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TITLE: A PROGRAM TO DEVELOP ANALYTICAL TOOLS FOR ENVIRONMENTAL AND SAFETY ASSESSMENT OF NUCLEAR MATERIAL SHIPPING CONTAINER SYSTEMS

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A PROGRAM TO DEVELOP ANALYTICAL TOOLS FOR ENVIRONMENTAL AND SAFETY ASSESSMENT OF NUCLEAR MATERIAL SHIPPING CONTAINER SYSTEMS*

by

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Abstract

This paper describes a program for developing analytical techniques to evaluate the response of nuclear material shipping containers to severe accidents. Both lumped-mass and finite element techniques are employed to predict shipping container and shipping container-carrier response to impact. The general impact problem is computationally expensive because of its nonlinear, three-dimensional nature. This expense is minimized by using approximate models to parametrically identify critical cases before more exact analyses are performed. The computer codes developed for solving the problem are being experimentally substantiated with test data from full-scale and scale-model container drop tests.

I. INTRODUCTION

To assess the environmental protection and public safety provided by their nuclear material shipping containers, the Department of Energy (DOE) must determine responses of these containers to a wide range of accident conditions. Rational determination of the margin of safety of a particular container requires that it be subjected to conditions severe enough to cause containment

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failure. Then, for less severe, realistic accident conditions, a container's true margin of safety can be determined. Resulting information can be used as input to risk assessment studies. Also, a container's design can be optimally improved by determining the most likely modes of failure.

At the Los Alamos Scientific Laboratory (LASL), we are developing analytical methods for determining container response to these severe accident conditions. The analysis is complex because under severe dynamic loads large deformations and strains occur. Thus the problem is generally nonlinear. Also, most containers are geometrically complex. Because of these factors, the problems cannot be solved using closed-form solutions. Our approach is to simulate the container response with discrete mathematical models. These models include the important nonlinear effects caused by the large loads and deformations, and they can handle complex geometries.

Before the resulting analytical models can be used with confidence for assessing the safety of DOE containers, they must be experimentally substantiated. To accomplish this, we are using data generated in test programs at the Battelle Columbus Laboratories (BCL), the Oak Ridge National Laboratory (ORNL), and LASL. The BCL test program involves dropping replica scale-model shipping containers onto a concrete and steel target. In the ORNL program, obsolete full-size nuclear material shipping containers are being dropped onto a similar target. At LASL small specialized test specimens are being used to study more fundamental impact phenomena. In addition to analytical substantiation, the data generated at the three laboratories are used to identify important response parameters and to characterize parameters that cannot be analytically determined.

In the following sections of this paper, the shipping container accident impact problem will be discussed along with our approach for solving it. Data will be presented to show how well the analytical predictions compare with experimental results. Also, we will describe a model that has been developed to determine the system response when a railcar carrying a shipping container strikes a moving or stationary train.

II. ANALYTICAL APPROACH

A typical Type B radioactive material shipping container is shown schematically in Fig. 1. Radioactive contents are held within an inner containment

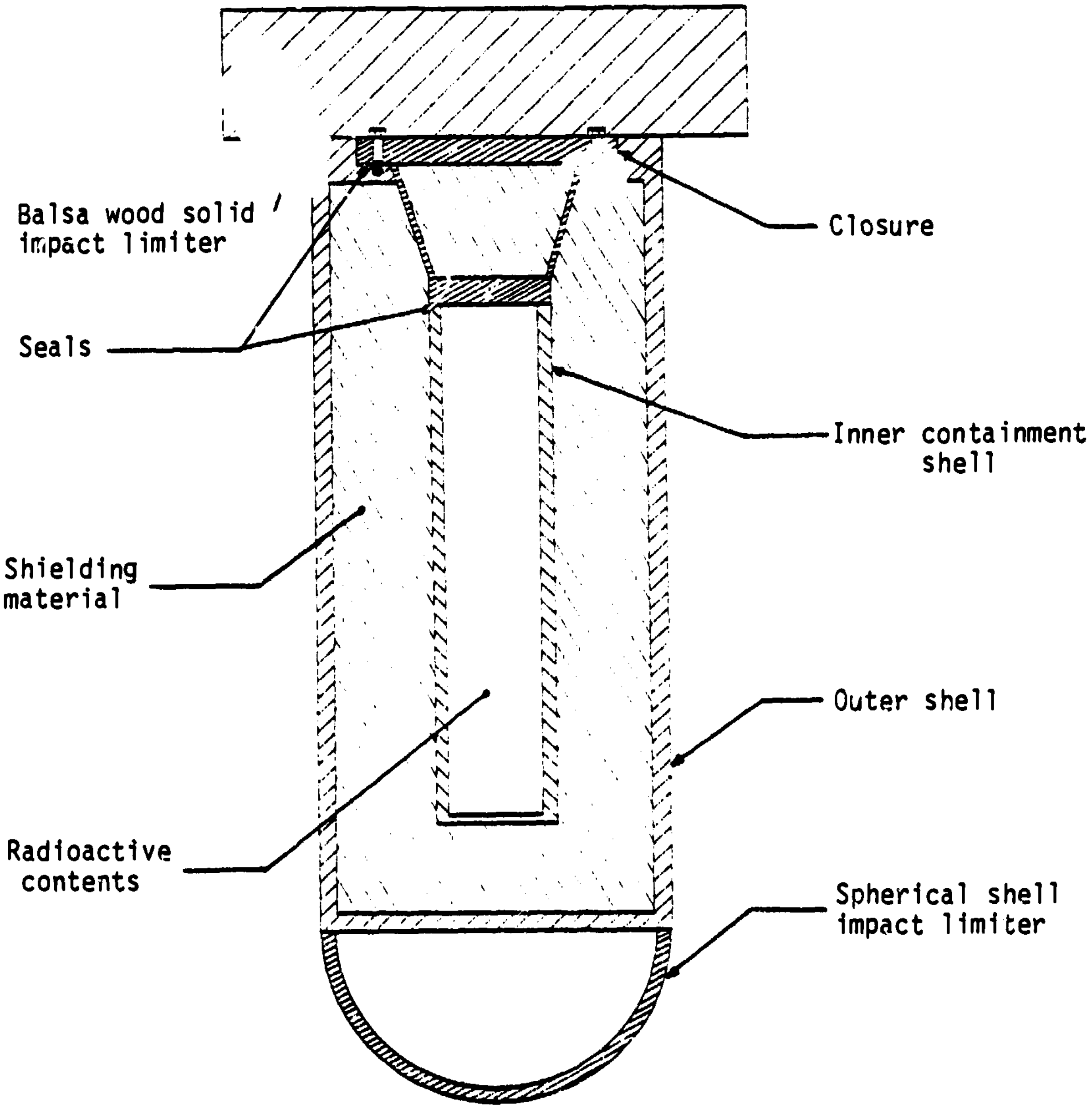


Fig. 1. Schematic of a typical Type B radioactive material shipping container.

shell. This shell is surrounded by a shielding material, usually lead or depleted uranium. A steel outer shell is the main structural member holding the container together and protecting the shielding material. One end of the container has a bolted closure with a seal, or a set of redundant seals, to prevent leakage. Some containers are designed with impact-limiting devices as an integral part of the structure such as the hemispherical metal shell shown in Fig. 1. Others have separate impact-limiting devices connected to the container by bolts or welds. The balsa wood impact limiter shown in Fig. 1 is an example of one of these devices.

Several parameters must be calculated to determine whether a particular container fails during an impact. Deformation of the shielding material and strains in the inner and outer shells are the basic parameters. Also important are the loads and displacements occurring in the closure area, strain in the shielding material, and the response of the radioactive contents. The problem is nonlinear because of the large displacements and strains. These also lead to nonlinear material properties and nonlinear behavior at component material interfaces.

The DOE must consider the lowest impact speed at which a particular container will fail to determine its margin of safety. This speed is highly dependent upon the orientation of the container at impact. Also, container damage must be assessed for both the primary and secondary (slap-down) impact events. Therefore, container response for several impact orientations must be assessed. By using judgement and preliminary hand calculations, the number of orientations that must be considered can be held to a minimum. However, the expense in computer time and man hours is still high for obtaining detailed container response with a nonlinear, three-dimensional finite element model.

We have developed a computational procedure that minimizes this expense. First, we limit the number of orientations that must be considered with the three-dimensional finite element code by using a relatively simple lumped-mass code. This determines the initial impact angle that gives the most severe initial conditions for the secondary impact event. Second, we developed a two-dimensional finite element code to parametrically study the response of the container to end-on impact orientations. This narrows the number of cases that must be considered with the three-dimensional code. Items that may be parametrically studied are unknown material properties, the effects of different impact targets, and the effects of ignoring minor structural details. This code can also be used for the development and evaluation of new analytical techniques before they are put into the larger three-dimensional code. The secondary impact code and the two-dimensional finite element code are described in more detail in the following section.

III. ANALYSIS TOOLS

We are developing a computer code (SIC) to predict gross container motion during oblique impacts for the time interval between initial impact and secondary impact. The initial impact angle that gives the maximum velocity of the first contact point at secondary impact is determined parametrically with SIC. Computed linear and rotational velocities and the position of the container at secondary impact can be used as input to a detailed three-dimensional finite element analysis.

SIC uses a lumped-mass model for calculating both rigid body and flexible motion of the container. The nonlinear force applied to the container at the primary contact point is determined from the distorted contact area and the yield strength of the container shielding material. Viscous damping and either linear or nonlinear stiffness elements can be included for individual analyses. SIC automatically predicts container motion for a specified range of initial impact angles. At the end of the computational sequence, velocity of the initial contact point at secondary impact is plotted as a function of initial impact angle.

Data from a full-scale container drop test at ORNL were used to help experimentally substantiate SIC. In that test, a Knapp Mills spent fuel shipping container was dropped 9.1 m (30 ft) at an angle of 35° from the horizontal. Prior to the test, we used SIC to determine that the initial impact angle of 35° would maximize the velocity of the initial contact point at secondary impact. Based on examination of high speed motion pictures of the test, the actual initial impact angle was 27°. Also, from the high speed motion pictures, the secondary impact speed was measured to be 19.4 m/s (762.0 in./s). We predicted that this velocity would be 20.9 m/s (823.0 in./s). This comparision is good considering that we used average handbook mechanical properties for the lead shielding in the container. However, because mechanical properties for lead are highly dependent on impurities and strain rates, the handbook values may be different from those for the lead in this container. Because the lead absorbs most of the energy at initial impact, container response is sensitive to these properties.

We are comparing SIC results with data obtained at BCL using special test specimens and replica scale model containers. The data obtained by BCL are especially valuable for experimental substantiation because the mechanical properties of the container component materials are known.

To calculate the detailed response of containers to end-on impacts, we are developing a two-dimensional finite element computer code called CRASHC. It is a nonlinear code that can handle large displacements and strains and nonlinear material properties. The two-dimensional continuum finite element and basic numerical solver were taken from the NONSAP computer code.[1] The nonlinear equations of motion are solved implicitly using the Newmark-β equations and an equilibrium iteration approach. The continuum finite element has an eight-node isoparametric formulation. It is used to simulate the shielding material in the container. A three-node isoparametric shell finite element was developed[2] and added to the code to simulate the container shell and plate components. An eight-node isoparametric element for simulating compressible fluid contents has also been developed.

Nonlinear material properties for both the solid continuum and shell components of the container are presently calculated using a bilinear stress-strain curve with the Von Mises yield criterion. This nonlinear material model has the advantage of being well tested and accepted. However, its coding is complex, and it cannot easily handle strain rate effects. Therefore, we are evaluating an endochronic material model developed at the Argonne National Laboratory (ANL).[3] The endochronic model has the advantage of being simple to code, and strain rate effects can be easily added. Also, it seems to simulate cyclic plastic loading better than the bilinear material model.

Accuracy of analytical predictions made using CRASHC is being checked using data obtained in impact tests at BCL and LASL. To date, the code has been checked for low-level drops where materials exhibit nonlinear behavior, but strains and displacements remain small. Figure 2 shows a test specimen that was used for some of these tests. The specimen was dropped a distance of .30 m (12.0 in.). Comparison of predicted vs experimental strains are shown in Figs. 3-5. Note that the analytical strain histories differ considerably from the experimental curves. However, the final plastic deformation and the overall time of the pulse are predicted quite well. Details of these tests

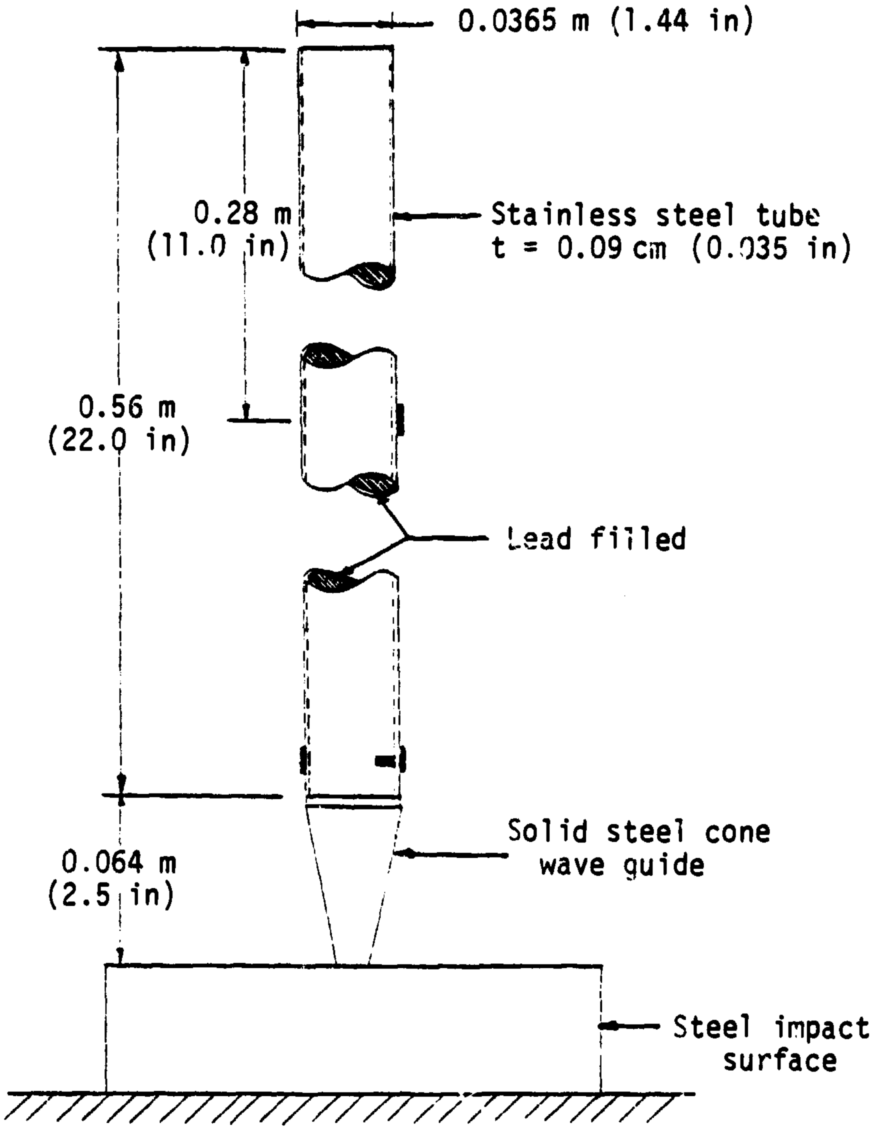


Fig. 2. Test specimen for simulating end-on shipping container impacts.

and their results along with a detailed discussion of the code CRASHC will appear in a LASL report to be published (Ref. 4).

As discussed in Section II, a primary purpose for developing the code CRASHC is to have an efficient and economical method for developing and checking new techniques before implementing them into a more complex three-dimensional finite element code. As new techniques are developed using CRASHC, they will be incorporated into the computer code ADINA.[5] It is a three-dimensional finite element code that can handle material nonlinearities as well as large displacements and strains. It is also constantly being upgraded by its authors at the Massachusetts Institute of Technology.

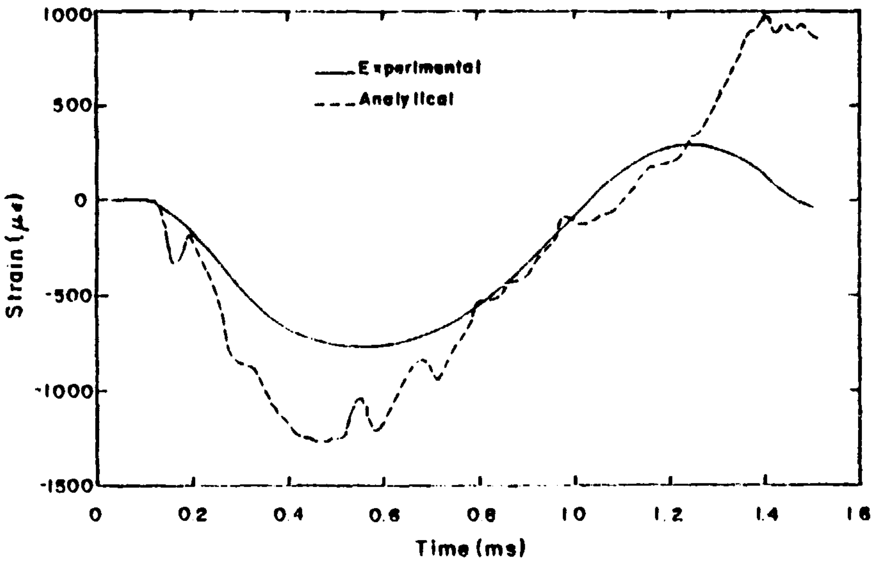
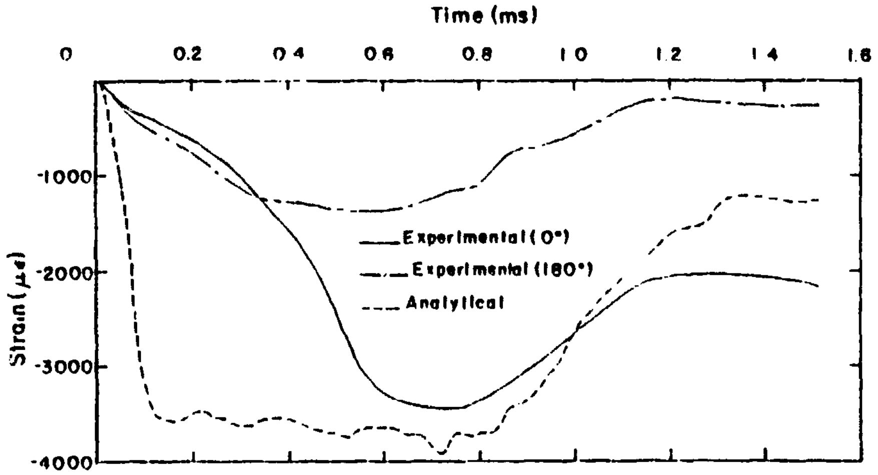


Fig. 3. Hoop response at base of test specimen for a 0.3-m (12.0-in.) drop.

Fig. 4. Longitudinal response at base of test specimen for a 0.3-m (12.0-in.) drop



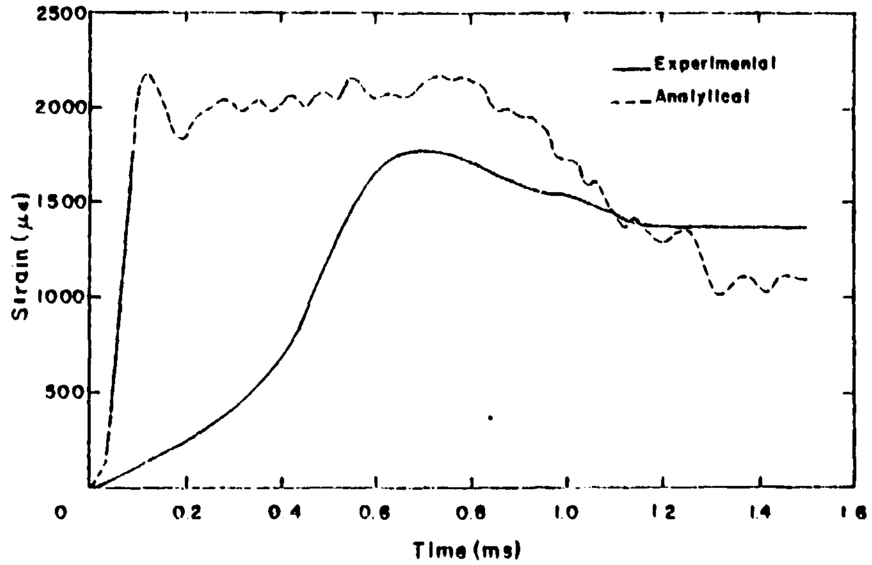


Fig. 5. Longitudinal response at middle of test specimen for a 0.3-m (12.0-in.) drop.

We are planning additional tests with BCL to check the capabilities of both CRASHC and ADINA for predicting shipping container failure. In these tests replica scale model containers will be dropped from heights sufficient to cause failure at various angles of initial impact. We will provide BCL with pretest predictions of the required drop heights and critical angles of impact. After the tests are performed the data will be used for updating and improving the codes.

IV. CONTAINER TRANSPORT SYSTEMS

A necessary part of shipping container safety evaluation is to predict the response of a container attached to a transport vehicle when that vehicle is involved in a severe impact accident. The response of the container needs to be evaluated as well as the loads experienced by the structure that connects the container to the transport vehicle. As a first step in developing a general code for performing these calculations, we developed the lumped-mass nonlinear code RICTL[5] (Railcar Impact Container Tiedown Loads). RICTL simulates the system response of a railcar carrying a shipping container when the railcar strikes a stationary or moving train at speeds up to 29 km/h (18 mph). We are using data from a series of tests performed at the Savannah River Plant (SRP) to experimentally substantiate RICTL and to characterize unknown parameters. In these tests, a railcar with a container attached was coupled to a set of stationary railcars at various speeds ranging up to 29 km/h (18 mph). Some tests were performed using a 36.3 tonne (40.0 ton) container and others with a 63.5 tonne (76.0 ton) container. Three different railcars were used with several different tiedown configurations. Before the tests were performed, we used RICTL to predict the railcar and container response. The model used for these predictions is shown in Fig. 6. Results for some of the test cases are shown in Table I. These analytical results were used to select instrumentation and to set calibration levels.

After we substantiate and revise RICTL with data from the SRP tests, we will extend the model to handle higher speed impact cases. Even though the model has been developed for a railcar-container configuration, it can be easily modified to represent a truck-trailer as the carrier.

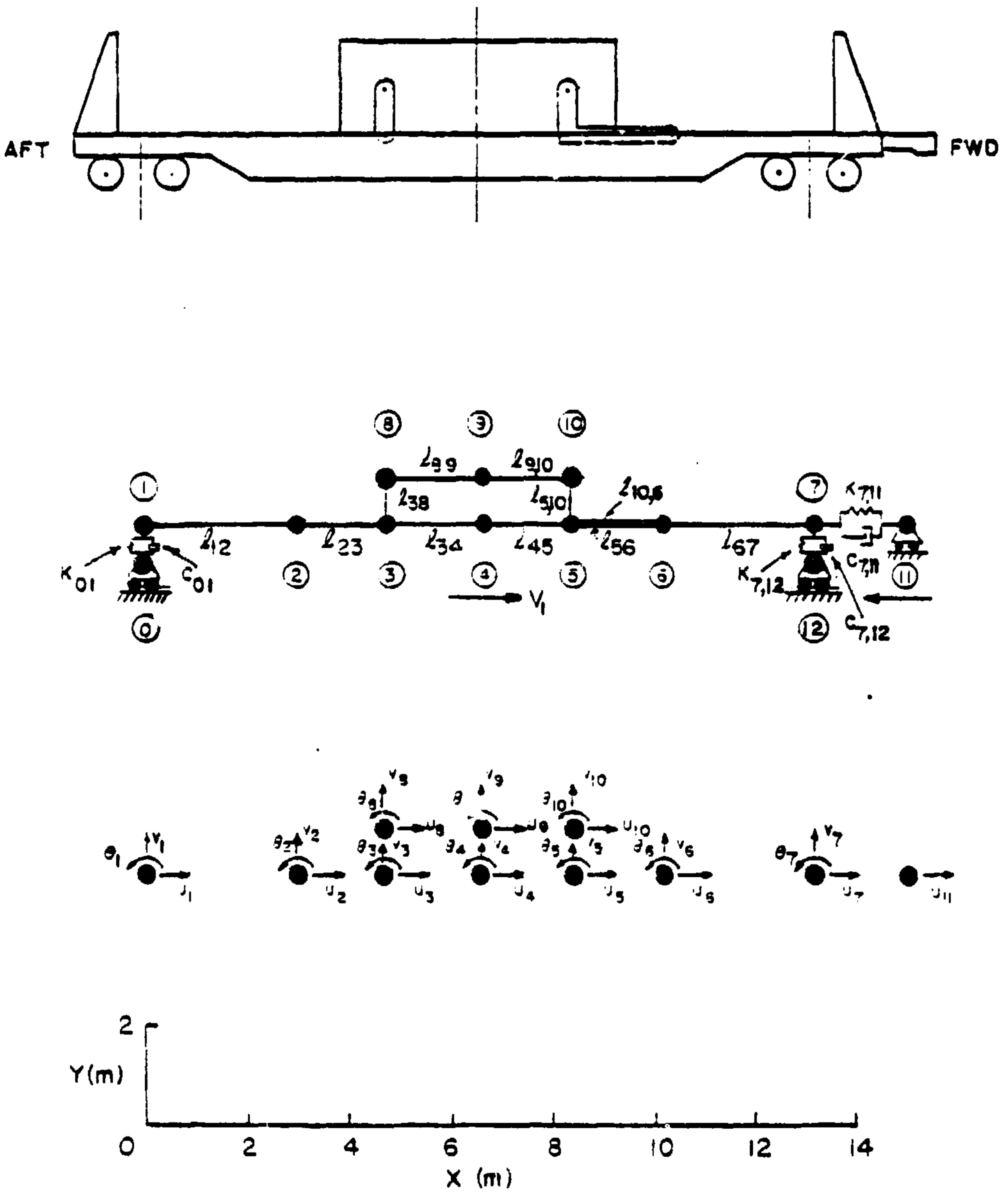


Fig 6. Structural dynamic model for railcar, container, and coupler.

TABLE I

PREDICTED RESPONSE OF SAVANNAH RIVER PLANT RAILCAR-CONTAINER CONFIGURATION

		Horizontal Deceleration (g/s)		
Container Weight (tonnes)	Impact Speed (km/h)	Railcar at Point of Impact	Container Center of Gravity	Maximum Absolute Vertical Acceleration of Container (g's)
36.3	8.0	25.0	-6.7	4.0
	17.7	54.5	-13.3	6.8
63.5	8.0	25.0	-5.0	2.4
	17.7	54.5	-8.5	6.5

			Maximum Container Tiedown Loads ($N \times 10^{-6}$)		
Container Weight (tonnes)	Impact Speed (km/h)	Coupler Force ($N \times 10^{-6}$)	Struck-End Vertical	Struck-End Horizontal	Far-End Vertical
36.3	8.0	-2.83	-0.79	-2.35	0.77
	17.7	-4.58	-1.30	-4.54	1.61
63.5	8.0	-2.85	-0.72	-2.91	0.72
	17.7	-4.85	-1.48	-5.07	1.67

V. CONCLUSIONS

Analytical techniques for predicting the response of nuclear material shipping containers and carrier-container transportation systems to severe impact accident conditions have been presented. These techniques are being experimentally substantiated for relatively low velocity impacts. Even though they have not been experimentally substantitated for higher speed impacts that cause severe nonlinearities, the container modeling techniques presented can be used to analyze these cases. Test plans are being developed to obtain data for substantiating the computer codes for higher velocity impacts.

Relative to the high cost of testing prototype or exact scale model containers, these analytical techniques are inexpensive and can be used effectively for parametric and sensitivity studies of shipping container response during transportation accidents. Results of these studies can be used for guiding future analytical and experimental development work. They can also be used for enhancing designs to optimize the environmental and public safety provided by the containers and the associated carriers.

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