Development of a Dynamic Finite Element Computer Code for the Inelastic Analysis of Cask Structures—Pronto 3D

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INTRODUCTION

Dynamic analyses of radioactive material packagings require accurate three-dimensional models of impact and puncture events. PRONTO 3D, a three-dimensional transient solid dynamics computer code, was developed to simulate and analyze impact events and associated problems. Examples of impact problems analyzed with PRONTO 3D are provided. The analysis of a sphere impacting into a deformable flat plate at high velocity demonstrates the proper operation of the contact surface (slide line) algorithm in the code. An analysis of a generic lead-stainless steel cask impacting onto an unyielding rail further demonstrates the utility of the contact surface algorithm and the ability to model inelastic deformations and finite rotations.

Designing transport packages often requires an expensive iterative testing and redesign proceedure. This paper describes a new, efficient, finite element code that, when used by an experienced analyst, can help reduce the amount of testing. For problems where testing is required, pre-test analyses can maximize the information gained from the test, while post-test analyses can help to interpret test results. The intent of this paper is to familiarize the reader with the capabilities of the new code PRONTO 3D.

CODE DESCRIPTION

PRONTO 3D (Taylor and Flanagan, 1989) is a three-dimensional transient solid dynamics code for analyzing large deformations of highly nonlinear materials subjected to extremely high strain rates. PRONTO 3D is a direct descendent of the PRONTO 2D code (Taylor and Flanagan, 1987) using three-dimensional generalizations of the formulations and numerical methods used in that code. The program includes nonlinear constitutive models, and geometric nonlinearities resulting from large deformaionts. PRONTO 3D is a powerful tool for analyzing a wide variety of problems, including problems in impact dynamics, rock blasting, metal forming, and structural response of transport cask to hypothetical accident conditions.

PRONTO 3D uses a Lagrangian finite element scheme with an explicit time integration operator to integrate the equations of motion. Eight-node uniform strain quadrilateral elements are used in the finite element formulation with single point integration of the stress. A number of new numerical algorithms were developed for the PRONTO codes. An adaptive time step control algorithm greatly improves stability and performance in plasticity problems. A robust hourglass control scheme (Flanagan and Belytschko, 1981) eliminates hourglass distortions without disturbing the finite element solution. Hourglassing results when an element distorts in such a way that no energy is absorbed. All constitutive models in PRONTO 3D are cast in an unrotated configuration defined using the rotation determined from the polar decomposition of the deformation gradient. An accurate incremental algorithm was developed for PRONTO 3D to determine this rotation.

Material Models

PRONTO 3D includes a representative set of constitutive models but was also designed to facilitate the development and implementation of constitutive models. Adding a new constitutive model to the code is a straightforward process that requires modifying some PARAMETER and DATA statements in one subroutine. An appendix of the PRONTO 3D manual and comment cards within the source code describe the steps required to add a new material model to the code.

The current material models in the code, as described in the theory manual include:

- **Elastic** - Hooke's Law
- **Elastic/Plastic** - Elastic/plastic Mises flow with combined isotropic or kinematic hardening
- **Soils and Crushable Foams** - Pressure dependent yield surface with planar end cap (Perfectly plastic deviatoric behavior but arbitrary hardening in the volumetric plasticity)
- **Low Density Foams** - Phenomenological model for describing the response of low density, closed-cell polyurethane foams
- **Rate and Temperature Dependent Plasticity** - Unified creep plasticity model (Bammann's model)
- **Damage** - A model which calculates brittle failure based on damage accumulation determined from microcrack growth and coalescence
- **Elastic/Plastic Hydrodynamic** - Elastic/plastic Mises flow with combined isotropic or kinematic hardening for the deviatoric response; hydrodynamic models described below for the volumetric response
- **Hydrodynamic** PRONTO contains the following Mie-Gruneisen equation of state models: *i)* Linear Us-Up Hugoniot Form, *ii)*Power Series Hugoniot Form, *iii)* Ideal Gas, and *iv)* JWL High Explosive

Failure Criteria

Elements can be adaptively deleted from the mesh based on a number of criteria. The user can define failure in terms of energy per unit volume, Von Mises stress, pressure, or maximum principal stress. Also, failure criteria can be defined in terms of any internal state variable found in a constitutive model (e.g., equivalent plastic strain). The flexible constitutive model architecture of PRONTO 3D allows a constitutive modeler to add any number of state variables. Also, the failure scheme supports all state variables; thus failure may be defined in any exotic manner that suits a particular material.

Initial/Boundary Conditions

PRONTO 3D allows the user to define initial velocities by material or node sets. Various kinematic boundary conditions allowed in the code include prescribed displacement, velocity, and accelerations. The code contains a Lysmer type nonreflecting boundary condition to model infinite boundaries. Users can specify prescribed nodal forces, pressure, and moving pressure boundary conditions.

Sliding Interface Logic

In addition to being able to prescribe initial and boundary conditions, PRONTO 3D allows boundary conditions to be defined through a robust contact algorithm. The contact surface algorithm in PRONTO 3D is a symmetric kinematic model that allows friction and opening and closing of the contact surfaces. There is no limit on the number of contact surfaces, and the user is not required to define intersections or corners. The contact surface logic is highly vectorized and computationally efficient, and the algorithm is versatile and reliable.

IMPLEMENTATION

PRONTO 3D is written in ANSI FORTRAN-77 and will run on any machine with a compliant compiler. All nonstandard FORTRAN is included in a support library called SUPES (Software Utilities Package for the Engineering Sciences). SUPES contains support software only; all computational mechanics software is contained within PRONTO 3D itself. The FORTRAN Extension Library of the SUPES (Flanagan, Mills-Curran, Taylor, 1986) support package, which ranges from the mundane (e.g., how to get the time of day) to the sophisticated (e.g., dynamic memory management), provides a standard interface to nonstandard features. Currently, versions of SUPES exist for VAX/VMS, CRAY under CTSS or COS, and most UNIX System V derivatives.

PRONTO 3D does not limit problem size. The user is only limited by the size of memory available on his machine. PRONTO 3D typically requires approximately 35 to 40 words of memory per quadrilateral element. On a CRAY X-MP 4/16, an elastic/plastic combined hardening problem with a moderate number of contact surfaces will run at approximately 8 microseconds per element cycle.

PRONTO 3D contains an external code interface that allows another code to be coupled to it with no changes to PRONTO itself.

EXAMPLE PROBLEMS

In this section, representative example problems that demonstrate many of the features of PRONTO 3D are presented. These examples are provided to show the types of complex problems that PRONTO 3D can solve. Detailed timing and size information is given for each example problem so that the relative speed of the code can be estimated.

Sphere Impact

This example problem is intended to demonstrate the robust nature of the contact surface algorithms, as well as the extremely large deformations and distortions that the uniform strain hexahedron can perform. Figure 1 illustrates a 1 cm thick deformable plate made of rolled homogeneous armor (RHA). The plate is impacted by a dense sphere with a 2 cm radius and made of Staballoy. Table 1 lists the elastic/plastic combined hardening material properties used in the analysis. The impact velocity is 1000 m/sec at a 30 degree angle of attack.

Table 1: Sphere Impact Problem Material Properties

	RHA	Staballoy
Density	7800 kg/m^3	18,620 kg/m^3
Young's Modulus	206.8 Gpa	195.8 Gpa
Poisson's Ratio	0.3	0.203
Yield Stress	1220 Mpa	1036 Mpa
Hardening Modulus	1220 Mpa	1036 Mpa
Beta	0.5	0.5

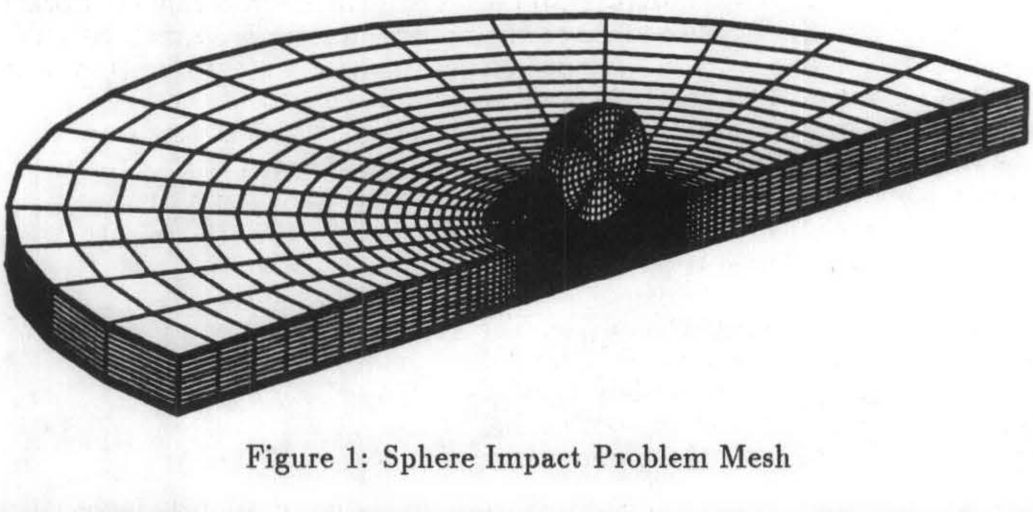

Figure 1: Sphere Impact Problem Mesh

There are 9052 elements and 10,897 nodes in the mesh. The problem ran for 94.4 cpu seconds on a CRAY X-MP 4/16 under CTSS with CFTLIB. The total number of time steps was 411; this yields a value of 25.4 microseconds per element cycle.

Figure 2 shows a sequence of four different times during the impact event. The analysis was run for 8.25 microseconds of problem time, at which time an element turned inside out and the code stopped. This represents the limit that the Lagrangian code can continue to model the event. Note the severe distortion in the elements which form the impact crater. This distortion poses a tremendous challenge to the contact surface algorithm because element faces along the edge of the crater become extremely warped. Figure 3 illustrates the formation of the impact crater at the same four times shown in Figure 2.

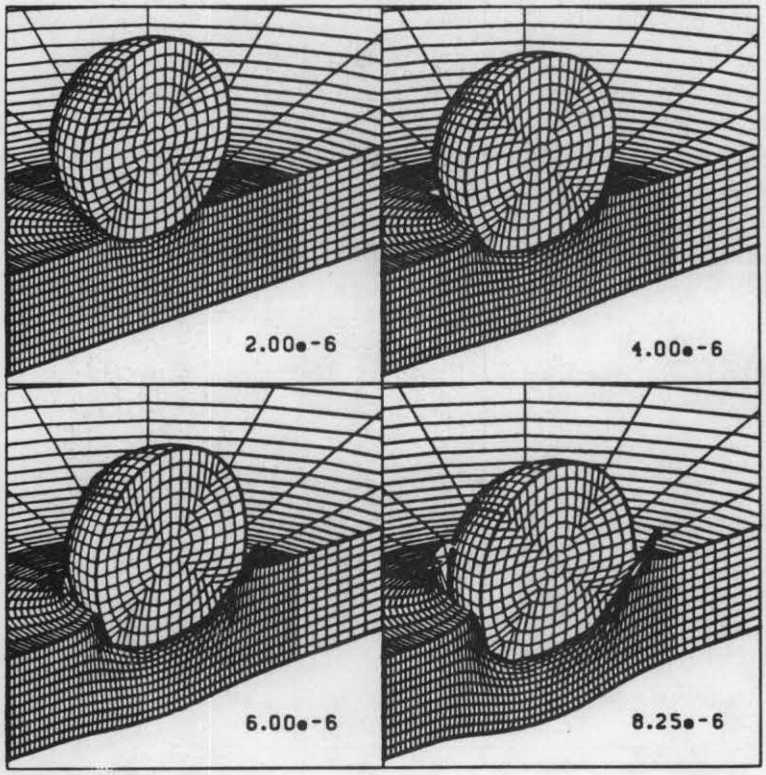

Figure 2: Time Sequence from the Sphere Impact Problem

Cask Impact

In this example problem, a generic waste transportation cask is dropped from 30 feet onto a rigid rail. The impact velocity is 43.95 feet per second. The angle of impact is such that the center of gravity is over the corner where the impact occurs. The mesh used in the analysis is shown in Figure 4. The cask has 0.5 inch thick steel inner and outer liners with 3.5 inches of lead shielding between them. Table 2 lists the elastic/plastic material properties used in the analysis.

The analysis was run for 5 milliseconds problem time. The total kinetic energy in the system is shown in Figure 5. Rebound occurs at 4.6 milliseconds, at which time the deformations in the cask are the largest. The configuration at that time is shown in Figure 5. The deformations in this analysis are not extremely large. Nevertheless, the materials in the cask, particularly the lead shielding, develop large plastic strains as shown in Figure 5.

This problem is included because it entails a large amount of contact data. A

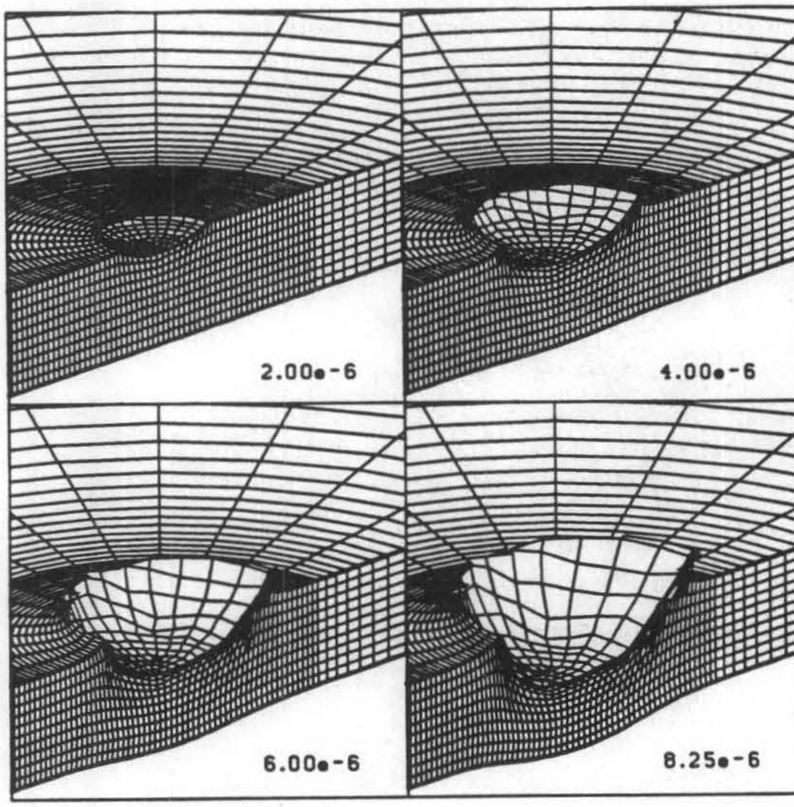

Figure 3: Impact Crater Formation during the Sphere Impact Problem

Table 2: Cask Impact Problem Material Properties

	Steel	Lead
Density	7.366×10^{-4} lb/in/sec^2	10.53×10^{-4} lb/in/sec^2
Young's Modulus	29×10^6 psi	2×10^6 psi
Poisson's Ratio	.33	.44
Yield Stress	40,000 psi	2,000 psi
Hardening Modulus	40,000 psi	0
Beta	1. (isotropic hardening)	1. (isotropic hardening)

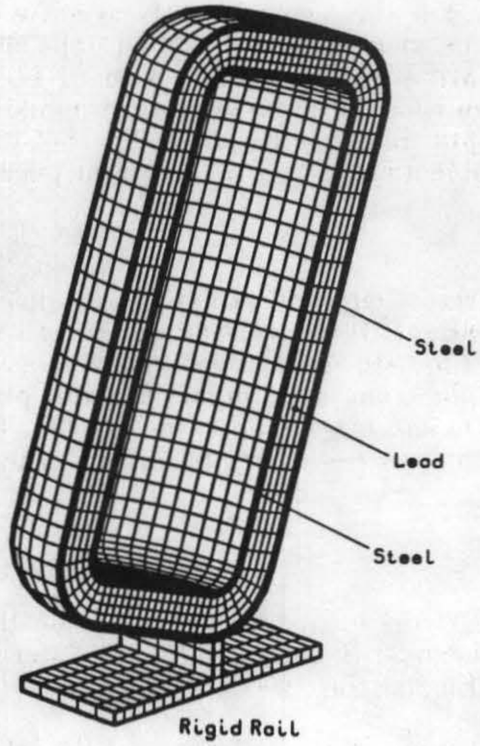

Figure 4: Cask Impact Problem Definition.

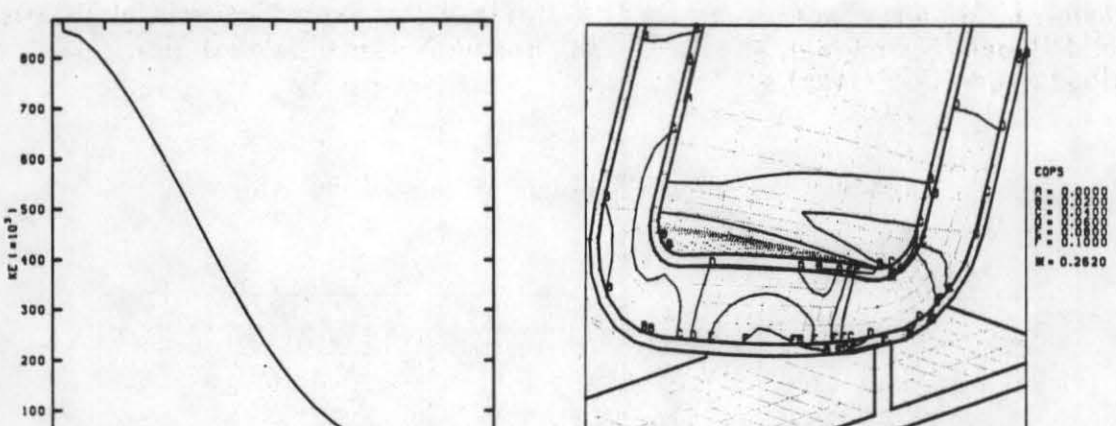

Figure 5: Kinetic Energy During the Cask Impact Problem and Equivalent Plastic Strain Developed in the Cask Impact Problem

contact surface is defined between the liners and the shielding, and between the outer liner and the rail. The three contact surfaces make this a highly contact intensive analysis. The problem took 10,932 time steps and used a total of 3732 cpu seconds on a CRAY X-MP 4/16 under CTSS with CFTLIB. This gives a value of 32.7 microseconds of cpu time per element cycle. Comparing this number with 25.4 microseconds from the previous problem, indicates that the intensive contact calculations for this problem carry only a 29 percent penalty.

CONCLUSIONS

The Engineering Analysis Department at Sandia National Laboratories has developed a three-dimensional transient solid dynamics computer code, PRONTO 3D, that can simulate and analyze radioactive material packaging impact and puncture events. Sphere and cask impact example problems demonstrated the contact surface algorithm and other aspects of the code. PRONTO 3D has proven to be a powerful tool for analyzing problems in impact dynamics, rock blasting, and accident analyses.

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Shipment of Plutonium by Air