Oblique penetration in ductile plates

by H. Lenselink

The MacNeal-Schwendler Company B.V.
Groningenweg 6
2803 PV Gouda
The Netherlands

Abstract

This paper presents the results of two three-dimensional coupled Euler-Lagrange simulations of oblique penetrations of a hard steel fragment in a copper plate.
The computations are performed with the MSC/DYTRAN code and the computed penetration regime ranged from full ricochet (thick plate) to regular oblique perforation (thin plate).
In both computed cases the plate deforms severely by the cratering process of the penetrating fragment.
By using a coupled Euler-Lagrange approach the fragment (Lagrange) and the plate (Euler) are modeled in the most accurate and efficient computational frame of reference.
To model the highly non-linear material behavior, a Johnson and Cook yield model for the copper plate material has been used to take into account strain, strain rate and temperature effects.
The computed penetration process, crater shapes and angle of exit of the fragment are compared with experimental data.
A good agreement between the DYTRAN results and experiments was found.

1. Introduction

The problem of the penetration of hard fragments into deformable plates has been a subject for experimental and analytical investigations for decades.
These kind of problems can occur in the following application areas:

- Containment problems, e.g. the fracture of a turbine blade in turbine engine
- Nuclear and chemical safety studies.
- Terminal ballistics in defense.

During the last decade this type of problem could also be tackled by employing numerical techniques. Two-dimensional computer codes were employed on a routine basis on smaller (mini) computer systems. These studies were mostly concerned with normal impacts, while the more complicated three-dimensional oblique impact and penetration problems mostly were treated in an analytical or semi-empirical way.
Until a few years ago, three-dimensional computations on smaller computer systems were impractical from the standpoint of both storage and CPU requirements. The advent of the super-mini's with inceased CPU speed and vector processors made it possible to employ three-dimensional computer codes on a routine basis on smaller systems.

For the full numerical solution of the oblique penetration problem three main numerical approaches are available. The Eulerian approach in which the the solution is sought on a space-fixed coordinate system, the Lagrangian approach in which the solution is sought on a material-fixed coordinate system and the ALE (Arbitrary Lagrange Euler) approach which tries to make use of the best capabilities of Euler and Lagrange by allowing grid motionsthat can vary between Lagrange and Euler motions.
For the problem of the penetration of a hard fragment into a ductile plate, where the trajectory of the fragment is not known beforehand, the most efficient and accurate approach would be to model the projectile in a Lagrangian frame of reference and to model the deformable plate in an Eulerian frame of reference. For the oblique impact problem the two distinct computational domains must then be coupled in time and space.

In this paper the ELK (Euler Lagrange Coupled) technology of the MSC/DYTRAN computer code, will be described and the results of two three-dimensional computations of the oblique impact and penetration of a hard fragment (projectile) on a ductile plate with varying thickness are presented.

2. Numerical approach

For the considered numerical simulations we have used a preliminary version of the MSC/DYTRAN code. The old MSC/PISCES-3DELK Eulerian technology has been included in the MSC/DYTRAN code. This Eulerian technology could handle fluid-structure interaction [1], but in the first version of the MSC/DYTRAN code a new Eulerian processor type with a full stress tensor has been implemented, that makes 3-dimensional oblique impact and penetration calculations on metal plates possible.

The new code contains now a number of numerical processors, solving the conservation equations of mass, momentum and energy in either a space-fixed coordinate system (Eulerian processors) or in a material-fixed coordinate system (Lagrangian processors, like Solids and Shells) .

A very powerful feature of the code is its ability to couple the different processor types in time and space and thus allowing the user to apply the most accurate and efficient numerical scheme to the different geometrical regimes of a given problem.

2.1 The mathematical model

The mathematical model consists of partial differential equations describing conservation of mass, momentum and energy. These are solved using an explicit finite-difference, finite-volume and finite-element method [2].

The conservation equations are expressed based on their integral form for an arbitrary hexahedral volume. The stress tensor is formulated for both materials with a hydrodynamic behavior (only pressure) and materials with strength (full stress tensor)

2.2 The Numerical Method

From the variety of processors the code offers the three processors relevant for the oblique impact and penetration applications discussed in this paper are:

- **Lagrange processor**

The (Solid) Lagrange processor has been chosen to model the hard fragment in the oblique impact problems. The Lagrange processor operates on a material-fixed mesh, which describes solid body motion. It uses a 8-node constant stress volume element and is the solid DYNA3D element developed by J. Hallquist [3].

- **Euler processor**

The Euler processor with a full stress tensor is used to model the plate in the oblique impact problems. The Euler processor operates on a space-fixed mesh with material and material interfaces moving from cell to cell.
The three-dimensional Euler processor uses a cell centered explicit finite volume method in which the conservation equations are solved in their integral form for an arbitrary 8-node volume element:

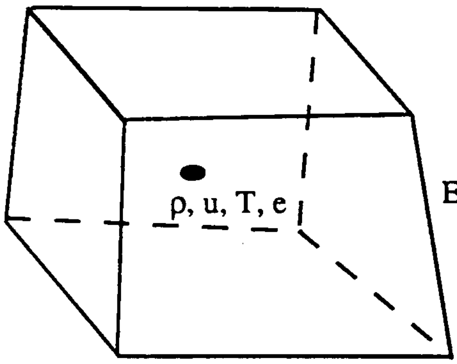

Fig. 1: Definition of the physical variables in the Euler cells.

Mass conservation

$$\frac{\partial}{\partial t}\iiint_{vol}\rho\, dV = -\iint_{surf}\rho u.dS$$

Momentum conservation

$$\frac{\partial}{\partial t}\iiint_{vol}\rho u dV = -\iint_{surf}\rho u\, u.dS + \iint_{surf} TdS$$

Total energy conservation

$$\frac{\partial}{\partial t}\iiint_{vol}\rho e_t dV = -\iint_{surf}\rho e_t\, u.dS + \iint_{surf} uTdS$$

, where ρ is the density, u is the velocity, e is the specific internal energy, e_t is the specific total energy, T is the stress tensor and dS is the outward pointing normal area vector on a cell face.

From these equations it is clear that the change in time of mass, momentum and energy in a Eulerian cell can be computed by evaluating the surface integrals on the six faces of the Euler cell. The first integral on the righthand side defines the amount of mass, momentum or energy transported through the faces of the Euler cell. The second term in the momentum conservation equation is the impuls exerted by the stress tensor on the Euler cell faces. The second term in the energy conservation equation is the amount of work done by the stress tensor on the Euler cell faces

The material interfaces are followed through the Euler grid by a material fraction scheme based on the rules used by W.E. Johnson in the TOIL code.

• **The Euler-Lagrange coupling algorithm**

The ELK (Euler-Lagrange Coupling) technology in the MSC/DYTRAN code is an extension to three dimensions of the two-dimensional ELK capabilities existing in the MSC/PISCES-2DELK code [4]. It allows arbitrary motion of structures through the Eulerian domain .

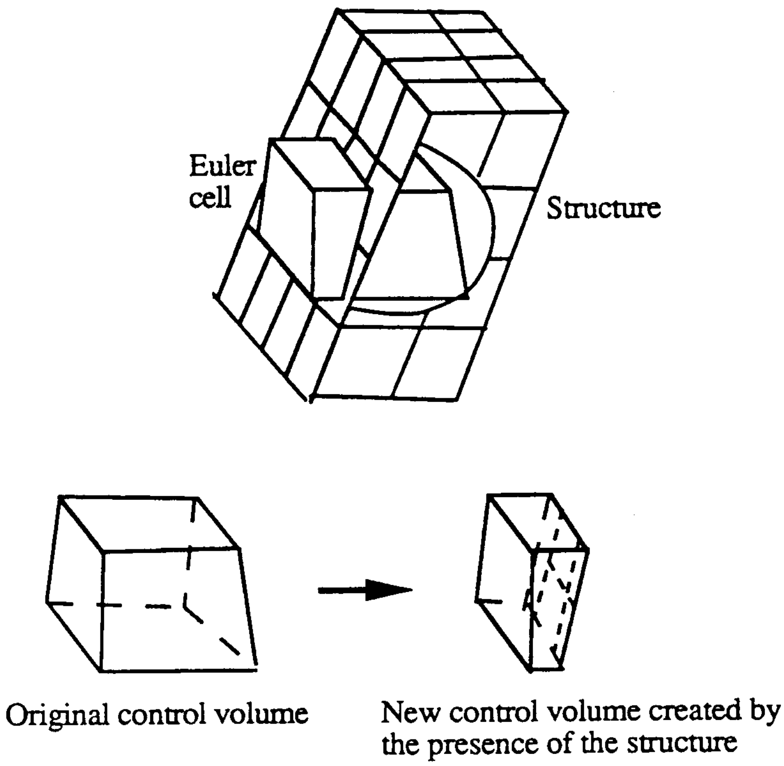

Fig. 2: The intersection of an Euler cell with a structure.

The convected Lagrangian structure presents a continuously moving wall boundary for the materials in the stationary Eulerian mesh. The shape of the Eulerian control volumes belonging to the eulerian cells that are intersected by a structure (interface cells) will change during the motion of the structure over the Eulerian domain. Some cells will become covered while others will become uncovered.
The surface integrals for interface cells are only evaluated for that part of the cell faces that is not covered by the structure.

The Euler materials in the interface cells will act as a continuously changing external loading boundary condition on the structures.(Fig. 3).

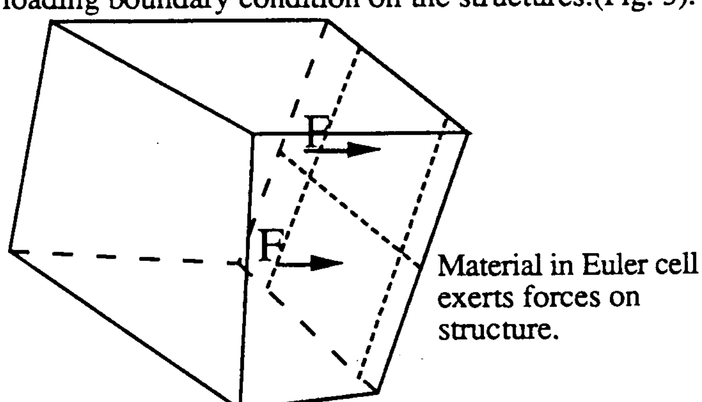

Fig. 3: Loading of the structure by Euler

As can be seen from figure 2, Eulerian cells can become partly covered or uncovered by the structure.
Small zone dimensions that are generate during this process would reduce the stable time step to unreasonable small values. Such situations are avoided by automatically blending smaller interface cells to larger stable cells to form new control volumes that can be computed with a much bigger timestep.
As is evident from the description of the ELK technology above that the coupling between the Eulerian domain and the Lagrangian domain simply results in doing a lot of geometrical computations to find the volume and surface area covered fractions of the interface cells and the construction of blended clumps.
Since three-dimensional Euler Lagrange coupled problems can easily produce a large number of interface cells, particular attention has been paid to the efficiency of computations and data management. The program has been designed to take maximum advantage of machines with vector processors.

4. Numerical model

As a test case for the ELK technology in oblique impact calculations, two oblique impact problems reported by J. Falcovitz et al [5] have been computed.
A cone-nosed hardened steel projectile, having a diameter of 9.5 mm, a length of 28.5 mm and a mass of 13 gr., is impacting on a copper plate with a diameter of 14 cm at a constant velocity of 914 m/s and a constant angle of obliquity of 60° (Fig. 4).
Only the thickness of the copper plates varied in the two computed cases.
The first case is a regular penetration through a thin plate of T/D = 0.68 , where T is the plate thickness and D is the projectile diameter. The second case is a full ricochet penetration into a thick plate of thickness T/D = 1.32.
Both cases provide an excellent test case for the ELK coupling because the impact ranges from regular penetration to full ricochet and therefore an arbitrary motion of the projectile must be allowed.

The numerical model used in the computations is given in figure 4. As can be seen only half of the problem has been computed because of symmetry reasons.
The bullet consists of a Lagrangian mesh of 64 zones. It was not expected that the bullit would deform much and therefore an elastic material model has been used.

The copper plate plate was modeled as an Eulerian mesh. The cell distribution in the plane of the plate is for both cases the same, only the number of computational cells over the thickness varied. For the thin plate calculation 23184 Eulerian cells were used and for the thick plate calculation 27216 zones were used. As can be seen in figure 4, the central part of the Euler mesh contained the copper material and behind and in front of the material there are a number of void Eulerian cells to allow the plate material to move into during deformation of the plate.
To account for strain, strain-rate and temperature effects during the cratering process, a Johnson and Cook yield model was used for the copper plate material .

5. Results

Both calculations were run on a Convex C-1 super mini computer. The thin plate case took 4.9 hrs of CPU while the thick plate case needed 16.7 hrs of CPU.
In this this paper some typical results of the computations are given in figure 5 to 8 as material contourplots and effective stress contourplots in the cross-section of the plate in the symmetry plane.

Thin Plate

As can be seen from the figures 6 and 7, the MSC/DYTRAN code calculates a regular oblique perforation for the thin plate. This has also been found in the reported tests. [5]
Upon impact of the projectile on the plate, the stresses immediately reach the yield limit and the plate material start to flow plastically around the cone-nose of the projectile. In the first phase of the penetration in the thin plate, the nose-cone will only be loaded at one side and the projectile starts to rotate a little. The back of the thin plate will very soon start to fail , because the plate is thin and the rotation of the projectile will stop then.
In the computations, a crater diameter of about 2 projectile diameter has been found. This agrees excellently with the test result; also the shape of the crater is in accordance with the tests.

Thick Plate

For this case the code calculates a full ricochet perforation of the plate (Fig. 7 and 8). The projectile makes a large hole in the front side of the plate and emerges also from the front side. Again this is exactly what has been found in the tests [5].
The first phase of the penetration process is the same as that of the thin plate. Due to a one-sided loading of the cone-nose the projectile starts to rotate. Because the plate is much thicker now, the back will not start to fail so soon. The cone-nose of the projectile will remain loaded at one side and the projectile can rotate from an impact angle of 16 to a exit angle that is much greater than the impact angle. This behavior has also been observed in the test.
The computed crater shape looks like the one found in the test. Only the bottom of the crater didn't fail in the tests. It was found in the tests that the bottom of the crater was very thin and due to the resolution of the Euler mesh, this thin layer of material can not be resolved. This situation is depicted in figure 9. If the cell dimensions of the Euler would be made (much) smaller than the thickness of the crater bottom, the crater bottom could also be resolved in the computation.

Conclusions

MSC/DYTRAN code is a powerful numerical tool for solving oblique impact problems even on smaller computer systems.
It is cost efficient and yields good results.

6 . References

[1] U. Steffens, R. Rittel, H. Lenselink, K. Florie;
"Application of a three-dimensional Gasdynamic Simulation Model to Interior Ballistics". 11th International Symposium on Ballistics, Brussels, May 1989.

[2] C.J.L. Florie, H. Lenselink, A. Buijk;
PISCES-3DELK Theory Manual.

[3] J. Hallquist;
Theoretical Manual for DYNA3D.

[4] S.L. Hancock;
PISCES-2DELK Theory Manual.

[5] J. Falcovitz, M. Mayseless, Z. Tauber, D. Keck, R. Kennedy, K. Ofstedahl and P. Singh;
"A computer Model for Oblique Impact of a Rigid Projectile at Ductile Layered Targets". 11th International Symposium on Ballistics, Brussels, May 1989.

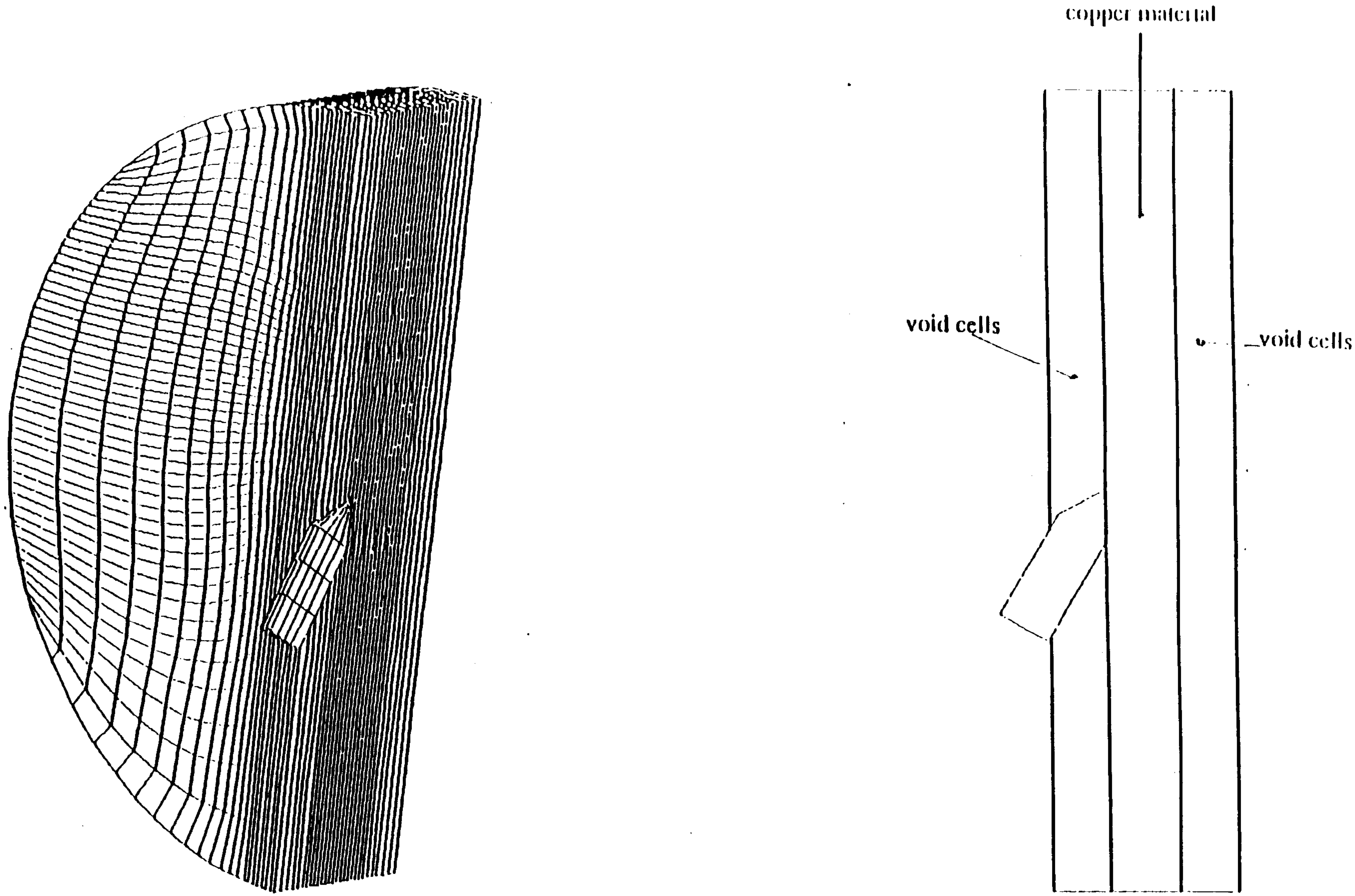

Figure 4 : Numerical model used in the calculations and the position of the copper material in the Euler mesh

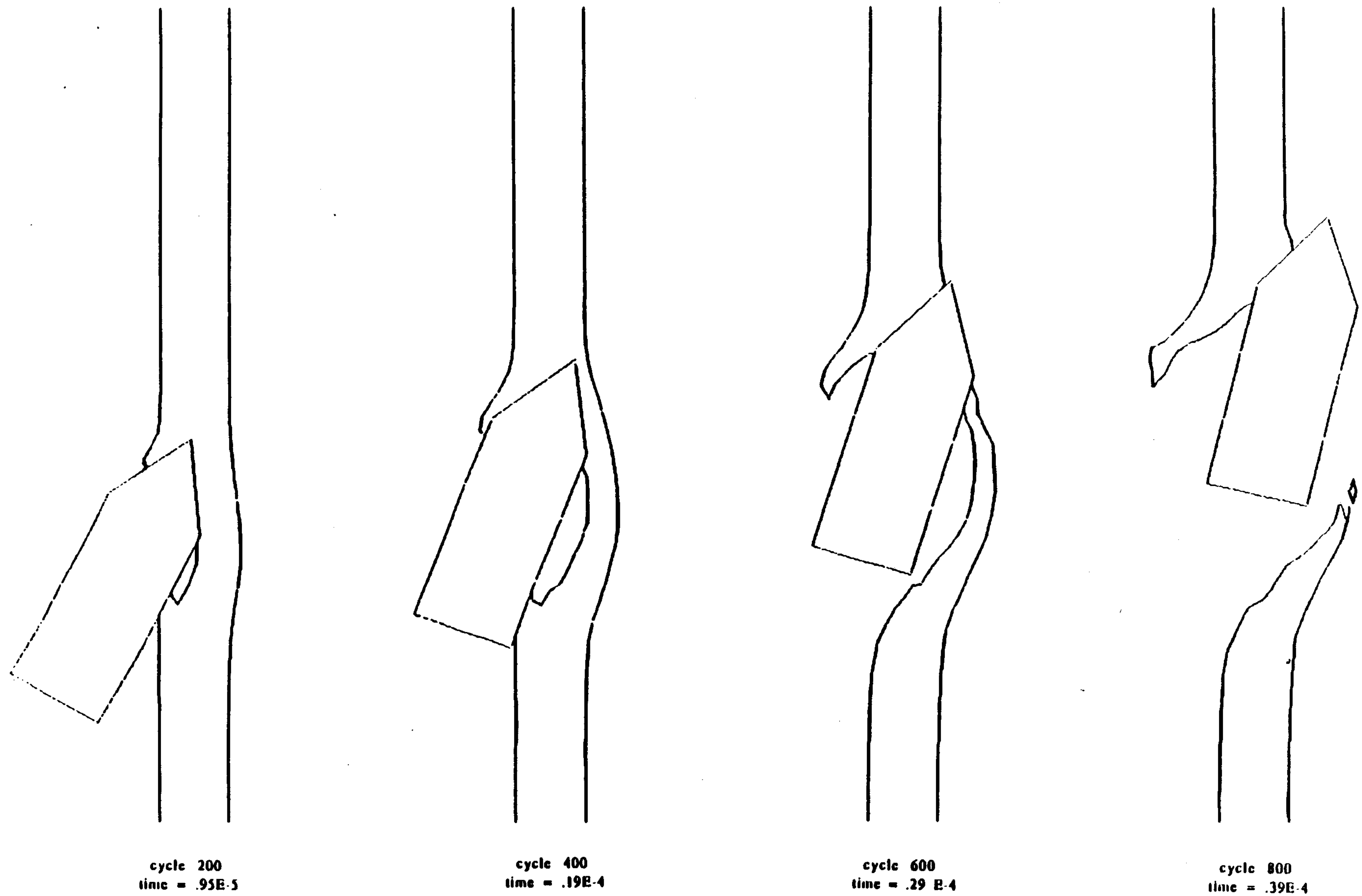

Figure 5 : Material contourplots in the symmetry plane for the thin plate at different times.

Effective stress contour levels in N/m2

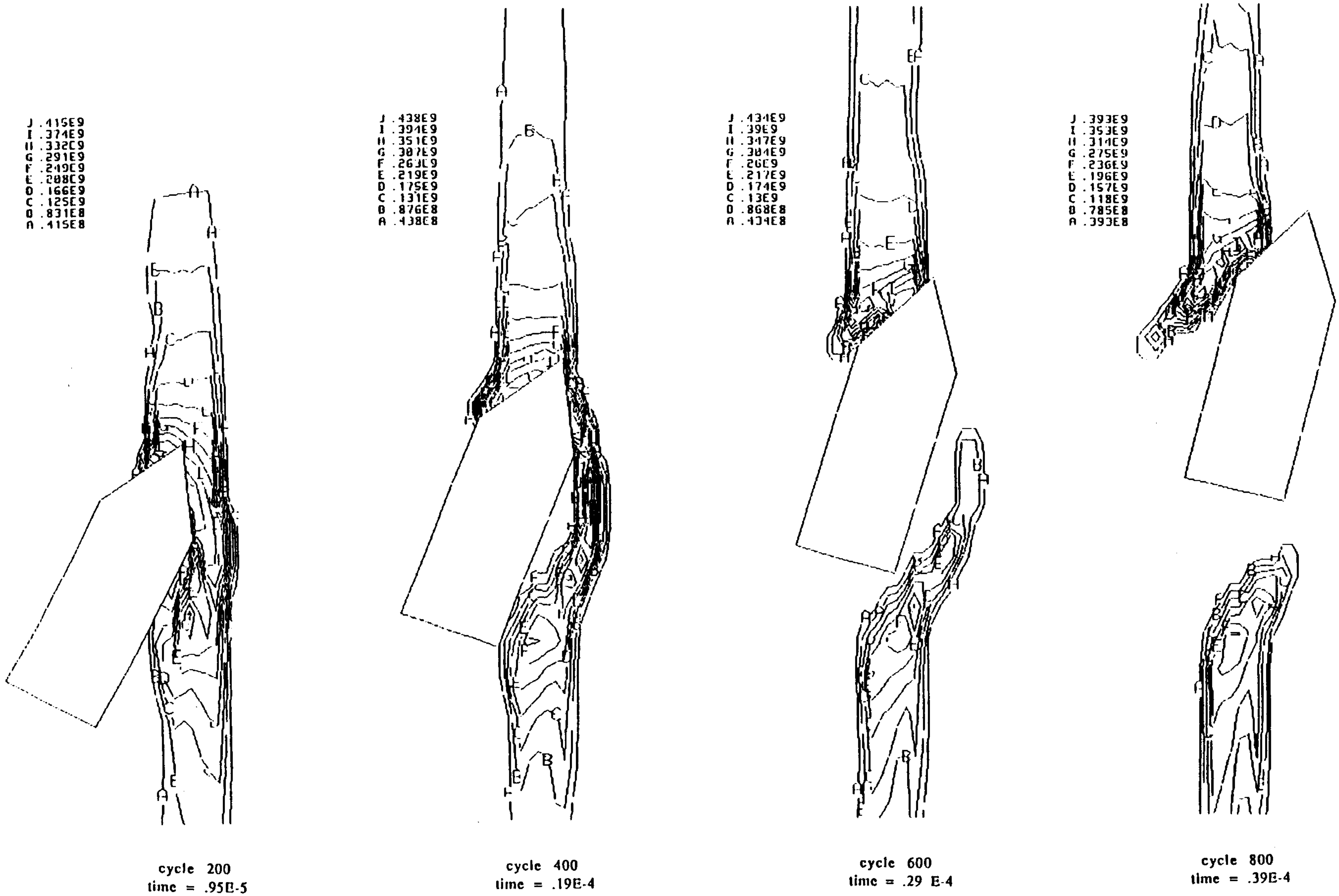

Figure 6 : Effective stress contourplots in the symmetry plane for the thin plate at different times.

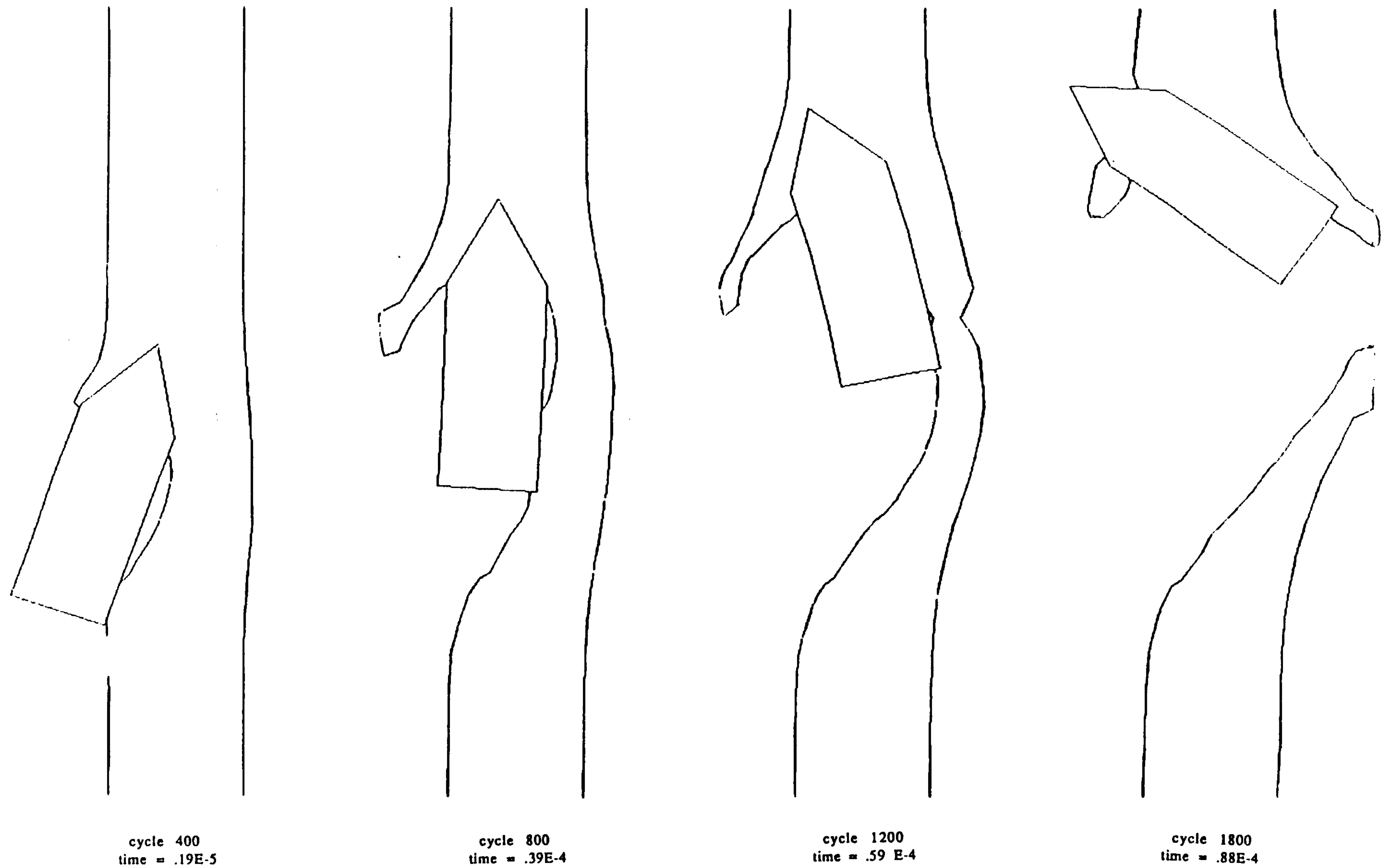

Figure 7 : Material contourplots in the symmetry plane for the thick plate at different times.

Effective stress contour level in N/m2

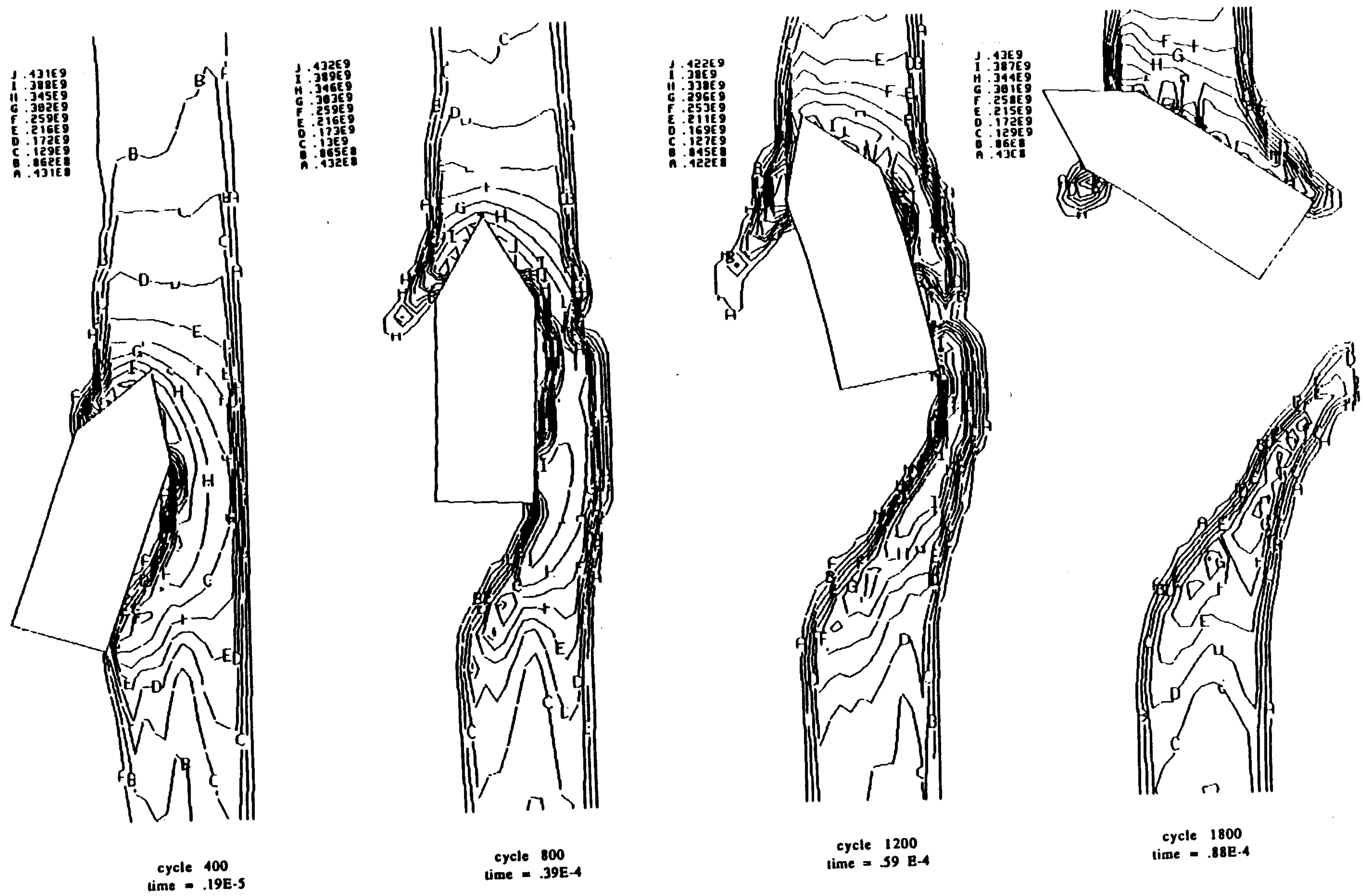

Figure 8 : Effective stress contourplots in the symmetry plane for the thick plate at different times

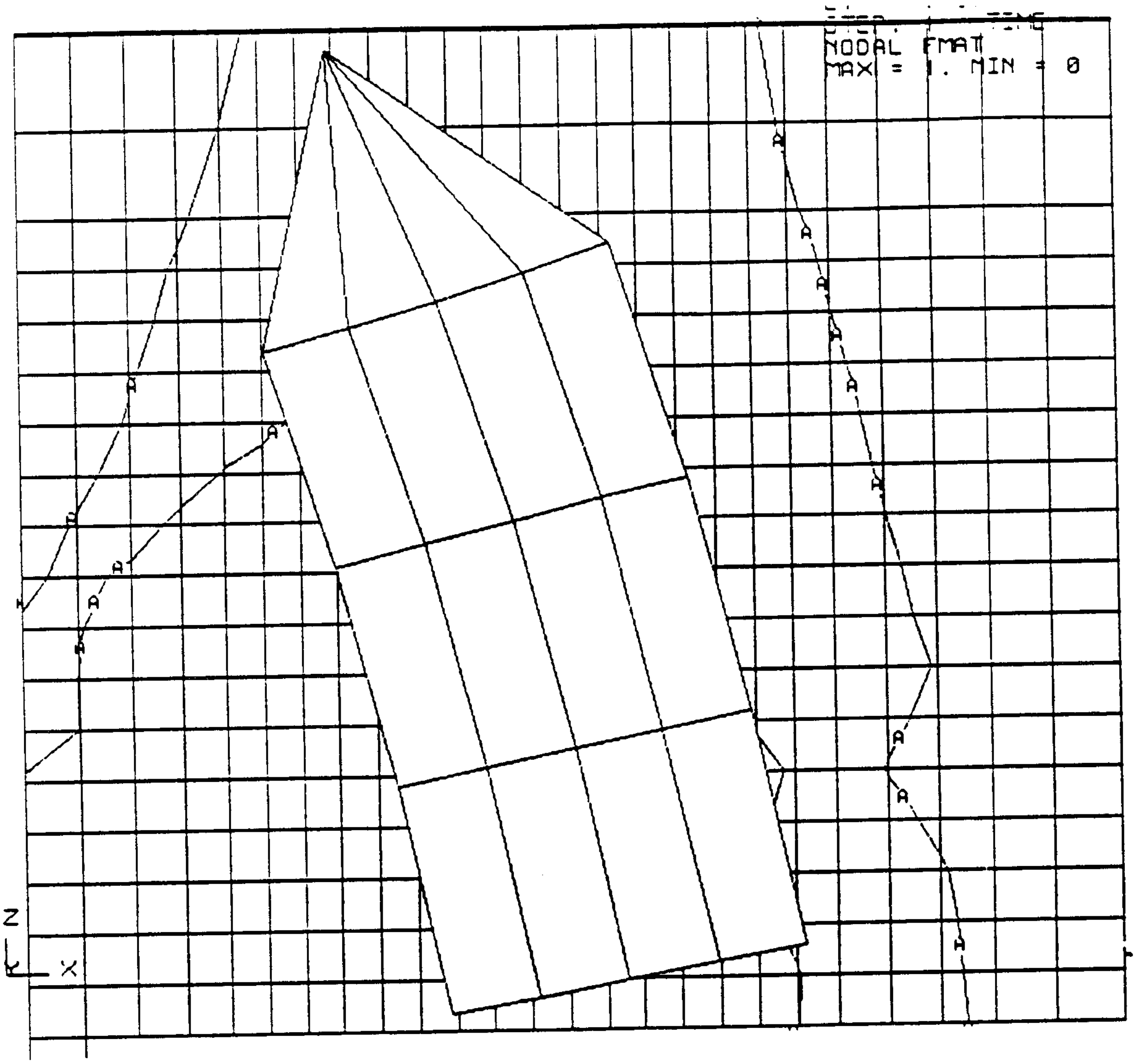

Figure 9: The Eulerian mesh at the location where the material starts to fail