Handbook values were used to establish baseline material properties and variations in properties were evaluated to optimize the neck model performance. These calculations found that a viscoelastic constitutive model is needed to match both the displacement and rotation criteria in the pendulum calibration test. The comparisons of the model predictions with the displacement and rotation qualification corridors are shown in Figure 4. The comparison shows good agreement of the model with the ATD head and neck performance criteria.

Occupant Kinematics Validation

A search of the literature was performed to identify an appropriate experiment that could be used for validation of the dummy model. The experiment configuration selected for the dummy model validation was a rigid sled test *(20)*. These tests have an advantage of a rigid seat that does not deform during the deceleration loading and, therefore, does not influence the dummy response. Therefore, a complex model of the seating system is not required as part of the validation effort.

A model of the rigid sled test configuration was developed and validation calculations were performed. The model includes both the rigid sled and seat and lap and shoulder belts to restrain the dummy. The dummy used in the test series was the 50% male Hybrid III dummy. The geometry of the model for the rigid sled test validation is shown in Figure 5. The size and weight of the occupant model shown in Figure 5 correspond to those of the 50% male dummy.

The loading was a 96 ms deceleration pulse with a peak value of approximately 27-g as shown in Figure 6. This acceleration pulse results in an approximately 34-mph change in velocity of the sled. The idealized restraint system was modeled using linear elastic behavior in webbing and the ends of the restraints rigidly attached to the sled. The resulting approximations result in a calculated peak belt load that is approximately 10% higher than measured in the tests. The calculated response of the dummy in the rigid sled experiment is shown in Figure 7. The belt resists the forward motion of the dummy relative to the seat. The head is bent forward and down as a result of the loading pulse and the arms flail upward. These qualitative behaviors were observed for the dummies used in the rigid sled tests.

The calculated head and chest accelerations are compared to the measured Hybrid III dummy response corridors in Figure 8. The comparisons show good agreement between the calculated and measured dummy responses. Some minor discrepancy is observed for the early portion of the crash pulse. During the initial 40 ms of the crash pulse the model under predicts the occupant accelerations measured in the sled tests. We believe that this is due to the modeling of the lap and shoulder restraints that did not include an initial tensile load. With the exception of this initial discrepancy, the model closely reproduces the measured head and chest accelerations.

SUMMARY AND CONCLUSIONS

An occupant model was developed for crash analyses using the LS-DYNA finite element code. The model was created using a combination of rigid bodies, joints, and deformable ATD components. This combination of modeling techniques provided a model that is computationally efficient. Initial validation calculations demonstrate the capability of the occupant model to simulate collision responses of ATDs.

The model has been validated against the measured head and chest accelerations for a 50% hybrid III dummy in a rigid seat sled test. In addition, limited application of the model for the evaluation and design of train seat systems has been effective. The deformable neck, lower spine, and abdominal insert components have previously been used within a detailed model of an ATD and partially validated for limited impact conditions *(7, 8)*. Additional validation of the model would be helpful for improving confidence in injury measures obtained by crash simulations.

Finally, the occupant model shows potential for use in crash analyses of roadside safety features. This computationally efficient model is ideally suited for use in roadside crash analysis that often require relatively long duration simulations and therefore have large computational requirements. The stability requirements for the occupant model will not limit the time step in roadside crash simulations. Using the occupant model in roadside crash analyses will improve the link between the vehicle accelerations and estimates of occupant injury. In addition, the model can be used to investigate the inertial effects of the occupants on the calculated vehicle crash response.

FUTURE MODEL DEVELOPMENT

One of the primary concerns for future development of the occupant model is additional calibration and validation work. Particular tasks include: (1) calibration of the various joint definitions to confirm the accurate simulation of the range of motion and resisting forces under a variety of loading conditions, and (2) validation of the full occupant model for additional test configurations. Of particular interest for roadside crash analysis is validation of the model for oblique and side impact test conditions.

Another area of model development is to expand the range of occupant types that can be represented by the model. The model was primarily developed and validated for the 50% male hybrid III dummy. Development and validation of similar occupant models for the 5% female and 95% male occupants is desirable. However, suitable test data for validation of ATDs beyond the 50% male hybrid III dummy is limited.

Finally, the utility of the occupant model needs to be demonstrated in roadside crash simulations. In many cases, this will require creation and/or modification of vehicle seat, restraint system, and interior components in the existing vehicle models *(e.g. 21)*. Subsequent crash simulations can be performed both with and without the occupant model to investigate the effect on vehicle response and evaluate the additional computational requirements of the occupant in the simulation. Ideally, the collision conditions to be analyzed should be for crash tests including instrumented ATDs that can be compared to the calculated occupant response.

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LIST OF FIGURES

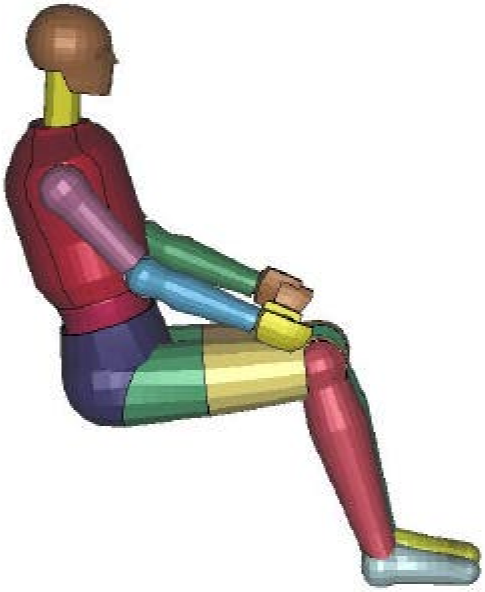

Figure 1 LS-DYNA finite element model of an occupant.

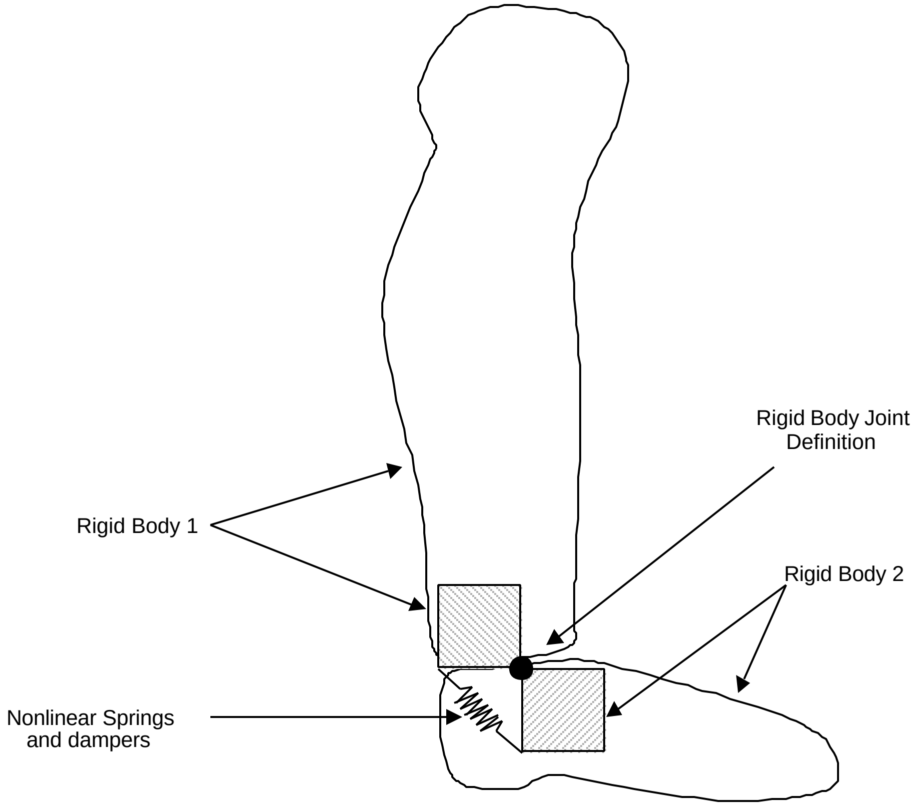

Figure 2 Sketch of the rigid joint definitions used in the occupant model extremities.

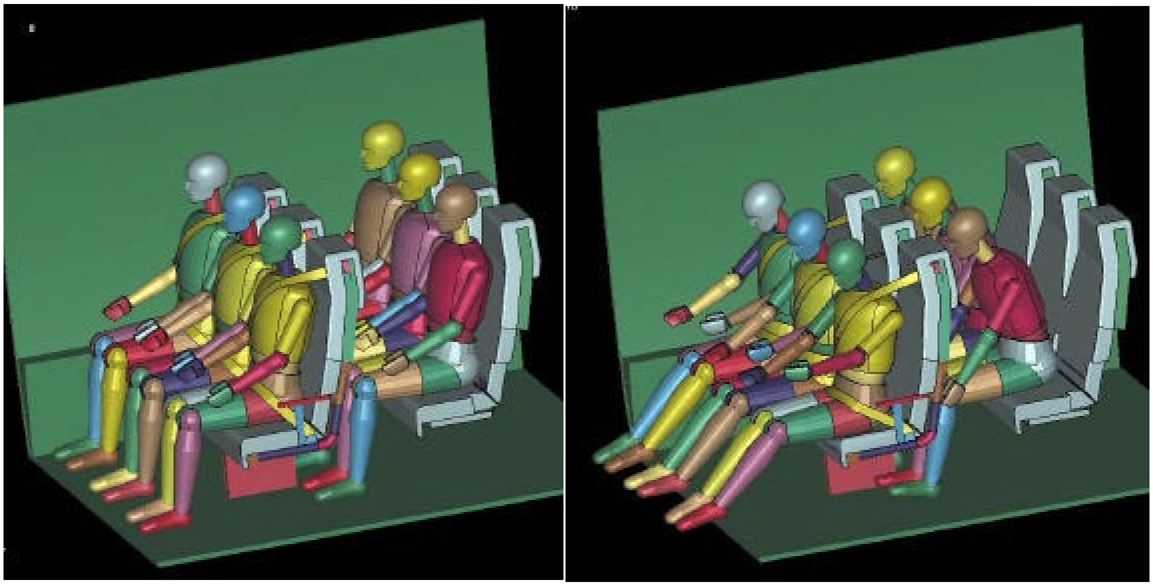

FIGURE 3 Finite element simulation of the seat and occupant response.

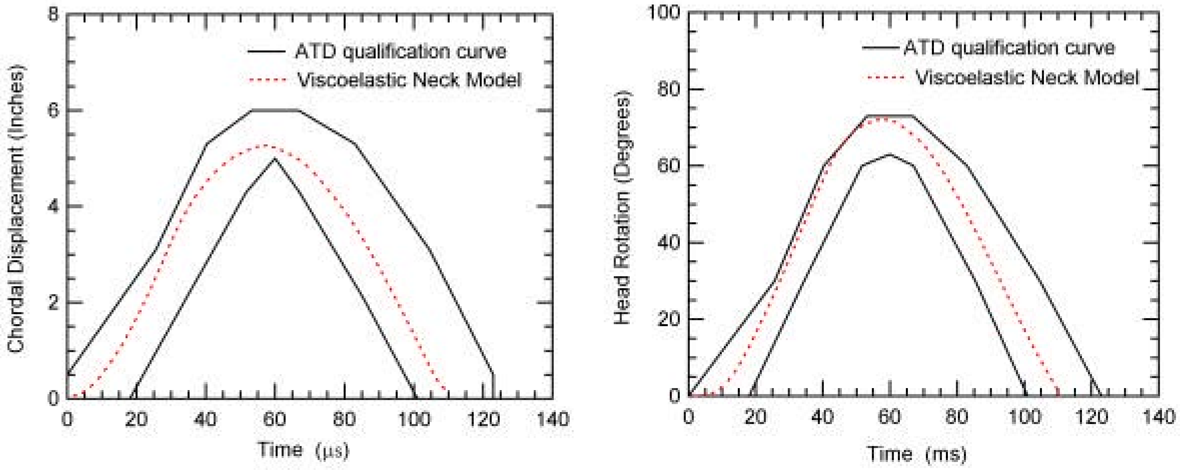

FIGURE 4 Calculated head displacements and rotations for the head and neck pendulum calibration test compared with the qualification corridors.

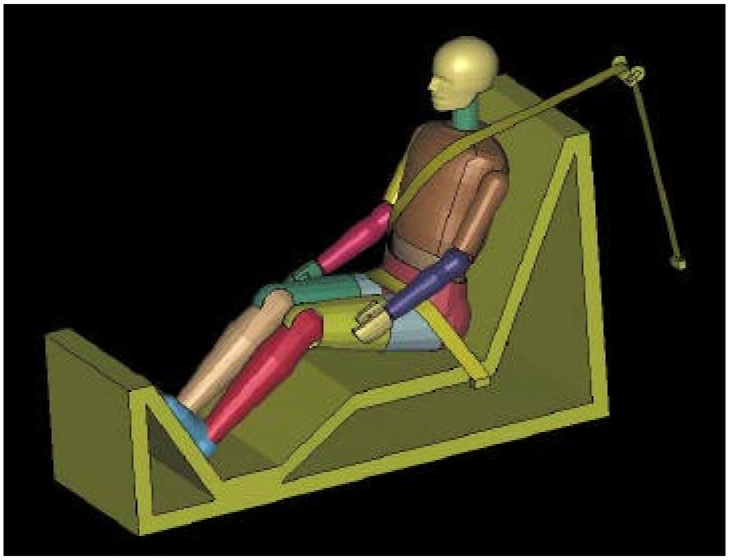

FIGURE 5 Finite element model for the rigid sled validation calculation.

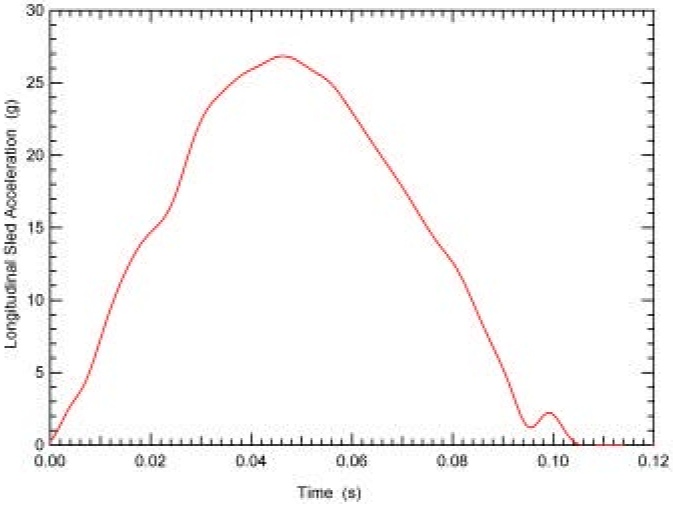

FIGURE 6 Sled acceleration pulse used for the validation calculation.

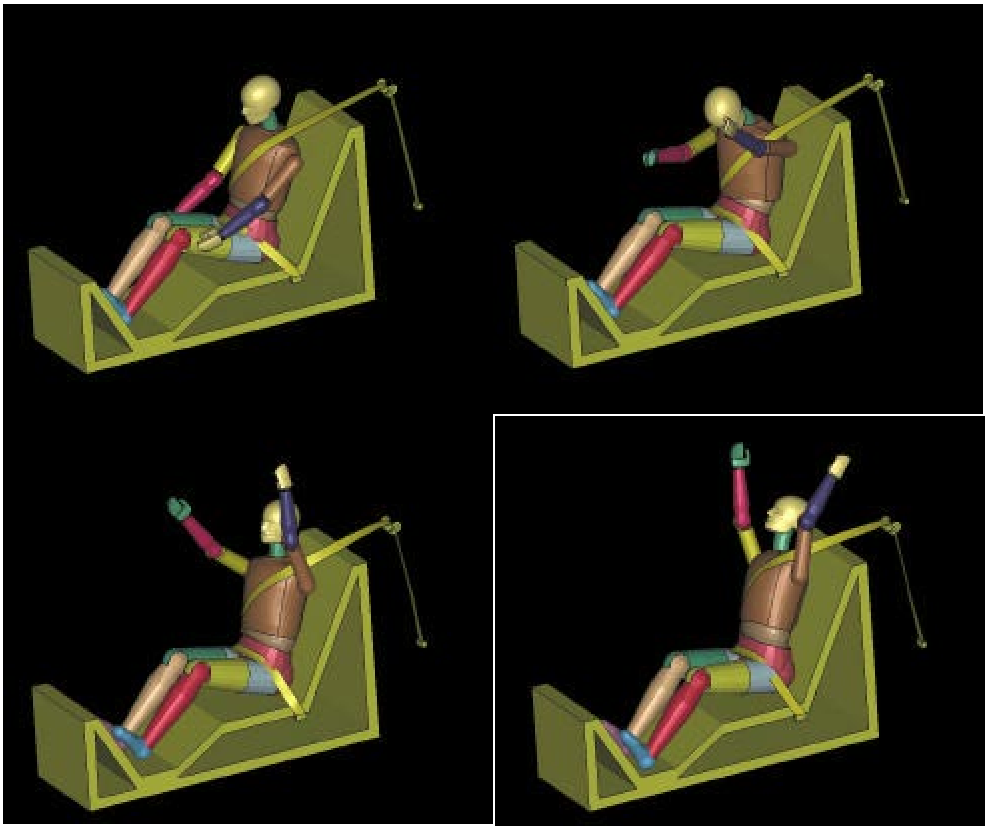

FIGURE 7 Calculated occupant response for the sled validation calculation.

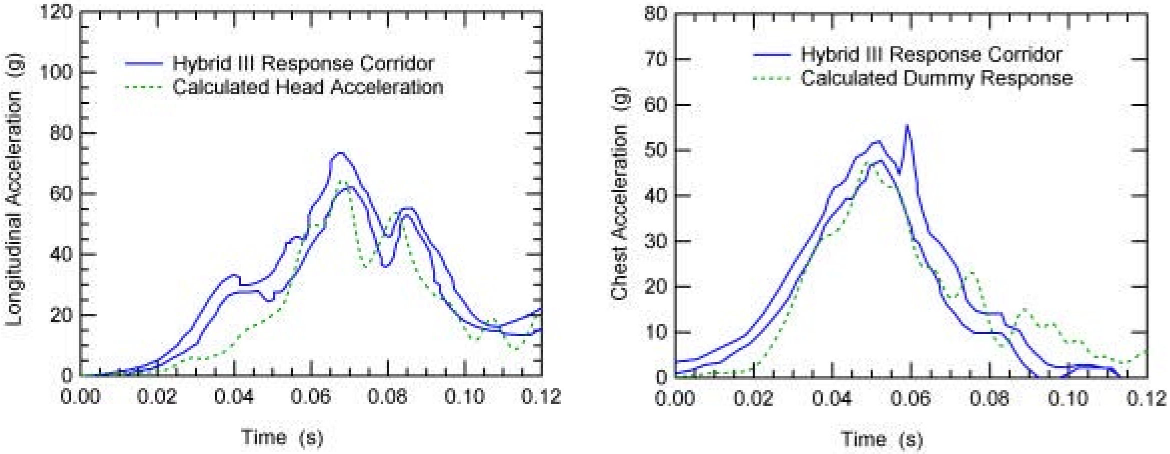

FIGURE 8 Calculated and measured head and chest accelerations for the rigid sled test.