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PRELIMINARY USER'S MANUALS FOR DYNA3D and DYNAP
(Nonlinear Dynamic Analysis of Solids in Three Dimensions)

J. O. Hallquist

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PRELIMINARY USER'S MANUALS FOR DYNA3D AND DYNAP
(Nonlinear Dynamic Analysis of Solids in Three Dimensions)

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ABSTRACT

DYNA3D is an explicit three-dimensional finite element code for analyzing the large deformation dynamic response of solids. Elastic-plastic and hyperelastic material behavior can be modeled. 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. In the near future a report will be released that will document the theory in considerable detail.

Post-processors for DYNA3D include SAMPPD for plotting deformed shapes and stress contours and DYNAP for plotting time histories of up to 9 quantities per node and 72 quantities per element. SAMPPD and DYNAP read the same set of familiar binary files which are generated by DYNA3D.

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BACKGROUND

DYNA3D, an explicit finite element code for analyzing the finite deformation dynamic response of three-dimensional hyperelastic and hypoelastic solids, has been recently developed. In this code, spatial discretization is achieved by the use of linear or quadratic cable, membrane, and solid elements, and the equations are integrated by the central difference method. Linear and quadratic bulk artificial viscosities are used to smooth shock fronts.

Five material models are presently implemented:

- 1) Elastic-plastic with isotropic work hardening — Wilkins,¹ Maenchen and Sack's,² formulation (small and large deformation theory),
- 2) Elastic-plastic with isotropic work hardening — Hartzman³ and Key's⁴ formulation (small and large deformation theory),
- 3) Soils and crushable foam — Key's formulation (small and large deformation theory),
- 4) Elastic (small and large deformation theory), and
- 5) Rubber (large deformation theory).

By opting for small deformation theory, a savings of nearly 40% in CPU charges can be achieved. Flexibility in the coding permits the mixing of elements based on large deformation theory with elements based on small deformation theory. If done properly, this feature can yield a considerable savings in CPU time with only a negligible loss in accuracy.

A variety of elements, some of which are shown in Figure 1, are presently available. These include the 4 to 8, 16, and 20 node solids, 3, 4, and 8 node membranes, and 2 node cables. Numerical integration is accomplished by a one point Gauss quadrature in the 8 node element, by an eight-

Figure 1. Some elements available in DYNA3D.

point Gauss quadrature in the quadratic 16 and 20 node elements, and by a four-point Gauss quadrature in the membrane elements.

Hourglass deformations do not occur in the 4, 16, and 20 node solid elements or in the 3, 4, and 8 node membrane elements, but can be a serious problem in the 8 node solids. A choice of two viscosities is provided to resist these deformation patterns.

The three-dimensional contact-impact algorithm is a simple and straightforward extension of the two-dimensional algorithm discussed in a recent report.⁵ As it is currently implemented, one surface of the interface is identified as a master surface whereas the other is identified as a slave surface. The master surface is defined by a set of four node quadrilateral segments, called master segments, on which the nodes of the slave surface, called slave nodes, must slide. Since the description of the master surface restricts the algorithm to four node membrane elements and eight node solid elements, some developmental effort is still needed. Input for the contact-impact algorithm requires that a list of master segments be defined along with a list of slave nodes. Internal logic identifies a master segment for each slave and updates this information every time step as the slave slides along the master surface. Three types of interfaces can presently be defined including

- 1) sliding,
- 2) tied,
- 3) sliding with gaps.

No limit exists in the logic on the number, type, or orientation of the contact surfaces. Stonewalls, which are discussed in the user's manual, should not be confused with the contact-impact algorithm.

Presently, the capacity of DYNA3D is controlled by and limited to 5000 nodal points; however, this can be expanded considerably with moderate effort. Storage allocation is dynamic so that no limit exists on the number of boundary condition codes, number of material cards, number of pressure cards, etc., which can be defined so long as the capacity of the computer is not exceeded.

Time histories of up to 9 nodal points and 72 element quantities can be plotted for each node and element by the post-processor, DYNAP. Output for *every node and element* is dumped by DYNA3D into automatically families, 1,000,000 octal long, binary files at intervals specified by the user. DYNAP is economical to run — even when a large number of files exist. As a result of this, the need for HSP (high speed printer) output has diminished.

A special version of SAMPP,⁶ called SAMPPD, has been developed for DYNA3D. This new version has highly optimized input and reads the families files directly. Hence, the need for the SAMID and SAMIS files has been eliminated. With minor exceptions, the interactive operation of SAMPPD is similar to that of SAMPP.

DYNA3D, DYNAP, and SAMPPD may be obtained and executed by typing

```
X GLGLIB DYNA3D / T V
```

```
X GLGLIB DYNAP FAMILY / T V
```

```
X GLGLIB SAMPPD FAMILY / T V
```

respectively, where FAMILY represents the six alpha-numeric characters that the families files,

FAMILY1, FAMILY2, ..., FAMILY11, ...

have in common. Input files named DIN and DYNAPI must be provided for DYNA3D and DYNAP. The format of these files is described in the following user's manuals.

INPUT FOR DYNA3D

I. TITLE Card (8A10)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-80	Heading to appear on output	1

II. Control Card (14I5)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Number of nodal points	
6-10	Number of boundary condition cards	
11-15	Number of materials used to describe cable elements	
16-20	Number of cable elements	
21-25	Number of materials used to describe membrane elements	
26-30	Number of 4-node membrane elements	2
31-35	Number of 8-node membrane elements	
36-40	Number of materials used to describe solid elements	
41-45	Number of 8-node solid elements	3
46-50	Number of 16-node solid elements	
51-55	Number of 20-node solid elements	
56-60	Number of pressure cards	
61-65	Number of pressure-time history points	
66-70	Number of stonewalls	

III. Nodal Point Cards (2I5, 3E10.0, 2I5)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Node number	
6-10	Boundary condition code	4
11-20	x coordinate	5
21-30	y (or r) coordinate	
31-40	z (or θ) coordinate	
41-50	Node increment k	6
46-50	Nonzero integer for cylindrical input	

IV. Boundary Condition Cards (3E10.0)

Supply the number of cards specified in columns 6-10 of the control card (Section II).

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	x coordinate of vector	7
11-20	y coordinate of vector	
21-30	z coordinate of vector	

V. Material and Cross-Sectional Property Cards for Cable Elements

Skip this section if the number in columns 11-15 of the control card (Section II) equals zero. Repeat cards 1-3 below for each material.

Card 1 (2I5, E10.0)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Material number	
6-10	Material type	8
11-20	Mass density	

Card 2 (8A10)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-80	Title to identify material	

Card 3 (3E10.0)

Material Model - Type 1

Elastic material behavior may be characterized with this model.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	Young's modulus	
11-20	Poisson's ratio	
21-30	Cross-sectional area of cable elements	

Material Model - Type 2

Hyperelastic (Mooney-Rivlin) material behavior may be characterized with this model.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	C_1	
11-20	C_2	
21-30	Cross-sectional area of cable elements	

VI. Cable Element Cards (5I5)

Skip this section if the number in columns 16-20 of the control card (Section II) equals zero.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Element number	
6-10	Material number	
11-15	Increment k	9
16-20	nodal point n_1	10
21-25	Nodal point n_2

Figure 2. Cable element.

VII. Material and Cross-Sectional Property Cards for Membrane Elements

Skip this section if the numbers in columns 21-25 of the control card (Section II) equals zero. Repeat cards 1-3 below for each material.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Material number	
6-10	Material type	11
11-20	Density	

Card 2 (8A10)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-80	Title to identify material	

Card 3 (3E10.0)

Material Model — Type 1

Hyperelastic (Mooney-Rivlin) material behavior may be characterized with this model.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	C_1	
11-20	C_2	
21-30	Thickness of membrane	

Material Model — Type 2

Hyperelastic (Blatz and Ko) material behavior may be characterized with this model.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	Shear modulus	
11-20	Blank	
21-30	Thickness of membrane	

VIII. Membrane Element Cards for 4-Node Elements (715)

Skip this section if the number in columns 26-30 of the control card (Section II) equals zero.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Element number	
6-10	Material number	
11-15	Increment k	9
16-20	Nodal point n_1	12
21-25	Nodal point n_2	
26-30	Nodal point n_3	
31-35	Nodal point n_4	

IX. Membrane Element Cards for 8-Node Elements (1115)

Skip this section if the number in columns 31-35 of the control card (Section II) equals zero.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Element number	
6-10	Material number	
11-15	Increment k	9
16-20	Nodal point n_1	13
21-25	Nodal point n_2	
26-30	Nodal point n_3	
.	.	
.	.	
.	.	
51-55	Nodal point n_8

Figure 3. Three and four node membrane elements.

Figure 4. Eight node membrane element.

X. Material Property Cards for Solid Elements

Skip this section if the number in columns 36-40 of the control card (Section II) equals zero. Repeat cards 1-8 below for each material.

Card 1 (2I5, E10.0)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Material number	
6-10	Material type	14
11-20	Density	

Card 2 (8A10)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-80	Title to identify material	

Cards 3-8 (5E10.0)

Material Model - Type 1

Elastic and elastic-plastic material with isotropic hardening may be characterized with this model. As explained in note 14, this model may be used with either the infinitesimal or finite strain formulations.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	Card 3 Young's modulus	15
1-10	Card 4 Poisson's ratio	
1-10	Card 5 Yield strength	
1-10	Card 6 Hardening modulus	
1-10	Card 7 Minimum pressure	
1-10	Card 8 C_1	
11-20	Card 8 C_2	
21-30	Card 8 C_3	

Material Model — Type 2

Elastic and elastic-plastic material with isotropic hardening may be characterized with this model. As explained in note 14, this model may be used with either the infinitesimal or finite strain formulations.

<u>Columns</u>		<u>Quantity</u>	<u>Note</u>
1-10	Card 3	Young's modulus	
1-10	Card 4	Poisson's ratio	
1-10	Card 5	Yield strength	
1-10	Card 6	Hardening modulus	
1-10	Card 7	Blank	
1-10	Card 8	Blank	

Material Model — Type 3

Soils and crushable foam may be characterized with this model. As explained in note 14, this model may be used with either the infinitesimal or finite strain formulations.

<u>Columns</u>		<u>Quantity</u>	<u>Note</u>
1-10	Card 3	Shear modulus	
11-20	Card 3	Bulk unloading modulus	16
21-30	Card 3	Yield function constant a_0	17
31-40	Card 3	Yield function constant a_1	
41-50	Card 3	Yield function constant a_2	
1-10	Card 4	Volumetric strain	16
11-20	Card 4	Pressure	
21-30	Card 4	Volumetric strain	
31-40	Card 4	Pressure	
1-10	Card 5	Volumetric strain	
11-20	Card 5	Pressure

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

<u>Columns</u>		<u>Quantity</u>	<u>Note</u>
21-30	Card 5	Volumetric strain	
31-40	Card 5	Pressure	
.	.	.	
.	.	.	
.	.	.	
1-10	Card 8	Volumetric strain	
11-20	Card 8	Pressure	
21-30	Card 8	Volumetric strain	
31-40	Card 8	Pressure	

Material Model — Type 4

Elastic material behavior may be characterized by this model. As explained in note 14 this material may be used with either the infinitesimal or finite strain formulations.

<u>Columns</u>		<u>Quantity</u>	<u>Note</u>
1-10	Card 3	Young's modulus	
1-10	Card 4	Poisson's ratio	
1-10	Card 5	Blank	

Card 8 Blank

Material Model — Type 5

Hyperelastic (Blatz and Ko) material behavior may be characterized with this model. As explained in note 14 this model may be used only with the finite strain formulation.

<u>Columns</u>		<u>Quantity</u>	<u>Note</u>
1-10	Card 3	Shear modulus

Figure 6. Four, six, and eight node solid elements.

<u>Columns</u>		<u>Quantity</u>	<u>Note</u>
1-10	Card 4	Blank	
	Card 8	Blank	

XI. Cards for 8-Node Solid Elements (11I5)

Skip this section if the number in columns 41-45 of the control card (Section II) equals zero.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Element number	
6-10	Material number	
11-15	Increment k	9
16-20	Nodal point n_1	
21-25	Nodal point n_2	18
26-30	Nodal point n_3	
.	.	
.	.	
.	.	
51-55	Nodal point n_8	

XII. Cards for 16-Node Solid Elements (16I5/3I5)

Skip this section if the number in columns 46-50 of the control card (Section II) equals zero.

<u>Columns</u>		<u>Quantity</u>	<u>Note</u>
1- 5	Card 1	Element number	
6-10	Card 1	Material number	
11-15	Card 1	Increment k	9
16-20	Card 1	Nodal point n_1	19

Figure 7. Sixteen-node solid element.

<u>Columns</u>		<u>Quantity</u>	<u>Note</u>
21-25	Card 1	Nodal point n_2	
76-80	Card 1	Nodal point n_{13}	
1- 5	Card 2	Nodal point n_{14}	
6-10	Card 2	Nodal point n_{15}	
11-15	Card 2	Nodal point n_{16}	

XIII. Cards for 20-Node Solid Elements (16I5/7I5)

Skip this section if the number in columns 51-55 of the control card (Section II) equals zero.

<u>Columns</u>		<u>Quantity</u>	<u>Note</u>
1- 5	Card 1	Element number	
6-10	Card 1	Material number	
11-15	Card 1	Increment k	9
16-20	Card 1	Nodal point n_1	20
21-25	Card 1	Nodal point n_2	
76-80	Card 1	Nodal point n_{13}	
1- 5	Card 2	Nodal point n_{14}	
6-10	Card 2	Nodal point n_{15}	
31-35	Card 2	Nodal point n_{20}

Figure 8. Twenty-node solid element.

Card 2 (8E10.0)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	Pressure multiplier at n_1	24
11-20	Pressure multiplier at n_2	
.	.	
.	.	
.	.	
71-80	Pressure multiplier at n_8	

XV. Pressure-Time History (2E10.0)

Supply the number of cards specified in columns 61-65 of the control card (Section II).

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	Time	25
11-20	Pressure	

XIV. Element Pressure Cards

Supply the number of cards (in pairs) specified in columns 56-60 of the control card (Section II).

Card 1 (2I5, E10.0, 8I5)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Pressure card number	
6-10	Increment k	21
11-20	Start time	22
21-25	Nodal point n_1	23
26-30	Nodal point n_2	
.	.	
.	.	
.	.	
56-60	Nodal point n_8

Figure 9. Nodal numbering for pressure cards. Positive pressure acts in negative t -direction.

XVI. Stonewall Cards

Skip this section if the number in columns 66-70 of the control card (Section II) equals zero. Repeat the following set of cards for each stonewall.

Card 1 (I5, 6E10.0)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Number of slave nodes	26
6-15	x coordinate of tail of any outward drawn normal vector originating on wall (tail) and terminating in space (head)	27
16-25	y coordinate of tail	
26-35	z coordinate of tail	
36-45	x coordinate of head	
46-55	y coordinate of head	
56-65	z coordinate of head	

Cards 2, 3, ..., etc. (2I5)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Slave number	28
6-10	Nodal point number	

XVII. Initial Velocity Conditions (I5, 3E10.0, 2I5)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Nodal point number	
6-15	Initial velocity in x direction	
16-25	Initial velocity in y (or r) direction	29
26-35	Initial velocity in z direction (or angle θ)	
36-45	Increment	
46-50	Nonzero integer for cylindrical input	

XVIII. Printing Interval (3E10.0)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	Initial output time	30
11-20	Final output time (calculations cease)	
21-30	Output interval	

XIX. Plotting Interval for Time Histories and Deformed Shapes (3E10.0)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	Initial output time	31
11-20	Final output time	
21-30	Output interval	

XX. Printed (HSP) Output — Nodes (16I5)

If this card is left blank no nodal information is printed. Up to 16 nodes may be specified.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	First node to be printed	
6-10	Second node to be printed	
11-15	Third node to be printed	
.	.	.
.	.	.
.	.	.

XXI. Printed (HSP) Output Elements (16I5/16I5)

If these cards are left blank no element strain information is printed. Up to 16 elements may be specified.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Card 1 Element type	32
6-10	Card 1 Element number	

<u>Columns</u>		<u>Quantity</u>	<u>Note</u>
1-15	Card 1	Element type	
.		.	
.		.	
.		.	
76-80	Card 1	Element number	
1- 5	Card 2	Element type	
6-10	Card 2	Element number	
.		.	
.		.	
.		.	
71-75	Card 2	Element type	
76-80	Card 2	Element number	

XXII. Viscosity Coefficient Card (3E10.0)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	Quadratic bulk viscosity coefficient	33
11-20	Linear bulk viscosity coefficient	
21-30	Hourlgass viscosity coefficient	

XXIII. Control Card for Contact-Impact Algorithm (3I5)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Number of master surfaces	
6-10	Total number of master segments	34
11-15	Total number of slave nodes	35

XXIV. Master Segment and Slave Node Definitions

Skip this section if the numbers in columns 1-5 of the preceeding control card (Section XXIII) equals zero. Repeat the following set of cards for each master surface.

Card 1 (3I5)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Type	36
6-10	Number of master segments (NMS)	
11-15	Number of slave nodes (NSN)	

Cards 2, 3, ..., NMS+1 (6I5)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Segment number	
6-10	Increment k	37
11-15	Nodal point n_1	38
16-20	Nodal point n_2	
21-25	Nodal point n_3	
26-30	Nodal point n_4	

Cards NMS+2, NMS+3, ..., etc. (2I5)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Slave number	28
6-10	Nodal point number

(a)

(b)

Figure 10. Numbering of master segments.
(a) Slave surface above master surface;
(b) Slave surface below master surface.

NOTES

- (1) The first six letters of this title are used to form the root name of the system of families of files which are generated for the time-history plots. If, for example, the first word on the heading card was PROBLEM the families of files would be generated as:

PROBLE1, PROBLE2, ..., etc.

For this procedure to work properly, columns 1-6 must contain alphanumeric characters.

- (2) Include 3-node membrane elements in this total.
- (3) Include 4-7 node solid elements in this total.
- (4) The boundary condition code is set as follows:
0	—	unconstrained
1	—	constrained in global x direction
2	—	constrained in global y direction
3	—	constrained in global z direction
4	—	constrained in x and y directions
5	—	constrained in y and z directions
6	—	constrained in z and x directions
7	—	constrained in x, y, and z directions
8	—	constrained in direction specified on the first boundary condition card read in below.
9	—	constrained in direction specified on the second boundary condition card read in below

- (5) Coordinates can be generated in a cylindrical (r, θ, z) coordinate frame. In this case, the body is assumed to be rotated about the x axis such that

$$x = z$$

$$y = r \cos \theta$$

$$z = r \sin \theta$$

Cylindrical generation is activated by placing a nonzero integer in column 50.

- (6) Nodal point cards do not need to be in order; however, the last nodal point number must terminate the nodal data. Whenever nodal data is missing, node numbers are generated according to the sequence

$$n_i, n_i + k, n_i + 2k, \dots, n_j$$

where n_i and n_j are the nodal numbers defined on two consecutive cards. Linear interpolation is used to obtain the coordinates of the generated nodes. The boundary condition code is set to zero whenever the boundary condition code of n_i differs from that of n_j . Unconstrained nodes can be generated between constrained nodes that have the same boundary condition by setting the code on one of the two cards negative. After the nodal data is generated, the signs of all negative boundary condition codes are reset. It should be noted that the default value of k is 1.

- (7) Any node may be constrained to move on an arbitrarily oriented plane. Each boundary condition card defines a normal vector to this plane originating at $(0., 0., 0.)$ and terminating at the specified coordinates. Since an arbitrary magnitude is assumed for this vector, the specified coordinates are not unique.

- (8) Two material models are available for cable elements:

Type 1 — finite deformation elastic material

Type 2 — finite deformation, hyperelastic, incompressible, Mooney-Rivlin material

- (9) Element cards are assumed to be in element number sequence.

Omitted data is automatically generated with respect to the first card prior to the omitted data as follows:

$$n_j^{i+1} = n_j^i + k$$

The material properties for the generated elements and the mesh generation parameter k are taken from the first card. The default value of k is 1. Element numbering begins with 1 for each element type.

- (10) Each cable element begins at node n_1 and terminates at node n_2 as shown in Figure 2.

- (11) Two material models are available for membrane elements.

Type 1 — finite deformation, hyperelastic, incompressible, Mooney-Rivlin material.

Type 2 — finite deformation, hyperelastic, compressible, Blatz and Ko (rubber-like) material.

- (12) Nodal points $n_1 - n_4$ define the corner nodes of the membrane element. Three node elements are specified by repeating a node.

Three and four node membrane elements are shown in Figure 3.

- (13) Nodal points $n_1 - n_4$ define the corner nodes of the 8-node membrane elements. Node 5 lies between nodes 1 and 2, node 6 lies between

nodes 2 and 3, and so on. Eight node membrane elements are illustrated in Figure 4.

(14) Five material models are available for solid elements.

Type 1 — elastic-plastic with isotropic hardening^{1,2}

Type 2 — elastic-plastic with isotropic hardening^{3,4}

Type 3 — soil and crushable foam

Type 4 — elastic

Type 5 — finite deformation, hyperelastic, compressible, Blatz and Ko (rubber-like) material.

Types 1 - 4 can be used in both the infinitesimal and finite strain formulations. As indicated type 5 applies only for finite strains. If the strains and rotations are known to be small, the infinitesimal strain formulation, which is activated by specifying the material type with a negative integer, can be used thereby saving a considerable amount of computer time. Infinitesimal and finite strain elements can be mixed within the same mesh.

(15) For elastic-plastic behavior with isotropic hardening and a linear pressure-volumetric strain relationship only cards 3 - 6 need to be defined with cards 7 and 8 left blank. The yield strengths are always defined as positive numbers. Also, the following rule holds:

- a. If card 5 is left blank an elastic analysis is assumed.
- b. If card 6 is left blank, elastic-plastic behavior is obtained.

- c. If card 7 is left blank or if C_1 on card 8 is zero, a minimum pressure of negative infinity is assumed.
- d. If columns 1-10 of card 8 are nonzero, the pressure, p , is calculated from the expression

$$p = C_1\mu + C_2\mu^2 + C_3\mu^3$$

where

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

and ρ/ρ_0 is the ratio of current density over initial density.

(16) See Figure 5.

(17) The deviatoric yield function ϕ is described in terms of the second invariant J_2 , pressure p , and constants a_0 , a_1 , and a_2 as:

$$\phi = J_2 - (a_0 + a_1p + a_2p^2)$$

Tensile fracture is assumed to occur when

$$p < mr$$

where mr is the minimum root of the polynomial

$$a_0 + a_1p + a_2p^2$$

(18) Nodal points $n_1 - n_8$ define the corner nodes of the 8-node solid elements. Elements having fewer than 8 nodes are obtained by repeating one or more nodes. Four, six, and eight node elements are shown in Figure 6. Input of nodes on the element cards for the former two elements would take the form

4-node n_1 n_2 n_3 n_4 n_4 n_4 n_4 n_4

6-node n_1 n_2 n_3 n_4 n_5 n_5 n_6 n_6

- (19) Nodal points $n_1 - n_8$ define the corner nodes of the 16-node solid element. Nodes 9 - 16 appear on the edges as shown in Figure 7. This element has very poor bending characteristics and should be used cautiously.
- (20) Nodal points $n_1 - n_8$ define the corner nodes of the 20-node solid element. Nodes 9 - 20 appear on the edges as shown in Figure 8. This element has good bending characteristics. Often it is permissible to use one of these elements across a shell thickness.
- (21) Pressure cards are assumed to be in sequence. Omitted data is automatically generated with respect to the first card prior to the omitted data as

$$n_j^{i+1} = n_j^i + k$$

The start times, pressure multipliers, and generation parameter k are all taken from the first card. The default value of k is 1.

- (22) At this time the pressure begins acting on the surface.
- (23) Generally, the surface of an element can have either 3, 4, 6, or 8 nodes. When the surface has 3 or 4 nodes, entries $n_5 - n_8$ must be set to zero. Likewise, when the surface has six node entries, n_7 and n_8 must be entered as zero. Surfaces having 3 nodes are denoted by repeating one of the nodes. Figure 9 shows the numbering sequence for 4, 6, and 8 nodes. This sequence must be adhered to.
- (24) For each nonzero nodal point entry on card 1 a pressure multiplier should be entered. The use of this multiplier permits linear (in the case of 4-node surfaces) or quadratic (in the case of 8-node surfaces) variations of the pressure over the surface of the element.

- (25) The time must begin at 0.0. After the last time the pressure is taken as zero.
- (26) A slave node cannot penetrate a "stonewall," other nodes can.
- (27) A stonewall is a planar surface which extends to infinity in every direction. It is defined by a normal vector of arbitrary magnitude drawn outward from the wall.
- (28) Omitted data is automatically generated by incrementing the nodal point numbers by

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

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

- (29) Velocity can be specified in a cylindrical (r, θ, z) coordinate system. In this case the body is assumed to be rotated about the x axis such that

$$v_x = v_z$$

$$v_y = v_r \cos \theta$$

$$v_z = v_r \sin \theta$$

Cylindrical generation is activated by a nonzero integer in column 50.

- (30) Nodal quantities and element stresses but not strains can be printed for up to 16 nodes and elements. Since time histories of every nodal and elemental quantity can be obtained by running DYNAP, the use of HSP output medium is discouraged.
- (31) Data is printed for every node and zone in the mesh. The post processor DYNAP is available to plot time histories of nodal and elemental quantities and SAMPPD is available to plot deformed shapes.

- (32) Elements are identified by specifying a pair of numbers. The first designates the element type:

Type 1 — truss elements

Type 2 — 3 and 4 node membrane elements

Type 3 — 8 node membrane elements

Type 4 — 4 to 8 node solid elements

Type 5 — 16 node solid elements

Type 6 — 20 node solid elements

and the second gives the element number.

- (33) The default values for the quadratic and linear bulk viscosity coefficients are 1.2 and 0.06, respectively. The hourglass viscosity coefficient defaults to 0.0. This latter viscosity is used only for the 8-node solid elements since it may cause instabilities if fewer than 8 nodes are used. Higher order elements such as the 16 and 20 node solid do not experience the hourglass deformations. The use of hourglass viscosity should be avoided, but if it is used a value of magnitude 0.10 should be adequate. A positive value defaults to a HONDO-⁴ like formulation whereas a negative value defaults to a HEMP-¹ like formulation.

- (34) Sum NMS (Section XXIV, Card 1, Cols. 6-10) over the number of master surfaces.

- (35) Sum NSN (Section XXIV, Card 1, Cols. 11-15) over the number of master surfaces.

- (36) Three types are considered:

Type 1 — sliding

Type 2 — tied sliding

Type 3 — sliding and voids.

- (37) Master segment cards are assumed to be in sequence (though the particular number assigned to a master segment is arbitrary). Omitted data is automatically generated with respect to the first card prior to the omitted data as

$$n_j^{i+1} = n_j^i + k$$

The generation parameter k is taken from the first card.

- (38) Nodal numbering is counter clockwise. Nodal points $n_1 - n_4$ define the corner nodes of the master segment (see Figure 10).

INPUT FOR DYNAP

I. Box and ID (3A10)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-30	Type Box "ann" and any suitable identification	

II. Control Card (15, 3E10.0)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Number of ordinate cards	
6-15	Minimum time (first output time)*	
16-25	Maximum time (last output time)	
26-35	Scale factor for gravity (386.4 in/sec ²)	

III. Nodal Points for which Time History Plots are Desired (16I5)

If no nodal point time history plots are desired insert one blank card.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Nodal numbers	
6-10		
11-15		

IV. Elements for which Stress and Effective Plastic Strain History Plots Are Desired (16I5)

If no element time history plots of these quantities are desired, insert one blank card.

* Numbers in parentheses are the default values.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Element type	1
6-10	Element number	
11-15	Element type	
16-20	Element number	
.	.	
.	.	
.	.	

V. Elements for which Strain and Strain Rate Time History Plots are Desired (16I5)

If no element time history plots of these quantities are desired, insert one blank card. Element type numbers must be between 4 and 6 inclusive.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1- 5	Element type	1
6-10	Element number	
11-15	Element type	
16-20	Element number	
.	.	
.	.	
.	.	

VI. Ordinate Cards (2E10.0, A10, E10.0)

Supply the number of cards specified in columns (11-15) of the control card.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
1-10	Minimum ordinate value	2
11-20	Maximum ordinate value	
21-30	Additional label to appear on ordinate	
31-40	Scale factor for data	

Note: The ordering of the cards described in Sections VII - X below is arbitrary. Furthermore, no limits exist on the number of cards which may be defined.

VII. Nodal Time Plots (3XA2, 13I5)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
3- 5	Type "NT"	
6-10	Component to be plotted	3
11-15	Ordinate card	4
16-20	Nonzero integer for smoothing	5
21-25	First node to be plotted	6
26-30	Second node to be plotted	
.	.	
.	.	
.	.	
66-70	Tenth node to be plotted	

VIII. Nodal Relative Plots (3XA2, 5I5)

These plots give the time history of the difference of the same quantity at any two nodal points. The quantity at the second node specified is subtracted from the same quantity at the first node specified.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
3- 5	Type "NR"	
6-10	Component to be plotted	3
11-15	Ordinate Card	4
16-20	Nonzero integer for smoothing	5
21-25	First node	
26-30	Second node	

IX. Element Time Plots (3XA2, 12I5)

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
3- 5	Type "ET"	
6-10	Component to be plotted	7
11-15	Ordinate card	4
16-20	Nonzero integer for smoothing	5
21-25	Element type	1
26-30	First element to be plotted	8
31-35	Second element to be plotted	
61-65	Eighth element to be plotted	

X. Energy and Momentum Plots (3XA2, I5)

These plots provide a means of checking on the solution. Global plots of kinetic energy, external work minus internal energy, total energy, rigid body velocities, and accelerations can be obtained.

<u>Columns</u>	<u>Quantity</u>	<u>Note</u>
3- 5	Type "EM"	
6-10	Component to be plotted	9

XI. Termination Card

Insert blank card.

NOTES

- (1) Elements are identified by specifying a pair of numbers. The first designates the element type:

Type 1 — truss elements

Type 2 — 3 and 4 node membrane elements

Type 3 — 8 node membrane elements

Type 4 — 4 to 8 node solid elements

Type 5 — 16 node solid elements

Type 6 — 20 node solid elements

and the second gives the element number.

- (2) Ordinate cards are not required. If they are not used the data is searched to establish the minimum and maximum values of the ordinate.

- (3) The components and their definitions can be tabulated as follows:

Component 1 — x displacement

Component 2 — y displacement

Component 3 — z displacement

Component 4 — x velocity

Component 5 — y velocity

Component 6 — z velocity

Component 7 — x acceleration

Component 8 — y acceleration

Component 9 — z acceleration

- (4) If no ordinate card is specified, the data is searched to establish the minimum and maximum values of the ordinate.

- (5) Each data point is replaced by an average of adjacent points. The number of points used in the averaging process is twice the number specified in columns 16-20.
- (6) Up to ten nodal points may be specified on each card. All time history plots appear on the same graph.
- (7) The components and their definitions can be tabulated for each element type as follows:

Type 1 Cable Element

- Component 1 — Axial force
- Component 2 — Axial stress
- Component 3 — Principal stretch ratio

Type 2-3 Membrane Elements

- Component 1 — Lagrange stress, T^{rx}
- Component 2 — Lagrange stress, T^{ry}
- Component 3 — Lagrange stress, T^{rz}
- Component 4 — Lagrange stress, T^{sx}
- Component 5 — Lagrange stress, T^{sy}
- Component 6 — Lagrange stress, T^{sz}

Type 4-6 Solid Elements

- Component 1 — σ_{xx} Cauchy stress
- Component 2 — σ_{yy}
- Component 3 — σ_{zz}
- Component 4 — σ_{xy}
- Component 5 — σ_{yz}
- Component 6 — σ_{zx}
- Component 7 — Effective plastic strain
- Component 8 — Pressure

- Component 9 — Effective stress
- Component 10 — S_{11} maximum principal deviator stress
- Component 11 — S_{22}
- Component 12 — S_{33} minimum principal deviator stress
- Component 13 — Maximum shear stress
- Component 14 — σ_{11} maximum principal stress
- Component 15 — σ_{22}
- Component 16 — σ_{33} minimum principal stress
- Component 17 — E_{xx} Green-St Venant strain at the integration points
- Component 18 — E_{yy}
- Component 19 — E_{zz}
- Component 20 — E_{xy}
- Component 21 — E_{yz}
- Component 22 — E_{zx}
- Component 23 — e_{xx} infinitesimal strains at the integration points
- Component 24 — e_{yy}
- Component 25 — e_{zz}
- Component 26 — e_{xy}
- Component 27 — e_{yz}
- Component 28 — e_{zx}
- Component 29 — E_{xx} Green-St Venant strains at the 8 corner points*
- Component 30 — E_{yy}
- Component 31 — E_{zz}

* Strain quantities can be obtained at the corner nodes in the 16 and 20 node solid elements. This option does not apply to the 8 node solid element.

Component 32	—	E_{xy}	
Component 33	—	E_{yz}	
Component 34	—	E_{zx}	
Component 35	—	e_{xx}	infinitesimal strains at the 8 corner nodal points*
Component 36	—	e_{yy}	
Component 37	—	e_{zz}	
Component 38	—	e_{xy}	
Component 39	—	e_{yz}	
Component 40	—	e_{zx}	
Component 41	—	$\dot{e}_{xx}$	strain rates at the integration points
Component 42	—	$\dot{e}_{yy}$	
Component 43	—	$\dot{e}_{zz}$	
Component 44	—	$\dot{e}_{xy}$	
Component 45	—	$\dot{e}_{yz}$	
Component 46	—	$\dot{e}_{zx}$	
Component 47	—	ω_{zz}	spin in the xy plane
Component 48	—	ω_{xx}	spin in the yz plane
Component 49	—	ω_{yy}	spin in the zx plane
Component 50	—	$\dot{e}_{xx}$	strain rates at the 8 corner points*
Component 51	—	$\dot{e}_{yy}$	
Component 52	—	$\dot{e}_{zz}$	
Component 53	—	$\dot{e}_{xy}$	
Component 54	—	$\dot{e}_{yz}$	
Component 55	—	$\dot{e}_{zx}$	

* Strain quantities can be obtained at the corner nodes in the 16 and 20 node solid elements. This option does not apply to the 8 node solid element.

- Component 56 — ω_{zz} spin in the xy plane
- Component 57 — ω_{xx} spin in the yz plane
- Component 58 — ω_{yy} spin in the zx plane
- Component 59 — $\rho/\rho_0 - 1$ integration points
- Component 60 — $\rho/\rho_0 - 1$ corner nodes*
- Component 61 — E_{11} maximum principal Green-St Venant strain at the integration points
- Component 62 — E_{22}
- Component 63 — E_{33} minimum principal strain
- Component 64 — e_{11} maximum principal infinitesimal strain at the integration points
- Component 65 — e_{22}
- Component 66 — e_{33} minimum principal strain
- Component 67 — E_{11} maximum principal Green-St Venant strain at the 8 corner nodal points*
- Component 68 — E_{22}
- Component 69 — E_{33} minimum principal strain
- Component 70 — e_{11} maximum principal infinitesimal strain at the 8 corner nodal points*
- Component 71 — e_{22}
- Component 72 — e_{33} minimum principal strain

- (8) If the type number of the element lies between 1 and 4 inclusive, up to eight elements may be specified, otherwise, the limit is one. This difference is due to the fact that eight time histories are plotted per graph per element of types 5 and 6, that is, one time history per integration (or nodal) point.

* Strain quantities can be obtained at the corner nodes in the 16 and 20 node solid elements. This option does not apply to the 8 node solid element.

(9) The components and their definitions can be tabulated as follows:

- Component 1 - Kinetic energy
- Component 2 - External work minus internal energy
- Component 3 - Total energy
- Component 4 - x rigid body velocity
- Component 5 - y rigid body velocity
- Component 6 - z rigid body velocity
- Component 7 - x rigid body acceleration
- Component 8 - y rigid body acceleration
- Component 9 - z rigid body acceleration

* Strain quantities can be obtained at the corner nodes in the 16 and 20 node solid element. This option does not apply to the 8 node solid element.

EXAMPLES

Bar Impact Problem

In this first example the elastic impact of the two identical bars shown in Figure 11 is considered. Fifty eight-node solid elements are used to model each bar. An initial gap of 0.04 in. exist between the bars. At the contact interface, the slave and master surfaces are defined to belong to bar #1 and bar #2, respectively. A listing of the input data is provided in Figure 12.

Several results were plotted with DYNAP. In Figures 13 and 14 the velocity and displacement time histories of a pair of interface nodes are given. Figure 15 shows the stress in element 51, the interface element in bar #2. From the plot of the total energy in Figure 16 a slight energy loss can be discerned; however, the momentum in the x-direction is conserved exactly as Figure 17 demonstrates. The foregoing results are in good agreement with the exact analytical solution. Input data for DYNAP is given in Figure 18.

Quantity	Bar #1	Bar #2
Initial x-velocity	600.0	0.0 in./sec
Density	0.001	0.001 lb-sec ² /in ⁴
Young's Modulus	10 ⁷	10 ⁷ psi
Poisson's Ratio	0.0	0.0
Cross-Section Area	1.0	1.0 in ²

Figure 11. Elastic impact of two identical bars.

```

1  IMPACT OF 1-D BARS IN THREE DIMENSIONS
2    408    0    0    0    0    0    0    1    100
3      1    5      0.      0.      0.
4     51    5      50.      0.      0.
5     52    5      50.04     0.      0.
6    102    5      100.04     0.      0.
7    103    5      0.      0.      1.
8    153    5      50.      0.      1.
9    154    5      50.04     0.      1.
10   204    5      100.04     0.      1.
11   205    5      0.      1.      1.
12   255    5      50.      1.      1.
13   256    5      50.04     1.      1.
14   306    5      100.04     1.      1.
15   307    5      0.      1.      0.
16   357    5      50.      1.      0.
17   358    5      50.04     1.      0.
18   408    5      100.04     1.      0.
19     1    1      .001
20  ELASTIC MATERIAL
21  10000000.
22
23
24
25
26
27     1    1    1    1    103    205    307    2    104    206    308
28     51    1    1    52    154    256    358    53    155    257    359
29    100    1    0    101    203    305    407    102    204    306    408
30     1      600.
31     51      600.
32     52
33    102
34    103      600.
35    153      600.
36    154
37    204
38    205      600.
39    255      600.
40    256
41    306
42    307      600.
43    357      600.
44    358
45    408
46      0. .001500 .001500
47      0. .001500 .000015
48
49
50
51    15.0 .10
52     1    1    4
53     3    1    4
54     1    1    52    154    256    358
55     1    51
56     4    357

```

Figure 12. Input data.

IMPACT OF 1-D BARS IN THREE DIMENSIONS
 NODE A 51 B 52

Figure 13. Velocity time histories of two interface nodes.

IMPACT OF 1-D BARS IN THREE DIMENSIONS
NODE A 51 B 52

Figure 14. Displacement time histories of two interface nodes.

IMPACT OF 1-D BARS IN THREE DIMENSIONS
TYPE=4 ELEMENT 51

Figure 15. Stress time history of interface element.

IMPACT OF 1-D BARS IN THREE DIMENSIONS

Figure 16. Conservation of energy.

IMPACT OF 1-D BARS IN THREE DIMENSIONS
RIGID BODY 0

Figure 17. Rigid body x-velocity (conservation of mometum).

```
1 HALLQUIST BOX 114
2
3     51     52
4     4     51
5
6     NT     1     Ø     Ø     51     52
7     NT     4     Ø     Ø     51     52
8     ET     1     Ø     Ø     4     51
9     EM     3
10    EM     4
11
```

Figure 18. Input for DYNAP.

Impact of Cylinder into Rail

In this problem the steel cylinder shown in Figure 18 is impacted into a long rigid rail at 660 in./sec. Attached to the ends of this cylinder are weights weighing 140 pounds apiece. An experimental test of a similar configuration was recently carried out. A detailed discussion of this calculation in light of the experimental data will be made in a forthcoming report.⁷ Here, only enough information is given to inform potential users of the capability of DYNA3D.

Figure 18. Weighted steel cylinder which impacts a 1.5 inch rail at 660 in./sec.

Because of two planes of symmetry, one quarter of the cylinder was modeled in the mesh illustrated in Figure 19. This mesh contains 160 elements of which 140 are of the 20 node type. Twenty 16 node bricks were used to model the rigid end mass. Elastic-perfectly plastic behavior was assumed for the steel, which had a yield strength of 190,000 psi.

Figure 19. Finite element discretization.

Deformed shapes at approximately millisecond increments are shown in Figures 20 and 21. At 6.4 ms the cylinder can be seen to have completely rebounded with its final deformed shape. A maximum residual dent of 1.5 inches was calculated as demonstrated in Figure 22 where the displacement of node 1218 is subtracted from node 38 (see Figure 19). A maximum dent of 1.44 inches was measured at the same location in the experimental test. Plots of the kinetic, internal, and total energy are shown in

$t = 0.0 \text{ ms}$

$t = 1.0 \text{ ms}$

$t = 2.0 \text{ ms}$

$t = 3.0 \text{ ms}$

$t = 4.0 \text{ ms}$

$t = 6.4 \text{ ms}$

Figure 20. Deformed shapes of cylinder impacting rail.

Figure 21. Deformed shapes of cylinder impacting rail.

1.538

STEEL CYLINDER DROP TEST 55FT/SEC INTO A 1.5IN RAIL
NODE 38 - 1218

Figure 22. Calculated maximum residual dent.

Figures 23, 24, and 25, respectively. Ninety percent of the energy was expended in plastic work. Plots of the rigid body velocity (momentum) and acceleration are given in Figures 26 and 27.

Figure 23. Kinetic energy.

STEEL CYLINDER DROP TEST 55FT/SEC INTO A 1.5IN RAIL
RIGID BODY 0

Figure 24. Internal energy.

STEEL CYLINDER DROP TEST 55FT/SEC INTO A 1.5IN RAIL
RIGID BODY 0

Figure 25. Conservation of energy.

STEEL CYLINDER DROP TEST 55FT/SEC INTO A 1.5IN RAIL
RIGID BODY 0

Figure 26. Rigid body x-velocity (conservation of momentum).

STEEL CYLINDER DROP TEST 55FT/SEC INTO A 1.5IN RAIL
RIGID BODY 0.

Figure 27. Rigid body x-acceleration in g's.

Inflation of a Thin Membrane into a Thick-Walled Cylinder

In this third example, which was used to debug the contact-impact algorithm, the thin membrane shown in Figure 28 is inflated by a uniform step pressure of 2 psi into a thick-walled cylinder. Though lacking in physical significance, the choice of material properties and pressure loading allowed an execution time of under one minute. A total of 100 membranes and 150 solid elements were used. A sequence of deformed shapes are provided in Figure 29. During the time frame considered, the massive thick-walled cylinder barely moves, but considerable sliding occurs. Rotated views of the deformed shape at time $t = 0.18$ in. Figure 30 shows no penetration of the membrane into the cylinder.

Figure 28. Inflation of thin membrane into a thick-walled cylinder.

Figure 29. Deformed configurations at selected output times.

$t = 0.12 \text{ sec}$

$t = 0.14 \text{ sec}$

$t = 0.18 \text{ sec}$

$t = 0.20 \text{ sec}$

Figure 29. (Continued)

Figure 30. Rotated view of the deformed shape at time $t = 0.18$ sec..

DISCUSSION

Three dimensional problems often require much computation time; consequently, some mention should be made here concerning expected run times. The execution speeds of several representative elements are given below in CPU minutes per million mesh cycles on the CDC 7600 computer.

<u>Element</u>	<u>min/10⁶ CPU mesh cycles</u>
8-node solid without hourglass control	~12
8-node solid with hourglass control	~37
16 and 20-node solid elements	~183

Since the 20-node solid element is probably equivalent to at least twelve 8-node solid elements and since it does not experience the severe hourglass problem inherent in the 8-node solid, it becomes a very useful and efficient element. It should be noted that the above CPU times can be reduced from 30% to 40% if small deformation theory is assumed.

Post-processing is considerably less expensive than the actual calculation. For example, in the cylinder impact problem only 20 seconds of CPU time was needed to read through the families files and generate approximately 20 time history plots. Nineteen, 1,000,000 octal families files were generated in this calculation.

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