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USER'S MANUAL FOR DYNA2D -- AN EXPLICIT TWO-DIMENSIONAL HYDRODYNAMIC FINITE-ELEMENT CODE WITH INTERACTIVE REZONING

John O. Hallquist

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Lawrence
Livermore
Laboratory

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USER'S MANUAL FOR DYNA2D -- AN EXPLICIT TWO-DIMENSIONAL HYDRODYNAMIC FINITE ELEMENT CODE WITH INTERACTIVE REZONING

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USER'S MANUAL FOR DYNA2D -- AN EXPLICIT TWO-DIMENSIONAL HYDRODYNAMIC FINITE ELEMENT CODE WITH INTERACTIVE REZONING

ABSTRACT

This revised report provides an updated user's manual for DYNA2D, an explicit two-dimensional axisymmetric and plane strain finite element code for analyzing the large deformation dynamic and hydrodynamic response of inelastic solids. A contact-impact algorithm permits gaps and sliding along material interfaces. By a specialization of this algorithm, such interfaces can be rigidly tied to admit variable zoning without the need of transition regions. Spatial discretization is achieved by the use of 4-node solid elements, and the equations-of-motion are integrated by the central difference method. An interactive rezoner eliminates the need to terminate the calculation when the mesh becomes too distorted. Rather, the mesh can be rezoned and the calculation continued. The command structure for the rezoner is described and illustrated by an example.

BACKGROUND

DYNA2D [1] was developed over five years ago and has since been applied in the analysis of a large number of problems. Originally, DYNA2D had a variety of elements including nine node Lagrange elements, constant pressure variable node elements with four integration points and constant stress quadrilaterals with single points integration. Three solution schemes were available:

- Finite element (Galerkin).
- Finite element (Petrov-Galerkin).
- Finite difference [2].

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*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-Eng-48.

The first scheme which included the variable node elements was eliminated because the radial weighting in axisymmetry caused centerline difficulties in large deformation, hydrodynamic calculations. Furthermore, variable node elements proved to be very expensive relative to the constant stress four node elements and, consequently, were seldom exercised. The finite difference scheme was eliminated since the second method gave comparable results with a smaller storage requirement.

Early in the development of DYNA2D, the author, reinforced by conversations with Goudreau [3] and our experiences with the finite difference method, decided to attempt a solution to the axisymmetric axis problems of the Galerkin finite element method by weighting the momentum equations in the discretization by the product of the basis functions and the reciprocal of the radius, r^{-1}. The attempt worked so well, the resulting scheme remains as the sole option in DYNA2D. We referred to the method as "area Galerkin" since it eliminated the radial weighting. Later conversations with Hughes [4] lead us to call the method by its proper name, Petrov-Galerkin. Although a time dependent mass vector is obtained, this has proven to be a very small penalty. The method is identical to the finite difference method [2] in plane strain, but in axisymmetric problems, the method is the same only if material strength is neglected.

In the sections that follow, some of the aspects of the current version of DYNA2D are briefly discussed.

Code Documentation

Presently, no formal (or informal) documentation exists for DYNA2D; however, many of the references cited in this report would be very helpful to those wanting more insight into the techniques employed.

Spatial Discretization

The elements shown in Fig. 1 are available. One element centered stress state is stored for each element in addition to any material parameters. An hourglass viscosity is used to control the zero energy modes.

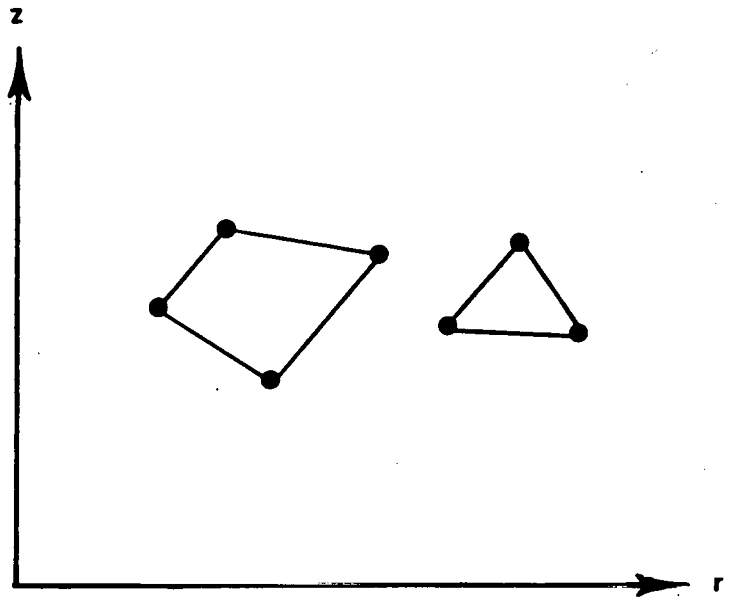

Fig. 1. Solid elements available in DYNA2D.

Material Models

The material models presently implemented are:

- elastic,
- orthotropic elastic,
- kinematic/isotropic elastic-plastic [5],
- thermo-elastic-plastic [6],
- soil and crushable foam [7],
- linear viscoelastic [7],
- rubber [7],
- isotropic elastic-plastic,
- temperature dependent elastic-plastic [8].

The latter two models determine only the deviatoric stresses. Pressure is determined by one of nine equations of state including:

- linear polynomial,
- JWL high explosive,
- Sack "Tuesday" high explosive [9],
- Gruneisen,
- ratio of polynomials
- linear polynomial with energy deposition,
- ignition and growth of reaction in HE [10,11],
- tabulated compaction,
- tabulated.

The soil and crushable foam, the linear viscoelastic, and the rubber subroutines were adapted from HONDO and recoded for vectorization; the ignition and growth EOS was adapted from KOVEC [12]; the other subroutines, programmed by the author, are based in part on the cited references and are nearly 100 percent vectorized. The forms of the first five equations of state are given in the KOVEC user's manual and are retained in the this mannual.

With the exception of the orthotropic elastic and the rubber material subroutines, a Jaumann stress rate formulation is used; these latter two use Green-St. Venant strains to compute second Piola-Kirchoff stresses, which are then subsequently transformed to Cauchy stresses.

DYNA2D is organized to accept new material models and equations of state of any complexity. The organization permits different material and EOS types to have unique storage requirements. All history variables except the stress tensor and the effective plastic strain are packed in a one-dimensional storage vector to ensure that no space is wasted.

HE Burns

Two burn models are presently available. One is the beta burn model used by KOVEC, and the other is the programmed burn model used by HEMP [13]. Both models permit detonations from points and lines.

Artificial Viscosities

The linear-quadratic bulk viscosity is used to smear shock fronts over several elements and to damp numerical oscillations. Two such formulations are implemented

- standard DYNA2D,
- Richards-Wilkins [14,15].

The former differs from the latter in that the strain rate and characteristic length used in the viscosity calculation are the volumetric strain rate and the square root of the area, respectively. In the latter formulation directional properties of the shock wave are considered. For most engineering problems, the less expensive standard DYNA2D formulation is usually sufficient. When DYNA2D is applied to problems where element aspect ratios are poor, the Richards-Wilkins algorithm tends to provide a more stable solution and is recommended.

Three viscosities are available for resisting zero energy deformation modes in constant stress elements. These are the

- standard DYNA2D [3],
- rotational [16,13],
- Flanagan-Belytechko [17].

Hourglass viscosity should always be used to prevent instabilities. All three formulations work well although one sometimes is better than another on a problem by problem basis. The standard DYNA2D formulation is very inexpensive and can be recommended for most problems.

Gravity

In soil-structure interaction problems, gravity effects may be significant. Element pressures can be initialized by DYNA2D. In the soil and crushable foam material subroutine, the volumetric strain is initialized as well. Care is taken to insure that an equilibrium state exists at time zero so that no oscillations are caused by the nonzero initial stress state. This option has not been used recently and may not work properly.

Loading Functions

A variety of loading functions may be used including:

- geometry-dependent pressure loadings,
- geometry-dependent shear loadings,
- body force loads due to spinning,
- body force loads due to base accelerations,
- concentrated nodal loads,
- follower forces,
- nodal velocity-time histories.

An unlimited number of time histories may be defined and may be referenced by any loading function.

Slide-Lines

Three slide-line options are available.

- sliding only [18],
- tied [19],
- sliding with voids (no tension interface) [18].

All slide-line types admit arbitrary zoning along interfaces, and, with the exception of the first two options, gaps may exist in the initial configuration. Slide-lines are permitted to intersect. When voids close, momentum is conserved. It should be noted that the current slide-line references are not up-to-date.

Rezoning

A rezoner has been embedded in DYNA2D. All element and nodal variables are remapped to a new mesh generated interactively. Internal energy, kinetic energy, r-momentum, z-momentum, and mass are computed and printed for each material before and after rezoning to enable the user to determine if the rezoned mesh is acceptable. A simple example is provided in the input section, but perhaps the best way to learn to use the rezoner is by experimentation.

Capacity

Presently, the capacity of DYNA2D is limited to approximately 5000 elements on the CDC 7600 and 30000-40000 elements on Cray-1. Storage allocation is dynamic so that the only limit that exists on the number of boundary condition cards, number of material cards, number of pressure cards, etc., is the capacity of the computer.

Code Organization

DYNA2D consist of one source that compiles under CFT [20] and FTN [21] on the Cray-1 and CDC 7600 computers, respectively. The programming is in FORTRAN IV. DYNA2D has seven overlays in addition to the main code. They are: They are:

- Input.
- Restart.
- Initialization.
- Finite element method.
- Rezoning initialization.
- Rezoning mesh redefinition.
- Rezoning remap.

All data are stored in core during execution.

Sense Switch Controls

DYNA2D has four teletypewriter sense switch controls that are tabulated below:

Type	Response
SW1.	A retart file is written and DYNA2D terminates.
SW2.	DYNA2D responds with time and cycle numbers.
SW3.	A restart file is written and DYNA2D continues.
SW4.	Plot state is dumped.

When DYNA2D terminates, all scratch files are destroyed. The restart file, plot files, and high-speed printer files remain on disk. Of these, only the restart file is needed to continue the interrupted analysis.

Execution

DYNA2D is a public file on the CDC 7600 and CRAY-1 computers at LLNL.

The teletypewriter execution line for DYNA2D is as follows:

```
DYNA2D I=inf O=otf G=ptf D=dpf T=tpf F=thf C=cfr
```

where

inf = input file,
otf = high speed printer file,
ptf = binary plot file for graphics,
dpf = dump file for restarting,
tpf = temperature file (TACO2D plotfile),
thf = binary plot file containing time histories of a selected number of nodes and elements,
cfr = command file for periodic noninteractive rezoning.

File names must not exceed six characters. If the time history file (**thf**) is not specified, time history data is written into the high speed printer file.

When restarting from a dump file, the execution line becomes

```
DYNA2D I=inf O=otf G=ptf D=dpf R=rtf
```

where

rtf = restart file.

When restarting from a dump file with the intent of rezoning, the execution line becomes

```
DYNA2D Z=REZONE I=inf O=otf G=ptf D=dpf R=rtf F=thf T=tpf
```

File name dropouts are permitted, for example

```
DYNA2D I=inf
DYNA2D R=rtf
DYNA2D Z=REZONE R=rtf
```

Default names for the output file, binary plot files, and the dump file are DYNOUT, PPDYNA, and DUMPFL, respectively.

Execution Speeds

The execution speeds of DYNA2D's various options are tabulated below in CPU minutes per million mesh cycles.

Machine	CPU Minutes/10^6 Mesh Cycles
CDC 7600	3.00 finite element method
Cray-1	0.30-0.50 finite element method

These timings do not account for the inclusion of sliding interfaces. Presently, the sliding interface logic is not vectorized.

Automated Input Generation

Complete input files for DYNA2D are generated by MAZE [22]. MAZE input is totally format free and can be inputted interactively, with a command file, or both. MAZE writes an input file in accordance with this user's manual.

Post-Processing

Post-processors, THOR, [23] and ORION [24] are available. These programs read the binary plot files that DYNA2D generates, and plot contours, time histories, and deformed shapes. Contours of nearly 100 different quantities may be plotted on meshes consisting of triangular and quadrilateral elements. They can compute a variety of strain measures, momentum by material, reaction forces along constrained boundaries, and interface pressures along sliding interfaces. ORION is fully interactive and will eventually replace THOR.

1. Title Card

Columns	Quantity	Format
1-72	Heading to appear on output	12A6

2. Control Cards

Card 1

Columns	Quantity	Format
1-2	Input form EQ."ND": input follows this manual EQ."OD"; input follows 1980 manual	A2
3-5	Number of materials (NUMMAT)	I3
6-10	Number of nodal points	I5
11-15	Number of elements	I5
16-20	Number of nodal printout blocks	I5
21-25	Number of element printout blocks	I5
26-30	Number of load curves	I5
31-35	Number of concentrated nodal loads and follower forces	I5
36-45	Time to begin periodic noninteractive rezoning	E10.0
46-55	Time to end periodic rezoning	E10.0
56-65	Time interval between rezoning	E10.0
66-75	Scale factor for computed time step size, SFCT (DEFAULT = .67)	E10.0

Parameters in columns 36-65 apply only if an input file is defined (C=cfr) on the execute line.

Card 2

Columns	Quantity	Format
1-5	Number of element sides having either pressure or shear loadings applied	I5
6-10	Number of velocity boundary condition cards	I5
11-15	Base acceleration in r-direction (see Fig. 2) EQ.0: no r-acceleration EQ.1: r-acceleration	I5

Columns	Quantity	Format
16-20	Base acceleration in z-direction EQ.0: no z-acceleration EQ.1: z-acceleration	I5
21-25	Angular velocity about z-axis EQ.0: no angular velocity EQ.1: angular velocity	I5
26-30	Initial condition parameter EQ.0: initialize velocities to zero EQ.1: initial velocities are read in	I5
31-35	Number of stonewalls	I5
36-40	Number of slide-lines	I5
41-45	Number of slide-lines intersections, NUMSI	I5
46-50	Analysis type EQ. 0: axisymmetric EQ. 1: plane strain	I5
51-55	Number of points in density vs. z-coordinate curve, NUMDZ EQ.0: initial stress due to gravational loads not considered	I5
56-65	Reduction factor, RF, to determine minimum permissible time step (<1.0) NE.0.0: calculation terminates when $DT \leq RF * DT_i$ where DT_i equals the initial time-step size	E10.0

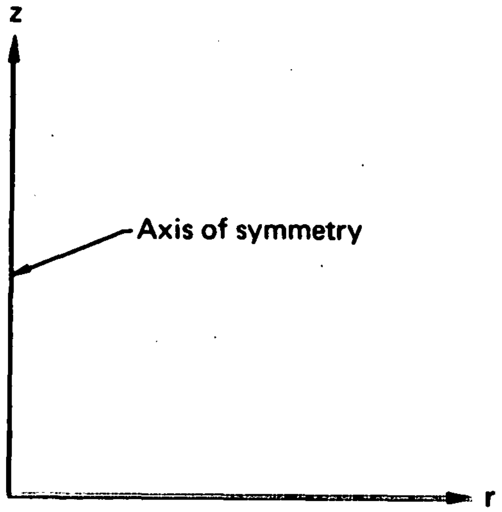

Fig. 2. Coordinate system with axis of symmetry about z-axis.

Card 3

Columns	Quantity	Format
1-10	Termination time	E10.0
11-20	Time interval between high-speed printouts	E10.0
21-30	Time interval between dumps of plot data	E10.0
31-40	Initial time-step size	E10.0

EQ.0.0: an initial time-step size is computed

Columns	Quantity	Format
41-45	HE burn option, IHE EQ.0: beta burn EQ.1: programmed burn - elements that are lit at time zero are flagged in the element data EQ.2: programmed burn - lighting is defined in Section 6 EQ.3: volume burn-lighting times are given on element cards	I5
46-50	Number of time steps between restart dumps EQ.0: restart dump is written when normal termination occurs	I5
51-55	Thermal effects option EQ.0: no thermal effects EQ.n: temperature-time history is defined by load curve n LT.0: nodal temperatures are defined in TACO2D generated disk files	I5
56-60	Dump option for internal energy EQ.0: internal energy is not written into data base EQ.1: internal energy is written into data base	I5
61-65	Special dump option	I5
66-70	Reset default viscosities, IRQ EQ.1: new defaults are read on next card	I5
71-75	Number of elements for momentum deposition	I5

Card 4 (define if IRQ=1)

Columns	Quantity	Format
1-5	Hourglass viscosity type, IHQ EQ.0: default set to "1" EQ.1: standard DYNA2D EQ.2: rotational EQ.3: Flanagan-Belytschko	I5
6-15	Hourglass viscosity coefficient, QH (default = .1) IHQ.EQ.1: $QH \le .15$ IHQ.EQ.2: $QH \le .20$ IHQ.EQ.3: $QH \le .40$	E10.0
16-20	Bulk viscosity type, IBQ EQ.0: default set to "1" EQ.1: standard DYNA2D EQ.2: Richards-Wilkins	I5
21-30	Quadratic viscosity coefficients, Q1 (default = 1.5)	E10.0
31-40	Linear viscosity coefficient, Q2 (default = .06)	E10.0

These are defaults that can, if desired, be overridden for each material defined below.

3. Material Cards

Repeat the following cards for each material model:

Card 1

Columns	Quantity	Format
1-5	Material indentification numer ($\leq$ NUMMAT)	I5
6-10	Material type, MT	I5

EQ. 1: elastic
EQ. 2: orthotropic elastic
EQ. 3: kinematic/isotropic elastic-plastic
EQ. 4: thermo-elastic-plastic
EQ. 5: soil and crushable foam
EQ. 6: linear viscoelastic
EQ. 7: rubber
EQ. 8: high explosive burn
EQ. 9: null material
EQ.10: elastic-plastic hydrodynamic
EQ.11: temperature dependent elastic-plastic

Columns	Quantity	Format
11-20	Density	E10.0
21-25	Equation-of-state type. Define if MT > 7	

EQ.1: linear polynomial
EQ.2: JWL high explosive
EQ.3: Sack "Tuesday" high explosive
EQ.4: Gruneisen
EQ.5: ratio of polynomials
EQ.6: linear polynomial with energy deposition
EQ.7: ignition and growth of reaction in HE
EQ.8: tabulated compaction
EQ.9: tabulated

If not defined, the following quanitities are set to their default values.

Columns	Quantity	Format
26-30	Hourglass viscosity type, IHQ	I5
	EQ.1: standard DYNA2D EQ.2: rotational EQ.3: Flanagan-Belytschko	
31-40	Hourglass viscosity coefficient	E10.0
41-45	Bulk viscosity type, IBQ	I5
	EQ.1: standard DYNA2D EQ.2: Richards-Wilkins	
46-55	Quadratic viscosity coefficient, Q1	
56-65	Linear viscosity coefficient, Q2	

Card 2

Columns	Quantity	Format
1-72	Material identification	12A6

Cards 3,4,5,...,8

Material Type 1 (Elastic) Material

Columns	Quantity		Format
1-10	Card 3	Young's modulus	E10.0
1-10	Card 4	Poisson's ratio	E10.0
1-10	Card 5	Blank	
1-10	Card 6	Blank	
1-10	Card 7	Blank	
1-10	Card 8	Blank	

Material Type 2 (Orthotropic Elastic)

Columns	Quantity		Format
1-10	Card 3	E_a (see Fig. 3)	E10.0
11-20		E_b	E10.0
21-30		E_c	E10.0
1-10	Card 4	ν_{ab}	E10.0
11-20		ν_{ac}	E10.0
21-30		ν_{bc}	E10.0
1-10	Card 5	G_{ab}	E10.0
1-10	Card 6	Material axes option, AOPT	E10.0
		EQ.0.0: locally orthotropic with material axes determined by ψ specified on each element card and element nodes n_1 and n_2 (see Fig. 3) EQ.1.0: locally orthotropic with material axes determined by a point in space and global location of element center EQ.2.0: globally orthotropic with material axes determined by ψ_G	
1-10	Card 7	y_p, define for AOPT = 1.0	E10.0
11-20		z_p, define for AOPT = 1.0	E10.0
1-10	Card 8	ψ_G in radians, define for AOPT = 2.0	E10.0

The material law that relates stresses to strains is defined as:

$$\underset{\sim}{C} = \underset{\sim}{T}_t \, \underset{\sim}{C}_L \underset{\sim}{T} \, ,$$

where $\underset{\sim}{T}$ is a tranformation matrix, and $\underset{\sim}{C}_L$ is the constitutive matrix defined in terms of the material constants of the orthogonal material axes, a and b:

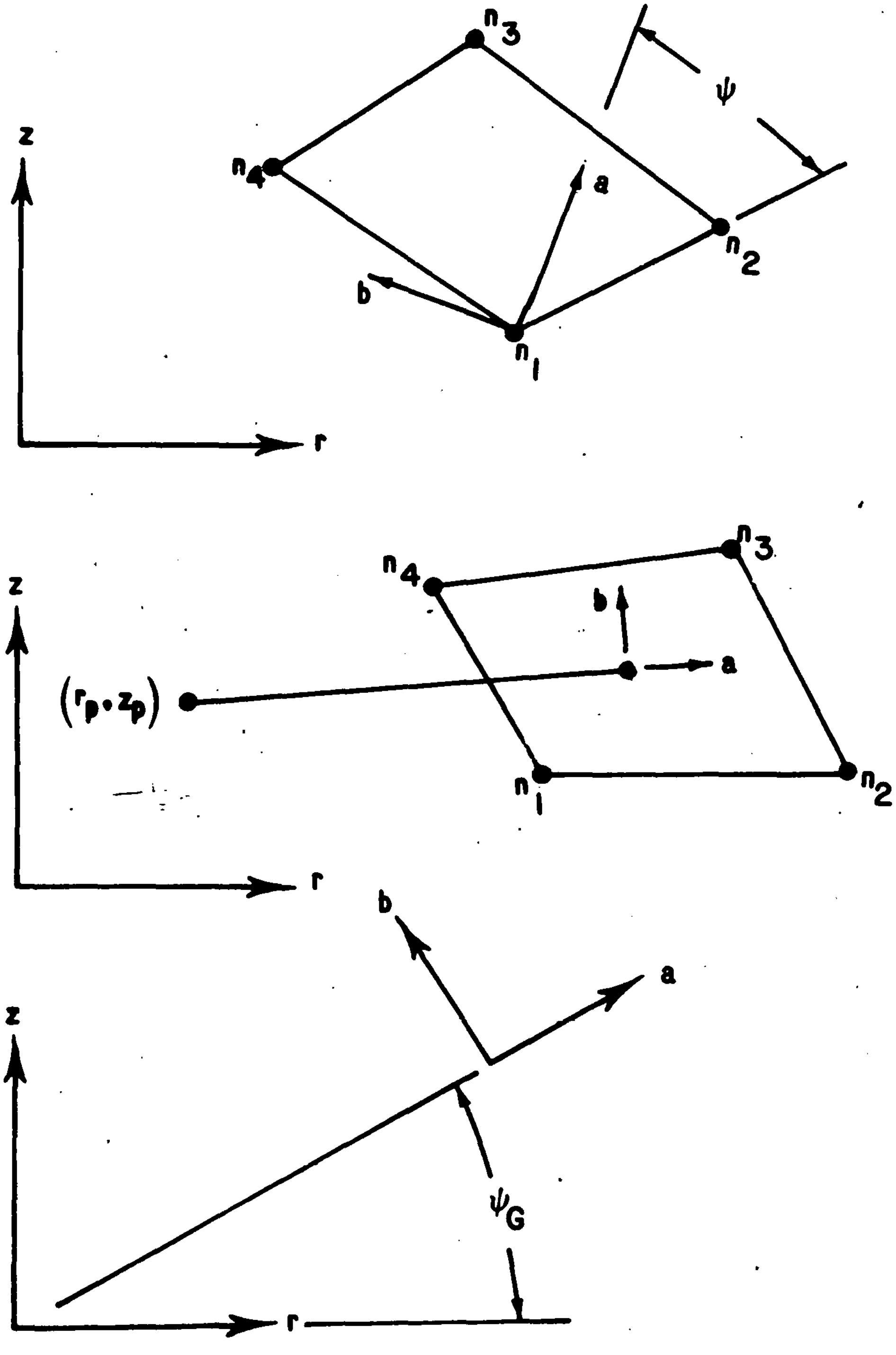

Fig. 3. Options for determining principal material axes:
AOPT = 0.0, (b) AOPT = 1.0, and (c) AOPT = 2.0.

$$\underset{\sim}{C}_L^{-1} = \begin{bmatrix} \frac{1}{E_a} & -\frac{\nu_{ab}}{E_b} & -\frac{\nu_{ac}}{E_c} & 0 \\ -\frac{\nu_{ba}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{bc}}{E_c} & 0 \\ -\frac{\nu_{ca}}{E_a} & -\frac{\nu_{cb}}{E_b} & \frac{1}{E_c} & 0 \\ 0 & 0 & 0 & \frac{1}{G_{ab}} \end{bmatrix}.$$

Note that $\nu_{ba}/E_a = \nu_{ab}/E_b$, $\nu_{ac}/E_c = \nu_{ca}/E_a$, and $\nu_{bc}/E_c = \nu_{cb}/E_b$.

Material Type 3 (Kinematic/Isotropic Elastic-Plastic)

Columns	Quantity		Format
1-10	Card 3	Young's modulus	E10.0
1-10	Card 4	Poisson's ratio	E10.0
1-10	Card 5	Yield stress	E10.0
1-10	Card 6	Hardening modulus, E_t	E10.0
1-10	Card 7	Hardening parameter, β' $0 < \beta' < 1$	E10.0
	Card 8	Blank	

Isotropic, kinematic, or a combination of isotropic and kinematic hardening may be specified by varying β' and between 1 and 0. For β' equal to 0 and 1, respectively, kinematic and isotropic hardening are obtained as shown in Fig. 4.

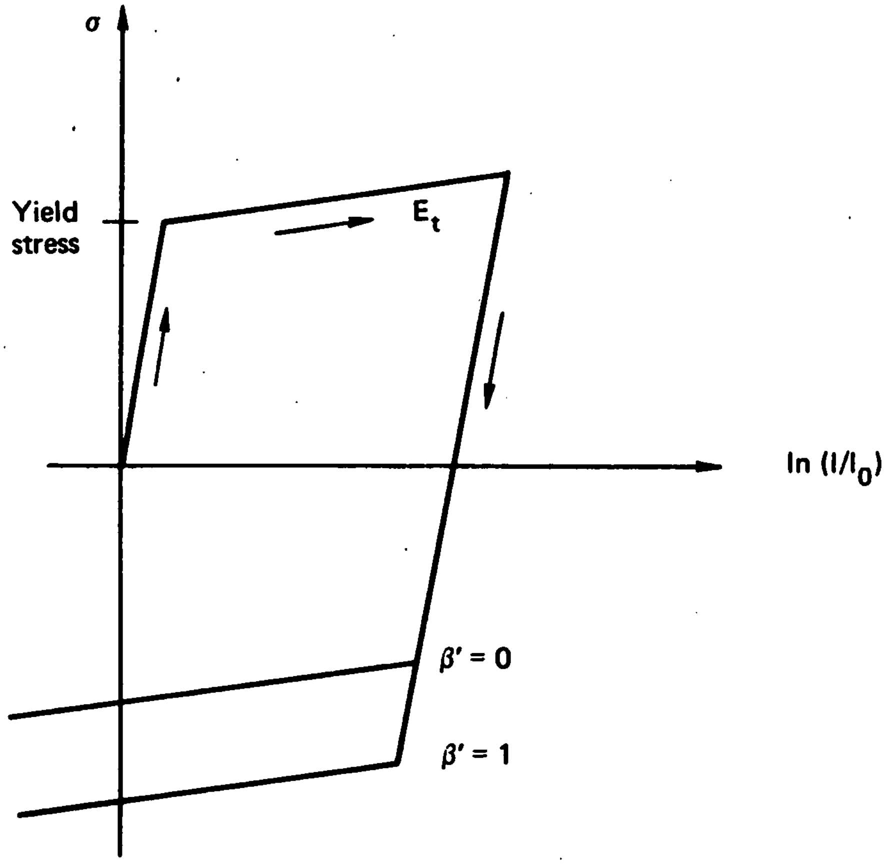

Fig. 4. Elastic-plastic behavior with isotropic and kinematic hardening where l_0 and l are undeformed and deformed lengths of uniaxial tension specimen.

Material Type 4 (Thermo-Elastic-Plastic)

Columns	Quantity		Format
1-10	Card 3	T_1, temperature	E10.0
11-20		T_2	E10.0
.		.	.
.		.	.
.		.	.
71-80		T_8	E10.0
1-10	Card 4	E_1, Young's modulus at T_1	E10.0
11-20		E_2	E10.0
.		.	.
.		.	.
.		.	.
71-80		E_8	E10.0
1-10	Card 5	ν_1, Poisson's ratio at T_1	E10.0
11-20		ν_2	E10.0
.		.	.
.		.	.
.		.	.
71-80		ν_8	E10.0
1-10	Card 6	α_1, coefficient of thermal expansion at T_1	E10.0
11-20		α_2	E10.0
.		.	.
.		.	.
.		.	.
71-80		α_8	E10.0
1-10	Card 7	σ_{y1}, yield stress at T_1	E10.0
11-20		σ_{y2}	E10.0
.		.	.
.		.	.
.		.	.
71-80		σ_{y8}	E10.0

Columns	Quantity		Format
1-10	Card 8	E_1^p, plastic hardening modulus at T_1	E10.0
11-20		E_2^p	E10.0
.		.	.
.		.	.
.		.	.
71-80		E_8^p	E10.0

At least two temperatures and their corresponding material properties must be defined. The analysis will be terminated if a material temperature falls outside the range defined in the input. If a thermoelastic material is considered, leave cards 7 and 8 blank. The coefficient of thermal expansion is defined with respect to a reference temperature.

Material Type 5 (Soil and Crushable Foam)

Columns	Quantity		Format
1-10	Card 3	Shear modulus	E10.0
11-20		Bulk unloading modulus	E10.0
21-30		Yield function constant a_0	E10.0
31-40		Yield function constant a_1	E10.0
41-50		Yield function constant a_2	E10.0
51-60		Pressure cutoff for tensile fracture	E10.0
1-10	Card 4	Volumetric strain (see Fig. 5)	E10.0
11-20		Pressure	E10.0
21-30		Volumetric strain	E10.0
31-40		Pressure	E10.0
1-10	Card 5	Volumetric strain	E10.0
11-20		Pressure	E10.0
21-30		Volumetric strain	E10.0
31-40		Pressure	E10.0
.		.	.
.		.	.
.		.	.
1-10	Card 8	Volumetric strain	E10.0
11-20		Pressure	E10.0
21-30		Volumetric strain	E10.0
31-40		Pressure	E10.0

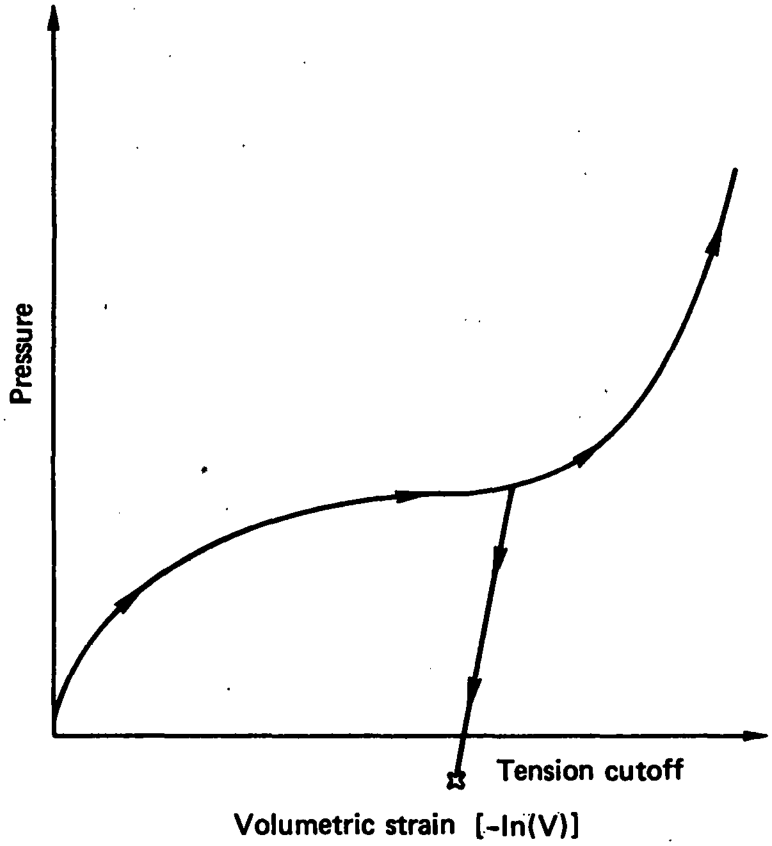

Fig. 5. Volumetric strain vs pressure curve for soil and crushable foam model.

The deviatoric yield function, ϕ, is described in terms of the second invariant J_2,

$$J_2 = \frac{1}{2} s_{ij} s_{ij}$$

pressure, p, and constants a_0, a_1, and a_2 as:

$$\phi = J_2 - \left[a_0 + a_1 p + a_2 p^2\right] .$$

The volumetric strain is given by the natural logarithm of the relative volume, V.

Material Type 6 (Viscoelastic)

Columns		Quantity	Format
1-10	Card 3	Bulk modulus (elastic)	E10.0
1-10	Card 4	Short-time shear modulus, G_0	E10.0
1-10	Card 5	Long-time shear modulus, G_∞	E10.0
1-10	Card 6	Decay constant, β	E10.0
	Card 7		
	Card 8		

The shear relaxation behavior as described by:

$$G(t) = G_\infty + (G_0 - G_\infty)\, e^{-\beta t}$$

Material Type 7 (Rubber)

Columns	Quantity		Format
1-10	Card 3	Shear modulus	E10.0
	Card 4	Blank	
•		•	•
•		•	•
•		•	•
	Card 8	Blank	

Material Type 8 (High Explosive Burn)

Columns	Quantity		Format
1-10	Card 3	D, Detonation velocity	E10.0
11-20		P_{CJ}, Chapman-Jouget pressure	E10.0
	Card 4	Blank	
	•		
	•		
	•		
	Card 8	Blank	

Material Type 9 (Null)

Columns	Quantity		Format
1-10	Card 3	pressure cutoff	E10.0
	Card 4	blank	
	.	.	
	.	.	
	.	.	
	Card 8	blank	

The null material may be used with an equation-of-state. No deviatoric stress is permitted with this material type.

Material Type 10 (Isotropic-Elastic-Plastic-Hydrodynamics)

Columns	Quantity		Format
1-10	Card 3	Shear modulus	E10.0
11-20		Yield strength, σ_0	E10.0
21-20		Plastic hardening modulus, E_h	E10.0
31-40		Pressure cutoff (< 0.0)	
		EQ.0.0: a cutoff of $-\infty$ is assumed	
41-50		Yield function constant, a_1	E10.0
51-60		Yield function constant, a_2	E10.0
	Card 4	Blank	
1-10	Card 5	ε_1, effective plastic strain	E10.0
.		ε_2,	.
.		ε_3	.
.		ε_4	.
41-50		ε_5	.
71-80		ε_8	E10.0
1-10	Card 6	ε_9	E10.0
.		.	.
.		.	.
.		.	.
71-80		ε_{16}	E10.0
1-10	Card 7	σ_1, effective stress	E10.0
.		.	.
.		.	.
.		.	.
41-50		σ_8	E10.0

Columns	Quantity		Format
1-10	Card 8	σ_9	E10.0
.		.	.
.		.	.
.		.	.
31-80		σ_{16}	E10.0

Whenever Cards 5-8 are blank, the yield stress and plastic hardening modulus are taken from Card 3. In this case assuming $a_1 = a_2 = 0$, the bilinear stress-strain curve shown in Fig. 4 is obtained with $\beta = 1$. The yield strength is calculated as

$$\sigma_y = \sigma_0 + E_h \bar{\varepsilon}^p + (a_1 + a_2 p) \max(0,p)$$

where p is the pressure. The quantity E_h is the plastic hardening modulus defined in terms of Young's modulus, E, and the tangent modulus, E_t, as follows

$$E_h = \frac{E_t\ E}{E - E_t}$$

If cards 5-8 are used, a curve like that shown in Fig. 6 may be defined. In this latter case, the yield stress and plastic hardening modulus, a_1 and a_2 on Card 3 are ignored. Effective stress is defined in terms of the deviatoric stress tensor, s_{ij}, as:

$$\bar{\sigma} = (\frac{3}{2} s_{ij}\ s_{ij})^{1/2} \qquad (1)$$

and effective plastic strain by:

$$\bar{\varepsilon}^p = \int_0^t \left(\frac{2}{3} D^p_{ij}\ D^p_{ij}\right)^{1/2} dt\ , \qquad (2)$$

where t denotes time and D_{ij}^{p} is the plastic component of the rate of deformation tensor.

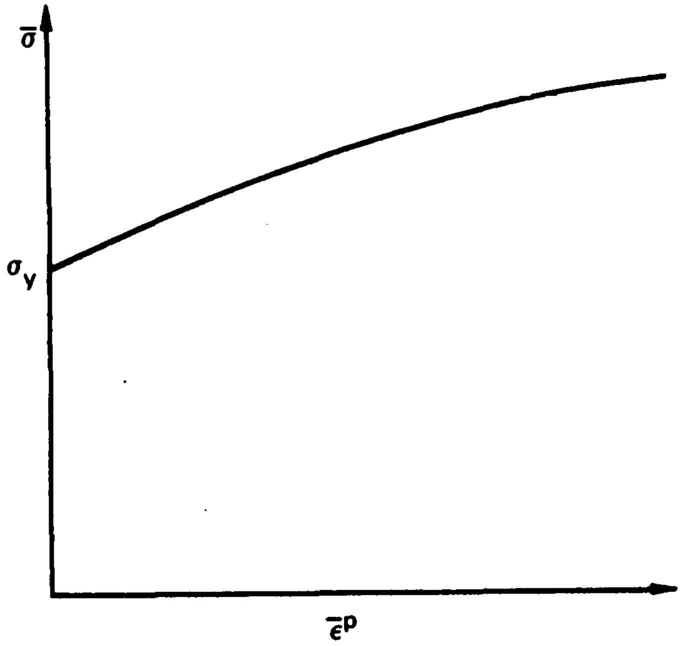

Fig. 6. Effective stress vs effective plastic strain curve.

Material Type 11 (Temperature Dependent, Elastic-Plastic, Hydrodynamic)

Columns	Quantity		Format
1-10	Card 3	G_0	E10.0
11-20		σ_0	E10.0
21-30		β	E10.0
31-40		n	E10.0
41-50		γ_i	E10.0
1-10	Card 4	σ_m	E10.0
11-20		b	E10.0
21-30		b'	E10.0
31-40		h	E10.0
41-50		f	E10.0
1-10	Card 5	A	E10.0
11-20		T_{mo}	E10.0
21-30		γ_0	E10.0
31-40		a	E10.0
41-50		p_{min} or failure stress, σ_f	E10.0
	Card 6	Spall type EQ.0.0: default set to "2.0" EQ.1.0: $p \geq p_{min}$ EQ.2.0: if $\sigma_{max} \geq \sigma_f$ element spalls and tension, $p < 0$, is never allowed EQ.3.0: if $p < p_{min}$ element spalls and tension, $p < 0$, is never allowed	E10.0
1-16	Card 5	EC_0	E16.0
17-32		EC_1	E16.0
33-48		EC_2	E16.0
49-64		EC_3	E16.0
65-80		EC_4	E16.0

Columns	Quantity		Format
1-16	Card 6	EC_5	E16.0
17-32		EC_6	E16.0
33-48		EC_7	E16.0
49-64		EC_8	E16.0
65-80		EC_9	E16.0

Users, who have an interest in this model, are encouraged to study the paper by Steinberg and Guinan which provides the theoretical basis. Another useful reference is the KOVEC user's manual.

In terms of the foregoing input parameters, we define the shear modulus, G, before the material melts as:

$$G = G_0 \left[1 + bpV^{1/3} - h \left(\frac{E_i - E_c}{3R'} - 300 \right) \right] e^{-\frac{fE}{E_m - E_i}}$$

where p is the pressure, V is the relative volume, E_c is the cold compression energy:

$$E_c(x) = \int_0^x pdx - \frac{900\ R'\ \exp(ax)}{(1-x)^{2(\gamma_0 - a - 1/2)}} \quad ,$$

$$x = 1 - V \ ,$$

and E_m is the melting energy:

$$E_m(x) = E_c(x) + 3R'T_m(x)$$

which is in terms of the melting temperature $T_m(x)$:

$$T_m(x) = \frac{T_{mo}\exp(2ax)}{V^{2(\gamma_0 - a - 1/3)}}$$

and the melting temperature at $\rho = \rho_0$, T_{mo}.

In the above equation, R' is defined by

$$R' = R\rho/A$$

where R is the gas constant and A is the atomic weight.

The yield strength σ_y is given by:

$$\sigma_y = \sigma_0' \left[1 + b'pV^{1/3} - h\left(\frac{E_i - E_c}{3R'} - 300 \right) \right] e^{-\frac{fE}{E_m - E_i}}$$

if E_m exceeds E_i. Here, σ_0' is given by:

$$\sigma_0' = \sigma_0\,[1 + \beta(\gamma_i + \varepsilon^{-p})]^n$$

where γ_i is the initial plastic strain. Whenever σ_0' exceeds σ_m, σ_0' is set equal to σ_m. After the material melts, σ_y and G are set to zero.

If the coefficients EC0,...,EC9 are not defined above, DYNA2D will fit the cold compression energy to the ten term polynomial expansion:

$$E_c = \sum_{i=0}^{9} EC_i\,\eta^i$$

where EC_i is the ith coefficient and $\eta = \rho/\rho_0$. The least squares method is used to perform the fit.

Define equation-of-state cards only if MT > 7.

Card 9

Columns	Quantity	Format
1-72	Equation-of-state identification	12A6

Cards 10,...

Equation-of-State Form 1 (Linear Polynomial)

Columns	Quantity	Format
1-10	Card 10 C_ϕ	E10.0
10-20	C_1	E10.0
21-30	C_2	E10.0
31-40	C_3	E10.0
41-50	C_4	E10.0
51-60	C_5	E10.0
61-70	C_6	E10.0
71-80	E_0 initial internal energy	E10.0
1-10	Card 11 V_0, initial relative volume	E10.0

The linear polynomial equation-of-state is linear in internal energy. The pressure is given by:

$$p = C_\phi + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2) E .$$

where terms $C_2\mu^2$ and $C_6\mu^2$ are set to zero if $\mu < 0$, $\mu = \rho/\rho_0 - 1$, and ρ/ρ_0 is the ratio of current density over initial density.

Equation-of-State Form 2 (JWL)

Columns	Quantity		Format
1-10	Card	A	E10.0
11-20		B	E10.0
21-30		R1	E10.0
31-40		R2	E10.0
41-50		ω	E10.0
51-60		E_0, initial internal energy	E10.0
61-70		V_0, initial relative volume	E10.0

The JWL equation-of-state defines the pressure as

$$p = A\left(1 - \frac{\omega}{R_1V}\right)e^{-R_1V} + B\left(1 - \frac{\omega}{R_2V}\right)e^{-R_2V} + \frac{\omega E}{V},$$

and is usually used for detonation products of high explosives.

Equation-of-State Form 3 (Sack)

Columns	Quantity		Format
1-10	Card 10	A_1	E10.0
11-20		A_2	E10.0
21-30		A_3	E10.0
31-40		B_1	E10.0
41-50		B_2	E10.0
51-60		E_0, initial internal energy	E10.0
61-70		V_0, initial relative volume	E10.0

The Sack equation-of-state defines pressure as

$$p = \frac{A_3}{V^{A_1}} e^{-A_2 V} \left(1 - \frac{B_1}{V}\right) + \frac{B_2}{V} E$$

and is used for detonation products of high explosives.

Equation-of-State Form 4 (Gruneisen)

Columns	Quantity	Format
1-10	Card 10 C	E10.0
11-20	S_1	E10.0
21-30	S_2	E10.0
31-40	S_3	E10.0
41-50	γ_0	E10.0
51-60	a	E10.0
61-70	E_0, initial internal energy	E10.0
71-80	V_0, initial relative volume	E10.0

The Gruneisen equation-of-state with cubic shock velocity-particle velocity defines pressure for compressed materials as

$$p = \frac{\rho_0 C^2 \mu[1 + (1 - \frac{\gamma_0}{2}) \mu - \frac{a}{2} \mu^2}{[1 - (S_1-1) \mu - S_2 \frac{\mu^2}{\mu+1} - S_3 \frac{\mu^3}{(\mu+1)^2}]^2} + (\gamma_0 + a\mu)E.$$

and for expanded materials as

$$p = \rho_0 C^2\mu + (\gamma_0 + a\mu)E.$$

where C is the intercept of the u_s-u_p curve; S_1, S_2, and S_3 are the coefficients of the slope of the u_s-u_p curve; γ_0 is the Gruneisen gamma; and a is the first order volume correction to γ_0.

Equation-of-State Form 5 (Ratio of Polynomials)

Columns	Quantity		Format
1-16	Card 10	A10	E16.0
17-32		A11	E16.0
33-48		A12	E16.0
49-64		A13	E16.0
1-16	Card 11	A20	E16.0
17-32		A21	E16.0
33-48		A22	E16.0
49-64		A23	E16.0
1-16	Card 12	A30	E16.0
17-32		A31	E16.0
33-48		A32	E16.0
49-64		A33	E16.0
1-16	Card 13	A40	E16.0
17-32		A41	E16.0
33-48		A42	E16.0
49-64		A43	E16.0
1-16	Card 14	A50	E16.0
17-32		A51	E16.0
33-48		A52	E16.0
49-64		A53	E16.0
1-16	Card 15	A60	E16.0
17-32		A61	E16.0
33-48		A62	E16.0
49-64		A63	E16.0

Columns	Quantity		Format
1-16	Card 16	A70	E16.0
17-32		A71	E16.0
33-48		A72	E16.0
49-64		A73	E16.0
1-16	Card 18	α	E16.0
17-32		β	E16.0
33-48		A14	E16.0
49-64		A24	E16.0
1-16	Card 19	E_0, initial internal energy	E16.0
17-32		V_0, initial relative volume	E16.0

The ratio of polynomials equation-of-state defines the pressure as

$$p = \frac{F_1 + F_2E + F_3E^2 + F_4E^2}{F_5 + F_6E + F_7E^2} (1 + \alpha\mu)$$

where

$$F_i = \sum_{j=0}^{n} A_{ij}\, \mu^j \quad . \qquad \begin{array}{l} n = 4 \text{ if } i < 3 \\ n = 3 \text{ if } i \geq 3 \end{array}$$

$$\mu = \rho/\rho_0 - 1$$

In expanded zones F_1 is replaced by $F_1' = F_1 + \beta\,\mu^2$

Equation-of-State Form 6 (Linear Polynomial with Energy Leak)

Columns	Quantity		Format
1-10	Card 10	C_ϕ	E10.0
10-20		C_1	E10.0
21-30		C_2	E10.0
31-40		C_3	E10.0
41-50		C_4	E10.0
51-60		C_5	E10.0
61-70		C_6	E10.0
71-80		E_0, initial internal energy	E10.0
1-10	Card 11	V_0, initial relative volume	E10.0
11-20		CN, number of time history curve that gives energy deposition rate.	E10.0

Equation-of-State Form 7 (Ignition and Growth of Reaction in HE)

Columns		Quantity	Format
1-10	Card 10	A_p	E10.0
11-20		B_p	E10.0
21-30		$R1_p$	E10.0
31-40		$R2_p$	E10.0
41-50		G, second ignition coefficient	E10.0
1-10	Card 11	$\omega_p c_p$	E10.0
11-20		A_e	E10.0
21-30		B_e	E10.0
31-40		$\omega_e c_e$	E10.0
41-50		$R1_e$	E10.0
1-10	Card 12	$R2_e$	E10.0
11-20		FCRIT, critial fraction reacted (usually=1.0)	E10.0
21-30		I, first ignition coefficient	E10.0
31-40		H, growth coefficient	E10.0
41-50		z, pressure exponent	E10.0
1-10	Card 13	x	E10.0
11-20		y	E10.0
21-30		c_p, heat capacity of reaction products	E10.0
31-40		c_e, heat capacity of unreacted HE	E10.0
1-10	Card 14	m (generally = 0)	E10.0
11-20		E_0, initial energy of HE per unit volume	E10.0
21-30		T_0, initial temperature (^oK)	E10.0
	Card 15	Blank	

A JWL equation-of-state defines the pressure in the unreacted HE as

$$P_e = A_e\left(1 - \frac{\omega_e}{R1_e V_e}\right)e^{-R1_e V_e} + B_e\left(1 - \frac{\omega_e}{R2_e V_e}\right)e^{-R2_e V_e} + \frac{\omega E_e}{V_e}$$

where V_e is the relative volume, E_e is the internal energy, and the constants A_e, B_e, ω_e, $R1_e$, and $R2_e$ are input constants.
Similarily, the pressure in the reaction products is defined by another JWL form

$$P_p = A_p\left(1 - \frac{\omega_p}{R1_p V_p}\right)e^{-R1_p V_p} + B_p\left(1 - \frac{\omega_p}{R2_p V_p}\right)e^{-R2_p V_p} + \frac{\omega E_p}{V_p}$$

The mixture of unreacted explosive and reaction products is defined by the fraction reacted F (F=0 → no reaction, F=1 → complete conversion from explosive to products). The pressures and temperature are assumed to be in equilibrium and the volumes are assumed to be additive.

$$V = (1-F)\ V_e + FV_p$$

The rate of reaction for material type 13 is

$$\frac{\partial F}{\partial t} = I\ (FCRIT-F)^y (V_e^{-1}-1)^3\ \ [1 + G(V_e^{-1}-1)] + H(1-F)^y F^x P^z (V_p^{-1}-1)^m$$

where I, G, H, x, y, z, and m (generally m=0) are input constants.

The JWL equations of state and the reaction rates have been fitted to one- and two-dimensional shock initiation and detonation data for four explosives: PBX-9404, RX-03-BB, PETN, and cast TNT. The details of the calculational method are described by Cochran and Chan [11]. The detailed one-dimensional calculations and parameters for the four explosives are given by Lee and Tarver [10].

Equation-of-State Form 8 (Tabulated-Compaction)

Columns		Quantity	Format
1-16	Card 10	ε_{V1} (ℓn V)	E16.0
17-32		ε_{V2}	E16.0
33-48		ε_{V3}	E16.0
49-64		ε_{V4}	E16.0
65-80		ε_{V5}	E16.0
1-16	Card 11	ε_{V6}	E16.0
17-32		ε_{V7}	E16.0
33-48		ε_{V8}	E16.0
49-64		ε_{V9}	E16.0
65-80		ε_{V10}	E16.0
1-16	Card 12	C_1	E16.0
17-32		C_2	E16.0
33-48		C_3	E16.0
49-64		C_4	E16.0
65-80		C_5	E16.0
1-16	Card 13	C_6	E16.0
17-32		C_7	E16.0
33-48		C_8	E16.0
49-64		C_9	E16.0
65-80		C_{10}	E16.0
1-16	Card 14	T_1	E16.0
17-32		T_2	E16.0
33-48		T_3	E16.0
49-64		T_4	E16.0
65-80		T_5	E16.0

Columns		Quantity	Format
1-16	Card 15	T_6	E16.0
17-32		T_7	E16.0
33-48		T_8	E16.0
49-64		T_9	E16.0
65-80		T_{10}	E16.0
1-16	Card 16	K_1	E16.0
17-32		K_2	E16.0
33-48		K_3	E16.0
49-64		K_4	E16.0
65-80		K_5	E16.0
1-16	Card 17	K_6	E16.0
17-32		K_7	E16.0
33-48		K_8	E16.0
49-64		K_9	E16.0
65-80		K_{10}	E16.0
1-16	Card 18	γ	E16.0
17-32		E_0, initial internal energy	E16.0
33-48		V_0, initial relative volume	E16.0

The tabulated compaction model is linear in internal energy. Pressure is defined by

$$p = C(\varepsilon_V) + \gamma T(\varepsilon_V)E$$

in the loading phase. The volumetric strain, ε_V, is given by the natural logarithm of the relative volume. Unloading occurs along the unloading bulk modulus to the pressure cutoff. Reloading always follows the unloading path to the point where unloading began, and continues on the loading path. See Fig. 7. Up to 10 points and as few as 2 may be used when defining the tabulated functions, DYNA2D will extrapolate to find the pressure if necessary.

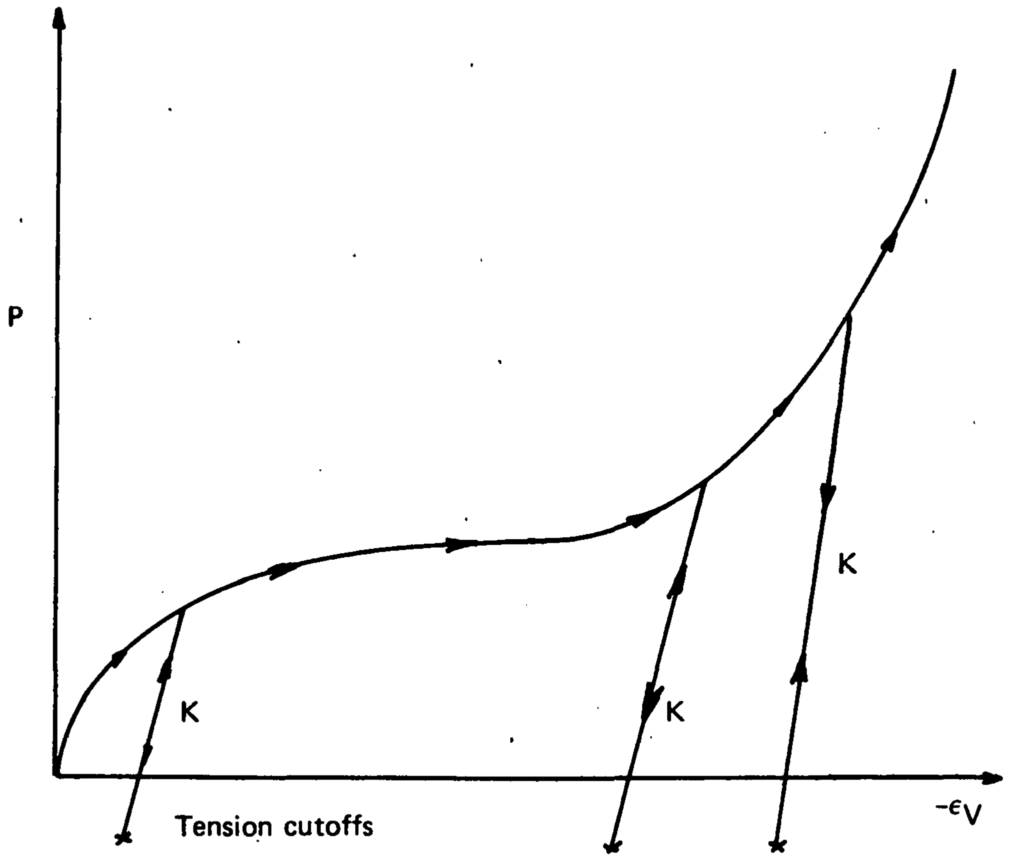

Fig. 7. Pressure versus volumetric strain curve for equation-of-state form 8 with compaction. In the compacted states the bulk unloading modulus depends on the peak volumetric strain.

Equation-of-State Form 9 (Tabulated)

Columns	Quantity		Format
1-16	Card 10	ε_{V1} (ℓn V)	E16.0
17-32		ε_{V2}	E16.0
33-48		ε_{V3}	E16.0
49-64		ε_{V4}	E16.0
65-80		ε_{V5}	E16.0
1-16	Card 11	ε_{V6}	E16.0
17-32		ε_{V7}	E16.0
33-48		ε_{V8}	E16.0
49-64		ε_{V9}	E16.0
65-80		ε_{V10}	E16.0
1-16	Card 12	C_1	E16.0
17-32		C_2	E16.0
33-48		C_3	E16.0
49-64		C_4	E16.0
65-80		C_5	E16.0
1-16	Card 13	C_6	E16.0
17-32		C_7	E16.0
33-48		C_8	E16.0
49-64		C_9	E16.0
65-80		C_{10}	E16.0
1-16	Card 14	T_1	E16.0
17-32		T_2	E16.0
33-48		T_3	E16.0
49-64		T_4	E16.0
65-80		T_5	E16.0

Columns	Quantity		Format
1-16	Card 15	T_6	E16.0
17-32		T_7	E16.0
33-48		T_8	E16.0
49-64		T_9	E16.0
65-80		T_{10}	E16.0
1-16	Card 16	γ	E16.0
17-32		E_0	E16.0
33-48		V_0	E16.0

The tabulated equation-of-state model is linear in internal energy. Pressure is defined by

$$P = C(\varepsilon_V) + \gamma \; T(\varepsilon_V)E$$

The volumetric strain, ε_V, is given by the natural logarithm of the relative volume. Up to 10 points and as few as 2 may be used when defining the tabulated functions. DYNA2D will extrapolate to find the pressure if necessary.

4. Nodal Point Cards

Supply one card for each nodal point with the following information:

Columns	Quantity	Format
1-5	Nodal point number, n^i	I5
6-10	Boundary condition code, BCC^i EQ.0.0: no constraint EQ.1.0: r-constraint EQ.2.0: z-constraint EQ.3.0: r and z constraints If BCC^i is not any of the above, it is assumed to be the angle in degrees between the positive r-axis and the direction of the motion along a sliding boundary (see Fig. 8)	F5.0
11-20	r^i - global coordinate	E10.0
21-30	z^i - global coordinate	E10.0
31-35	Generation interval KN EQ.0: default set to "1"	I5

Nodal point cards do not need to be in order; however, the highest nodal point number must terminate the nodal data. When nodal data are missing, node numbers are generated according to the sequence:

$$n^i, n^i + KN, n^i + 2KN, \ldots, n^j ,$$

where n^i and n^j are the nodal numbers defined on two consecutive cards, and KN is taken from the first card. Linear interpolation is used to obtain the coordinates of the generated nodes. The boundary conditions code of generated data is set to zero whenever BCCi ≠ BCCj; otherwise, the code

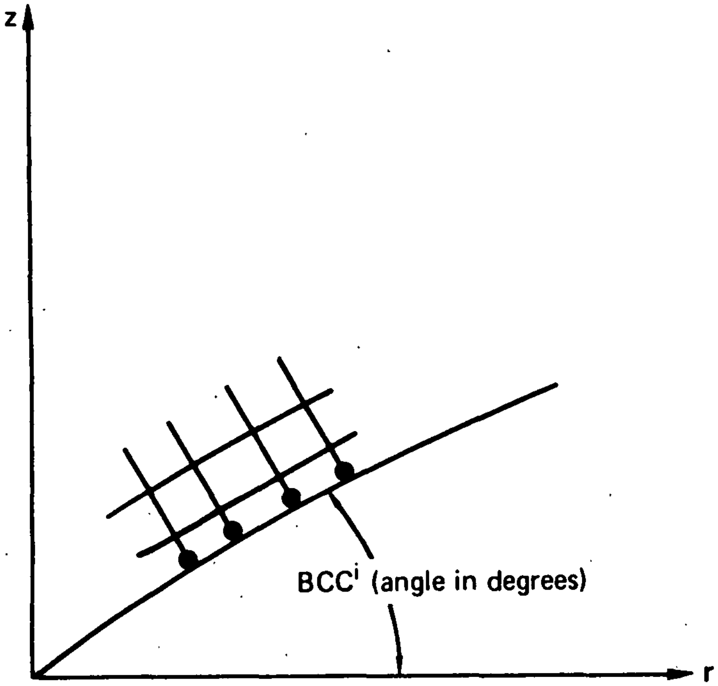

Fig. 8. Roller boundary condition that is obtained if BCC^i is not equal to 0, 1, 2, or 3.

is assumed to be the same. Unconstrained nodes can be generated between constrained nodes that have the same boundary condition by making the code on the second card (node n^j) negative. After the data are generated, the code is reset.

5. Element Cards

Supply one card for each element with the following information:

Columns	Quantity	Format
1-5	Element number	I5
6-10	Node n_1	I5
11-15	Node n_2	I5
16-20	Node n_3	I5
21-25	Node n_4	I5
26-30	Material number	I5
31-35	Generation increment, KN	I5
36-45	Material dependent parameter	E10.0

MT.EQ.2: angle ψ in degrees
MT.EQ.8 or MT.EQ.9: input "1.0" if
element is lit at time zero
MT.GE.10: initial internal energy

Element cards are assumed to be in element number sequence with the last element terminating the data. Omitted data are automatically generated with respect to the first card prior to the omitted data as follows:

$$n_j^{i+1} = n_j^i + KN \quad .$$

The material properties, the mesh generation parameter, print code, and ψ are taken from the first card. The convention for numbering nodal points is shown in Fig. 9 where n_1, n_2, ..., n_4 stand for global node numbers. Triangular zones are defined by setting node $n_4 = n_3$.

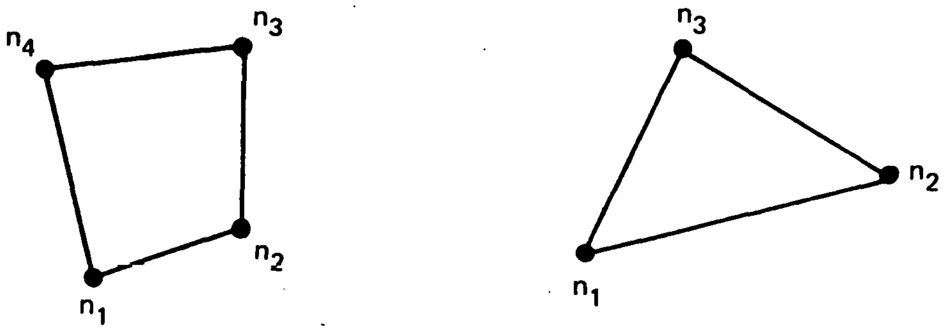

Fig. 9. Plane strain and axisymmetric elements available in DYNA2D.

6. High Explosive Burn Definition

Skip this section if IHE (Card 3, Section 2) is not equal to 2. Three options are available (see Fig. 10): they are the multiple point detonation, the line detonation, and Huygen detonation.

Card 1

Columns	Quantity	Format
1-5	Detonation type, IBTYP	I5
	EQ.0: multiple point detonation EQ.1: line detonation EQ.2: Huygens detonation	
6-10	NUMPTS	I5
	IBTYP.NE.1: NUMPTS is the number of detonation points IBTYP.EQ.1: NUMPTS is the number of points in detonation line	

Repeat the following set of cards NUMPTS times:

Card 2

Columns	Quantity	Format
1-5	Nodal point number	I5
	IBTYP.NE.1: lying at detonation point IBTYP.EQ.1: lying on detonation line	
6-15	Lighting time	E10.0
	EQ.0.0: if IBTYP = 1	
16-20	Material number of HE to be lit (IBTYP = 0 only)	I5
	EQ.0: The possibility of all HE elements being lit by this point is considered	

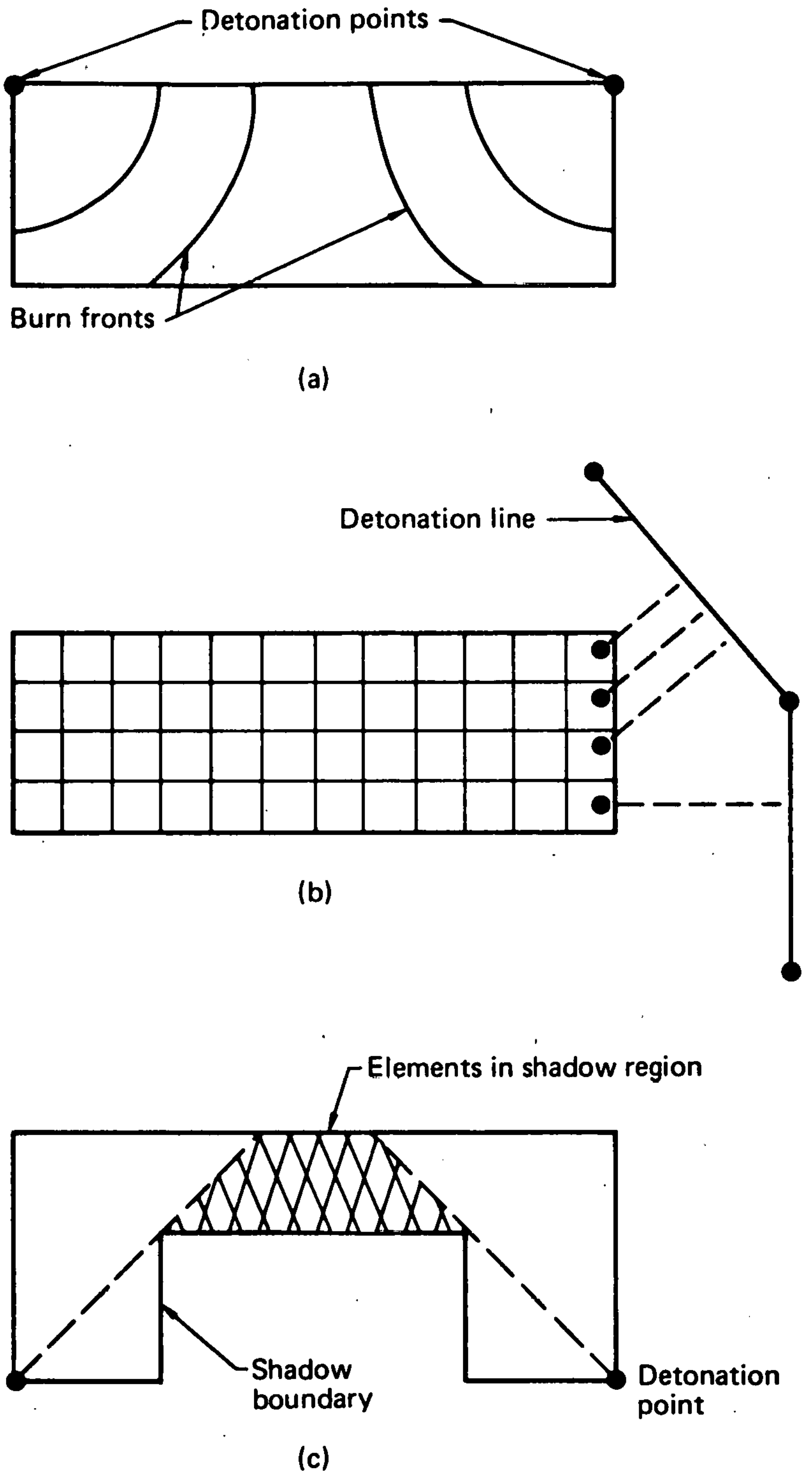

Fig. 10. Burn options: (a) multiple point, (b) line, and (c) Huygens.

Columns	Quantity	Format
21-30	Detonation velocity outside shadowed HE (optional input)	E10.0
31-40	Detonation velocity in shadowed HE (optional input)	E10.0

Card 3

Include the following card only if IBTYP = 2

Columns	Quantity	Format
1-5	NPSS, number of nodal points defining shadow boundary	I5

Card 4,5,...,NPSS+3

Include the following cards only if IBTYP =2

Columns	Quantity	Format
1-5	Shadow point number	I5
6-10	Nodal point number	I5

A line detonation must be defined by at least two points. Nodal points that define a line must be given in the order in which they appear as one moves along the line.

In a Huygens detonation, a shadow boundary must be given for each detonation point. The first point on the shadow boundary must be closest to the detonation point - if it is not the detonation point. The shadow points must be defined in the order in which they are encountered as one moves along the boundary. Omitted data are automatically generated by incrementing the nodal point numbers by:

$$(n_i - n_j) / (sn_i - sn_j) ,$$

where sn_i, sn_j are the shadow point numbers on two successive cards and n_i and n_j are their corresponding code numbers.

7. Nodal Printout Blocks

Skip this section if the number of nodal printout blocks (Card 1, Section 2) is zero. Otherwise, insert one card with the following information (up to eight printout blocks may be defined):

Columns	Quantity	Format
1-5	First node of first printout block	I5
6-10	Last node of first printout block	I5
11-15	First node of second printout block	I5
16-20	Last node of second printout block	I5

•

•

•

8. Element Printout Blocks

Skip this section if the number of element printout blocks (Card 1, Section 2) is zero. Otherwise, insert one card with the following information (up to eight printout blocks may be defined):

Columns	Quantity	Format
1-5	First element of first printout block	I5
6-10	Last element of first printout block	I5
11-15	First element of second printout block	I5
16-20	Last element of second printout block	I5

•
•
•

9. Time History Curve Cards

Define the number of load curve sets specified in columns 26-30 of Card 1 in Section 2. Repeat the following cards for each set: Define the number of load curve sets specified in columns 26-30 of Card 1 in Section 2. Repeat the following cards for each set:

Card 1

Columns	Quantity	Format
1-5	Load curve number	I5
6-10	Number of points in load curve (NPTS)	I5

Card 2,...,NPTS+1

Columns	Quantity	Format
1-10	Time	E10.0
11-20	Load value	E10.0

10. Concentrated Nodal Load and Follower Force Cards

Define the number of concentrated nodal point loads specified in columns 31-35 of Card 1 in Section 2.

Columns	Quantity	Format
1-5	Nodal point number (m) on which this load acts	I5
6-10	Direction in which load acts EQ.1: and IFW.EQ.0: r-direction EQ.2: and IFW.EQ.0: z-direction EQ.n: and IFW.EQ.1: n is a node number that defines a plane beginning at m and ending at n (the force points to the right as one moves along the surface from m to n)	I5
11-15	Load curve number	I5
16-25	Scale factor EQ.0.0: default set at "1.0"	E10.0
26-30	IFW, follower force flag EQ.0: concentrated force acts in either r or z direction EQ.1: follower force considered	I5

11. Pressure and Shear Boundary Condition Cards

Define the number of cards specified in Columns 1-5 of Card 2 in Section 2.

Columns	Quantity	Format
1-5	Card number	I5
6-10	Load curve number	I5
11-15	Node n_1	I5
16-20	Node n_2	I5
21-30	Multiplier of load curve at n_1, M_{n1} EQ.0.0: default set to "1.0"	E10.0
31-40	Multiplier of load curve at n_2, M_{n2} EQ.0.0: default set to "1.0"	E10.0
41-50	Arrival time of load on the surface	E10.0
51-55	Generation interval, KN EQ.0: default set to "1"	I5
56-60	Loading type EQ.0: pressure EQ.1: shear	I5

The start times, multipliers, and generation interval are taken from the first card. The interior is kept to the left as one progresses from node n_1 to n_2 (see Fig. 11). Traction loads are always evaluated with respect to the deformed geometry.

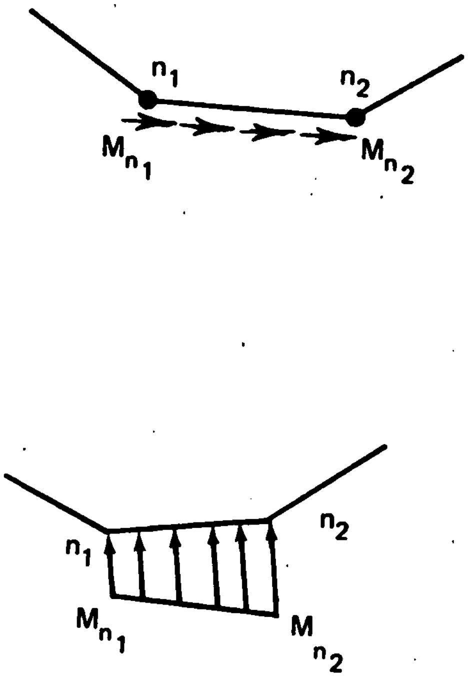

Fig. 11. Definition of nodes n_1 and n_2 for traction boundary conditions on bilinear elements.

12. Velocity Boundary Condition Cards

Define the number of cards specified in columns 6-10 of Card 2 in Section 2.

Columns	Quantity	Format
1-5	Nodal point number to which this velocity is applied	I5
6-10	Load curve number	I5
11-15	Direction in which the node is displaced EQ.1.0: r-direction EQ.2.0: z-direction NE.1.0 and NE.2.0: the angle in degrees between the r-axis and the direction of the prescribed velocity vector	E5.0
16-25	Scale factor	E10.0

13. Base Acceleration in r-Direction

Skip this card if columns 11-15 of Card 2 in Section 2 are blank.

Columns	Quantity	Format
1-5	Load curve number	I5
6-10	Scale factor on r-acceleration EQ.0.0: default set at "1.0"	E10.0

This card applied only to plane strain geometries.

14. Base Acceleration in z-Direction

Skip this card if columns 16-20 of Card 2 in Section 2 are blank.

Columns	Quantity	Format
1-5	Load curve number	I5
6-10	Scale factor on z-acceleration	E10.0
	EQ.0.0: default set to "1.0"	

15. Angular Velocity

Skip this card if columns 21-25 of Card 2 in Section 2 are blank.

Columns	Quantity	Format
1-5	Load curve number	I5
6-10	Scale factor on angular velocity	E10.0
	EQ.0.0: default set to "1.0"	

Nodal loads due to the angular velocity are always calculated with respect to the deformed configuration. Angular velocity is assumed to have the units of radians per unit time.

16. Initial Conditions

Skip this section if the initial condition parameter, in columns 26-30 of Card 2 in Section 2 is zero.

Columns	Quantity	Format
1-5	Nodal point number	I5
6-15	Initial velocity in r-direction	E10.0
16-25	Initial velocity in z-direction	E10.0
26-35	Nodal point increment EQ.0: default set to "1"	I5

Initial velocity must be defined for each nodal point. These cards do not need to be in order; however, the highest nodal point number must terminate the data. Missing data are generated as described in Section 4.

17. Stonewall

Skip this section if the number of stonewalls specified in columns 31-35 of Card 2 in Section 2 is zero. Repeat the following sets of cards for each stonewall.

Card 1

Columns	Quantity	Format
1-5	Number of slave nodes	I5
6-15	r-coordinate of tail of any outward drawn normal vector originating on wall (tail) and terminating in space (head)	E10.0
16-25	z-coordinate of tail	E10.0
26-35	r-coordinate of head	E10.0
36-45	z-coordinate of head	E10.0

Cards 2,3...,etc.

Columns	Quantity	Format
1-5	Slave number	I5
6-10	Nodal point number	I5

A stonewall extends to infinity and is defined by a normal vector of arbitrary magnitude drawn outward from the wall. Nodes that are designated as slave nodes cannot penetrate a stonewall: other nodes can penetrate.

Omitted slave nodes are automatically generated by incrementing the nodal point numbers by

$$\frac{n_i - n_j}{sn_i \quad sn_j}$$

where sn_i and sn_j are slave numbers on two successive cards and n_i and n_j are their corresponding node numbers.

Sections 18-20 will be skipped if the number of slide-lines is zero.

---

18. Slide-Line Control Cards

Define a control card for each slide-line. A discussion about the proper use of the slide-line capability is provided in Appendix A.

Columns	Quantity	Format
1-5	Number of slave nodes in slide-line (NSN)	I5
6-10	Number of master nodes in slide-line (NMN)	I5
11-15	Slide-line type number, ISLT EQ.1: sliding only EQ.2: tied sliding EQ.3: sliding with voids	I5
16-25	SLFAC, tolerance for determining initial gaps EQ.0.0: SLFAC = 0.001	E10.0
26-35	θ_1, angle in degrees of slide-line extension at first master node EQ.0.0: extension remains tangent to first master segment	E10.0
36-45	θ_2, angle in degrees of slide-line extension at last master node EQ.0.0: extension remains tangent to last master segment	E10.0

Angles θ_1 and θ_2 are measured counterclockwise from the r-axis and remain constant. If θ_1 and θ_2 are zero, the extensions are made tangent to the first and last master segments and remain so throughout the calculation. The force exerted by a slave node lying on an extension of the master node at the origin of the extension diminishes to zero as the slave node moves away a distance equal to the length of one slave segment.

19. Slide-Line Definitions

Repeat the following cards for each slide-line.

Card 1

Columns	Quantity	Format
1-72	Any suitable identification	12A6

Cards 2,3,...,NSN+1

Columns	Quantity	Format
1-5	Slave number	I5
6-10	Nodal point number	I5

Omitted data are automatically generated by incrementing the nodal point numbers by:

$$(n_i - n_j)/(sn_i - sn_j) \quad ,$$

where sn_i, sn_j are the slave numbers on two successive cards and n_i and n_j are their corresponding numbers.

Cards NSN+2,...,NSN+NMN+1

Columns	Quantity	Format
1-5	Master number	I5
6-10	Nodal point number	I5

Omitted data are generated as described above. The master and slave nodes must be given in the order in which they appear as one moves along the surface. **The slave surface must be to the left of the master surface.**

20. Slide-Line Intersections

If no slide-lines intersect (NUMSI.EQ.0) skip this section; otherwise, define NUMSI cards.

Cards 1,2,...,NUMSI

Columns	Quantity	Format
1-5	Number of slide-line that is intersected	I5
6-10	Number of slide-line that intersects the above line	I5

21. Density vs. z-Coordinate Curve

Skip this section of the number of points in the density versus z-coordinte curve (Card 2, Section 2) is zero; otherwise supply NUMDZ+1 cards.

Card 1

Columns	Quantity	Format
1-10	Gravitational acceleration	E10.0

Cards 2,3,...,NUMDZ+1

Columns	Quantity	Format
1-10	Density	E10.0
11-20	z-Coordinate	E10.0

22. Momentum Deposition Data

Skip this section if the number of elements for momentum deposition is zero (Card 3, Section 2). Otherwise enter one card as follows for each element receiving momentum deposition.

Columns	Quantity	Format
1-5	Element number	I5
6-15	r-momentum per unit radian	E10.0
16-25	z-momentum per unit radian	E10.0
26-35	Deposition time	E10.0
		E10.0

RESTART INPUT DECK

An input deck is generally not needed to restart DYNA2D. It may be used, however, to reset the following parameters:

- Termination time
- Output printing interval
- Output plotting interval
- Viscosity coefficients
- Time histories

In addition, slide-lines and blocks of elements may be eliminated from the calculations. All changes made when restarting will be reflected in subsequent restart dumps.

1. Title Card

Columns	Quantity	Format
1-66	Any suitable title	12A6

2. Control Cards

Columns	Quantity	Format
1-10	Termination time	E10.0
	EQ.0.0: termination time remains unchanged	
11-20	Output printing interval	E10.0
	EQ.0.0: output printing interval remains unchanged	
21-30	Output plotting interval	E10.0
	EQ.0.0: output plotting interval remains unchanged	
31-32	Input form	A2
	EQ."ND": input follows this manual EQ."OD": input follows 1980 manual	
33-35	Number of time histories to be redefined (NTHRD)	I5
36-40	Number of slide-lines to be eliminated from calculation	I5
41-45	Number of element blocks to be eliminated from calculation	I5
46-50	Number of material blocks to be eliminated from calculation	I5
51-55	Number of slide-lines to be defined	I5
56-60	Number of slide-line intersections, NUMSI	I5

If the number of slide-lines to be defined is nonzero, each slide-line used in the subsequent calculation must be defined - even if it already exists in the restart file. The total number of slide-lines to be defined must not exceed the number used in the original input deck.

3. Time-History Cards

Skip these cards if NTHRD equals zero; otherwise, define NTHRD card sets.

Card 1

Columns	Quantity	Format
1-5	Number associated with time history curve to be redefined	I5

Cards 2,...,NPTS+1

Columns	Quantity	Format
1-10	Time	E10.0
11-20	Function value	E10.0

The number of points in the load curve, NPTS, may not change from the original input.

4. Deleted Slide-Lines

Skip this section if the number of slide-lines to be deleted is zero.

Columns	Quantity	Format
1-5	Number of first slide-line to be deleted	I5
6-10	Number of second slide-line to be deleted	I5
.	.	.
.	.	.
.	.	.

5. Deleted Element Blocks

Skip this section if the number of element blocks to be deleted is zero.

Columns	Quantity	Format
1-5	First element of first block to be eliminated	I5
6-10	Last element of first block to be eliminated	I5
11-15	First element of second block to be eliminated	I5
16-20	Last element of second block to be eliminated	I5
•	•	•
•	•	•
•	•	•

6. Deleted Material Blocks

Skip this section if the number of material blocks to be deleted is zero.

Columns	Quantity	Format
1-5	Material number of first material to be deleted	I5
6-10	Material number of second material to be deleted	I5
.	.	.
.	.	.
.	.	.

Sections 7 to 9 may be skipped if the number of slide-lines to be redefined is zero.

---

7. Slide-Line Control Cards

Define a control card for each slide-line.

Columns	Quantity	Format
1-5	Number of slave nodes in slide-line (NSN)	I5
6-10	Number of master nodes in slide-line (NMN)	I5
11-15	Slide-line type number, ISLT EQ.1: sliding only EQ.2: tied sliding EQ.3: sliding with voids	I5
16-25	SLFAC, tolerance for determining initial gaps EQ.0.0: SLFAC = 0.001	E10.0
26-35	θ, angle in degrees of slide-line extension at first master node EQ.0.0: extension remains tangent to first master segment	E10.0
36-45	θ_2 angle in degrees of slide-line extension at last master node EQ.0.0: extension remains tangent to last master segment	E10.0

8. Slide-Line Definitions

Repeat the following cards for each slide-line:

Card 1

Columns	Quantity	Format
1-72	Any suitable identification	12A6

Cards 2,3,...,NSN+1

Columns	Quantity	Format
1-5	Slave number	I5
6-10	Nodal point number	I5

Cards NSN+2,...,NSN + NMN+1

Columns	Quantity	Format
1-5	Master number	I5
6-10	Nodal point number	I5

9. Slide-Line Intersections

If there are no slide-line intersections (NUMSI.EQ.0) skip this section.

Cards 1,2,...,NUMSI

Columns	Quantity	Format
1-5	Number of slide-line which is intersected	I5
6-10	Number of slide-line which intersects the above line	I5

COMMANDS FOR REZONING

General commands include:

TV, T, F, FR, G, A, SN, SC, SD, MN, MC, MD, Z, R, TR

General commands will not result in a material being rezoned; therefore, materials whose boundaries are changed by the SC, SD, MC, MD commands must be rezoned.

Commands for rezoning material (may be used with above commands):

M, V, B, S, TN, CN

Commands that are available for adjusting boundary nodes following the "B" command:

ER, EZ, ES, VS, BD

The "B" command is available if and only if a material has been designated for rezoning.

1. Command Definitions

TV n	-	Use TMDS where n is the monitor number.
G	-	Display complete mesh with material numbers.
T	-	Terminate without remap.
F	-	Terminate interactive phase, remap, continue in execution phase.
FR	-	Terminate interactive phase, remap, write restart dump, and call exit.
A	-	Display all slide-lines. Slave sides are plotted as dashed or dotted lines.
SN n	-	Display slide-line n with slave node numbers.

1. Command Definitions (cont'd.)

SC n - Check slave nodes of slide-line n and put any nodes that have penetrated through the master surface back on the master surface.

SD n - Dekink slave side of slide-line n - after using this command, the SC or MC command is sometimes advisable.

MN n - Display slide-line n with master node numbers.

MC n - Check master nodes of slide-line n and put any nodes that have penetrated through the slave surface back on the slave surface.

MD n - Dekink master side of slide-line n. After using this command, the SC or MC command is sometimes advisable.

Z r z $\Delta\ell$ - Zoom in at point (r,z) with window $\Delta\ell$.

R - Restore original mesh.

M n - Material n is to be rezoned.

V - Display material n on TMDS.

S - Smooth mesh of material n.

TN r z $\Delta\ell$ - Type node numbers and coordinates of all nodes within window $(r \pm \Delta \ell/2, z \pm \Delta \ell/2)$.

CN m r z - Node m has new coordinate (r,z).

B - Determine boundary nodes of material n and display boundary with nodes on TMDS.

ER m n - Equal space in r-direction boundary nodes m to n (counterclockwise).

EZ m n - Equal space in z-direction boundary nodes m to n (counterclockwise).

ES m n - Equal space along boundary, boundary nodes m to n (counterclockwise).

VS m n r - Vary the spacing of boundary nodes m to n such that r is the ratio of the first segment length to the last segment length.

BD m n - Dekink boundary from boundary node m to boundary node n (counterclockwise).

TR t - At time t DYNA2D will stop and enter interactive rezoning phase.

Use of the rezoner is demonstrated in the example which follows. In order to minimize the size of the graphics segment of DYNA2D. No graphics files are created. A special version of DYNA2D was compiled to obtain the figures that follow. In the table below, teletypewriter lines are correlated to the figures.

2. Example

DYNA2D	User Response	Resulting TMDS Figure
;TMDS; ?	1625 G	12
;OK-M; ?	Z 2 12 8	13
;OK-M; ?	A	14
;OK-M; ?	M 3 V	15
;OK-M; ?	B	16
;OK-M; ?	ES 758 773 VS 773 1093 .5 ES 1093 1078 MC 1 V	17
;OK-M; ?	S V	18
;OK-M; ?	BD 773 1093 MC 1 S V	19
;OK-M; ?	G	20
;OK-M; ?	FR	

Table 1. DYNA2D prompts, user response, and resulting TMDS displays for a typical problem.

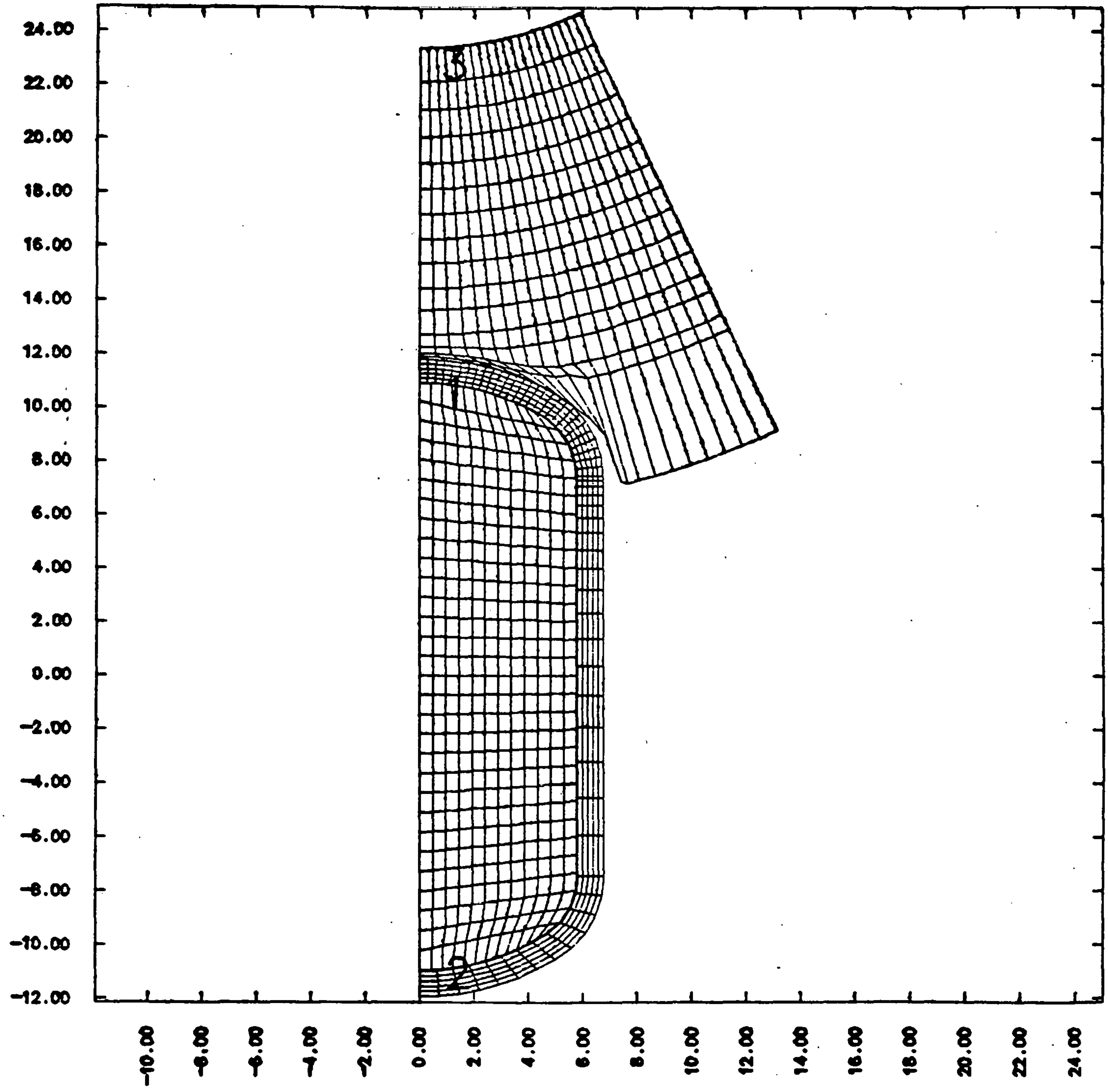
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Fig. 12.

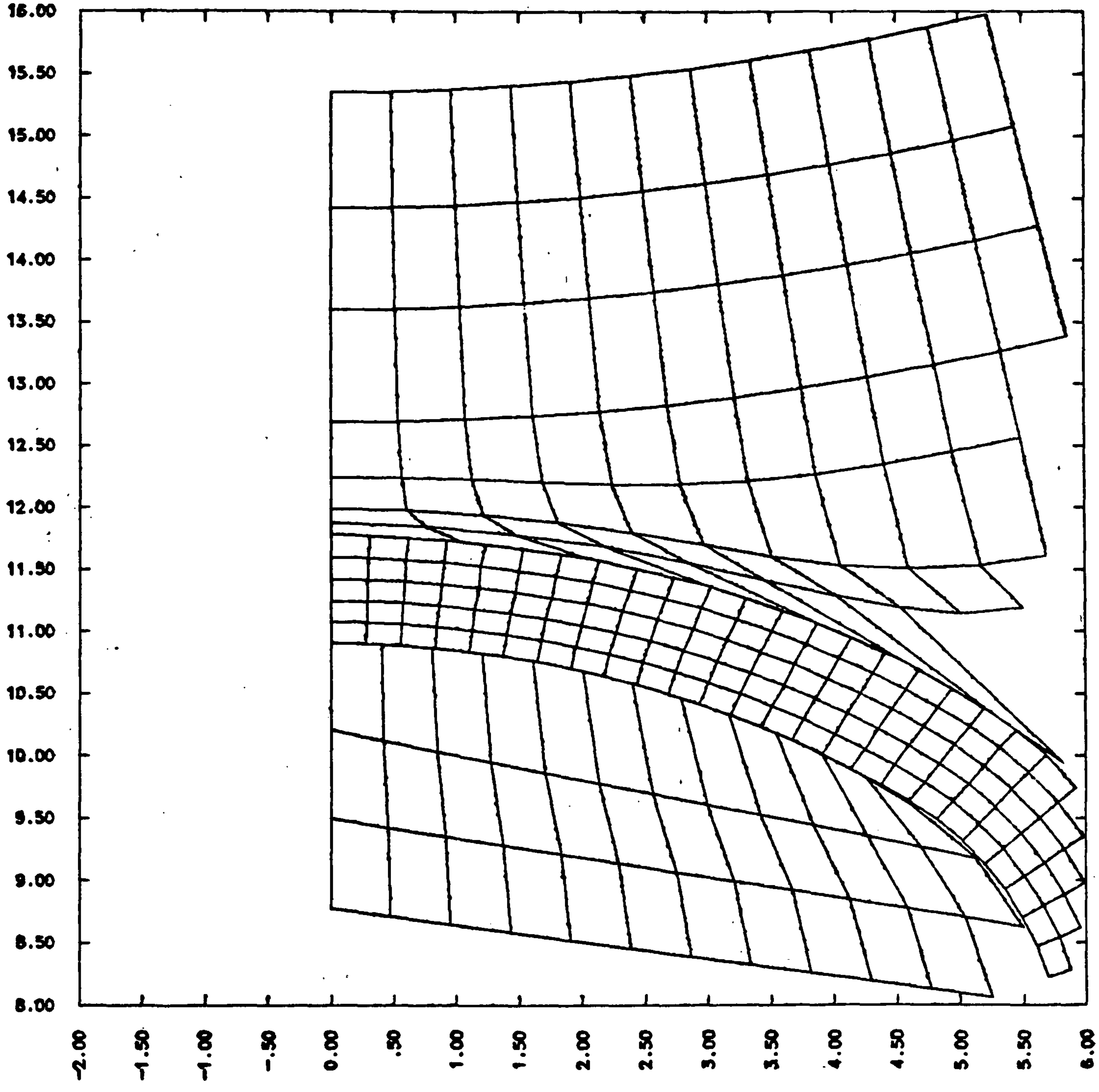
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Fig. 13.

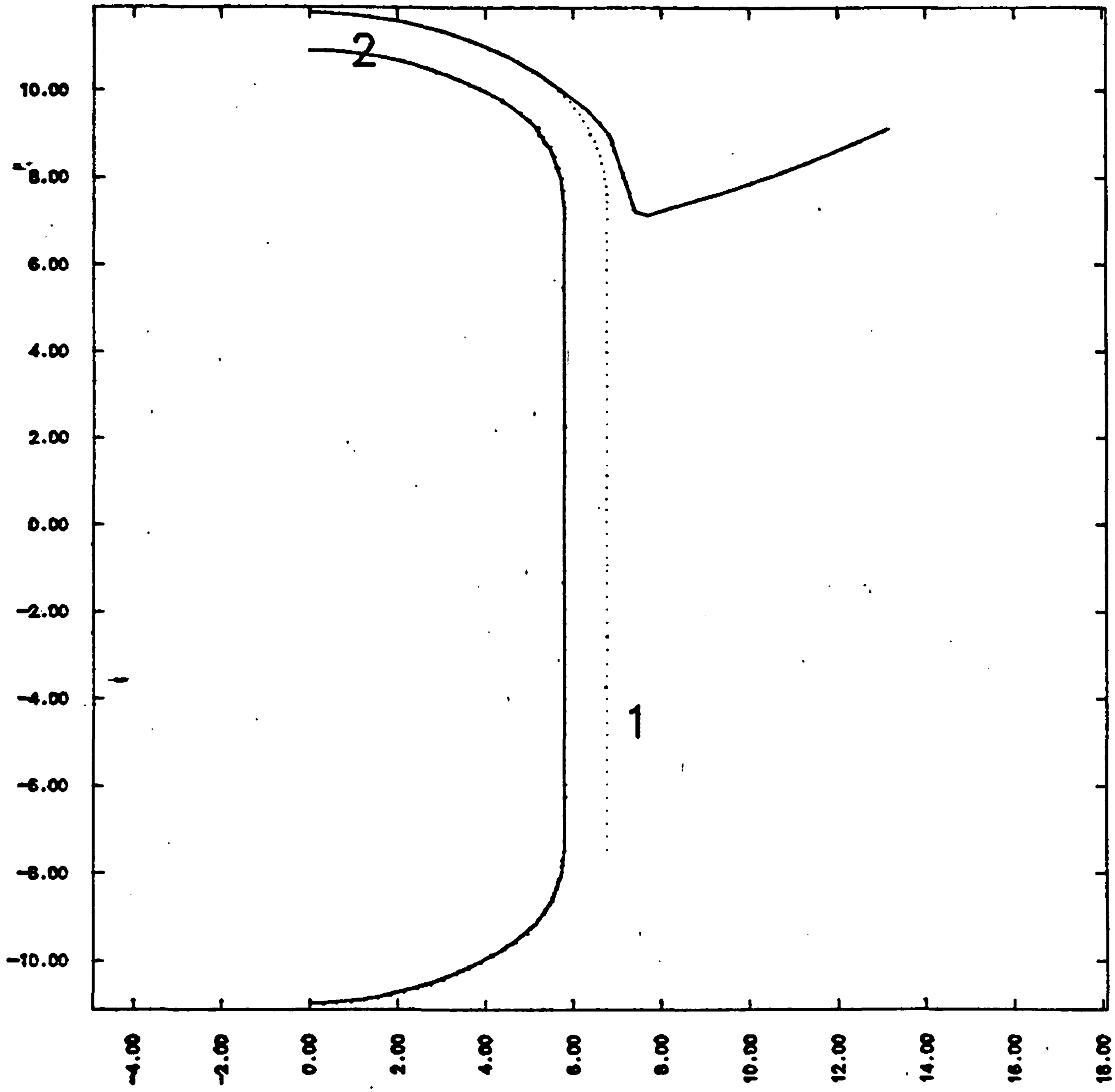
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Fig. 14.

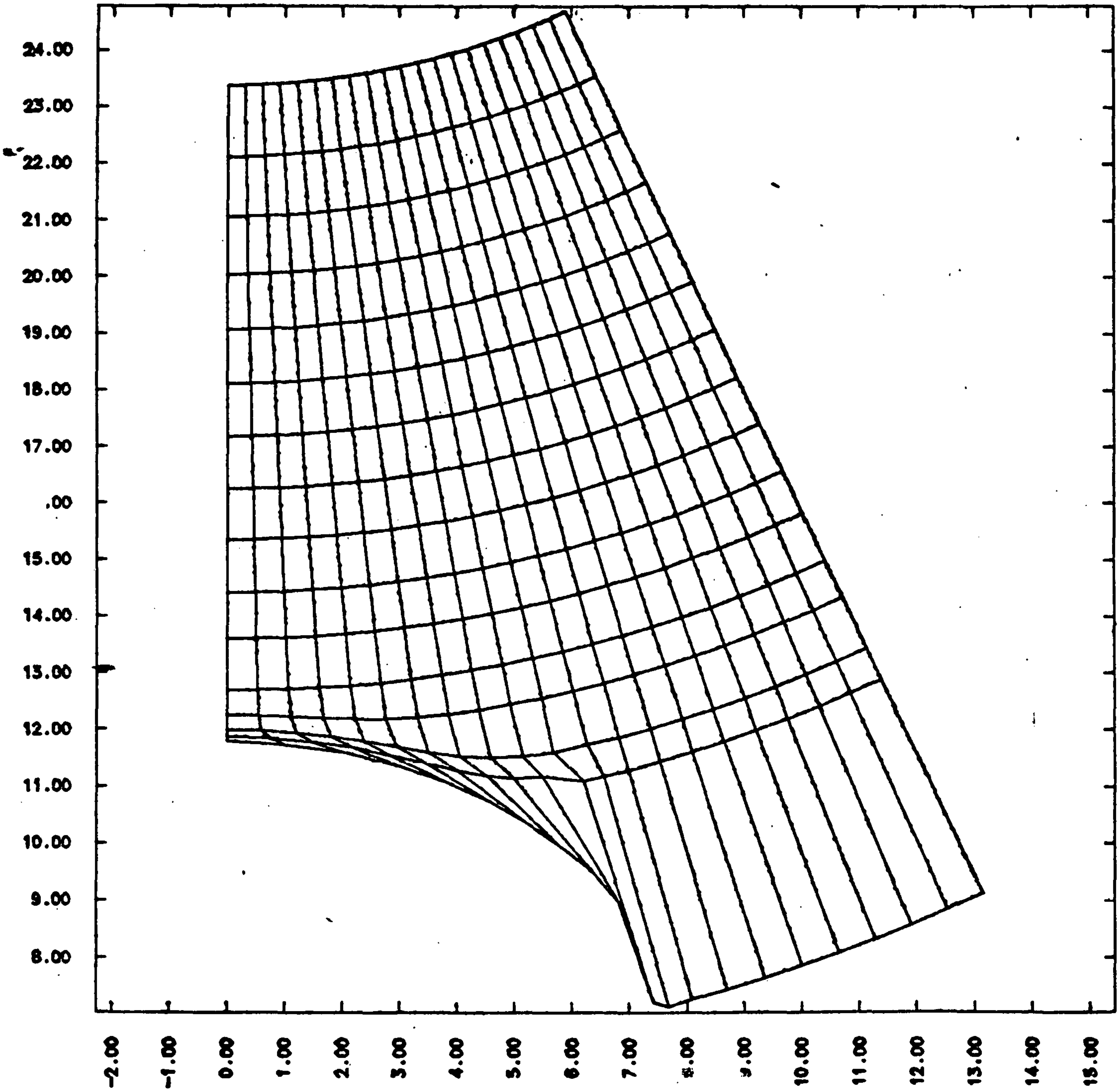
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Fig. 15.

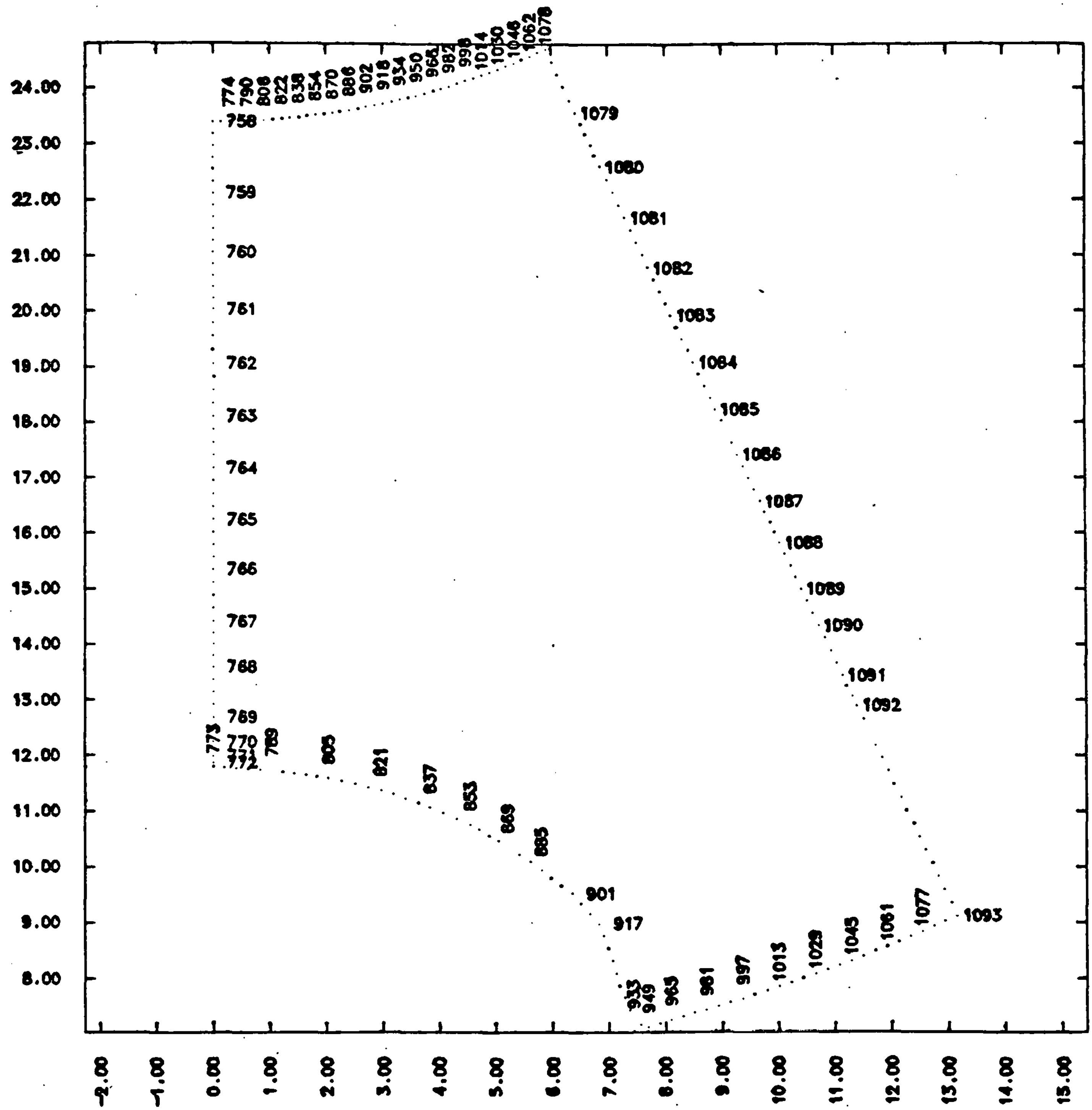
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Fig. 16.

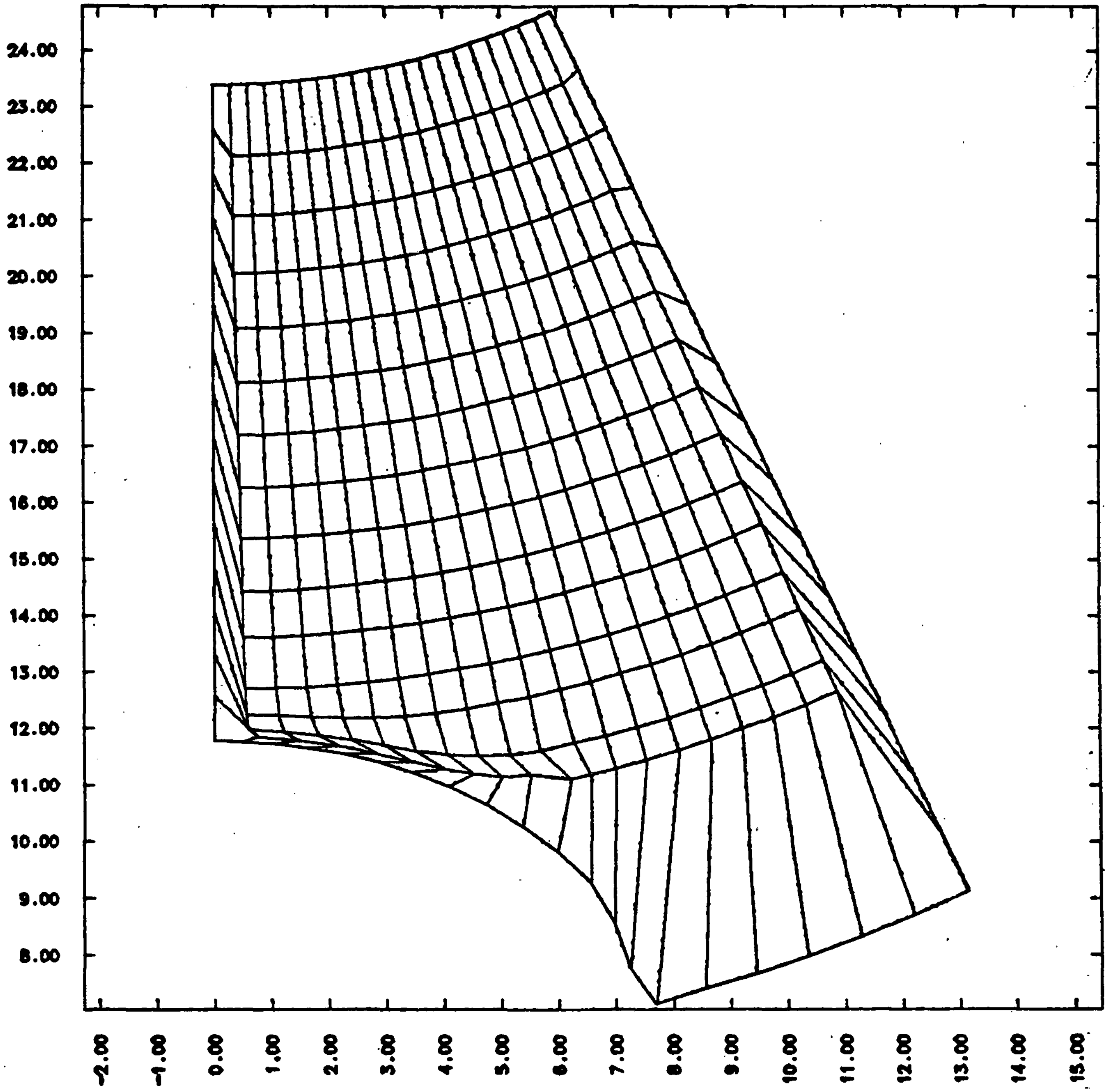

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Fig. 17.

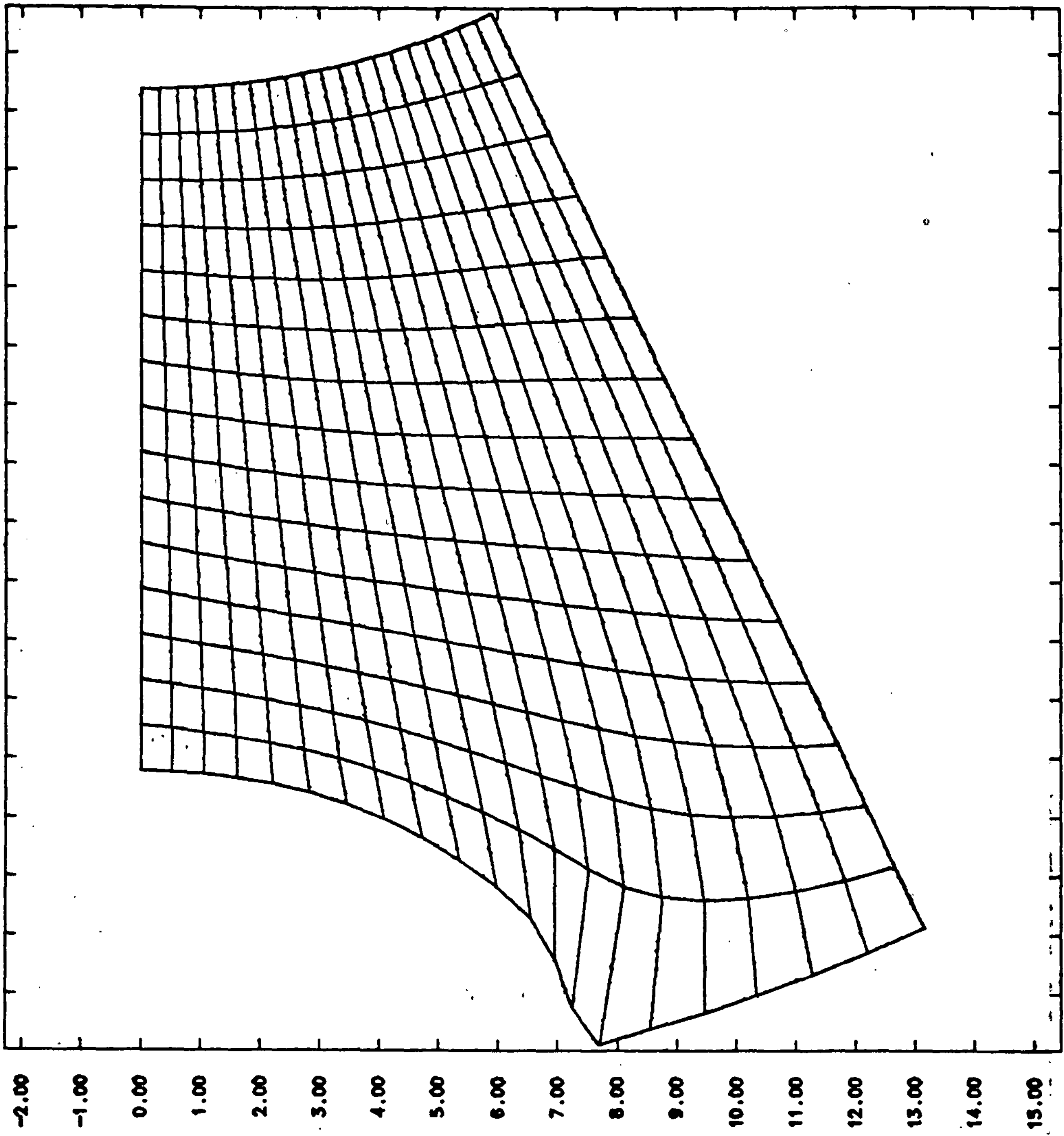
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Fig. 18.

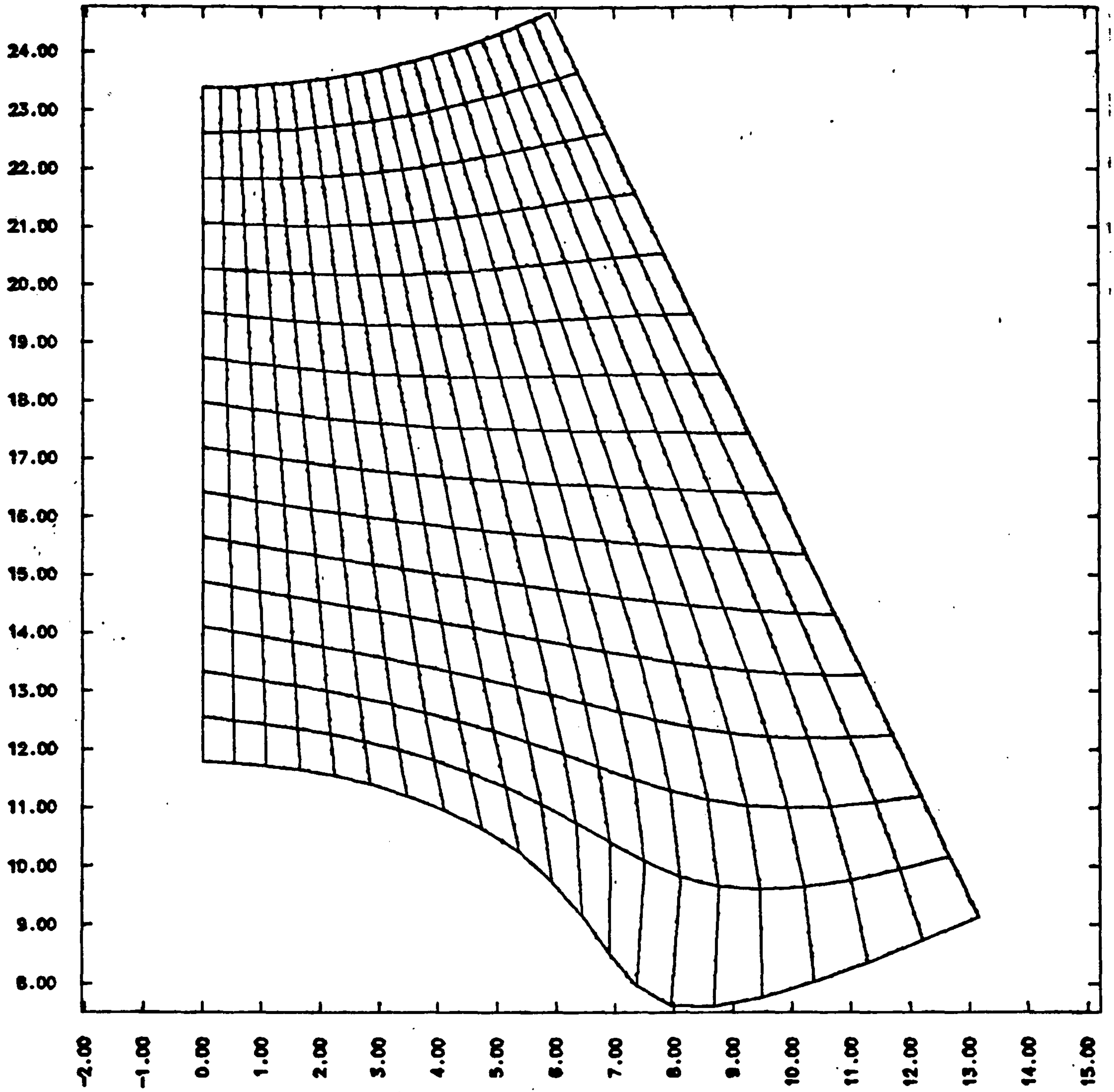
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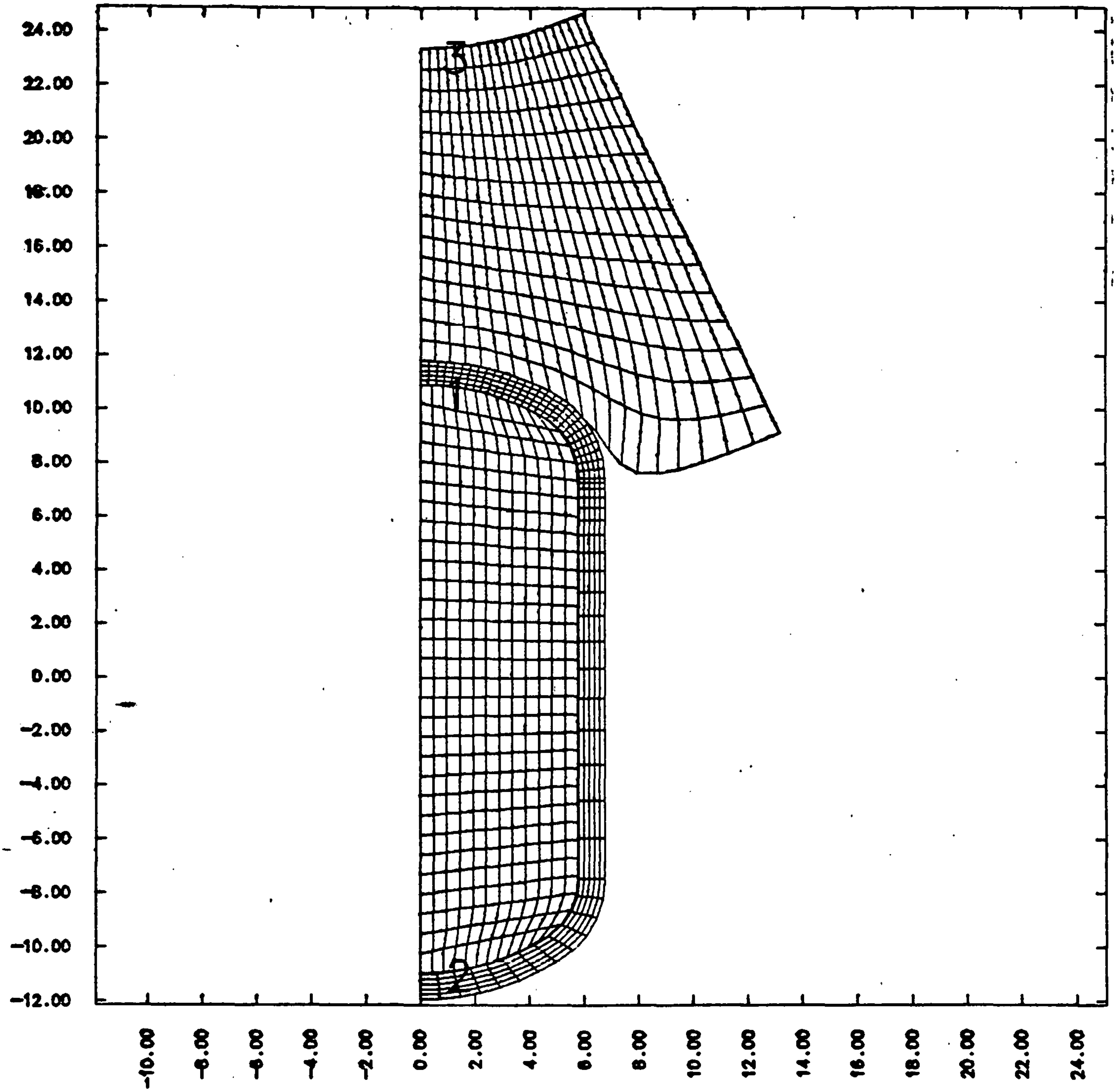
Fig. 19.


24.00
22.00
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-2.00
-4.00
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3
1
2

Fig. 20.

EXAMPLE PROBLEM

Shaped Charge Calculation

In Fig. 21, a finite element mesh of 600 elements models a type of shaped charge called a self-forging fragment [25]. Calculations were carried out to compute the formation of the fragment produced by the upper plate. Slide-lines

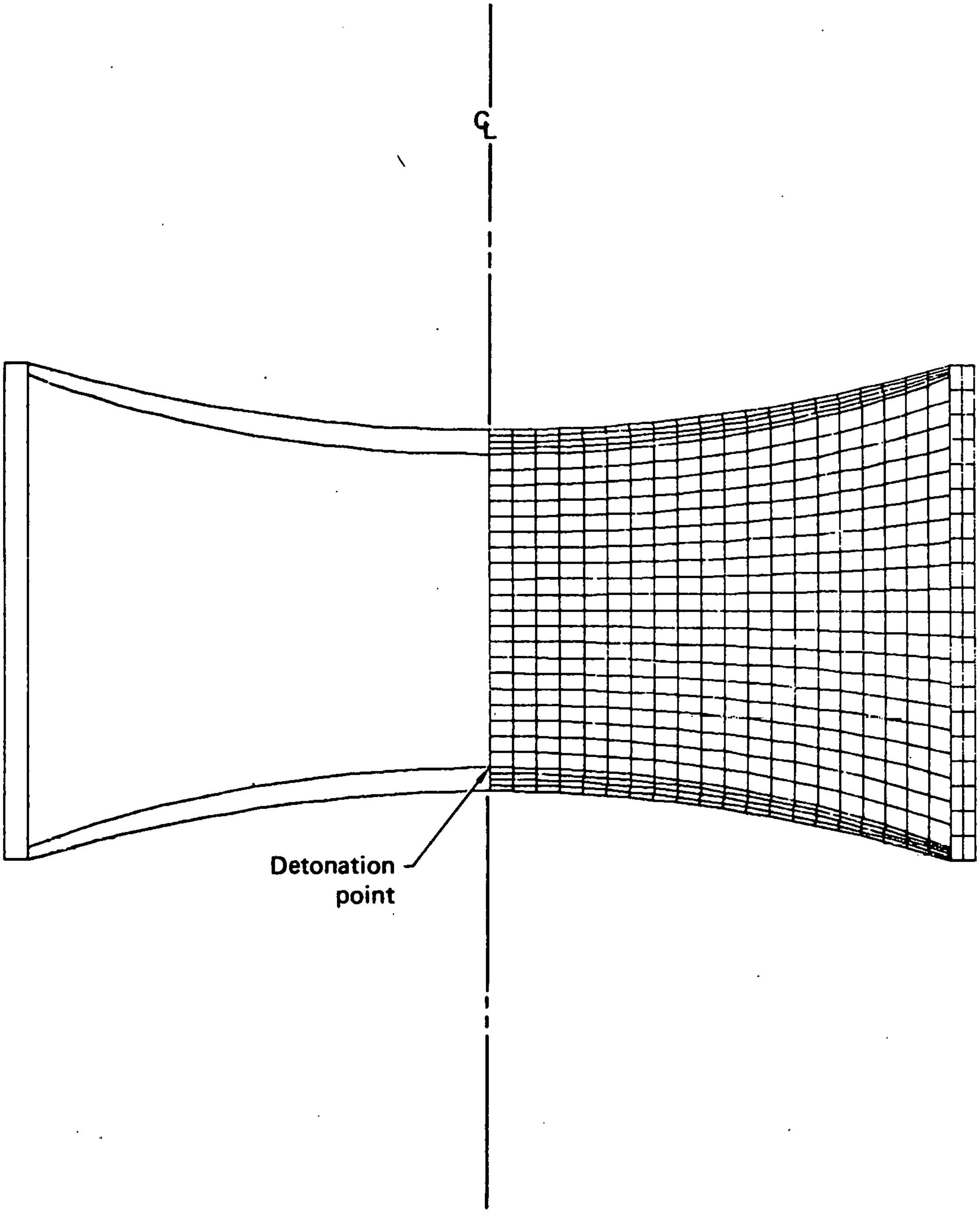


Fig. 21. Finite difference mesh used in shaped charge calculation.

are initially placed between the plate-HE and cyliner-HE interfaces. By 10 μs the HE has burned, and by 50 μs the pressure in the HE has dropped to negligible levels. At 50 μs, therefore, all elements but those in the upper plate are eliminated from the calculation. Between 12 and 50 μs, zones at the outer edges of the plate become elongated and cause a significant decrease in the time-step size. These latter elements are eliminated prior to 50 μs. Before the calculation is continued at 50 μs, a new slide-line is defined along the upper surface to prevent the plate from penetrating through itself as it folds.

Figure 22 shows a view of the deformed shape at 50 μs. The formation of the fragment is depicted in Fig. 23, which contains a sequence of deformed shapes at 20 μs intervals. To verify DYNA2D's accuracy, an additional calculation was performed with the HE tied along the outer case and compared to a similar calculation with HEMP. As expected, excellent agreement was obtained.

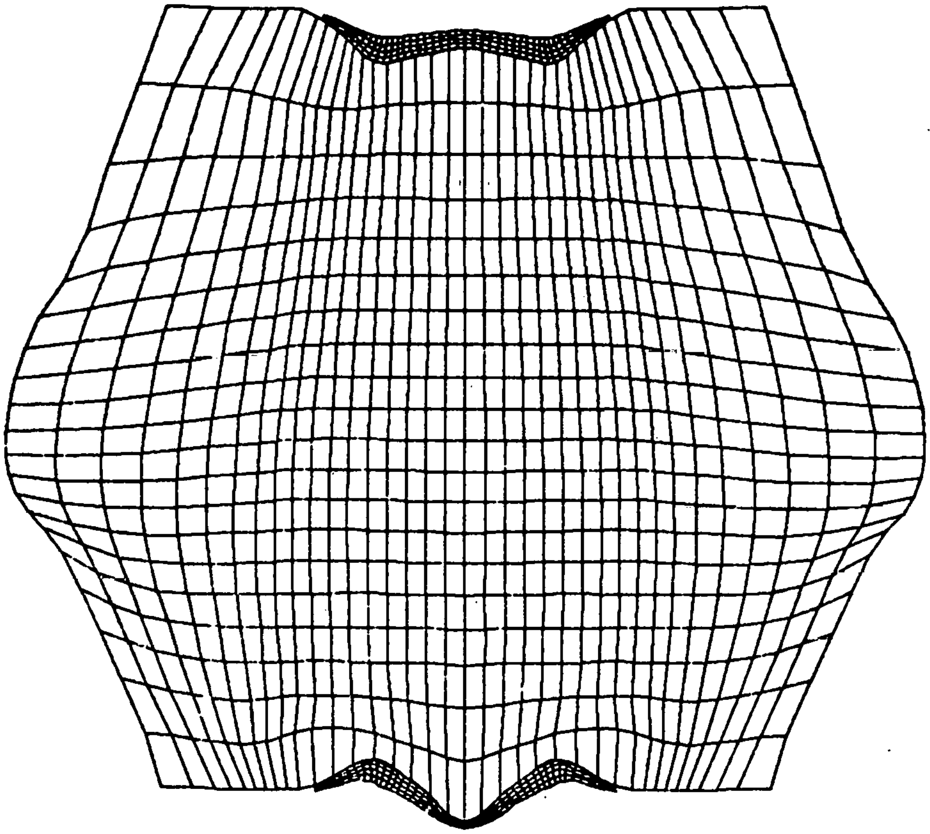
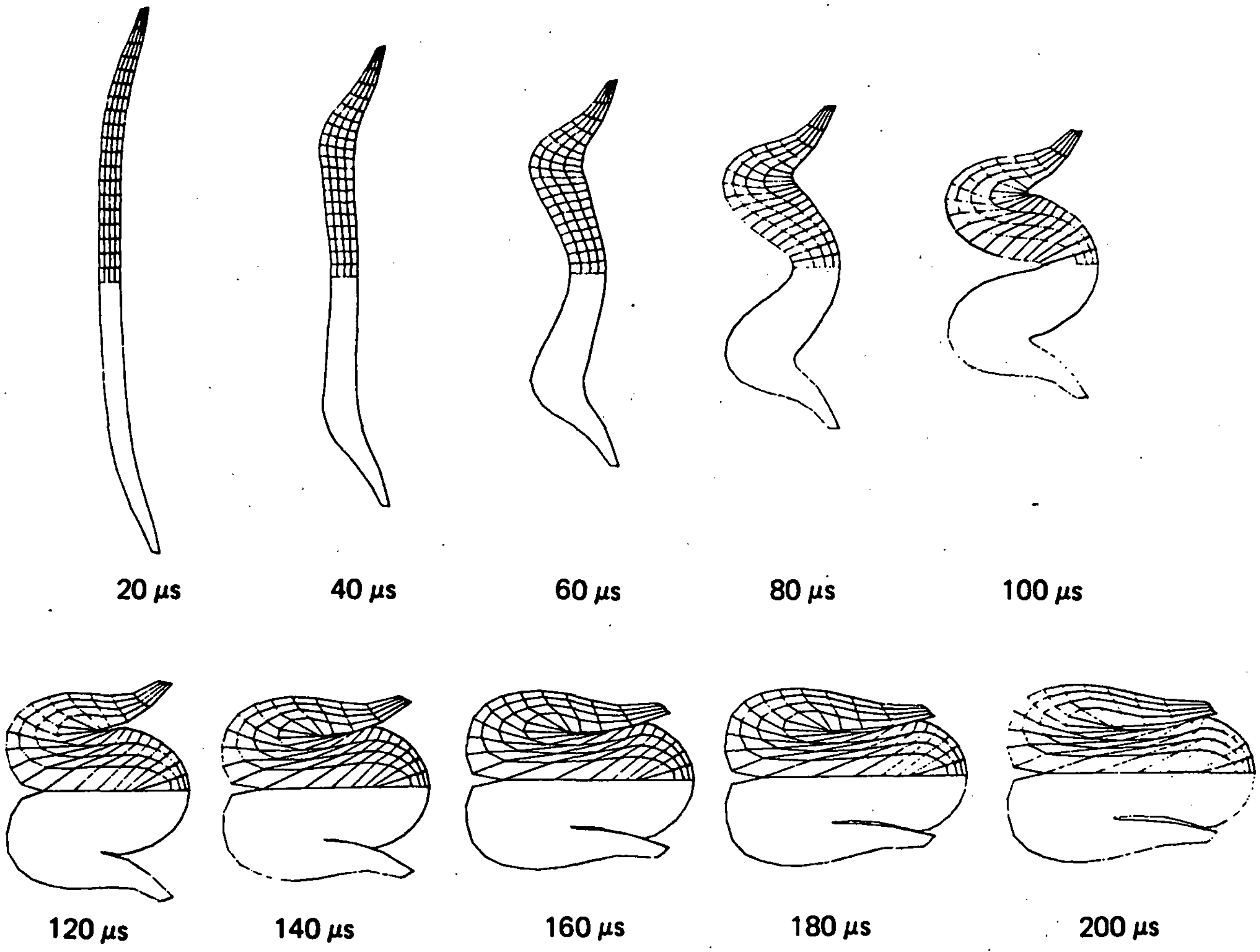


Fig. 22. Deformed shape at 50 μs.


20 μs 40 μs 60 μs 80 μs 100 μs

120 μs 140 μs 160 μs 180 μs 200 μs

Fig. 23. Formation of fragment.

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APPENDIX A

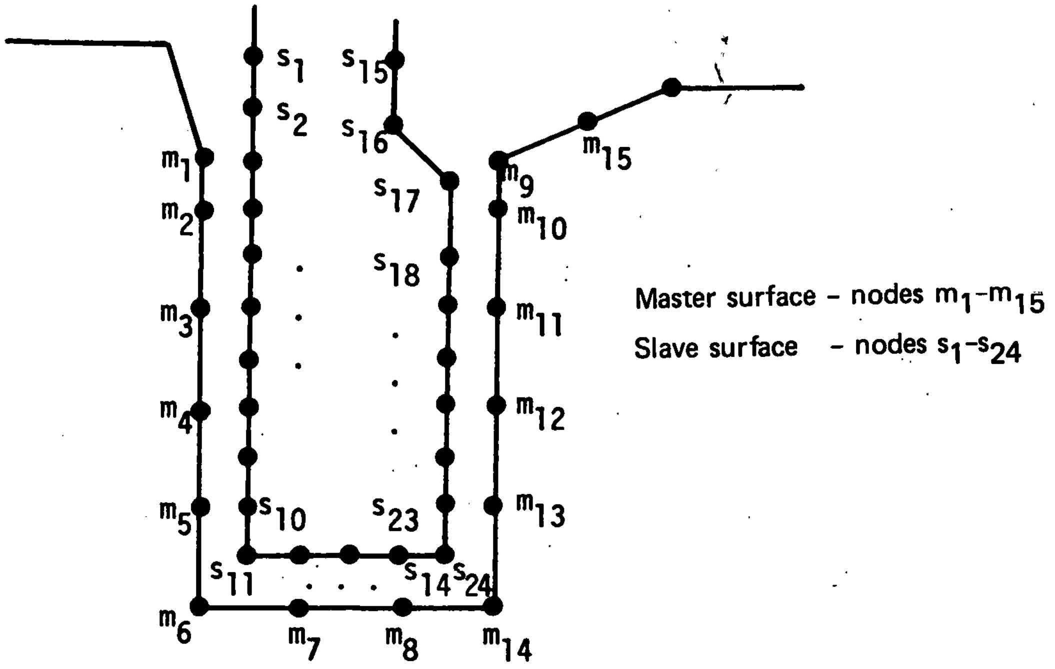
Use of Slide-Lines

The purpose of this appendix is to describe briefly the proper use of slide-lines.

Consider two surfaces in contact. In DYNA2D it is necessary to designate one as a slave surface and the other as a master surface. Nodal points defining the slave surface are called slave nodes, and similarly, nodes defining the master surface are called master nodes. Each slave-master surface combination is referred to as a slide-line.

Many potential problems with the algorithm can be avoided by observing the following precautions:

- If one surface is more finely zoned, it should be used as the slave surface.
- A slave node may have more than one master segment, and may be included as a member of a master segment if a slide-line intersection is defined.
- Angles in the master side of a slide-line that approach 90 deg must be avoided. Whenever such angles exist in a master surface, two or more slide-lines should be defined. This procedure is illustrated in Fig. A1. An exception for the foregoing rule arises if the surfaces are tied. In this case, only one slide-line is needed.
- Rigid walls are defined by a series of fixed master nodes (boundary condition code 3.0), which outline the desired profile. For best results, the spacing of these nodes should be approximately the same as that of the slave nodes. If very large spacing is used, errors may occur during the initialization phase.
- Whenever two surfaces are in contact, the smaller of the two surfaces should be used as the slave surface. For example, in modeling a missile impacting a wall, the contact surface on the missile should be used as the slave surface.
- Care should be used when defining a master surface to prevent the extension from interfering with the solution. In Figs. A2 and A3, slide-line extensions are shown.
- Whenever slide-lines intersect as shown in Fig. A4, an intersection should be defined to insure proper treatment of the intersection.



1		2		3	
Slaves	Masters	Slaves	Masters	Slaves	Masters
s_1	m_1	s_{11}	m_6	s_{24}	m_{14}
s_2	m_2	s_{12}	m_7	s_{23}	m_{13}
.	.	.	m_8	.	.
.	.	.	m_{14}	.	.
.	.	.	.	.	.
		s_{14}			m_9
s_{11}	m_6	s_{24}		s_{15}	m_{15}

Fig. A1. Proper definition of illustrated slave-master surface requires three slide-lines (note that slave surface is to left of master surface as one moves along master nodes in order of definition).

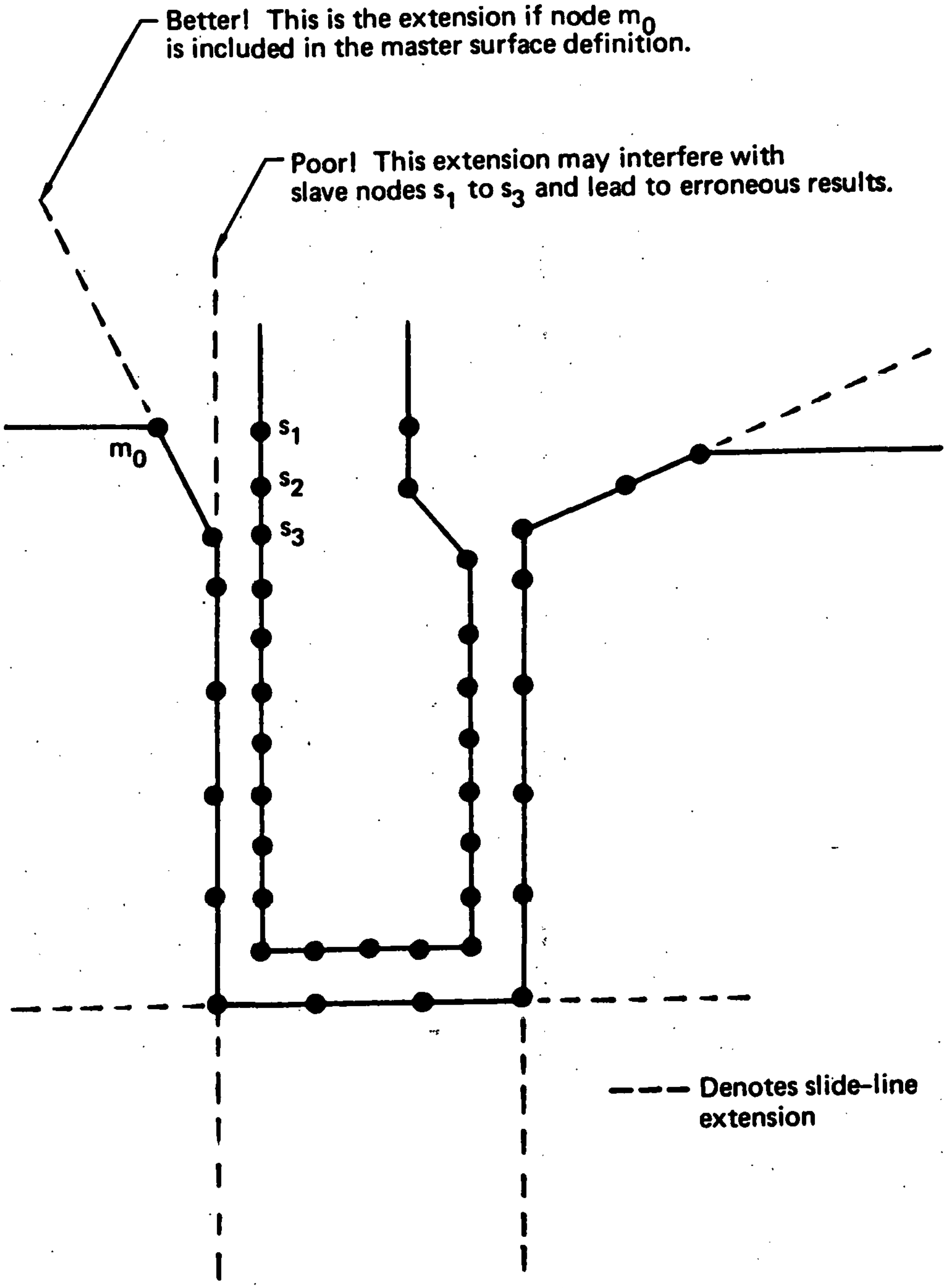


Fig. A2. Master surface extensions defined automatically by DYNA2D (extensions are updated every time step to remain tangent to ends of master sides of slide-lines unless angle of extension is defined in input).

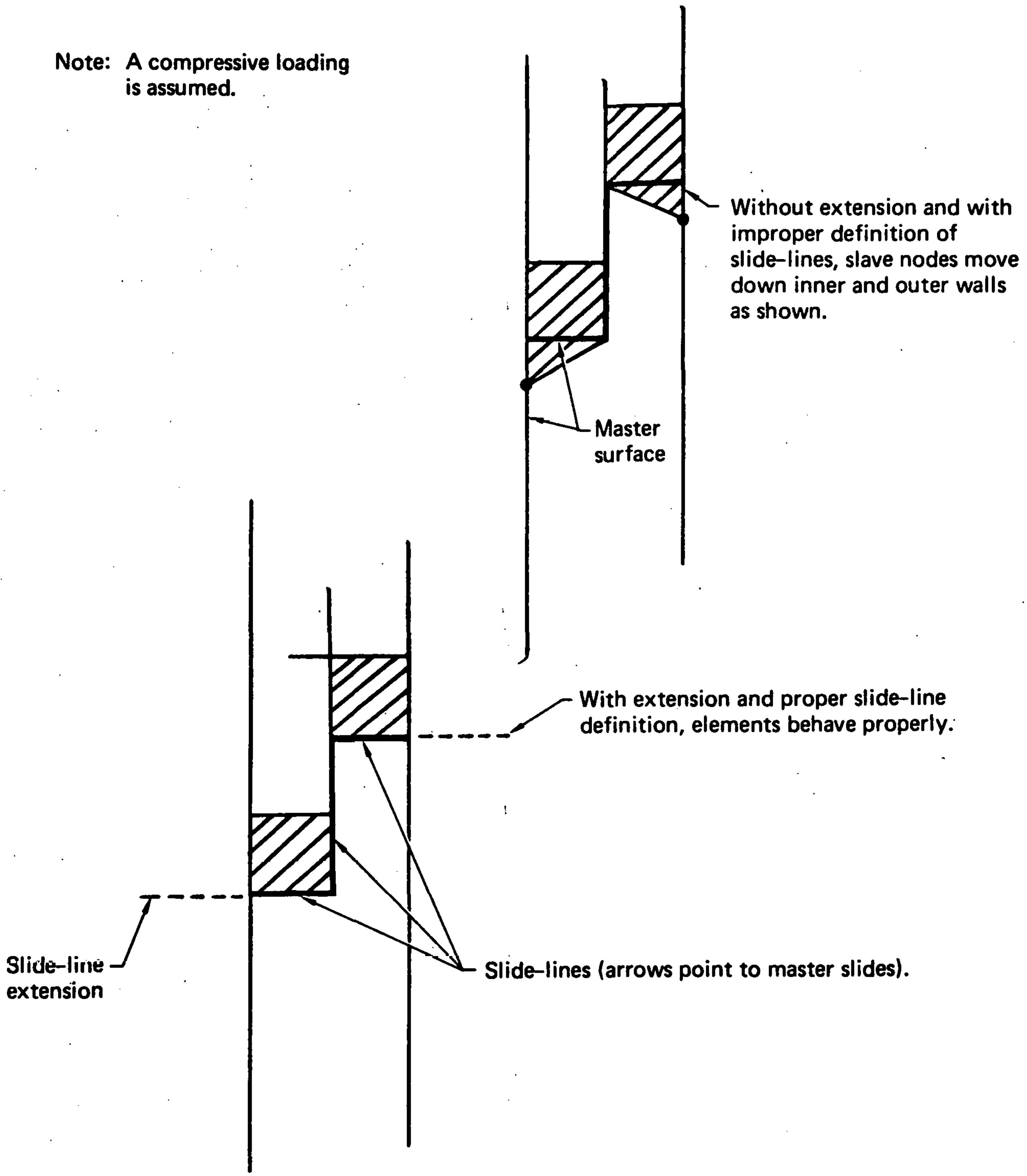


Fig. A3. Example of slide-line extensions helping to provide realistic response.

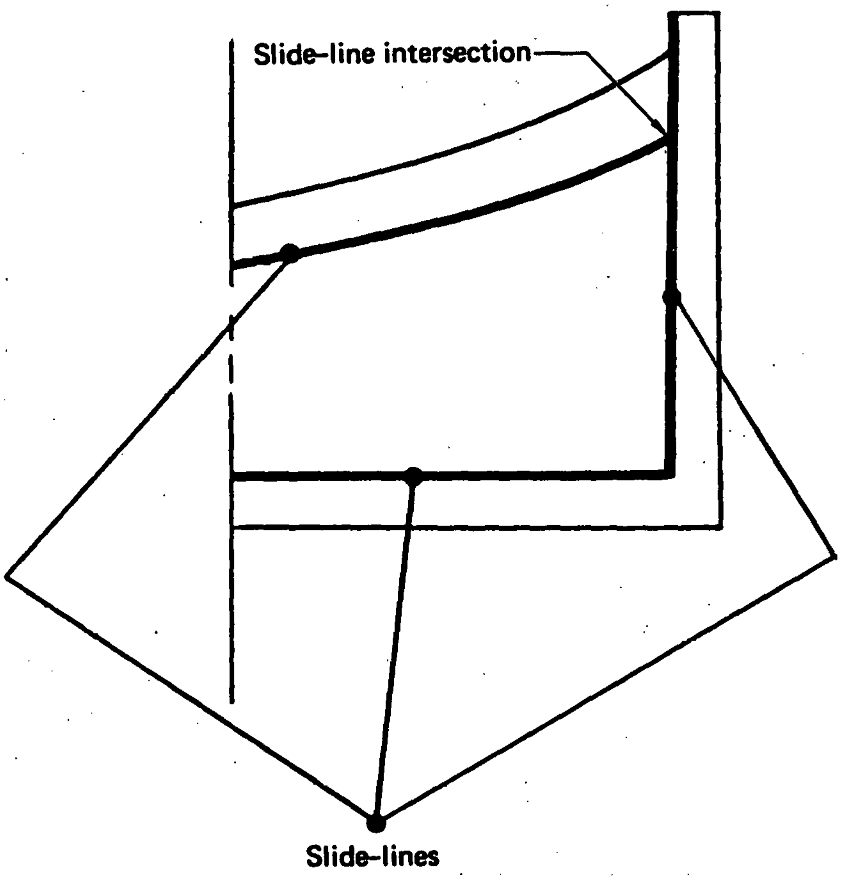


Fig. A4. Example of slide-line intersection.

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