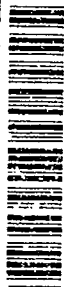


AD-A243 527



WL-TR-91-3006

DTIC  
S ELECTE D  
DEC 18 1991  
C

**EXPLICIT FINITE ELEMENT METHOD FOR  
TRANSPARENCY IMPACT ANALYSIS**



R. A. Brockman  
T. W. Held

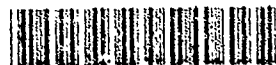
University of Dayton Research Institute  
Dayton, Ohio 45469-0110

June 1991

Final Report for Period September 1988 - September 1990

Approved for public release; distribution unlimited

**91-18064**



FLIGHT DYNAMICS DIRECTORATE  
WRIGHT LABORATORY  
AIR FORCE SYSTEMS COMMAND  
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6553

91 1216 026

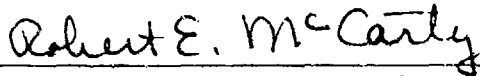
## NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder, or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

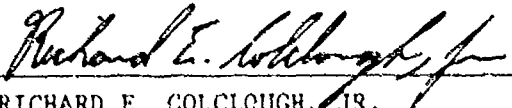
This report is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

  
\_\_\_\_\_  
RICHARD A. SMITH  
Aerospace Engineer

  
\_\_\_\_\_  
ROBERT E. MCCARTY, Supervisor  
Aircrew Protection Branch

FOR THE COMMANDER

  
\_\_\_\_\_  
RICHARD E. COLCLOUGH, JR.  
Chief  
Vehicle Subsystems Division

If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify WL/FIVR, WPAFB, OH 45433-6553 to help us maintain a current mailing list.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |       |                                                 |                                                                                                   | Form Approved<br>OMB No. 0704-0188                 |                               |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------------------------------------------------|---------------------------------------------------------------------------------------------------|----------------------------------------------------|-------------------------------|
| 1a. REPORT SECURITY CLASSIFICATION<br>Unclassified                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |       |                                                 | 1b. RESTRICTIVE MARKINGS                                                                          |                                                    |                               |
| 2a. SECURITY CLASSIFICATION AUTHORITY                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |       |                                                 | 3. DISTRIBUTION/AVAILABILITY OF REPORT<br>Approved for public release; distribution is unlimited  |                                                    |                               |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |       |                                                 |                                                                                                   |                                                    |                               |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)<br>UDR-TR-90-114                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |       |                                                 | 5. MONITORING ORGANIZATION REPORT NUMBER(S)<br>WL-TR-91-3006                                      |                                                    |                               |
| 6a. NAME OF PERFORMING ORGANIZATION<br>University of Dayton<br>Research Institute                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |       | 6b. OFFICE SYMBOL<br>(if applicable)            | 7a. NAME OF MONITORING ORGANIZATION<br>Flight Dynamics Directorate (WL/FIVR)<br>Wright Laboratory |                                                    |                               |
| 6c. ADDRESS (City, State, and ZIP Code)<br>300 College Park Avenue<br>Dayton, OH 45469-0110                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |       |                                                 | 7b. ADDRESS (City, State, and ZIP Code)<br>Wright-Patterson AFB, OH 45433-6553                    |                                                    |                               |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION<br>Flight Dynamics Directorate                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |       | 8b. OFFICE SYMBOL<br>(if applicable)<br>WL/FIVR | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br>F33600-88-D-0414                               |                                                    |                               |
| 8c. ADDRESS (City, State, and ZIP Code)<br>Wright-Patterson AFB, OH 45433-6553                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |       |                                                 | 10. SOURCE OF FUNDING NUMBERS                                                                     |                                                    |                               |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |       |                                                 | PROGRAM<br>ELEMENT NO.<br>62201F                                                                  | PROJECT<br>NO.<br>2402                             | TASK<br>NO.<br>03             |
| 11. TITLE (Include Security Classification)<br>EXPLICIT FINITE ELEMENT METHOD FOR TRANSPARENCY IMPACT ANALYSIS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |       |                                                 |                                                                                                   |                                                    |                               |
| 12. PERSONAL AUTHOR(S)<br>R. A. Brockman, T. W. Held                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |       |                                                 |                                                                                                   |                                                    |                               |
| 13a. TYPE OF REPORT<br>Final                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |       | 13b. TIME COVERED<br>FROM SEP88 TO SEP90        |                                                                                                   | 14. DATE OF REPORT (Year, Month, Day)<br>1991 June |                               |
| 15. PAGE COUNT<br>170                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |       |                                                 |                                                                                                   |                                                    |                               |
| 16. SUPPLEMENTARY NOTATION                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |       |                                                 |                                                                                                   |                                                    |                               |
| 17. COSATI CODES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |       |                                                 | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)                 |                                                    |                               |
| FIELD                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | GROUP | SUB-GROUP                                       | Structural analysis soft-body impact X3D                                                          |                                                    |                               |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |       |                                                 | finite element birdstrike PATRAN                                                                  |                                                    |                               |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |       |                                                 | explicit methods aircraft transparency                                                            |                                                    |                               |
| 19. ABSTRACT (Continue on reverse if necessary and identify by block number)<br>This report documents new analytical methods for the solution of soft-body impact problems, including birdstrike. The approach is based on explicit finite element techniques which allow for very detailed material modeling and make efficient use of the current generation of supercomputers. The most important improvements in the present work over previous efforts are in the areas of soft-body impact loading, material modeling, and treatment of layered wall constructions. Impact loads are obtained directly by including the impacting body in the finite element model, eliminating the need for ad hoc loading models. Both the transparency and the soft body materials may be rate-sensitive, exhibit nonlinear bulk behavior, and may fail during the finite element solution. Methods have been developed to make commercial graphics software (PATRAN) deal correctly with failed elements for results output. An improved model of laminated shells is included in the plate and shell element so that each layer of a multilayered transparency need not be modeled with distinct elements, even<br>(continued) |       |                                                 |                                                                                                   |                                                    |                               |
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT<br><input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |       |                                                 | 21. ABSTRACT SECURITY CLASSIFICATION<br>Unclassified                                              |                                                    |                               |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>Richard A. Smith                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |       |                                                 | 22b. TELEPHONE (Include Area Code)<br>(513) 255 - 2516                                            |                                                    | 22c. OFFICE SYMBOL<br>WL/FIVR |

BLOCK 19 (continued)

when soft interlayers are present. The methods described have been implemented in an explicit finite element code X3D. User and programmer information are included in the report as appendices. Applications described in the report include two standard test problems and an F-16 birdstrike simulation.

## FOREWORD

This report documents the development and application of new analytical methods for the solution of soft-body impact problems, including birdstrike. The effort was conducted between September 1988 and September 1990, by the Structures Group of the Aerospace Mechanics Division, University of Dayton Research Institute (UDRI), Dayton, Ohio, under Air Force Contract F33600-88-D-0414. The program was sponsored by the Air Force Aeronautical Systems Division, Scientific Applications Division, Wright-Patterson Air Force Base, Ohio. Air Force administrative direction was provided by Mr. Les Whitford, ASD/SCEA, and technical direction and support was provided by Mr. Richard A. Smith, WL/FIVR.

University of Dayton project supervision was provided by Mr. Dale H. Whitford, Supervisor, Aerospace Mechanics Division, and Mr. Blaine S. West, Head, Structures Group. The principal investigators were Dr. Robert A. Brockman and Mr. Thomas W. Held. The authors wish to acknowledge the contribution of Mr. Michael P. Bouchard, also of the UDRI Structures Group, for his assistance in bird model development and verification, and Mr. Michael Gran of WL/FIVR for his useful technical and editorial suggestions.



|                    |                                            |
|--------------------|--------------------------------------------|
| Accession For      |                                            |
| NTIS GRA&I         | <input checked="checked" type="checkbox"/> |
| DTIC TAB           | <input type="checkbox"/>                   |
| Unannounced        | <input type="checkbox"/>                   |
| Justification      |                                            |
| By                 |                                            |
| Distribution/      |                                            |
| Availability Codes |                                            |
| Avail and/or       |                                            |
| Dist               | Special                                    |
| A-1                |                                            |

# TABLE OF CONTENTS

| <u>Section</u>                           | <u>Page</u> |
|------------------------------------------|-------------|
| FOREWORD                                 | iii         |
| LIST OF FIGURES                          | vii         |
| 1 INTRODUCTION                           | 1           |
| 1.1 TRANSPARENCY IMPACT PROBLEMS         | 1           |
| 1.2 COMPUTER CODE X3D                    | 2           |
| 2 THEORETICAL BACKGROUND                 | 3           |
| 2.1 EXPLICIT FINITE ELEMENT SOLUTION     | 3           |
| Principle of Virtual Displacements       | 3           |
| Finite Element Discretization            | 4           |
| Implicit Solution                        | 6           |
| Explicit Solution                        | 7           |
| 2.2 FINITE ELEMENT TYPES                 | 9           |
| Solid Hexahedral Element                 | 9           |
| Solid Tetrahedral Element                | 11          |
| Plate and Shell Element                  | 11          |
| 2.3 MATERIAL MODELS                      | 17          |
| Equation of State                        | 17          |
| Elastic-Plastic Deviatoric Stress Model  | 18          |
| Plane Stress Elastic-Plastic Model       | 20          |
| Newtonian Fluid Model                    | 21          |
| 2.4 LAYERED PLATE AND SHELL MODEL        | 21          |
| 3 SAMPLE ANALYSES                        | 25          |
| 3.1 TAYLOR CYLINDER                      | 25          |
| 3.2 EXPLOSIVELY LOADED CYLINDRICAL SHELL | 36          |
| 3.3 F-16 BIRDSTRIKE SIMULATIONS          | 42          |
| 4 SUMMARY AND CONCLUSIONS                | 61          |
| REFERENCES                               | 63          |
| Appendix A. X3D INPUT DATA               | A.1         |
| Appendix B. PRE- AND POST-PROCESSING     | B.1         |
| Appendix C. PROGRAMMING INFORMATION      | C.1         |
| Appendix D. MATERIAL PROPERTY TABLES     | D.1         |

## LIST OF FIGURES

| Figure | Title                                                                                                | Page |
|--------|------------------------------------------------------------------------------------------------------|------|
| 2.1    | Explicit Solution Procedure                                                                          | 8    |
| 2.2    | Eight-Node Solid Hexahedron Element                                                                  | 10   |
| 2.3    | Hourglass Deformation Patterns for Solid Element                                                     | 12   |
| 2.4    | Four-Node Solid Tetrahedron Element                                                                  | 13   |
| 2.5    | Four-Node Quadrilateral Plate Element                                                                | 14   |
| 3.1    | Finite Element Model of Taylor Cylinder Problem                                                      | 26   |
| 3.2    | Deformed Geometry of Taylor Cylinder, View #1                                                        | 27   |
| 3.3    | Deformed Geometry of Taylor Cylinder, View #2                                                        | 28   |
| 3.4    | Cylinder Length versus Time                                                                          | 29   |
| 3.5    | Cylinder End Velocity versus Time                                                                    | 30   |
| 3.6    | Cylinder Radius versus Time at Impact Surface                                                        | 31   |
| 3.7    | Cylinder Radial Velocity versus Time                                                                 | 32   |
| 3.8    | Plastic Strains on Symmetry Plane at 80 $\mu$ s                                                      | 33   |
| 3.9    | Plastic Strains on Impact Surface at 80 $\mu$ s                                                      | 34   |
| 3.10   | Geometry of Explosively Loaded Cylindrical Shell                                                     | 37   |
| 3.11   | Final Deformed Shape of Cylindrical Shell                                                            | 38   |
| 3.12   | Plastic Strains in Explosively Loaded Shell                                                          | 39   |
| 3.13   | Mid-span Displacement History                                                                        | 40   |
| 3.14   | Quarter-span Displacement History                                                                    | 41   |
| 3.15   | Geometry of F-16 Transparency and Bird                                                               | 43   |
| 3.16   | Contact Element Grid for Bird Impact Problem                                                         | 44   |
| 3.17   | Deformed Geometry of F-16 Canopy for Low-Strength Bird<br>350-Knot Impact (2-ms Intervals)           | 47   |
| 3.18   | Centerline Profiles of Deformed Canopy for 350-Knot Impact<br>(4-ms Intervals)                       | 52   |
| 3.19   | Carpet Plot of Centerline Shape versus Time Step for<br>Low-Strength Bird 350-Knot Impact            | 53   |
| 3.20   | Deformed Geometry of F-16 Canopy for High-Strength Bird<br>350-Knot Impact (2-ms Intervals)          | 54   |
| 3.21   | Deformed Geometry of Failed Canopy at 450-Knot Impact                                                | 56   |
| B.1    | Transparency Impact Deformed-Shape Plot With and Without<br>Failed Elements Removed from the Display | B.11 |

# SECTION 1

## INTRODUCTION

This report documents the development of new computational techniques for analyzing structural response to high-speed impact. While much of the work is applicable to a variety of impact problems, the focus of the present study is the problem of *soft body impact* on aircraft transparencies, which presents a number of unique challenges (Brockman, 1988).

In what follows, we describe the elements of a practical method of analyzing soft body impact problems. The key improvements in the present technique include:

- *Soft-body impact loads*: the bird appears explicitly in the finite element model, so that ad hoc estimates of the impact loading distribution are unnecessary;
- *Material modeling*: the material models include strain rate sensitivity and failure; and
- *Layered shells*: multilayered constructions, including those with soft interlayers, can be modeled using a single layer of surface elements.

The results obtained thus far are encouraging, although more work is needed in the areas of model validation (versus experimental data) and materials characterization.

### 1.1 TRANSPARENCY IMPACT PROBLEMS

Impact phenomena encompass a broad range of structural behavior and response times, which depend on the stiffness, strength, mass, geometry, velocities, and failure characteristics of the bodies involved. Soft body impacts, such as transparency birdstrikes, are distinctive among impact problems: while the response is often highly nonlinear, critical features of the response may occur either at early times or long (milliseconds) after the impact is finished.

The current generation of birdstrike analysis software (Brockman, 1982) has been in use for about ten years, and has been employed in a number of successful applications (McCarty, 1983, 1989a, 1989b; Bouchard, 1989). However, practical transparency analysis remains a time-consuming and laborious process, and in some circumstances the present inventory of analysis tools may not be optimal. For instance, an impact solution may be dominated by complicated contact conditions which preclude the use of large time steps, so that the advantages of an implicit solution are lost. Much of the material in this document reflects our continuing search for new methods which apply to unusual or more highly nonlinear situations.

The analytical technique discussed in this report is an *explicit* finite element method, of the type used widely for the numerical solution of shock and wave propagation problems. The explicit family of time integration algorithms is attractive because it is readily adapted to high

performance on the current generation of supercomputers, which combine parallel or pipelined processors, moderate amounts of high-speed memory, and relatively slow disk performance. An added benefit is the ability to implement more detailed material and failure models. In subsequent sections, we present the underlying theory of the explicit technique, compare the characteristics of implicit and explicit integration algorithms, and address some of the problems which remain in the application of these methods to soft body impact simulation.

## 1.2 COMPUTER CODE X3D

The analytical methods described in the body of this report are implemented in a computer code called X3D. X3D is an explicit, three-dimensional finite element program intended for use in solving impact, wave propagation, and other short-duration problems in structural dynamics. A number of utility programs also exist for exchanging data between X3D and commercial modeling software, and for certain specialized data reduction tasks. The appendices of this document summarize the data preparation requirements for X3D, and the operation of the supporting software for pre- and postprocessing.

X3D contains two types of finite elements, solids and plates. The solid elements are an eight-node hexahedron, based on a mean-stress approximation with anti-hourglass stabilization, as described by Flanagan and Belytschko (Flanagan, 1981); and a four-node tetrahedron. The material model used for solids consists of a polynomial equation of state coupled with a von Mises plasticity model, a simple power-law correction for strain rate sensitivity, and a failure criterion based upon the ultimate stress.

The plate element in X3D is a four-node quadrilateral based upon a Mindlin-Reissner type thick-plate theory. A corotational axis system, which rotates with the element but does not deform, is used to simplify the element kinematics. The plate element uses a reduced (one-point) Gaussian quadrature, in conjunction with anti-hourglass stabilization techniques. An approximate model for layered media is implemented for the plate element, so that plates and shells having layers with large differences in stiffness can be represented effectively using a single element in the thickness direction. For each layer the material is elastic, perfectly plastic, and obeys plane stress assumptions. Transverse shear stresses in the plate element are uncoupled from the tangential stresses, and follow an elastic constitutive relation.

Applied forces in X3D may consist of body forces and surface pressure. Kinematic boundary conditions may include prescribed nodal displacements, rigid-wall constraints, and contact between specified surfaces within the mesh. Initial conditions may be specified for the translational velocity components for all or part of the finite element model.

Output from X3D consists of a printed solution log, a "trace" output file, and one or more restart files. A restart file is used to resume an analysis from the point of interruption; during a restart, selected data (e.g., external forces) may be replaced as needed to define the remainder of the problem. The restart file also is used for generating printed output and graphics. The trace output file contains results for a selected set of node points or elements. This form of output is useful for quick reviews of results at key points in a model, and for producing time-history plots.

## SECTION 2 THEORETICAL BACKGROUND

This Section describes the underlying theory for each component of the impact solution: the explicit time integration procedure, the solid and plate finite element approximations, and the material models. For the plate element, the treatment of layered constructions is described separately in some detail.

### 2.1 EXPLICIT FINITE ELEMENT SOLUTION

This section presents a brief introduction to the theoretical aspects of the explicit finite element solution. The reader familiar with the more traditional implicit finite element solutions implemented in general purpose analysis codes will recognize most of the steps in this development. We begin with the principle of virtual work, and outline the process of spatial discretization common to all transient finite element solution techniques. The result of this step is a semidiscrete system which may be analyzed by numerous time integration algorithms (Belytschko, 1983). The remainder of the discussion shows how implicit and explicit time integration schemes derive from the same semi-discretized system of equations.

#### Principle of Virtual Displacements

The starting point for the explicit finite element solution consists of the momentum equations in spatial coordinates (Malvern, 1969):

$$\sigma_{ji,j} + \rho b_i = \rho a_i$$

Here  $\sigma_{ij}$  is the Cauchy stress (true stress),  $\rho$  is the current density,  $b_i$  is the prescribed body force per unit mass, and  $a_i$  are the acceleration components. A comma is used to denote partial differentiation with respect to the spatial coordinates  $x_i$ ; for example,  $f_{,i} = \partial f / \partial x_i$ . A superimposed dot denotes a material time derivative. The boundary conditions state that either the displacement assumes a prescribed value, or that the traction condition

$$n_j \sigma_{ji} = t_i$$

is satisfied. The prescribed tractions are denoted by  $t_i$ , and  $n_i$  are the components of the outward normal to the boundary. One and only one of these conditions applies at every point of the boundary, in each of three linearly independent directions. On contacting surfaces (which we identify by superscripts ' $\alpha$ ' and ' $\beta$ '), the velocities satisfy the unilateral constraint:

$$(v_i^\beta - v_i^\alpha) n_i^\alpha \geq 0$$

Whenever the geometric constraint is an equality, the normal component of the tractions on the opposing surfaces must be equal and opposite:

$$\sigma_{ij}^{\alpha} n_i^{\alpha} n_j^{\alpha} - \sigma_{ij}^{\beta} n_i^{\beta} n_j^{\beta} = 0$$

We will assume that the kinematic boundary conditions are satisfied, including the unilateral contact constraints. The weak form of the system above is (Reddy, 1984b):

$$\int_V [\sigma_{ji,j} + \rho b_i - \rho a_i] \delta v_i dV + \int_{A_\sigma} [t_i - n_j \sigma_{ji}] \delta v_i dA - \int_{A_\alpha} [\sigma_{ij}^{\alpha} n_i^{\alpha} n_j^{\alpha} - \sigma_{ij}^{\beta} n_i^{\beta} n_j^{\beta}] \delta v_k^{\alpha} n_k^{\alpha} dA = 0$$

The test functions  $\delta v_i$  must vanish where the displacements are prescribed but are arbitrary and independent elsewhere. If  $\delta v_i$  are interpreted as a virtual velocity field, the weak form above represents the rate at which existing forces do work and corresponds to the principle of virtual work. Applying Gauss' divergence theorem and noting that every point of the boundary must belong to  $A_\sigma$ ,  $A_\alpha$ , the segment  $A_\beta$  corresponding to  $A_\alpha$ , or the remainder of the boundary  $A_u$  on which  $\delta v_i$  vanishes, one obtains:

$$\int_V \sigma_{ji} \delta v_{i,j} dV + \int_V \rho a_i \delta v_i dV - \int_V \rho b_i \delta v_i dV - \int_{A_\sigma} t_i \delta v_i dA = 0$$

The unknown quantities in the virtual work equation are the velocity components  $v_i$ , which are the fundamental unknowns, and the stresses  $\sigma_{ij}$ , which are determined from  $v_i$  using the appropriate constitutive relations. The interpretation of the virtual work principle  $\delta W = 0$  is as follows: among all kinematically admissible velocity fields  $v_i(\mathbf{x}, t)$ , the velocity field which makes  $\delta W = 0$  vanish for arbitrarily chosen test functions  $\delta v_i$  is the true velocity field.

### Finite Element Discretization

Constructing a finite element approximation of the principle involves the following steps:

- express  $\delta W$  as a sum of contributions from individual elements:

$$\delta W = \sum_{e=1}^N \delta W^{(e)}$$

- approximate the velocity field within each element in terms of discrete nodal values:

$$v_i^{(e)}(\mathbf{x}, t) = N_J(\mathbf{x}) V_{iJ}(t)$$

- approximate the arbitrary test functions  $\delta v_i$  within an element in terms of discrete nodal values:

$$\delta v_i^{(e)}(\mathbf{x}, t) = N_J(\mathbf{x}) \delta V_{iJ}(t)$$

in which  $\delta V_{iJ}$  are arbitrary and independent.

The  $N_j(\mathbf{x})$  are known functions of position, called *shape functions*; with this approximation, the unknowns are reduced to the set of nodal values  $V_{ij}$ , which are functions solely of time. Therefore the resulting system will consist of *ordinary differential equations*, with time the independent variable. The division of the virtual work expression into contributions from disjoint elements requires that either  $v_i$  be continuous across the element boundaries, or that jump conditions be introduced to account for the unboundedness of the derivatives  $v_{ij}$ . We choose to select the shape functions  $N_j(\mathbf{x})$  so that the velocity field remains continuous everywhere.

Introducing the finite element approximations in the virtual work expression gives the semidiscrete equation:

$$\sum_{e=1}^N \left[ \int_V \sigma_{ji} N_{K,j} dV + \int_V \rho N_K N_L \dot{V}_{iL} dV - \int_V \rho b_i N_K dV - \int_{A_0} t_i N_K dA \right] \delta V_{iK} = 0$$

Since the nodal test function values  $\delta V_{iK}$  are arbitrary and independent, the coefficient of  $\delta V_{iK}$  (consisting of the sum of all bracketed terms) must vanish. This condition yields one equation corresponding to each unconstrained nodal value  $\delta V_{iK}$  (or  $V_{iK}$ ).

We define the internal nodal force vector,

$$F_{iK}^{int} = \sum_{e=1}^N \int_V \sigma_{ji} N_{K,j} dV$$

the mass matrix,

$$M_{KL} = \sum_{e=1}^N \int_V \rho N_K N_L dV$$

and the external force vector,

$$F_{iK}^{ext} = \sum_{e=1}^N \left[ \int_V \rho b_i N_K dV + \int_{A_0} t_i N_K dA \right]$$

Then the semidiscrete equations of motion for the finite element model are simply:

$$M_{KL} \dot{V}_{iL} = F_{iK}^{ext} - F_{iK}^{int}$$

subject to the initial conditions and the prescribed displacement/velocity boundary conditions. To this point, the formulation of both implicit and explicit solution techniques is the same, although the best choice for the element shape functions often is different for the two classes of temporal solutions.

### Implicit Solution

The most common approach to solving the semidiscrete equations of motion in structural dynamic (as opposed to wave propagation) problems is to adopt an implicit finite difference approximation in time for each degree of freedom. We present a brief summary of this approach below, for comparison with the explicit technique.

A common choice for the implicit integration method is the trapezoidal rule (Newmark, 1959; Hughes, 1983):

$$\frac{V_{iK}^{(t+\Delta t)} + V_{iK}^{(t)}}{2} \approx \frac{U_{iK}^{(t+\Delta t)} - U_{iK}^{(t)}}{\Delta t}$$
$$\frac{\dot{V}_{iK}^{(t+\Delta t)} + \dot{V}_{iK}^{(t)}}{2} \approx \frac{V_{iK}^{(t+\Delta t)} - V_{iK}^{(t)}}{\Delta t}$$

When the equation of motion is applied at time  $t+\Delta t$  (assuming the state at time  $t$  is known), the difference formulas can be used to eliminate all of the unknowns except the nodal displacements at the end of the time step:

$$\frac{4}{\Delta t^2} M_{KL} U_{iL}^{(t+\Delta t)} + F_{iK}^{int}[U^{(t+\Delta t)}] = F_{iK}^{ext} + M_{KL} \left[ \dot{V}_{iL}^{(t)} + \frac{4}{\Delta t} V_{iL}^{(t)} + \frac{4}{\Delta t^2} U_{iL}^{(t)} \right]$$

If the internal forces depend linearly on the nodal displacements at time  $t+\Delta t$ , that is,

$$F_{iK}^{int}[U^{(t+\Delta t)}] = K_{iKjL} U_{jL}^{(t+\Delta t)}$$

then the system resembles an equilibrium system with the "effective" stiffness coefficients

$$K^{eff} = K + \frac{4}{\Delta t^2} M$$

which remain constant unless properties or constraints change or the time step is modified. If the system is nonlinear, the algebraic system must be solved iteratively (usually by some variant of Newton's method).

Since the balance equations at time  $t+\Delta t$  determine the state of the system at  $t+\Delta t$ , the stability properties of the implicit technique are quite good. For linear systems, the trapezoidal rule used above is known to be *unconditionally stable*; that is, the numerical integration remains stable for any choice of the time step. The method is accurate for frequency components whose period is much larger than  $\Delta t$ ; when the period and time step are similar in magnitude, accuracy degrades quickly. This "low-pass filter" behavior is responsible for the favorable stability properties of the implicit family of integration methods (Hughes, 1983).

A transparency model of moderate size may contain upwards of 10,000 degrees of freedom, and the stiffness  $\mathbf{K}$  (stored in sparse format) occupies several million words of computer storage. While the computational effort required to form, triangularize, and solve the matrix at each iteration is considerable, the most serious problems with efficiency involve input and output. Present-day supercomputers are still too small to cope with the system in high-speed memory, so that disk transfers become the limiting factor in problem throughput.

### Explicit Solution

The explicit solution approach is preferred in the solution of problems of wave propagation and short-duration impact response. The temporal discretization uses the central difference formulas:

$$V_{iK}^{(t+\frac{1}{2}\Delta t)} \approx \frac{U_{iK}^{(t+\Delta t)} - U_{iK}^{(t)}}{\Delta t}$$

$$\dot{V}_{iK}^{(t)} \approx \frac{V_{iK}^{(t-\frac{1}{2}\Delta t)} - V_{iK}^{(t+\frac{1}{2}\Delta t)}}{\Delta t}$$

A typical step in the solution consists of applying the equations of motion at time  $t$  to determine the accelerations:

$$M_{KL} \dot{V}_{iL}^{(t)} = F_{iK}^{ext} - F_{iK}^{int}$$

and then using the finite difference formulas to obtain new velocities

$$V_{iK}^{(t+\frac{1}{2}\Delta t)} = V_{iK}^{(t-\frac{1}{2}\Delta t)} + \Delta t \dot{V}_{iK}^{(t)}$$

and positions:

$$U_{iK}^{(t+\Delta t)} = U_{iK}^{(t)} + \Delta t V_{iK}^{(t+\frac{1}{2}\Delta t)}$$

The new displacement and velocity solutions are used to update the element stresses and internal forces in preparation for the next time step (see Figure 2.1).

In practice, the mass matrix  $M_{KL}$  is *lumped* (made diagonal), so that no equation-solving is required, and in fact the system matrices need never be formed. Krieg and Key (Krieg, 1973) show that mass lumping is desirable in explicit solutions, as it tends to counteract the temporal discretization error.

The explicit integration process is *conditionally stable*; that is, stability is assured only if the time step is less than a critical value. For the central difference method:

$$\Delta t \leq \frac{2}{\omega_{\max}}$$

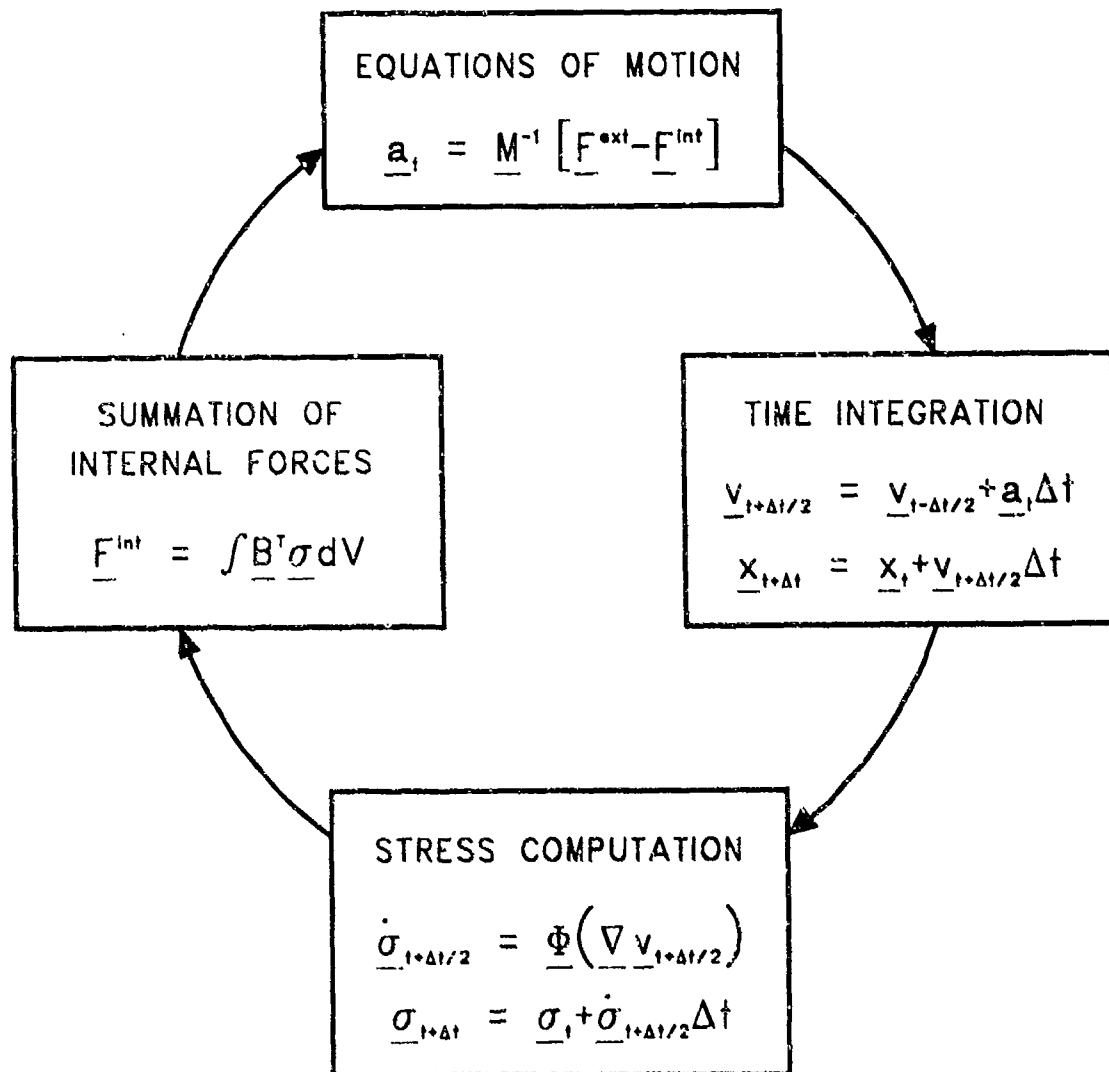


Figure 2.1. Explicit Solution Procedure.

where  $\omega_{\max}$  is the highest natural frequency of the discrete system. In practice we bound the highest frequency by determining the maximum *element* frequency (Belytschko, 1983), a calculation which can be performed very quickly at each time step.

Because explicit techniques are best suited for solving short-duration dynamic problems, which typically involve nonlinear response, they are less familiar to most engineers than the implicit methods used most commonly for statics and structural dynamics. Explicit finite element methods were first used in the early 1970's (Chiapetta, 1973; Key, 1974) and now are used extensively for analyzing ballistic and hypervelocity impact, detonation physics, crash response, forging and high-speed forming, and other highly nonlinear dynamic events (Johnson, 1979; Goudreaux, 1982; Zukas, 1982; Anderson, 1987).

## 2.2 FINITE ELEMENT TYPES

Three finite elements are implemented in X3D: an eight-node solid hexahedron, a four-node solid tetrahedron, and a four-node plate or shell element. In the explicit solution, the distinguishing features of a finite element lie in the way its mass properties and internal forces are computed. We describe each of the three elements in some detail below.

### Solid Hexahedral Element

The solid hexahedral finite element (Figure 2.2) uses a displacement and velocity approximation based upon trilinear polynomials; that is, the element's displacement and velocity components each vary linearly along each edge of the element. In addition, we compute the stress components from a *mean stress approximation*, using only the mean velocity gradient for the element (Flanagan, 1981). This measure is desirable to maintain good element performance, and also reduces the effort required for element computations. However, the resulting element is a *constant stress element*, and therefore a generous number may be necessary for accurate modeling. In particular, a single layer of these solids is incapable of developing a bending moment.

Besides the stress relation, the key computation performed for the solid element involves the shape function derivatives needed to form the mean velocity gradient and the internal forces. The mean velocity gradient is defined as:

$$\bar{v}_{i,j} = \frac{1}{V} \int_V v_{i,j} dV \approx \frac{1}{V} v_{iK} \int_V N_{K,j} dV = \frac{1}{V} B_{jK} v_{iK}$$

The "B matrix"  $B_{jK}$  also is important in evaluating the internal force vector, since

$$F_{iK}^{int} = \int_V \bar{\sigma}_{ji} N_{K,j} dV = B_{jK} \bar{\sigma}_{ji}$$

Because of the mean stress approximation, certain modes of deformation exist for the hexahedron which are stress-free but do not represent rigid body motions. These *hourglassing deformation*

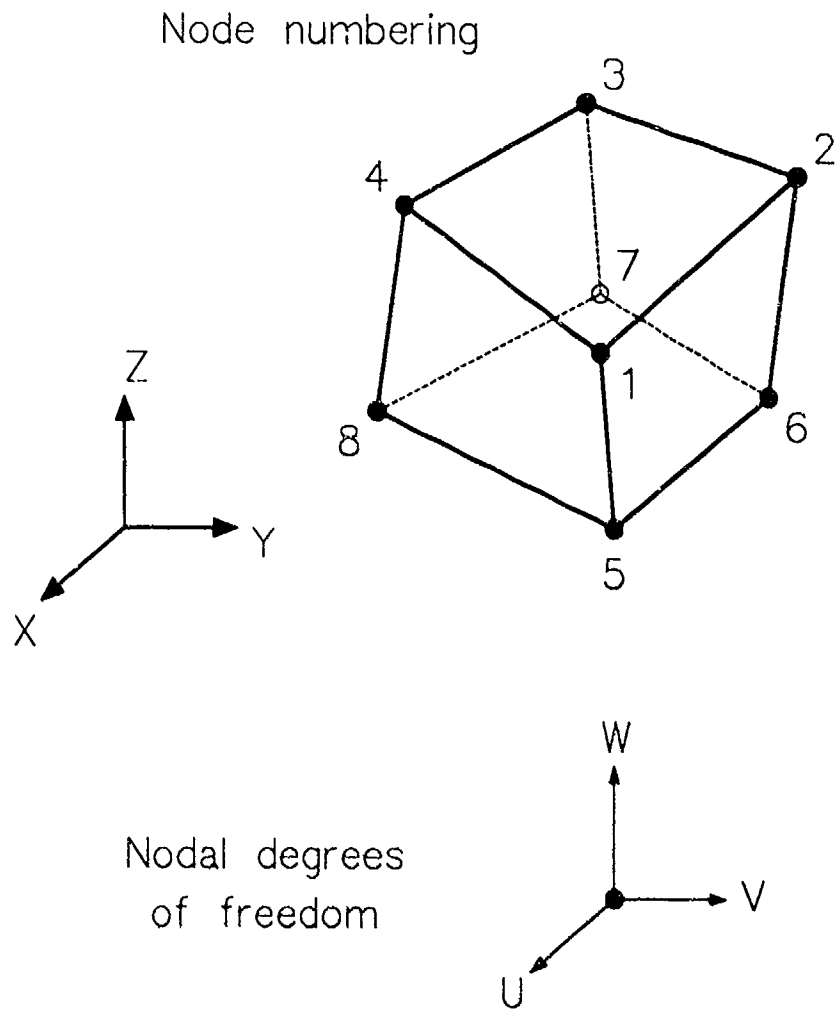


Figure 2.2. Eight-Node Solid Hexahedron Element.

*modes* correspond to linearly varying stress patterns which are not detected by the mean stress approximation (Figure 2.3). To stabilize these potentially unstable motions, we employ an *anti-hourglass viscosity* to resist the hourglass motions through internal damping forces, as described by Flanagan (1981) and Brockman (1984).

#### Solid Tetrahedral Element

The tetrahedral solid (Figure 2.4) is a constant-strain, constant-stress element based upon a fully linear displacement and velocity field approximation. The element is quite similar to the hexahedron of the previous subsection, but does not use an anti-hourglass viscosity. The twelve degrees of freedom for the element capture the six rigid-body motions and the six uniform strain/stress modes, so that no unstable deformation patterns exist for individual elements.

The tetrahedron is included in X3D for its utility in soft-body impact modeling. Since the element has no unstable modes, it can be used to follow very large distortions without causing numerical problems. We use the tetrahedron to model the bird in bird impact simulations, using an equation of state typical of water, a very low strength deviatoric model, and an ultimate failure strain of about 5 (500%).

The tetrahedron usually is inconvenient for modeling because of its basic shape: even filling a rectangular region with tetrahedra can be a confusing process. However, it is possible to generate tetrahedral elements automatically with PATRAN and other modeling packages.

In X3D, the tetrahedron is implemented as a *five-node* element, the fifth node coinciding with the first. This artifice serves to distinguish the four-node tetrahedron from the four-node quadrilateral plate element during input. Ordering of the nodes of the tetrahedron is not crucial. If the element is defined "inside out", X3D reverses the connections to define a valid element.

#### Plate and Shell Element

The plate and shell element in X3D is a four-node quadrilateral with six degrees of freedom per node (Figure 2.5). The displacement and rotation components each are interpolated separately, using bilinear polynomials. The resulting element is quite similar to that described in (Belytschko, 1984).

Unlike the solid elements, the plate element must be formulated in a local axis system because of the differing treatment of the plate thickness from that of the planform directions. We employ a *corotational coordinate system* which rotates with the element (Belytschko, 1973), and therefore is constructed anew at each time step of the solution based upon the current element geometry. The element local coordinate system is shown in Figure 2.5. We summarize the construction of the local axis system below, since the axis directions are potentially useful in interpreting the finite element results.

HOURGLASS DEFORMATION PATTERNS FOR 8-NODE SOLID

DISPLACEMENT DIRECTION  $\longleftrightarrow$

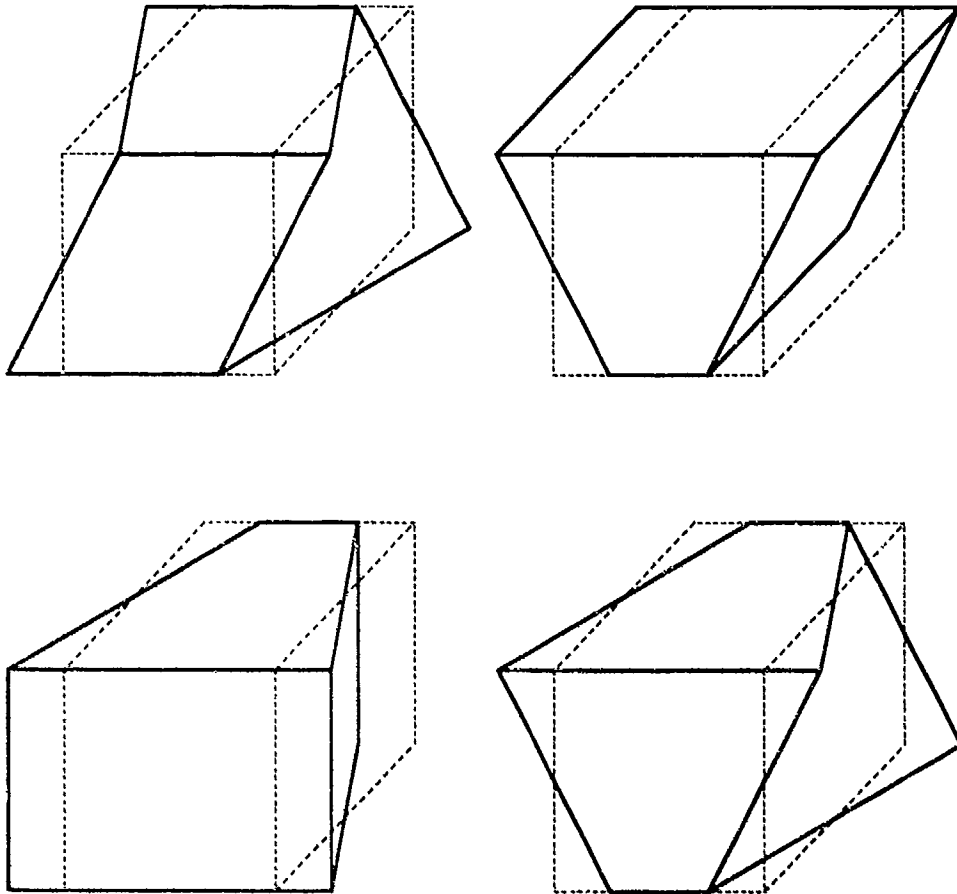


Figure 2.3. Hourglass Deformation Patterns for Solid Element.

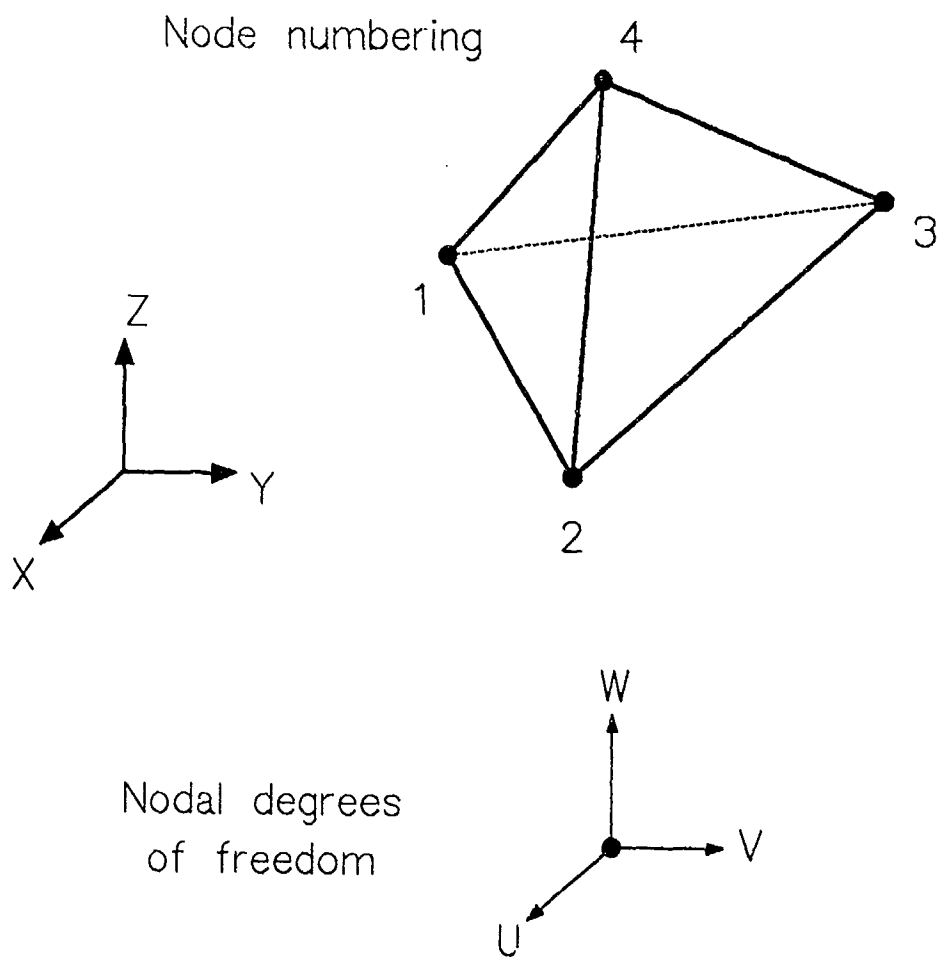


Figure 2.4. Four-Node Solid Tetrahedron Element.

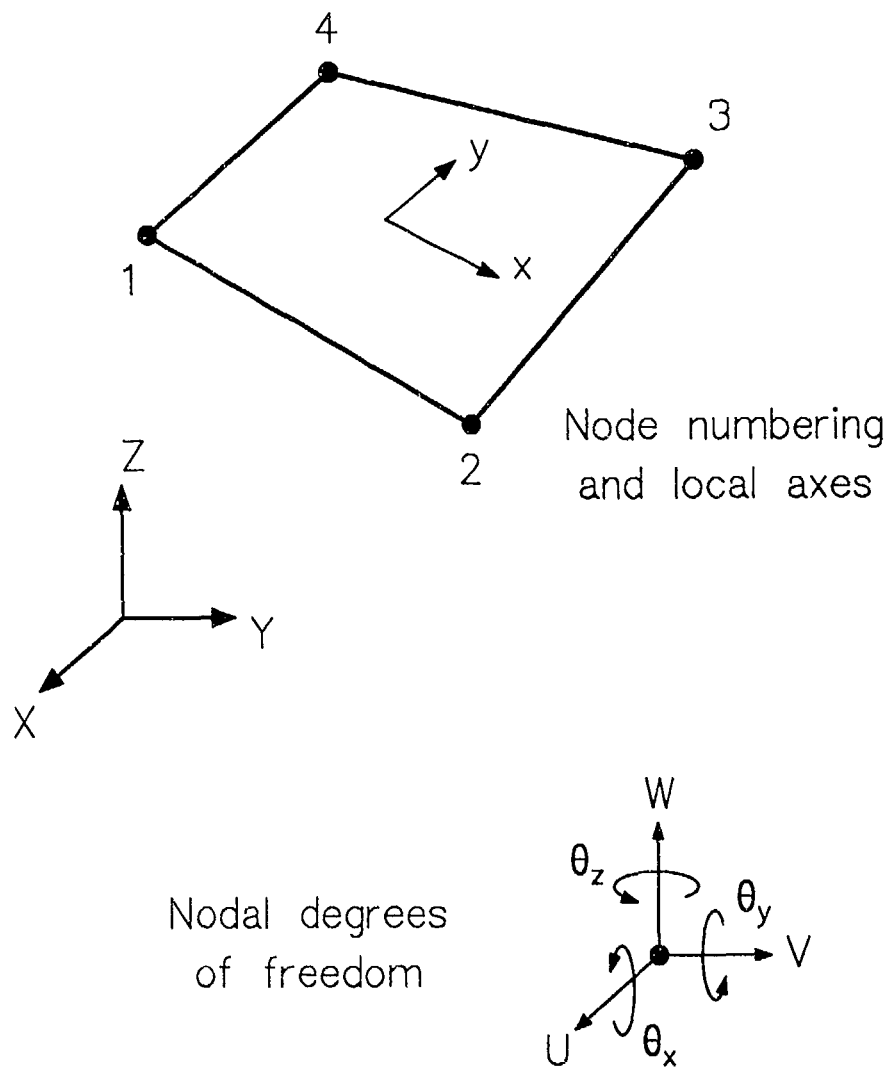


Figure 2.5. Four-Node Quadrilateral Plate Element.

Let  $X_i$ ,  $Y_i$ , and  $Z_i$  denote the global coordinates at the  $i^{\text{th}}$  element corner. We will denote the differences in nodal coordinates by double-subscripted quantities; for instance, for two nodes 'i' and 'j' within an element:

$$X_{ij} = X_i - X_j \quad Y_{ij} = Y_i - Y_j \quad Z_{ij} = Z_i - Z_j$$

We represent a vector from the  $i^{\text{th}}$  node to the  $j^{\text{th}}$  node by:

$$\vec{r}_{ij} = \vec{r}_i - \vec{r}_j = X_{ij}\hat{i} + Y_{ij}\hat{j} + Z_{ij}\hat{k}$$

The local axis transformation for the plate element is computed as follows:

$$\vec{s}_3 = \vec{r}_{31} \times \vec{r}_{42}$$

$$\vec{e}_3 = \frac{\vec{s}_3}{\|\vec{s}_3\|}$$

$$\vec{s}_1 = \vec{r}_{21} - (\vec{r}_{21} \cdot \vec{e}_3) \vec{e}_3$$

$$\vec{e}_1 = \frac{\vec{s}_1}{\|\vec{s}_1\|}$$

$$\vec{e}_2 = \vec{e}_3 \times \vec{e}_1$$

$$[\mathbf{A}]^T = [\vec{e}_1 \mid \vec{e}_2 \mid \vec{e}_3]$$

The rows of  $\mathbf{A}$  are the basis vectors for the local coordinates; that is:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\text{local}} = [\mathbf{A}] \begin{bmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{bmatrix}_{\text{global}}$$

The point  $(X_0, Y_0, Z_0)$  is the origin of the local coordinate system, which is placed at the element center.

The plate element shape functions are formulated entirely in local coordinates. The element calculations are performed with respect to the "mean plane" of the element, and corrected as necessary to account for out of plane warping of the reference surface. Denoting the local coordinates by lower-case symbols  $(x, y, z)$ , the shape function derivatives for the bilinear four-node element are:

$$N_{,x} = \frac{1}{2A} \begin{bmatrix} y_{24} \\ y_{31} \\ y_{42} \\ y_{13} \end{bmatrix} \quad N_{,y} = \frac{1}{2A} \begin{bmatrix} x_{42} \\ x_{13} \\ x_{24} \\ x_{31} \end{bmatrix}$$

Here A is the element planform area,

$$A = \frac{1}{2} (x_{31}y_{42} + x_{24}y_{13})$$

If a vector  $f$  contains the nodal values  $[f_1, f_2, f_3, f_4]$  of a function  $f(x,y)$  defined on the element, then:

$$\left. \frac{\partial f}{\partial x} \right|_{x=0, y=0} = N_{,x}^T f \quad \left. \frac{\partial f}{\partial y} \right|_{x=0, y=0} = N_{,y}^T f$$

The plate uses a mean-stress approximation for its inplane directions, similar to the solid hexahedron. At any thickness station, the velocity gradient is evaluated at the centroid of the element, and assumed to be constant throughout the element (except through the thickness). To resist unstable motions resulting from the assumption of a uniform velocity gradient, the X3D plate element uses a stiffness hourglass control scheme (Flanagan, 1981).

Integration through the shell thickness uses Simpson's Rule, with the number of points controlled by user input. If  $h$  is the thickness of a plate element (or a layer of a laminated element), and  $N$  is the number of integration points, the integration points and weights for an  $N$ -point Simpson's rule ( $N$  odd) are defined by:

$$z_k = \left[ \frac{k-1}{N-1} - \frac{1}{2} \right] h$$

$$W_k = \frac{h}{3(N-1)} [1, 4, 2, 4, 2, \dots, 4, 1]$$

The integral of an arbitrary function  $f(z)$  is evaluated using:

$$\int_{-h/2}^{h/2} f(z) dz = \sum_{k=1}^N f(z_k) W_k$$

Notice that an integration point always is present at the extreme surfaces of any layer, so that yielding in any layer is captured immediately as it occurs.

The integration rule shown above applies *within each layer* of a plate element. For an element with 'L' layers, the force and moment resultants are:

$$N_{ij} = \int_{-h/2}^{h/2} \sigma_{ij} dz = \sum_{l=1}^L \sum_{k=1}^N W_k^{(l)} \sigma_{ij} \left( z_k^{(l)} \right)$$

$$M_{ij} = \int_{-h/2}^{h/2} z \sigma_{ij} dz = \sum_{l=1}^L \sum_{k=1}^N W_k^{(l)} z_k^{(l)} \sigma_{ij} \left( z_k^{(l)} \right)$$

Since point stress relations are used in the constitutive models (rather than, say, moment-curvature relationships), each layer may be a different material, and even use a different material model. Layered constructions in which the stiffness characteristics vary dramatically from layer to layer require special treatment; this question is addressed in subsection 2.4.

Formulation of the lumped mass coefficients for a plate element is an intriguing issue. Calculation of the rotational inertias by Lobatto rules (a common method of lumping) leads to very strict time step restrictions which are not justified by the accuracy obtained. Hughes, Cohen, and Haroun (Hughes, 1978) have described an alternative scheme for computing the rotational lumped masses which relieves the stringent time step restriction without upsetting convergence, and which is used in X3D. The lumped mass coefficients are, for a homogeneous element,  $M_{\alpha\alpha} = \rho Ah/4$  for the translational degrees of freedom, and  $M_{\alpha\alpha} = \rho Ah/48$  for the bending rotations. No inertia is assigned to the "drilling" rotation  $\theta_z$  in the local coordinate system.

## 2.3 MATERIAL MODELS

The material constitutive relationships used for both the solid and plate finite elements consist of a *deviatoric* (shear) relation and a *bulk* (pressure-volume) model. The hydrostatic pressure (mean compressive stress) is defined by:

$$p = -\frac{1}{3} \sigma_{kk}$$

We take the stress tensor to be composed of a hydrostatic, or pressure, stress, and a deviatoric stress tensor  $\sigma'$  which is independent of the pressure:

$$\sigma_{ij} = -p \delta_{ij} + \sigma'_{ij}$$

These two contributions to the stress tensor are determined independently in the material model by a *deviatoric stress model* and a *mechanical equation of state*.

### Equation of State

The equation of state, which describes pressure-volume behavior, relates the hydrostatic pressure  $p$  to the compression ratio  $\eta$  as follows:

$$-p = K_1 \eta \quad (\text{tension}, \eta < 0)$$

$$-p = K_1 \eta + K_2 \eta^2 + K_3 \eta^3 \quad (\text{compression}, \eta > 0)$$

in which

$$\eta = \frac{\rho - \rho_0}{\rho_0}$$

so that  $\eta > 0$  implies compression of the element. In the material model subroutines, the corresponding rate forms are used:

$$\frac{d\eta}{dt} = -(1+\eta)d_{kk} \quad \frac{dp}{dt} = -K_{eff}d_{kk}$$

Note that the effective bulk modulus (which is used in computing allowable time steps) is

$$K_{eff} = \rho_0 \frac{dp}{d\rho}$$

or

$$K_{eff} = K_1 + 2K_2\eta + 3K_3\eta^2$$

The input parameters which define the pressure-volume behavior of the material are:

|                 |                                                |
|-----------------|------------------------------------------------|
| $\rho_0$        | reference state density                        |
| $K_1, K_2, K_3$ | linear, quadratic, and cubic bulk coefficients |

### Elastic-Plastic Deviatoric Stress Model

The deviatoric material model used for solids is a rate-dependent, isotropic, hypoelastic theory appropriate for moderate to large deformations. A brief summary of the model is given below.

The rate of deformation tensor  $\mathbf{D}$  and spin tensor  $\mathbf{W}$  are the primary kinematic quantities used in the model. They are defined in terms of the velocity gradient in current coordinates as:

$$d_{ij} = \frac{1}{2}(v_{i,j} + v_{j,i}) \quad w_{ij} = \frac{1}{2}(v_{i,j} - v_{j,i})$$

The elastic part of the model assumes a linear relationship between the deviatoric part of the rate of deformation at a point and the time derivative of the deviatoric Cauchy (true) stress, as seen by an observer which rotates with the material:

$$\dot{\sigma}'_{ij} = 2G d'_{ij}$$

A stress rate of this type is said to be a *corotational* rate. The particular corotational rate used here is the *Jaumann rate*; it is related to the material time derivative of the true stress by:

$$\frac{d\sigma'_{ij}}{dt} = \dot{\sigma}'_{ij} + \sigma'_{ik} w_{kj} - w_{ik} \sigma'_{kj}$$

Notice that, if no rotation occurs at a point, the spin tensor  $\mathbf{W}$  vanishes and the two rates are the same; otherwise, the state of stress must be "rotated" at each step as indicated above.

The severity of the current stress state is measured in terms of the *von Mises effective stress*  $\sigma_e$ :

$$\sigma_e = \sqrt{\frac{3}{2} \sigma'_{ij} \sigma'_{ij}}$$

The effective stress is a scalar quantity which may be compared with the yield stress in simple tension to determine when yielding occurs. The current yield stress is a rate-dependent quantity which is assumed to vary with strain rate and effective plastic strain according to:

$$\sigma_y = \sigma_y^0 \left[ 1 + \left( \frac{\dot{\epsilon}}{D} \right)^{1/p} \right] + H \epsilon_p$$

The effective strain rate is defined by:

$$\dot{\epsilon} = \sqrt{\frac{2}{3} d'_{ij} d'_{ij}}$$

The *hardening modulus*  $H$ , also used in the definition of the current yield stress, is defined by

$$H = \frac{E E'}{E - E'}$$

Here  $E$  is the elastic modulus, and  $E'$  is the slope of the uniaxial stress-strain curve past the point of yielding. Note that in the case of uniaxial stress, both the von Mises stress and the effective strain rate reduce to the corresponding axial components.

The elastic model and yield criterion above are applied at each integration point in the model for each time step. The elastic stress, sometimes called a *trial stress*, is correct if  $\sigma_e \leq \sigma_y$ ; that is, provided the effective stress is within the current yield surface. Plastic flow is assumed to occur whenever  $\sigma_e > \sigma_y$ . In this case the computed stresses are returned to the yield surface using the radial return correction:

$$\sigma'_{ij} \leftarrow \sigma'_{ij} \frac{\sigma_y}{\sigma_e}$$

When plastic flow occurs, the updated effective plastic strain and the effective shear modulus (used in determining the allowable time step) are evaluated using:

$$\epsilon_p \leftarrow \epsilon_p + \frac{\sigma_e - \sigma_y}{3G + H} \quad G_{eff} = \frac{GH}{3G + H}$$

The parameters which define the material's deviatoric behavior with this model are:

|                |                               |
|----------------|-------------------------------|
| G              | linear shear modulus          |
| $\sigma_y$     | quasi-static yield stress     |
| 1/D            | rate sensitivity scale factor |
| 1/p            | rate sensitivity exponent     |
| H              | hardening modulus             |
| $\sigma_{ult}$ | ultimate stress               |

Notice that  $H = 0$  for materials which exhibit no work hardening, and that setting  $1/D = 0$  and  $1/p = 1$  causes the yield stress to be independent of the strain rate.

#### Plane Stress Elastic-Plastic Model

In plate elements, the elastic-plastic material model is slightly more complicated than for three-dimensional solids because of the *zero normal stress constraint*,  $\sigma_{zz} = 0$ . During the plasticity calculation, it is necessary to determine a final state of stress which not only lies on the yield surface, but which satisfies the condition  $\sigma_{zz} = 0$ . In terms of the deviatoric stress, we require:

$$\sigma'_{zz} = p$$

This means that the deviatoric model and the bulk model (equation of state) are not entirely independent, and must be solved simultaneously with the normal stress constraint.

Since the volumetric strain in plate and shell structures tends to be relatively small, we employ a linear equation of state in the plane stress case,

$$p = -K\epsilon_{kk}$$

with

$$K = \frac{E}{3(1-2\nu)}$$

being the bulk modulus. If the time step involves plastic flow, the pressure obtained in this way must be determined iteratively.

When plastic flow occurs, the three-dimensional plasticity equations are solved, using an assumed value of the normal strain rate. The starting estimate is the elastic value

$$\frac{d\epsilon_{zz}}{dt} = -v \left( \frac{d\epsilon_{xx}}{dt} + \frac{d\epsilon_{yy}}{dt} \right)$$

Notice that the value assumed for the normal strain rate also affects the pressure. The value of  $\epsilon_{zz}$  which gives a final stress state with  $\sigma_{zz} = 0$  is determined using a Newton-Raphson iteration:

$$\dot{\epsilon}_{zz} \leftarrow \dot{\epsilon}_{zz} - \frac{\sigma_{zz}}{\partial \sigma_{zz} / \partial \dot{\epsilon}_{zz}}$$

The derivative is estimated by differencing about the current estimate of  $\epsilon_{zz}$ . Each cycle of the iteration requires an application of the three-dimensional plasticity model, the (linear) equation of state, and the radial return correction. Typically, the point stress solution requires two or three iterations to converge, even for strain steps on the order of several percent.

#### Newtonian Fluid Model

The isotropic Newtonian fluid model provided for the three-dimensional solid elements is an experimental feature intended for potential use in hydrodynamic impact modeling. The bulk behavior is described in polynomial form as for a solid, while the deviatoric stress is related linearly to the rate of deformation:

$$\sigma_{ij} = -p\delta_{ij} + 2\mu d'_{ij}$$

Here  $p$  is determined from the polynomial equation of state. The constant  $\mu$  is the *dynamic viscosity* of the fluid, in force length-time units (i.e.,  $\text{FT/L}^2$ ).

## 2.4 LAYERED PLATE AND SHELL MODEL

This section presents a method of approximation for plates and shells having large stiffness variations from layer to layer. Layered structures of this type often require detailed and expensive models, since conventional plate and shell finite elements do not reproduce the correct transverse shear strain distributions through the wall thickness. The present approach requires a single layer of elements having six engineering degrees of freedom per node, regardless of the number of layers.

The approximation discussed here uses closed-form elasticity solutions to develop transverse shear flexibility corrections, which bring this contribution to the energy into line with that caused

by pure bending, twisting, and extension. For large displacement problems, the technique is applied in corotational coordinates. Changes in stiffness caused by plasticity can be accounted for by recomputing the flexibility corrections based upon instantaneous moduli.

The Mindlin-Reissner theory of plates (Mindlin, 1951) is based upon kinematic assumptions through which the displacement components (U,V,W) at a generic point in the plate are determined by the midsurface components (u,v,w) and two cross-sectional rotations ( $\theta_x, \theta_y$ ). If z is the direction normal to the plate midsurface, then:

$$U(x,y,z) = u(x,y) + z\theta_y(x,y)$$

$$V(x,y,z) = v(x,y) - z\theta_x(x,y)$$

$$W(x,y,z) = w(x,y)$$

The assumption that the tangential displacements (U,V) vary linearly through the plate thickness provides an extremely crude representation of the transverse shear strain field. For monolithic, isotropic elements, a uniform reduction factor often is applied to the shear strain energy to obtain more realistic behavior. Equating the transverse shear strain energy consistent with the assumed displacements to that of a parabolic strain field satisfying the equilibrium conditions yields the correction factor of 5/6, which is used commonly for isotropic plates and shells.

In the present development, we rely on a generalization of this idea first proposed by Whitney (Whitney, 1973) for arbitrary wall constructions. The correction is approximate, but proves sufficient to bring the shear strain energy into line with that of other modes of deformation, in a way which reflects the relative flexibility of these modes for a given material layup. Several investigators have employed a similar concept for fiber-reinforced composite laminates (Chow 1971, 1975; Noor 1975, 1989; Chatterjee, 1979).

Consider first a layered construction for which the shear strains and resultant forces are related by:

$$\begin{bmatrix} Q_{xz} \\ Q_{yz} \end{bmatrix} = \begin{bmatrix} k_1 A_{44} & 0 \\ 0 & k_2 A_{55} \end{bmatrix} \begin{bmatrix} \gamma_{xz} \\ \gamma_{yz} \end{bmatrix}$$

Based solely on the elastic stress-strain relationship of the material, factors  $k_1$  and  $k_2$  both should equal one. However, due to the excessive constraint imposed by the kinematic assumptions of the plate theory, the strains  $\gamma_{iz}$  produced by given shear forces  $Q_{iz}$  are too large over much of the plate thickness. Accordingly, the total strain energy predicted is too large, and the approximation appears "too stiff." This error does not respond to mesh refinement, since the displacement field approximation through the thickness remains linear. Our intent is to select values for  $k_1$  and  $k_2$  which lead to stored energies of a more reasonable magnitude, and thus yield better element behavior.

Since the shear resultants are uncoupled for the case noted above, the basic aspects of the method can be outlined within a single plane. Below, we discuss the determination of  $k_1$ , the shear correction factor for the (x,z) plane.

The shear corrections suggested by Whitney (Whitney, 1973) depend upon the assumption of cylindrical bending, for which an analytical relationship may be established between the local bending stress and the transverse shear force resultant (Whitney, 1970):

$$\sigma_{x,x}^{(m)} = \frac{-Q_{11}^{(m)}}{D} (B_{11} - A_{11}z) Q_{xz}$$

The superscript (m) refers to a particular layer within the laminate cross-section, and parameter D is defined by:

$$D = D_{11} A_{11} - B_{11}^2$$

When combined with the analytic solution, the equilibrium equation

$$\sigma_{x,x}^{(m)} + \sigma_{xz,z}^{(m)} = 0$$

can be integrated through the plate thickness to obtain the shear stress within a layer:

$$\sigma_{xz}^{(m)} = \frac{1}{2D} \left[ a^{(m)} + Q_{11}^{(m)} z (2B_{11} - A_{11}z) \right] Q_{xz}$$

The constants of integration  $a^{(m)}$  are determined by the condition that  $\sigma_{xz}$  be continuous at the layer interfaces, and from the free surface boundary condition at either the upper or lower surface. From the condition that  $\sigma_{xz} = 0$  at  $z = -t/2$ , we obtain:

$$a^{(1)} = \frac{1}{4} Q_{11}^{(1)} t (A_{11}t + 4B_{11})$$

in which  $m = 1$  refers to the bottom layer of the laminate. Letting  $z_l^{(m)}$  be the lower surface of layer m, the interface continuity conditions for  $m = 2, 3, \dots$  give:

$$a^{(m)} = a^{(m-1)} + \left[ Q_{11}^{(m)} - Q_{11}^{(m-1)} \right] \left( A_{11} z_l^{(m)} - 2B_{11} \right) z_l^{(m)}$$

With the above definitions, the strain energy density in any layer may be written in the form:

$$V^{(m)} = \frac{1}{2} g^{(m)}(z) Q_{xz}$$

with

$$g^{(m)}(z) = \frac{1}{G_{xz}^{(m)}} \left[ \frac{a^{(m)}}{2D} + \frac{Q_{11}^{(m)} z}{2D} (2B_{11} - A_{11} z) \right]^2$$

Integrating the shear strain energy through the laminate thickness, and equating the result to the total strain energy per unit area obtained from the plate theory resultants,

$$V = \frac{Q_{xz}^2}{2k_1 A_{55}}$$

we obtain for the shear correction factor:

$$k_1 = \left[ A_{44} + \int_{-t/2}^{t/2} g^{(m)}(z) dz \right]^{-1}$$

The remaining factor  $k_2$  may be determined similarly, using the appropriate elastic constants for the (y,z) plane.

For layered elements composed solely of elastic, orthotropic material, the foregoing approximation of the transverse shear stress distribution is used to predict delamination based on a maximum resolved shear stress criterion. The transverse shear stress components  $\sigma_{xz}$  and  $\sigma_{yz}$  are recovered at each integration point, and the magnitude of the maximum interlaminar shear stress compared with a critical *delamination stress*,  $\sigma_d$ . Delamination is predicted at a point when:

$$\sqrt{\sigma_{xz}^2 + \sigma_{yz}^2} = \sigma_d$$

When delamination is predicted at a point, the stress field is adjusted to reflect *only the midsurface strain state*. Therefore, as delamination progresses through the thickness of a laminate, the ability to resist bending deformation gradually disappears.

## SECTION 3

### SAMPLE ANALYSES

This section presents selected problems which demonstrate the analysis techniques described in Section 2. The first two are common benchmark problems with well-known solutions, and illustrate the accuracy of the method for both thin shell and three-dimensional continuum problems. The final example is a simulation of a birdstrike on a monolithic aircraft transparency under conditions which are near the maximum capacity of the structure.

#### 3.1 TAYLOR CYLINDER

The Taylor cylinder experiment, which is used to estimate the mechanical properties of metals at high strain rates, involves the normal impact of a cylinder onto a rigid surface. Although the event is axisymmetric, we will use a three-dimensional model of one quarter of the cylinder. The X3D model (Figure 3.1) consists of 1350 8-node solids. The geometry and material properties for the case considered are:

$$\begin{array}{ll}
 E &= 117,000 \text{ MPa} \\
 \nu &= 0.350 \\
 \sigma_y &= 400 \text{ MPa} \\
 E_t &= 100 \text{ MPa} \\
 \rho &= 8.93 \times 10^{-9} \text{ N-sec}^2/\text{mm}^4 \text{ (8930 kg/m}^3\text{)} \\
 R_0 &= 3.2 \text{ mm} \\
 L_0 &= 32.4 \text{ mm} \\
 V_0 &= 227,000. \text{ mm/sec}
 \end{array}$$

These material constants are typical of copper. Purely isotropic strain hardening is assumed, and no ultimate stress is specified (i.e., elements may not fail during the solution).

Virtually all of the kinetic energy of the cylinder is dissipated through plastic deformation within about 80  $\mu$ s. Figures 3.2 and 3.3 show deformed mesh plots of the cylinder in its final state. Figures 3.4-3.7 show time histories of the cylinder's length and the radius at the impact surface, as well as the corresponding velocities. Figures 3.8 and 3.9 are contour line plots of effective plastic strain after 80  $\mu$ s. The analysis was performed in 8886 time steps, and required 6 hours, 36 minutes on a VAX 8650 computer (about 0.00198 CPU seconds per element time step). The same analysis runs in about 40 minutes on A CRAY X-MP (0.0002 seconds per element time step).

Results from the X3D solution compare very well with analyses using the DYNA and NIKE codes, as shown in the table below.

| QUANTITY                       | X3D   | DYNA2D | DYNA3D | NIKE2D |
|--------------------------------|-------|--------|--------|--------|
| Final length, mm               | 21.47 | 21.47  | 21.47  | 21.47  |
| Maximum radius, mm             | 7.081 | 7.127  | 7.034  | 7.068  |
| Maximum $\epsilon_p$ at center | 2.95  | 3.05   | 2.95   | 2.97   |

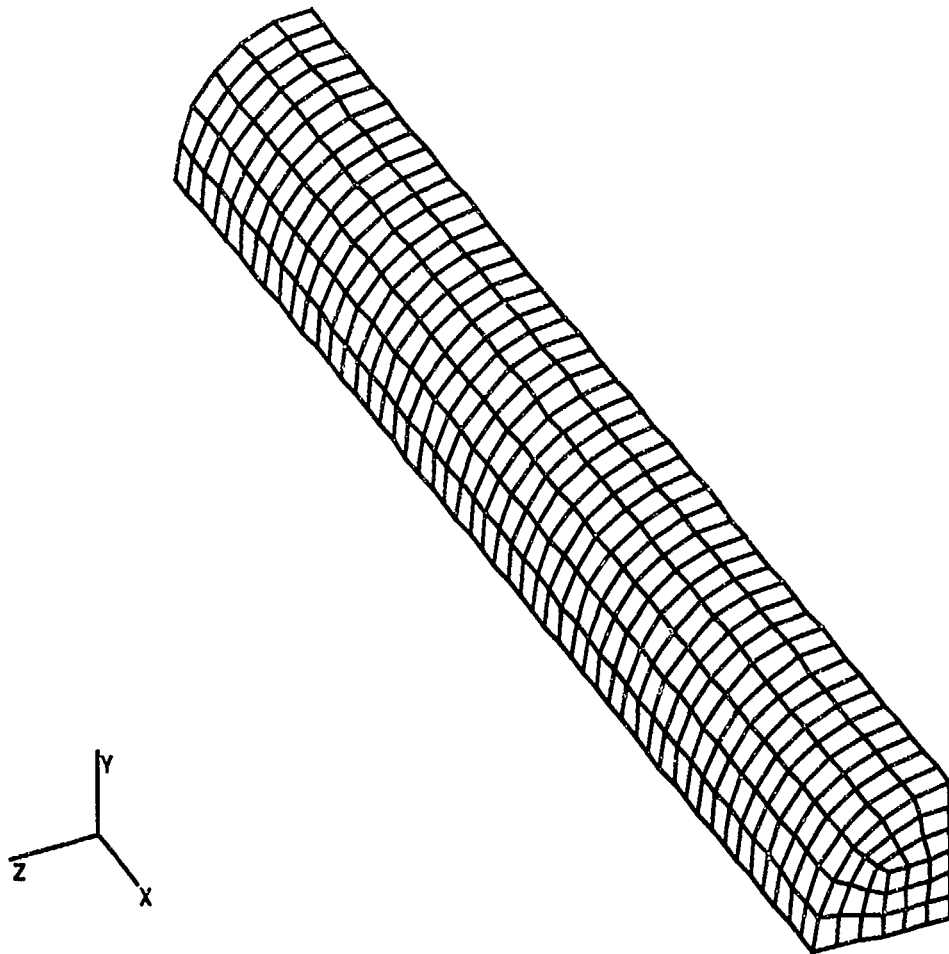


Figure 3.1. Finite Element Model of Taylor Cylinder Problem.

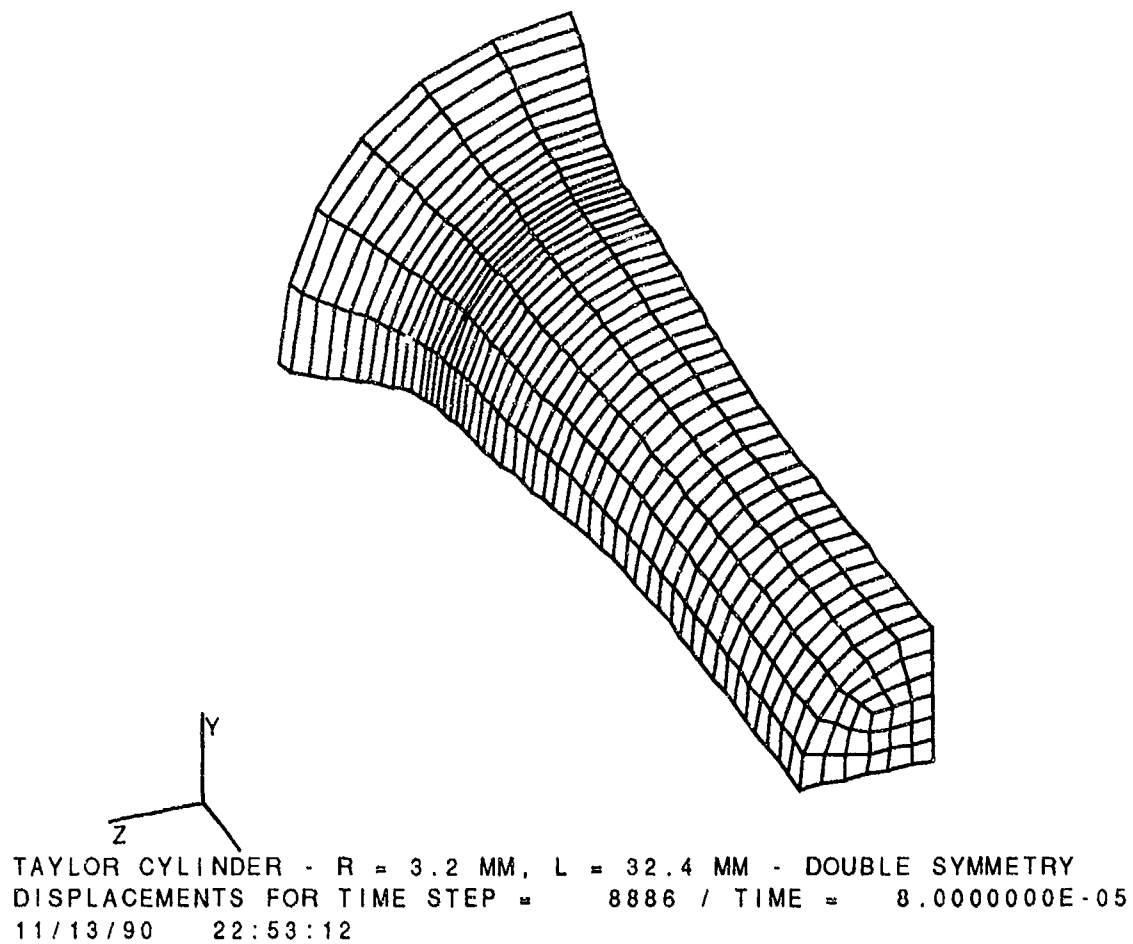
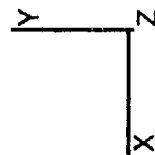
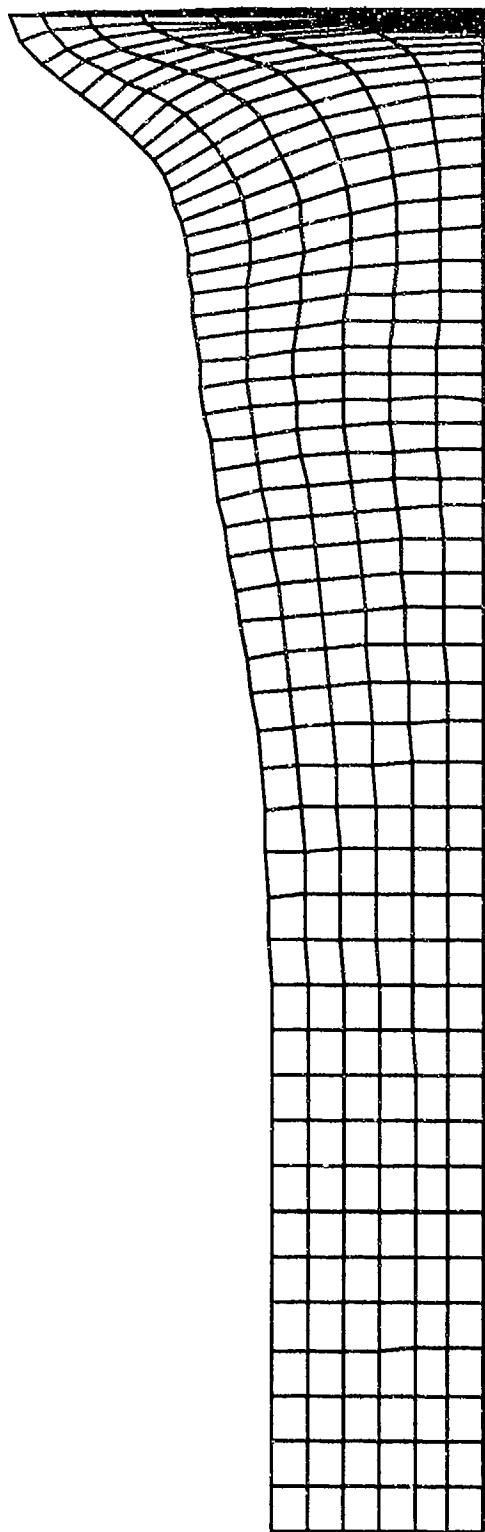


Figure 3.2. Deformed Geometry of Taylor Cylinder, View #1.



TAYLOR CYLINDER - R = 3.2 MM, L = 32.4 MM - DOUBLE SYMMETRY  
 DISPLACEMENTS FOR TIME STEP = 8886 / TIME = 8.0000000E-05  
 11/13/90 22:53:12

Figure 3.3. Deformed Geometry of Taylor Cylinder, View #2.

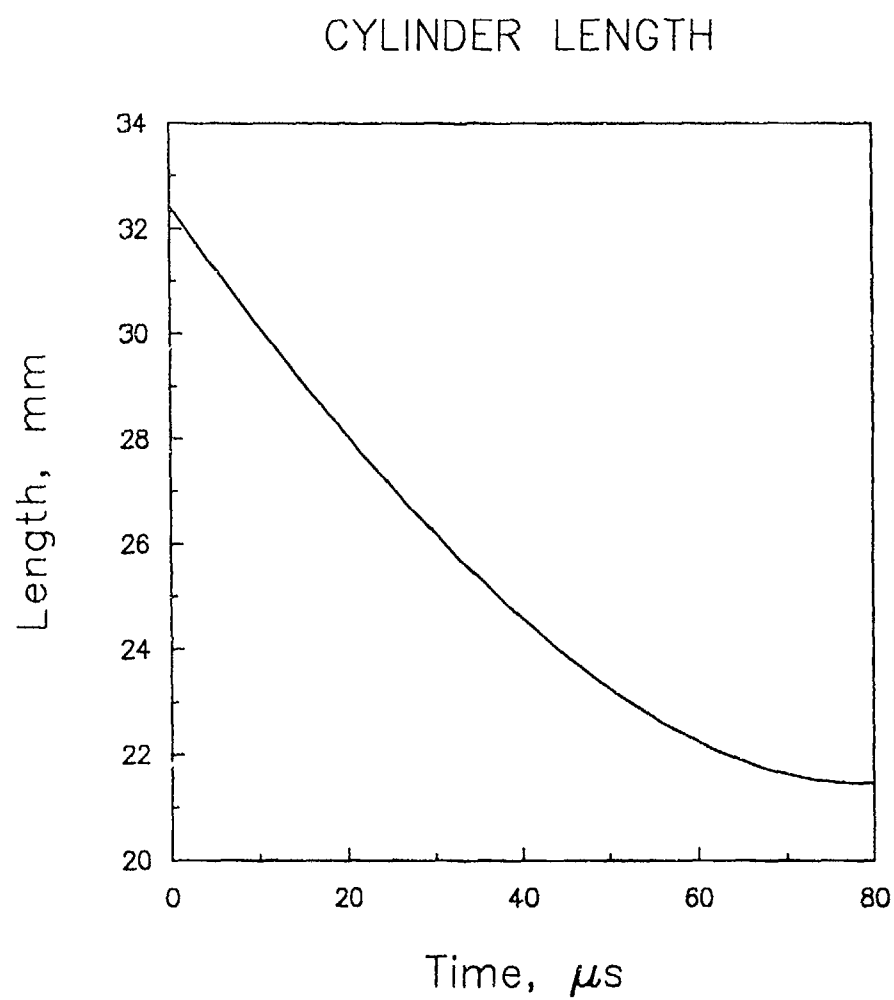


Figure 3.4. Cylinder Length versus Time.

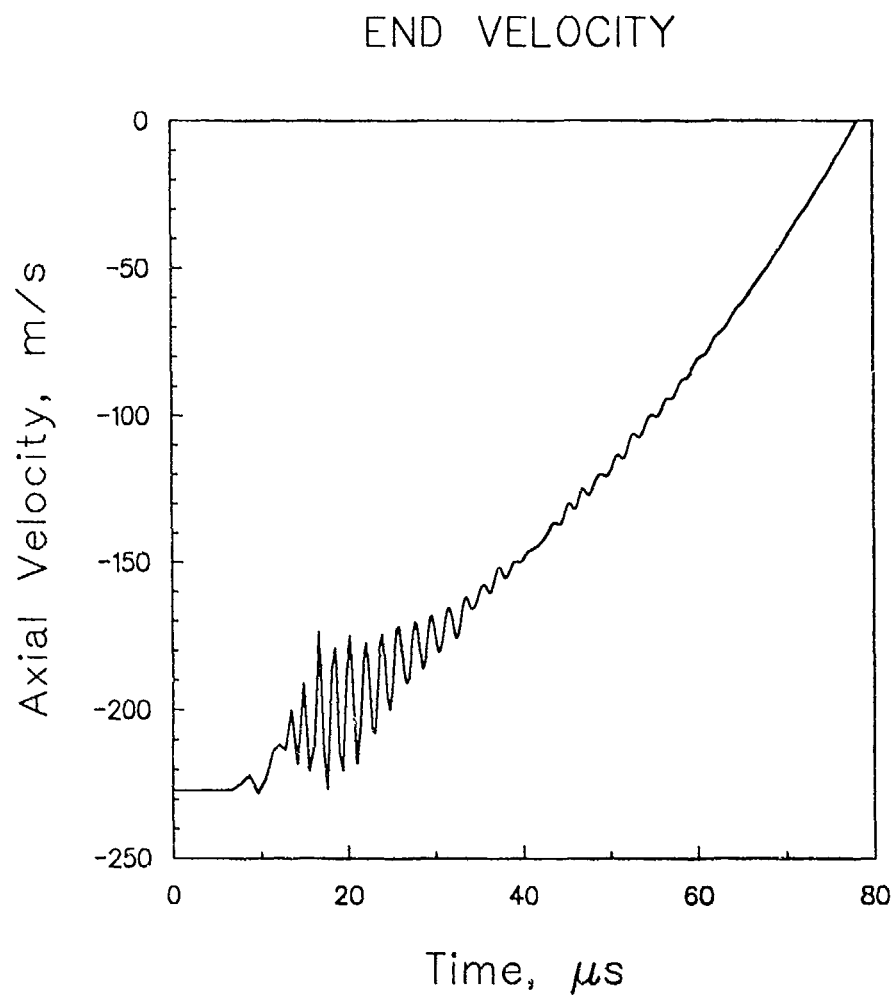


Figure 3.5. Cylinder End Velocity versus Time.

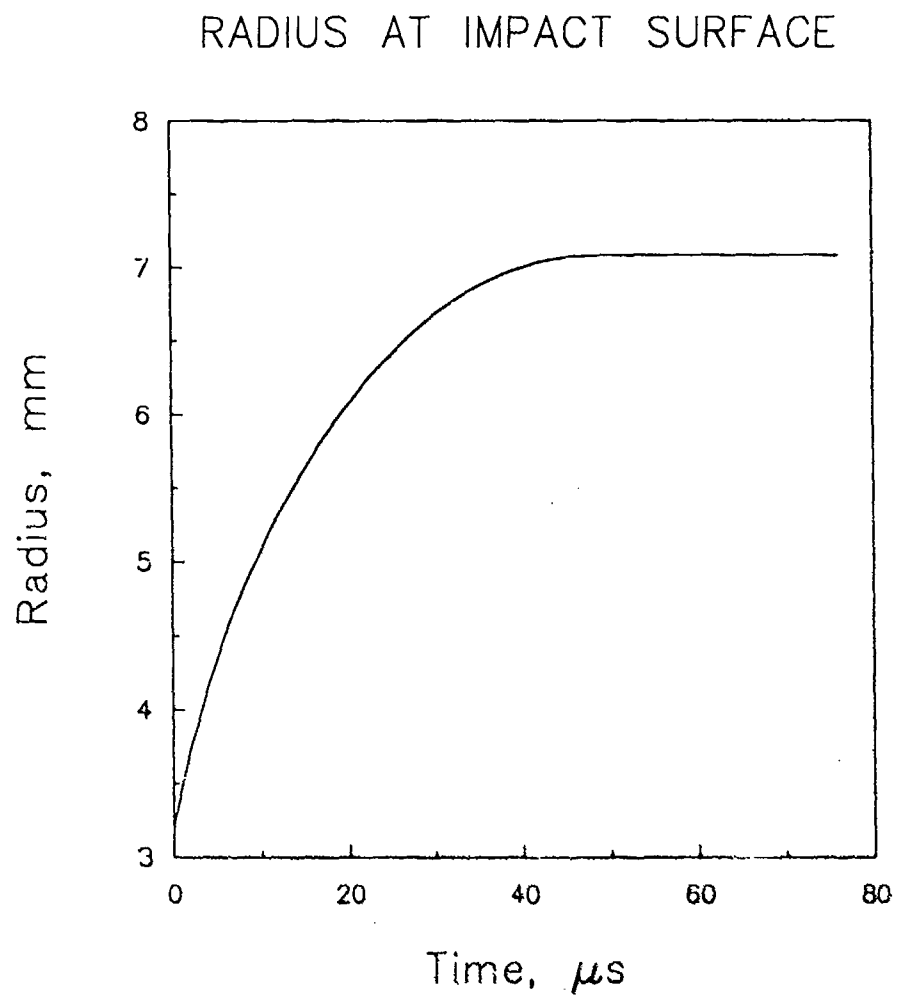


Figure 3.6. Cylinder Radius versus Time at Impact Surface.

## RADIAL VELOCITY AT IMPACT SURFACE

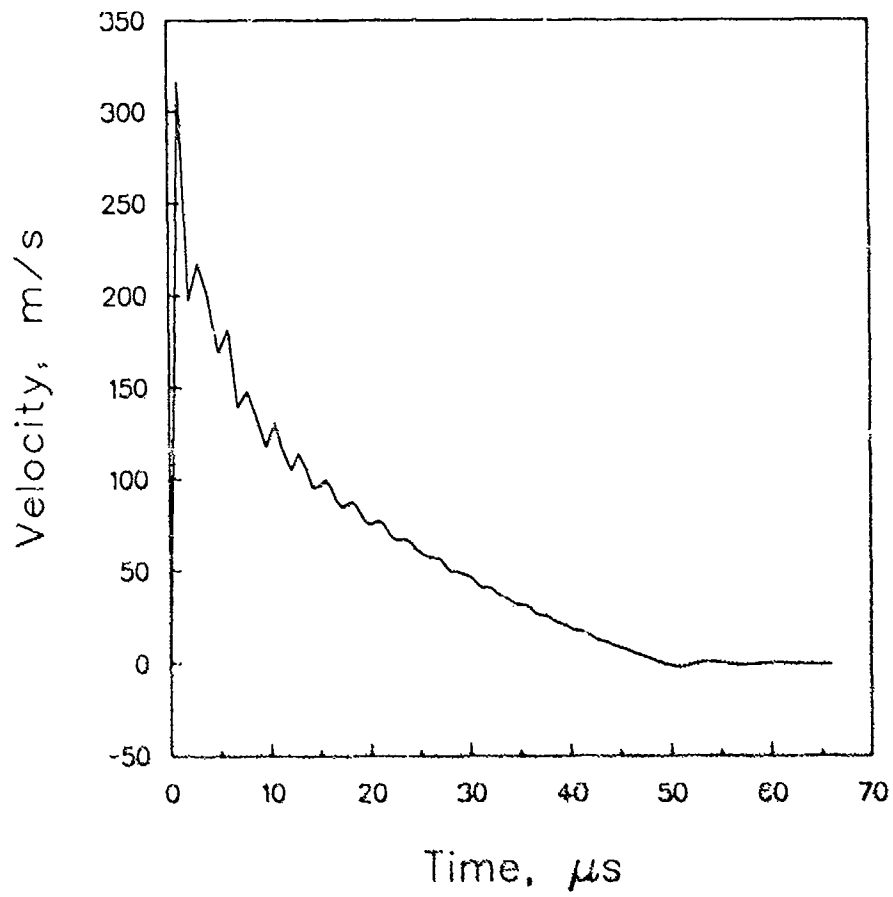


Figure 3.7. Cylinder Radial Velocity versus Time.

0. = A

.500 = B

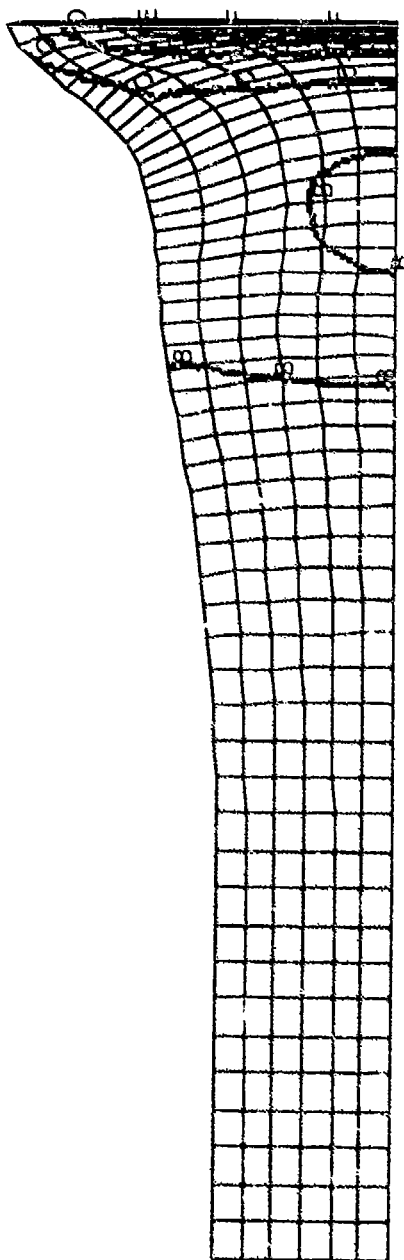
1.00 = C

1.50 = D

2.00 = E

2.50 = F

3.00 = G



TAYLOR CYLINDER - R = 3.2 MM, L = 32.4 MM - DOUBLE SYMMETRY  
DISPLACEMENTS FOR TIME STEP = 8886 / TIME = 8.0000000F-05  
11/13/90 22:53:12

Figure 3.8. Plastic Strains on Symmetry Plane at 80  $\mu$ s.

0. = A  
 .500 = B  
 1.00 = C  
 1.50 = D  
 2.00 = E  
 2.50 = F  
 3.00 = G

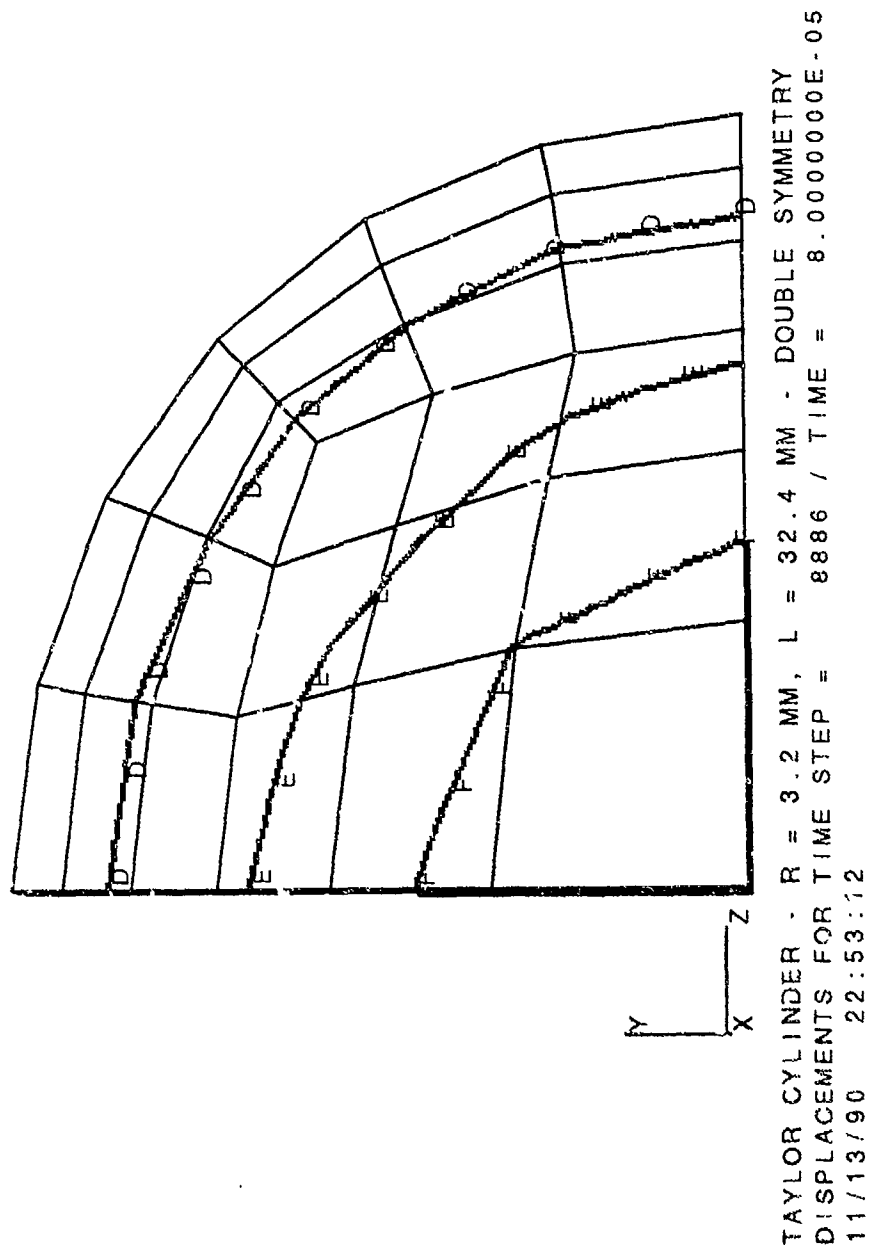


Figure 3.9. Plastic Strains on Impact Surface at 80  $\mu$ s.

The listing below shows the PATRAN modeling directives needed to construct a geometric model of the cylinder and generate the finite element mesh (note that the resulting model must then be "equivalenced" to merge coincident node points).

```
GO
1
1
GR,1,,0/0/0
GR,2,,0/3.2/0
LI,1,ARC,0/0/0/1/0/0/45,2
LI,2,ARC,0/0/0/1/0/0/45,3
GR,5,,0/1.6/0
GR,6,,0/0/1.6
GR,7,,0/1.46/1.46
LI,3,2G,,1,5
LI,4,2G,,1,6
LI,5,2G,,5,7
LI,6,2G,,6,7
PATCH,1,2L,,1,5
PATCH,2,2L,,2,6
PATCH,3,2L,,4,5
HPAT,1T3,EXT,32.4/0/0,1T3
GFEG,HP1T3,,4/4/51
CFEG,HP1T3,HEX,,1
DFEG,HP1,DISP,,/0/0/0/0,1,F1
DFEG,HP2,DISP,,/0/0/0/0,1,F2
DFEG,HP3,DISP,,/0/0/0/0,1,F1
DFEG,HP3,DISP,,/0/0/0/0,1,F3
```

Additional data needed to complete the model for X3D are shown below. These items normally would be added to the X3D input file generated by PATX3D (see Appendix B).

```
INITIAL CONDITIONS
-227000 0 0      17      816  1
-227000 0 0      829     1428  J
-227000 0 0     1438     1887  1
END

MAT3D
1 1 8.93E-9 130000. 0. 0. 43333. 400. 0. 1. 100.
END

PARAMETERS
0. 80.E-6 10.E-6 0. 0. 0 15000 1 5 0 20
END

TOLERANCES
0.90 0.1
END

REFERENCE
-0.01 32.5 -0.1 15. -0.1 15.
END

TRACE NODES
1 819 1879
END
```

### 3.2 EXPLOSIVELY LOADED CYLINDRICAL SHELL

This example is taken from Marchertas and Belytschko (1974), who present both computational and experimental results for the problem. A 120° cylindrical panel (Figure 3.10) is loaded by igniting a charge spread over most of the surface. In the numerical solution, we represent this impulsive loading by a uniform initial velocity along the radius of the shell. The geometric and material parameters for the shell are:

|       |                            |            |                             |
|-------|----------------------------|------------|-----------------------------|
| $R$   | $= 2.9375 \text{ in.}$     | $E$        | $= 10.5 / 10 \text{ psi}$   |
| $t$   | $= 0.125 \text{ in.}$      | $\rho$     | $= 0.0965 \text{ lb/cu.in}$ |
| $L$   | $= 12.56 \text{ in.}$      | $\sigma_y$ | $= 44,000 \text{ psi}$      |
| $V_0$ | $= 5,650 \text{ in./sec.}$ |            |                             |

A three-point integration through the thickness of the shell has been used in the present case. This is the minimum thickness integration order, and may give a solution which is slightly too flexible.

Results of the X3D solution, which was performed in 886 time steps, are shown in Figures 3.11 through 3.14. The response consists mainly of a flattening of the inner portion of the shell, consisting mostly of permanent deformation. The displacements peak at around 0.4 ms, with the largest inward displacements approaching half the radius. After this point, there is some elastic recovery (lasting about another 0.1-0.2 ms), but only very small vibration, since most of the energy has been dissipated through plastic flow. Displacement histories at selected points (Figures 3.13 and 3.14) agree quite well with experimental results.

The listing below shows a PATRAN session file which creates the geometric and finite element models for the cylinder problem.

```
GO
1
1
GR,1,,0/2.9375/0
LI,1,ARC,5(0)/-1/60,1
LI,2,TR,0/0/12.56,1
VIEW
1
27.1,-31,-14.8
PLOT
PATCH,1,2L,,1,2
SET,LI,0
PLOT
PATCH,1,SHOW
GFEG,P1,G,9/17
SET,LABN,OFF
PLOT
CFEG,P1,QUAD,,1
```

Additional data needed to complete the model for analysis with X3D are listed below. Note that the initial velocity components are directed radially inward, and have a magnitude at each node of 5.650 in/sec. Points on the edges of the loaded region are assigned half the nominal initial velocity to provide the correct impulse to the shell.

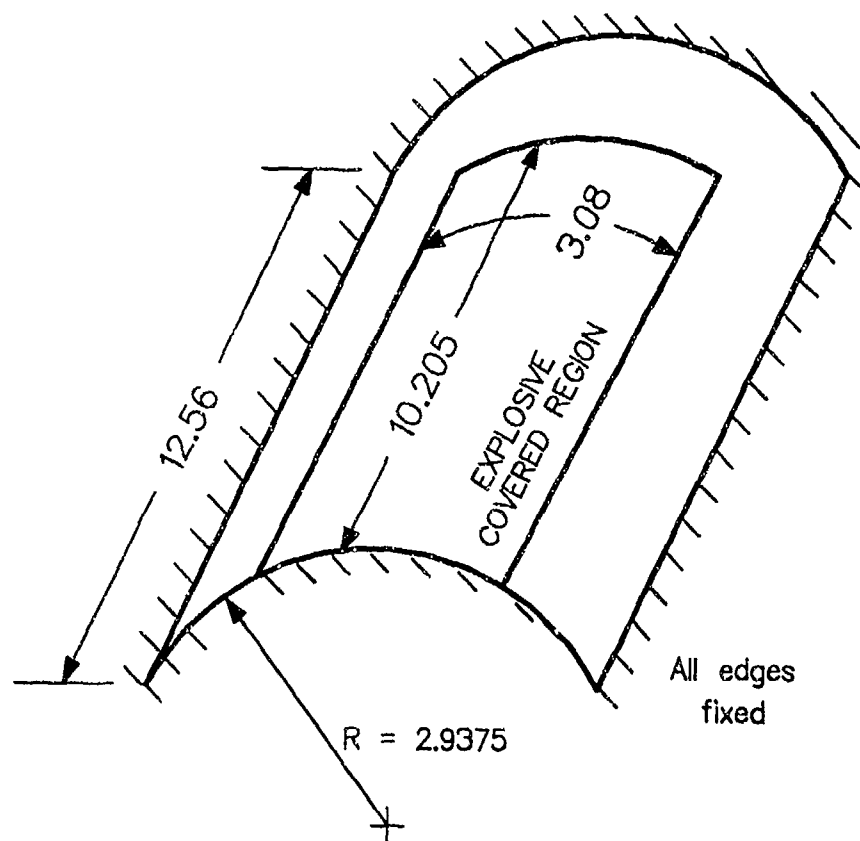


Figure 3.10. Geometry of Explosively Loaded Cylindrical Shell.

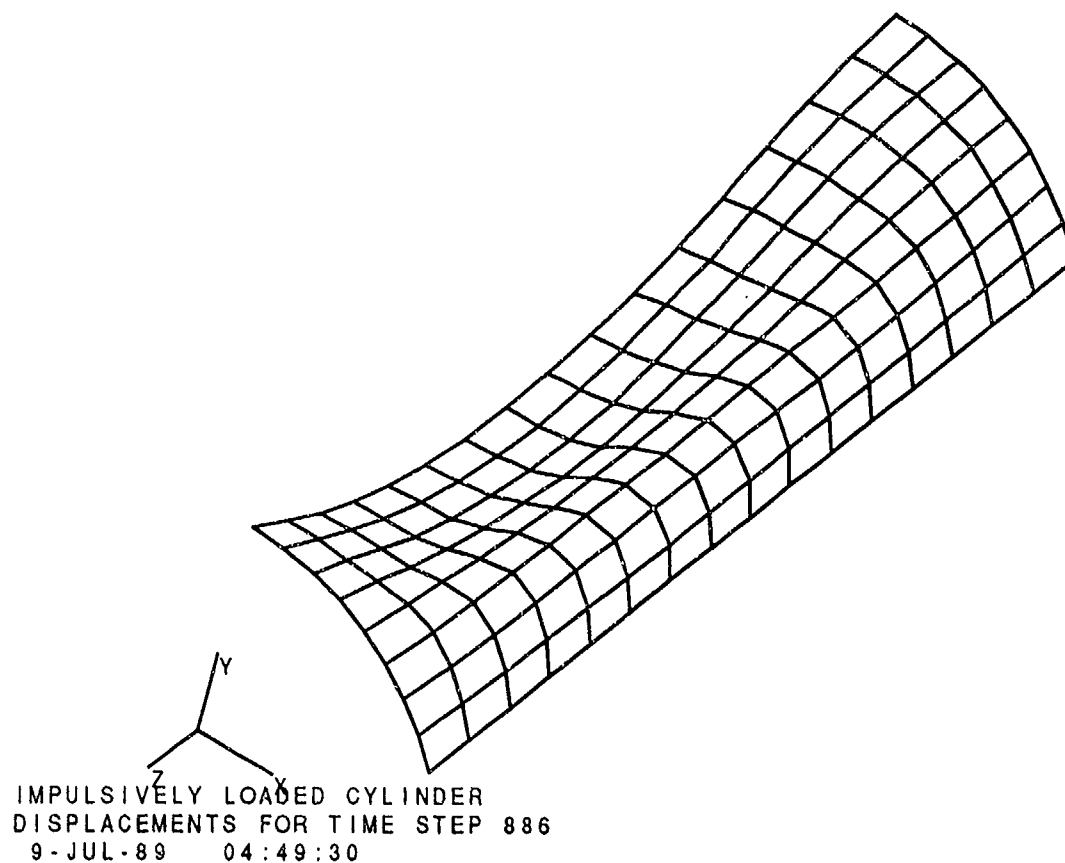
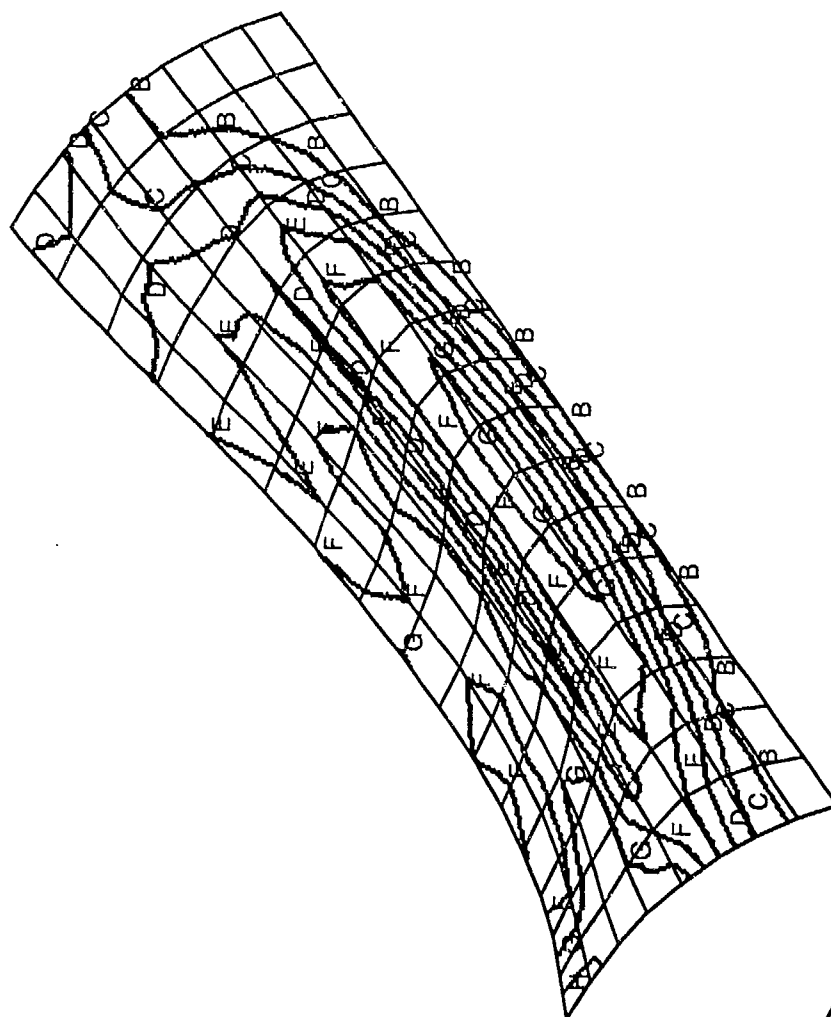


Figure 3.11. Final Deformed Shape of Cylindrical Shell.

0. = A  
 .0100 = B  
 .0200 = C  
 .0300 = D  
 .0400 = E  
 .0500 = F  
 .0600 = G  
 .0700 = H  
 .0800 = I  
 .0900 = J  
 .100 = K  
 .110 = L  
 .120 = M  
 .130 = N  
 .140 = O



Y  
 Z  
 X

IMPULSIVELY LOADED CYLINDER  
 DISPLACEMENTS FOR TIME STEP 886  
 9-JUL-89 04:49:30

Figure 3.12. Plastic Strains in Explosively Loaded Shell.

## MID-SPAN DISPLACEMENT

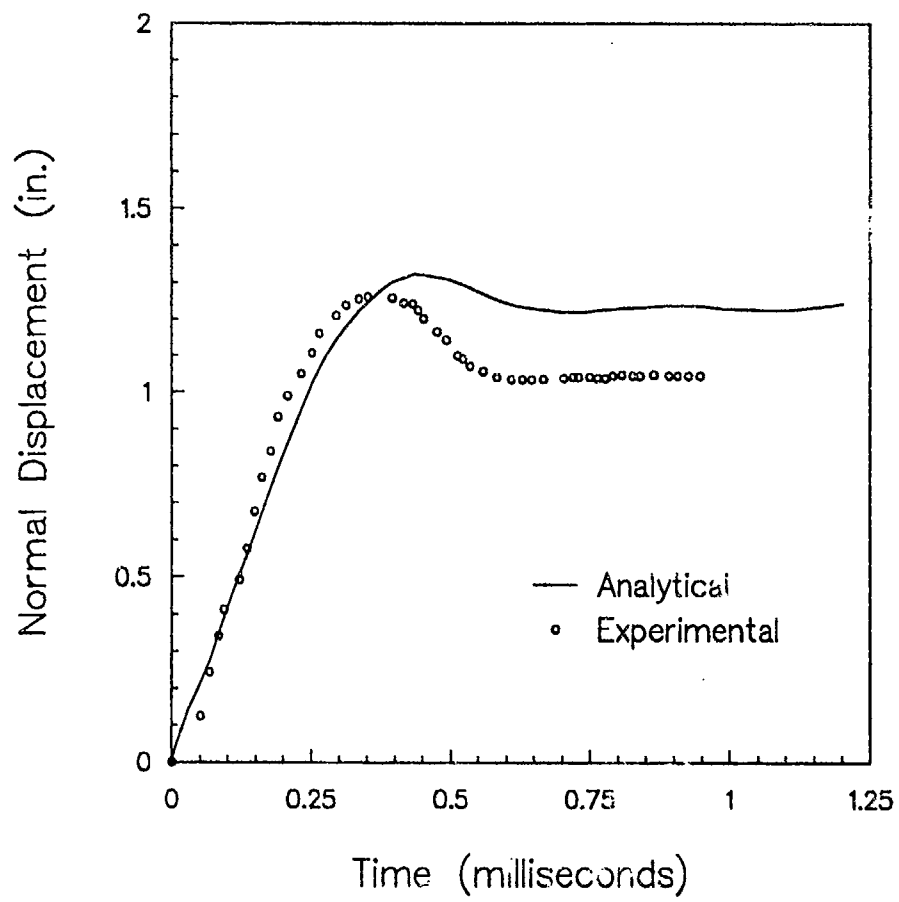


Figure 3.13. Mid-span Displacement History.

### 3/4 SPAN DISPLACEMENTS

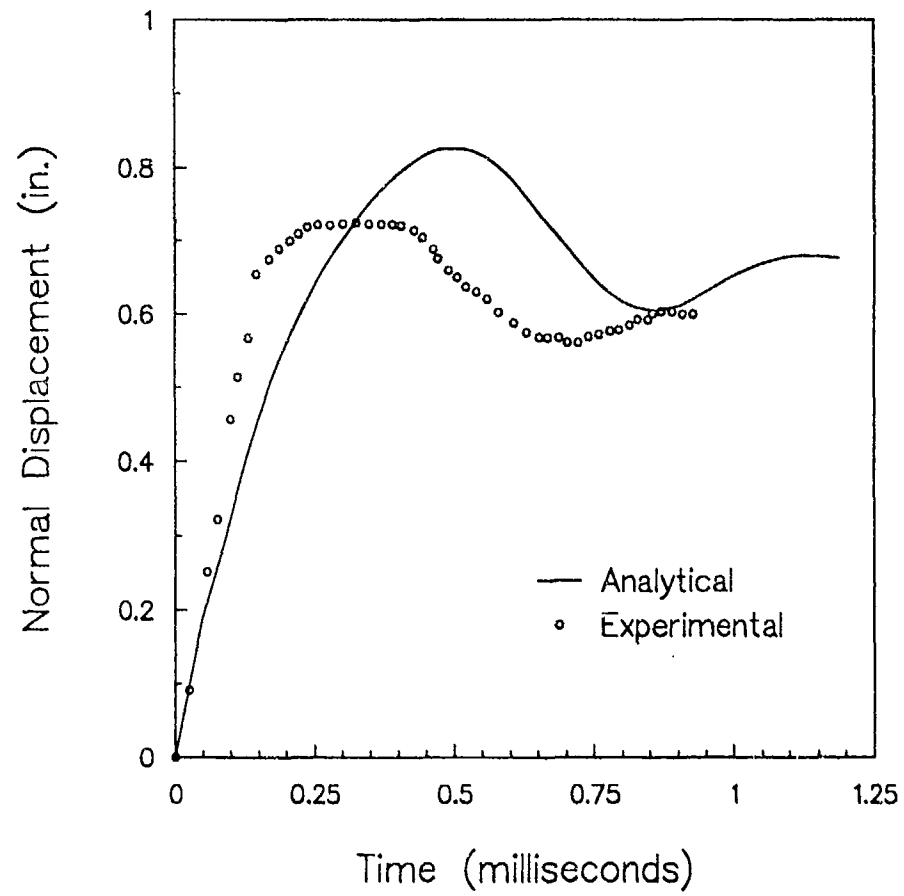


Figure 3.14. Quarter-span Displacement History.

```

BOUNDARY CONDITIONS
  1  9  1  1  2  3      ! Rear end pinned
145 153 1  1  2  3      ! Front end pinned
  9 153 9  1  2  3      ! Hinge along side
  1 145 9  1  6         ! Symmetry on x=0
END

INITIAL VELOCITY
  0. -2825.0  0.  28  28  1
  0. -5650.0  0.  37 145  9      ! Theta = 0.
-368.8 -2800.9  0.  29  29  1
-737.5 -5601.7  0.  38 146  9      ! Theta = 7.5
-731.2 -2728.8  0.  30  30  1
-1462.3 -5457.5  0.  39 147  9      ! Theta = 15.
-1081.1 -2610.0  0.  31  31  1
-2162.2 -5219.9  0.  40 148  9      ! Theta = 22.5
-706.3 -1223.3  0.  32  32  1      ! (the corner)
-1412.5 -2446.5  0.  41 149  9      ! Theta = 30.
END

LAMINATES
  1, 1, 1, -0.0625, 0.0625
END

MAT2D
  1, 1, 0.000250, 10.5E6, 0.3, 0., 44000., 0.
END

PARAMETERS
  0. 0.0012 0.0002 0. 0. 0 2500 1 3 0 5
END

TOLERANCES
  0.9 0.03 0.03 0.03 0.03
END

TRACE NODES
  37 &      ! Node 37 is 9.42" from end
  73      ! Node 73 is 6.28" from end (center)
END

```

### 3.3 F-16 BIRDSTRIKE SIMULATIONS

The F-16 bubble transparency provides a useful example for validation since the impact response involves very large motions, and the coupling between the load distribution and the deformation is strong. As a first step in validating the X3D code for birdstrike simulation, we have carried out several analyses of centerline impacts on the original production canopy, a ½ inch thick monolithic polycarbonate design. This part is capable of defeating birdstrikes up to about 350 knots.

Figure 3.15 shows the geometry of the transparency and of the projectile, a four-pound bird idealized as a circular cylinder. The patch outlined around the crown of the transparency, as well as the entire bird, are covered with contact elements (Figure 3.16).

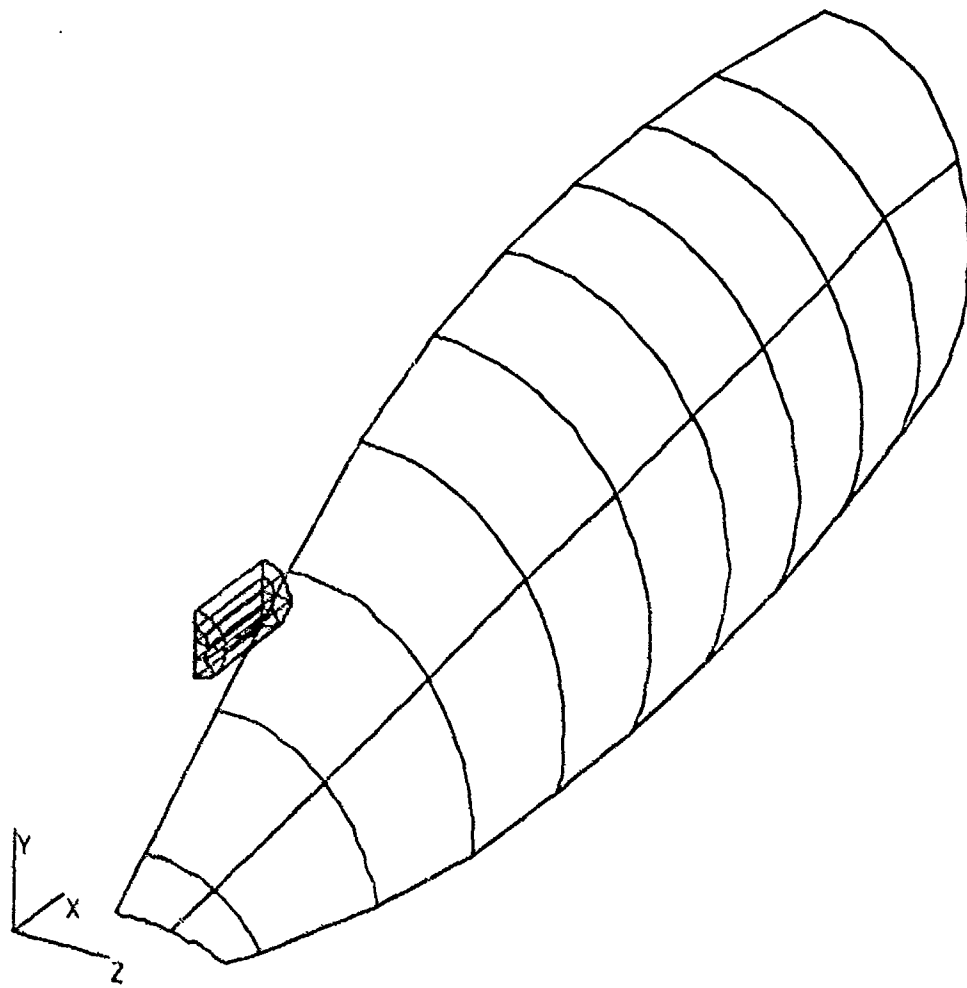


Figure 3.15. Geometry of F-16 Transparency and Bird.

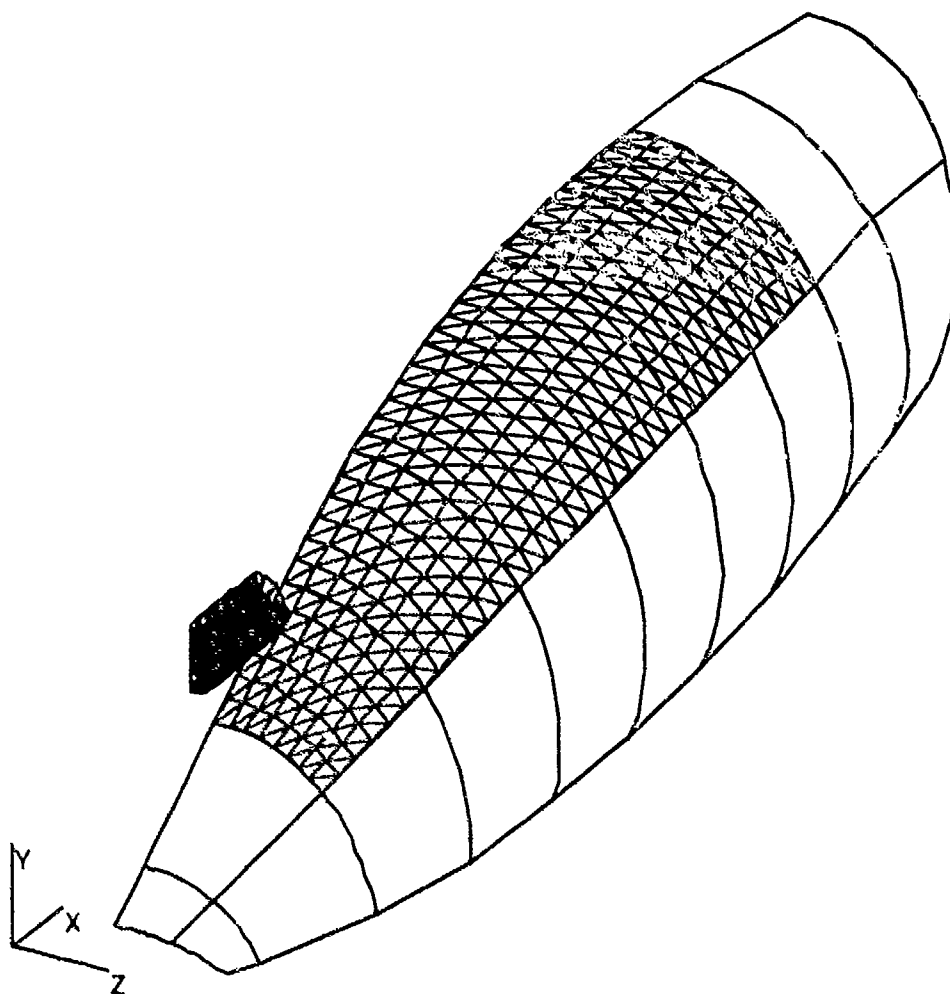


Figure 3.16. Contact Element Grid for Bird Impact Problem.

The transparency model consists of 928 quadrilateral plate elements. The polycarbonate material is represented by the following material properties:

|            |                                            |                |                                 |
|------------|--------------------------------------------|----------------|---------------------------------|
| $E$        | $= 325,000 \text{ psi}$                    | $H$            | $= 36,100 \text{ psi}$          |
| $\nu$      | $= 0.36$                                   | $D$            | $= 196,560 \text{ /sec}$        |
| $\rho$     | $= 0.0001113 \text{ lb-sec}^2/\text{in}^4$ | $p$            | $= 12$                          |
| $\sigma_y$ | $= 7,140 \text{ psi}$                      | $\sigma_{ult}$ | $= 13,000 - 16,000 \text{ psi}$ |

The bird is represented by 960 tetrahedral solids with equation-of-state coefficients typical of water, and very small shear stiffness and strength. The *low-strength* bird model, used in about half of our simulations, uses the properties:

|        |                                            |                |                        |
|--------|--------------------------------------------|----------------|------------------------|
| $\rho$ | $= 0.0000888 \text{ lb-sec}^2/\text{in}^4$ | $G$            | $= 30,000 \text{ psi}$ |
| $K_1$  | $= 337,000 \text{ psi}$                    | $\sigma_y$     | $= 3,000 \text{ psi}$  |
| $K_2$  | $= 729,000 \text{ psi}$                    | $H$            | $= 300 \text{ psi}$    |
| $K_3$  | $= 2,020,000 \text{ psi}$                  | $\sigma_{ult}$ | $= 3,000 \text{ psi}$  |
| $K_t$  | $= 1,000 \text{ psi (tension)}$            |                |                        |

This model of the bird material produces a pressure-volume response similar to water, and a "brittle" shear behavior: the ultimate and yield stresses coincide, so that element failure occurs at relatively small strains. A *high-strength* bird model has been used as well, with  $\sigma_{ult} = 4,500 \text{ psi}$ . This model permits roughly 500% plastic (deviatoric) strain before the material is declared failed. Note that when elements of the bird model fail due to large shear distortion, their mass is retained in the problem, and the corresponding nodes continue to be used in contact calculations. Therefore, portions of the impacting body which have "failed" continue to transfer momentum to the target, but do not contribute to the summation of internal forces. In the deformed plots which follow, nodes attached to failed elements in the bird model are shown as small circles representing the center of mass positions.

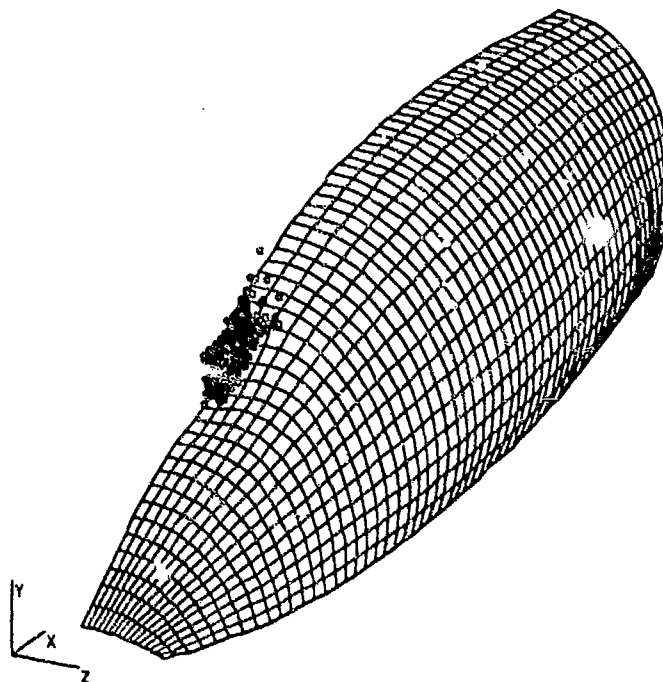
For the cases considered, the center of impact is at fuselage station 112 (measured in inches), which is about two feet aft of the forward edge of the transparency. The initial velocity of the bird is horizontal, and equal to 350 knots (7,094 in/sec) at all nodes.

Figure 3.17 shows a sequence of deformed shapes at two millisecond intervals for a 350-knot impact. This solution employs the low-strength bird model, and a relatively high (16,000 psi) ultimate strength for the polycarbonate. The impact response is elastic, although the von Mises stresses near the crown (where the maximum curvature occurs at 10-12 ms) are well above the static yield stress. The displacement data are similar to experimentally observed values (Figure 3.18), although the computed deformed shape exhibits larger displacements in the forward region. Minor differences in the exact center of impact from that assumed in the calculation may be responsible for this discrepancy. Figure 3.19 shows a carpet plot obtained from the deformed centerline shapes at closer intervals during the solution. The time axis moves from right to left in the figure (that is, the right boundary corresponds to the undeformed geometry). The finer time resolution in this plot reveals additional detail, including the reflection of bending waves from the aft support.

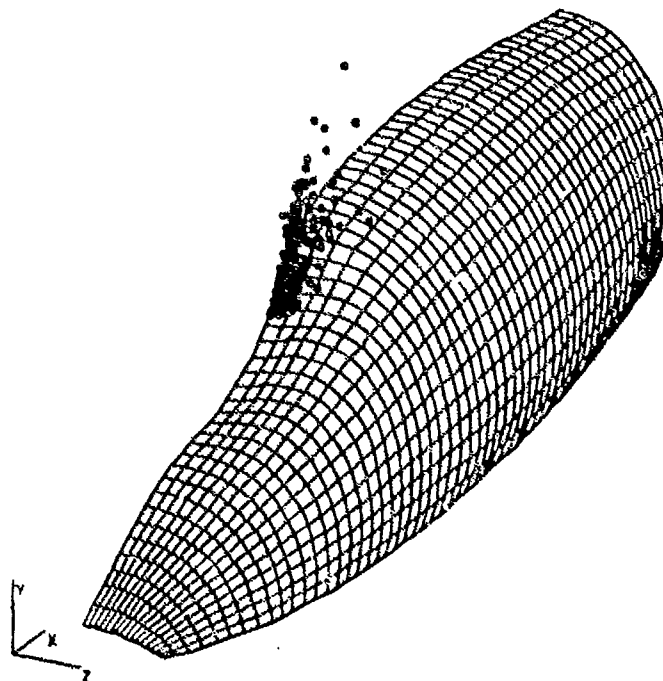
Results from a similar calculation using the higher-strength bird model are shown in Figure 3.20. This solution predicts a predominantly elastic response as well. The impact loading computed with the stronger bird model obviously is quite different from that resulting from the weaker model, and generally provides somewhat greater energy transfer to the target. The question of which bird model is more realistic cannot be resolved without additional experimental data.

Sensitivity studies based upon perturbations of these basic models reveal very promising results. In particular, a modest reduction in ultimate stress for the polycarbonate (13 000 psi, probably a more realistic value) results in localized failure (two plate elements) at 350 knots, indicating that this impact velocity is close to the maximum capability of the transparency. Increasing the impact speed to 450 knots and decreasing the polycarbonate ultimate stress to 9,150 psi results in fairly dramatic failure (Figure 3.21).

In experiments performed at AEDC (Watt, 1978), massive failures were observed for impacts in excess of 350 knots for the 1/2 inch part. No attempt has been made to iterate for a critical velocity in this study, since so many details are unknown with regard to the material properties, precise support conditions, and center of impact location.

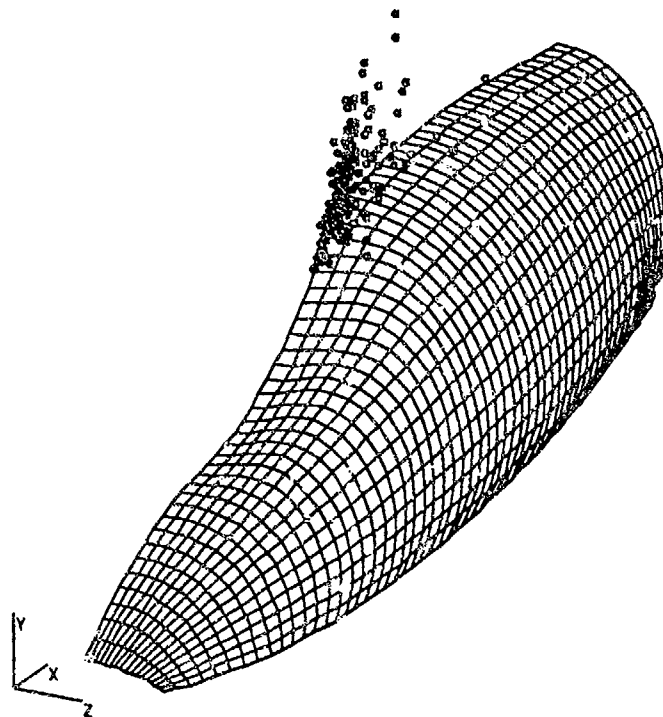


F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 792 / TIME = 2.0000001E-03  
 05-JUN-91 04:25:22  
 F16BE - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

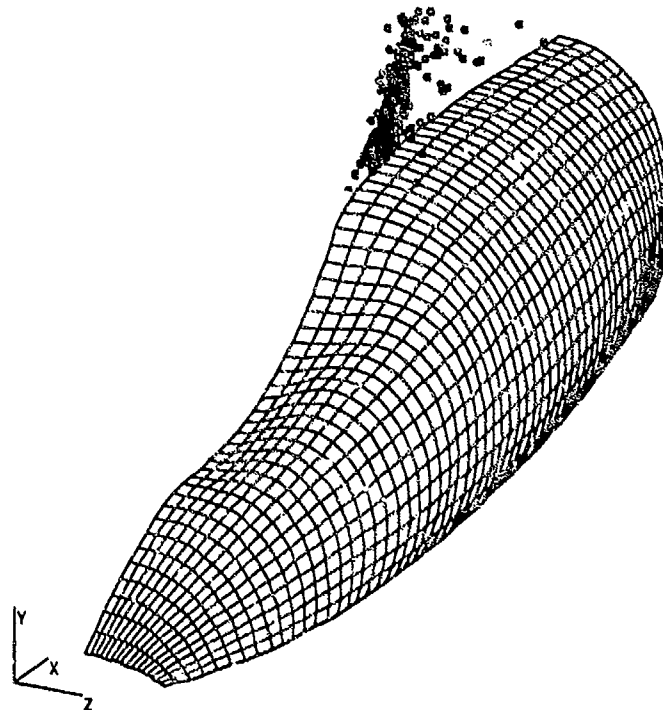


F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 1348 / TIME = 4.0000002E-03  
 05-JUN-91 04:26:32  
 F16BE - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

Figure 3.17. Deformed Geometry of F-16 Canopy for Low-Strength Bird 350-Knot Impact (2-ms Intervals).

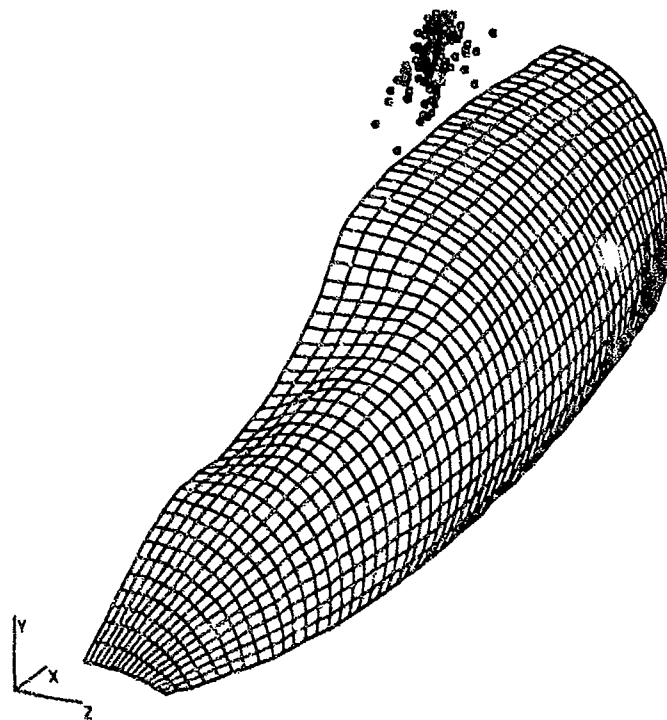


F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 1731 / TIME = 6.0000001E-03  
 05-JUN-91 04:27:38  
 F16BE - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

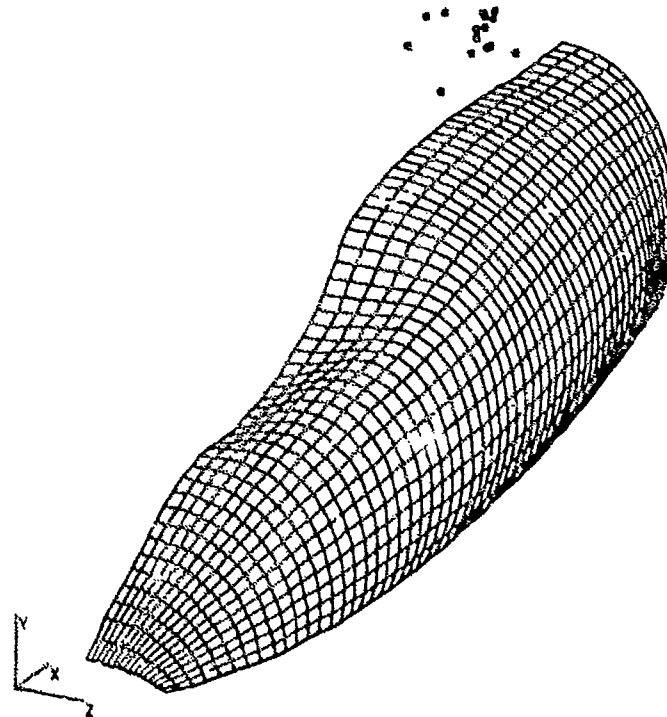


F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 2111 / TIME = 8.0000004E-03  
 05-JUN-91 04:28:47  
 F16BE - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

Figure 3.17. Deformed Geometry of F-16 Canopy for Low-Strength Bird 350-Knot Impact (2-ms Intervals). (Continued)

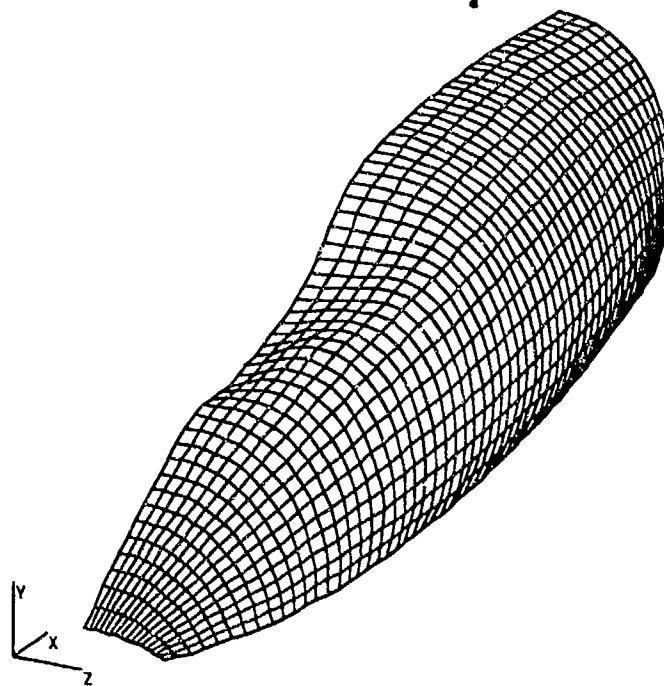


F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 2493 / TIME = 1.0000001E-02  
 05-JUN-91 04:29:55  
 F16BE - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

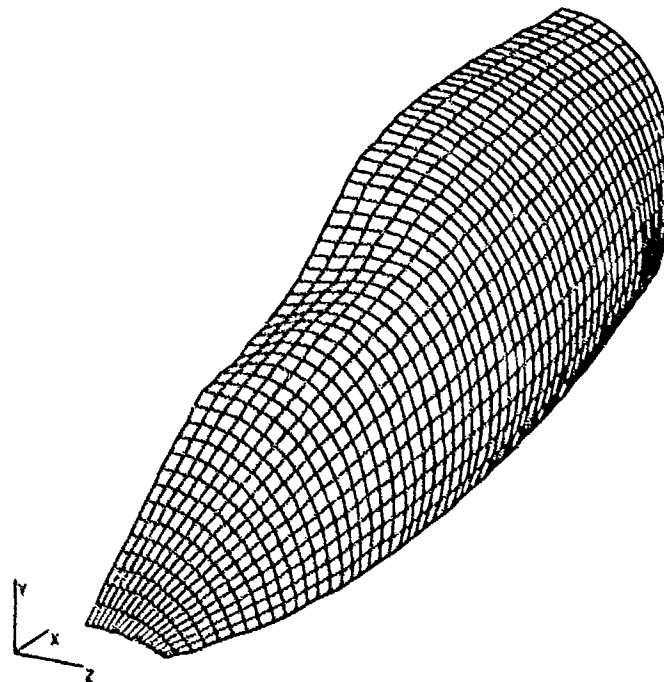


F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 2874 / TIME = 1.2000000E-02  
 05-JUN-91 04:31:11  
 F16BE - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

Figure 3.17. Deformed Geometry of F-16 Canopy for Low-Strength Bird 350-Knot Impact (2-ms Intervals). (Continued)

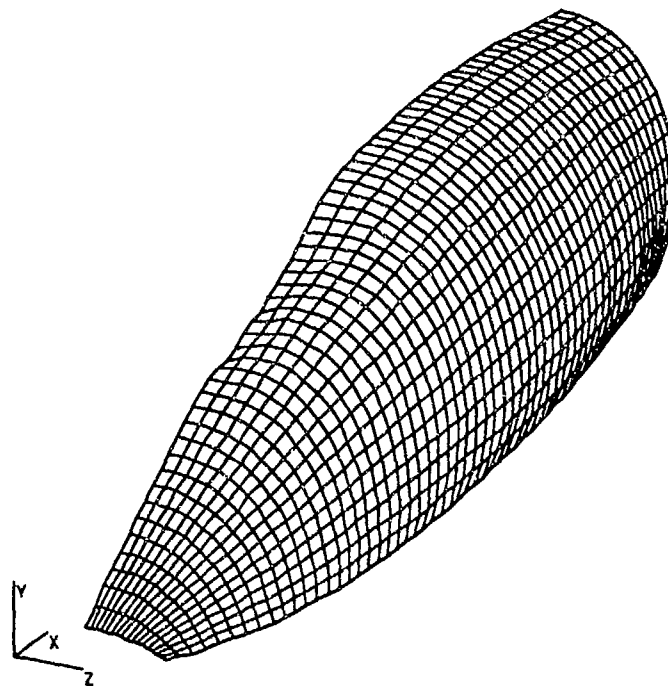


F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 3256 / TIME = 1.4000900E-02  
 05-JUN-91 04:32:25  
 F16BE - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

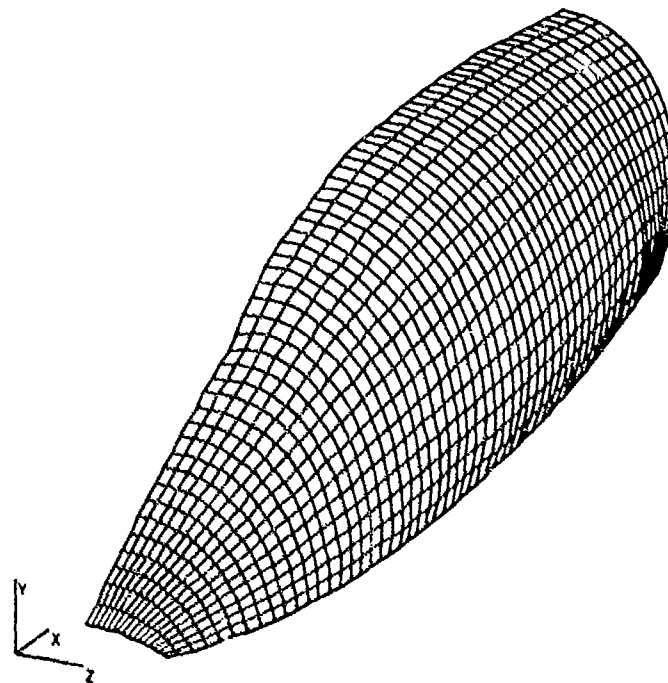


F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 3637 / TIME = 1.6000001E-02  
 05-JUN-91 04:33:41  
 F16BE - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

Figure 3.17. Deformed Geometry of F-16 Canopy for Low-Strength Bird 350-Knot Impact (2-ms Intervals). (Continued)



F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 4017 / TIME = 1.8000001E-02  
 05-JUN-91 04:34:59  
 F16BE - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000



F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 4307 / TIME = 2.0000001E-02  
 05-JUN-91 04:35:21  
 F16BE - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

Figure 3.17. Deformed Geometry of F-16 Canopy for Low-Strength Bird 350-Knot Impact (2-ms Intervals). (Concluded)

# F-16 Transparency Deformed Geometry

CENTERLINE PROFILES AT 0, 4, 8, 12 MILLISECONDS

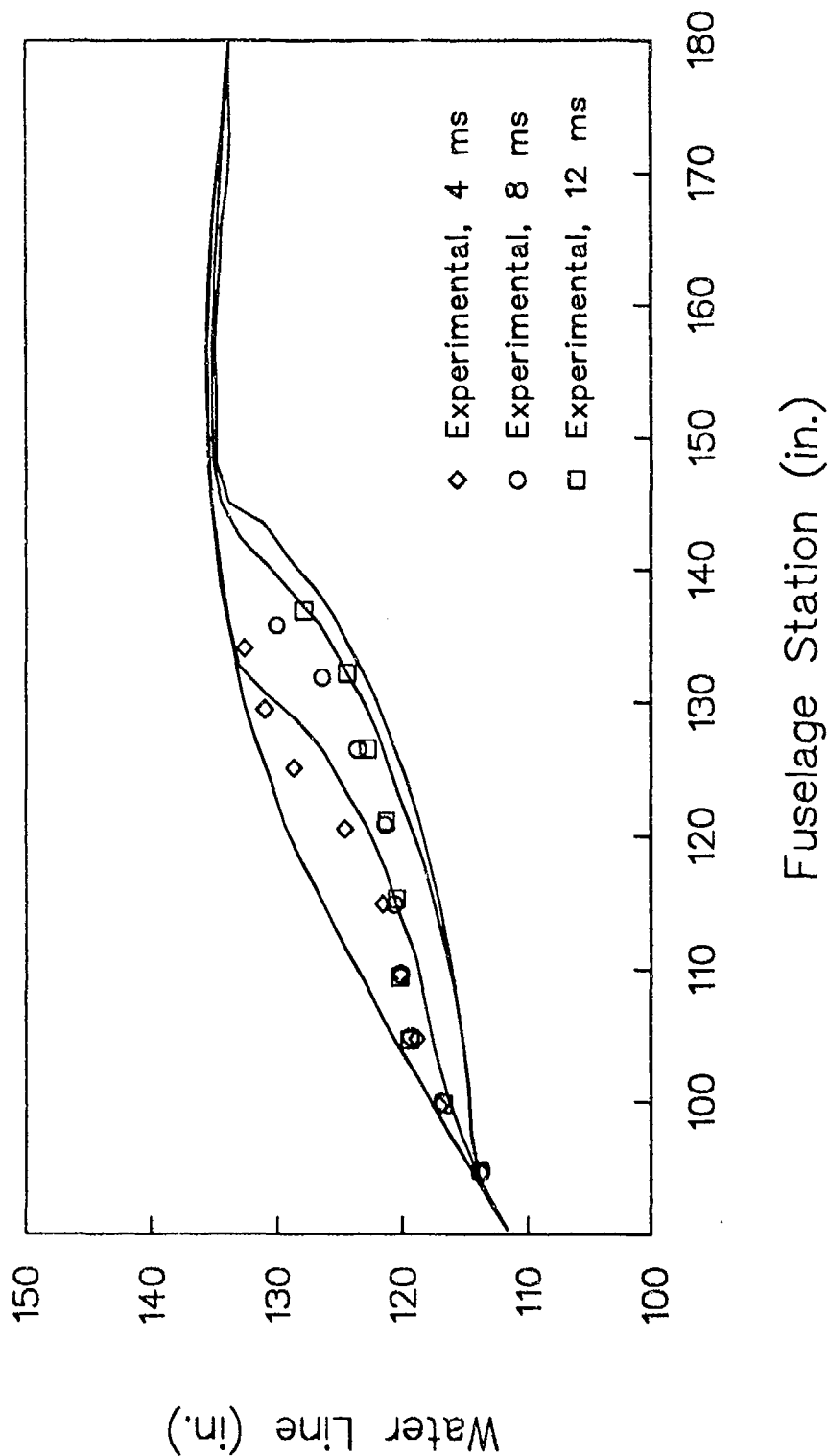


Figure 3.18. Centerline Profiles of Deformed Canopy for 350-Knot Impact (4-ms Intervals).

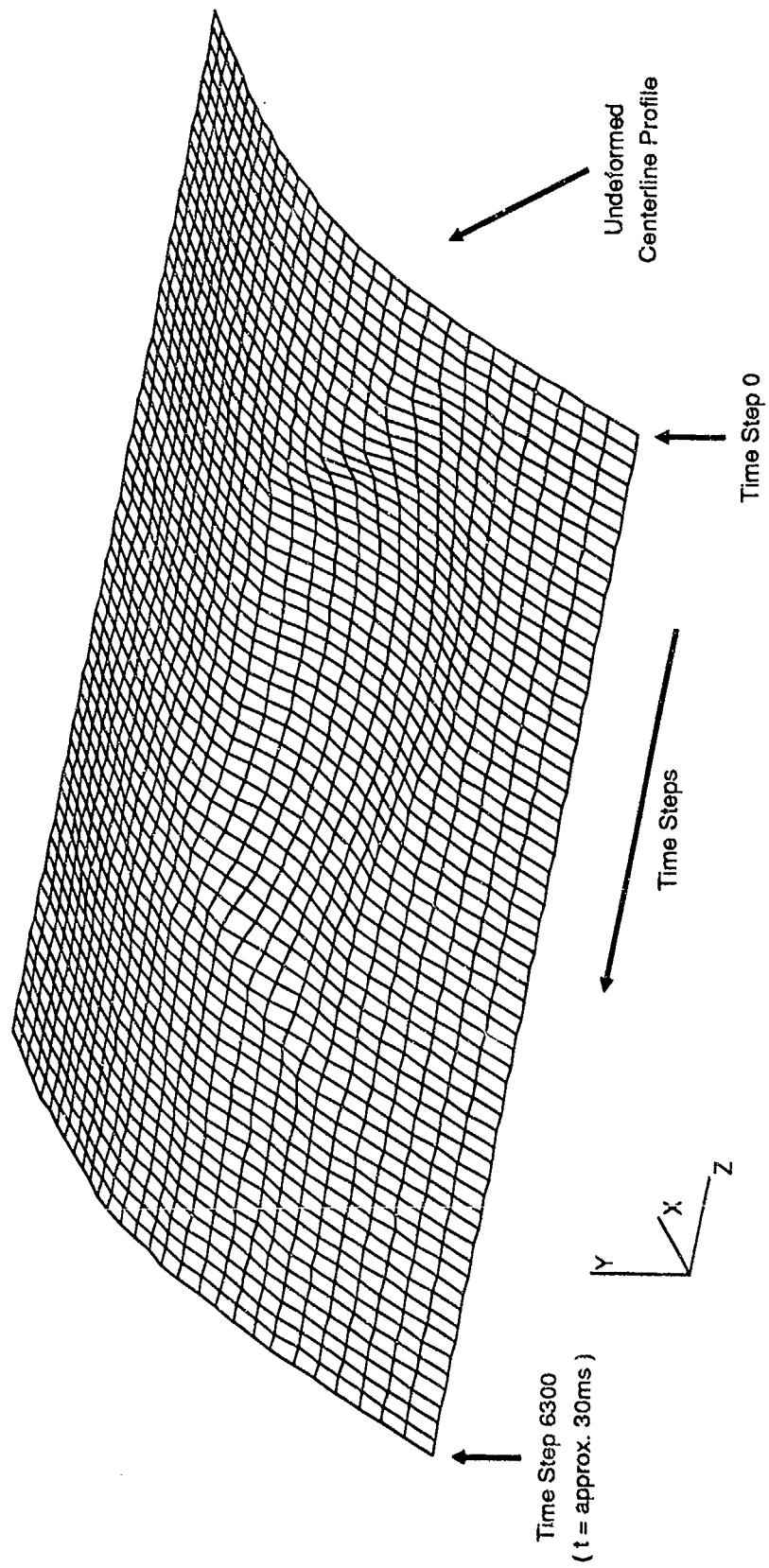
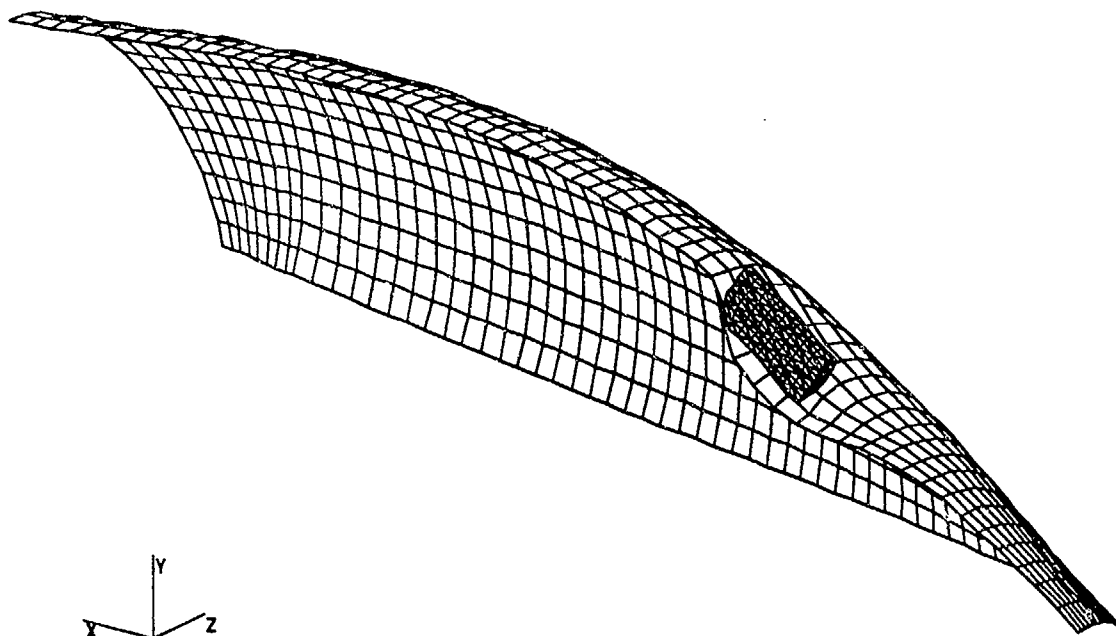
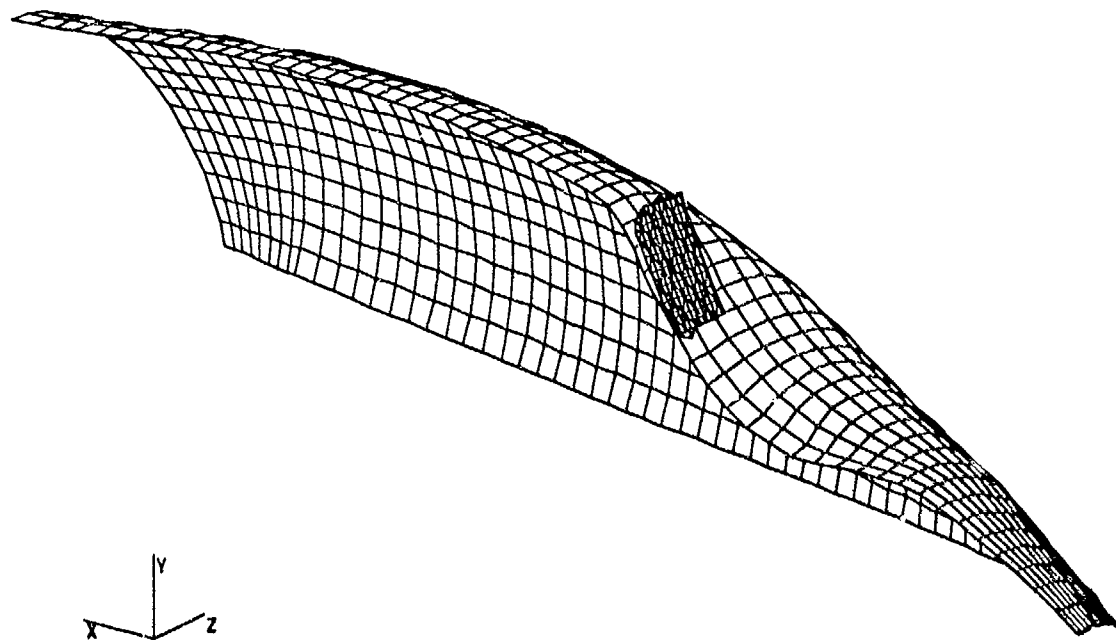


Figure 3.19. Carpet Plot of Centerline Shape versus Time Step for Low-Strength Bird 350-Knot Impact.

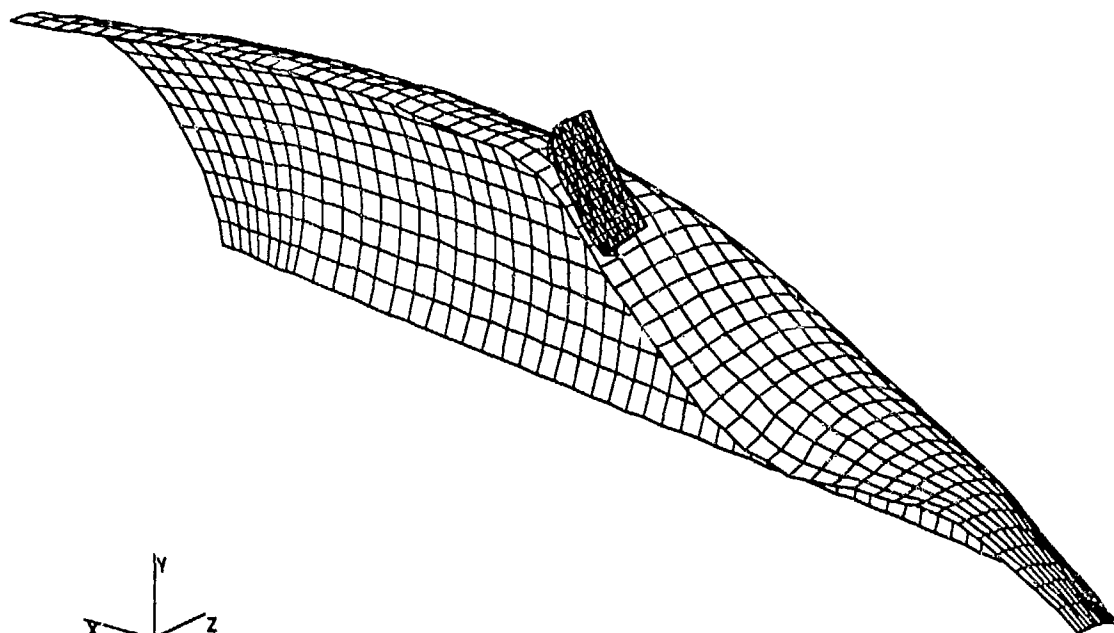


F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 805 / TIME = 1.9999999E-03  
 09-JUN-91 21:10:00  
 F16BD - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

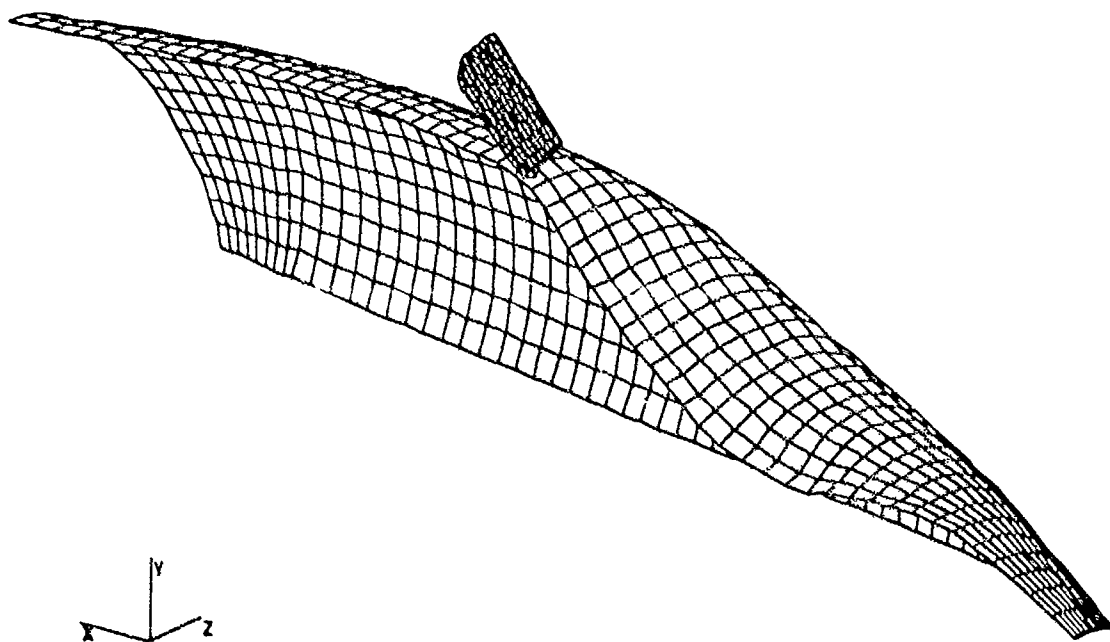


F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 1682 / TIME = 3.9999997E-03  
 09-JUN-91 21:12:02  
 F16BD - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

Figure 3.20. Deformed Geometry of F-16 Canopy for High-Strength Bird 350-Knot Impact (2-ms Intervals).



F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 2563 / TIME = 6.0000001E-03  
 09-JUN-91 21:14:01  
 F16BD - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000



F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS  
 DISPLACEMENTS FOR TIME STEP = 3445 / TIME = 7.9999994E-03  
 09-JUN-91 21:16:01  
 F16BD - 0.5 INCH - POLYCARBONATE: SY=7140 / SU=16000

Figure 3.20. Deformed Geometry of F-16 Canopy for High-Strength Bird 350-Knot Impact (2-ms Intervals). (Concluded)

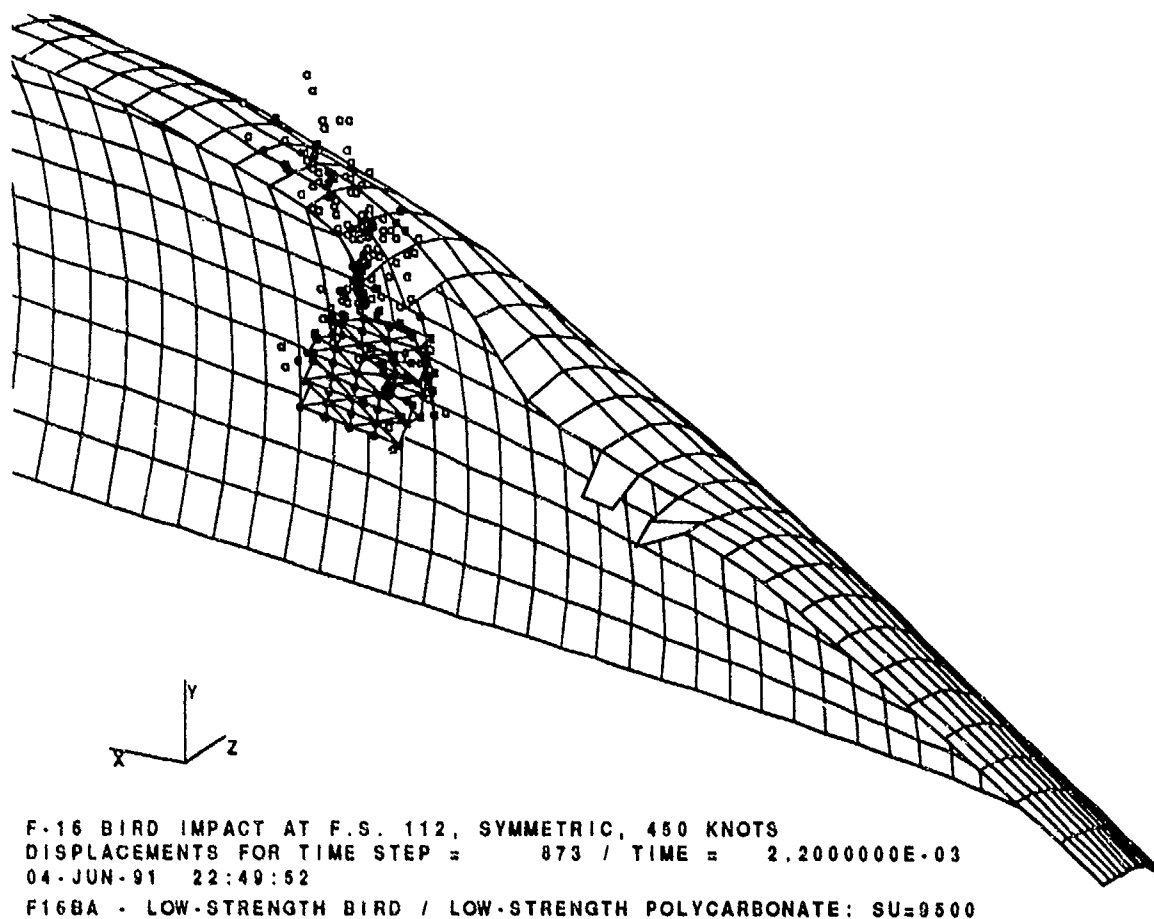


Figure 3.21. Deformed Geometry of Failed Canopy at 450-Knot Impact.

Below, we summarize the PATRAN modeling directives needed to generate both the transparency and the bird geometry. Note that the contact elements (TRI elements in PATRAN) must be generated after the "real" finite elements, since those corresponding to slave surfaces will be retained only in the form of slave *nodes* in the final model. It should be mentioned also that the model generated below must be EQUIVALENCED in PATRAN to merge coincident nodes; these commands are not reproduced in the listing since they consist chiefly of menu responses.

### Bird Geometry

```
GR,1,,0/0/0
GR,2,,2.1/0/0
LI,1,ARC,0/0/0/0/0/1/45,2
LI,2,ARC,0/0/0/0/0/1/45,3
GR,5,,0.8/0.8/0.
GR,6,,1.05/0/0
GR,7,,0/1.05/0
LI,10,ARC,0/0/0/0/0/-1/45,2
LI,11,ARC,0/0/0/0/0/-1/45,8
GR,10,,0.8/-0.8/0
GR,11,,0/-1.05/0
LI,3,2G,,1,6
LI,4,2G,,6,2
LI,5,2G,,1,7
LI,6,2G,,7,4
LI,7,2G,,5,6
LI,8,2G,,5,7
LI,9,2G,,3,5
LI,12,2G,,1,11
LI,13,2G,,9,11
LI,14,2G,,6,10
LI,15,2G,,10,11
LI,16,2G,,8,10
PAT,1,2L,,3,8
PAT,2,2L,,2,8
PAT,3,2L,,1,7
PAT,4,2L,,3,15
PAT,5,2L,,11,15
PAT,6,2L,,10,14
HPAT,1T6,EXT,0/0/8.4,1T6
HPAT,11T16,ROTATE,0/0/0/0/1/0/-90,1T6
HPAT,1T6,DEL
HPAT,1T6,TRANS,8.295/24.865/0,11T16
HPAT,11T16,DEL
```

### Transparency Geometry

```
VIEW
6
-30,50,40
SET,LAB1,OFF
SET,LAB2,OFF
PLOT
GRID,500,,80/32/15
GRID,401,, -9.6466217/11.733902/0.0
GRID,402,, -8.1981583/9.657295/6.80838490
GRID,403,, -6./14.042999/0.0
GRID,404,, -6./9.652824/8.06249428
GRID,405,,3./19.615303/0.0
GRID,406,,2.999992/9.735832/11.2527800
GRID,407,,12./24.868202/0.0
```

```

GRID,408,,12./10.000626/12.9540672
GRID,409,,21./29.506805/0.0
GRID,410,,20.999985/10.451752/13.8953772
GRID,411,,30./32.737701/0.0
GRID,412,,30./11.093910/14.3166628
GRID,413,,39./34.642700/0.0
GRID,414,,39./11.932182/14.4222097
GRID,415,,48./35.502502/0.0
GRID,416,,48./12.972084/14.4203587
GRID,417,,57./35.627899/0.0
GRID,418,,57./14.219543/13.9449654
GRID,419,,66./35.238403/0.0
GRID,420,,66./15.681000/13.2272902
GRID,421,,79.991043/33.902252/0.
GRID,422,,71.540497/16.690796/12.7192183
GRID,423,, -9.5191574/11.551163/2.47858191
GRID,424,, -9.0153732/10.828903/4.78343964
GRID,425,, -6./13.552261/3.25448656
GRID,426,, -6./12.001816/5.97303820
GRID,427,, 3./18.333733/5.30707264
GRID,428,, 2.999992/14.722885/9.17022038
GRID,429,, 12./22.767708/7.00296783
GRID,430,, 12./17.187294/11.5525970
GRID,431,, 20.999985/26.665382/8.44793892
GRID,432,, 20.999969/19.360451/13.4951038
GRID,433,, 30./29.437210/9.42669487
GRID,434,, 30./21.036125/14.8301888
GRID,435,, 39./31.164444/9.86274910
GRID,436,, 39./22.312538/15.4056635
GRID,437,, 48./32.064651/9.80831242
GRID,438,, 48./23.295860/15.3382416
GRID,439,, 57./32.385376/9.37167931
GRID,440,, 57./24.063339/14.7139320
GRID,441,, 66./32.319046/8.65612888
GRID,442,, 66./24.737915/13.7020693
GRID,443,, 78.652328/31.175598/8.00284386
GRID,444,, 75.374023/24.498642/12.6071825
GRID,500,DEL
LINE,401,4G,,401/423/424/402
LINE,402,4G,,403/425/426/404
LINE,403,4G,,405/427/428/406
LINE,404,4G,,407/429/430/408
LINE,405,4G,,409/431/432/410
LINE,406,4G,,411/433/434/412
LINE,407,4G,,413/435/436/414
LINE,408,4G,,415/437/438/416
LINE,409,4G,,417/439/440/418
LINE,410,4G,,419/441/442/420
LINE,411,4G,,421/443/444/422
PATCH,501T510,2L,,401T410,402T411
PATCH,401T420,BREAK,0.5,501T510
PATCH,501T510,DEL

```

### Finite Element Mesh

```

GFEG,P401T402,,9/3
GFEG,P403T418,,9/7
GFEG,P419T420,,9/9
CFEG,P401T420,QUAD,,1
GFEG,HP1T6,,3/3/9
CFEG,HP1T6,TET,,1

```

## Contact Elements and Boundary Conditions

```
SET,LINES,0
ERASE
HP,1T6,PLOT
PAT,401T420,PLOT
CFEG,P405T415B2,TRI/3/1,T1
1
1
1
1
1
1
1
CFEG,HP1T6,TRI/3/2,T11
1
1
1
1
1
1
DFEG,HP1,DISP, //0/0/0/0,1,F1
DFEG,HP2,DISP, //0/0/0/0,1,F2
DFEG,HP4,DISP, //0/0/0/0,1,F3
DFEG,HP5,DISP, //0/0/0/0,1,F4
DFEG,P401T419B2,DISP, //0///,1,EDGE1
DFEG,P401T402,DISP,0/0/0///,1,EDGE4
1
DFEG,P402T420B2,DISP,0/0/0///,1,EDGE3
DFEG,P419T420,DISP,0/0/0///,1,EDGE2
1
```

Additional data needed to complete the model consists of material and laminate definitions, initial velocities for the bird nodes, and solution control parameters. Typical input for these items is shown in the listing below, which describes parameters for a 350-knot impact against a 1/2 inch polycarbonate transparency. The example uses material properties for the high-strength bird shown in previous figures, and uses a conservative ultimate stress of 13,000 psi for the polycarbonate. This model's analysis results predicted a small failure in the transparency (2 plate elements failed), with no bird elements marked as failed.

### TITLE

```
F-16 BIRD IMPACT AT F.S. 112, SYMMETRIC, 350 KNOTS
$ Data translated by PATX3D - 26-OCT-90 03:26:56
$ Last mod 17-May-91 for X3D 2.5 - this is F16BI.DAT:
$ 1. High-strength bird - should be no failure in TET elements.
$ 2. Lower-strength polycarbonate: SU=13000 psi.
END
```

### PARAMETERS

```
$ TIME TMAX TREST DTMIN DTMAX INCR INCMAX IREST NINTPL ISTAT ITRAC
0. 0.018 0.00020 0. 0. 0 170000 1 5 0 20
END
```

### INITIAL VELOCITY

```
7093.65 0. 0. 1004 1300 1 ! 350 KNOTS
$ 8107.03 0. 0. 1004 1300 1 ! 400 KNOTS
END
```

## RIGID

\$ Use a rigid wall at z=0; all nodes must remain positive z.  
 \$ This will constrain bird nodes which may be set loose from  
 \$ failed tet elements.  
 \$ 15-Apr-91  
 0.0, 0.0, 1.0, 0.0  
 END

## TOLERANCES

0.90 0.1 0.01 0.01 0.01  
 END

## LAMINATES

1 1 1 -0.5 0.0  
 END

## TANG

\$ F-16 transparency symmetry-plane rotational constraints. 22-Apr-91  
 1 2 3 52 53 54 55 56 57 154 155 156 157 158 &  
 159 256 257 258 259 260 261 358 359 360 361 362 363 460 &  
 461 462 463 464 465 562 563 564 565 566 567 664 665 666 &  
 667 668 669 766 767 768 769 770 771 868 877 886 895 904 &  
 913 922 931  
 END

## MAT2D

\$ Polycarbonate. -- 23-Oct-90  
 \$ Mod for alternate curve fit; lower SU to 13,000 -- 12-Apr-91  
 1 0 0.0001113 325000. 0.36 1.0 7140. 36100. 5.088E-6 0.083333 13000.  
 \$ Initial curve fit values are below...  
 \$ 1 0 0.0001113 325000. 0.36 1.0 9400. 36100. 13. 1. 16000.  
 END

## MAT3D

\$ Water bird -- Mat type 3 -- 10-Apr-91  
 \$ MATLNO RHO BULK2 SHEAR RSCALE H Q2 Q1  
 \$ ITYPE BULK1 BULK3 BULK4 YIELD REXP SULT  
 1 3 0.0000888 3.37E5 7.29E5 20.2E5 1000. 30000. 3000. 0. 1. 300. 4500. 1.5 .06  
 END

## TRACE

\$ Track some of the F-16 transparency midline nodes (z=0).  
 1 3 53 55 57 155 157 159 257 259 261 359 361 &  
 363 461 463 465 563 565 567 665 667 669 767 769 771 &  
 877 895 913 931  
 END

## NODE COORDINATES

|   |           |          |               |
|---|-----------|----------|---------------|
| 1 | -9.646622 | 11.73390 | 0.0000000E+00 |
| 2 | -7.823311 | 12.88845 | 0.0000000E+00 |
| 3 | -6.000000 | 14.04300 | 0.0000000E+00 |

...

End of the example. All remaining data blocks are generated by PATX3D.

## SECTION 4

### SUMMARY AND CONCLUSIONS

This report describes an improved analytical capability for soft-body impact simulation. Important advances have been made in the modeling of impact loads, nonlinear materials, and layered wall constructions. The explicit approach adopted in the present work exploits the strengths of the current generation of supercomputer hardware, so that analysis cost and turnaround times are reduced significantly over the previous generation of birdstrike analysis software. Our experiences thus far in performing applications indicates that the solution methodology is very reliable, requiring minimal user intervention to avoid or correct problems with the solution. The implicit methods used in our earlier work on these problems demand a great deal of user attention for stable, accurate, and convergent results, while the explicit technique is relatively trouble-free.

We feel that the work reported herein is a significant step toward a reliable capability for design screening and parametric investigations. The most important work which is needed to complete such a capability includes:

*Model Validation.* Additional comparisons of analytical predictions with full-scale impact test data are needed to develop confidence in the accuracy of the analysis and our knowledge of its limitations.

*Materials Characterization.* The transparency materials in wide use are high-polymer compounds with very complex characteristics. Much more experimental and analytical work is needed to understand these materials adequately and model their behavior faithfully.

With a modest effort in these areas, the techniques and software described herein can become a truly useful and reliable tool for the design and evaluation of a new generation of impact-resistant transparency systems.



## REFERENCES

The references listed below describe much of the theoretical basis of the X3D computer program. Some include instructive sample problems which have been used in the validation of the code. All of them contain valuable background information on dynamic analysis and are highly recommended.

---

Anderson, C. E. Jr. (1987), An Overview of the Theory of Hydrocodes, *Int. J. Impact Engng.* **5**, 33-59.

Barber, J. R., H. R. Taylor, and J. M. Wilbeck (1978), *Bird Impact Forces and Pressures on Rigid and Compliant Targets*, AFFDL-TR-77-60, Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio.

Belytschko, T. and B. J. Hsieh (1973), Nonlinear Transient Finite Element Analysis with Convected Coordinates, *Int. J. Num. Meth. Engng.* **7**, 255-271.

Belytschko, T. (1983), An Overview of Semidiscretization Procedures, in T. Belytschko and T. J. R. Hughes (eds.), *Computational Methods for Transient Analysis*, Chapter 1, North-Holland Co., Amsterdam.

Belytschko, T., J. I. Lin, and C.-S. Tsay (1984), Explicit Algorithms for the Nonlinear Dynamics of Shells, *Comp. Meths. Appl. Mech. Engng.* **42**, 225-251.

Belytschko, T. and J. I. Lin (1986), Eigenvalues and Stable Time Steps for the Bilinear Mindlin Plate Element, Preprint, Northwestern University.

Brockman, R. A. (1981), MAGNA: A Finite Element System for Three-Dimensional Static and Dynamic Structural Analysis, *Comp. Struct.* **13**, 415-423.

Brockman, R. A. (1982), *MAGNA (Materially And Geometrically Nonlinear Analysis), Part I - Finite Element Analysis Manual*, AFWAL-TR-82-3098, Part I, Air Force Wright Aeronautical Laboratories, Wright Patterson Air Force Base, Ohio.

Brockman, R. A. (1983), Current Problems and Progress in Aircraft Transparency Impact Analysis, in S. A. Morolo (ed.), *Proceedings of the 14th Conference on Aerospace Transparent Materials and Enclosures*, AFWAL-TR-83-4154, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, 1058-1082.

Brockman, R. A. (1984), *Finite Element Analysis of Soft-Body Impact*, AFWAL-TR-84-3035, Wright-Patterson Air Force Base, Ohio.

- Brockman, R. A. (1987), *A Simple Finite Element Approximation for Multilayered Plates and Shells*, UDR-TR-87-113, University of Dayton.
- R. A. Brockman (1988), Computational Methods for Soft-Body Impact Problems, in S. Atluri and G. Yagawa (eds.), *Computational Mechanics 1988*, Volume 1, pp. 10.vi.1-4, Springer-Verlag.
- Bouchard, M. P. (1989), Finite Element Analysis of the B-1B Windshield System, *Proceedings of the 15th Conference on Aerospace Transparent Materials and Enclosures*, Monterey, CA, January 1990.
- Chatterjee, S. N. and S. V. Kulkarni (1979), Shear Correction Factors for Laminated Plates, *AIAA J.* **17**(5), 498-499.
- Chiapetta, R., T. Belytschko, and J. Rouse (1973), *A Computer Code for Dynamic Stress Analysis of Media-structure Problem with Nonlinearities (SAMSON)*, AFWL-TR-72-104, Air Force Weapons Laboratory, Kirtland AFB, New Mexico.
- Chow, T. S. (1971), On the Propagation of Flexural Waves in an Orthotropic Laminated Plate and its Response to an Impulsive Load, *J. Comp. Matls.* **5**, 306-319.
- Chow, T. S. (1975), Theory of Unsymmetric Laminated Plates, *J. Appl. Physics* **46**, 219-221.
- Dodds, R. H. Jr. (1987), Numerical Techniques for Plasticity Computations in Finite Element Analysis, *Comp. Struct.* **26**(5), 767-779.
- Flanagan, D. P. and T. Belytschko (1981), A Uniform Strain Hexahedron and Quadrilateral with Orthogonal Hourglass Control, *Int. J. Num. Meth. Engng.* **17**, 679-706.
- Goudreaux, G. L. and J. O. Hallquist (1982), Recent Developments in Large-Scale Finite Element Lagrangian Hydrocode Technology, *Comp. Meth. Appl. Mech. Engng.* **33**, 725-757.
- Hughes, T. J. R., M. Cohen, and M. Haroun (1978), Reduced and Selective Integration Techniques in the Finite Element Analysis of Shells, *Nuc. Engng. Des.* **46**, 203-222.
- Hughes, T. J. R. (1983), Analysis of Transient Algorithms with Particular Reference to Stability Behavior, in T. Belytschko and T. J. R. Hughes (eds.), *Computational Methods for Transient Analysis*, Chapter 2, North-Holland Co., Amsterdam.
- Johnson, G. R., D. D. Colby, and D. J. Vavrick (1979), Three Dimensional Computer Code for Dynamic Response of Solids to Intense Impulsive Loads, *Int. J. Num. Meth. Engng.* **14**, 1865-1871.
- Jones, R. M. (1975), *Mechanics of Composite Materials*, Scripta Book Co., Washington, D. C.

Key, S. W. (1974), *HONDO - A Finite Element Computer Program for the Large Deformation Dynamic Response of Axisymmetric Solids*, SLA-74-0039, Sandia National Laboratories, Albuquerque, New Mexico.

Krieg, R. D. and S. W. Key (1973), Transient Shell Response by Numerical Time Integration, *Int. J. Num. Meth. Engng.* **17**, 273-286.

Malvern, L. E. (1969), *An Introduction to the Mechanics of a Continuous Medium*, Prentice-Hall Co., Englewood Cliffs, N.J.

Marchertas, A. H. and T. B. Belytschko (1974), *Nonlinear Finite Element Formulation for Transient Analysis of Three-Dimensional Thin Structures*, Report ANL-8104, Argonne National Laboratory.

McCarty, R. E. (1983), MAGNA Computer Simulation of Bird Impact on the TF-15 Aircraft Canopy, in S. A. Morolo (ed.), *Proceedings of the 14th Conference on Aerospace Transparent Materials and Enclosures*, AFWAL-TR-83-4154, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, 973-1008.

McCarty, R. E. (1985), Three Dimensional Nonlinear Dynamic Finite Element Analysis for the Response of a Thick laminated Shell to Impact Loads, *Proc. AIAA/ASME/ASCE/AHS 26th Structures, Structural Dynamics, and Materials Conference*, Orlando, Florida.

McCarty, R. E. (1989a), Analytic Assessment of Bird Impact Resistant T-46A Aircraft Windshield System Designs using MAGNA, *Proc. 15th Conference on Aerospace Transparent Materials and Enclosures*, Monterey, CA.

McCarty, R. E. (1989b), MAGNA Analysis of Space Shuttle Orbiter Windshield System Bird Impact Protection, *Proc. 15th Conference on Aerospace Transparent Materials and Enclosures*, Monterey, CA.

Mindlin, R. D. (1951), Influence of Rotatory Inertia and Shear on the Bending of Elastic Plates, *J. Appl. Mech.* **18**, 1031-1036.

Newmark, N. M. (1959), A Method of Computation for Structural Dynamics, *J. Eng. Mech. Div.* **85**, 67-94.

Noor, A. K. (1975), Stability of Multilayered Composite Plates, *Fibre Sci. Tech.* **8**, 81-89.

Noor, A. K. and W. S. Burton (1989), Stress and Free Vibration Analyses of Multilayered Composite Plates, *Compos. Struc.* **11**(2).

Pagano, N. J. (1970), Exact Solutions for Rectangular Bidirectional Composites and Sandwich Plates, *J. Comp. Matls.* **4**, 20-34.

Palazotto, A. N. and W. P. Witt (1985), Formulation of a Nonlinear Compatible Finite Element for the Analysis of Laminated Composites, *Comput. Struct.* **21**, 1213-1234.

Reddy, J. N. (1984a), *Introduction to the Finite Element Method*, McGraw-Hill Co., New York.

Reddy, J. N. (1984b), *Energy and Variational Methods in Applied Mechanics*, John Wiley & Sons, New York.

Watt, R. M. (1978), *AFFDL F-16 Canopy Bird Impact Test*, Test Report, Project V41S-18A, von Karman Gas Dynamics Facility, Arnold Engineering Development Center, Arnold AF Station, Tennessee.

West, B. S. and R. A. Brockman (1980), *Evaluation of Bird Load Models for Dynamic Analysis of Aircraft Transparencies*, AFWAL-TR-80-3092, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio.

Whitney, J. M. and N. J. Pagano (1970), Shear Deformation in Heterogeneous Anisotropic Plates, *J. Appl. Mech.* **37**, 1031-1036.

Whitney, J. M. (1973), Shear Correction Factors for Orthotropic Laminates under Static Load, *J. Appl. Mech.* **40**, 302-304.

Zukas, J. A., T. Nicholas, H. F. Swift, L. B. Greszczuk, and D. R. Curran (1982), *Impact Dynamics*, John Wiley & Sons, New York.

# **APPENDIX A**

## **X3D INPUT DATA**

## OVERVIEW

Input data are supplied to X3D on a formatted file containing a series of *input data blocks*. Each block begins with a descriptive header, lists the data, and ends with a record containing the string "END". Data in an input block consists of one or more records; typically there is one record for each element, node, or other model entity. Within a record, data may be arranged in free format, with data items separated by commas or blanks. Data blocks may appear in the input file in any order; however, large models usually are processed more efficiently if the shorter blocks are placed near the beginning of the file. The Table below summarizes all of the input block types recognized by X3D.

**TABLE A.1**  
**SUMMARY OF X3D INPUT BLOCKS**

| INPUT BLOCK NAME            | DESCRIPTION                            |
|-----------------------------|----------------------------------------|
| <b>BODY</b> forces          | Body forces for entire model           |
| <b>BOUND</b> ary conditions | Nodal displacement constraints         |
| <b>CON</b> Tact             | Surface contact data                   |
| <b>EDIT</b>                 | Edit model entities                    |
| <b>ELEM</b> ents            | Element connections and properties     |
| <b>FORC</b> e               | Nodal point force data                 |
| <b>HIST</b> ory functions   | Time history functions                 |
| <b>INIT</b> ial conditions  | Initial velocity conditions            |
| <b>LAM</b> inates           | Plate cross-section data               |
| <b>LINK</b> ed elements     | Element failure links                  |
| <b>MASS</b>                 | Concentrated mass data                 |
| <b>MAT</b> 2d               | Plate (2-D) material properties        |
| <b>MAT</b> 3d               | Solid (3-D) material properties        |
| <b>MPOST</b>                | Request MPOST format output file       |
| <b>NODE</b> coordinates     | Initial nodal positions                |
| <b>PARA</b> meters          | Solution control parameters            |
| <b>PRES</b> surre           | Element pressure loading data          |
| <b>REFE</b> rence volume    | Coordinate limits for plotting         |
| <b>RE</b> Start             | Request restart of a previous analysis |
| <b>RIGI</b> d walls         | Rigid barrier constraints              |
| <b>SOFT</b> body            | Soft body impact data                  |
| <b>TANG</b> ential rotation | Tangential rotation BC's for shells    |
| <b>TITL</b> e               | Descriptive problem title              |
| <b>TOLE</b> rances          | Additional solution parameters         |
| <b>TRAC</b> e nodes         | Trace nodes for summary output         |
| <b>@DEB</b> ug              | Dagnostic output requests              |

For new analyses (as opposed to restarts) several input data blocks, such as the **NODE** and **ELEMent** blocks, are required; others, like **MASS** and **CONtact**, are needed only when the problem calls for them. In a *restart* run, an analysis can be resumed from a point of interruption, possibly with modified data. When a restart is performed, normally only the modified data blocks are required. Table A.2 shows the input block requirements and options for both new and restarted analyses with X3D.

**TABLE A.2**  
**SUMMARY OF INPUT DATA BLOCK REQUIREMENTS**  
**FOR NEW AND RESTARTED ANALYSES**

| INPUT DATA<br>BLOCK | STATUS FOR<br>NEW ANALYSIS | STATUS FOR<br>RESTART RUN | ACTION IF PRESENT<br>AT RESTART |
|---------------------|----------------------------|---------------------------|---------------------------------|
| BODY                | Optional                   | N/A                       |                                 |
| BOUN                | <b>REQUIRED</b>            | N/A                       |                                 |
| CONT                | Optional                   | Optional                  | Replace old data                |
| EDIT                | Optional                   | Optional                  | Modify old data                 |
| ELEM                | <b>REQUIRED</b>            | N/A                       |                                 |
| FORC                | Optional                   | Optional                  | Replace old data                |
| HIST                | Optional                   | Optional                  | Replace old data                |
| INIT                | Optional                   | N/A                       |                                 |
| LAMI                | Optional                   | N/A                       |                                 |
| LINK                | Optional                   | N/A                       |                                 |
| MASS                | Optional                   | N/A                       |                                 |
| MAT2                | Optional                   | N/A                       |                                 |
| MAT3                | Optional                   | N/A                       |                                 |
| MPOS                | Optional                   | Optional                  | Replace old data                |
| NODE                | <b>REQUIRED</b>            | N/A                       |                                 |
| PARA                | <b>REQUIRED</b>            | <b>REQUIRED</b>           | Replace old data                |
| PRES                | Optional                   | Optional                  | Replace old data                |
| REFE                | Optional                   | N/A                       |                                 |
| REST                | N/A                        | <b>REQUIRED</b>           | Read restart file               |
| RIGI                | Optional                   | N/A                       |                                 |
| SOFT                | Optional                   | N/A                       |                                 |
| TANG                | Optional                   | N/A                       |                                 |
| TITL                | <b>REQUIRED</b>            | Optional                  | Replace old data                |
| TOLE                | Optional                   | Optional                  | Replace old data                |
| TRAC                | Optional                   | Optional                  | Replace old data                |
| @DEB                | Optional                   | Optional                  | Replace old data                |

## INPUT FORMAT CONVENTIONS

Input formatting in X3D is relatively flexible. Problem data may be entered in free format, and may contain omitted items, continuation lines, and embedded comments. Data must be entered in columns 1 through 80 in order to be processed correctly. Important special characters in the X3D input include:

|    |                                                                                               |
|----|-----------------------------------------------------------------------------------------------|
| !  | Comment character; the remainder of the current line will be ignored                          |
| \$ | Comment character; equivalent to !                                                            |
| &  | Continuation character; the current record continues on the next line                         |
| ,  | Separator for data items; a string of commas (,,,) may be used to skip a series of data items |

The examples below illustrate the use of these special characters, as well as the conventions used in interpreting input to X3D.

All X3D input items follow FORTRAN naming conventions. That is, names beginning with I-N denote integer values, while names beginning with A-H or O-Z are floating-point (real) data. The only exceptions are alphanumeric (character) inputs, which consist only of the block headers, END lines, and problem title.

As an example, suppose that a particular input record calls for six data items: N1, N2, N3, A, B, and C. By the FORTRAN convention, N1, N2, and N3 are integer data, and A, B, and C define real-valued parameters.

X3D will read all six items as floating-point numbers, and truncate them to integer values as necessary. Omitting an item of data is equivalent to entering a zero value (although X3D may supply non-zero defaults for some data items).

Table A.3 shows several possible data records corresponding to the data items of the previous example: N1, N2, N3, A, B, C. The center column of the Table lists the values which X3D actually assigns to these six variables. The right-hand column contains comments explaining the rules or conventions which have been used in interpreting the input data.

**TABLE A.3**  
**EXAMPLES OF X3D INPUT FORMAT CONVENTIONS**

| INPUT RECORD                                                                   | VALUES ASSIGNED                                                  | EXPLANATION & COMMENTS                                                                                                                    |
|--------------------------------------------------------------------------------|------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| 1 2 3 4 5.5 6                                                                  | N1 = 1<br>N2 = 2<br>N3 = 3<br>A = 4.0<br>B = 5.5<br>C = 6.0      | Multiple spaces are the same as a single space<br><br>Integer values are converted to reals as necessary                                  |
| 1.5, 2,, 4.4, 5 6                                                              | N1 = 1<br>N2 = 2<br>N3 = 0<br>A = 4.4<br>B = 5.0<br>C = 6.0      | Real values are truncated to integers as necessary<br><br>Repeated commas signify an omitted value                                        |
| 1.E4,,,,, 27                                                                   | N1 = 10000<br>N2 = 0<br>N3 = 0<br>A = 0.0<br>B = 0.0<br>C = 27.0 | Exponents may be used anywhere, and are converted to integers where appropriate<br><br>A data item is assumed between each pair of commas |
| 2,, 7 1 &<br>8.5                                                               | N1 = 2<br>N2 = 0<br>N3 = 7<br>A = 1.0<br>B = 8.5<br>C = 0.0      | & indicates that the record is continued on the next line<br><br>When trailing items are omitted, zero values are assigned                |
| \$ a comment line<br>1 -0.2, &! note<br>! another comment<br>3,,, ! note<br>-1 | N1 = 1<br>N2 = 0<br>N3 = 3<br>A = 0.0<br>B = 0.0<br>C = 0.0      | Comments after ! or \$ ignored<br>-0.2 is truncated to zero<br><br>Last line (-1) is not read since the preceding line contains no &      |

## X3D FILE SUMMARY

Although X3D works entirely in memory, operating the code involves several input and output files. They are:

| FILE NAME        | FORM      | DESCRIPTION                   |
|------------------|-----------|-------------------------------|
| (logical unit 5) | Formatted | Input data                    |
| (logical unit 6) | Formatted | Printed output                |
| NREST            | Binary    | Restart output                |
| OREST            | Binary    | Restart input                 |
| TRACE            | Formatted | Trace node output             |
| MPOST            | Formatted | MAGNA-compatible results file |

All files use the system default naming conventions. For instance, the TRACE file would be named TRACE on a CRAY/UNICOS system, where file extensions are not used; on a VAX/VMS system, where the default file type for FORTRAN-generated files is .DAT, the same file would be called TRACE.DAT. The NREST, OREST, TRACE, and MPOST files are opened using the basic file names only.

The input and output files are not opened explicitly by the program, due to differences in the ways various systems treat the standard FORTRAN input and output units. On most UNIX-based machines, these files correspond to the system's standard input and standard output. For other systems, the user may need to take additional measures. For example, on a VAX/VMS system, input must either be stored on the file FOR005.DAT, or assigned to the logical name FOR005 (e.g., ASSIGN MYDATA.DAT FOR005).

Two external files are used for restart functions. NREST is the "new" restart file; that is, the restart output file, and is created whenever restart output is requested. OREST, the "old" file, supplies restart input to the program. OREST must exist whenever an analysis restart is requested. Note also that the restart file is used by postprocessing utilities to recover results for plotting. Therefore, one usually requests restart file output even if the analysis will not be resumed at a later time.

In general, restart files are not portable between machines of different architectures. For example, a VAX/VMS user could not copy a restart file from a Sun to the VAX and then run X3POST using that file. There are some exceptions to this restriction (CRAY machines, in particular, using special system utilities), but these are not discussed here. This means that a user must run X3POST on the machine that created the restart file, or on a machine like it.

Two additional external files, TRACE and MPOST, contain formatted results suitable for listing, plotting, or other postprocessing. The TRACE file contains formatted output for a user-specified list of nodes. The MPOST file contains model data and results in a form compatible with output from the MAGNA finite element program. Both of these files are ASCII files and may be transferred between computer systems without difficulty.

## X3D INPUT SUMMARY

The remainder of this Appendix contains detailed descriptions of the individual X3D input blocks. Table A.4 below gives a summary of the data items required in each block.

**TABLE A.4**  
**SUMMARY OF X3D INPUT PARAMETERS**

---

|       |                                                                                                                          |
|-------|--------------------------------------------------------------------------------------------------------------------------|
| BODY  | BX, BY, BZ                                                                                                               |
| BOUN  | IBEG, IEND, ISTEP, IFIX1, IFIX2, IFIX3, IFIX4, IFIX5, IFIX6                                                              |
| CONT  | ISSET, NODEA, NODEB, NODEC                                                                                               |
|       | END                                                                                                                      |
|       | JSET, NODE1, NODE2, NODE3, ..., NODEn                                                                                    |
|       | END                                                                                                                      |
| EDIT  | /DEL N1, N2, N3, ...                                                                                                     |
| ELEM  | IEL, MATL, N1, N2, N3, N4, N5, N6, N7, N8, IEGEN, INGEN                                                                  |
| FORC  | NODE, IDIR, IFUNC, SCALE                                                                                                 |
| HIST  | ICURV, NPT, $t_1$ , $F_1$ , $t_2$ , $F_2$ , ..., $t_{NPT}$ , $F_{NPT}$                                                   |
| INIT  | $V_x$ , $V_y$ , $V_z$ , NFIRST, NLAST, NINCR                                                                             |
| LAMI  | LAMNO, NLAYER, MATL <sub>1</sub> , MATL <sub>2</sub> , ..., MATL <sub>NLAYER</sub> , $Z_1$ , $Z_2$ , ..., $Z_{NLAYER+1}$ |
| LINK  | $M_1$ , $NS_1$ , $M_2$ , $NS_2$ , ..., $M_n$ , $NS_n$                                                                    |
| MASS  | NODE, TRMASS, XRI, YRI, ZRI                                                                                              |
| MAT2  | MATL, 1, RHO, E, XNU, ALPHA, YIELD, H, RSCALE, REXP, SULT                                                                |
| or    | MATL, 2, RHO, E1, E2, XNU*2, G12, G13, G23, SF, SD                                                                       |
| MAT3  | MATL, 1, RHO, BULK1, BULK2, BULK3, SHEAR, YIELD, RSCALE, REXP, H, SULT, Q2, Q1                                           |
| or    | MATL, 2, RHO, BULK1, BULK2, BULK3, VISC, Q2, Q1                                                                          |
| or    | MATL, 3, RHO, BULK1, BULK2, BULK3, BULK4, SHEAR, YIELD, RSCALE, REXP, H, SULT, Q2, Q1                                    |
| MPOST | (none)                                                                                                                   |
| NODE  | IPT, X, Y, Z, IGEN                                                                                                       |
| PARA  | TIME, TMAX, TREST, DTMIN, DTMAX, INCR, INCMAX, IREST, NINTPL, ISTAT, ITRACE                                              |
| PRES  | IBEG, IEND, IFACE, IFUNC, SCALE                                                                                          |
| REPE  | XMIN, XMAX, YMIN, YMAX, ZMIN, ZMAX                                                                                       |
| REST  | INCOLD                                                                                                                   |
| RIGI  | A, B, C, D                                                                                                               |
| TANG  | $N_1$ , $N_2$ , $N_3$ , ..., $N_n$                                                                                       |
| TITL  | ITITLE                                                                                                                   |
| TOLE  | DTFRAC, HGDAMP, HGCONS(1), HGCONS(2), HGCONS(3), FRATIO, VRATIO                                                          |
| TRAC  | $N_1$ , $N_2$ , $N_3$ , ..., $N_n$                                                                                       |
| @DEB  | KEYWORD = value                                                                                                          |

---



## BODY FORCES

### INPUT DATA BLOCK

*Defines uniform body forces (such as gravity) which act on the model.*

**STATUS:** Optional (ignored when restarting)

**FORMAT:**

BODY  
BX, BY, BZ  
END

**EXAMPLE:**

BODY  
0., 0., -386.4  
END

**VARIABLES:**

BX    Body force per unit mass in the X direction  
BY    Body force per unit mass in the Y direction  
BZ    Body force per unit mass in the Z direction

**NOTES:**

1. Body forces per unit mass have units of acceleration.
2. Positive values act in the positive global coordinate directions.
3. BX, BY, BZ are constant with respect to time, and act on all finite elements in the model.

## BOUNDARY CONDITIONS

### INPUT DATA BLOCK

*Defines velocity constraints at the nodes of the model.*

**STATUS:** Optional (ignored when restarting)

**FORMAT:**

BOUND

IBEG, IEND, ISTEP, IFIX1, IFIX2, IFIX3, IFIX4, IFIX5, IFIX6

<repeat as needed>

END

**EXAMPLE:**

BOUND

1, 15, 2, 1, 5, 6

! Nodes 1,3,5,...,15 fixed in  $U_x$ ,  $R_y$ ,  $R_z$

7, 10,, 3

! Nodes 7-10 fixed in  $U_z$

20,,,1,2,3

! Node 20 fixed in  $U_x$ ,  $U_y$ ,  $U_z$

END

**VARIABLES:**

IBEG

First node in the series of points to be constrained

IEND

Last node in the series of points to be constrained

ISTEP

Node number increment

IFIXn

Values of nodal degree of freedom components to be constrained. Component numbers 1, 2, 3 correspond to translational DOFs  $U_x$ ,  $U_y$ , and  $U_z$ , respectively; components 4, 5, 6 are rotational DOFs  $R_x$ ,  $R_y$ , and  $R_z$ .

**NOTES:**

1. IBEG, IEND, and ISTEP define a sequence of nodes to which a common set of velocity constraints will be applied. The sequence consists of nodes IBEG, IBEG+ISTEP, IBEG+2\*ISTEP, ..., IEND.
2. If IEND is omitted, only node IBEG is constrained.
3. If ISTEP is omitted, an increment of 1 is assumed. If present, ISTEP must be positive.
4. IFIX values may be entered in any order, omitting component numbers which are unnecessary.

## CONTACT SURFACES

### INPUT DATA BLOCK

*Defines opposing surfaces which may interact through contact constraints.*

**STATUS:** Optional (replaced if present when restarting)

**FORMAT:**

```
CONT  
ISET, NODEA, NODEB, NODEC  
<repeat as needed to define all master surfaces>  
END  
JSET, NODE1, NODE2, NODE3, ..., NODEn  
<repeat as needed to define all slave nodes>  
END
```

**EXAMPLE:**

```
CONT  
1, 400, 401, 402      ! 3-D master surface defined by 3 nodes  
2, 10, 12, -1         ! 2-D master surface in Y-Z plane  
END                  ! (End of master surface data)  
1, 20, 512, 316 &    ! Slave nodes for set 1, continued on next line  
    18, 358  
2, 15, 19, 45         ! Slave nodes for set 2  
END                  ! (End of slave node data)
```

**VARIABLES:**

|       |                                                               |
|-------|---------------------------------------------------------------|
| ISET  | Contact constraint set number for master surface              |
| NODEA | First connected node defining a master surface segment        |
| NODEB | Second connected node defining a master surface segment       |
| NODEC | Third connected node defining a master surface segment        |
| JSET  | Contact constraint set number for current list of slave nodes |
| NODEn | Slave node number(s)                                          |

**NOTES:**

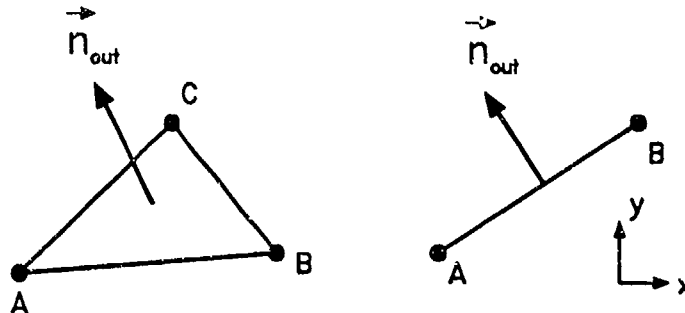
1. Contact constraints will be enforced between all master surface segments and slave nodes which have the same constraint set number (ISET=JSET).
2. A master surface segment normally is a triangle defined by three nodes. It may correspond to a portion of the surface of a solid element, or of a quadrilateral plate element. Boundary surface segments (e.g., those which lie on symmetry planes) have a different form (see Note 4).

## CONTACT SURFACES

### INPUT DATA BLOCK (CONTINUED)

#### NOTES (Continued):

3. The ordering of the three nodes defining a master surface defines its orientation. When viewed from the "outside", the three nodes NODEA, NODEB, NODEC appear in *counterclockwise* order.



4. On symmetry planes or partially constrained boundary lines, a two-node master surface is appropriate. Usually this occurs when the slave nodes must move in a plane. For a 2-D master segment, NODEA and NODEB specify the nodes at the two endpoints of the segment; *NODEC must be set to -1, -2, or -3 to define the global axis (X, Y, or Z) normal to the plane containing the master segment and the slave nodes.* The outward direction for a 2-D master surface segment is defined by the cross product of a vector along the given normal axis (X, Y, or Z) with a vector directed from NODEA to NODEB. Therefore, the outward direction of the segment can be reversed simply by interchanging NODEA and NODEB.
5. Master surface segments may be defined in any order. Set numbers (ISET) should be numbered from 1 through the maximum number of constraint sets.
6. Two- and three-node master surfaces may appear in the same set; however, we have not yet encountered a situation in which this is appropriate.
7. NODE1, ..., NODEn is a list of nodes to be included in a particular constraint set. Nodes may be listed in any order.

## CONTACT SURFACES

INPUT DATA BLOCK (CONTINUED)

### NOTES (Continued):

8. The contact solution is most efficient when a given number of master surfaces and slave nodes are segregated into as many separate sets as possible, since the number of potential contact pairs (master surface, slave node) is minimized. *A surface segment or slave node may appear in more than one set*, so potential contact constraints in adjacent areas can be overlapped. It is more efficient to duplicate slave nodes than surface segments.

## EDIT

### INPUT DATA BLOCK

*Defines editing operations to be performed on the model (usually when restarting).*

**STATUS:** Optional

**FORMAT:**

```
EDIT  
KEYWORD, N1, N2, N3, ...  
<repeat as needed to define all edits>  
END
```

**EXAMPLE:**

```
EDIT  
/DEL 10, 22, 312      ! Mark elements 10, 22, and 312 as failed  
/DEL 502, 26      &    ! Specify more elements with either another  
      362, 1004      ! 'delete' command, or continuation line(s)  
END
```

**VARIABLES:**

KEYWORD Editing command  
Ni List of entities to be operated upon

**NOTES:**

1. Currently, the only valid editing keyword is /DEL (delete elements). This command may be used to remove inactive or unimportant elements from the solution, usually to reduce computation time or achieve a larger time step in the remaining solution. Elements modified with /DEL are deleted *permanently* from the solution.

# ELEMENTS

## INPUT DATA BLOCK

*Defines connections and materials for all finite elements in the model.*

**STATUS:** Required (ignored when restarting)

**FORMAT:**

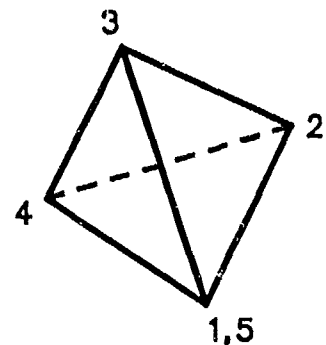
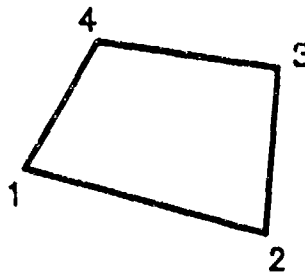
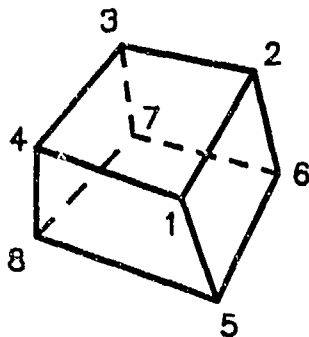
ELEM  
 IEL, MATL, N1, N2, N3, N4, N5, N6, N7, N8, IEGEN, INGEN  
 <repeat as needed to define all elements>  
END

**EXAMPLE:**

|                                |                                   |
|--------------------------------|-----------------------------------|
| ELEM                           |                                   |
| 25, 1, 14,12,13,16,20,22,28,27 | ! 3-D HEX element, material no. 1 |
| 30, 1,,,,,,,, 1, 6             | ! Generate elements 26-30         |
| 4, 3, 7, 9, 12, 15             | ! Plate element, laminate no. 3   |
| 9, 3,,,,,,,, 1, 10             | ! Generate elements 5-9           |
| END                            |                                   |

**VARIABLES:**

|       |                                                                           |
|-------|---------------------------------------------------------------------------|
| IEL   | Element number to be defined                                              |
| MATL  | Material property number (solids) or laminate number (plates)             |
| Ni    | Nodes defining the element, listed in the order shown below               |
| IEGEN | Element number increment for successive elements in a generation sequence |
| INGEN | Node number increment for successive elements in a generation sequence    |



## ELEMENTS

### INPUT DATA BLOCK (CONTINUED)

#### NOTES:

1. Finite elements must be numbered sequentially from 1 to  $N_e$ , the number of elements in the model. Elements may be defined in any order.
2. MATL refers to a material property ID for 3-D solid elements (see input block **MAT3D**). For plate/shell elements, MATL is a *laminare number*, as defined in the **LAMI** input block.
3. X3D identifies the type of element by the number of nodes connected to it. 3-D solid hexahedra (bricks) have eight nodes; tetrahedra are defined by five nodes, with  $N_5 = N_1$ . Plate/shell elements are defined by four corner nodes.
4. To generate elements, first enter the beginning element in the series, with IEGEN and INGEN omitted. On the next line, enter the last element in the series, with appropriate values for the generation parameters. For example, the data

```
5, 1, 4, 6, 8, 9, 2, 10, 15, 12
25, 1,,,,,,,,, 5, 4
```

generates a sequence of elements with numbers 5, 10, 15, 20, and 25, in which the node numbers for each element are 4 greater than for the previous element. That is, the input above is equivalent to:

```
5, 1, 4, 6, 8, 9, 2, 10, 15, 12
10, 1, 8, 10, 12, 13, 6, 14, 19, 16
15, 1, 12, 14, 16, 17, 10, 18, 23, 20
20, 1, 16, 18, 20, 21, 14, 22, 27, 24
25, 1, 20, 22, 24, 25, 18, 26, 31, 28
```

Only nonzero node numbers are incremented during element generation.

5. Node numbers need not be entered for the second line of a generation sequence (see the example above).
6. The material property number for all elements in a generation sequence is the same as the property number for the last element input.

## FORCES

### INPUT DATA BLOCK

*Defines time-dependent concentrated forces and moments at selected nodes.*

**STATUS:** Optional

**FORMAT:**

FORC  
NODE, IDIR, IFUNC, SCALE  
<repeat as needed to define all forces>  
END

**EXAMPLE:**

FORC  
125, 3, 2, -100.                      ! Force at node 125, acting in the Z direction.  
                                         ! The magnitude at any time is interpolated from  
                                         ! time history curve #2, and multiplied by -100.  
  
END

**VARIABLES:**

|       |                                                                                    |
|-------|------------------------------------------------------------------------------------|
| NODE  | Node at which the force is applied                                                 |
| IDIR  | Loading direction: 1= $F_x$ , 2= $F_y$ , 3= $F_z$ , 4= $M_x$ , 5= $M_y$ , 6= $M_z$ |
| IFUNC | Number of time history function defining load magnitude versus time                |
| SCALE | Scale factor to be applied to time function value                                  |

**NOTES:**

1. Positive forces act in the positive global coordinate directions. Positive moments act in the direction of a positive right-handed rotation about the axis in question.
2. Time history function values are obtained at a given time by linear interpolation of curve number IFUNC, and then multiplied by SCALE to obtain the actual load value at that time.

# HISTORY FUNCTIONS

## INPUT DATA BLOCK

*Defines the time variation of element pressure forces and nodal loads.*

**STATUS:** Optional (Required if a **PRESSURE** or **FORCE** input block is present)

**FORMAT:**

HIST

ICURV, NPT,  $t_1$ ,  $F_1$ ,  $t_2$ ,  $F_2$ , ...,  $t_{NPT}$ ,  $F_{NPT}$   
<repeat as needed to define all time functions>

END

**EXAMPLE:**

HIST

1, 2, 0, 50, 1000, 50

! Constant function  $F(t) = 50$

3, 4

! Function no. 3, defined by 4 points:

0, 0, 0.0001, 1000 &

! Linear rise up to  $F(0.0001) = 1000$ ,

0.0002, 0 &

! linear decrease down to 0 at time  $t = 0.0002$ ,

1, 0

! then  $F = 0$  for all subsequent times

END

**VARIABLES:**

ICURV

ID number of time history function to be defined ( $\leq 20$ )

NPT

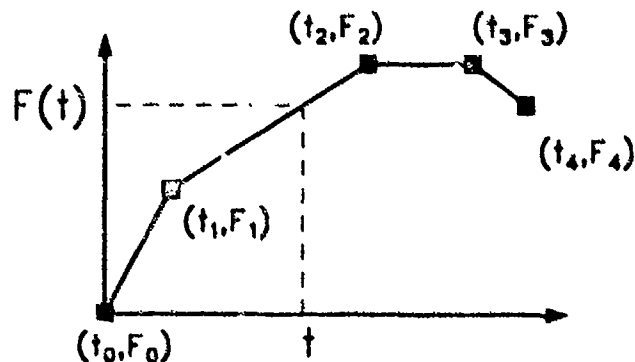
Number of data points  $[t, F(t)]$  for this time function ( $\leq 50$ )

$t_i$

Time value for the  $i^{\text{th}}$  data point

$F_i$

Function value for the  $i^{\text{th}}$  data point



## HISTORY FUNCTIONS

### INPUT DATA BLOCK (CONTINUED)

#### NOTES:

1. Time values must increase monotonically for each function.
2. Function values  $F(t)$  are used in computing the magnitude of element pressure loads and nodal forces. Values at times between the data points are obtained by linear interpolation.
3. To define a time function which goes to zero at a given time, and remains zero thereafter, make sure that the last two data points define  $F=0$  (see the example above). Function values for times  $t > t_{NPT}$  are computed by extrapolation using the last two data points.

## INITIAL VELOCITY

### INPUT DATA BLOCK

*Defines initial conditions on nodal velocity components at selected nodes.*

**STATUS:** Optional (ignored when restarting)

**FORMAT:**

```
INIT  
Vx, Vy, Vz, NFIRST, NLAST, NINCR  
<repeat as needed to define all initial conditions>  
END
```

**EXAMPLE:**

```
INIT  
0, 0, -5000, 1, 7, 2      ! Z velocity of -5000 at nodes 1, 3, 5, 7  
0, -2500, 0, 20          ! Y velocity of -2500 at node 20  
END
```

**VARIABLES:**

|                |                                                                                               |
|----------------|-----------------------------------------------------------------------------------------------|
| V <sub>x</sub> | Initial velocity in the global X direction                                                    |
| V <sub>y</sub> | Initial velocity in the global Y direction                                                    |
| V <sub>z</sub> | Initial velocity in the global Z direction                                                    |
| NFIRST         | First node to which initial velocities V <sub>x</sub> , V <sub>y</sub> , V <sub>z</sub> apply |
| NLAST          | Last node to which initial velocities V <sub>x</sub> , V <sub>y</sub> , V <sub>z</sub> apply  |
| NINCR          | Node number increment                                                                         |

**NOTES:**

1. Initial velocities specified here are applied only to nodes which are otherwise unconstrained. That is, velocity constraints defined in the **BOUNDARY CONDITIONS** input block take precedence over the initial conditions.

## LAMINATES

### INPUT DATA BLOCK

*Defines cross-sectional properties for plate/shell elements.*

**STATUS:** Optional (ignored when restarting)

**FORMAT:**

```

LAMI
LAMNO, NLAYER, MATL1, MATL2, ..., MATLNLAYER, &
Z1, Z2, ..., ZNLAYER+1, ANG1, ANG2, ..., ANGNLAYER
<repeat as needed to define all laminates>
END

```

**EXAMPLE:**

```

LAMI
1, 1, 3, -0.125, 0.125      ! One layer, material #3, t=0.25
3, 1, 4, 0, 0.050          ! One layer, midsurface offset from nodes
2, 2, 1, 3, -0.1, 0, 0.1   ! Two layers with different materials
8, 5, 1, 2, 4, 2, 3,      & ! Five-layer laminate constructed from four
-0.25, -0.0004, 0.,      & ! different materials
0.246, 0.250, 0.255
END

```

**VARIABLES:**

|                   |                                                                                                                                  |
|-------------------|----------------------------------------------------------------------------------------------------------------------------------|
| LAMNO             | Laminate ID number                                                                                                               |
| NLAYER            | Number of layers                                                                                                                 |
| MATL <sub>i</sub> | Material ID for the i <sup>th</sup> layer (bottom to top)                                                                        |
| Z <sub>i</sub>    | Thickness coordinate at the lower surface of the i <sup>th</sup> layer. The last value is the top of the last (uppermost) layer. |
| ANG <sub>i</sub>  | Material orientation angle $\theta$ for the i <sup>th</sup> layer (see figure), in degrees.                                      |

**NOTES:**

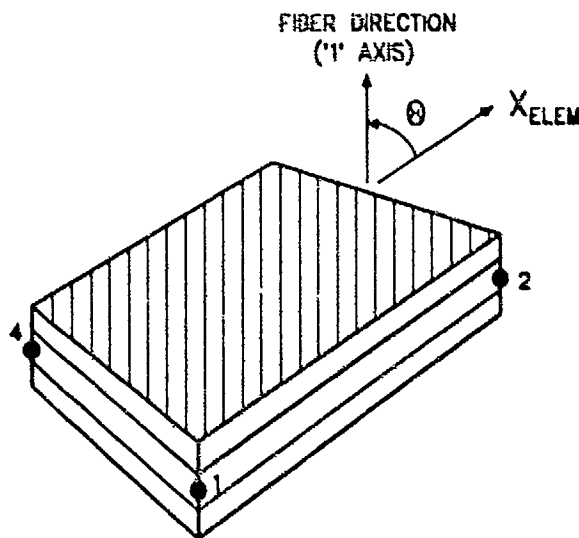
1. Laminate ID's should be numbered from 1 to the total number of laminates. Laminates may be defined in any order.
2. Material ID's refer to materials defined in the **MAT2D** input block.
3. Note that the thickness of layer 'i' is defined by the difference  $Z_{i+1} - Z_i$ .

## LAMINATES

### INPUT DATA BLOCK (CONTINUED)

#### NOTES (Continued):

4.  $ANG_i$  is important only if the material is orthotropic (material model '2' in the **MAT2D** input block). The figure shows the positive sense of  $ANG_i$  as seen from the top of an element.



## LINKED ELEMENTS

### INPUT DATA BLOCK

*Defines pairs of elements whose failure properties are linked*

**STATUS:** Optional (ignored when restarting)

**FORMAT:**

LINK

$M_1, NS_1, M_2, NS_2, \dots, M_n, NS_n$

<repeat as needed to define all failure links>

END

**EXAMPLE:**

LINK

1, 2

! Element 2 fails when element 1 fails

7, 13, 18, 100

! Element 13 linked to 7, 100 linked to 18

2120, 3159

! Use additional lines as needed

END

**VARIABLES:**

$M_i$   $i^{\text{th}}$  master element

$NS_i$   $i^{\text{th}}$  slave element

**NOTES:**

1. Only 3-D solid elements (8-node HEX or 4-node TET) may be linked.
2. Failure of a master element is determined by the material model for that element. When a master element fails, the corresponding slave element is marked as failed also.
3. The usual use of this option is to eliminate very soft, elastic layers (e.g., silicone or PVB interlayers) when adjacent structural layers have failed. If such elements are retained in the calculation, they normally contribute little to the internal forces, but may cause numerical problems due to excessive deformation.
4. When an element is deleted, its mass is retained at all connected nodes, but the element no longer develops internal forces.

# MASS

## INPUT DATA BLOCK

*Defines concentrated masses at selected points of the model*

**STATUS:** Optional (ignored when restarting)

**FORMAT:**

MASS  
 NODE, TRMASS, XRI, YRI, ZRI  
 <repeat as needed to define all point masses>  
END

**EXAMPLE:**

MASS  
 1022, 0.001, 0, 0, 0                      ! Point mass of 0.001 units at node 1022  
 END

**VARIABLES:**

|        |                                                        |
|--------|--------------------------------------------------------|
| NODE   | Node at which the concentrated mass is attached        |
| TRMASS | Translational mass (the same for all three directions) |
| XRI    | Rotational inertia about an axis parallel to global X  |
| YRI    | Rotational inertia about an axis parallel to global Y  |
| ZRI    | Rotational inertia about an axis parallel to global Z  |

**NOTES:**

1. Translational mass values should have units of  $FT^2/L$  (weight divided by the appropriate gravitational constant). For instance, in pound-inch-second units, the mass of a one-pound weight is:

$$m = \frac{1 \text{ lb.}}{386 \text{ in./sec}^2} = 0.00259 \text{ lb-sec}^2/\text{in.}$$

2. Concentrated masses are added to the mass of all finite elements connected to a node to obtain the total mass of the node.
3. Body forces (see the **BODY** input block) are *not* applied automatically to concentrated masses. If a force per unit mass acts on a point mass, the force must be defined in terms of nodal forces (see the **FORC** and **HIST** input blocks).

## MAT2D

### INPUT DATA BLOCK

*Defines material properties to be used in 2-D (plate/shell) elements.*

**STATUS:** Required when 2-D elements are used (ignored when restarting)

**FORMAT:**

MAT2

MATL, ITYPE,  $p_1$ ,  $p_2$ , ...,  $p_n$

<repeat as needed to define all materials>

END

#### FORMATS FOR INDIVIDUAL MATERIAL MODELS:

Material Model 1: Elastic-Plastic, Rate-Sensitive Isotropic Material

MATL, 1, RHO, E, XNU, ALPHA, YIELD, H, RSCALE, REXP, SULT

Material Model 2: Orthotropic Material with Brittle Failure

MATL, 2, RHO, E1, E2, XNU12, G12, G13, G23, SF, SD

#### EXAMPLE:

MAT2

1, 1, 0.000254, 10.E6, 0.3, 8.5E-6, & I Aluminum 6061-T6

40000, 416000, 0.0001538, 0.25, 45000.

2, 2, 0.000373, 33.22E6, 23.35E6, 0.268, & I Titanium MMC

9.071E6, 9.071E6, 8.922E6, 160000., 65000.

END

#### VARIABLES:

|        |                                                         |
|--------|---------------------------------------------------------|
| MATL   | Material property ID                                    |
| ITYPE  | Material model type (1 = isotropic, 2 = orthotropic)    |
| RHO    | Reference state density                                 |
| E      | Young's modulus in tension, E                           |
| XNU    | Poisson's ratio, $\nu$                                  |
| ALPHA  | Coefficient of thermal expansion, $\alpha$              |
| YIELD  | Static yield stress, $\sigma_y$                         |
| H      | Work-hardening modulus, $H = EE'/(E-E')$                |
| RSCALE | Factor for strain rate sensitivity of yield stress, 1/D |
| REXP   | Exponent for rate sensitivity of yield stress, 1/p      |
| SULT   | Ultimate stress, $\sigma_{ult}$                         |

# MAT2D

## INPUT DATA BLOCK (CONTINUED)

### VARIABLES (Continued):

|       |                                                      |
|-------|------------------------------------------------------|
| E1    | Extensional modulus in material '1' direction, $E_1$ |
| E2    | Extensional modulus in material '2' direction, $E_2$ |
| XNU12 | Inplane Poisson's ratio, $\nu_{12}$                  |
| G12   | Inplane shear modulus, $G_{12}$                      |
| G13   | Transverse shear modulus, $G_{13}$                   |
| G23   | Transverse shear modulus, $G_{23}$                   |
| SF    | Failure stress for fiber direction, $\sigma_f$       |
| SD    | Failure stress for delamination, $\sigma_d$          |

### NOTES:

1. The bulk (pressure-volume) behavior of a 2-D isotropic material is assumed to be linear, with the bulk modulus defined by

$$K = \frac{E}{3(1-2\nu)}$$

The 2-D material model assumes a zero transverse normal stress for use in plate elements (i.e.,  $\sigma_{zz}=0$ ). The bulk response and the elastic-plastic deviatoric response are determined simultaneously, in such a way that the zero normal stress constraint is satisfied.

2.  $H$  defines the work-hardening characteristics of the material, and is assumed to be constant. This implies a *bilinear* representation of the stress-strain curve. If  $E$  is the elastic modulus, and  $E'$  is the slope of the post-yield stress-strain curve, then

$$H = \frac{EE'}{E - E'}$$

3. The rate sensitivity of the yield stress is defined by RSCALE (1/D) and REXP (1/p). If  $d$  is the effective deviatoric strain rate, the instantaneous yield stress is computed from  $\text{YIELD}^*(1 + (d \cdot \text{RSCALE})^{\text{REXP}})$ . That is:

$$\sigma_y = \sigma_y^0 \left[ 1 + \left( \frac{d}{D} \right)^{\frac{1}{p}} \right]$$

## MAT2D

### INPUT DATA BLOCK (CONTINUED)

#### NOTES (Continued):

4. When the von Mises effective stress at an integration point reaches  $SULT$ , the point in question is marked as failed and is dropped from the calculation.
5. Orthotropic properties  $E_1$ ,  $E_2$ ,  $\nu_{12}$ ,  $G_{12}$ ,  $G_{13}$ , and  $G_{23}$  are referred to *material axis directions* 1, 2, 3. Normally the 1 axis corresponds to the fiber, or stiff, direction. The orientation of the material '1' axis with respect to the local coordinate axes for a plate element is part of the laminate definition data (see the **LAMINATE** input block). The material '3' axis must correspond to the thickness direction.
6. The orthotropic 2-D material model is *linear to failure*. The material behaves elastically until the fiber-direction normal stress reaches  $\sigma_f$ , at which time the integration point is considered to be failed.
7. When the resultant transverse shear stress at a point reaches  $\sigma_d$ , failure by delamination is predicted. After delamination occurs, the point in question cannot transmit the transverse shear forces which normally accompany local bending stress. Stresses at delaminated points are computed on the basis of the membrane (reference surface) strains only. In other words, a plate/shell element in which all points are delaminated is incapable of developing bending stresses, and behaves like a membrane element.

# MAT3D

## INPUT DATA BLOCK

*Defines material properties to be used in 3-D (solid) elements.*

**STATUS:** Required when 3-D elements are used (ignored when restarting)

**FORMAT:**

MAT3  
 MATL, ITYPE,  $p_1$ ,  $p_2$ , ...,  $p_n$   
 <repeat as needed to define all materials>  
END

**FORMATS FOR INDIVIDUAL MATERIAL MODELS:**

Material Model 1: Elastic-Plastic, Rate-Sensitive Isotropic Material

MATL, 1, RHO, BULK1, BULK2, BULK3, SHEAR, &  
 YIELD, RSCALE, REXP, H, SULT, Q2, Q1

Material Model 2: Newtonian Viscous Fluid

MATL, 2, RHO, BULK1, BULK2, BULK3, VISC, Q2, Q1

Material Model 3: Elastic-Plastic Material with Discontinuous P-V Behavior

MATL, 3, RHO, BULK1, BULK2, BULK3, BULK4, SHEAR, &  
 YIELD, RSCALE, REXP, H, SULT, Q2, Q1

**EXAMPLE:**

```

MAT3
1, 1, 0.000254, 8.333E6, 0, 0, 3.846E6,      &      ! Aluminum 6061-T6
40000, .0001538, 0.25, 416000, 4500 ...
2, 1, 5.E-5, 2000, 1200, 800, 500           &      ! Nonlinear elastic
3, 3, 0.0000888, 337000, 729000, 2020000,   &      ! "Bird properties" for
      1000, 30000, 3000, 0, 1, 300, 1500     ! birdstrike simulation
END
  
```

**VARIABLES:**

|       |                                                              |
|-------|--------------------------------------------------------------|
| MATL  | Material property ID                                         |
| ITYPE | Material model type (1 = isotropic solid, 2 = viscous fluid) |
| RHO   | Reference state density                                      |

# MAT3D

## INPUT DATA BLOCK (CONTINUED)

### VARIABLES (Continued):

|        |                                                           |
|--------|-----------------------------------------------------------|
| BULK1  | Linear bulk (pressure-volume) modulus, $K_1$              |
| BULK2  | Quadratic bulk modulus, $K_2$                             |
| BULK3  | Cubic bulk modulus, $K_3$                                 |
| BULKT  | Bulk modulus in tension, $K_t$                            |
| SHEAR  | Elastic shear modulus, $G$                                |
| YIELD  | Static yield stress, $\sigma_y$                           |
| RSCALE | Factor for strain rate sensitivity of yield stress, $1/D$ |
| REXP   | Exponent for rate sensitivity of yield stress, $1/p$      |
| H      | Work-hardening modulus, $H = EE'/(E-E')$                  |
| SULT   | Ultimate stress, $\sigma_{ult}$                           |
| Q2     | Quadratic artificial bulk viscosity coefficient, $Q_2$    |
| Q1     | Linear artificial bulk viscosity coefficient, $Q_1$       |
| VISC   | Viscosity coefficient $2\mu$ for viscous fluid            |

### NOTES:

- The bulk (pressure-volume) behavior of a 3-D isotropic material is assumed to be linear in tension, with the rates of change of pressure and

compression ratio  $\eta = \frac{\rho}{\rho_0} - 1$  being related by the linear bulk modulus

$K_1$ . In compression, the remaining moduli  $K_2$  and  $K_3$  define the nonlinear pressure-volume behavior. In particular:

$$p = \begin{cases} K_1 \rho_0 \eta & \eta < 0 \\ K_1 \rho_0 \eta + K_2 \rho_0 \eta^2 + K_3 \rho_0 \eta^3 & \eta > 0 \end{cases}$$

For material model 3, a different bulk modulus ( $K_t$ ) is used when  $\eta < 0$ .

- The rate sensitivity of the yield stress is defined by RSCALE ( $1/D$ ) and REXP ( $1/p$ ). If  $d$  is the effective deviatoric strain rate, the instantaneous yield stress is computed from  $YIELD * (1 + (d * RSCALE)^{REXP})$ . That is:

$$\sigma_y = \sigma_y^0 \left[ 1 + \left( \frac{d}{D} \right)^{\frac{1}{p}} \right]$$

# MAT3D

## INPUT DATA BLOCK (CONTINUED)

### NOTES (Continued):

3. H defines the work-hardening characteristics of the material, and is assumed to be constant. This implies a *bilinear* representation of the stress-strain curve. If E is the elastic modulus, and E' is the slope of the post-yield stress-strain curve, then

$$H = \frac{EE'}{E - E'}$$

4. When the von Mises effective stress in an element reaches SULT, the point in question is marked as failed and is dropped from the calculation.
5. For the viscous fluid model, the current stress is defined by:

$$\sigma_{ij} = 2\mu d_{ij} - p\delta_{ij}$$

in which  $2\mu = \text{VISC}$ , and p is computed from the equation of state (see note 1 above).

6. Q2 and Q1 define the *artificial bulk viscosity*, a numerical device used to suppress "noise" associated with shock wave propagation. Normally the default values (Q2 = 1.5, Q1 = 0.06) are adequate. The artificial pressure in a compressed element is

$$q = \rho L \theta (Q_2 L \theta - Q_1 c)$$

Here  $L = V^{1/3}$  is a characteristic element length,  $\theta = d_{kk}$  is the volumetric strain rate, and c is the local sound speed.

## MPOST

### INPUT DATA BLOCK

*Requests an MPOST-formatted results file.*

**STATUS:** Optional

**FORMAT:**  
MPOST  
END

**NOTES:**

1. Output is written to the MPOST file whenever restart output is written.
2. The output file is assigned the name 'MPOST'; if the computer system uses file extensions, the default extension is used (e.g., MPOST.DAT under VAX/VMS).

## NODE COORDINATES

### INPUT DATA BLOCK

*Defines initial positions for all nodes in the model.*

**STATUS:** Required (ignored when restarting)

**FORMAT:**

NODE  
IPT, X, Y, Z, IGEN  
<repeat as needed to define all node points>  
END

**EXAMPLE:**

NODE  
1, 5.2, 3.6, -4.2           ! Single node  
9, 9.2, 3.6, -4.2, 2       ! Generate nodes 3, 5, 7, 9  
END

**VARIABLES:**

|         |                                                  |
|---------|--------------------------------------------------|
| IPT     | Current node number                              |
| X, Y, Z | Cartesian coordinates of the node                |
| IGEN    | Node number increment for use in node generation |

**NOTES:**

1. To generate a series of nodes equally spaced along a line, enter the first node in the series (with IGEN=0), followed by the last node with an appropriate value of IGEN. For example, the data:

7, 34., -20.3, 0.  
13, 40., -20.0, 0., 2

is equivalent to:

7, 34., -20.3, 0.  
9, 36., -20.2, 0.  
11, 38., -20.1, 0.  
13, 40., -20.0, 0.

## PARAMETERS

### INPUT DATA BLOCK

*Defines parameters and options which control the dynamic solution and results output.*

**STATUS:** Required

**FORMAT:**

PARA  
TIME, TMAX, TREST, DTMIN, DTMAX, INCR, INCMAX, IREST, &  
NINTPL, ISTAT, ITRACE  
END

**EXAMPLE:**

PARA  
0, 0.0025, 0.00125, 0.00025,, & ! New analysis; solution up to 2.5 ms but  
0, 1000, 1, 5, 0, 40 ! not exceeding 1000 time steps;  
! restart/results output every 1.25 ms;  
! trace output every 40 time steps;  
! 5 int. points/layer in shells.  
  
END

**VARIABLES:**

|        |                                                                    |
|--------|--------------------------------------------------------------------|
| TIME   | Time at start of solution (ignored when restarting)                |
| TMAX   | Final time value for which a solution is requested                 |
| TREST  | Time interval for restart file output                              |
| DTMIN  | Lower limit on solution time step                                  |
| DTMAX  | Upper limit on solution time step                                  |
| INCR   | Time step number at start of solution (ignored when restarting)    |
| INCMAX | Maximum allowable time step number                                 |
| IREST  | Switch for restart/results file output (0 = no output, 1 = output) |
| NINTPL | Number of integration points per layer for plate elements          |
| ISTAT  | 0 = dynamic solution, 1 = static solution by dynamic relaxation    |
| ITRACE | Number of time steps between output dumps to TRACE file            |

## PARAMETERS

### INPUT DATA BLOCK (CONTINUED)

#### NOTES:

1. TMAX and INCMAX provide *termination conditions* for the analysis. The solution stops whenever the time value reaches TMAX or the time step number reaches INCMAX, whichever comes first. If either TMAX or INCMAX is omitted (or set to zero), the other parameter provides the termination condition. If both TMAX and INCMAX are zero or missing, no analysis will be performed.
2. TREST is a *time interval* (real valued) between restart output dumps. When the solution time value approaches a multiple of TREST, the time step is modified so that output can be saved at the requested time.
3. DTMIN is useful for ensuring that the solution does not become "bogged down" with an extremely small time step when severe mesh distortions occur. If the critical time step falls below DTMIN, restart output is written and the solution stops.
4. DTMAX can be used to force a small time step in situations where stability is not a limiting factor. An example is an impact problem in which the initial spacing and relative velocity of the impacting bodies is such that extreme penetration might occur on the first time step, when contact has not yet been established.
5. NINTPL *must be odd*, and is limited to the range 3-11.
6. Normally ISTAT = 0 (transient dynamic analysis). When ISTAT = 1, the program attempts to obtain a static solution for the specified external forces, by computing the damped dynamic response of the finite element model. This process is called *dynamic relaxation*. If this option is selected, it usually is appropriate to:
  - set TMAX very large (e.g.,  $TMAX = 10^{20}$ );
  - make INCMAX rather large, to allow sufficient time steps for convergence;
  - request restart/results output at the end of the analysis (IREST = 1, TREST = TMAX), since intermediate states are rarely of interest; and
  - supply the tolerances FRATIO and VRATIO in the TOLERANCES input block.

## PRESSURE INPUT DATA BLOCK

*Defines time-dependent pressure loads on element faces*

**STATUS:** Optional

**FORMAT:**

```
PRES
IBEG, IEND, IFACE, IFUNC, SCALE
<repeat as needed to define all pressure loads>
END
```

**EXAMPLE:**

```
PRES
1, 10, 4, 2, -20.75      ! Load face 4 of HEX elements 1-10
70, 90, 6, 1, -1.0      ! Load plate elements 70-90
END
```

**VARIABLES:**

|       |                                                     |
|-------|-----------------------------------------------------|
| IBEG  | First element in a series of elements to be loaded  |
| IEND  | Last element in the series                          |
| IFACE | Face (surface) number on which load is applied      |
| IFUNC | Time history function defining pressure versus time |
| SCALE | Scale factor to be applied to time history function |

**NOTES:**

1. All elements with ID's between IBEG and IEND are loaded. If IEND is omitted, a pressure load is applied only to element IBEG.
2. Valid face numbers are between 1 and 6 for solid elements. *For plate elements, set IFACE = 6.* In terms of the element connectivity pattern (see **ELEMENTS** input block), the six surfaces are defined as follows:

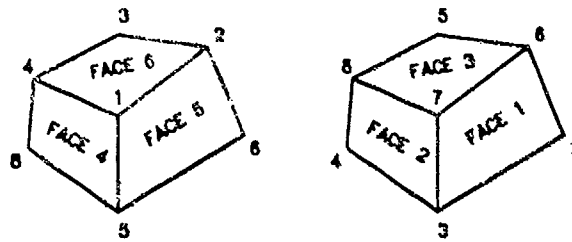
| Face Number | Nodes Defining Face |
|-------------|---------------------|
| 1           | 2 6 7 3             |
| 2           | 3 7 8 4             |
| 3           | 5 8 7 6             |
| 4           | 1 4 8 5             |
| 5           | 1 5 6 2             |
| 6           | 1 2 3 4             |

## PRESSURE

### INPUT DATA BLOCK (CONTINUED)

#### NOTES (Continued):

3. Positive values of the pressure define a force acting *outward* from the element face.
4. At any particular time in the solution, the actual pressure to be applied to an element is determined by interpolating time history function IFUNC linearly, and then multiplying by SCALE.



## REFERENCE

### INPUT DATA BLOCK

*Defines geometric limits for the mesh for use in plotting*

**STATUS:** Optional (ignored when restarting)

**FORMAT:**

```
REFE  
XMIN, XMAX, YMIN, YMAX, ZMIN, ZMAX  
END
```

**EXAMPLE:**

```
REFE  
0, 10, 0, 20, -1, 1  
END
```

**VARIABLES:**

|            |                               |
|------------|-------------------------------|
| XMIN, XMAX | Plotting limits on the X axis |
| YMIN, YMAX | Plotting limits on the Y axis |
| ZMIN, ZMAX | Plotting limits on the Z axis |

**NOTES:**

1. Results output from X3D is not affected by this option. It is provided for use in situations where a program to be used for output needs "help" in finding appropriate geometric limits for plotting.

## RESTART

### INPUT DATA BLOCK

*Requests a restart of a previous analysis, and initiates restart file input.*

**STATUS:** Optional (required when restarting)

**FORMAT:**

REST  
INCOLD  
END

**EXAMPLE:**

```
REST
3500      ! Read restart dump from time step 3500 and continue
END
```

**VARIABLES:**

INCOLD      Time step number from which the analysis is to be resumed

**NOTES:**

1. This block is required whenever an analysis is to be resumed from a point of interruption.
2. The old restart file is assumed to reside on file "OREST". Default values are used for file extensions on all systems (e.g., OREST.DAT under VAX/VMS).
3. If no restart checkpoint for time step INCOLD exists on the restart file, a fatal error occurs and execution stops.
4. Input data in many of the input blocks may be changed when restarting. Only data which are being replaced or modified need to be present in the input file for the restart job. Note that the **PARAMETERS** input block must be changed when restarting, to define new termination conditions (e.g., a later TMAX or higher INCMAX).

## RIGID WALL

### INPUT DATA BLOCK

*Defines arbitrary planar surfaces through which nodes may not move.*

**STATUS:** Optional (ignored when restarting)

**FORMAT:**

```
RIGI  
A, B, C, D  
<repeat as needed to define all rigid walls>  
END
```

**EXAMPLE:**

```
RIGI  
1, 0, 0, -5      ! Barrier at X = -5 (nodes to right)  
-1, 0, 0, 5      ! Barrier at X = -5 (nodes to left)  
0.5, 0.8660254, & ! 30° incline in (X,Y) plane, passing through  
0, 2             ! the points (0, 2.3095) and (4, 0)  
END
```

**VARIABLES:**

|         |                                                          |
|---------|----------------------------------------------------------|
| A, B, C | X, Y, and Z coefficients in equation of constraint plane |
| D       | Constant on right-hand side of constraint equation       |

**NOTES:**

1. Each rigid wall constraint defines a surface in space through which nodes of the model may not pass. Each constraint has the general form:

$$AX + BY + CZ \geq D$$

where X, Y, and Z refer to the current position of *any node* in the finite element model. For example, to define a barrier at  $X = -2$ , with all nodes confined to the side toward the origin, we impose the constraint  $X \geq -2$ . Therefore, let  $A = 1$ ,  $B = 0$ ,  $C = 0$ , and  $D = -2$ .

## SOFT BODY INPUT DATA BLOCK

*Defines properties and initial conditions for soft-body impact modeling.*

### CAUTION

*This input block defines data for an "unstructured mesh" technique for soft-body impact problems. The method is experimental, and is not recommended for production analyses. Presently the most reliable approach for this class of problems is to use tetrahedral elements for the projectile, and define CONTACT surfaces through which the projectile and target may interact.*

**STATUS:** Optional (ignored when restarting)

**FORMAT:**

SOFT  
NODLIM, CHDIST, VOLNOD, RHOZRO, BK1, BK2, BK3, BKT, &  
VX0, VY0, VZ0  
END

**EXAMPLE:**

```
SOFT
2000      &      ! Soft body mesh starts with node 2001
0.25      &      ! Characteristic mesh dimension is 0.25 units
0.025     &      ! Each mass element has initial volume 0.025
0.888E-4  &      ! Specific gravity 0.95 (0.03431 lb/in3)
337322, 729253 & ! P-V properties for water (3 terms) with
2020809, 0  &      ! no tensile stiffness
0, 0, -8000      ! Initial velocity -8000 along Z axis
END
```

**VARIABLES:**

|                  |                                                              |
|------------------|--------------------------------------------------------------|
| NODLIM           | Number of last node point in structure mesh                  |
| CHDIST           | Characteristic dimension (interaction zone) for nodal forces |
| VOLNOD           | Initial volume of each mass element in soft body mesh        |
| RHOZRO           | Initial density of the soft body mesh                        |
| BK1              | Linear bulk modulus in compression                           |
| BK2              | Quadratic bulk modulus in compression                        |
| BK3              | Cubic bulk modulus in compression                            |
| BKT              | Linear bulk modulus in tension                               |
| V <sub>i</sub> 0 | Initial velocity components for all nodes in soft body mesh  |

## SOFT BODY

### INPUT DATA BLOCK (CONTINUED)

#### NOTES:

1. The soft body mesh consists of nodes NODLIM+1 through the highest-numbered node in the model. All nodes in this range are controlled by a self-contained internal force model, and should not be connected to other finite elements.
2. CHDIST defines the maximum separation of neighboring mass elements which may interact through internal forces. Normally CHDIST should be set to about twice the mesh spacing in the most coarsely divided direction.
3. VOLNOD and RHOZRO define the size and density of each mass element in the soft body mesh. Note that if the highest-numbered node in the model is  $N_{\max}$ , the the total mass of the soft body mesh is:

$$M = [ N_{\max} - \text{NODLIM} ] \times \text{VOLNOD} \times \text{RHOZRO}$$

Nonuniform masses may be added to nodes in the soft body mesh using the **MASS** input block.

4. The equation of state used for the soft-body mesh is identical to that used for 3-D solids (see the **MAT3D** block), except that the tensile bulk modulus (BKT) may be different from the compressive value.
5. VX0, VY0, and VZ0 define the initial components of velocity for all nodes in the soft body mesh. Nonuniform initial velocity values may be input using the **INITIAL** input block. All initial velocity values are subject to the boundary conditions prescribed in the **BOUN** input block.

## TANGENTIAL ROTATION INPUT DATA BLOCK

*Defines constraints on rotational DOFs along a shell edge.*

**STATUS:** Optional (replaced if present when restarting)

**FORMAT:**

```
TANG
N1, N2, N3, ..., NMAX
<repeat as needed to define all edge lines>
END
```

**EXAMPLE:**

```
TANG
12, 32, 65, 84, 0   &   ! A list of four nodes (0 marks the end),
92, 105, 128        ! followed by a list of three nodes
END
```

**VARIABLES:**

N<sub>i</sub>                      List of nodes whose tangential rotation is to be constrained

**NOTES:**

1. The usual use of this data block is to define symmetry boundary conditions on rotational degrees of freedom. A shell with a symmetry edge in the (x,y) plane, for instance, should have constraints applied to the Z translation DOF, and also to the rotational DOF *about a line tangent to the edge*. The particular DOF involved generally is some combination of  $\theta_x$  and  $\theta_y$ , and changes as the shell deforms.
2. The list of nodes N<sub>1</sub>, N<sub>2</sub>, ... defines a series of nodes along a shell edge, each of which is subjected to a tangential rotation constraint. The tangent direction to the edge at node N<sub>k</sub> in the list is determined by passing a curve through the current positions of nodes N<sub>k-1</sub>, N<sub>k</sub>, and N<sub>k+1</sub>, and finding the tangent to this curve at node N<sub>k</sub>. For the first and last nodes in a list, only two nodes are used to find the tangent direction. The direction about which the rotation is constrained is updated at each time step of the solution.
3. A zero value within this data block ends one list of nodes and begins a new list (i.e., a new shell edge). Be sure to use only *one* zero to separate lists of nodes; two successive zeros will cause subsequent data to be ignored.

## TITLE

### INPUT DATA BLOCK

*Defines a descriptive problem title for printer and file output.*

**STATUS:** Required (optional when restarting)

**FORMAT:**

TITL  
ITITLE  
END

**EXAMPLE:**

TITL  
Spherical shell with initial velocity at equator  
END

**VARIABLES:**

ITITLE      Alphanumeric problem title, 80 characters or less in length

## TOLERANCES

### INPUT DATA BLOCK

*Defines parameters and tolerances which control the time integration procedure.*

**STATUS:** Optional

**FORMAT:**

TOLE  
DTFRAC, HGDAMP, HGCONS(1), HGCONS(2), HGCONS(3), FRATIO, &  
VRATIO, CONTOL  
END

**EXAMPLE:**

TOLE  
0.95, 0.10, 0.02, 0.02, 0.02, 0.01, 0.01, 0.2  
END

**VARIABLES:**

|           |                                                                                            |
|-----------|--------------------------------------------------------------------------------------------|
| DTFRAC    | Fraction of the critical time step to be used for integration                              |
| HGDAMP    | Anti-hourglass damping fraction for eight- node solid elements                             |
| HGCONS(1) | Anti-hourglass stiffness fraction for membrane modes in plate finite elements              |
| HGCONS(2) | Anti-hourglass stiffness fraction for transverse deflection modes in plate finite elements |
| HGCONS(3) | Anti-hourglass stiffness fraction for rotational modes in plate finite elements            |
| FRATIO    | Force convergence tolerance for static solution by dynamic relaxation                      |
| VRATIO    | Velocity convergence tolerance for static solution by dynamic relaxation.                  |
| CONTOL    | Relative motion tolerance for contact solution.                                            |

**NOTES:**

1. DTFRAC is used at each solution time step to modify the allowable time step computed by the program, and must be between 0 and 1. The default value is 0.75.

## TOLERANCES

### INPUT DATA BLOCK (CONTINUED)

#### NOTES (Continued):

2. HGDAMP controls the magnitude of the restoring forces used to suppress the unstable deformation modes which are possible in 8-node solid elements with one-point integration. Too small a value may permit instabilities to grow and propagate throughout the model, while too large a value may affect accuracy. HGDAMP values between 0.1 and 0.3 are typical. Note that large values of HGDAMP reduce the allowable time step: for HGDAMP = 0.1, the critical time step is reduced by about 11%; when HGDAMP = 0.3, the time step is 35% smaller than the undamped critical value.
3. HGCONS(i) are anti-hourglass coefficients for plate elements. The plate element uses a stiffness method of hourglass control (rather than damping). The three values define independent anti-hourglass controls for membrane, transverse displacement, and rotational hourglassing modes, respectively. While the values of HGCONS(i) do not affect the allowable time step, larger values may reduce the accuracy of the solution. HGCONS(i) values in the range 0.01-0.05 are recommended.
4. FRATIO and VRATIO control the criteria for convergence of a static solution by dynamic relaxation. The unbalanced forces at all nodes are required to be less than FRATIO times the maximum applied nodal force. The velocity components at all nodes are required to be less than VRATIO times the largest velocity component occurring in the solution.
5. CONTOL controls the amount of motion which may occur during a time step due to the enforcement of contact constraints. The absolute displacement of any node, divided by the length of the shortest element edge to which the node is connected, will be made less than CONTOL. The magnitude of the nodal motions is controlled by reducing the solution time step. Specifying a DTMIN value (see **PARAMETERS** input block) is highly recommended when CONTOL is small, to prevent the time step from approaching zero.

## TRACE NODES

### INPUT DATA BLOCK

*Defines a list of nodes for which output will be written to the TRACE output file.*

**STATUS:** Optional

**FORMAT:**

```
TRAC  
N1, N2, N3, ..., Nn  
END
```

**EXAMPLE:**

```
TRAC  
1, 12, 13, 16, 17, 22, 35, 7, 9 &  
302, 485, 2217, 666  
END
```

**VARIABLES:**

N<sub>i</sub>                      i<sup>th</sup> node for which intermediate results are to be recorded  
                                 during the solution

**NOTES:**

1. Results recorded for each trace node consist of the initial conditions, the current position, and the current velocity.
2. Nodes are listed on the TRACE file in the order defined in this input block.
3. TRACE file results are recorded after a prescribed number of time steps (see parameter ITRACE in the **PARAMETERS** input block).

## @DEBUG

### INPUT DATA BLOCK

*Requests diagnostic output or other undocumented operations.*

STATUS: Optional

FORMAT:

```
@DEB  
KEYWORD = value  
<repeat as needed to select all options>  
END
```

EXAMPLE:

```
@DEB  
SBPRES = 10  
END
```

VARIABLES:

|         |                                                         |
|---------|---------------------------------------------------------|
| KEYWORD | Name of a diagnostic output option or internal function |
| value   | Value to be assigned (typically an output frequency)    |

NOTES:

1. This input block normally is used for debugging and quality control purposes. Refer to the X3D source code for further information.

## **APPENDIX B**

### **PRE- AND POST-PROCESSING**

## INTRODUCTION

This Appendix describes several utility programs which support pre- and post-processing of X3D finite element models. They are:

- PATX3D: convert PATRAN finite element model to X3D format
- X3POST: produce tabular output listings and PATRAN results files

## PATX3D: PATRAN INPUT DATA INTERFACE

PATX3D is a data conversion utility which translates finite element model data from PATRAN to X3D. Some of the more specialized data types which exist in each of the programs are not supported by PATX3D; however, the basic geometric data, which represent the bulk of most models, are converted automatically. The remainder of this section describes the conventions used by the PATX3D interface, and defines modeling guidelines and restrictions which will minimize problems with data conversion.

### Overview

PATX3D accepts as input a PATRAN formatted Neutral File, and writes an input data file for X3D. The most common data types which are common to PATRAN and X3D (node coordinates, elements, and constraints) are read from the Neutral File and written to the X3D data file. The X3D data must be edited to add materials data, loads, and control information, which typically represent a very small fraction of the final input.

Basic documentation of the PATRAN Neutral File is contained in Chapter 29 of the PATRAN User's Manual. The X3D input formats are documented in this report (see Appendix A).

### Data Types

The relationship between data types in X3D and PATRAN is summarized in the Table on the next page. Data conversion is limited to node coordinates, elements, constraints, and contact surface data. Since the elements in X3D are low-order (bilinear or trilinear), they correspond to the simplest element configurations available in PATRAN. Note that the normal method of creating contact surface data for X3D is with PATRAN TRI elements, while QUAD (or HEX) shapes are preferred for the "real" finite elements.

## RELATIONSHIP BETWEEN X3D AND PATRAN DATA TYPES

| X3D DATA BLOCK      | PATRAN DATA TYPE         | CREATED BY |
|---------------------|--------------------------|------------|
| NODE coordinates    | NODE                     | GFEG       |
| ELEMents            | HEX, TET, WEDGE,<br>QUAD | CFEG, PFEG |
| BOUNDary conditions | NODE                     | GFEG, DFEG |
| CONtact surfaces    | TRI/3/n1, TRI/3/n2       | CFEG       |

### Finite Elements

The standard X3D finite elements are a 4-node plate, corresponding to PATRAN QUAD elements, and 4 or 8 node solids, corresponding to the PATRAN TET and HEX elements respectively. The steps required to create nodes and elements in PATRAN are:

1. use GFEG to create a regular array of nodes on one or more patches or hyperpatches;
2. generate finite elements on the same region(s) with CFEG;  
and
3. assign property ID's to the elements using PFEG (if not done in the CFEG step).

For both QUAD (plate) and HEX or TET (solid) elements, the element configuration is defined in PATRAN using the notation "QUAD/n/e" or "HEX/n/e", where 'n' is the number of nodes per element and 'e' is a configuration code. X3D uses the simplest form of each element, with the configuration code omitted. For example:

CFEG, P100, QUAD

creates 4-node plate elements compatible with X3D on patch number 100, and

CFEG, HP79, HEX

creates 8-node solids compatible with X3D on patch 79.

The use of WEDGE and TRI elements is not recommended, even though these elements will be converted properly by the translator. These shapes are treated as degenerate cases of the standard X3D elements and are inferior to QUAD and HEX elements. When a model is constructed from degenerate patches, a few WEDGE or TRI elements may be created when the region is paved with QUAD or HEX elements. It is for this reason (only) that PATX3D supports the degenerate element forms. We recommend that their

use be limited to situations in which PATRAN is forced to create them. The TET element normally is less effective than the HEX element, but may be useful for some situations in which extremely large mesh distortions occur.

#### Property Data

Even though PATX3D does not translate material properties data from PATRAN, it is a good idea to assign material ID's to elements as they are created in PATRAN. This can be accomplished with either the CFEG or PFEG commands in PATRAN. Suppose, for instance, we wish to generate solid elements for X3D on hyperpatch number 22, and assign the material ID 3 to each of these elements. We can use either:

CFEG, HP22, HEX/8  
PFEG, HP22, HEX/8,, 3

or

CFEG, HP22, HEX/8,, 3

The X3D data created by PATX3D will contain the material code (3) for all of the solid elements generated, although the properties for material 3 must be entered "by hand" in the X3D data file.

The use of negative numbers to distinguish between material ID's and property ID's, as used in PATRAN, is not necessary with PATX3D. In X3D, only a single property ID is needed for each element, corresponding to the material number for solids and the laminate number for plates. PATX3D uses the absolute value of the property ID specified in the PATRAN PFEG (or CFEG) command.

#### Boundary Conditions

Nodal constraints may be created during the GFEG (node generation) operation, or later using the PATRAN DFEG command. Both types of nodal constraints will be translated properly by PATX3D, but the enforced value of the displacement must be zero. A single enforced displacement value, as supported in PATRAN, is not appropriate in a transient dynamic solution. Note that all constraints listed in the neutral file will be applied in the basic coordinate system (X,Y,Z) in X3D, since PATX3D does not translate coordinate system definitions.

#### Contact Surface Data

PATRAN may be used to create contact surface data for X3D, provided certain conventions are followed. All surfaces to be analyzed for contact in X3D must be classified as "master" or "slave" surfaces, which then are arranged in pairs, or "sets". During the dynamic solution, all points on the slave surface for set '1' are tested for contact with all master elements in set '1'; slave points in set '2' are compared with all master elements in set '2'; and so on. Usually the master surface is the more rigid (or more coarsely meshed) of the two potential contact surfaces.

In PATRAN, we create contact surface sets as if they were finite elements, using a different element type and configuration code. All contact elements created in PATRAN

for X3D must be TRI elements (3-node triangles). If a contact surface actually consists of plate finite elements, it must be CFEG'ed twice: once to create the plate elements (QUADs), and once again to create the contact elements (TRIs). For solid regions, one or more of the bounding surfaces must be CFEG'ed with TRI elements to define the contact surface. For solids in which failure may occur over a significant region of the body, it may be appropriate to mesh the entire solid with TRI contact elements.

The contact surface set is defined by the element configuration code (e.g., TRI/3/e) in PATRAN. Master surfaces must be assigned configuration codes ending in '1': 1, 11, 21, 31, and so on. The corresponding slave surfaces are numbered 2, 12, 22, etc. If, for example, there is a single pair of potential contact surfaces, use:

CFEG, Pmmm, TRI/3/1

to create contact elements on the master surface, and:

CFEG, Pnnn, TRI/3/2

for the slave surface. PATX3D will translate up to 10 pairs of contact surfaces.

One further restriction exists in creating contact data, since the elements so created are not treated as finite elements in X3D. All "real" finite elements (QUADs, HEXes, and TETs) must be numbered before the contact surface elements. The simplest ways of ensuring that this is the case are to generate the contact elements (TRI's) last; or specify a high starting value when CFEGing the contact surfaces (so the contact element numbers are the largest), and then compress the element numbers before writing the neutral file.

While this limitation is likely to disappear in later versions of X3D, it may cause problems with the present release of the code.

## X3POST: POSTPROCESSING OUTPUT FROM X3D RESTART FILE

X3POST is an interactive program which reads the X3D standard restart file, and produces detailed output at specific points in time (as opposed to time histories). The program is menu-driven, and offers the following output options:

### *Tabular Output Listings:*

- Solid element state variables
- Plate element integration point stresses

### *PATRAN Results File Output:*

- Displacement results file
- Nodal results file
- Element results file

### *PATRAN Session/PCL File Output:*

- Single-increment failed-element list file
- Multi-increment displacement PCL file

X3POST works with data for one time step at a time, providing "snapshots" of deformed geometry and element state variables as output.

X3POST reads the X3D restart file, OREST, immediately on startup, and loads model data for the first time step found on the file. The file OREST (or OREST.DAT on VAX/VMS systems) must be present in the current ID or file directory, or linked to file OREST through logical name assignments. Data for following time steps may be loaded by requesting the next available time step, or by requesting a specific time step number.

The tabular output options in X3POST allow for listing of either solid element or plate element results at integration points. For solid elements, the results listed consist of centroid values of:

- mean stress (hydrostatic pressure)
- von Mises effective stress
- average density
- effective plastic strain

For plate elements, results are listed at each integration point through the element thickness; quantities output are:

- inplane stresses  $\sigma_{xx}$ ,  $\sigma_{yy}$ ,  $\sigma_{xy}$
- von Mises effective stress
- effective plastic strain
- flag for integration point failure

In either case, a range of elements can be specified for which output will be listed.

X3POST produces PATRAN results files, session files, and PCL files which can be used to produce plots of deformed geometry, nodal velocities, and element stresses and state variables. The format of the results files is as described in Chapter 27 of the PATRAN User's Manual, *Results Evaluation*. All PATRAN-related output files are formatted files, so they can be created on one machine and later transferred to another machine of a different architecture and still be useful.

X3POST-related files are summarized in the following Table. File contents and options are described more fully in the subsequent section.

| FILE NAME        | FORM      | DESCRIPTION                                                                                                                                    |
|------------------|-----------|------------------------------------------------------------------------------------------------------------------------------------------------|
| (logical unit 5) | Formatted | Terminal input.                                                                                                                                |
| (logical unit 6) | Formatted | Terminal output.                                                                                                                               |
| OREST            | Binary    | Input restart/postprocessing data. This was created by X3D with the file name NREST, and can also be used as a restart input data file by X3D. |
| Dxxx             | Formatted | Output PATRAN displacements results file for time step xxx.                                                                                    |
| Nxxx             | Formatted | Output PATRAN nodal results file for time step xxx.                                                                                            |
| Exxx             | Formatted | Output PATRAN element results file for time step xxx.                                                                                          |
| Fxxx             | Formatted | Output failed-element list PATRAN session file for time step xxx.                                                                              |
| DISPPCL          | Formatted | Output displacements processing PATRAN PCL file for all increments found in file OREST.                                                        |

All files use the system default naming conventions. For instance, the DISPPCL file would be named DISPPCL on a UNIX system; on a VAX/VMS system, where the default file type for FORTRAN-generated files is .DAT, the same file would be called DISPPCL.DAT. File names which are generated using time step numbers do not include leading zeros; for example, the PATRAN displacements results files for time steps 72 and 258 would be called D72 and D258, respectively, on a UNIX system.

The Displacement Results File contains the model displacements at a particular time step by nodes. This file is needed for plotting deformed model geometry. The data are stored in three columns, with x, y, and z displacements in columns 1, 2, and 3 respectively. Nodal rotational displacements are not calculated within X3D and are not recorded here.

The Nodal Results File contains additional nodal variables for plotting in PATRAN. At present these nodal variables consist of the three velocity components at the node, followed by the magnitude of the velocity vector. The data are stored in four columns, with x, y, and z velocity components stored in columns 1, 2, and 3 respectively; column 4 contains the magnitude of the nodal velocity vector.

The Element Results File contains results for a single time step, by elements. Results are arranged in columns, which are listed in the following Table:

#### COLUMN DEFINITIONS FOR PATRAN ELEMENT RESULTS OUTPUT

| Column | 3-D Solid Element Result                            | Plate Element Result                                  |
|--------|-----------------------------------------------------|-------------------------------------------------------|
| 1      | Stress $\sigma_{xx}$                                | Force resultant $N_x$                                 |
| 2      | Stress $\sigma_{yy}$                                | Force resultant $N_y$                                 |
| 3      | Stress $\sigma_{zz}$                                | Force resultant $N_{xy}$                              |
| 4      | Stress $\sigma_{yz}$                                | Moment resultant $M_x$                                |
| 5      | Stress $\sigma_{xz}$                                | Moment resultant $M_y$                                |
| 6      | Stress $\sigma_{xy}$                                | Moment resultant $M_{xy}$                             |
| 7      | Density $\rho$                                      | Max. principal stress                                 |
| 8      | Pressure $p$                                        | Min. principal stress                                 |
| 9      | von Mises stress $\sigma_{eq}$                      | Max. von Mises stress                                 |
| 10     | Effective plastic strain                            | Max. eff. plastic strain                              |
| 11     | Failure index (1 if element is failed, otherwise 0) | Failure index (fraction of integration points failed) |
| 12     | Internal energy                                     | Internal energy                                       |

The stress components listed in the Table for solids refer to the global coordinate directions, and occur at the element center. The solid element results may be interpreted as mean values for the element.

Element results for plates include the effect of several integration points through the element thickness. The force and moment resultants are integrals through the plate thickness:

$$N_{ij} = \int_{z_l}^{z_u} \sigma_{ij} dz \qquad M_{ij} = \int_{z_l}^{z_u} z \sigma_{ij} dz$$

The results columns labeled "max" or "min" are the largest or smallest values of all the integration points in a particular element. The failure index computed for plates is a fraction between 0 and 1, since the plate element may be failed through part of its thickness only.

X3POST also can produce PATRAN session and PCL files. These can help automate the processing of deformed geometry plots. Because large deformations are possible during analysis using X3D, including failed elements in a deformed geometry model plot can obscure the behavior of the model. The X3POST session files help a PATRAN user eliminate failed elements from the PATRAN active set. This can provide a clearer visualization of the model's response. As an example, Figure B.1 shows a transparency impact hidden-surface plot with and without failed elements included in the display. When the failed elements have been removed, the example clearly shows transparency failure; in the other view, transparency failure is not apparent.

The single-increment Failed-Element List Session File contains a list of all failed elements in the model during a particular time step. The file contains PATRAN directives that store the list of failed elements as a *named component*, specific for that time step, in the user's model database. The named component can later be used to erase those elements from the PATRAN active set in order to eliminate those elements from the deformed geometry plot. The user can process the file directives by invoking the unprompted PATRAN READ command, then entering the failed-element list file name for a particular increment. However, most users prefer instead to invoke the multi-increment displacement processing PCL file, described below, which automatically reads in the directives stored in the failed-element list files.

The multi-increment Displacement Processing PCL File contains PATRAN Command Language directives which automate the processing of a large number of displacement results files for a model. The file is generated by X3POST only when the user requests the option to create PATRAN results files for *all* increments. In that case, X3POST generates a single displacement processing PCL file, and displacement results files, element results files, and failed-element list session files for all time steps found on the

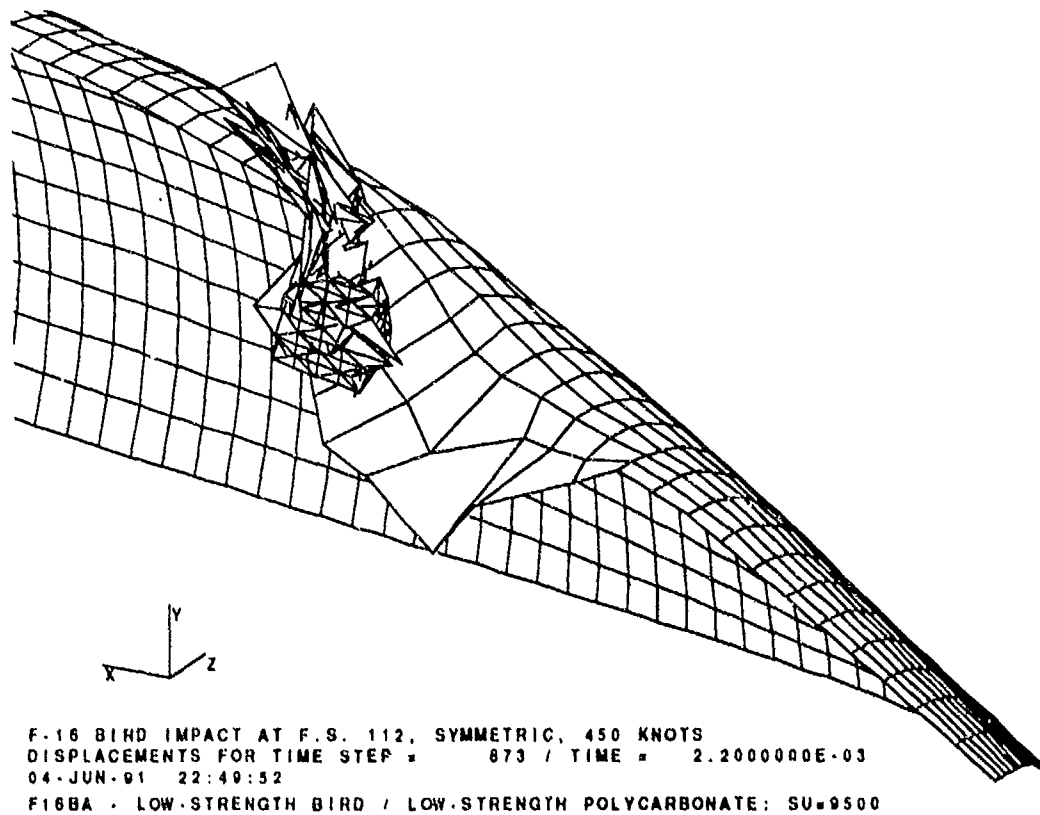
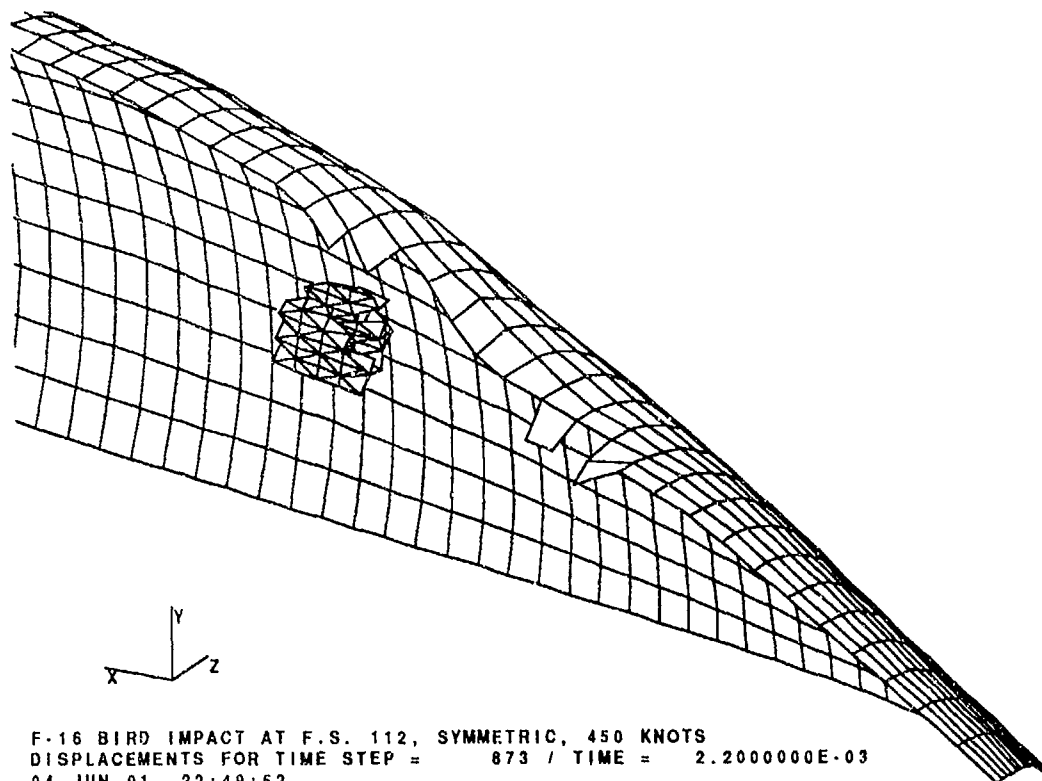


Figure B.1. Transparency Impact Deformed-Shape Plot With and Without Failed Elements Removed from the Display.

X3D restart file. Using the displacement processing PCL file requires version 2.4 or later of PATRAN. The PCL file's routines have been tested with versions 2.4 and 2.5 of PATRAN.

The remainder of this section discusses using PATRAN and the displacement processing PCL file DISPPCL to display multiple displacement results.

A displacement processing PCL file generated by X3POST is a standalone PCL program, specific to the analysis from which it was generated. When used within PATRAN, the file requires presence of the PATRAN displacement results files, failed-element list session files, and optionally, element results files which X3POST generated at the same time as the PCL file. Files within the group should not be substituted for files generated by another analysis. If a user should do so inadvertently, the PCL file may process displacements incorrectly with no warnings to the user.

Below are some steps a user might follow in processing displacements with PATRAN. This example describes an X3D analysis performed on a CRAY under UNICOS. It shows procedures used in displaying PATRAN results from this analysis on a Sun which is connected to the CRAY via a network link.

1. **Run X3POST on the CRAY.**

Generate results for all increments found in the X3D restart file. Use the "All Increments" option from the X3POST main menu: this also generates the PCL file *DISPPCL*.

2. **Transfer appropriate analysis results files to the Sun.**

Put these in their own directory to avoid confusion with results files from other analyses. Required files are:

- All *Dxxx* files (displacements results files).
- All *Fxxx* files (failed-element list session files).
- All *Exxx* files (element results files); these are required only if you want to plot element results.
- The displacement processing PCL file *DISPPCL*.

File names should not be changed when the files are copied: the PCL program uses file names which are explicitly stored within its code for reference to the other files.

3. **Use a copy of the PATRAN database file for this model.**

The PCL program makes many permanent changes to the PATRAN database file. No model parts are created or deleted, but the active set is modified substantially. It's probably most convenient for the user to work with a copy of the model database, then discard the database copy when the plotting session is completed.

4. **Run PATRAN from the directory where the results files are located.**

Get the PATRAN file ready to display displacement results:

- Define the NORMAL named component if it doesn't yet exist.
- Set the displacements scale factor to 1.0 if desired:

```
SET, SINTERP, ON  
SET, SFACT, 1.0
```

- Set ZNULL off if desired:

```
SET, ZNULL, OFF
```

- Define an appropriate view angle if your terminal does not let you change the viewing angle locally.

5. **Read in the displacements processing PCL file.**

Use the standard PATRAN PCL syntax:

```
!!INPUT DISPPCL
```

You should need to read in the PCL file only once per PATRAN session: once the PCL functions have been stored, they can be invoked repeatedly.

6. **Run the displacements processing PCL function EXEC\_HIDE.**

Use the standard PATRAN PCL syntax:

```
!EXEC_HIDE()
```

This brings up the main menu for the PCL program. Note that the program temporarily turns off the on-screen menu mode ("SET,MENU,OFF") if you have that turned on. The menu mode is restored, if necessary, when the program is completed.

Note that when responding to EXEC\_HIDE's prompts, you can usually enter either the number of a menu choice or its first letter. If using the first letter would be considered an ambiguous response for a particular menu, then only the number is valid.

7. **Modify file name convention if needed.**

When you invoke it, EXEC\_HIDE internally sets a default file name ending according to an initial file search. The search patterns, in order of preference, are ".DAT", ".", and "" (blank). You should rarely need to change the default. If the file ending is determined incorrectly by the program, then EXEC\_HIDE has an option that lets you manually define a string to be added to the end of the file name it uses. For example, if your PATRAN displacement file names on a VAX

looked like "D123.;1", then the PCL program's trailing string might have to be changed to a period (".").

In particular, you probably need this option if you see the PATRAN error message:

**\*RESULTS FILE HAS A WIDTH THAT IS NOT...**

Invoke the option by selecting menu item number 5 ("File names") and enter the required string; don't include double quotes.

**8. Process the failed-element list session files.**

Select menu item number 4 ("Process failed-element lists"), then item number 1 ("Read in lists"). The process may take some time to complete. This step needs to be run only once for a PATRAN session.

**9. Plot the displacements.**

From the main menu, select menu item number 1 ("Do plots"). This brings up a menu with several options, with some options that are not displayed on the menu bar:

- To display the time value and other information associated with the current time step, press the space bar and enter <Return>.
- You can step through the stored increment list without plotting, if you like. Enter "2" or "+" and <Return> to change to the next stored time step; enter "-" and <Return> to move a step backwards.
- The menu has two lines of choices; to save display space only one line is shown at a time. To view the second line of choices, select item number 3 ("More commands"). Note that for the "Do plots" menu, you can select an item even if it is not displayed on the current menu line.
- If you want to specify an increment, select menu item number 5 ("Specify incrt"). The PCL program will jump to the increment number which you specify; or, if the requested increment does not exist in the stored increment list, the program will select the first increment on the list which is greater than the value specified.
- You can invoke a single-line PATRAN command by selecting item number 6 ("Enter PATRAN cmd") if needed. This is meant to be used only for quick SET/SHOW commands.
- To plot the current time step displacements, select menu item number 1 ("Plot"). When the plot is complete, the PCL program will pause to allow for a hardcopy or screen capture.

10. **Enter "End" when done.**

You can quit running the PCL procedure at any time. If you want to rerun the PCL program during the same PATRAN session, you can skip the `!! INPUT DISPPCL` step; enter `! EXEC_HIDE()` to restart the process. Again, if the failed-element lists have been already read during this PATRAN session, they do not need to be read in again (although it won't hurt anything to do so).

11. **Options to set PATRAN WINDOW or VIEW parameters.**

By default, the PCL program uses the current PATRAN view when displaying deformed-geometry results. Users may wish to display several views of a model's behavior at a particular time step, and users with older-technology graphics terminals have to change views by using PATRAN commands.

The PCL program can read and store PATRAN commands that request several views of a model when the PCL program is processing a time step; this permits a user to see the model from several angles without having to run the PCL program several times. The commands are stored internally by sets, and the PCL program processes each set of commands before issuing a "RUN,HIDE". The PCL program pauses after each "RUN,HIDE" for a possible hardcopy or screen capture operation.

There is a maximum of 5 sets permitted; each set can have a maximum of 10 commands; each command may have a maximum of 80 characters.

Currently, the only way to invoke this option is to have command sets stored in a file and to read the file from within `EXEC_HIDE`. The user should select the main menu item number 3 ("Set WINDOW/VIEW params"), then item number 1 from the next menu ("Read sets from file").

The command set file is basically a PATRAN session file fragment. No command checking is performed on these commands before they are executed within the PCL program, so the user should be sure that the commands will work as desired before reading the file. The data format for the file is simple: command sets are terminated by a line with a "%" character in it at any position. Any other contents of that line are ignored. An example data file is shown below; this file contains two command sets:

```

VIEW
1
10.18, -63.2, 0.
WIN
1
.85
7
%
VIEW
6
-1000, 0, 0
%
```

Note that EXEC\_HIDE communicates with PATRAN by issuing its commands from the PATRAN "MODE" menu; commands that you use within these optional sets should not leave PATRAN at a menu level with an unsatisfied request for input.

You can clear these command sets from the PCL program memory by getting back to the WINDOW/VIEW Parameters menu and selecting item 2 ("Clear all sets").

#### 12. Entering a PATRAN command from within the PCL program.

You can enter a PATRAN command by selecting menu item number 2 from the main menu ("Enter a PATRAN command"). This option is meant to provide quick access to SET/SHOW commands; do not enter a command that will require terminal input, because PATRAN will attempt to read those values from the PCL program. To execute more elaborate commands, it's best to exit EXEC\_HIDE, execute the PATRAN command, and then run EXEC\_HIDE again.

This function is also available from the "Do plots" menu.

#### 13. Changing the plot type.

EXEC\_HIDE works by invoking the PATRAN command RUN,HIDE with several options. By default, EXEC\_HIDE plots deformed-shape plots by invoking RUN,HIDE,DEFORM. You can change the options from the main menu by selecting item 6 ("Modify plot type"); this function is also available from the "Do plots" menu.

Most of the items on the Options menu are on/off switches: if an item is currently marked "ON" and you select it, then it will be set off.

Some items require presence of the element results files: the CONTOUR, FILL, and FRINGE options all use element results files. If you use one of these options, then define the appropriate file column by selecting item number 7 ("Results col"). Note that you must set the appropriate assignment or contour levels outside of EXEC\_HIDE; the PCL procedure always uses the current contour level or

assignment level settings. Item 5 ("PARIN") is an option, used to request parametric interpolation, that can be invoked if either FILL or CONT is active.

You can also request a different base name from this menu. By default, EXEC\_HIDE works from the database component named NORMAL; you can request a different name if you like. The named component must exist in your PATRAN database before it is accepted here. This option would be useful, for example, if you wanted to define one named component that showed nodes and one that didn't. In that case, you could define one as NORMAL and the other as BASE2 before you ran EXEC\_HIDE, and could select either one of those from this menu.

You can request that the plot images be stored in a PATRAN hardcopy file by switching on the HARDCOPY option.

Finally, you can define up to two title strings to be placed on resulting plots. These are displayed using PATRAN's RUN,TITLE,X=x,Y=y command. If you need only one title line, enter blanks in the other when you define it. When placing the title strings, note that if you have HARDCOPY switched on and the title lines are plotted in the terminal alpha region, the titles may not end up on the hardcopy file. In that case, try to make the Y values larger than 20 per cent. This is a PATRAN limitation.

A log file of an interactive terminal session which illustrates the preceding steps is listed below. The session shows activities on a Sun machine, and includes TCP/IP file transfers and PATRAN commands which use the PCL program to plot displacements. The results have been edited to remove some redundant information.

The example uses an X3D model of a bird impact against an aluminum plate. In this example, the bird is modeled with tetrahedral elements, and the aluminum plate is modeled with quadrilateral elements.

As shown in the log file, X3POST has already been run on a CRAY/UNICOS machine. A PATRAN database file of the model already exists on the Sun (patran.dat.1). In the example session, the user defines the NORMAL named component so as to include:

- All aluminum plate quad elements.
- All bird model tetrahedral elements.
- All bird model nodes (these begin with node number 106).

The user excludes from the NORMAL set the following:

- All contact elements (any triangle element is assumed to be a contact element here).
- Any node not used in the bird model. Nodes not included in the bird model are in the range 1 through 105.

The example log file follows below:

```
ss2:/scratch/held/b45wa01/ ls -l
total 0
```

```
ss2:/scratch/held/b45wa01/ ftp cray
```

```
Connected to sn418.wpafb.af.mil.
```

```
220 sn418 FTP server (Version 5.5 Sun Sep 23 14:27:26 EDT 1990) ready.
```

```
Name (cray:mccartre): heldtw
```

```
230 User heldtw logged in.
```

```
ftp> cd /tmp/held/b45wa01
```

```
250 CWD command successful.
```

```
ftp> dir
```

```
200 PORT command successful.
```

```
150 Opening ASCII mode data connection for /usr/ucb/ls.
```

```
total 12048
```

|          |   |        |         |        |     |   |       |         |
|----------|---|--------|---------|--------|-----|---|-------|---------|
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:00 | D114    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:00 | D153    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:00 | D192    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:00 | D231    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:00 | D270    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:00 | D310    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:00 | D350    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 22:59 | D38     |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:00 | D391    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:00 | D432    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:00 | D468    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:01 | D491    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:01 | D512    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:01 | D530    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:01 | D545    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:01 | D560    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:01 | D575    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:01 | D590    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:01 | D605    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 23:01 | D606    |
| -rw----- | 1 | heldtw | D840200 | 19485  | Jun | 5 | 22:59 | D76     |
| -rw----- | 1 | heldtw | D840200 | 51547  | Jun | 5 | 23:01 | DISPPCL |
| -rw----- | 1 | heldtw | D840200 | 5510   | Jun | 5 | 23:01 | DISPSES |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 22:59 | E114    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:00 | E153    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:00 | E192    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:00 | E231    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:00 | E270    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:00 | E310    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:00 | E350    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 22:59 | E38     |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:00 | E391    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:00 | E432    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:00 | E468    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:01 | E491    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:01 | E512    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:01 | E530    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:01 | E545    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:01 | E560    |
| -rw----- | 1 | heldtw | D840200 | 182846 | Jun | 5 | 23:01 | E575    |

```

-rw----- 1 heldtw D840200 182846 Jun 5 23:01 E590
-rw----- 1 heldtw D840200 182846 Jun 5 23:01 E605
-rw----- 1 heldtw D840200 182846 Jun 5 23:01 E606
-rw----- 1 heldtw D840200 182846 Jun 5 22:59 E76
-rw----- 1 heldtw D840200 1180 Jun 5 23:00 F114
-rw----- 1 heldtw D840200 1299 Jun 5 23:00 F153
-rw----- 1 heldtw D840200 1247 Jun 5 23:00 F192
-rw----- 1 heldtw D840200 1445 Jun 5 23:00 F231
-rw----- 1 heldtw D840200 1355 Jun 5 23:00 F270
-rw----- 1 heldtw D840200 1291 Jun 5 23:00 F310
-rw----- 1 heldtw D840200 1486 Jun 5 23:00 F350
-rw----- 1 heldtw D840200 846 Jun 5 22:59 F38
-rw----- 1 heldtw D840200 1463 Jun 5 23:00 F391
-rw----- 1 heldtw D840200 1342 Jun 5 23:00 F432
-rw----- 1 heldtw D840200 1141 Jun 5 23:00 F468
-rw----- 1 heldtw D840200 991 Jun 5 23:01 F491
-rw----- 1 heldtw D840200 832 Jun 5 23:01 F512
-rw----- 1 heldtw D840200 785 Jun 5 23:01 F530
-rw----- 1 heldtw D840200 785 Jun 5 23:01 F545
-rw----- 1 heldtw D840200 785 Jun 5 23:01 F560
-rw----- 1 heldtw D840200 785 Jun 5 23:01 F575
-rw----- 1 heldtw D840200 785 Jun 5 23:01 F590
-rw----- 1 heldtw D840200 785 Jun 5 23:01 F605
-rw----- 1 heldtw D840200 785 Jun 5 23:01 F606
-rw----- 1 heldtw D840200 1026 Jun 5 22:59 F76
-rw----- 1 heldtw D840200 93089 Jun 5 22:44 b45wa01.dat
-rw----- 1 heldtw D840200 1393016 Jun 5 22:59 b45wa01.dmp
-rw----- 1 heldtw D840200 404 Jun 5 22:59 b45wa01.err
-rw----- 1 heldtw D840200 195967 Jun 5 22:59 b45wa01.out
-rw----- 1 heldtw D840200 47483 Jun 5 22:59 b45wa01.trc
-rw----- 1 heldtw D840200 9931 Jun 5 23:01 xpout

```

226 Transfer complete.

4376 bytes received in 1.2 seconds (3.6 Kbytes/s)

ftp> prompt

Interactive mode off.

ftp> mget D\* F\* E\*

200 PORT command successful.

150 Opening ASCII mode data connection for D114 (19485 bytes).

226 Transfer complete.

local: D114 remote: D114

19891 bytes received in 0.48 seconds (40 Kbytes/s)

200 PORT command successful.

150 Opening ASCII mode data connection for D153 (19485 bytes).

226 Transfer complete.

local: D153 remote: D153

19891 bytes received in 0.49 seconds (40 Kbytes/s)

(Gets all the Dxxx, Fxxx, and Exxx files, and the DISPPCL file.)

226 Transfer complete.

ftp> bye

221 Goodbye.

ss2:/scratch/held/b45wa01/ cp ~/ss2-files/b45/patran.dat.1 .

ss2:/scratch/held/b45wa01/ cp ~/ss2-files/b45/b45-view.txt .

ss2:/scratch/held/b45wa01/ ls

|      |         |      |      |              |
|------|---------|------|------|--------------|
| D114 | D545    | E310 | E606 | F512         |
| D153 | D560    | E350 | E76  | F530         |
| D192 | D575    | E38  | F114 | F545         |
| D231 | D590    | E391 | F153 | F560         |
| D270 | D605    | E432 | F192 | F575         |
| D310 | D606    | E468 | F231 | F590         |
| D350 | D76     | E491 | F270 | F605         |
| D38  | DISPPCL | E512 | F310 | F606         |
| D391 | DISPSES | E530 | F350 | F76          |
| D432 | E114    | E545 | F38  | b45-view.txt |
| D468 | E153    | E560 | F391 | patran.dat.1 |
| D491 | E192    | E575 | F432 |              |
| D512 | E231    | E590 | F468 |              |
| D530 | E270    | E605 | F491 |              |

ss2:/scratch/held/b45wa01/ cat b45-view.txt

```
VIEW
1
10.18,-63.2,0.
WIN
1
.85
7
%
VIEW
6
-1000,0,0
%
```

ss2:/scratch/held/b45wa01/ patran2

```
=====
                        P A T R A N
                        RELEASE 2.5
                        COPYRIGHT 1979-1990  PDA ENGINEERING
=====

ENTER DEVICE MNEMONIC, "?" OR "STOP": 4107

INPUT "GO", "SES", "HELP", PATRAN EXECUTIVE DIRECTIVE OR "STOP".

>GO

PATRAN DATA FILE?  1.NEW  2.OLD  3.LAST  4.STOP

>3

PREPARING THE DATA BASE SUB-SYSTEM FOR "OLD" FILE:
"patran.dat.1"
RESTART FROM THE FILE LAST CLOSED 27-MAY-91   20:43:25

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS
      5.INTERFACE 6.STOP 7.PDA_PCL 8.USER_MENU

>SET,GRAPHICS,OFF
"GRAPHICS" IS NOW OFF (WAS ON ).
```

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

>SET,ACTIVE,ALL  
PHASE1 IS OFF.

>NODE,1T105,ERASE

>TRI,1T#,ERASE

>NAME,NORMAL,ADD

>SET,GRAPHICS,ON  
"GRAPHICS" IS NOW ON (WAS OFF).

>SET,SINTERP,ON  
"SINTERP" IS NOW ON (WAS OFF).

>SET,SFACT,1.0  
"SFACTOR" IS NOW 1.0000 (WAS 0.1000 ).

>SET,ZNULL,OFF  
"ZNULL" IS NOW OFF (WAS ON ).

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

>VIEW

VIEW? 1.AXES ABS 2.AXES REL 3.SCREEN ABS 4.SCREEN REL  
5.INCREMENTAL 6.FROM 7.VIEW PLANE 8.END

>1

INPUT AXES ABSOLUTE THETA X,Y,Z FOR SCREEN 1

>20.2,60.3,0.0

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

>WIN

WINDOW? 1.ZOOM 2.MOVE 3.CENTER 4.FIND 5.CORNERS 6.RESTORE 7.EXIT

>4

WINDOW? 1.ZOOM 2.MOVE 3.CENTER 4.FIND 5.CORNERS 6.RESTORE 7.EXIT

>1

INPUT MAGNIFICATION POWER FOR SCREEN 1

>0.85

WINDOW? 1.ZOOM 2.MOVE 3.CENTER 4.FIND 5.CORNERS 6.RESTORE 7.EXIT

>2

INPUT DECIMAL OFFSET FACTOR IN X,Y FOR SCREEN 1 (EG: .33,.25)

>0,-0.05

WINDOW? 1.ZOOM 2.MOVE 3.CENTER 4.FIND 5.CORNERS 6.RESTORE 7.EXIT

>E

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

>!!INPUT DISPPCL

!!INPUT DISPPCL  
Compiling: exec\_hide  
Compiled: exec\_hide  
Compiling: check\_up  
Compiled: check\_up  
...  
Compiling: mod\_opts  
Compiled: mod\_opts  
Compiling: show\_cols  
Compiled: show\_cols

>!EXEC\_HIDE()

!EXEC\_HIDE()

MENU,MODE

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

Hidden Surface Plotter Main Menu for Analysis:

45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL  
1. Do plots 2. Enter a PATRAN command 3. Set WINDOW/VIEW params  
4. Process failed-elemt lists 5. File names 6. Modify plot type 7. End

>5

Current file name ending is:

Enter new name ending to use (eg .DAT):

>(Enter a space and <Return> to keep the name ending blank.)

File name ending now is.....:

Hidden Surface Plotter Main Menu for Analysis:

45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL  
1. Do plots 2. Enter a PATRAN command 3. Set WINDOW/VIEW params  
4. Process failed-elemt lists 5. File names 6. Modify plot type 7. End

>4

Failed-element list processing.

1. Read in lists 2. Delete existing failed-element names 3. End

>1

Warning: Current active set will be modified.

Continue ? Y/N...:

>Y

Number of files to process: 21

Processing file number 1 of 21: F38

Processing file number 2 of 21: F76

...

Processing file number 21 of 21: F613

1. Read in lists 2. Delete existing failed-element names 3. End

>E

Hidden Surface Plotter Main Menu for Analysis:

45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL

1. Do plots 2. Enter a PATRAN command 3. Set WINDOW/VIEW params  
4. Process failed-elemt lists 5. File names 6. Modify plot type 7. End

>1

Begin or resume hidden surface plot processing.

Now: 38 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>(space bar and <Return>: This displays information about time step 38.)

Incr: 38 (1 of 21) / Time: 1.0000e-04 / Hardcopy: OFF / Title: OFF

Now: 38 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>2

Now: 76 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>+

Now: 114 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>+

Now: 153 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>-

Now: 114 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>3

Now: 114 - Enter: 5. Specify incrt 6. Enter PATRAN cmd 7. Options 8. End

>5

Enter requested increment:

>275

Incr: 309 (8 of 21) / Time: 8.0000e-04 / Hardcopy: OFF / Title: OFF

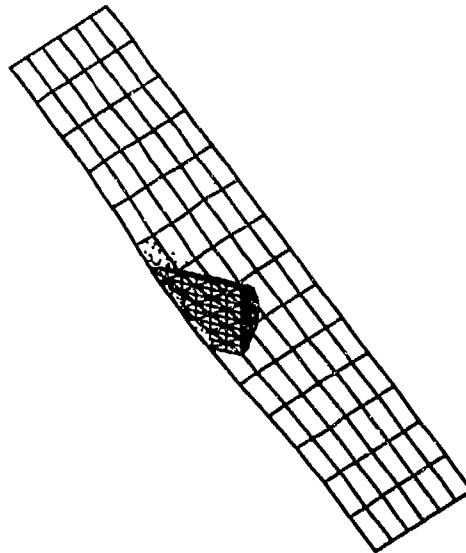
Now: 309 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>1

Processing increment 309 (Number 8 of 21)...

Command as processed: RUN,HIDE,DEFO

(Now does a plot.)



45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL  
 DISPLACEMENTS FOR TIME STEP = 300 / TIME = 7.0000000E-04  
 27-MAY-91 18:08:53

Done with incrt 309; hardcopy was: OFF...  
 Now: 349 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End  
 >E

Hidden Surface Plotter Main Menu for Analysis:  
 45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL  
 1. Do plots 2. Enter a PATRAN command 3. Set WINDOW/VIEW params  
 4. Process failed-elemt lists 5. File names 6. Modify plot type 7. End  
 >E

MENU,MODE  
 MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
 5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

>!EXEC\_HIDE()

!EXEC\_HIDE()

Using some of the values from your last run.  
 Enter any character to continue:  
 >

MENU,MODE  
 MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
 5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

Hidden Surface Plotter Main Menu for Analysis:

45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL

1. Do plots 2. Enter a PATRAN command 3. Set WINDOW/VIEW params  
4. Process failed-elemt lists 5. File names 6. Modify plot type 7. End

>3

WINDOW/VIEW Parameter Command Sets.

1. Read sets from file 2. Clear all sets 3. End and return to main menu

>1

Enter the name of the file with command set(s):

>B45-VIEW.TXT

B45-VIEW.TXT

Set 1 - Add: VIEW

Set 1 - Add: 1

Set 1 - Add: 10.18,-63.2,0.

Set 1 - Add: WIN

Set 1 - Add: 1

Set 1 - Add: .85

Set 1 - Add: 7

Set 2 - Add: VIEW

Set 2 - Add: 6

Set 2 - Add: -1000,0,0

WINDOW/VIEW Parameter Command Sets.

1. Read sets from file 2. Clear all sets 3. End and return to main menu

>E

Hidden Surface Plotter Main Menu for Analysis:

45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL

1. Do plots 2. Enter a PATRAN command 3. Set WINDOW/VIEW params  
4. Process failed-elemt lists 5. File names 6. Modify plot type 7. End

>1

Begin or resume hidden surface plot processing.

Now: 349 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>3

Now: 349 - Enter: 5. Specify incrt 6. Enter PATRAN cmd 7. Options 8. End

>6

Enter a single-line PATRAN command:

>SET,RADN,1.8

SET,RADN,1.8

\*RADNODE\* IS NOW 1.8000 (WAS 0. ).

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

Now: 349 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>1

Processing increment 349 (Number 9 of 21)...

Command as processed: RUN,HIDE,DEFO

(Echoes some commands stored in b45-view.txt -- no keyboard input below.)

VIEW

VIEW? 1.AXES ABS 2.AXES REL 3.SCREEN ABS 4.SCREEN REL  
5.INCREMENTAL 6.FROM 7.VIEW PLANE 8.END

1

INPUT AXES ABSOLUTE THETA X,Y,Z FOR SCREEN 1  
10.18,-63.2,0.

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

WIN

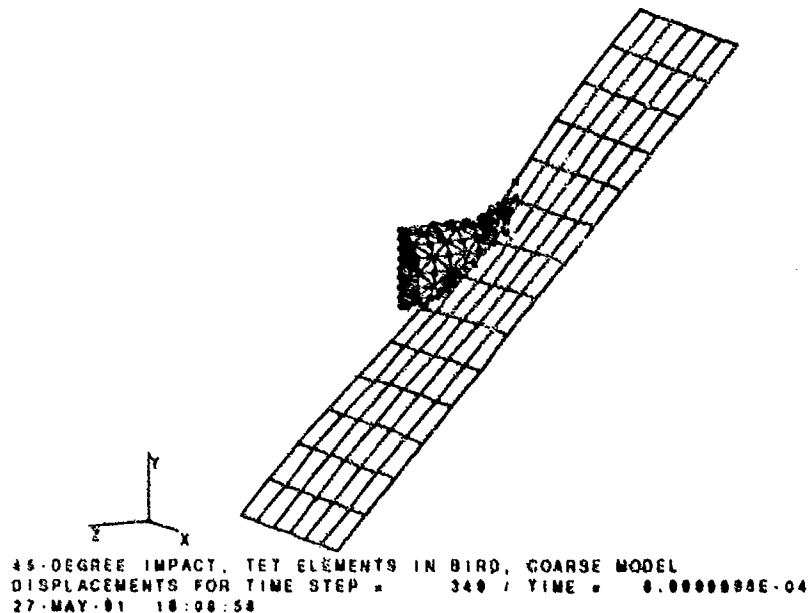
WINDOW? 1.ZOOM 2.MOVE 3.CENTER 4.FIND 5.CORNERS 6.RESTORE 7.EXIT  
1

INPUT MAGNIFICATION POWER FOR SCREEN 1  
.85

WINDOW? 1.ZOOM 2.MOVE 3.CENTER 4.FIND 5.CORNERS 6.RESTORE 7.EXIT  
7

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

(Now does a plot.)



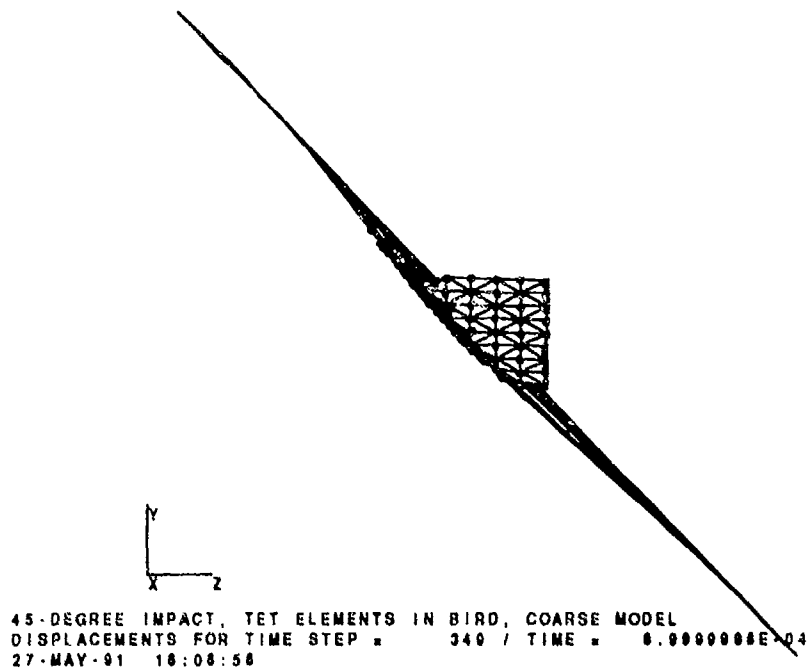
Done with incrt 349, view set 1 of 2; hardcopy was: OFF...  
Enter Y to continue, N to end:

>Y

(Echoes more commands stored in b45-view.txt -- no keyboard input below.)

```
VIEW
VIEW? 1.AXES ABS 2.AXES REL 3.SCREEN ABS 4.SCREEN REL
      5.INCREMENTAL 6.FROM 7.VIEW PLANE 8.END
6
  INPUT VIEW POINT FOR SCREEN 1
-1000,0,0
  VIEW POINT= -1000.0      0.      0.
  CENTER= 6.0000      0.      -2.1200 AND DCENTER= 1006.0
MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS
      5.INTERFACE 6.STOP 7.PDA_PCL 8.USER_MENU
```

(Now does a plot.)



Done with incrt 349, view set 2 of 2; hardcopy was: OFF...  
Now: 389 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>E

Hidden Surface Plotter Main Menu for Analysis:  
45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL  
1. Do plots 2. Enter a PATRAN command 3. Set WINDOW/VIEW params  
4. Process failed-element lists 5. File names 6. Modify plot type 7. End

>E

MENU,MODE  
MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
 5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

>STOP

RESTART DATA BEING WRITTEN ON 27-MAY-91 21:10:57 TO:  
"patran.dat.1"  
PDA/PATRAN COMPLETED

The next example continues post-processing of the above bird impact analysis, and shows how one might use some of the optional settings available in EXEC\_HIDE. In this case, the user wants to display von Mises stresses in the aluminum target, and to store the resulting image on a PATRAN hardcopy file.

This example illustrates the following options:

- Use of a different base named component. Here, the user wants to view only the target stresses, and defines a named component BASE3 with all nodes, TRI elements, and TET elements removed. BASE3 is actually named component NORMAL, which was defined earlier, minus the remaining nodes and all TET elements (the bird elements are TET elements);.
- Definition and placement of title strings.
- Use of the hardcopy switch. Output goes to a PATRAN hardcopy file, and the user is responsible for any actual hardcopy output.
- Definition of spectrum colors and assignment levels appropriate for this analysis. These must be defined before running EXEC\_HIDE.

The example log file follows below:

```
ss2:/scratch/held/b45wa01/ patran2
```

```
=====
                                P A T R A N
                                RELEASE 2.5
                                COPYRIGHT 1979-1990  PDA ENGINEERING
=====
ENTER DEVICE MNEMONIC, "?" OR "STOP": 4107
INPUT "GO", "SES", "HELP", PATRAN EXECUTIVE DIRECTIVE OR "STOP".
>GO
PATRAN DATA FILE?  1.NEW  2.OLD  3.LAST  4.STOP
>3
(Use the PATRAN database file from the prior example.)
PREPARING THE DATA BASE SUB-SYSTEM FOR "OLD" FILE:
"patran.dat.1"
RESTART FROM THE FILE LAST CLOSED 27-MAY-91   21:10:57
```

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

(Modify NORMAL so only the plate elements remain; name the new component BASE3.)

>SET,GRAPHICS,OFF  
"GRAPHICS" IS NOW OFF (WAS ON ).

>NAME,NORMAL,PLOT  
DO YOU WANT THE CURRENT ACTIVE SET CLEARED? (Y/N)  
>Y

>NODE,1T#,ERAS

>TET,1T#,ERAS

>NAME,BASE3,ADD  
NAMED COMPCNENT "BASE3" ADDED.

>SET,GRAP,ON  
"GRAPHICS" IS NOW ON (WAS OFF).

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

(Change the spectrum to values appropriate for Postscript hardcopy.)

>SET,SPEC,5,0/3/2/6/4

(Look at von Mises stresses; these are in column 9 of the element results file.)

>RUN,ASSIGN,COL.9

INPUT THE NAME OF THE ELEMENT RESULTS FILE:

>E567

DATA WIDTH = 12  
FILE TITLE =45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL  
ELEMENT RESULTS FOR TIME STEP = 567 / TIME = 1.6999999E-03  
27-MAY-91 18:09 35  
DATA VALUES RANGE FROM 0.270E+05 TO 0.743E+05

(If you want to process several time steps, pick results values that will be appropriate for them all.)

ASSIGNMENT? 1.AUTO 2.MANUAL 3.SEMI-AUTO 4.THRESHOLD  
5.CURRENT LEVELS 6.END  
3

INPUT THE BASE VALUE AND A DELTA VALUE

>0.8E5, -.2E5

ASSIGNED COLOR CODE RANGES FOLLOW:

|   |                          |   |                          |
|---|--------------------------|---|--------------------------|
| A | 0.8000E+05 TO 0.6000E+05 | B | 0.6000E+05 TO 0.4000E+05 |
| C | 0.4000E+05 TO 0.2000E+05 | D | 0.2000E+05 TO 0.0000E+00 |

ASSIGNING COLORS TO 84 ELEMENTS: ^G

\*NOTICE\*\*\* SETTING "COLCODE" ON.

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

```

(Adjust the viewing angle and window for this model.)

>VIEW

VIEW? 1.AXES ABS 2.AXES REL 3.SCREEN ABS 4.SCREEN REL
      5.INCREMENTAL 6.FROM 7.VIEW PLANE 8.END

>1

      INPUT AXES ABSOLUTE THETA X,Y,Z FOR SCREEN 1

>10.18,-63.2,0.

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS
      5.INTERFACE 6.STOP 7.PDA_PCL 8.USER_MENU

>WIN

WINDOW? 1.ZOOM 2.MOVE 3.CENTER 4.FIND 5.CORNERS 6.RESTORE 7.EXIT

>1

      INPUT MAGNIFICATION POWER FOR SCREEN 1

>0.85

WINDOW? 1.ZOOM 2.MOVE 3.CENTER 4.FIND 5.CORNERS 6.RESTORE 7.EXIT

>2

      INPUT DECIMAL OFFSET FACTOR IN X,Y FOR SCREEN 1 (EG: .33,.25)

>0, -0.05

WINDOW? 1.ZOOM 2.MOVE 3.CENTER 4.FIND 5.CORNERS 6.RESTORE 7.EXIT

>E

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS
      5.INTERFACE 6.STOP 7.PDA_PCL 8.USER_MENU

>!!!INPUT DISPPCL

!!!INPUT DISPPCL
Compiling: exec_hide
Compiled: exec_hide
Compiling: check_up
Compiled: check_up
...
Compiling: mod_opts
Compiled: mod_opts
Compiling: show_cols
Compiled: show_cols

>!EXEC_HIDE()

MENU,MODE
MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS
      5.INTERFACE 6.STOP 7.PDA_PCL 8.USER_MENU

```

Hidden Surface Plotter Main Menu for Analysis:

45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL

1. Do plots 2. Enter a PATRAN command 3. Set WINDOW/VIEW parms  
4. Process failed-elemt lists 5. File names 6. Modify plot type 7. End

>6

(Turn on the FILL switch below.)

Options mods -- current command is: RUN,HIDE,DEFO

1. DEFO=ON 2. CONT=OFF 3. FILL=OFF 4. FRIN=OFF 5. PARIN=OFF  
6. HARDC=OFF 7. Results col=1 8. Title=OFF 9. Base name=NORMAL 10. END

>3

Current assignment levels will be used.

Enter a character to continue:

>

(Set the RUN,ASSIGN results column number below; von Mises stresses are in column 9.)

Options mods -- current command is: RUN,HIDE,DEFO,FILL

1. DEFO=ON 2. CONT=OFF 3. FILL=ON 4. FRIN=OFF 5. PARIN=OFF  
6. HARDC=OFF 7. Results col=1 8. Title=OFF 9. Base name=NORMAL 10. END

>7

Current results columns is: 1

Enter new results column number or zero to show types:

>9

(Request a different base named component below.)

Options mods -- current command is: RUN,HIDE,DEFO,FILL

1. DEFO=ON 2. CONT=OFF 3. FILL=ON 4. FRIN=OFF 5. PARIN=OFF  
6. HARDC=OFF 7. Results col=9 8. Title=OFF 9. Base name=NORMAL 10. END

>9

Current base name is: NORMAL

Enter a new base name or a blank to keep the old one:

>BASE3

Checking the new base name...

(BASE3 is accepted; next, turn on the hardcopy switch below.)

Options mods -- current command is: RUN,HIDE,DEFO,FILL

1. DEFO=ON 2. CONT=OFF 3. FILL=ON 4. FRIN=OFF 5. PARIN=OFF  
6. HARDC=OFF 7. Results col=9 8. Title=OFF 9. Base name=BASE3 10. END

>6

(Define some title strings and their placement below. Note that there are two title strings available; define them in order.)

Options mods -- current command is: RUN,HIDE,DEFO,FILL HARDC

1. DEFO=ON 2. CONT=OFF 3. FILL=ON 4. FRIN=OFF 5. PARIN=OFF  
6. HARDC=ON 7. Results col=9 8. Title=OFF 9. Base name=BASE3 10. END

>8

Title option is now: OFF  
Title line 1 location command is now: RUN,TITLE,X=1.,Y=10.  
Title line 1 string is now :  
1. Chng option (ON/OFF) 2. Chng locations 3. Chng strings 4. Test 5. End

>1

Title option is now: ON  
Enter a character to continue:  
>

Title option is now: ON  
Title line 1 location command is now: RUN,TITLE,X=1.,Y=10.  
Title line 1 string is now :  
1. Chng option (ON/OFF) 2. Chng locations 3. Chng strings 4. Test 5. End

(Define locations: put the title strings in the upper left corner of the image.)

>2

Title location command (1) is now: RUN,TITLE,X=1.,Y=10.  
Choose: 1. X=1./Y=10. 2. X=55./Y=95. 3. Input X/Y 4. End/no change

>3

Enter screen X percent value (0-100):

>1

Enter screen Y percent value (0-100):

>98

Title location command (2) is now: RUN,TITLE,X=1.,Y=5.  
Choose: 1. X=1./Y=5. 2. X=55./Y=90. 3. Input X/Y 4. End/no change

>3

Enter screen X percent value (0-100):

>1

Enter screen Y percent value (0-100):

>95

Title option is now: ON  
Title line 1 location command is now: RUN,TITLE,X=1.,Y=98.  
Title line 1 string is now :  
1. Chng option (ON/OFF) 2. Chng locations 3. Chng strings 4. Test 5. End

(Enter the title strings. If a string is currently blank, nothing will show in the prompt. If you want only one title string to be displayed, then enter some blanks for the other string.)

>3

Title string (1) is now :  
Change it ? Y/N...:

>Y

Enter a title string (max 75 chars):

>B45W10A - BRITTLE BIRD IMPACT AT 45 DEGREES

Title string (2) is now :  
Change it ? Y/N...:

>Y

Enter a title string (max 75 chars):

>MAXIMUM VON MISES STRESSES

Title option is now: ON

Title line 1 location command is now: RUN,TITLE,X=1.,Y=98.

Title line 1 string is now : B45W10A - BRITTLE BIRD IMPACT AT 45 DEGREES

1. Chng option (ON/OFF) 2. Chng locations 3. Chng strings 4. Test 5. End

>E

(Done setting the plot options. Note the options on the RUN,HIDE command below:  
this is how the images will be displayed.)

Options mods -- current command is: RUN,HIDE,DEFO,FILL,HARDC

1. DEFO=ON 2. CONT=OFF 3. FILL=ON 4. FRIN=OFF 5. PARIN=OFF

6. HARDC=ON 7. Results col=9 8. Title=ON 9. Base name=BASE3 10. END

>E

Hidden Surface Plotter Main Menu for Analysis:

45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL

1. Do plots 2. Enter a PATRAN command 3. Set WINDOW/VIEW params

4. Process failed-elemt lists 5. File names 6. Modify plot type 7. End

>1

Begin or resume hidden surface plot processing.

Now: 38 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>3

Now: 38 - Enter: 5. Specify incrt 6. Enter PATRAN cmd 7. Options 8. End

>5

Enter requested increment:

>567

Incr: 567 (17 of 21) / Time: 1.7000e-03 / Hardcopy: ON / Title: ON

Now: 567 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>P

Processing increment 567 (Number 17 of 21)...

Command as processed: RUN,ASSIGN,COL,9

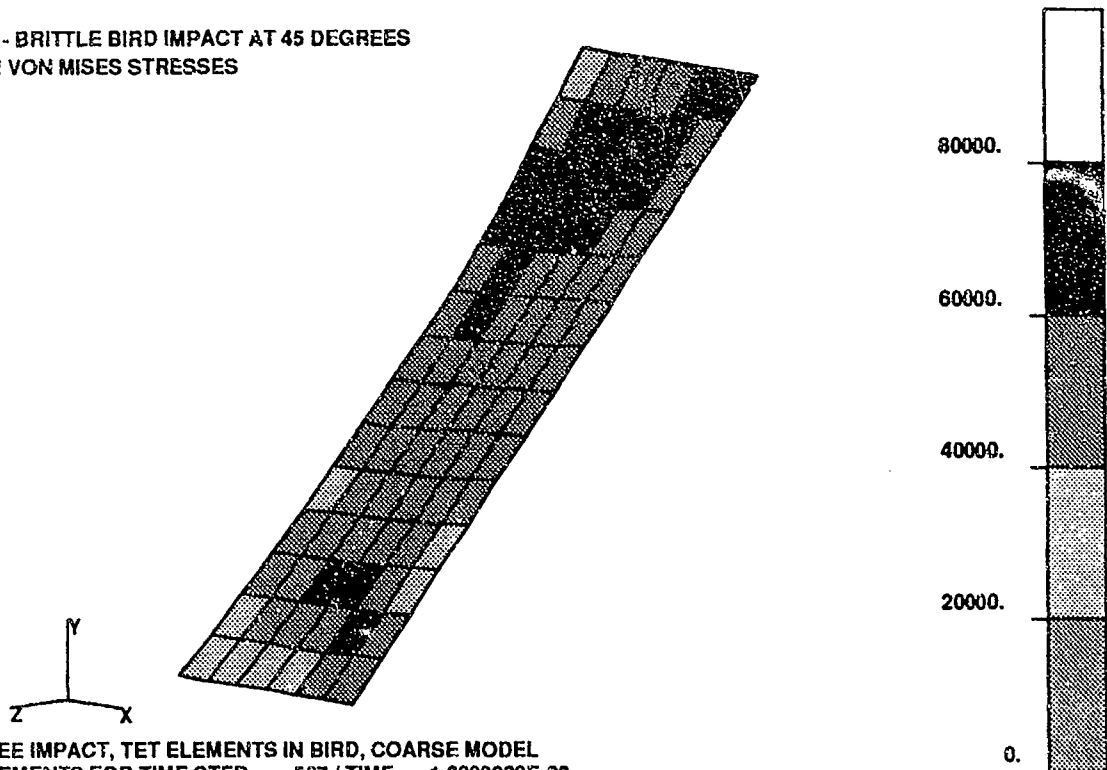
Command as processed: RUN,HIDE,DEFO,FILL,HARDC

Command as processed: RUN,TITLE,X=1.,Y=98.,HARDC

Command as processed: RUN,TITLE,X=1.,Y=95.,HARDC

(Now does the plot.)

**B45W10A - BRITTLE BIRD IMPACT AT 45 DEGREES  
MAXIMUM VON MISES STRESSES**



45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL  
DISPLACEMENTS FOR TIME STEP = 567 / TIME = 1.6999999E-03  
27-MAY-91 18:09:39

Done with incrt 567; hardcopy was: ON...  
Now: 582 - Enter: 1. Plot 2. +/- Step incrt 3. More commands 4. End

>E

Hidden Surface Plotter Main Menu for Analysis:

45-DEGREE IMPACT, TET ELEMENTS IN BIRD, COARSE MODEL  
1. Do plots 2. Enter a PATRAN command 3. Set WINDOW/VIEW params  
4. Process failed-elemt lists 5. File names 6. Modify plot type 7. End

>E

MENU,MODE

MODE? 1.GEOMETRY 2.ANALYSIS MODEL 3.ANALYZE 4.RESULTS  
5.INTERFACE 6.STOP 7.PDA\_PCL 8.USER\_MENU

>STOP

RESTART DATA BEING WRITTEN ON 27-MAY-91 22:43:25 TO:  
"patran.dat.1"  
PDA/PATRAN COMPLETED

(End of example.)

# **APPENDIX C**

## **PROGRAMMING INFORMATION**

This Appendix provides brief technical information on installing and using X3D and the related pre- and post-processing programs, PATX3D and X3POST.

The X3D programs have been run on several types of machines. Some of the computer systems and the operating systems which were current at the time of this documentation are as follows:

*CRAY X-MP/216:*

- Operating system: UNICOS 5.1.1
- FORTRAN compiler: cf77 4.0.3.8

*CRAY Y-MP8/864:*

- Operating system: UNICOS 6.0.11
- FORTRAN compiler: cf77 4.0.3.10

*DEC VAX 8650:*

- Operating system: VMS 5.3-1
- FORTRAN compiler: DEC FORTRAN 5.4-79

*Sun 4:*

- Operating system: SunOS 4.1.1
- FORTRAN compiler: f77 1.4

*IBM RS/6000 Model 530:*

- Operating system: AIX 3.1
- FORTRAN compiler: xlf 01.01

Machine-specific instructions for compiling and running the X3D programs are described in later paragraphs. General information about installing the programs follows below.

The X3D programs are written entirely in FORTRAN, and comply closely with the ANSI FORTRAN 77 standard. However, each machine version includes a small amount of nonstandard code which is specific to that machine alone. Except for the nonstandard "INCLUDE" statement (discussed below), any nonstandard code is highly localized within the programs, and can be replaced with standard (but less aesthetic) FORTRAN code if required.

The X3D programs are maintained in a nonrunning "master" format, in which the machine-specific code has been commented out with strings corresponding to the target machines. The comment strings must be removed with an editor to create valid FORTRAN source code. The strings which must be removed are "C-VAX" for the VAX versions; "C-CRY" for the CRAY versions; "C-SUN" for the Sun versions; and "C-IBM" for the IBM RS/6000 RISC workstations.

The X3D programs use the nonstandard "INCLUDE" FORTRAN statement to include COMMON block definitions and double precision information in the source code at compilation time. The machines listed above (and many other machines) support use of the INCLUDE statement in their compilers. The include-files required to be present when compiling the X3D programs are:

```
patx3d.ins  
x3com.ins  
x3d.ins  
x3hid.ins  
x3post.ins  
xpcom.ins  
xscom.ins
```

References to these file names within the code are always specified using lower case letters, so UNIX-based machines require that the include-files, as present in the appropriate directory, have file names with lower case letters.

PATX3D is a standalone program, and X3D can be compiled and linked as a standalone program. X3POST, however, requires routines from the X3D source file. Normally, the user should create an object library from the X3D object file, and use the library when linking to create the X3POST executable file.

X3D and X3POST typically are run using single precision floating point variables (32 bit words on VAX, Sun, and IBM machines; 64 bit words on CRAY machines). Users who wish to create double precision versions of the codes must edit the include-file *x3d.ins* and remove the "C-DBL" string there; this is the only change required to convert the codes to double-precision. The **entire** versions of the codes then must be recompiled using the new version of the include-file.

Most users should not need to use double precision versions of the codes. IBM RS/6000 users may find that a double-precision version of X3D actually runs slightly faster for some cases than the single-precision version, but note that disk space requirements for the double-precision restart file are approximately twice that of the single-precision version. Note also that X3POST must be compiled as a double-precision version if it is to read a double-precision restart file, or if it is to be linked with a double-precision version of the X3D object library.

Some transparency analysis runtime statistics are shown below. Note that a critical resource in an analysis is disk space. This can be further aggravated by running X3POST later: the example problem shown stored 60 time steps worth of data in the restart file, and if the user requests PATRAN results files for all 60 time steps, there is an additional 24 Mbyte disk requirement beyond the amount shown in the table.

Example problem specifics (this is a version of the examples described in Section 3.3):

- Problem title . . . . . : F16BEDAT
- Number of plates (transparency elements) . . : 928
- Number of tetrahedral solids (bird elements) . : 960
- Bird material model . . . . . : low-strength
- Initial bird velocity . . . . . : 350 knots
- Restart file output . . . . . : total of 60  
time steps  
written
- Trace file output . . . . . : 30 nodes,  
every 20  
time steps
- All X3D program versions were single-precision versions. This gave 32-bit precision results on all the listed machines except the Cray machines, which gave 64-bit precision results.
- The number of time steps calculated varies because of differing architectures and round-off errors.

## SAMPLE TRANSPARENCY ANALYSIS RUNTIME STATISTICS

| Machine Vendor and Model        | Operating System and Compiler Versions      | F16BE Run Time Seconds (Hrs:Mins) | Time Steps Calculated | OREST File Size (Mbytes) | TRACE File Size (Mbytes) | Printable Output File (Mbytes) | Total Disk Space (Mbytes) |
|---------------------------------|---------------------------------------------|-----------------------------------|-----------------------|--------------------------|--------------------------|--------------------------------|---------------------------|
| CRAY Y-MP8/864                  | UNICOS 6.0.11<br>cft77 4.0.3.10             | 2,418<br>(0:40)                   | 6,327                 | 27.574                   | 0.870                    | 0.409                          | 28.853                    |
| CRAY X-MP/216                   | UNICOS 5.1.10<br>cft77 4.0.3.8              | 3,199<br>(0:53)                   | 6,327                 | 27.574                   | 0.870                    | 0.409                          | 28.853                    |
| IBM RS/6000 Model 530           | AIX 3.1<br>xlf 01.01                        | 5,380<br>(1:30)                   | 6,302                 | 13.767                   | 0.865                    | 0.408                          | 15.040                    |
| Silicon Graphics SGI 4D/320 VGX | IRIX Sys. V,<br>Rel. 3.3.2<br>MIPS f77 2.01 | 6,448<br>(1:47)                   | 6,275                 | 13.767                   | 0.861                    | 0.408                          | 15.036                    |
| Sun 4 (SPARC)                   | SunOS 4.1.1<br>Sun f77 1.4                  | 15,689<br>(4:21)                  | 6,368                 | 13.767                   | 0.875                    | 0.408                          | 15.050                    |
| VAX 8650                        | ULTRIX 3.1<br>VAX fort 4.7-271              | 20,054<br>(5:34)                  | 6,318                 | 13.767                   | 0.867                    | 0.408                          | 15.042                    |
| VAX 8650                        | VMS 5.3-1<br>Fortran 5.4-79                 | 20,345<br>(5:39)                  | 6,316                 | 13.791                   | 0.878                    | 0.416                          | 15.085                    |
| Harris HCX-9                    | CX/UX 4.1-A<br>f77 4.1                      | 37,734<br>(10:39)                 | 6,380                 | 13.767                   | 0.878                    | 0.408                          | 15.053                    |

## CRAY X-MP and Y-MP UNICOS Versions

CRAY machines provide the fastest processing times of the all machines supported. A sample NQS batch job file used to run X3D on a CRAY X-MP is listed below.

```
# QSUB -s /bin/sh
# QSUB -lM 4mw -lT 9900 -lt 9800
# QSUB -eo
# QSUB -r f16an

set -vxS
ja
trap 'ja -stc' 0 15

#
# -- X3D on Cray X-MP / UNICOS 5.1.10
#
#   Current with X3D 2.5.

# -- Get into TMPDIR and copy input data.

cd $TMPDIR

cp $HOME/f16an/f16an.dat f16an.dat

# -- Run X3D.

$HOME/x3d25/x3d.exe <f16an.dat >f16an.out 2>errfile

cat errfile

ls -l

# -- Save some files.

cp f16an.out $HOME/f16an/.
cp NREST $HOME/f16an/f16an.dmp
cp TRACE $HOME/f16an/f16an.trc

# -- All done.
```

A sample NQS batch job used to compile X3D, PATX3D, and X3POST on a CRAY X-MP is listed below. The code inlining option available with the cft77 compiler can speed up execution times by several per cent, so its use is illustrated below. Note that the procedure creates FORTRAN source files from the master versions of the codes.

```
# QSUB -s /bin/sh
# QSUB -lM 4mw -lT 250
# QSUB -eo
# QSUB -r x3dcom5

# -- Compile X3D, X3POST, and PATX3D under UNICOS.
#
#   Current with UNICOS 5.1.1 and cft77 4.0.3.8
#
#   Current with X3D 2.5.
#
```

```

# Use the cf77 tool to request automatic vectorization.
#
# Compile x3d.f twice - once to get an executable that has
# been code inlined, and once to get a non-inlined object
# file for use with a library.
#
# Note that the inlined version of x3d.exe did not work correctly
# for us under an early version of UNICOS 6.0.0 - use the
# non-inlined compile option if you think you will have problems.
#
# -- File information:
# -----
# You will need the following files in your working directory
# to compile the three codes:
#
# Master source versions:
# 1. x3d.mas
# 2. patx3d.mas
# 3. x3post.mas
#
# Include-files (not all are used in all programs).
# File names must be exactly as shown below, with
# lower case letters:
# 1. patx3d.ins
# 2. x3d.ins
# 3. x3com.ins
# 4. x3hid.ins
# 5. x3post.ins
# 6. xpcom.ins
# 7. xscom.ins
#
# -- End of file information.
#
# 04-Jun-91 -- TH

set -vXS
ja
trap 'ja -stc' 0

# -- Code is in $HOME/x3d25.
# We need routines in x3d.f to link with x3post,
# so create object files for both and then a library
# of the x3d code.

cd $HOME/x3d25

ls -l

# -- Check up on the precision we're compiling with.
# Should be single on this machine...

cat x3d.ins

# -- Commented out code above means we're compiling single
# precision...

# -- Edit up some Fortran source from the master files.
# First x3d, then others...

if [ -f x3d.f ]
then
mv x3d.f x3d.$$
fi

```

```

ex x3d.mas <<EOF
%s/C-CRY//g
w! x3d.f
q
EOF

if [ -f x3post.f ]
then
mv x3post.f x3p.$$
fi

ex x3post.mas<<EOF
%s/C-CRY//g
w! x3post.f
q
EOF

if [ -f patx3d.f ]
then
mv patx3d.f pat.$$
fi

ex patx3d.mas<<EOF
%s/C-CRY//g
w! patx3d.f
q
EOF

# -- Now compile everything, and link x3d and patx3d.

# Use the statement below instead if you don't want
# code inlining in x3d.exe:
# cf77 -Zv -v -o x3d.exe x3d.f

cf77 -Zv -v -Wf"-o inline" -o x3d.exe x3d.f

cf77 -Zv -v -o patx3d.exe patx3d.f

cf77 -Zv -v -Wf"-b x3d.o" x3d.f

cf77 -Zv -v -Wf"-b x3post.o" x3post.f

# -- Make a library.

bld rzv x3d.a x3d.o

# -- Now link these to get x3post.

segldr -l ./x3d.a -o x3post.exe -V x3post.o

# -- Clean up.

rm *.o

# -- Done.

```

A sample UNICOS Bourne shell script used to run X3POST interactively on the CRAY is listed below:

```
#!/bin/sh
# -- Bourne shell script to run X3POST with a command line
# option to specify the restart file name.
# Good only for UNICOS because of the non-standard "assign"
# command (this uses the UNICOS 5.1 syntax for "assign").
# 04-Jun-91 -- TH
#
# Usage:
# 1. Store this file in your $HOME/bin subdirectory.
# Call this file "x3post".
# Make sure that x3post has user executable privilege:
# chmod u+x x3post
# 2. Make sure that your $HOME/bin subdirectory is in your
# path (enter "set" to see the current path value).
# 3. Log out then log in again.
# 4. To run x3post, enter:
# x3post restartfile.name
#
FILENV=assign.$$
export FILENV
if [ $# -eq 0 ]
then
    echo "Error:"
    echo "You must specify the restart file name as parameter 1."
    echo "Example: x3post cylinder.dmp"
elif [ -f $1 ]
then
    assign -a $1 OREST
#
# Edit the path below to be the directory where you have
# x3post.exe stored.
#
$HOME/x3d25/x3post.exe
else
    echo "Error: Cannot find file $1 to use with x3post."
fi
it [ -f assign.$$ ]
then
    rm assign.$$
fi
```

## VAX/VMS Versions

A sample DCL batch command procedure used to run X3D is listed below:

```
$! VAX/VMS Command Procedure to Run X3D in Batch Mode
$! -----
$!
$! This file is called B45C.COM on the VAX.
$! It runs X3D on the B45C dataset.
$!
$! Usage: $submit /keep /noprint /log=[] B45C
$!
$! Results are written to the following files:
$!     B45C.OUT - line printer file
$!     B45C.DMP - restart file
$!     B45C.TRC - trace file
$!
$!
$! set verify
$!
$! set def [scratch.b45c]
$!
$! assign/user b45c.dat for005
$! assign/user b45c.out for006
$! assign/user b45c.dmp nrest
$! assign/user b45c.trc trace
$!
$! run work$fiel:[scratch.x3d]x3d
$!
$! sho process /all
```

A sample DCL command procedure used to compile the X3D programs is listed below. Note that the procedure creates the FORTRAN source code from the master versions of the codes.

```
$! -- VAX/VMS command procedure to compile and link
$! PATX3D, X3D, and X3POST.
$!
$! 1. You must have the following include-files in the
$!    working subdirectory:
$!     1. PATX3D.INS
$!     2. X3COM.INS
$!     3. X3D.INS
$!     4. X3HID.INS
$!     5. X3POST.INS
$!     6. XPCOM.INS
$!     7. XSCOM.INS
$!
$! 3. The procedure builds VAX FORTRAN source code from
$!    master versions of the codes. By default, programs
$!    use single precision real arithmetic. You must have
$!    the following master code files in your working
$!    subdirectory:
$!     1. PATX3D.MAS
$!     2. X3D.MAS
$!     3. X3POST.MAS
$!
```

```

$! 4. PATX3D is a standalone program.
$!   X3POST requires some routines from X3D, so the
$!   procedure builds an object library from X3D and
$!   uses it when linking X3POST.
$!
$   on error then goto getout
$!
$! -- Make PATX3D.
$!
$   edit/nocommand patx3d.mas
s/c-vax// w
write patx3d.for
quit
$   for patx3d
$   del patx3d.for;0
$   link patx3d
$!
$! -- Make X3D.
$!
$   edit/nocommand x3d.mas
s/c-vax// w
write x3d.for
quit
$   for x3d
$   del x3d.for;0
$   lib/create x3d x3d
$   del x3d.obj;0
$   lib/extract=(x3d)/output=x3d.obj x3d
$   link x3d,x3d/lib
$!
$! -- Make X3POST.
$!
$   edit/nocommand x3post.mas
s/c-vax// w
write x3post.for
quit
$   for x3post
$   del x3post.for;0
$   link x3post,x3d/lib
$!
$ getout:
$   exit

```

A sample DCL interactive command procedure used to run X3POST is listed below:

```
$! VAX/VMS Command Procedure to Run X3POST Interactively
$! ~~~~~
$!
$! Usage:  @X3POST name
$!          (this command file is called X3POST.COM)
$! Where:  'name' is the root name of the restart file
$!
$! Results are read from:
$!      name.DMP - restart file
$!
$ ver_set = 'f$verify()'
$ set verify
$ assign/user sys$command sys$input
$ assign/user 'Pl'.dmp orest
$ run work$fier:[scratch.x3d]x3post
$ set noverify
$ if ver_set then set verify
$ exit
```



## Sun SunOS Versions

An example UNIX script file used to run X3D in the background on a Sun is listed below:

```
#!/bin/sh

set -vx

#
# X3D script file for SunOS 4.x background run.
#
# This script is file: tbcyl.scr.
# Make sure it has execute permission:
#   chmod +x tbcyl.scr
#
# From the C shell use:
#   /usr/bin/nohup tbcyl.scr > tbcyl.log &
#
# 04-Jun-91 -- TH

pwd

date

# What host ran this job?

/bin/uname -a

cd /scratch

mkdir tbcyl

cd tbcyl

cp $HOME/x3d-runs/tbcyl/tbcyl.dat .

ls -l

# --- Now run...

/usr/bin/time $HOME/x3d25/x3d.exe \
  < tbcyl.dat > tbcyl.out 2>tbcyl.err

cat *err

# --- Note - time above is in seconds...

# --- Now run x3post.

mv NREST OREST

$HOME/x3d25/x3post.exe <<EOF >xpout
o
a
s
EOF

ls -l

# --- Done.
```

An example Bourne shell script file used to compile the X3D programs is listed below. Note that we have had problems with code optimization under versions 1.2 and 1.3 of the Sun FORTRAN compiler. This procedure creates FORTRAN source files from the master versions of the codes.

```
#!/bin/sh

set -vx

# --- X3D / X3POST / PATX3D compile script for Sun 4.
#
# Current with X3D 2.5.
#
# This system uses SunOS 4.1.1; Sun FORTRAN 1.4.
#
# Note: Optimization causes problems in prior releases
# of Sun's FORTRAN on SPARC machines.
#
# For f77 1.2 use:
#   f77 -Nx400 -c x3d.f
#
# For f77 1.3.1 use:
#   f77 -V -fast -O1 -Nx400 -c x3d.f
#
# This script is file x3dcomp.scr.
# Make sure it has execute permission:
#   chmod +x x3dcomp.scr
# From the C shell (normal shell for the Sun), use:
#   /usr/bin/nohup x3dcomp.scr >x3dcomp.log &
#
# -- File information:
# -----
#   You will need the following files in your working directory
#   to compile the three codes:
#
#   Master source versions:
#     1. x3d.mas
#     2. patx3d.mas
#     3. x3post.mas
#
#   Include-files (not all are used in all programs).
#   File names must be exactly as shown below, with
#   lower case letters:
#     1. patx3d.ins
#     2. x3d.ins
#     3. x3com.ins
#     4. x3hid.ins
#     5. x3post.ins
#     6. xpcom.ins
#     7. xscom.ins
#
# -- End of file information.
#
# 04-Jun-91 -- TH

pwd

date
```

```

# --- What host ran this problem?

/bin/uname -a

# --- Make a working subdirectory and go there.
#       This job will create a bunch of files, so put them
#       in a place that will be easy to clean up.

cd /tmp
mkdir x3dcomp

cd x3dcomp
mkdir $$
cd $$

pwd

cp $HOME/x3d25/*.ins .
cp $HOME/x3d25/*.mas .

# -- Check up on the precision we're compiling with.
#       Should be single on this machine...

cat x3d.ins

# -- Commented out code above means we're compiling single
#       precision...

# --- Edit up x3d first to get FORTRAN files from the master file.
#       We want to make a library file for later use with x3post.

ex x3d.mas <<EOF
%s/C-SUN//g
w! x3dfull.for
q
EOF

# --- Now fsplit into separate files and compile.
#       ar-type library modules are stored by file, not by
#       program section, so we need one program per file.

fsplit x3dfull.for >fsplit.out

rm x3dfull.for

f77 -V -fast -Nx400 -c *.f

# --- Make a library.

ar crv x3d.a *.o

ranlib x3d.a

# --- Make an executable.
#       Note that fsplit may have named the main program X3D.f,
#       so change the object file name if necessary...

if [ -f X3D.o ]
then
mv X3D.o x3d.o
fi

f77 -V -fast -o x3d.exe x3d.o x3d.a

```

```

# --- Clean up the mess and work on x3post and/or other
#      codes.

rm *.o *.f

# --- Another edit to get Sun-specific source.

ex x3post.mas<<EOF
%s/C-SUN//g
w! x3post.f
q
EOF

f77 -V -fast -Nx400 -c x3post.f

f77 -V -fast -Nx400 -o x3post.exe x3post.o x3d.a

ex patx3d.mas<<EOF
%s/C-SUN//g
w! patx3d.f
q
EOF

f77 -V -fast -Nx400 -o patx3d.exe patx3d.f

# --- Done with compiles -- copy back the executables.
#      Clean up the rest of the subdirectory later, in case
#      something needs checking.

cp *.exe $HOME/x3d25/.

cp *.a $HOME/x3d25/.

date

ls -l

# --- All done.

```

## IBM RS/6000 AIX Versions

An example AIX script file used to run X3D in the background on an IBM RS/6000 is listed below:

```
#!/bin/ksh

set -vx

# X3D run on an IBM RS/6000 AIX 3.1.
#
# Korn shell script file for background run.
#
# This file is: f16bj.scr
# Make sure it has execute permission:
#   chmod +x f16bj.scr
#
# Do:
#   nohup f16j.scr >f16j.log &
# to run in no-logout background.
#
# X3D 2.5 - single-precision run.
#

date

cd /m115/scratch

mkdir f16bg

cd f16bg
pwd

cp $HOME/f16/f16bg.dat .

timex $HOME/x3d25/x3d.exe \
  <f16bg.dat >f16bg.out 2>errfile

cat err*

df /m115

ls -l

# -- Run x3post...

mv NREST OREST

timex $HOME/x3d25/x3post.exe <<e-o-f >xpout
o
a
s
e-o-f

df /m115

ls -l

# -- Done.
```

An example Korn shell script file used to compile the X3D programs is listed below. Note that this procedure creates FORTRAN source files from the master versions of the codes.

```
#!/bin/ksh

set -vx

# IBM RS/6000 script file to compile X3D and
# X3POST. No version of PATX3D yet, but it should be
# easy to port.
#
# Current with X3D 2.5.
#
# This sytem uses AIX 3.1 and XLF FORTRAN 01.01.
#
# This file is: x3dcomp.scr
# Make sure it has execute permission:
#   chmod +x x3dcomp.scr
#
# Do:
#   nohup x3dcomp.scr >x3dcomp.log &
# to run in no-logout background.
#
# Note: ibmtim.c is a user-written C routine
# that gets time/date from the system. See
# SUBROUTINE TSTAMP in X3D.MAS for the source
# code and instructions (also on what to do if
# you don't want to use ibmtim.c / ibmtim.o).
#
# -- File information:
#   -----
#   You will need the following files in your working directory
#   to compile the three codes:
#
#   Master source versions:
#     1. x3d.mas
#     2. patx3d.mas
#     3. x3post.mas
#
#   Include-files (not all are used in all programs).
#   File names must be exactly as shown below, with
#   lower case letters:
#     1. patx3d.ins
#     2. x3d.ins
#     3. x3com.ins
#     4. x3hid.ins
#     5. x3post.ins
#     6. xpcom.ins
#     7. xscom.ins
#
# -- End of file information.
#
# 14-May-91 -- TH

date

cd $HOME/x3d25

pwd
```

```

# --- Verify what precision we're working with here...
cat x3d.ins

# --- Code commented out above means a single-precision compile.

# --- Edit up some master files.
#       Rename existing FORTRAN files to something else
#       first, if necessary.
#       First compile x3d, then x3post...

if [ -f x3d.f ]
then
    mv x3d.f x3d.$$
fi

if [ -f x3post.f ]
then
    mv x3post.f x3p.$$
fi

# -- This edit sequence includes activation of the call to IBMTIM:

ex x3d.mas <<EOF
/IBMTIM ( DAT
s/C-IBM//g
%s/C-IBM//g
w! x3d.f
q
EOF

ex x3post.mas<<EOF
%s/C-IBM//g
w! x3post.f
q
EOF

# --- Now compile and link.
#       Routine ibmtim.c is already in the directory...

xlf -c -O x3d.f

xlf -c -O x3post.f

xlc -c    ibmtim.c

# All compiled now (hopefully), so link them
# together. The Wl,-bloadmap option generates
# a fairly small load map - good to see what
# happened at link/bind time.

xlf -o x3d.exe -Wl,-bloadmap:x3d.map \
      x3d.o ibmtim.o

xlf -o x3post.exe -Wl,-bloadmap:x3post.map \
      x3post.o x3d.o ibmtim.o

ls -l

# --- Done.

```

# **APPENDIX D**

## **MATERIAL PROPERTY TABLES**

The table of properties in this Appendix presents typical material constant values for several engineering materials. These data are intended as a useful reference and basis for comparison with properties from other sources. However, we wish to emphasize that the values in the table are taken from a variety of sources, and may vary considerably in quality. Some data simply are not available for particular materials, and are omitted from the table; for example, the absence of a value for 'D' or 'p' does not necessarily imply that the material in question is insensitive to strain rate.

When using the listed material properties with X3D, remember that:

- densities should be converted to force-length-time units (i.e., divided by 'g'); and
- values of  $1/D$  and  $1/p$  (not  $D$  and  $p$ ) are required to define the strain rate sensitivity in the X3D input.

Additional details on the material models and data requirements can be found in Section 2 (theory) and Appendix A (input data descriptions).

# MATERIAL CONSTANTS FOR SEVERAL COMMON MATERIALS

| Material Description    | Density<br>lb/in <sup>3</sup> | E<br>ksi | H<br>ksi | $\nu$ | $\alpha$<br>$\mu\text{E}/^\circ\text{F}$ | $\sigma_y$<br>ksi | D<br>sec <sup>-1</sup> | $\rho$ | $\sigma_u$<br>ksi | Data Source |
|-------------------------|-------------------------------|----------|----------|-------|------------------------------------------|-------------------|------------------------|--------|-------------------|-------------|
| Acrylic                 | 0.043                         | 450      | 50       | 0.35  | 41                                       | 10                |                        |        | 20                |             |
| Aluminum<br>2024-T3     | 0.098                         | 10,600   |          | 0.33  | 12.6                                     | 50                |                        |        | 70                | 2,5         |
| Aluminum<br>6061-T6     | 0.098                         | 10,600   | 416      | 0.33  | 13.3                                     | 40                | 6,500                  | 4      | 45                | 2,5         |
| Beryllium<br>QMV        | 0.067                         | 40,000   |          | 0.024 | 6.4                                      | 27                |                        |        | 33                | 5           |
| Copper,<br>annealed     | 0.322                         | 15,600   |          | 0.355 | 9.2                                      | 5                 |                        |        | 32                | 5           |
| Glass,<br>common        | 0.094                         | 10,000   |          | 0.244 |                                          | 10                |                        |        |                   | 5           |
| Magnesium,<br>HK31A-H24 | 0.065                         | 6,400    |          | 0.35  | 14                                       | 29                |                        |        | 37                | 5           |
| Polycarbonate           | 0.043                         | 325      | 36.1     | 0.36  | 34.7                                     | 7.14              | 196,560                | 12     | 11                | 6,7         |
| Polyurethane            | 0.037                         | 1        |          | 0.43  | 110                                      |                   |                        |        | 2.7               | 6           |
| PVB 38 DBS              | 0.038                         | 0.2      |          | 0.5   | 130                                      |                   |                        |        | 3.1               | 6           |
| PVB 3GH                 |                               |          |          | 0.17  | 50                                       |                   |                        |        | 4.4               | 6           |
| Silicone                | 0.037                         | 0.2      |          | 0.33  | 184                                      |                   |                        |        | 0.5               | 6           |
| Steel, mild             | 0.283                         | 29,500   | 30.0     | 0.287 | 8.4                                      | 30                | 40.4                   | 5      | 60                | 2,3,4       |
| Steel, 304<br>stainless | 0.283                         | 28,000   | 395.5    | 0.30  | 9.9                                      | 25                | 100                    | 10     | 90                | 1           |
| Titanium<br>6Al-4V      | 0.164                         | 16,800   |          | 0.30  | 4.7                                      | 120               |                        |        | 130               | 5           |
| Titanium<br>B120VCA     | 0.175                         | 14,800   | 108.8    | 0.30  | 5.2                                      | 190               |                        |        | 200               | 5           |
|                         |                               |          |          |       |                                          |                   |                        |        |                   |             |
|                         |                               |          |          |       |                                          |                   |                        |        |                   |             |
|                         |                               |          |          |       |                                          |                   |                        |        |                   |             |

## Notes

1.  $H = E E' / (E + E')$  where  $E'$  is the post-yield modulus.
2. 1 psi = 0.006895 MPa (1 MPa = 145.03 psi)

## DATA SOURCES FOR MATERIAL PROPERTY TABLE

1. M. J. Forrestal & M. J. Sagartz, Elastic-plastic response of 304 stainless steel beams to impulse loads, *J. Appl. Mech.* **45**, 685-7, 1978.
2. N. Perrone & P. Bhadra, A simplified method to account for plastic rate sensitivity with large deformations, *J. Appl. Mech.* **46**, 811-6, 1979.
3. S. A. Meguid & J. D. Campbell, Elastic-plastic tension-torsion in a circular bar of rate-sensitive material, *J. Appl. Mech.* **46**, 311-6, 1979.
4. M. J. Manjoine, Influence of rate of strain and temperature on yield stresses of mild steel, *J. Appl. Mech.* **11**, 211-8, 1944.
5. T. Baumeister & L. S. Marks, *Standard Handbook for Mechanical Engineers*, 7ed., McGraw Hill, New York, 1967.
6. J. H. Lawrence, Jr., *Guidelines for the Design of Aircraft Windshield/Canopy Systems*, AFWAL-TR-80-3003, Wright-Patterson AFB, 1980.
7. J. T. Ryan, Impact and yield properties of polycarbonate as a function of strain rate, molecular weight, thermal history, and temperature, *Pol. Engng. & Sci.* **18**(4), 264-7, 1978.