

## **Evaluation of Passenger Rail Vehicle Crashworthiness**

S W Kirkpatrick\*, M Schroeder\*\*, and J W Simons\*

\*Applied Research Associates, Inc., 830 E. Evelyn Ave., Suite C, Sunnyvale, CA 94086 USA

\*\*Transportation Technology Center, Inc., P.O. Box 11130, 5550 DOT Road, Pueblo, CO 81001 USA

**Abstract** - In recent years there has been an increased effort to investigate and improve the crashworthiness of passenger rail vehicles in the United States. The structural crashworthiness requirements for new rail vehicles are changing to include specifications for crash energy management and crush zones rather than primarily specifications of vehicle and component strengths. In addition, the structural requirements to improve crashworthiness of rail vehicles can vary significantly from high-speed rail to light-rail transit vehicles depending on the service conditions.

In this paper we compare the various experimental, analytical, and computational approaches used to evaluate rail vehicle crashworthiness. The experimental approaches include static and dynamic testing of vehicles and components using scale model and full-scale structures. The appropriate type of test can vary significantly depending on the test objective. Scale model component tests may be the most efficient approach for developing a new crash energy management concept in a vehicle crush zone. Alternatively, a full-scale vehicle test may be required to demonstrate that the final design meets structural requirements. Similarly, there is a wide range of analyses that can be performed to evaluate various aspects of rail vehicle crashworthiness. Analyses can range from simplified one-dimensional models used to evaluate interactions between vehicles and study the effects of varying parameters such as crush strength to detailed three-dimensional finite element crash simulations that can be used as part of the vehicle design process. Here we show example analyses to provide further insight on the appropriate application of modeling approaches.

### **INTRODUCTION**

In recent years there has been an ongoing research program sponsored by The U.S. Federal Railroad Administration (FRA) and administered by the Volpe National Transportation Systems Center to improve the crashworthiness and passenger safety for existing and future rail equipment in the United States. These studies contribute to the ongoing research efforts worldwide to improve the crashworthiness of passenger rail vehicles. FRA's overall research program involves both computational analyses and experiments to further the understanding of rail vehicle crash responses and to design crash energy management structures for train cars.

Rail transit is a relatively safe method of transportation and trains typically perform well in collisions. Typically, most of the train suffers minor damage and most of the passengers are uninjured. However, rail transportation has unique crashworthiness problems in comparison with both highway and air travel. The large weight of rail equipment results in very large crash energies that must be dissipated in a collision. If override occurs in the collision, the crash energy absorption of the vehicles is greatly reduced, and usually results in a large loss of occupied volume and increases the potential for significant numbers of fatalities. Additionally, for a significant percentage of collisions, the lateral instability of consists under compressive longitudinal load leads to buckling and uncontrolled motions of the train cars.

Although developing crashworthy structures under this environment has some difficulties, rail vehicles also have some unique advantages over other transportation modes. Compared with automobiles, the longer rail car geometries and lower strength-to-weight ratios result in lower crash decelerations of the occupants in a collision. In addition, structural and interior modifications to improve crashworthiness can be added to rail equipment without the stringent weight penalty associated with aerospace applications.

### **CRASHWORTHINESS TESTING**

A wide variety of test methods are applied to evaluate the crashworthiness and structural strength of rail vehicles. When planning a test program the objectives of the tests need to be clearly defined and several

decisions about the appropriate type of test need to be made. For example, (1) whether static or dynamic testing is most appropriate, (2) whether to test components of the rail vehicle, a single vehicle, or multiple coupled vehicles, and (3) whether the test will be performed with scale-model or full-scale structures. Each of these testing methods can be appropriate depending on the objective of the test being performed. A comparison of these various test types is given below.

Static testing has been used extensively to evaluate the structural integrity of rail vehicles. Typical rail vehicle structural specifications require the various sills and posts to withstand a variety of loads applied at various positions without either plastic deformation or catastrophic failure. This type of strength specification is useful to define the structural integrity of the vehicle. If the applied loading is less than the yield strength of the structure the static testing can provide a nondestructive proof test to demonstrate the design exceeds minimum strength requirements. If the static load is sufficiently large to fail the structure, testing will determine a minimum load level for the onset of structural collapse.

However, static testing can produce misleading results when used to evaluate the performance of a component or vehicle to a collision or impact loading. During collisions, rail vehicles can experience high level loads for short times that lead to dynamic buckling of the structure. The characteristics of dynamic buckling can be quite different than those introduced by static testing. Dynamic buckling occurs when the load duration is shorter than the overall structural response time of the vehicle. In dynamic buckling, the amplitude of the load is higher than the static buckling load, and in general, the buckling mode is different. At these higher load levels, higher buckling modes are excited. These shorter wavelength higher buckling modes typically grow much faster than the longer wavelength modes. Thus the final dynamic buckling mode is determined by a combination of both the magnitude and duration of the collision load.

An example of the difference between static and dynamic buckling is clearly demonstrated in a study on the axial buckling of thin cylindrical shells shown in Figure 1 [1, 2]. The dynamic buckling was produced by an axial impact at the lower end of the shell. The impact produced an axial stress wave with an amplitude 1.5 times the classical static buckling stress. The observed dynamic buckling still illustrated the familiar diamond pattern, shown for the static response in Figure 1a, but with much shorter wavelengths. The permanent deformation resulting from the formation of plastic hinges is concentrated near the impacted end of the shell. Other studies investigating the energy absorption of impacted structural members have reported 10% increase in aluminum and 30%-70% increase for mild steels over the static crush energy for impact velocities in the range of 10-15 m/s [3].

A useful testing approach that has not been used extensively in recent crash safety studies is scale model testing. Scale model testing has a long history of successful application for crashworthiness research. Scale-model testing referred to as "replica scaling" uses a geometrically scaled test article made of the same material and construction methods as the full-scale vehicle. Holmes and Sliter, 1974 [4] give a good description of the application of scale model testing for crashworthiness studies. When applied properly, scale-model testing can very accurately reproduce the crash responses observed in full-scale testing. A comparison of 1/4-scale and full-scale frontal impact behaviors for an energy absorbing frame design is shown in Figure 2. The comparison shows good agreement both for the overall deformations and the failure mechanisms at the plastic hinge locations [4].

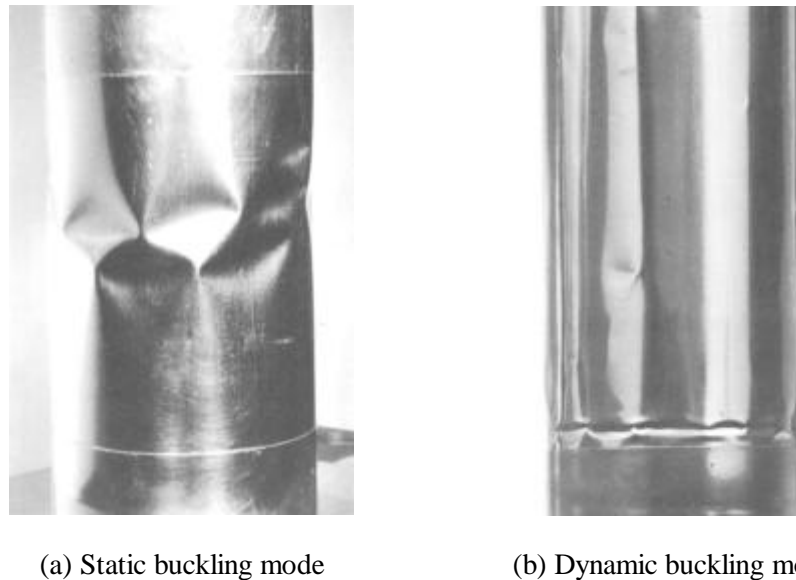


Figure 1. Comparison of static and dynamic buckling behaviors for an axially loaded thin cylindrical shell.

The primary advantage of scale-model testing is that it can be considerably less expensive than full scale testing. The fabrication of a prototype test structure at a smaller size is typically much easier and less expensive. Often performing the test and fabricating the required test fixtures are also significantly less expensive for a smaller scale test. A cost analysis in Reference 2 showed a 50% cost savings for testing at 1/3 scale and a 75% cost savings for performing tests at 1/6 scale for impact tests on a prototype highway vehicle.

One situation where the cost advantages of scale-model testing are not realized in crash testing is where existing vehicles are available for use as test articles. The cost of developing the tooling and fabricating the smaller scale vehicle may be higher than the cost of obtaining a full-scale vehicle that is already in production. This is the reason that small scale testing is rarely used for highway vehicle crash testing. An exception is when developing a completely new conceptual design, for which existing vehicle components or manufacturing facilities are not available.. An example of this type of study is shown in Figure 3 where scale model tests were used in the development of the Research Safety Vehicle (RSV). The RSV was constructed using sheet metal box sections filled with an energy-absorbing crushable foam. By crash testing 1/5-scale vehicle models, as shown in Figure 3a, potential weaknesses in the RSV design were discovered and eliminated prior to the construction of the full scale prototype vehicles [5]. The resulting RSV prototype is shown in Figure 3b.

A concern of using small scale testing is that there may be components of the response that do not scale correctly. For example, one factor that does not scale correctly is gravity. The scaling laws require that accelerations in the scale model test be increased by the scale factor. However, methods to produce increased gravitational acceleration, such as testing in a centrifuge, are difficult and expensive. Therefore, scale-model testing is probably not appropriate for collision responses in which gravitational effects are important. This would include investigations into override and anti-climbing or lateral buckling motions of a derailed train in a post-collision response.

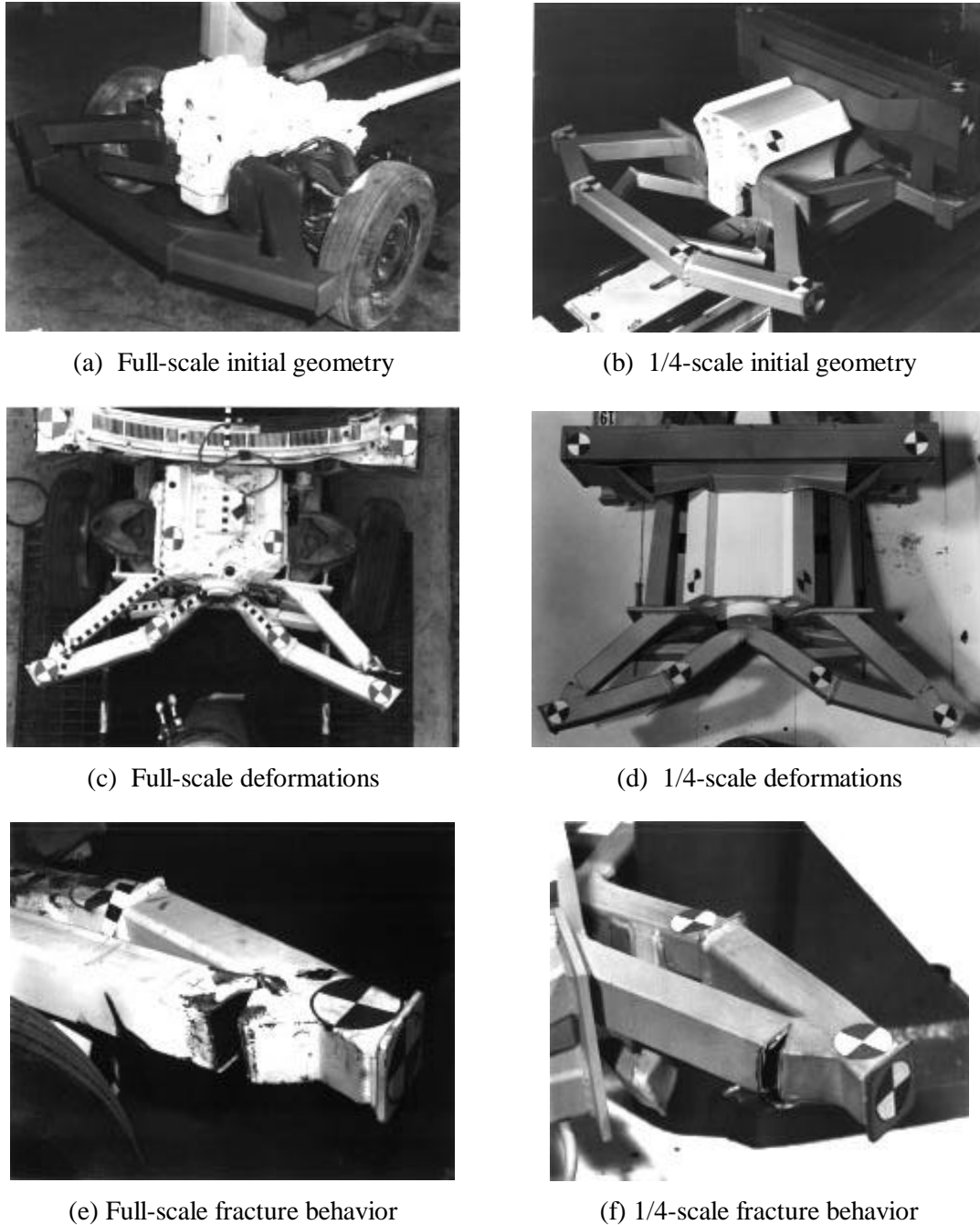


Figure 2. Comparison of the collision response for the full-scale and 1/4-scale frames.

Scale model testing has also been used for analysis of rail vehicle crashworthiness. Examples of scale model testing to investigate train-to-train collisions and grade crossing accidents are given in References 6 and 7 respectively. In more recent years, scale model testing has been very successfully used in the development of crash energy management systems for the TGV rail equipment [8]. The general approach in these studies was to use scale models to design and validate the behavior of crash energy absorbing structures, then to perform full-scale tests at the conclusion of the development program to qualify the structures.



vehicles to perform the test. In addition, the more complex response makes the test more difficult to use in the development and validation of computational models.

## **CRASHWORTHINESS ANALYSES**

There are a wide variety of analysis methods that are applied to the rail crashworthiness assessment problem. These range from simple energy balance and one-dimensional dynamics models to very detailed high fidelity three-dimensional finite element crash simulations. Any of these methods can be appropriate depending on the objective of the analyses being performed. Some examples and discussion of the various methods are given below.

The highest fidelity method of analysis for rail vehicle crashworthiness is application of three-dimensional nonlinear finite element analyses. The simulation of this type of vehicle crash response involves many complex features that need to be reproduced. These collision response mechanisms include:

- Nonlinear material behavior,
- Large deflections and rotations,
- Contacts at interfaces between structural components,
- Fracture and failure of structural elements, welds, and fasteners.

The finite element codes are often divided into two major classifications depending on whether they use implicit or explicit time integration. Implicit codes allow the analysis to be performed with relatively large time steps but result in a coupled system of equations for the response that require much greater computational effort per step. These codes are widely used in structural calculations and design. The ANSYS and ABAQUS codes are commonly used implicit finite element codes.

Alternatively, explicit codes require a very small time step for numerical stability (governed by the smallest elastic wave transit time across an element). However, the equations of motion are solved locally for each node, rather than solving a global system of coupled equations, and thus the response in each time step can be solved quickly. Thus, explicit codes are ideally suited for dynamic applications such as shock simulation, impact analysis, and crashworthiness. The explicit finite element codes commonly used for crashworthiness analyses are DYNA3D, LS-DYNA3D, PAMCRASH, RADIOSS, and MSC-DYTRAN.

Detailed finite element analyses of rail vehicles have been performed both in the vehicle design process and for assessment of existing rail equipment crashworthiness. Some good examples of nonlinear finite element analyses used in the design phase for rail vehicle crashworthiness are given in References 8 through 12. Reference 12 is unique because the analyses described in the reference were used to design retrofit modifications for an existing rail vehicle to improve the crash behavior. These analyses include both simulations of crash energy absorbing components such as sections of the vehicle end underframe and analyses of complete rail cars (passenger cars and power cars). An example simulation of an energy-absorbing frame similar in design to the frame on the end trailer car for the TGV 2N is shown in Figure 4. This type of simulation can be very helpful for determining effects on collapse strength from variations in material and geometric properties and for optimizing the collision behavior.

The refinement required to accurately model the collision response of a complete rail vehicle requires a minimum of approximately 50,000 to 250,000 elements. The large number of elements required and small time step (approximately 5 microseconds) in collision simulations require from several hours up to several days CPU time on an engineering workstation.

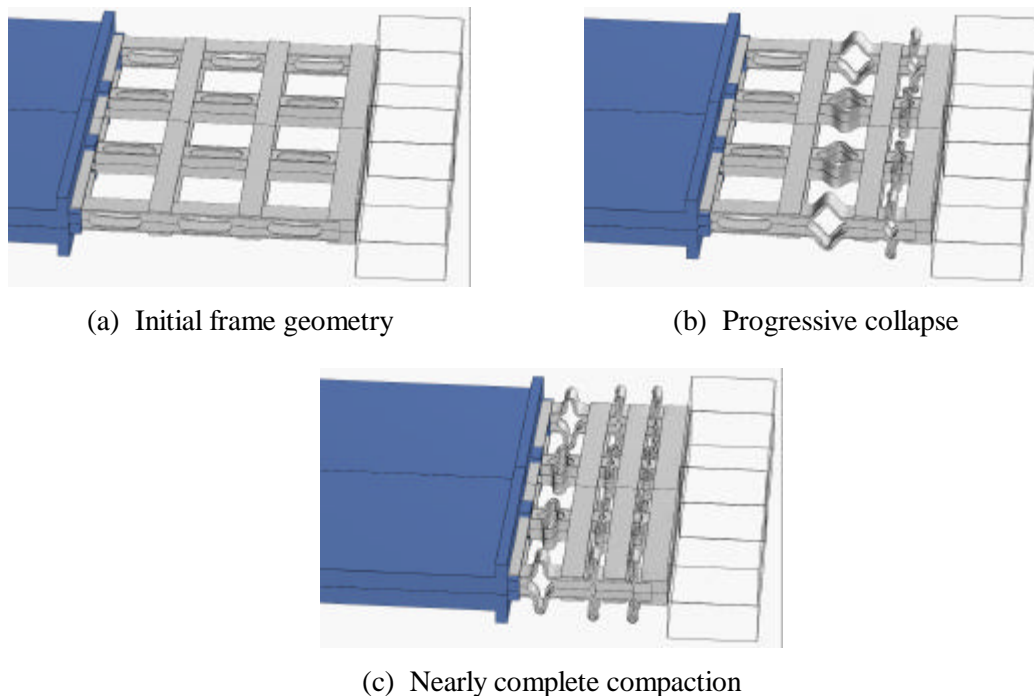


Figure 4. Finite Element Simulation of a TGV type crash energy management structure.

An example simulation of a 100,000-element passenger car model colliding with a rigid wall is shown in Figure 5. The simulation was performed using the LS-DYNA3D finite element code. LS-DYNA3D has advanced capabilities for modeling impact, including contacting surfaces, large strains and deformations, and an extensive library of nonlinear material models. LS-DYNA3D also has capabilities for reducing calculation times where appropriate. For example, a collection of elements that contribute only inertial effects to the crash response can be identified as a rigid body, reducing to six the number of degrees of freedom for that group of elements. The simulation shown in Figure 4 required approximately two days on a Silicon Graphics workstation with a single R10000 processor. Although the speed of computers is rapidly increasing and multi-processor machines are now readily available, this level of fidelity is currently not feasible when modeling train-to-train collisions, except on super computers.

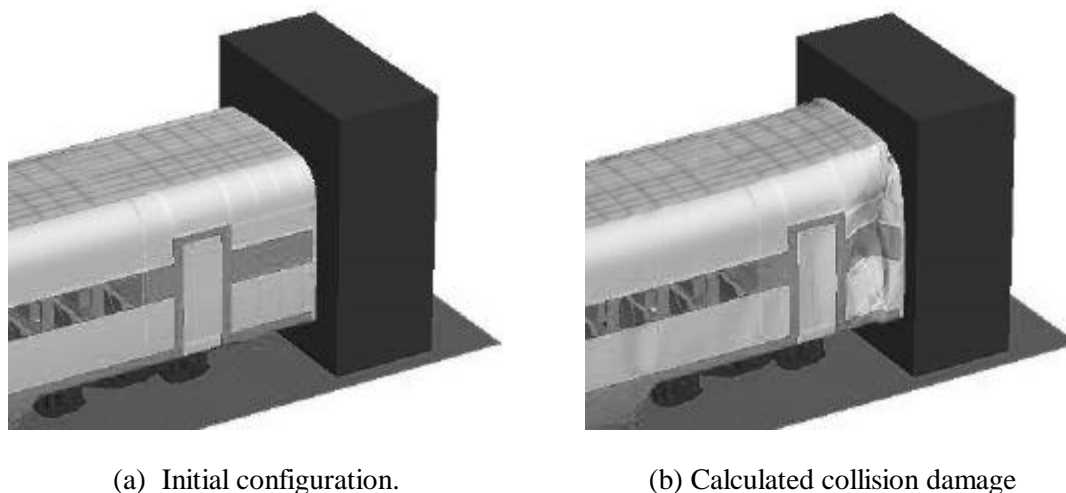


Figure 5. Detailed simulation of a passenger car collision response.

A number of different methods have been used to analyze the overall collision dynamics (i.e. the train car motions) for train-to-train collisions and derailments. The first approach is to use the same finite element codes used for the high fidelity vehicle simulations but use lower fidelity models for the train cars. An example of this type of approach is given in Reference 13. In this study a simplified finite element model of a passenger train car was developed that had crush characteristics similar to those calculated for the detailed car model. Alternatively, some finite element codes have the capability to further simplify the train models using a set of rigid bodies representing the car bodies, trucks, and couplers with springs, dampers, and joints used to define the connections and interactions.

An example of this later type of rigid train model, run with the DYNA3D finite element code, is shown in Figure 6 for a derailment of a train on a curved guideway. This relatively simple model predicts the train will initially buckle in a saw tooth mode in the early post-derailment motions. As the train continues to slide along the guideway the lateral buckling mode transitions into a zigzag mode and finally becomes unstable and large scale lateral displacements are produced. These various buckling modes have been observed both in actual train collisions and predicted in analyses of the collision dynamics of trains [14].

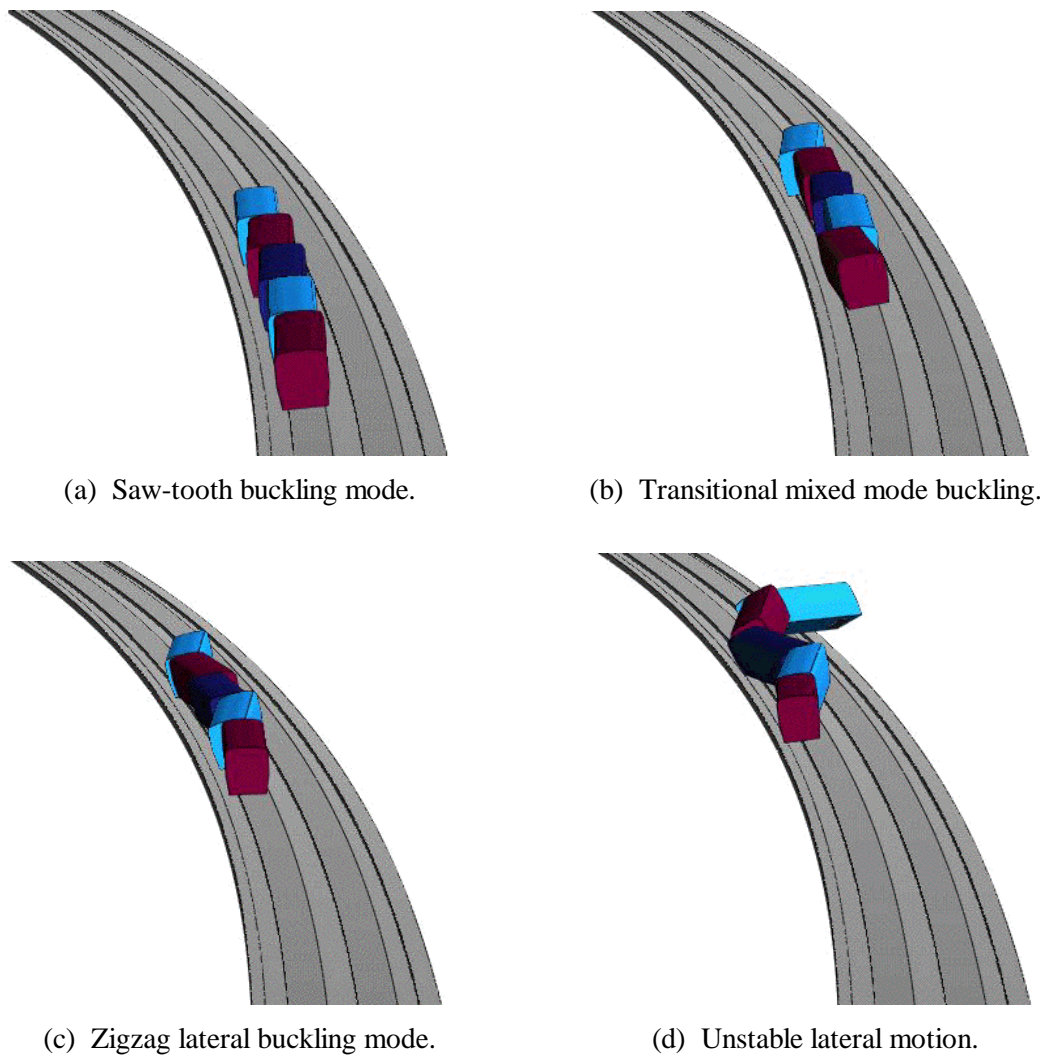


Figure 6. Calculated progression of lateral buckling for a derailment on a curved guideway.

Rigid-body models, often referred to as lumped-mass models, are relatively simple and can be solved in a fraction of the time of detailed finite element simulations. Reduced solution time may be very important when modeling a wide range of parameter variations. Multi-body dynamic models such as ADAMS and NUCARS can be used to model structural masses, mass interconnections, and wheel to rail contact mechanics. Car-end crush characteristics in the form of force-deflection curves can be added to these models using data from tests or from single-car finite element simulations. These force-deflection curves can be used for each car in the consist to model energy absorbing behaviors of the car body and coupler. To make the model as general as possible, force-deflection curves can be generated for components of the vehicle structure as well, for example, the coupler, center sill, and collision posts.

Varying these force-deflection curves can help determine the effect of design changes on consist collision behavior. Such parameter variation studies can also be used to investigate how the overall system safety would be influenced by the introduction of new rail vehicles with different crashworthiness specifications. This type of rigid body analysis would be appropriate when considering the purchase of new vehicles for a rail system that incorporate more advanced crashworthiness designs.

In many cases, the rigid-body models do not include sophisticated wheel to rail interaction mechanics, but instead assume that the wheels are locked in emergency braking and are not rotating. Such a condition can be simply modeled using a constant coefficient of friction to represent the wheel to rail contact. In some cases, this may oversimplify actual conditions and more detailed models of the wheel to rail contact for rotating wheels may be needed, such as those contained within NUCARS or ADAMS-Rail. These analysis features would be important for determining whether a set of collision conditions, such as those at a grade crossing accident, would lead to a potential derailment.

An additional objective of analysis used in the evaluation of train crashworthiness and safety is the assessment of the occupant response and injury potential. The most common analysis tool used to evaluate the occupant response is the MADYMO occupant kinematics code. MADYMO has been used extensively to evaluate occupant response and injury potential in the automotive industry. MADYMO has also been used to evaluate the response of occupants in train collisions [15, 16].

An alternative to using MADYMO for occupant response simulations is to develop models of occupants or crash test dummies using finite elements. This approach has also been applied to rail crashworthiness studies [13, 17]. An example of this type of analysis is shown in Figure 7. The train car interior model included two rows of double seats. The occupant impacts the seat back in the forward row. The seat was modeled with stiffness characteristics estimated from static test data for the seat back with a high load application [18]. From dynamic test data [19], variations in the seat stiffness were considered to evaluate the effect of seat stiffness on injury potential. The occupant model was developed from SRI's SID model [20,21]. Several components (including arms and an abdominal insert) were added and joint flexibility was introduced in the hips, knees, and ankles.

To simulate the occupant secondary collision behavior, the floor was given an acceleration history that produces the desired relative velocity at impact. Figure 7 shows the response of the occupant to a 6.7 m/s secondary impact. As the seat starts to decelerate, the occupant remains in much the same position. At a relative distance of about 0.5 m, the occupant's knees hit the seat in front. The seats deform, and the occupant's head continues to move relatively forward. Because of the large forward rotation of the seat back, the occupant experiences a very minor head impact against the seat back. From the calculation of the occupant collision response the potential for injury can be assessed with a variety of occupant injury criteria [22].

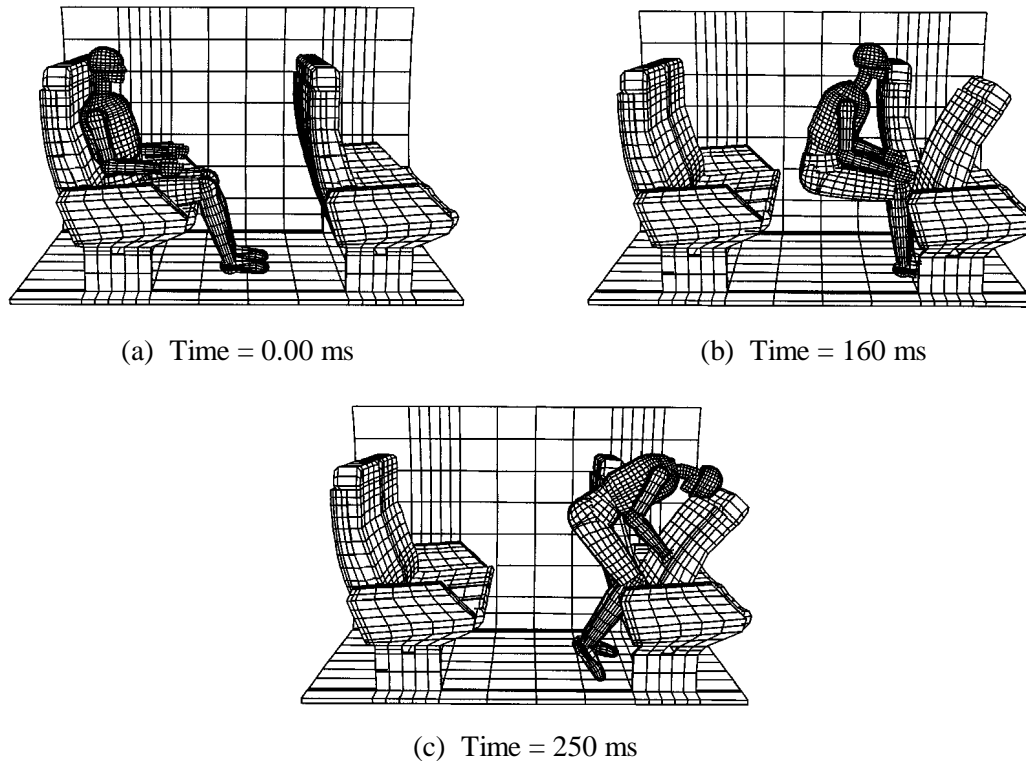


Figure 7. Finite element simulation of occupant secondary impact in a train collision.

## CONCLUSIONS

Significant advances have been made in recent years to improve the crashworthiness of modern rail vehicles. A variety of experimental and analytical methods are available for the ongoing research to further improve rail crash safety. Scale model testing can provide significant cost savings and is, in our opinion, an underutilized approach. Full-scale vehicle testing provides the greatest possible fidelity and will always be important for the validation of new crashworthy vehicle designs.

Various analysis tools are available and the appropriate choice is dependent on the objectives of the study. Detailed nonlinear finite element simulations are appropriate for designing crash energy structures for a rail vehicle. A series of analyses of potential train collision scenarios using simple lumped mass analyses would be appropriate when performing a safety assessment of a proposed rail system.

Advances in nonlinear finite element code capabilities and computer speeds have made detailed crash simulations of rail cars and components an important component of the rail crashworthiness research and development effort. These simulations can be used to better understand the collision responses of existing rail equipment as well as develop new crashworthy vehicle and component designs. Although these current computational tools are very useful, experiments are still necessary to validate and improve the models and demonstrate the performance for the complex train collision responses. Future rail crashworthiness research will continue to improve the predictive capabilities of computational models and develop safer rail vehicle structures in collisions. The most successful crash safety research programs will use a combination of testing and analysis.

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