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PREPRINT

Simulation of Underwater Explosion Benchmark Experiments with ALE3D

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The interaction at slide surfaces can consist of pure sliding in which there are no tangential forces on interface nodes, or the nodes may be tied to inhibit sliding entirely, a coulomb friction algorithm can be used, or turbulence models can be applied. Voids may open or close between the surfaces depending on the dynamics of the problem, and there is an option to allow a block to fold back on itself (single-sided sliding). Where no void is present, as is the case in most fluid/structure interactions, the forces on either side of the slide surface are accumulated and used to produce a net acceleration of the nodes on the surface consistent with the center-of-mass motion. In this manner the dynamics of both the fluid and structure are treated in a consistent manner There is no advection allowed across slide surfaces

The basic computational step consists of a Lagrangian step followed by an advection, or remap step. This combination of operations is formally equivalent to an Eulerian solution while providing increased flexibility and, in some cases, greater accuracy. In the Lagrangian phase, nodal forces are accumulated and an updated nodal acceleration is computed. Following DYNA3D (Hallquist, 1982), the stress gradients and strain rates are evaluated by a lowest order finite element method. A diagonal mass matrix is used. Second order accuracy is obtained with a grid that is staggered in both space and time. The stress tensor for the elastic-plastic material strength model is integrated by an incremental strain method. The Jauman rate derivative is used for the stress tensor, and the von Mises yield condition is applied.

At the end of the Lagrangian phase of the cycle the velocities and nodal positions are updated. At this point several options are available. If the user wishes to run the code in a pure-lagrangian mode, no further action is taken and the code proceeds to the next time step. If a pure-Eulerian calculation is desired, the nodes are placed back in their original positions. This nodal motion or relaxation generates inter-element fluxes which must be used to update velocities, masses, energies, stresses and other constitutive properties. This re-mapping process is referred to as advection. Second-order-accurate schemes are required to perform this operation with sufficient accuracy. In addition it is not generally adequate to allow advection only within material boundaries. ALE3D has the ability to treat multimaterial elements, thus allowing relaxation to take place across material boundaries.

The full potential of the ALE approach is realized when the code user has options available to tailor the evolution of the mesh to maximize either efficiency or accuracy. In the simplest implementation the code is instructed to relax nodes as required to eliminate distortions in the mesh. A more powerful approach has the code relax nodes on the basis of an optimization scheme. To this purpose ALE3D utilizes a finite element based equipotential method developed by R. Tipton (Tipton, 1992). This method accommodates weighting functions which can be used to optimize the mesh based on some defined criterion. ALE3D currently allows weighting by pressure, by artificial viscosity, by plastic strain, by material number and along designated slip surfaces. The solution will result in a more highly resolved mesh in the volumes containing the highest weights. This provides a form of dynamic mesh refinement. This technique has proved useful in improving the effective resolution in shock tracking simulations. There are also a number of options available for selecting predetermined or dynamically programmed mesh evolution in cases where that is appropriate.

ALE3D has a reasonably broad range of material models for use in the simulation of underwater explosion events. The Steinberg-Guinan and Johnson-Cook models are available for treating a wide range of materials in the high strain rate regime. Bi-linear and k-epsilon models are available when less complex constitutive models are appropriate. An isotropic, tabular temperature based model is also available. These are equivalent to DYNA3D models 12 and 18 and 4, respectively. Several options are available with structural elements. In that case pure elastic, and bilinear yield curve with the option for kinematic hardening are available (DYNA3D models 1 and 3), as well as a tabular stress-strain representation with rate effects (DYNA3D model 24). Detonation of high explosives can be modeled by volume burn, programmed lighting times, or a reactive flow model.

ALE3D has been ported to most platforms running under unix systems including various CRAY machines and workstations from SGI, HP, IBM and SUN. The option to run on multiple processors exists but this mode is still in the developmental stage. ALE3D has been distributed to a number of DoD facilities and DoD contractors under a collaborative licensing agreement. It is accompanied by MESHTV a graphics post processor. The user must have access to a mesh generator. Currently, INGRID and TRUEGRID are the only mesh generators that write output files that ALE3D can read directly.

Simulation of the Benchmark Experiments

There are peculiarities related to the simulation of underwater explosions that require some actual experience in order to determine how best to approach the problem. One is the disparity in time scales. The explosive detonation is generally on the order of microseconds in duration, while the bubble expansion and collapse and structural loading is more often on time scales of seconds. It would appear at first that an implicit time integration scheme might be most appropriate for the expansion and collapse phase. Two points must be made with respect to that hypothesis. The first is that while the bubble radius might be a slowly varying quantity, the flow of material within the bubble can be very turbulent. An implicit scheme would tend to damp out those degrees of freedom with unknown effects on the ultimate bubble dynamics. Our experience has been that explicit codes can be made reasonably efficient by tailoring the solution approach to this particular class of problem. Steps that have been taken to improve the solution efficiency include;

1. *Subcycling the Lagrangian step:* since ALE3D is structured to consist of a Lagrangian step followed by a remap step, one need not perform the remap step every cycle unless required by accuracy considerations. Our experience is that one can often perform 2-3 Lagrangian steps per advection step. Since the advection step is generally 2-4 times as expensive as the Lagrangian, run times can be cut in half by a judicious use of this approach. In the course of these simulations we implemented several modifications to the mesh relaxation logic in ALE3D in order to facilitate the use of this subcycling approach.

2. *Minimize the number of advecting elements:* the region of the problem in the vicinity of the bubble is very dynamic and requires continual remapping, but the regions near the problem boundaries see relatively little flow. Since the advection logic is relatively expensive considerable efficiency can be derived from keeping regions Lagrangian when advection is not essential

3. *Take advantage of an unstructured mesh:* simulating underwater explosion problems generally requires the generation of a mesh whose spatial extent is much larger than that required to contain the region where the dynamics are significant. This "outer" region is associated with trying to provide appropriate boundary conditions. Several approaches to minimizing the number of elements associated with the boundary become available with an unstructured mesh. One is the typical cut and paste technique which allows the user to transition from a logically rectangular mesh to one that is spherical. Another involves the use of transition elements which effectively decrease the mesh density by factors of two at the transition points. A third takes advantage of the mesh discontinuity that can exist at slide surfaces. One can define a slide surface at a location where fluid flow will be small and transition to a coarser mesh.

Another peculiarity of underwater explosion simulations is the disparity in length scales. In most calculations of explosive events an adequate mesh can be constructed so that the problem is large enough to contain one sound transit time, thus simplifying any boundary effects. In simulations involving bubble dynamics the evolution of the bubble is so slow relative to sound speed in water that a different approach must be taken.

The approach taken in this project was to recognize that the most important factor is to allow the bubble to expand and contract unimpeded by any boundary effects. That means that within the mesh there is either the equivalent of a free surface or an inflow/outflow boundary condition. The variations on the former approach have been used in this study. The boundary treatment used will be discussed for each individual simulation. At the time the project was initiated the ability to have material flow into or out of the mesh was not available in ALE3D. This capability has subsequently been added, but this method has not been evaluated in the underwater explosions context.

A precise representation of the explosive equation of state is difficult. The standard JWL representation is generally available with parameters determined by measurements of the prompt acceleration of metal plates in the low expansion regime. In the case of bubble dynamics, the time scale is much greater than the detonation time. Consequently, the energy contained within the explosive products at completion of burn can be significantly different from that sensed by the prompt experiments. We have chosen to use a set of JWL parameters provided to us by Clark Souers. These parameters were obtained by applying the dual constraints of matching the prompt acceleration data and the complete burn energetics at large expansions.

Description of ALE3D Code System

- 3D finite element solution with Arbitrary Lagrange-Eulerian features
  - Lagrangian step followed by a remap
  - block structured mesh with slide surfaces
  - brick, shell and beam elements
  - explicit or implicit time integration for dynamics
  - heat conduction with chemical reaction
  - real and artificial viscosities
- Applications: fluid/structure interactions
  - metal forming
  - steady state and transient fluid dynamics
  - shock hydrodynamics

Characteristics of Underwater Explosion Simulations

- disparity in distance and time scales
  - explosive size Vs bubble size
  - prompt Vs late time effects
  - sound transit time Vs bubble collapse time
- importance of boundary conditions
  - far field treatment
  - air/water interface
  - buoyancy
- tightly coupled fluid/structure interactions
  - hydrodynamics plus structural mechanics
  - response and failure modes for complex geometries

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Figure 2: Illustration of the mesh used in the calculation of shot 5. The mesh on the charge side of the plate was generated using a logically rectangular core of elements. The diagonal corners of the mesh were deleted. The remaining surface nodes were projected on either the plane of the target plate or on a spherical surface. Overlapping internal nodes were merged away.

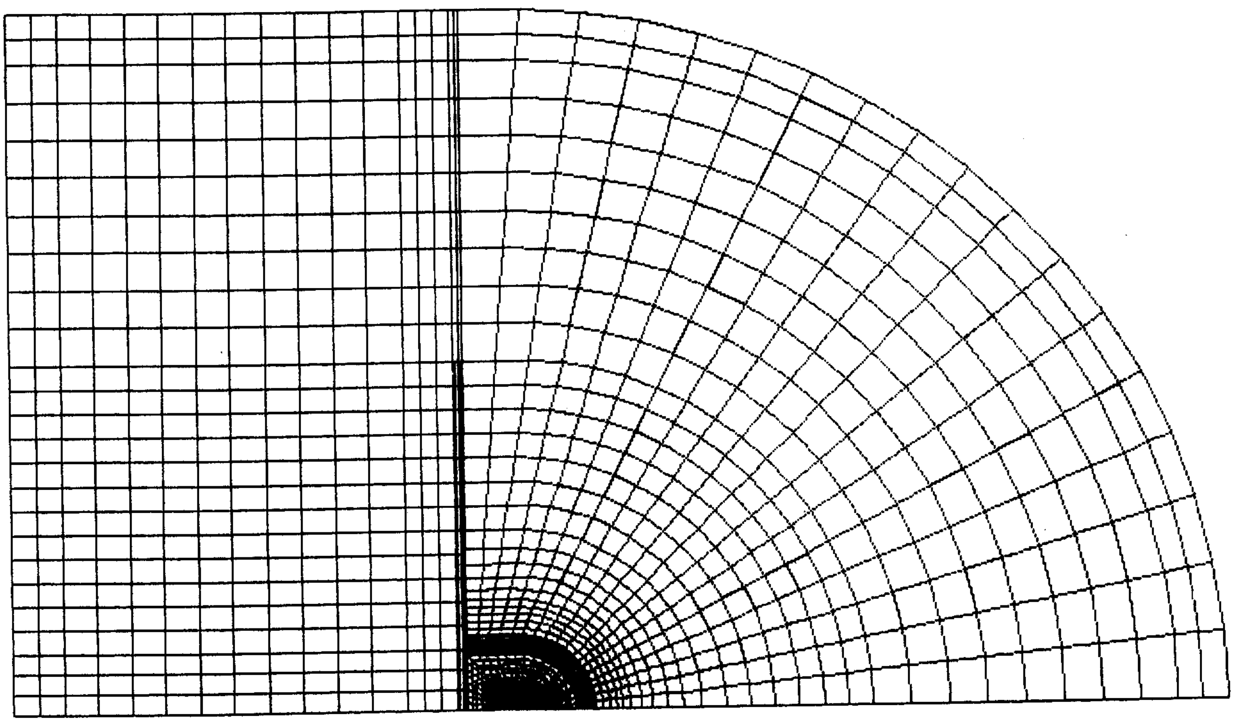
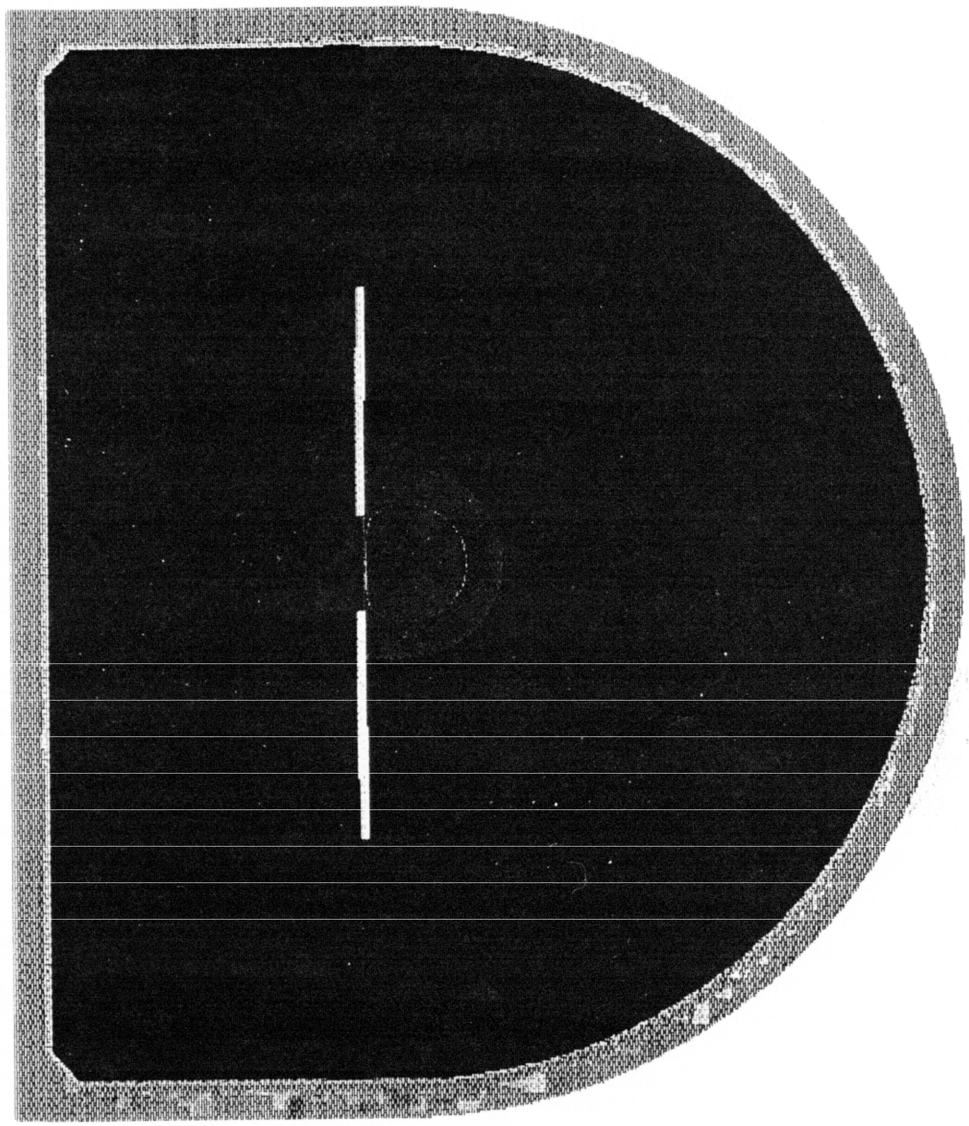
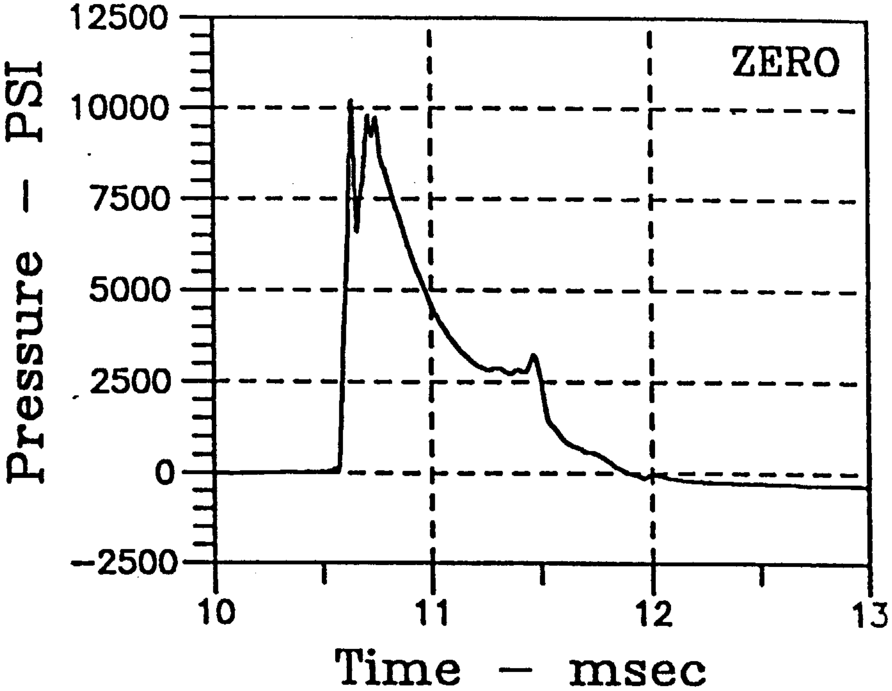
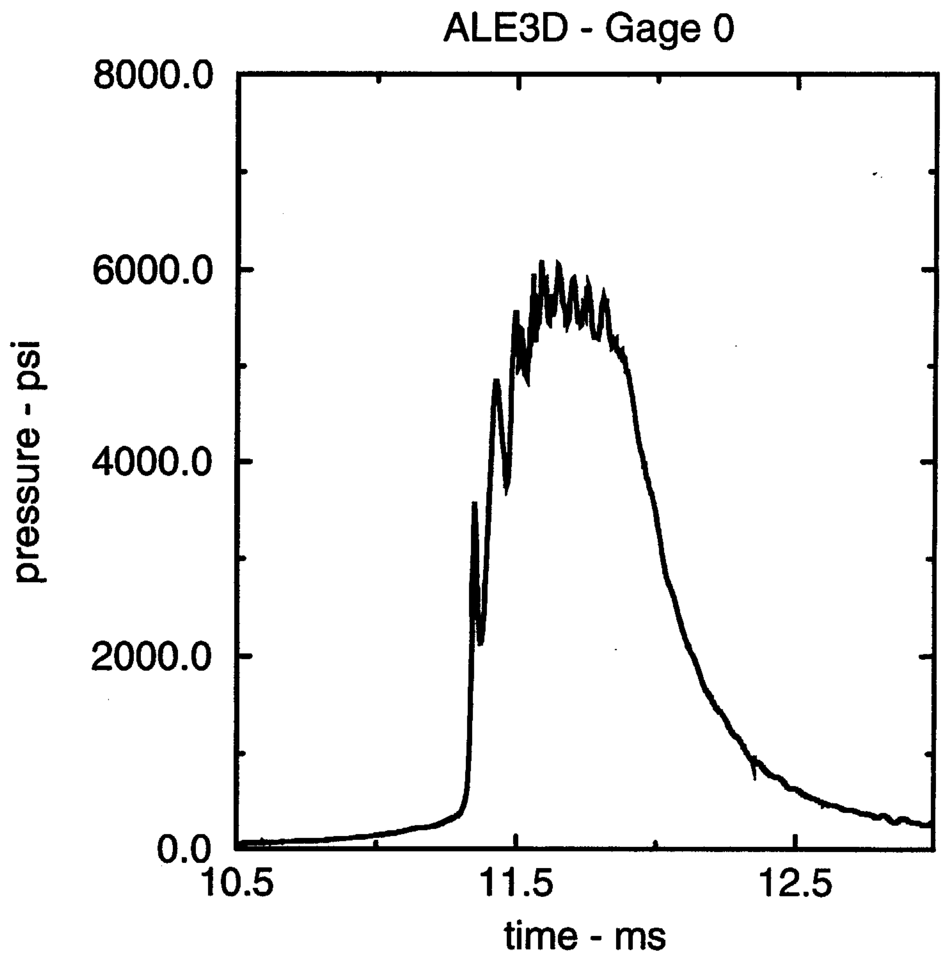


Figure 4: Bubble shape near peak volume at 6.0 milliseconds after initiation. The bending of the plate is apparent



Flat Plate Loading - Test 3





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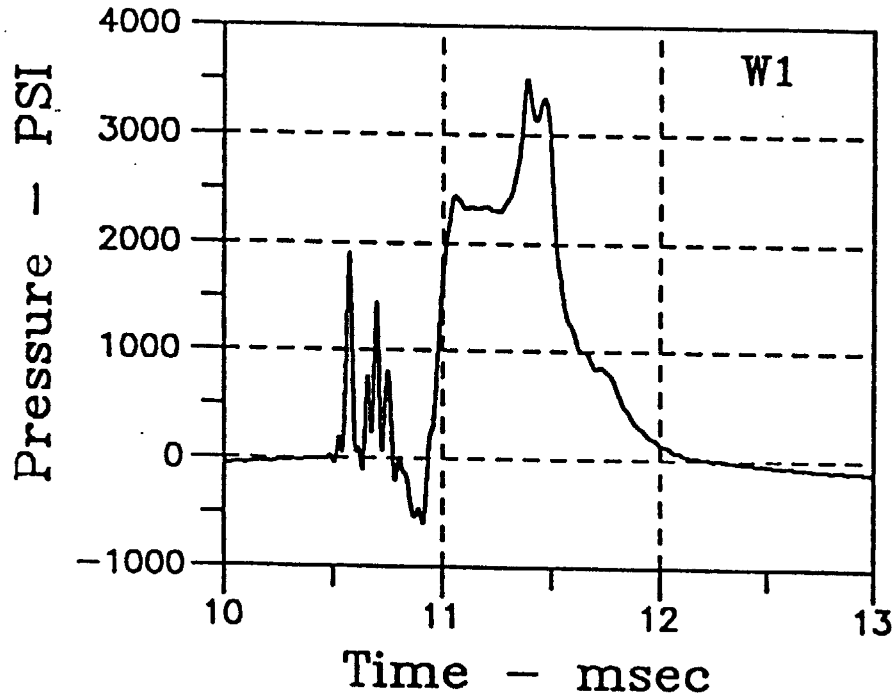
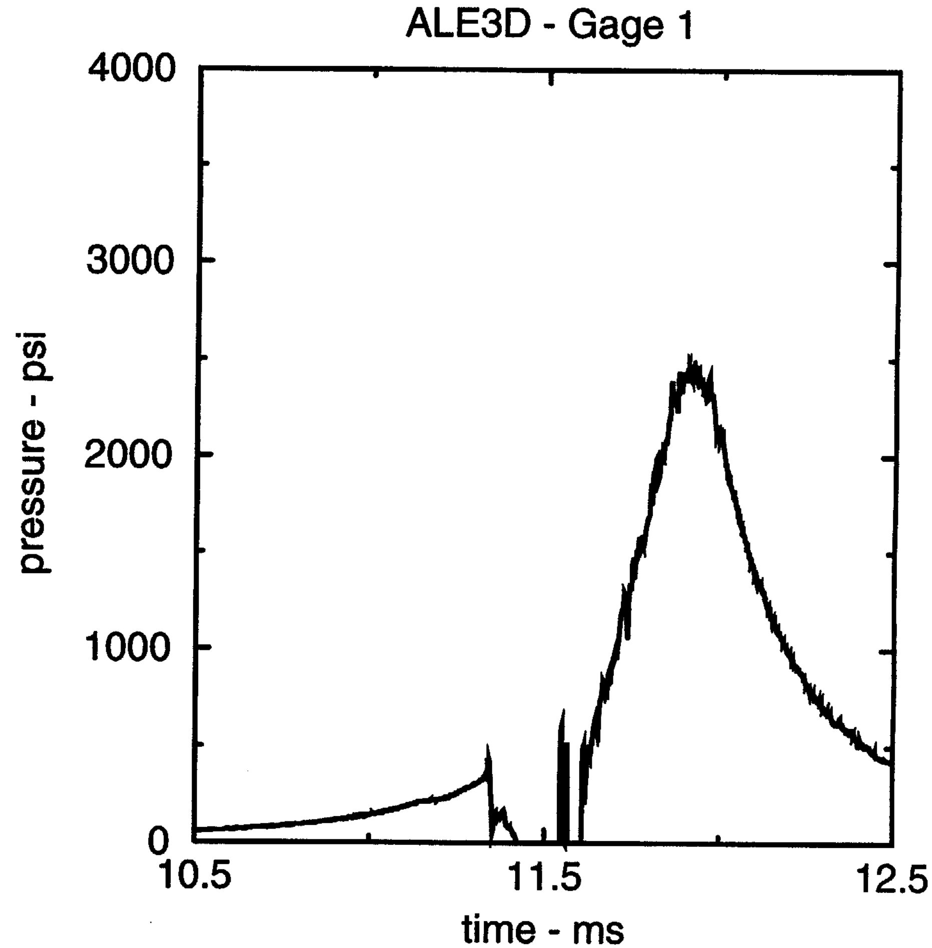




Simulation of Underwater Explosion Benchmark Experiments with ALE3D

Richard Couch and Douglas Faux
Lawrence Livermore National Laboratory
May 19, 1997

Introduction

This work was supported by the Office of Naval Research. The programmatic management was provided by the Naval Surface Warfare Center (NSWC) located at Silver Spring, Maryland. The goal of the project was to evaluate the 3D Arbitrary Lagrangian-Eulerian (ALE) code, ALE3D, as a numerical simulation of phenomena associated with underwater explosive events. NSWC selected five controlled underwater tests that were well enough diagnosed and simple enough in structure to allow straight forward analysis, yet sufficiently representative of the class of problems of programmatic importance to the Navy to allow meaningful evaluation of the capabilities of ALE3D. This exercise was intended to investigate the utility of ALE techniques and provide a comparison with results obtained using other computational approaches. The number of tests to simulate was subsequently reduced to four. They included:

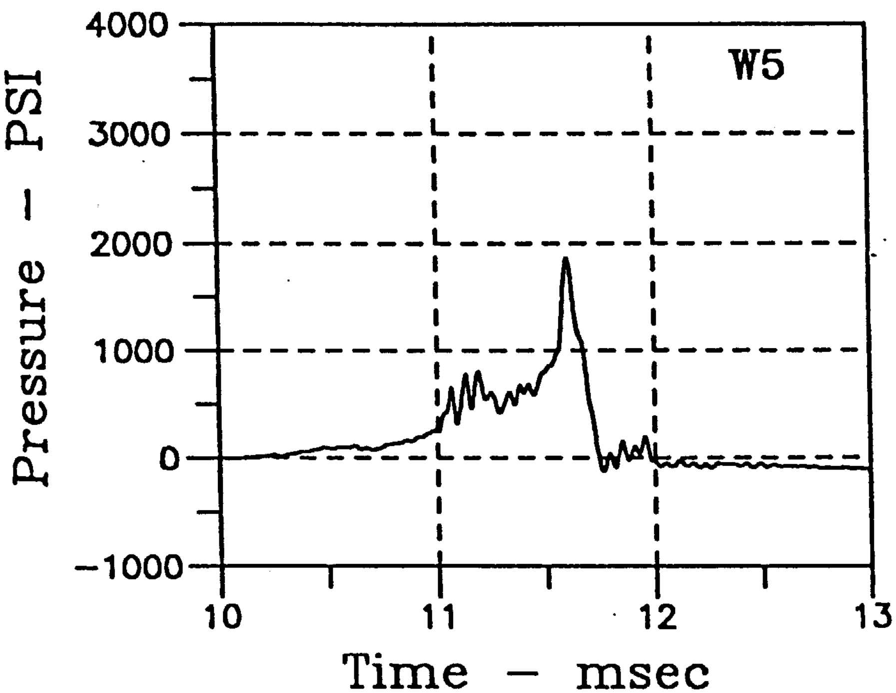
1. loading of a flat plate by an explosive charge,
2. bubble evolution dynamics under the combined effects of a nearby structure and buoyancy forces,
3. deformation of a cylinder by an explosive charge,
4. pipe whipping effect in a long cylinder under explosive loading.

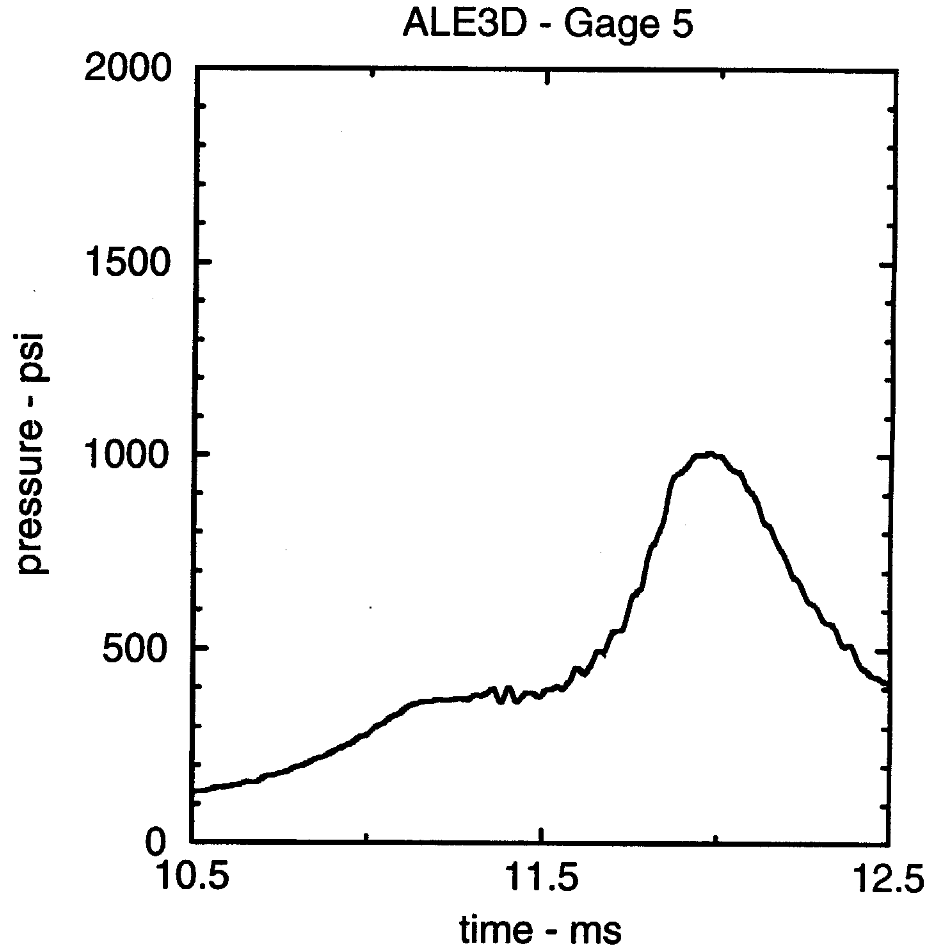
A brief description of ALE3D is provided. There techniques used and the results obtained for each of the test cases are provided. A discussion of salient lessons learned from this study will be provided in the context of delineating the strengths and weaknesses of the ALE technique, in general, and the ALE3D implementation in particular.

Description of ALE3D

ALE3D is a finite element code that treats fluid and elastic-plastic response on an unstructured grid. The grid may consist of arbitrarily connected hexahedral, shell and beam elements. There is currently no allowance for tetrahedra or wedge shaped elements. The mesh can be constructed from disjoint blocks of elements which interact at the boundaries via slide surfaces or other types of boundary conditions. Nodes can be designated as relax nodes and ALE3D will adjust their position relative to the material in order to relieve distortion or to improve accuracy or efficiency. This relaxation process can allow nodes to cross material boundaries and create mixed or multi-material elements.

Flat Plate Loading - Test 3





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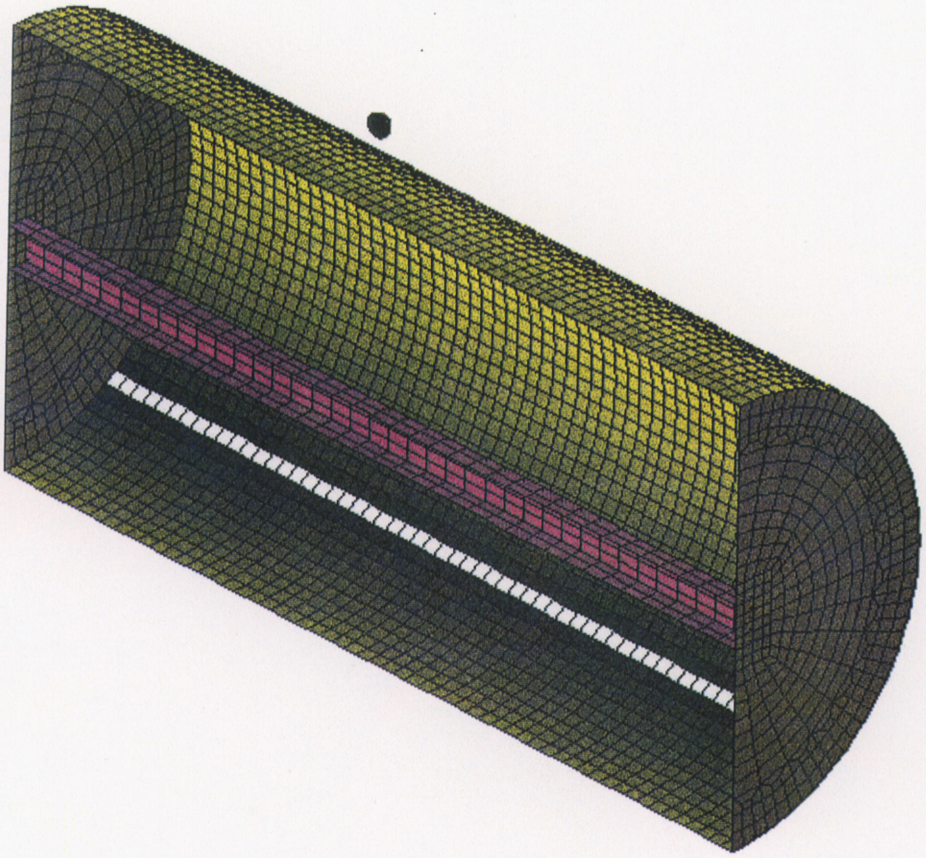

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mats 1 5 6 7

user:couch
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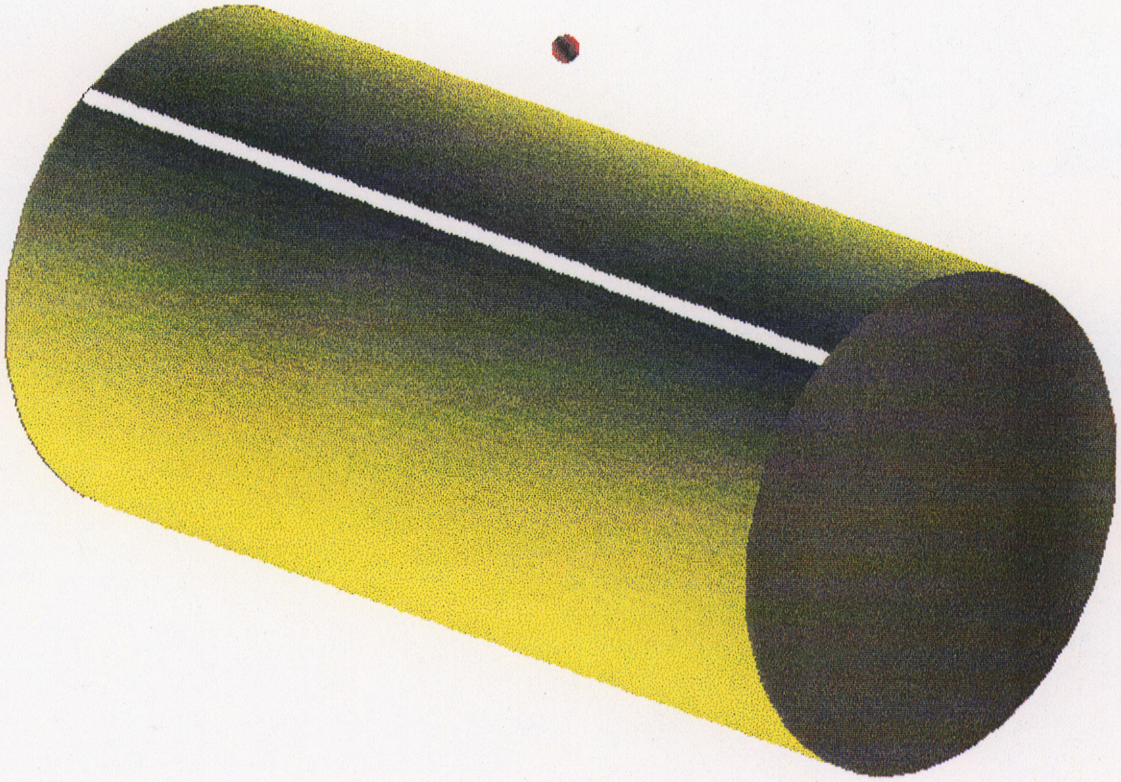

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mats 1 5 6 7

user:couch
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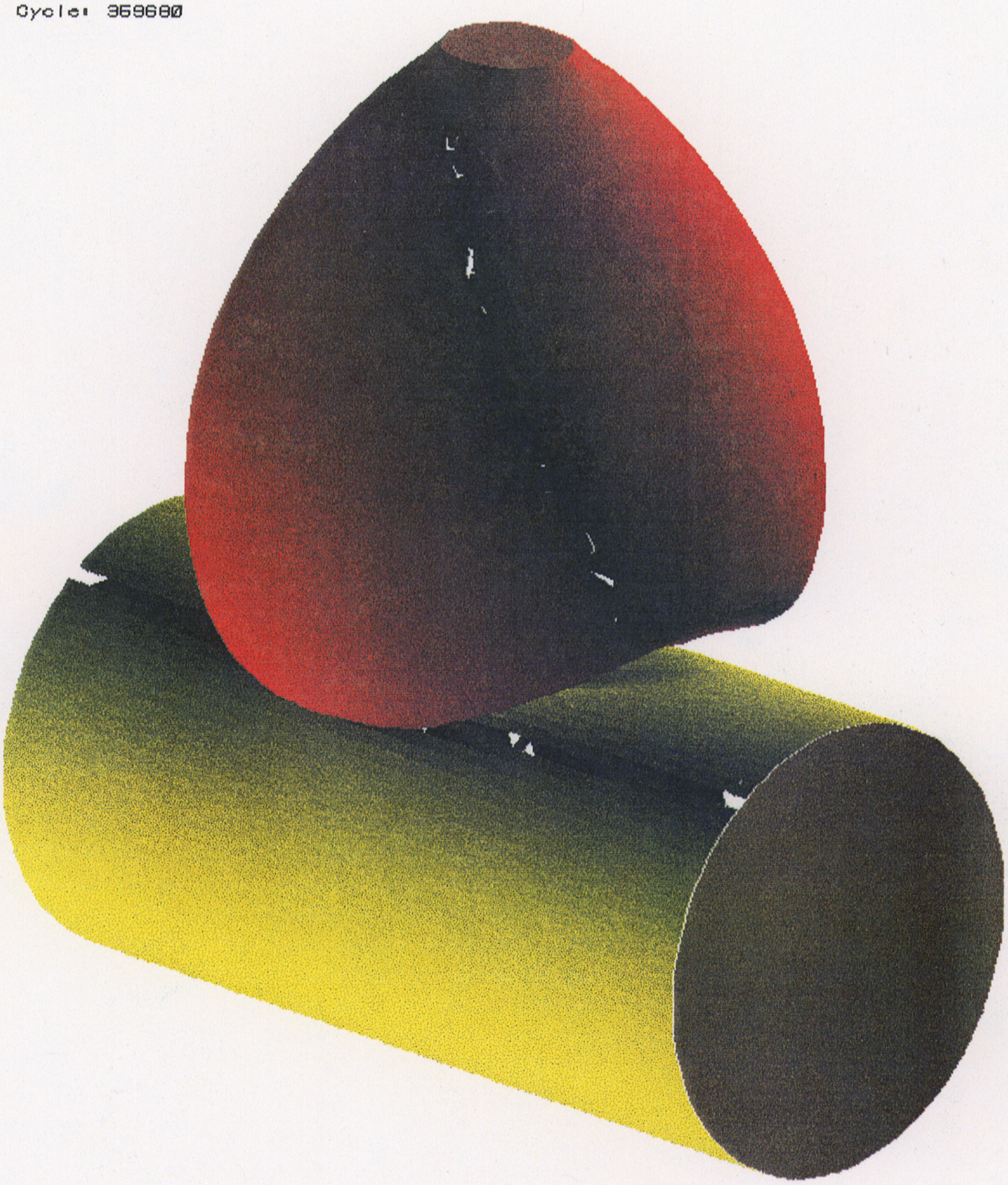

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mats 1 5 6 7

user:couch
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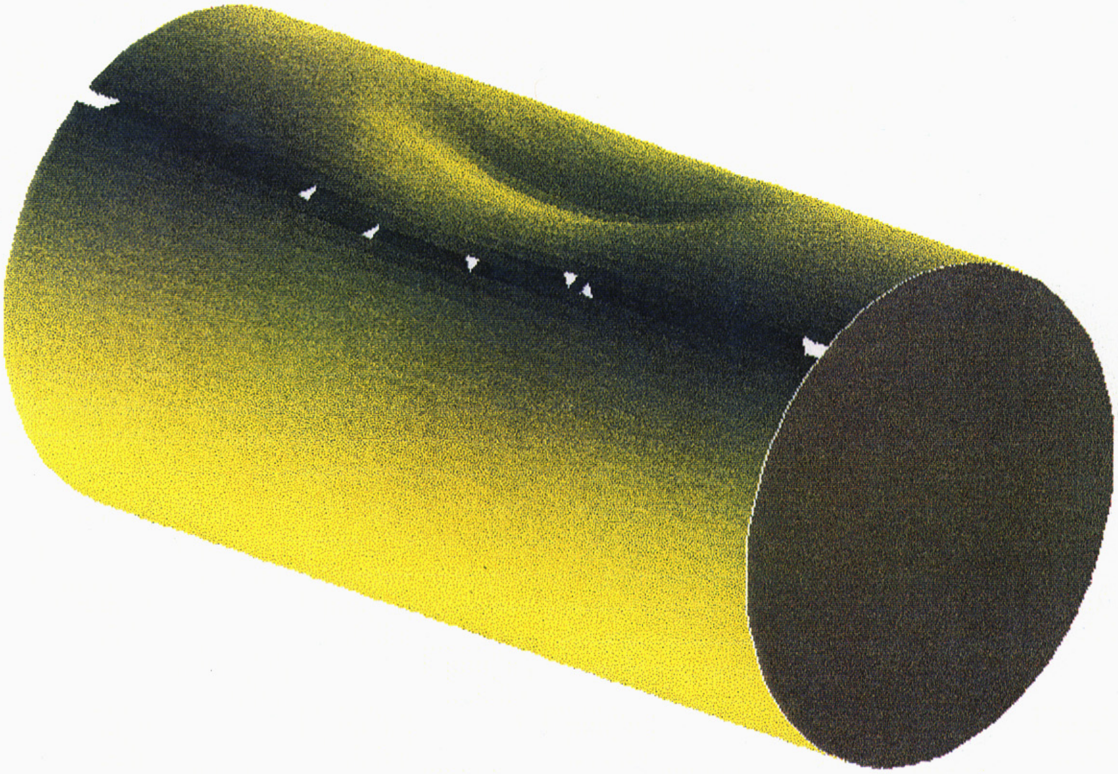

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mats 5 6 7

user:couch
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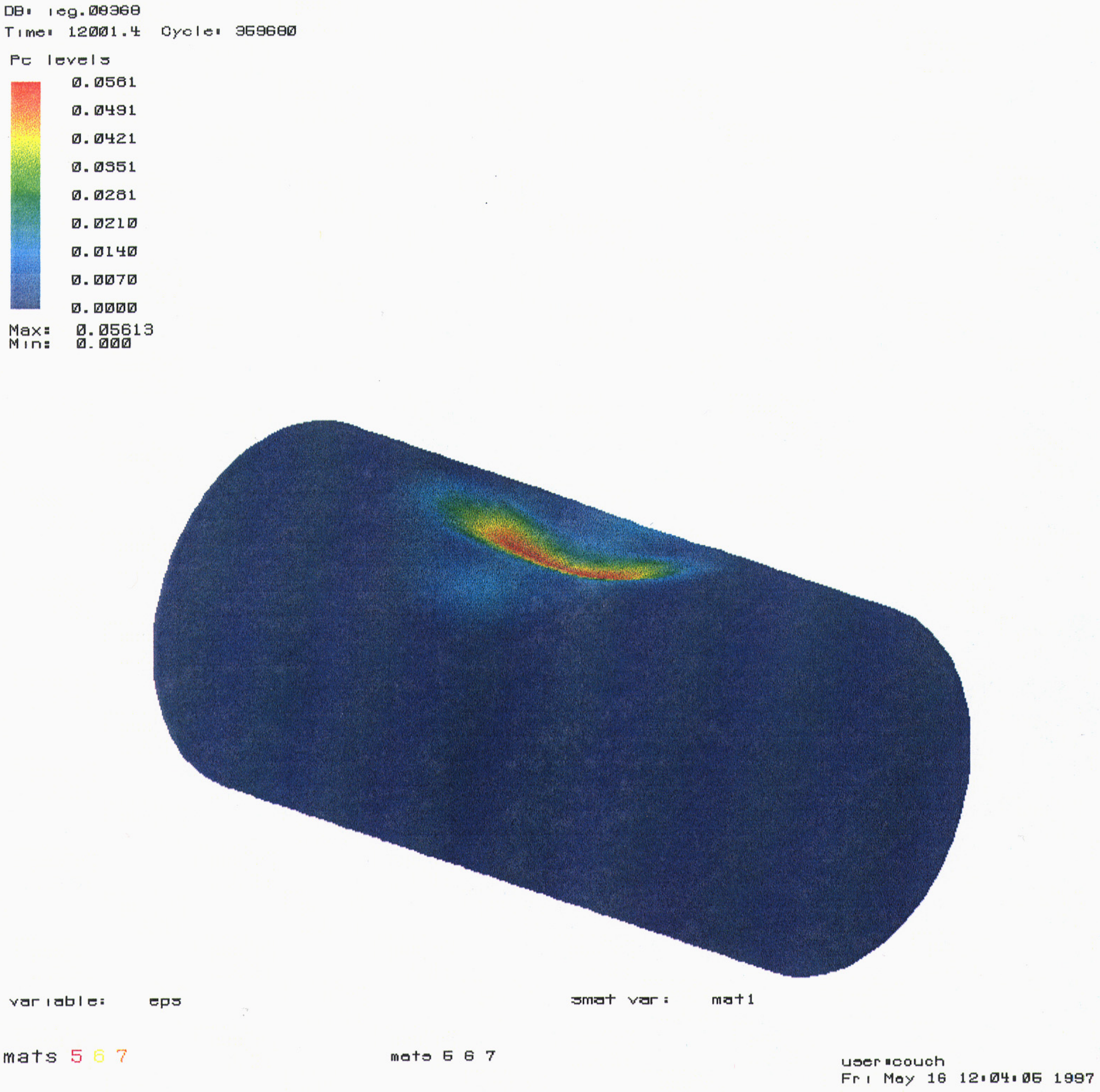

DB: ieg.00360
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Pc levels
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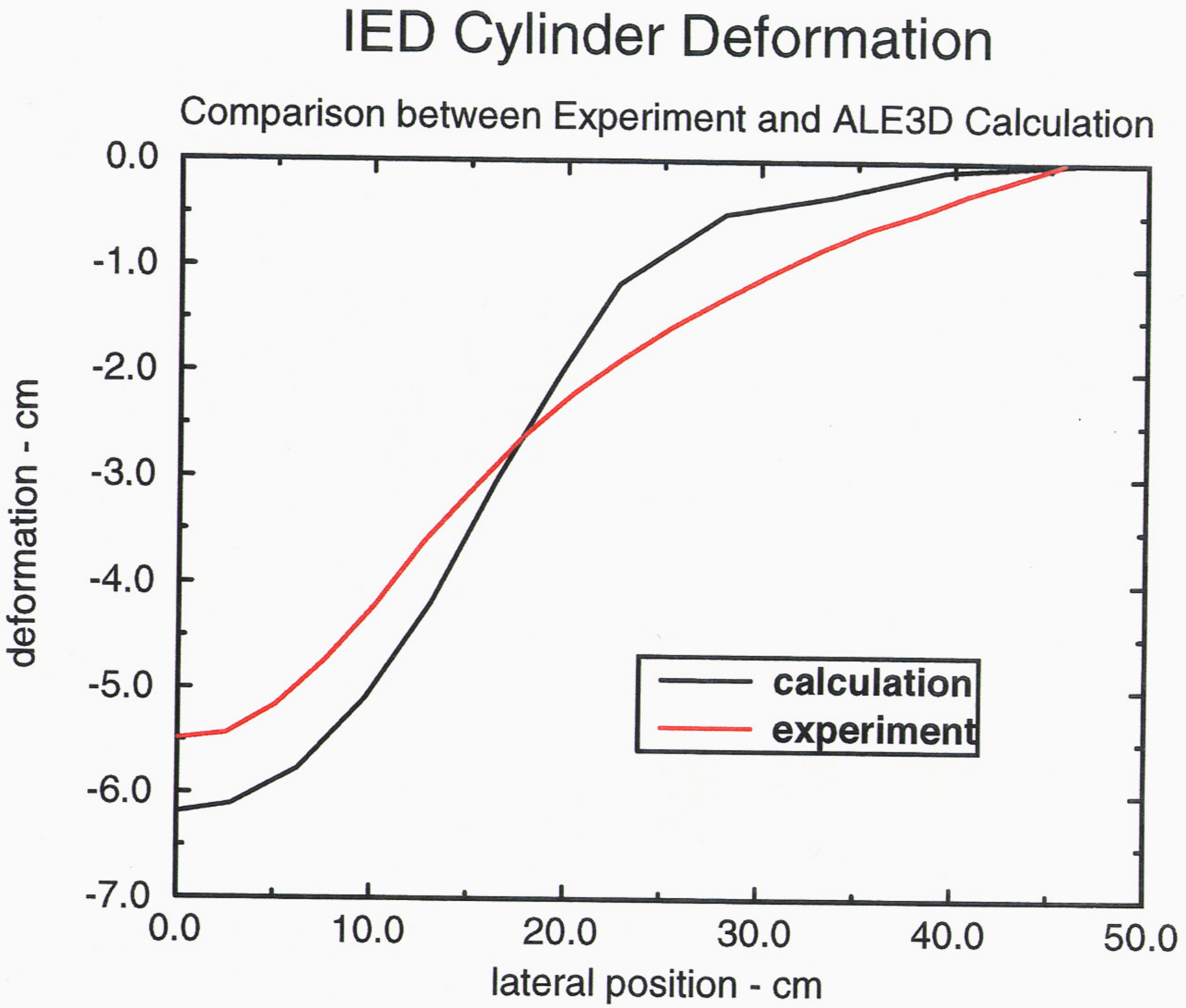
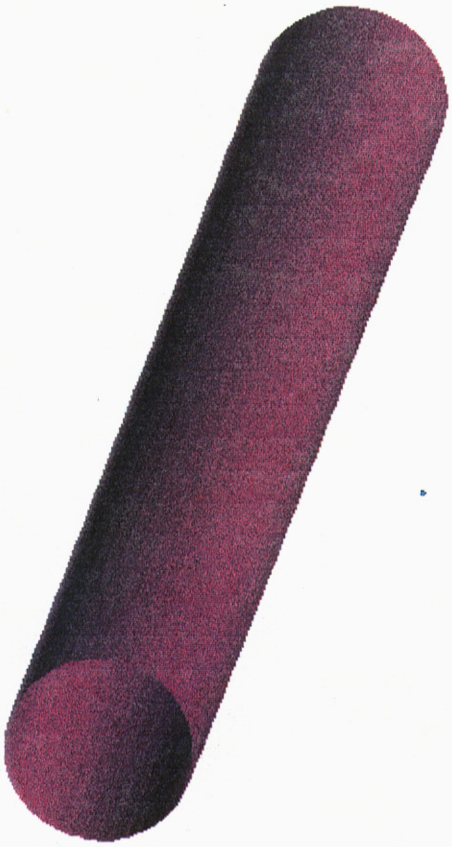
0.0491
0.0421
0.0351
0.0281
0.0210
0.0140
0.0070
0.0000
Max: 0.05613
Min: 0.000
variable: eps
smat var: mat1
mats 5 6 7
mats 5 6 7
user:couch
Fri May 16 12:04:05 1997


IED Cylinder Deformation
Comparison between Experiment and ALE3D Calculation
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
deformation - cm
calculation
experiment
0.0
10.0
20.0
30.0
40.0
50.0
lateral position - cm

DB: nck.00000
Time: 0 Cycle: 300312



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mats 4 5

mats 4 5

user:couch
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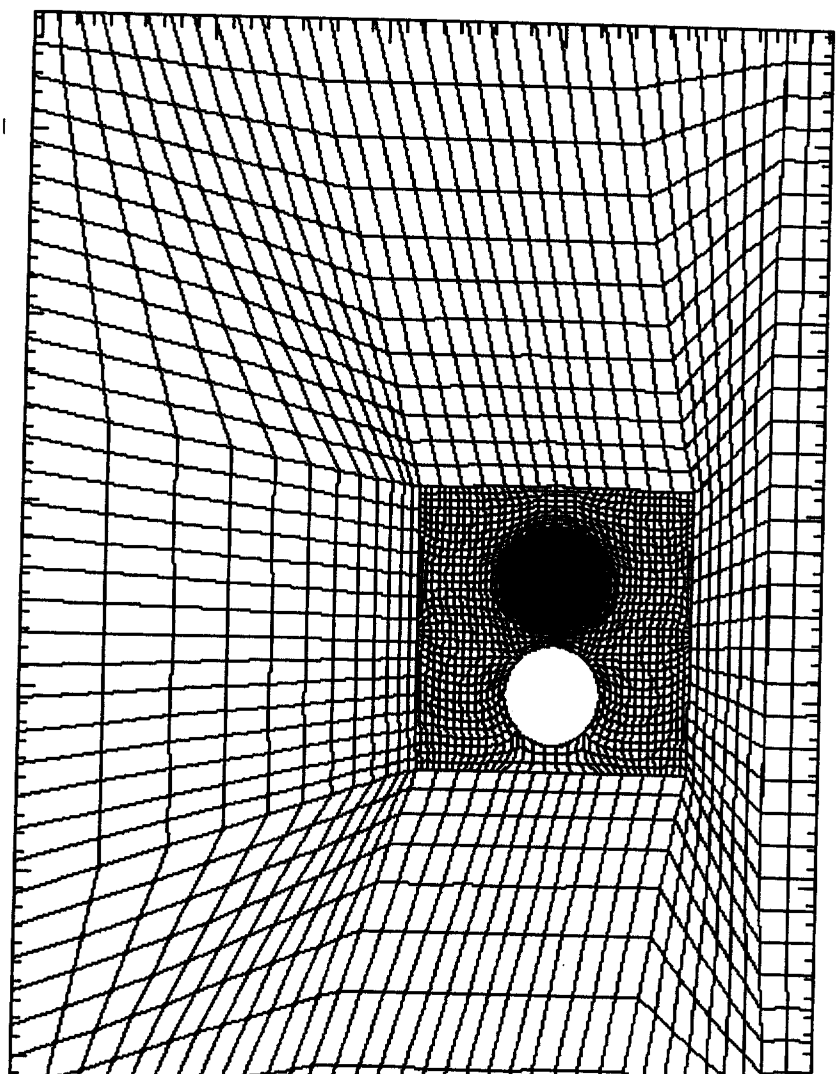

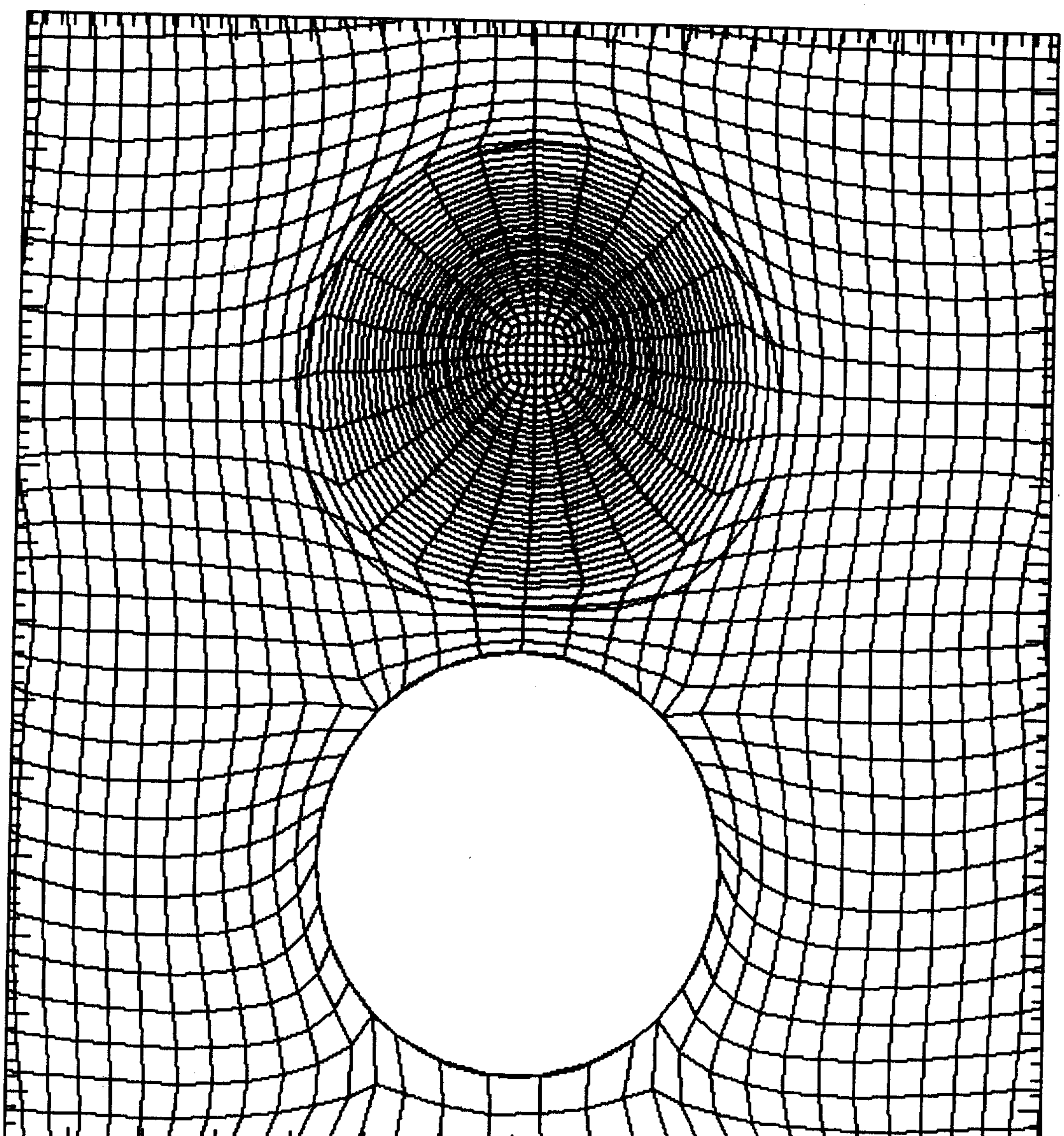

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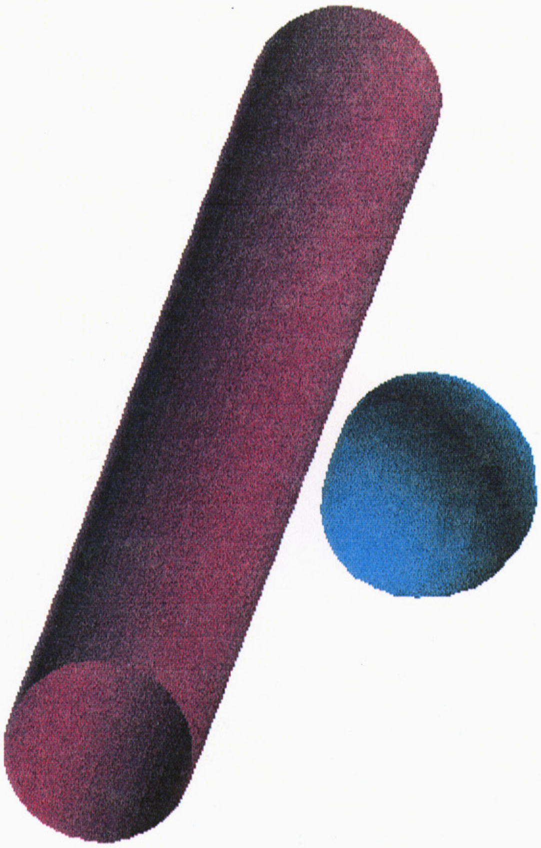

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mats 4 5

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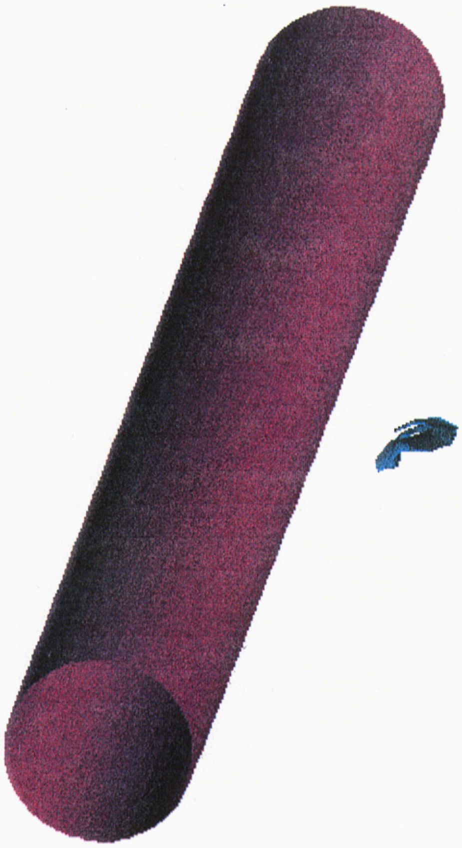


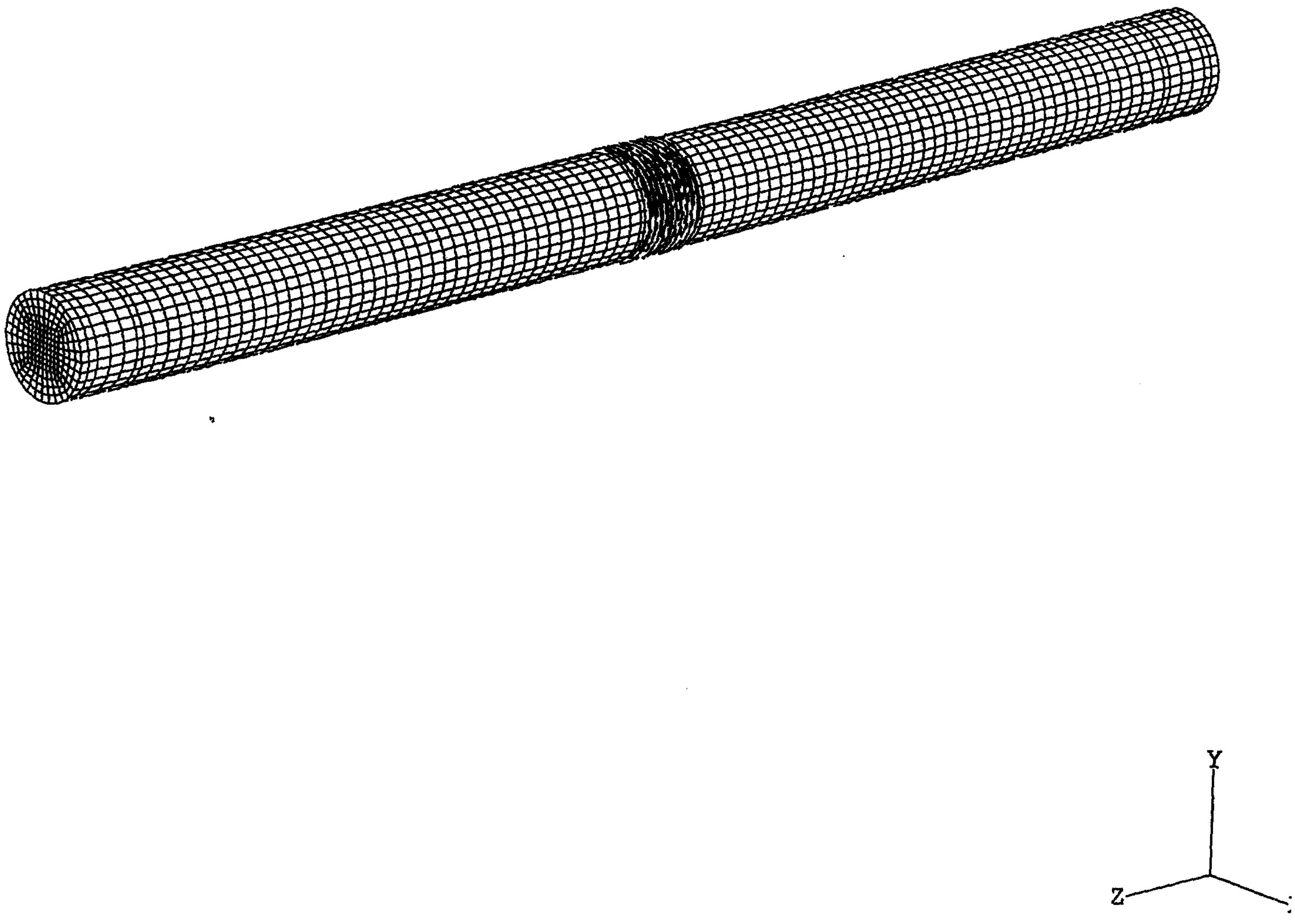
smat var: mat1

mats 4 5

mats 4 6

user:couch
Fri May 16 02:30:28 1997

Figure 41: A plot of the mesh used to represent the cylinder.



...the mesh used to represent the internal steel ballasts, end caps and center section.

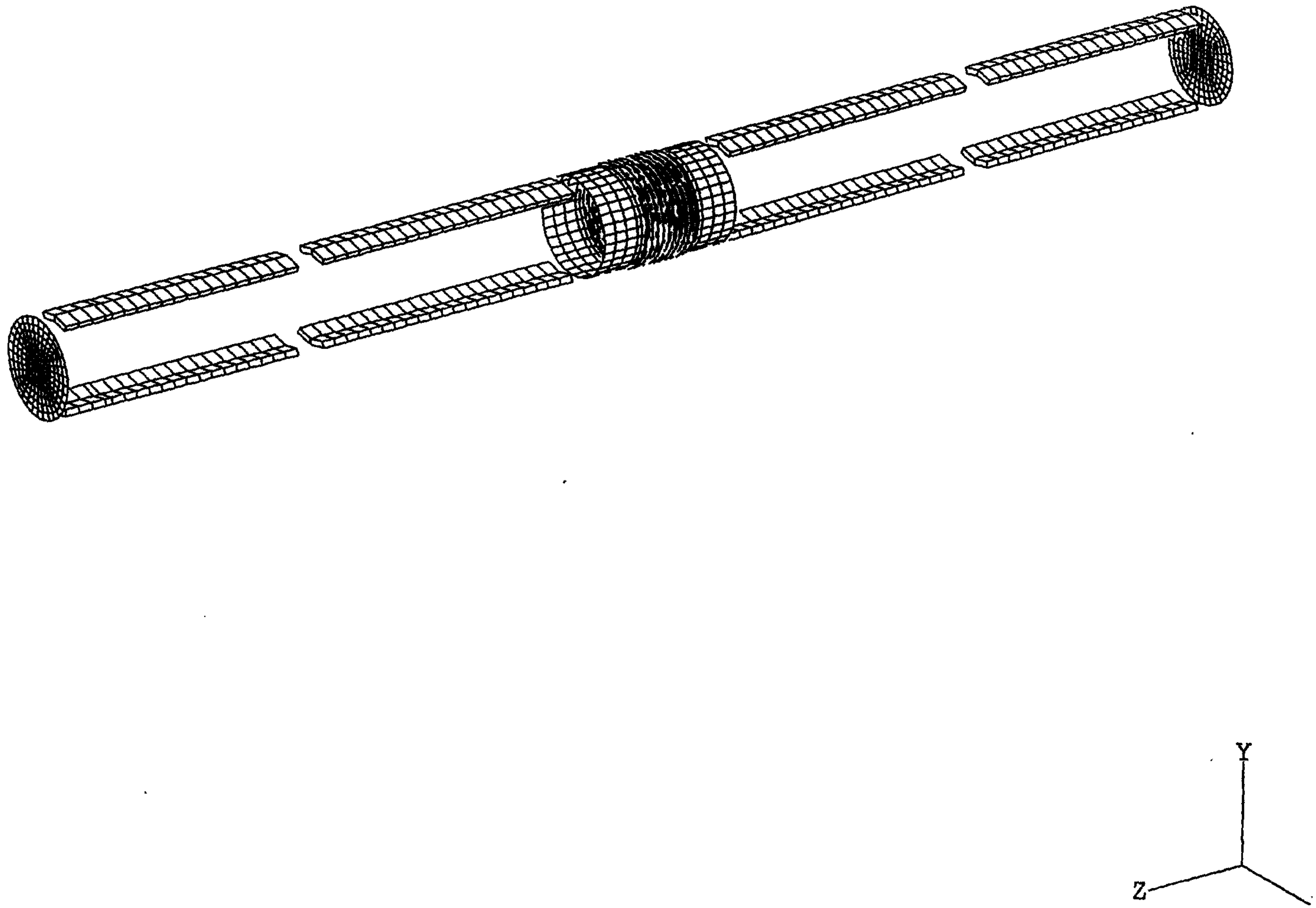


Figure 43: An illustration of the details of the center section with the 10 stiffening rings.

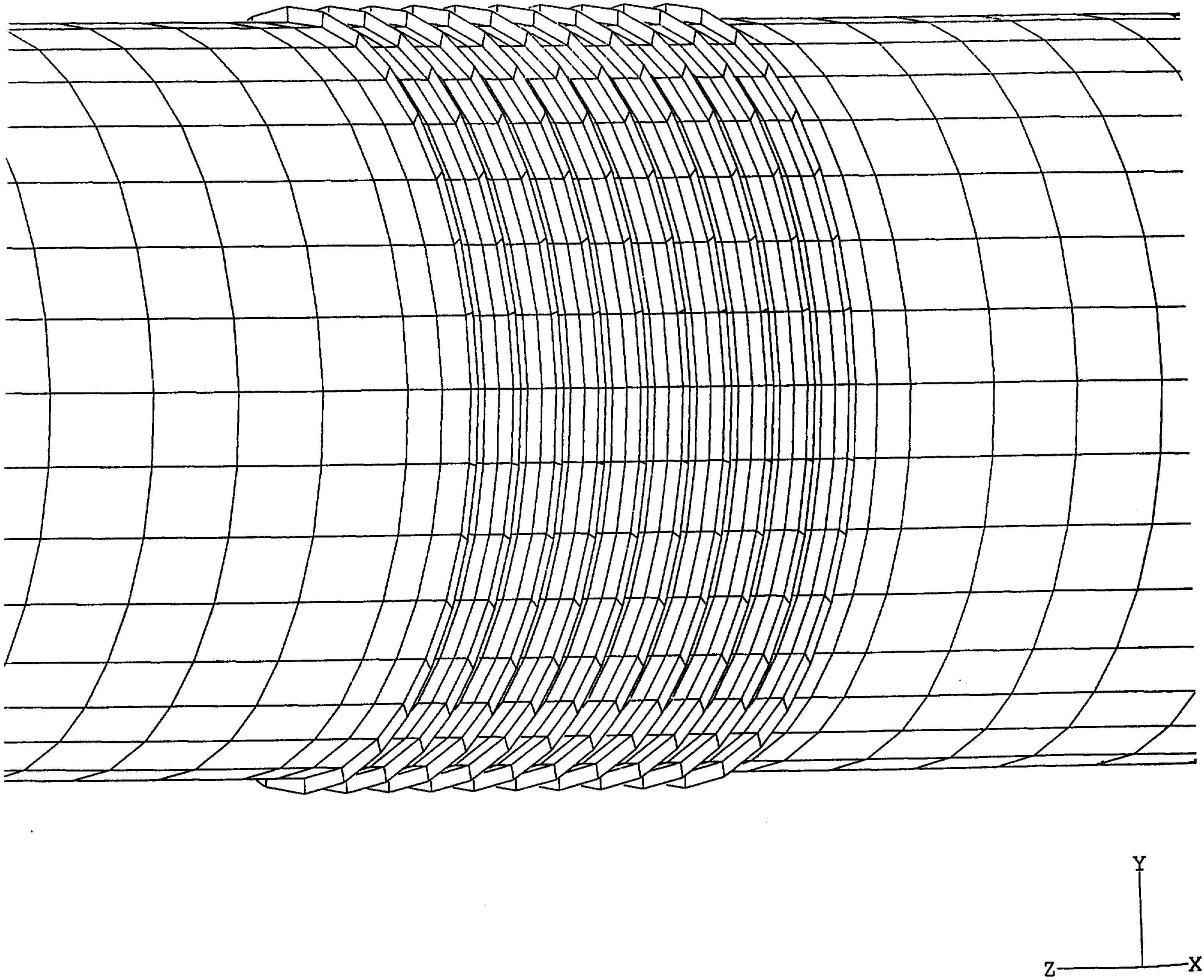
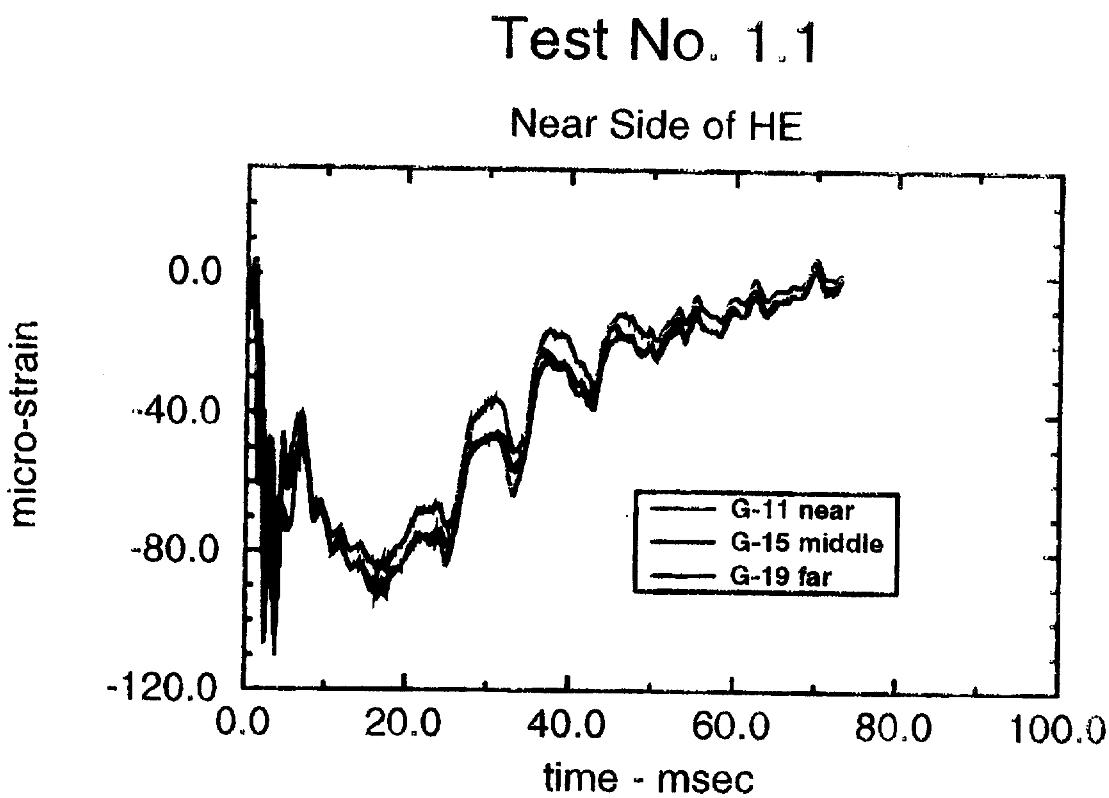


Figure 46: Plots of calculated axial strain at various gage locations.



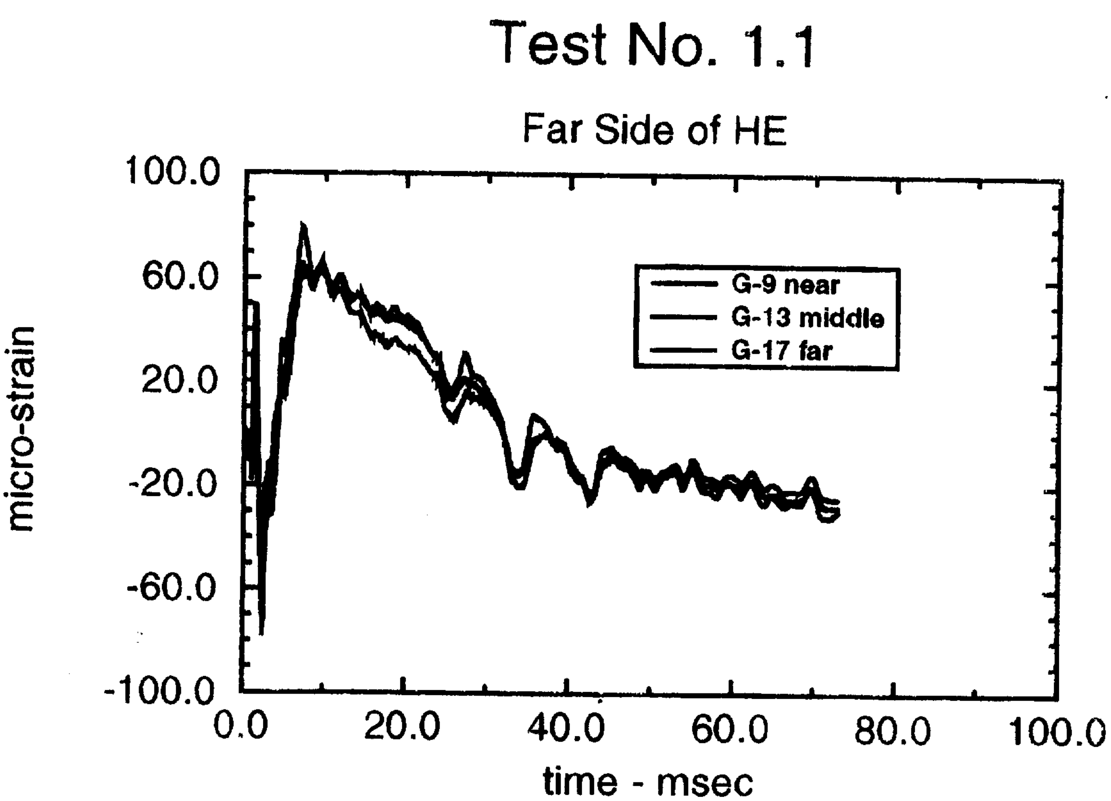
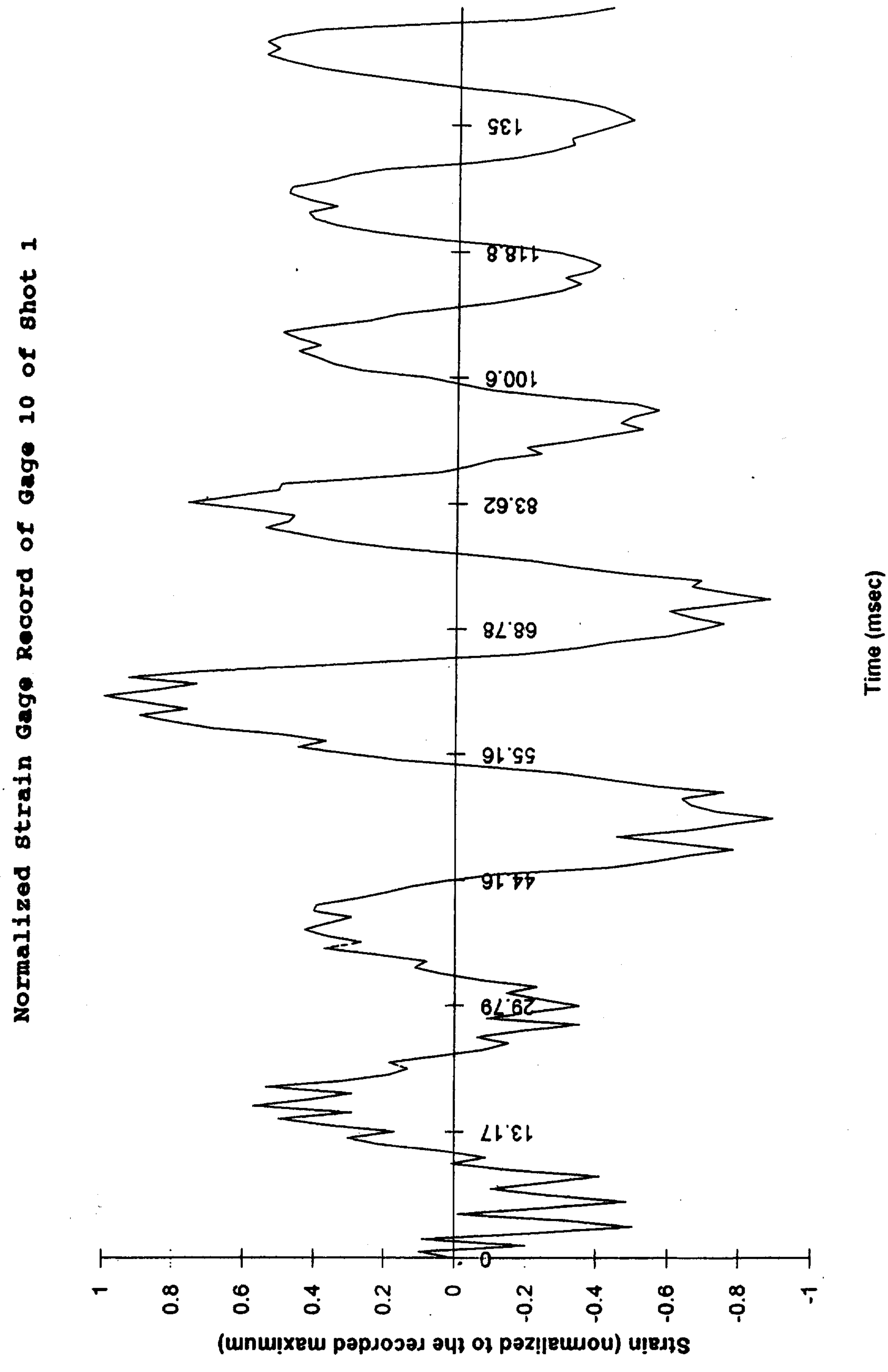


Figure 47: Normalized plot of the experimental strain record for gage 10.



Conclusions

- ALE3D demonstrated utility for underwater explosion simulations
- more work needs to be done
  - better understanding of mesh effects
  - better understanding of boundary condition effects
  - more detailed structural models
  - structural models including failure and failure propagation

Conclusions

Although much was learned about the simulation of underwater explosion phenomena, the authors do not feel that the results presented here are optimal for a code like ALE3D. Questions like the sensitivity of bubble shape and diameter to meshing have only been addressed in a qualitative sense. The results obtained do give an indication of the potential for the ALE approach to this class of problem, and have provided the motivation to make code improvements that improve the accuracy and efficiency of ALE3D for this application.

Some code improvements have been made during the course of this study. One immediately obvious need was for more flexibility in the constitutive representation for materials in shell elements. To remedy this situation, a model with a tabular representation of stress versus strain and rate dependent effects was implemented. This was required in order to obtain reasonable results in the IED cylinder simulation. Another deficiency was in the ability to extract and plot variables associated with shell elements. The pipe whip analysis required the development of a scheme to tally and plot time dependent shell quantities such as stresses and strains. This capability had previously existed only for solid elements. Work was initiated to provide the same range of plotting capability for structural elements that exist with the DYNA3D/TAURUS tools. One of the characteristics of these problems is the disparity in zoning required in the vicinity of the charge and bubble compared to that needed in the far field. This disparity can cause the equipotential relaxation logic to provide a less than optimal solution. Various approaches were utilized to bias the relaxation to obtain more optimal meshing during relaxation. Extensions of these techniques have been developed to provide more powerful options, but more work still needs to be done.

The results presented here are representative of what can be produced with an ALE code structured like ALE3D. They are not necessarily the best results that could have been obtained. More experience in assessing sensitivities to meshing and boundary conditions would be very useful. A number of code deficiencies discovered in the course of this work have been corrected and are available for any future investigations.

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