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A METHOD FOR COMPUTER-AIDED DESIGN OF SABOT-PENETRATOR PACKAGES

Kent D. Kimsey

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The application of interactive computer graphics in developing a tool for expediting the analysis and design of axisymmetric structures such as sabot-penetrator packages is discussed. A pre-processor which has been developed to allow the designer to interactively modify finite element models of sabot-penetrator packages for quasi-static analysis with SAP IV (Structural Analysis Program) is described along with the accompanying post-processor. User manual for the pre- and post-processors are provided.

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I. INTRODUCTION

Most numerical methods for evaluating the structural integrity of system components require a large portion of the analyst's time to generate a numerical model representative of the physical situation which he is simulating. Furthermore, analyzing the mountains of data commonly generated by numerical methods can also be a tedious and time-consuming task. The application of interactive computer graphics has the potential to significantly reduce the time the analyst devotes to constructing a numerical model and reviewing the computational results[1]. Another paramount advantage in applying the principles of interactive graphics is the potential of decreased cost per analysis.

In an effort to expedite the design and analysis of lightweight and efficient sabots for today's KE penetrators a set of pre- and post-processors have been developed to interface with SAP IV[2] (Structural Analysis Program). The application of interactive computer graphics in designing sabot-penetrator packages has been termed computer-aided design of sabot-penetrator packages and is shown schematically in Figure 1. The technique begins with an engineer's conceptual design or a design being field tested. Then, using the convenient but somewhat limited node and element date generators available with SAP IV, a crude finite element model of a package is generated. The crude model serves as a benchmark for the pre-processor, BOWGEN, which allows the engineer to interactively refine the crude model by moving nodal points, generating elements, or using one of a number of other options available, to be discussed later.

The SAP IV program is used to obtain a quasi-static analysis of the sabot-penetrator package. SAP IV is a finite element program for static and dynamic analysis of linear structural systems. Two-dimensional axisymmetric quadrilateral and triangular elements are used to discretize the sabot-penetrator package. A detailed discussion of the SAP IV program is contained in Reference 2.

The post-processor, POSTBOW, allows the engineer to interactively review the quasi-static solution to determine if stress levels and deformations are acceptable. If not, the finite element model can again be modified with BOWGEN in an effort to reduce regions of high stress and stiffen those regions which have excessive deformations. Once a satisfactory design is obtained, construction of a prototype may be warranted. The rapidity inherent in this technique makes it ideal for support at high priority tasks.

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[1] *W. M. Newman and R. F. Sproull, Principles of Interactive Computer Graphics, McGraw-Hill, 1973.*

[2] *K. Bathe, E. L. Wilson, and F. E. Peterson, "SAP IV A Structural Analysis Program for Static Dynamic Response of Linear Systems," Earthquake Engineering Research Center, EERC 73-11, June 1973.*

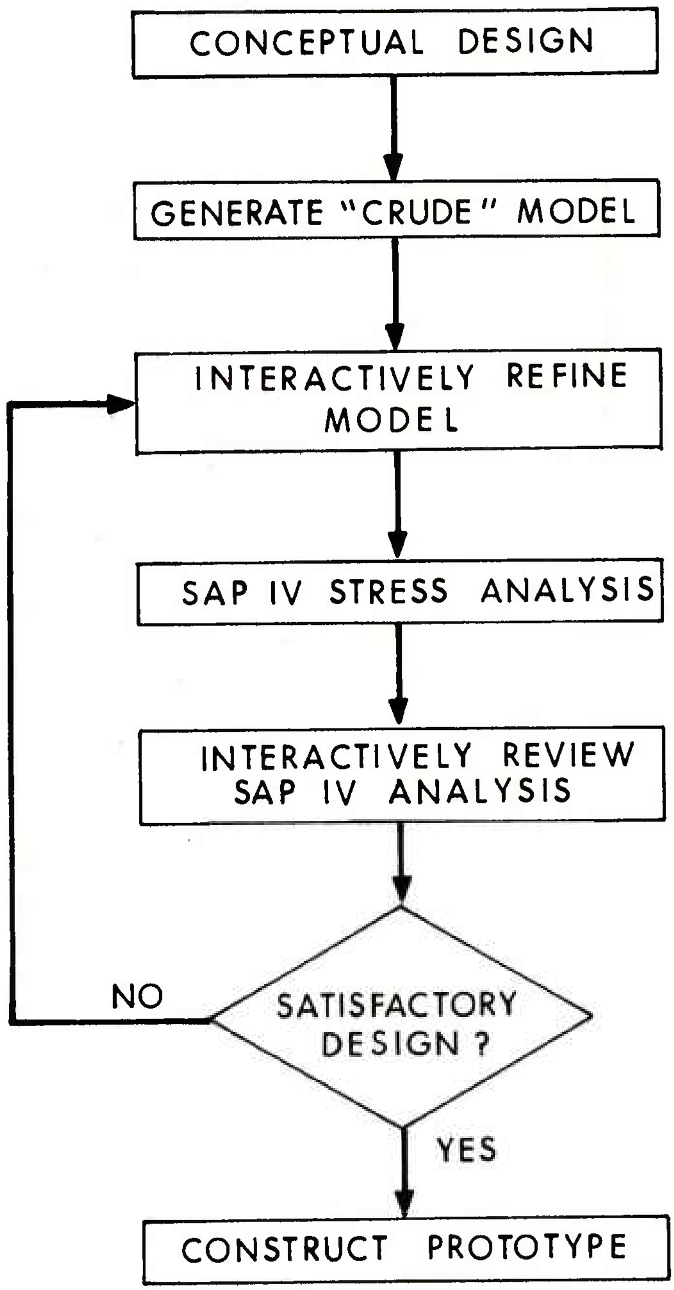

Figure 1. Computer-aided design of sabot-penetrator packages

Although this report emphasizes the utility of BOWGEN and POSTBOW for expediting the design and analysis of sabot-penetrator packages, these programs can be employed in the analysis of any axisymmetric structure. The pre- and post-processors, designed to be used with a TEKTRONIX 4014 graphics terminal, are written in FORTRAN and require the support of TEKTRONIX Plot 10 software. Reference 3 will acquant the novice user with the operation of the graphics terminal. Sections II and III present user manuals for the pre- and post-processor, respectively.

II. REFERENCE MANUAL FOR BOWGEN

The pre-processor, BOWGEN, allows the engineer to interactively modify a finite element model of a structure. The application of interactive computer graphics can significantly reduce the amount of time devoted to generating a finite element model of a system component. This section serves as reference manual for the pre-processor.

BOWGEN requires a complete SAP IV input data deck which defines a crude finite element model of the system component being analyzed. Currently, the finite element model can consist of only two-dimensional axisymmetric quadrilateral and triangular elements (SAP IV element TYPE 4), and spring boundary elements (SAP IV element TYPE 7). The axisymmetric element is used to subdivide the structure and the boundary element is used to inhibit rigid body translation which may arise in a quasi-static analysis. The axisymmetric and boundary elements are the only members of the SAP IV element library that are supported by BOWGEN and POSTBOW in anticipation that most structures to be analyzed with their aid would be axisymmetric. However, other members of the SAP IV element library can be readily incorporated into BOWGEN. The crude model serves as a benchmark finite element model for the pre-processor. The user is referred to Reference 2 for preparing the crude model data deck.

Figure 2 depicts the screen layout of the pre-processor. A finite element model can be interactively modified by randomly selecting menu items from the command menu. The command menu is displayed in a tabular format along the left margin of the Cathrode Ray Tube and is summarized in Table 1. A detailed description of the command menu is provided in Appendix A. A menu item is selected by using the terminal thumbwheels or joystick to position the terminal crosshairs over the box containing the desired menu item. Some menu items query the user for additional information (see Appendix A).

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[3] *TEKTRONIX 4014 and 4014-1 Computer Display Terminal Users Instruction Manual, TEKTRONIX Incorporated, July 1974.*

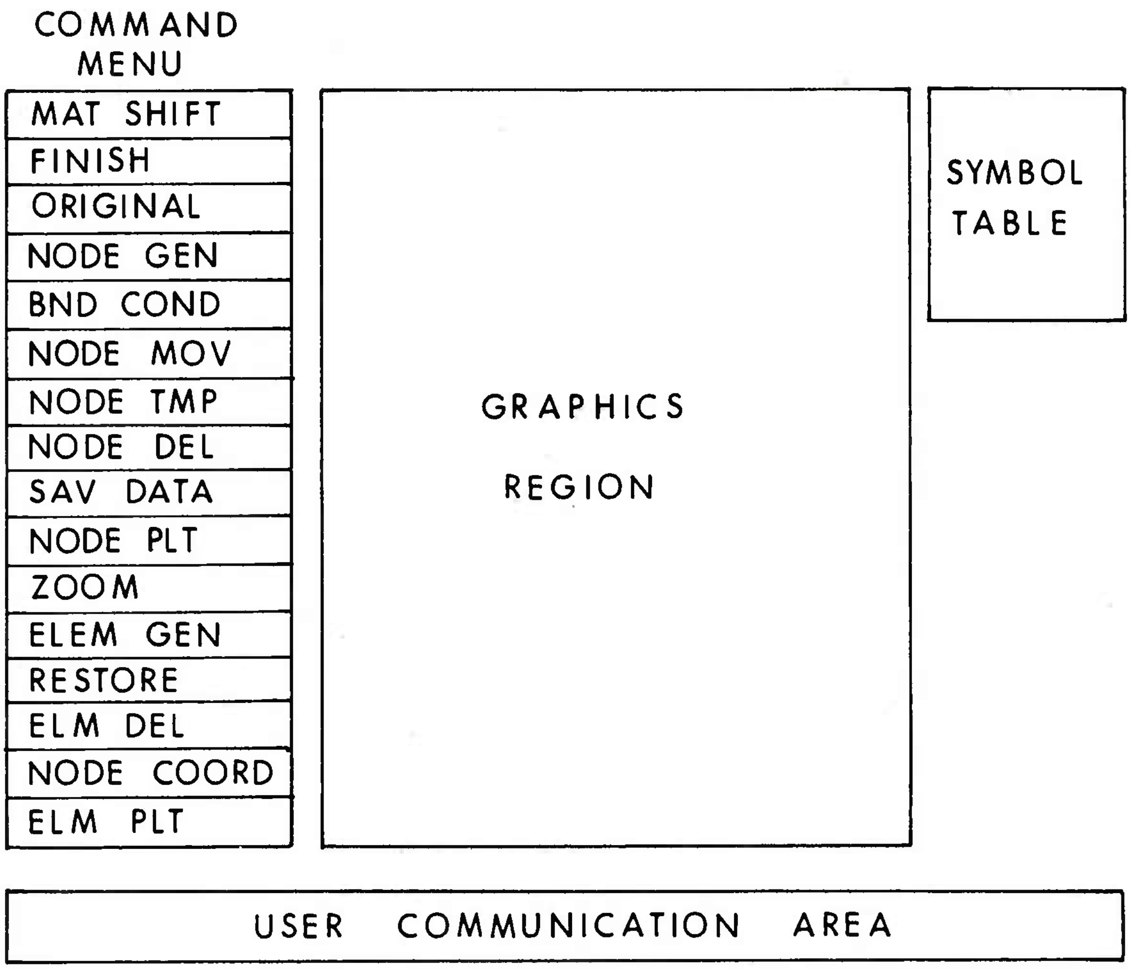

Figure 2. Pre-processor screen layout

Table 1. Description of BOWGEN command menu

Menu Item	Function
MAT SHIFT	Rigid body translation of specified material.
FINISH	Exit from BOWGEN to the operating system.
ORIGINAL	Reset the working finite element model to the benchmark model.
NODE GEN	Generate nodal points using terminal crosshairs to define coordinates.
BND COND	Assign boundary condition to nodal points.
NODE MOV	Move a specified nodal point to the location specified by the terminal crosshairs.
NODE TMP	Assign a temperature value to a specified node.
NODE DEL	Delete a specified node.
SAV DATA	Make a scratch file copy of current finite element model.
NODE PLT	Plot nodal points.
ZOOM	Enlarge a specified region of the model.
ELM GEN	Generate an axisymmetric element.
RESTORE	Reset plotting limits to include the entire model, used after zooming.
ELM DEL	Delete a specified element.
NODE COORD	Move a specified node point to the coordinates entered via terminal keyboard.
ELM PLT	Plot element connectivity.

Using BOWGEN to generate nodes and elements can lead to a large stiffness matrix bandwidth which increases the storage requirements and CPU time for solving the equilibrium equations. However, if one generates a number of "spare" nodes which have all associated degrees of freedom restrained and are in numerical sequence with other nodes in regions where mesh refinement is anticipated in the crude model, an acceptable bandwidth will be preserved. When the crude model is refined with BOWGEN the "spare" nodes can be moved to the desired location for generating elements and the appropriate boundary conditions can be prescribed. "Spare" nodes which are not used in the refinement process are removed from the final set of equilibrum equations in SAP IV.

BOWGEN currently resides on the BRL CYBER 70/Model 173 and can be accessed with the following NOS/BE control cards:

```
ATTACH,DATA,pfn,*ID=yourid.
ATTACH,LGO,OBJBOWGEN,ID=KIMSEY.
BEGIN,PLOTII,PLOT10,LF=LGO.
```

*pfn = permanent file name of the data file containing the finite element model to be processed.

After the crude model has been refined to the desired level of sophistication the SAV DAT menu item should be selected to save the refined model for SAP IV analysis. In order for the inertial forces and applied loads to be in equilibrium the appropriate acceleration must be specified in the SAP IV quasi-static analysis. This acceleration can be computed directly if the mass of the structure and the area over which the applied load acts are known. If not, these items can be computed using SAP IV as follows: (a) apply a unit pressure to the appropriate elements of the model without any acceleration. The resulting force in the boundary element which restrains the system from rigid body translation is equal to the area on which the applied load acts; (b) apply a unit acceleration to the system without any applied loads. This will result in a boundary element force equal to the mass of the structure; and (c) knowing the mass of the structure and the area the applied load acts on the appropriate acceleration for a given applied load can be computed to maintain equilibrum.

The pre-processor requires approximately 67.5k words of memory to process a finite element model consisting of 350 nodes, 300 elements, 5 different materials, 50 concentrated load/mass definitions, and 20 spring boundary elements. Larger models can be accommodated by increasing the size of the arrays.

III. REFERENCE MANUAL FOR POSTBOW

The post-processor, POSTBOW, allows the user to interactively review the finite element solution. Figure 3 depicts the screen layout for the post-processor. The solution is reviewed by randomly selecting menu items from the command menu. The post-processing capabilities of POSTBOW are summarized in Table 2 and a detailed description of the command menu is provided in Appendix B. As with the pre-processor, a menu item is selected by using the terminal thumbwheels or joystick to position the terminal crosshairs over the box containing the desired menu item. Some menu items query the user, by displaying a prompting message in the user communication area, for additional information.

POSTBOW currently resides on the BRL CYBER 70/Model 173 and can be accessed with the following NOS/BE control cards:

```
ATTACH,TAPE10,pfn*,ID=yourid.
ATTACH,LGO,OBJPOSTBOW,ID=KIMSEY.
BEGIN,PLOTII,PLOT10,LF=LGO.
```

*pfn = permanent file name of the file containing the SAP IV tape 10 dump. To get this dump N10SV of the SAP IV Master Control Card must be set to one.

Those items listed in Table 2 are not the only ones of interest to the design engineer. Other items such as shear, axial, and radial stress distributions can be readily incorporated into the post-processor. The post-processor requires approximately 61.4k words of memory to review a solution for model consisting of 300 elements.

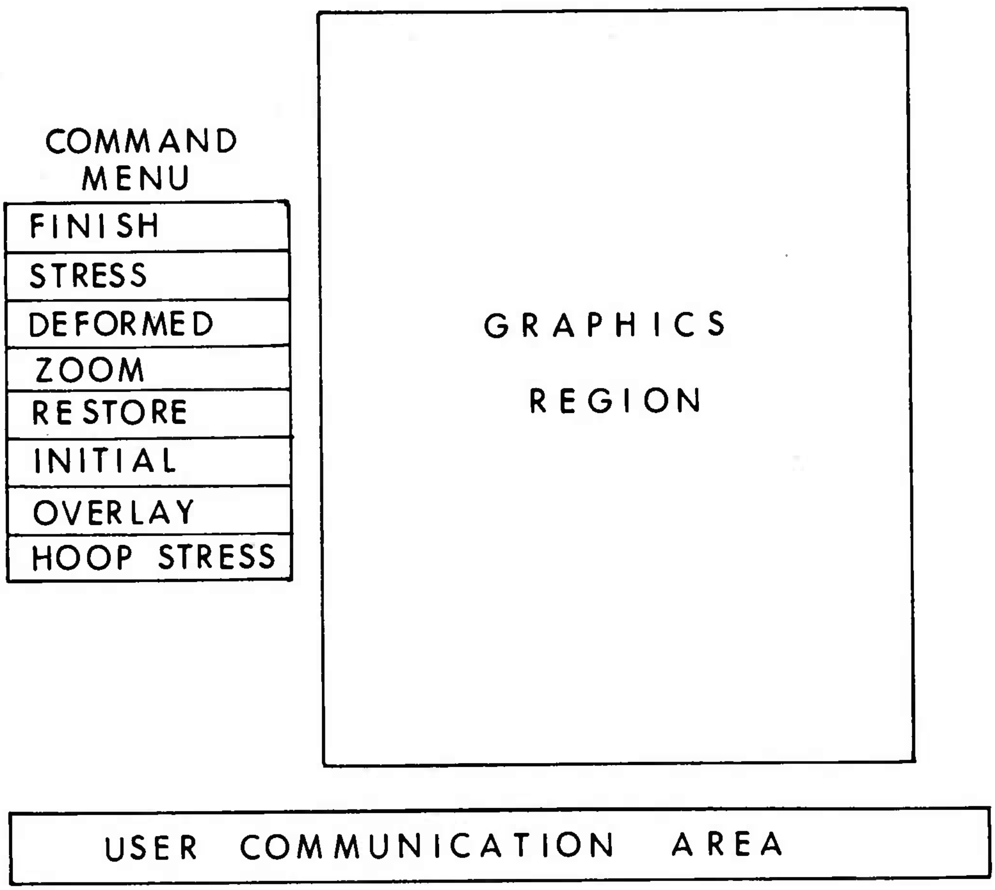

Figure 3. Post-processor screen layout

Table 2. Description of POSTBOW command menu

Menu Item	Function
FINISH	Exit from POSTBOW to the operating system.
STRESS	Plot effective stress for each element scaled to the overall maximum value.
DEFORMED	Plot element connectivity using deflected nodal point coordinates.
ZOOM	Enlarge a user specified region of the model.
RESTORE	Reset plotting limits to include the entire model, used after zooming.
INITIAL	Plot element connectivity using the underformed nodal coordinates.
OVERLAY	Superimpose an undeformed element connectivity plot and a deformed element connectivity plot.
HOOP STRESS	Plot the sense of the hoop stress for each element in the model.

REFERENCES

1. W.M. Newman and R.F. Sproull, Principles of Interactive Computer Graphics, McGraw-Hill, 1973.

2. K. Bathe, E.L. Wilson, and F.E. Peterson, "SAP IV A Structural Analysis Program for Static Dynamic Response of Linear Systems", Earthquake Engineering Research Center, EERC 73-11, June 1973.

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3. TEKTRONIX 4014 and 4014-1 Computer Display Terminal users Instruction Manual, TEKTRONIX Incorporated, July 1974.

Appendix A: Unabridged description of BOWGEN Command Menu

Menu Item: BND COND

Function: Assign boundary condition to nodal points.

Notes:

1. The user is queried for the starting and terminating node numbers of a linear string of node numbers for which the boundary conditions are to be assigned.

2. The user is queried for the boundary conditions;

   x-translation, y-translation, z-translation
   x-rotation, y-rotation, z-rotation CR*
   where 1 = fixed, 0 = free.

3. If an invalid node number is contained in the string it is ignored and the remainder of the string is processed.

* Throughout this appendix CR means carriage return to signify the transmission of information to the host computer.

Menu Item: ELM DEL

Function: Delete a specified element.

Notes:

1. Queries user for the element number of the element to be deleted.

2. Deleted element is annotated with a triangle.

3. When the element deletion phase is terminated some elements will have new element numbers.*

4. User is queried for a node or element plot upon termination of the element deletion phase.

* Several menu items query the user with the prompt, "(C or E)?". An "E" response will terminate the menu item currently being accessed.

Menu Item: ELM GEN

Function: Generate an axisymmetric element.

Notes:

1. User is queried for the 4 nodes defining the element. If a triangular element is generated the last two node numbers should be identical. The element is defined in a clockwise direction on the CRT.

2. User is queried for the material number of the generated element.

3. User is queried for the I-J face pressure of the generated element, see reference 2.

4. If an invalid node number is specified in the element definition the element is not generated and the user is again queried for the 4 nodes defining the element.

Menu Item: ELM PLT

Function: Plot element connectivity.

Notes:

1. User is queried, (Y or N), for plotting nodal point symbols, i.e. boundary conditions.

2. User is querried, (Y or N), for plotting the individual element numbers.

Menu Item: FINISH

Function: Exit from BOWGEN to the operating system.

Notes:

1. If a scratch copy of the finite element model was generated the local file TAPE99 should be cataloged as a permanent file. If not, any refinements to the finite element model will be lost.

Menu Item: MAT SHIFT

Function: Rigid body translation of a specified material.

Notes:

1. Queries user for the material number for which rigid body translation is to be preformed.

2. Queries user for the coordinate shift values ($\Delta x, \Delta y, \Delta z$), in units consistant with the model. Values must be separated by a comma, e.g. (10.2,4.6,5.0 CR).

3. Queries user, (Y or N), for clearing the shift table. Once a node is "shifted" a flag is set in the shift table signifying that the node has undergone a rigid body translation and unless the flag is cleared, (by clearing the shift table), no other rigid body translations will be applied to the node. This feature is primarily used for nodes along material interfaces in which the elements are unit and squares.

Consider the benchmark model in Figure A-1 (A) in which the elements are unit squares. In Figure A-1 (B) a unit shift, in the negative Z direction, has been applied to all nodes which define elements of material 2. The skewed material 1 elements in (B) can be corrected by applying another unit shift in the negative Z direction to all nodes which define elements of material 1, and <u>not</u> clearing the shift table. By not clearing the shift table in going from (B) to (C) those nodes common to both material 1 and material 2 elements are <u>not</u> "shifted" twice; i.e. once for the material 2 shift in (B) and again for the material 1 shift in (C). If the shift table is cleared in going from (B) to (C) the result would be as shown in (D). Figure A-1 (C) represents a rigid body translation of both materials and by deleting those elements in (C) which lie in negative Z and regenerating them in positive Z, a rigid body translation of material 2 relative to material 1 can be achieved as shown in (E).

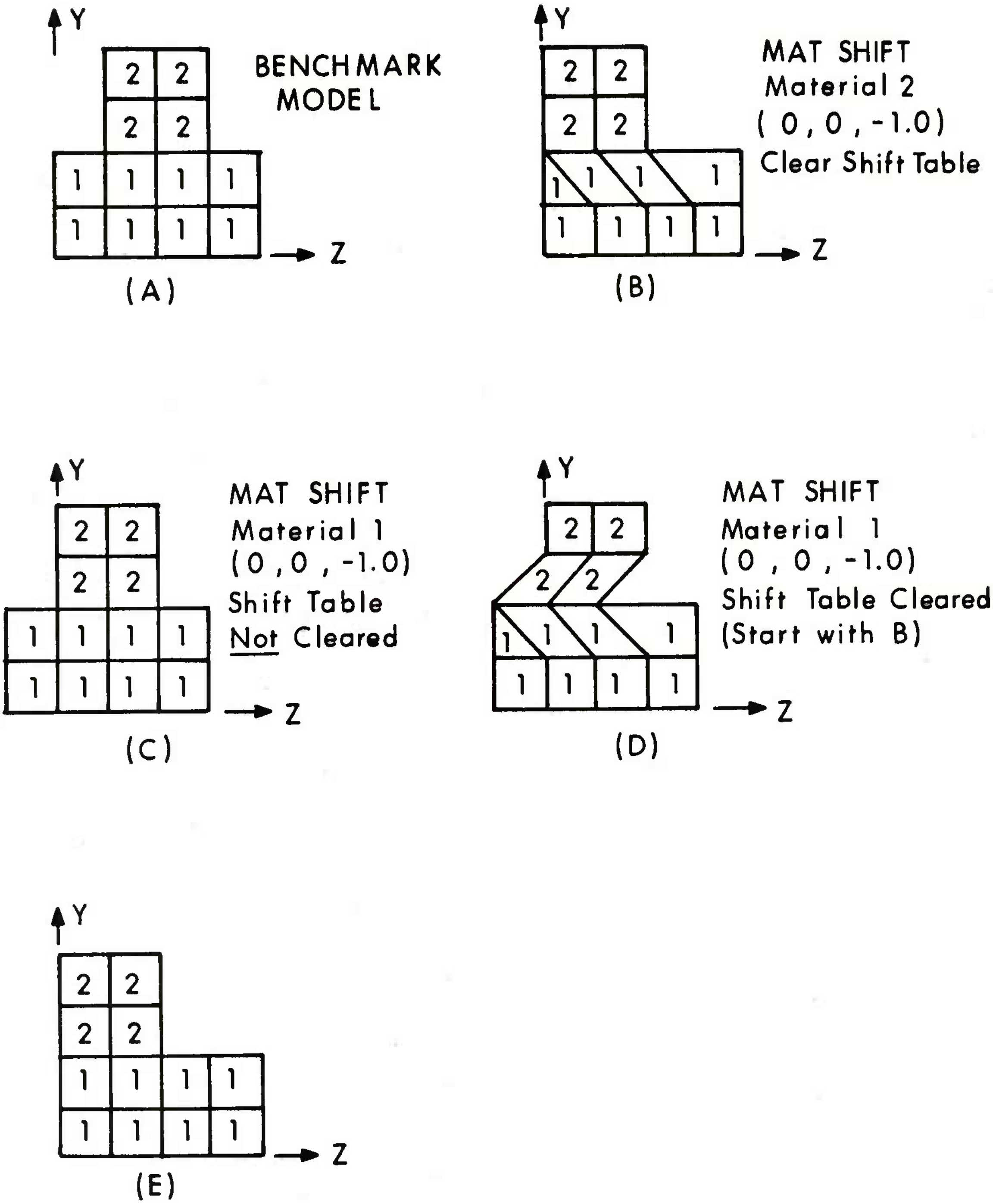

Figure A-1. Example use of MAT SHIFT menu item

<u>Menu Item</u>: NODE COORD

<u>Function</u>: Move a nodal point to coordinates entered via keyboard.

<u>Notes</u>:

1. User is queried for the node number of the node to be moved.

2. User is queried for the new X, Y, Z coordinates of the node, (e.g. 4.2,3.1,0.0 CR). If a value of -999. is specified for a coordinate, the old coordinate value is retained.

Menu Item: NODE DEL

Function: Delete a specified node.

Notes:

1. The user is queried for the total number of nodes to be deleted, (a maximum of 5 nodes can be deleted for each NODE DEL request).

2. User is queried for the individual node numbers of the nodes that are to be deleted.

Menu Item: NODE GEN

Function: Generate nodal points using the terminal crosshairs to define the coordinates.

Notes:

1. Terminal crosshairs will appear to define the location of the generated node. Simply position the crosshairs at the desired location, depress on alphanumeric key followed by CR.

2. The user is queried to accept or reject the generated node.

3. Queries user for the node number of the generated node.

4. The generated node is free to translate in Y and Z, all other degrees of freedom are fixed. BND COND can be used to alter the boundary condition.

Menu Item: NODE MOV

Function: Move a specified nodal point to the location specified by the terminal crosshairs.

Notes:

1. User is queried for the node number of the node to be moved.

2. When the crosshairs appear position them at the desired location, strike an alphanumeric key followed by CR.

Menu Item: NODE PLT

Function: Plot nodal points of the model.

Notes:

1. User is queried, (Y or N), to see if individual node numbers are to be plotted.

2. This menu item plots only nodal points, i.e. element connectivity is not plotted.

Menu Item: NODE TMP

Function: Assign a temperature value to a specified node.

Notes:

1. User is queried for the node number of the node for assigning a temperature value to.

2. User is queried for the nodal temperature.

Menu Item: ORIGINAL

Function: Reset the working finite element model to the benchmark model.

Notes:

1. Any modifications to the model up to this point are lost unless the SAV DATA menu item has been executed prior to executing this menu item.

2. The user is queried for a node or element plot once the benchmark model has been restored.

Menu Item: RESTORE

Function: Reset plotting limits to include the entire model, used after zooming.

Notes:

1. User is querried for a node or element plot after plotting limits have been reset.

Menu Item: SAV DATA

Function: Generate a scratch file copy of the current finite element model.

Notes:

1. User is queried, (Y or N), to see if the scratch file (TAPE99) is to be rewound before the current model is saved on the scratch file.

2. See note under FINISH menu item.

Menu Item: ZOOM

Function: Enlarge a specified region of the model.

Notes:

1. Crosshairs will appear to define the lower left and upper right hand corner of the region to be enlarged. Each corner is defined by positioning the crosshairs, striking an alphanumeric key followed by CR.

2. A zoom window is plotted and the user is queried, (Y or N), to see if this is the region to be enlarged. If not, the crosshairs will appear to define another zoom window.

Appendix B: Unabridged description of POSTBOW Command Menu

Menu Item: DEFORMED

Function: Plot geometry (elements) using nodal point coordinates computed after application of the load.

Notes:

1. User is queried, (Y or N), for plotting nodal point symbols, i.e. boundary conditions.

2. User is queried, (Y or N), for plotting the individual element numbers.

3. User is queried for the deflection magnification factor, FAC, (i.e. $X=X_0+FAC*\Delta X$).

Menu Item: FINISH

Function: Exit from the postprocessor to the operating system.

Menu Item: HOOP STRESS

Function: Plot the sense of the hoop stress for each element in the model.

Notes:

1. User is queried for the deflection magnification factor, FAC, (i.e. $X=X_0+FAC*\Delta X$).

2. A "+" symbol is plotted inside those elements that have a tensile hoop stress.

Menu Item: INITIAL

Function: Plot geometry (elements) using nodal coordinates for undeformed (initial) state.

Notes:

1. User is queried, (Y or N), for plotting nodal point symbols, i.e. boundary conditions.

2. User is queried, (Y or N), for plotting the individual element numbers.

Menu Item: OVERLAY

Function: Superimpose an undeformed element connectivity plot and a deformed element connectivity plot.

Notes:

1. See notes under DEFORMED and INITIAL menu items.

2. The deformed element connectivity is plotted first.

Menu Item: RESTORE

Function: Reset plotting limits to include the entire model, used after zooming.

Notes:

1. User is queried for a node or element plot after plotting limits have been reset.

Menu Item: STRESS

Function: Plot the effective stress scaled to the overall maximum value, for each element of the model.

Notes:

1. Queries user for the deflection magnification factor, FAC, (i.e. $X=X_0+FAC*\Delta X$).

2. The effective (generalized or von Mises) stress, $\bar{\sigma}$, is expressed in terms of the principal stresses σ_1, σ_2, σ_3, as

$$\bar{\sigma} = \left\{ \frac{1}{2} \left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2 \right] \right\}^{1/2}$$

The principal stresses are labled S33, S-MAX, and S-MIN in the SAP IV printout for TYPE 4 elements.

3. The effective stress for each element is scaled from 1 to 10 with 10 being the maximum effective stress found in the system. Thus, an element with a "4" plotted inside it would signify that the effective stress in that element is 31-40% of the overall maximum effective stress found in the system.

4. The overall maximum effective stress is displayed, in units consistant with the finite element model, above the graphics region of the post-processor screen layout (see Figure 3).

Menu Item: ZOOM

Function: Enlarge a specified region of the model.

Notes:

1. Crosshairs will appear to define the lower left and upper right hand corner of the region to be enlarged. Each corner is defined by positioning the crosshairs, striking an alphanumeric key followed by CR*.

2. A zoom window is plotted and the user is queried, (Y or N), to see if this is the region to be enlarged. If not, the crosshairs will appear to define another zoom window.

* Throughout this appendix CR means carriage return to signify the transmission of information to the host computer.

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